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Lake Changes in Inner Mongolia over the Past 30 Years and the Associated Factors

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Abstract: Lakes are important water resources in Inner Mongolia and play essential roles in flood storage, water source maintenance, aquaculture, water volume regulation, and the regional ecological balance. However, most lakes in Inner Mongolia have undergone significant shrinkage over the past few decades. In order to quantify the lake changes in Inner Mongolia and analyze the factors associated with these changes, information about 546 lakes in seven years (1990, 1995, 2000, 2005, 2010, 2015, and 2018) was retrieved using 30 m resolution Landsat images taken of the entire region over 29 years (1989–2018). In addition, water census data from 2010 and 1:250,000 geological maps were used as references. The analysis revealed that the lakes in Inner Mongolia exhibited rapidly decreasing trends during the past three decades, with both the area and the number of lakes decreasing to a minimum by 2010. The number of lakes with areas of >1 km^2 decreased from 384 in 1990 to 301 in 2018; the total area of lakes with individual areas of >1 km^2 decreased from 4905.74 km^2 in 1990 to 4187.45 km^2 in 2018. With respect to the lake distribution among different geomorphological units, the analysis revealed that the lake shrinkage was most pronounced on the West Liaohe Plain, followed by the northern Inner Mongolian Plateau. Furthermore, in relation to different climatic zones, lake shrinkage primarily occurred in the mid-temperate semi-arid zone, wherein the lake area decreased by 776.6 km^2. We hypothesize that the changes in the lake number and area in Inner Mongolia resulted from the combined effects of natural conditions and anthropogenic disturbances; possibly, lake shrinkage was mainly driven by the rising temperature and decreasing precipitation, along with water regulation projects, agricultural irrigation, mining development, and population growth that also had non-negligible effects on the lakes.

Keywords: Inner Mongolia; lake shrinkage; climate change; human activities; agricultural irrigation; mining

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1. Introduction

Lakes are nodes for interactions between the various components of the terrestrial surface system. As they serve as important freshwater reservoirs, flood-regulating reservoirs, and species gene pools on Earth, lakes play irreplaceable roles in maintaining the ecological balance of watersheds, conserving water sources, holding soil and water, preventing floods and droughts, regulating climate, and maintaining biodiversity [1–3]. China has a vast territory and contains a large number of lakes, including 2759 lakes with individual areas of more than 1 km^2 and a total combined area of 91,019.6 km^2, according to the Records of Chinese Lakes [4]. These lakes are mainly distributed in five major lake areas: the East Plain, Qinghai–Tibet Plateau, Yunnan–Guizhou Plateau, Mongolia–Xinjiang Plateau, and Northeast Plain and mountains [5,6]. In recent years, climate change and continuous rapid socioeconomic development coupled with irrational exploitation by humans have prompted lake shrinkage and even disappearance [7–9]. Statistics [10] show that the areas of 229 lakes in China with individual areas greater than 10 km^2 have shrunk by a total of 13,776 km^2, including 89 dried-up lakes that had a combined area of 4289 km^2. In addition, nearly 1000 natural lakes in China have disappeared due to the country's nationwide lake reclamation project.

Inner Mongolia, located on the Mongolian Plateau within the hinterland of the Eurasian continent, mostly comprises arid and semi-arid zones, with a typical mid-temperate monsoon climate. Owing to its special geographical conditions, it is home to several particularly vulnerable lake ecosystems in China [11,12]. In recent years, the areas of the lakes in this region have been shrinking due to climate change and human activities, and some lakes have even dried up. For example, a study by Academician Fang focusing on the shrinkage of lakes on the Mongolian Plateau [13] revealed that the number of lakes in Inner Mongolia has decreased by 145 (34.0%) over the past 30 years, whereas the total area of lakes has decreased by about 30.3%, from 4160 km^2 around 1987 to 2901 km^2 in 2010, exhibiting a rapidly decreasing trend. Furthermore, numerous studies conducted in Inner Mongolia and lakes have found stark decreases in the total lake areas over the past 50 years. Zhang et al. [14] found that the lake area in the hinterland of the Badain Jaran Desert decreased by 3.69 km^2 during 1973–2010. In another study, Wang et al. [15] showed that the area of the Wuliangsuhai Lake decreased by about 20 km^2 during 1960–2010. Liu et al. [16] discovered that the area of the Daihai Lake decreased by 89.01 km^2 during 1976–2015. Bai et al. [17] found that the area of the lakes in the Hunsandake Sandy Land decreased by 198.62 km^2 during 1969–2013. In their study, Yang et al. [18] reported that the area of the Dalai Nur Lake decreased by 25 km^2 during 1985–2014. Additionally, Zhao et al. [19] showed that the area of the Hulun Lake decreased by 436.06 km^2 during 1986–2012. Jia et al. [20] found that the area of lakes in the dune–meadow ecotone of the Horqin Sandy Land decreased by 9.378 km^2 during 1986–2012.

Along with the declining water levels and shrinkage of the lake areas in Inner Mongolia, wetland area shrinkage, lake water imbalance, land desertification, and eco-environmental deterioration are becoming increasingly severe problems. In fact, the lakes are gradually proving themselves to be the most vulnerable, influential, and difficult-to-manage geographical unit in terms of the interactions between human society and the natural environment [21–23]. In this study, we examined 546 lakes in Inner Mongolia using multi period remote sensing data, measured the lake number, area, and distribution during seven specific years since 1990, analyzed the lakes' change characteristics, and discussed the impacts of climate change and human activities on these changes, as well as the precipitation, temperature data, and the main modes of human production activities in Inner Mongolia. The findings from this study can improve our understanding of the current situation and the changing lake trends in this region. Notably, this is important for maintaining human survival and environmental security in the region.

2. Description of the Study Area

Inner Mongolia is located along the northern border of China, extending obliquely from the northeast to the southwest in a narrow fashion, with a length of about 2400 km from east to west and spanning more than 1700 km from north to south at its maximum, covering a total area of 1.183 million km^2. Due to its geographical location and topography, the entire region has a complex and diverse climate, dominated mainly by a temperate continental monsoon climate with an annual precipitation of 100–500 mm and generally more than 2700 h of sunshine per year.

There are more than 1000 rivers in Inner Mongolia, of which 107 have a watershed area of more than 1000 km^2 each. The Yellow River, Argun River, Nengjiang River, and West Liaohe River are the four major rivers. The lakes in Inner Mongolia span a large geographical area and are scattered throughout the region, but they are mainly located in the Hulun Buir Plateau, the West Liaohe Plain, the Xilingole Plateau, the Wulanchabu Plateau, the Hetao Plain, and the Ordos Plateau, as well as in the hilly areas. Most of the lakes in Inner Mongolia are small and shallow. A few are freshwater lakes, but most are salt lakes. Only a few lakes that receive river runoff and groundwater recharge have large surface areas and depths. In particular, the only lake with an area greater than 1000 km^2 is the Hulun Lake; the Buir Lake has an area of 500–1000 km^2 and is shared by China and Mongolia; the other large lakes are the Wuliangsuhai Lake, Dalinuoer Lake, Chagannor Lake, Daihai Lake, and Huangqihai Lake, which have areas ranging from 100–500 km^2. Notably, more than 80% of the lakes in Inner Mongolia are salt lakes, making this an important distribution area of salt lakes in China.

3. Data and Methods

3.1. Data Sources

Landsat thematic mapper/enhanced thematic mapper/orbital land imager (TM/ETM/OLI) remote sensing images with 30 m resolution and covering the entire region were collected for 29 consecutive years (1989–2018). In order to estimate the maximum area of each lake in each year, the high-water period from June–August in Inner Mongolia was selected as the monitoring period for all years. To better analyze the change process and development trend of the lakes throughout a certain period of time and to consider the lake changes between different years, seven years (1990, 1995, 2000, 2005, 2010, 2015, and 2018) were selected for region-wide data analysis. The meteorological data were obtained from the China Meteorological Data Sharing Network, and the annual average precipitation and temperature data were procured from 69 meteorological stations active across the region from 1970–2017.

3.2. Lake Analysis

Due to the cloudy weather characteristic of the high-water period from June–August, images with low or no cloud cover for a given geographical site within this period could only be obtained by synthesizing images of the same geographical site during the same period over 3 consecutive years. For example, the synthesized images for 1995 were based on the raw images acquired in June–August of 1994, 1995, and 1996 (though mainly 1995), and the synthesized images for 2018 were based on the raw images acquired in 2017 and 2018, primarily during the period of May–August.

By analyzing 7 years' image data, such as by feature image construction, water sample selection, intelligent detection of water bodies, classification post-processing (removal and correction of false spots), manual editing optimization, and summary statistics, information on 546 lakes was compiled from the lake images captured by Landsat. The water census data for 2010 and 1:250,000 geological maps were used as references. Of the 546 lakes, 468 were included in the census data and 78 were new lakes identified by interpretating the remote sensing images.

4. Results

4.1. Changes in the Area of the Lakes

The total lake areas in 1990, 1995, 2000, 2005, 2010, 2015, and 2018 are listed in Table 1. It is evident that the total lake area generally exhibited a decreasing trend, with a decrease of 859.43 km^2 (17.31%) during 1990–2010, i.e., from 4965.35 km^2 in 1990 to 4105.92 km^2 in 2010. The lake areas increased slightly during 2010–2018, with an increase of 186.46 km^2 (4.54%). In summary, the net decrease during 1990–2018 was 672.97 km^2, with a mean annual decrease of 24.03 km^2 (13.55%).

Table 1. Changes in lake area in Inner Mongolia during 1990–2018.

Year	Total Lake Areas (km^2)	Area of Lakes with Individual Areas of >1 km^2 (km^2)							Area of Lakes with Individual Areas of <1 km^2 (km^2)		
		Sum	>500 km^2	500–100 km^2	100–10 km^2	10–5 km^2	5–3 km^2	3–1 km^2	Sum	<0.5 km^2	<0.2 km^2
1990	4965.35	4905.24	2107.15	1229.98	582.26	358.67	220.08	407.10	60.11	11.85	4.15
1995	4981.23	4919.48	2109.11	1180.01	656.00	297.06	264.62	412.69	61.75	12.66	2.99
2000	4930.87	4864.15	2102.31	1072.10	692.66	324.76	248.64	423.68	66.72	12.03	2.41
2005	4358.51	4280.56	2039.90	757.40	620.28	277.49	186.45	399.04	77.95	15.66	3.92
2010	4105.92	4014.97	1871.28	673.04	683.00	250.67	167.88	369.10	90.95	19.30	4.64
2015	4270.72	4187.40	2074.40	647.04	622.46	266.35	208.90	368.24	83.31	17.24	4.51
2018	4292.38	4187.45	2083.67	666.16	708.12	183.47	226.28	319.76	104.93	23.41	4.11

From 1990 to 2018, the total area of the lakes with individual areas of >1 km^2 exhibited a general decline, decreasing from 4905.24 km^2 in 1990 to 4014.97 km^2 in 2010, and then rebounding to 4187.45 km^2 in 2018, with a net decrease of 14.63%. Among these lakes, the following trends were observed: (1) The total area of one lake with an area of >500 km^2 decreased and then increased, reaching a minimum in 2010 and then rebounding and essentially recovering to its normal state. (2) The total area of six lakes with individual areas of 100–500 km^2 decreased annually and reached a minimum in 2015, with a net decrease of 563.82 km^2 (45.84%). (3) Conversely, the total area of 25 lakes with individual areas of 10–100 km^2 generally increased, with a net growth of 125.86 km (21.62%). (4) The total areas of 50 lakes with individual areas of 5–10 km^2 and of 243 lakes with individual areas of 1–3 km^2 exhibited decreasing trends, shrinking by 175.2 km^2 and 87.34 km^2 (48.85% and 21.45%), respectively. (5) Lastly, the total area of 58 lakes with individual areas of 3–5 km^2 exhibited a minimal net change, as the lakes experienced an increase from 1990–2000, a decrease from 2000–2010, and then a rebound from 2010–2018.

During the period of 1990–2018, the total area of the lakes with individual areas of <1 km^2 generally increased, from 60.11 km^2 in 1990 to 104.93 km^2 in 2018, a net increase of 74.56%.

4.2. Changes in the Number of Lakes

The analysis results (Table 2) revealed that the total number of lakes with individual areas of >1 km^2 increased and then subsequently decreased during 1990–2018, increasing from 384 in 1990 to 397 in 2000, and then decreasing to 323 in 2010 and 301 in 2018, with net decreases of 61 (15.9%) and 83 (21.6%) during 1990–2010 and 1990–2018, respectively. Additionally, the total number of lakes in 2018 was 29.5% lower than that reported in 1987 [13]. Compared with the data for 1987, the following changes were observed in 2018: (1) The number of lakes with individual areas of >500 km^2 remained unchanged (i.e., one). (2) Conversely, the number of lakes with individual areas of 100–500 km^2 decreased from six to three. (3) The number of lakes with individual areas of 10–100 km^2 remained basically unchanged. (4) Additionally, the number of lakes with individual areas of 5–10 km^2 decreased annually, with a total decrease of 24 since 1990. (5) The number of lakes with individual areas of 3–5 km^2 fluctuated. (6) Lastly, the number of lakes with individual areas of 1–3 km^2 decreased the most (by 57), accounting for 68.67% of the total decrease in the combined number of lakes.

Table 2. Changes in the number of lakes in Inner Mongolia during 1990–2018.

Year	Total Lake Numbers	Number of Lakes with Individual Areas of >1 km^2							Number of Lakes with Individual Areas of <1 km^2		
		Sum	>500 km^2	500–100 km^2	100–10 km^2	10–5 km^2	5–3 km^2	3–1 km^2	Sum	<0.5 km^2	<0.2 km^2
1990	513	384	1	6	24	51	59	243	129	69	44
1995	519	391	1	6	31	42	69	242	128	65	35
2000	525	397	1	4	29	46	65	252	128	59	31
2005	527	358	1	4	25	41	50	237	169	86	50
2010	519	323	1	3	25	37	44	213	196	105	60
2015	520	335	1	3	24	37	54	216	185	98	59
2018	527	301	1	3	27	27	57	186	226	119	63

From 1990 to 2018, the number of lakes with individual areas of <1 km^2 increased, from 129 in 1990 to 226 in 2018, a net gain of 75.19%. In particular, the number of lakes with water surface areas of <0.5 km^2 decreased from 69 in 1990 to 59 in 2000, and then rose to 119 in 2018, a net increase of 72.46%. The number of lakes with water surface areas of <0.2 km^2 (nearly or completely dried-up) also exhibited a decreasing–increasing trend, i.e., initially decreasing from 44 in 1990 to 31 in 2000, and then rebounding to 63 in 2018, with an overall net increase of 43.18% in 1990–2018.

4.3. Changes in Lakes in Different Geomorphological Units

Inner Mongolia is divided into eight geomorphological units, namely, the Daxinganling Mountains, the West Liaohe Plain, the northern Inner Mongolian Plateau, the Yinshan Mountains, the Hetao Plain, the Ordos Plateau, the Alxa Plateau, and the deserts [24,25], with each unit having a characteristic pattern of temporal variations in the number and area of its lakes (Figure 1).

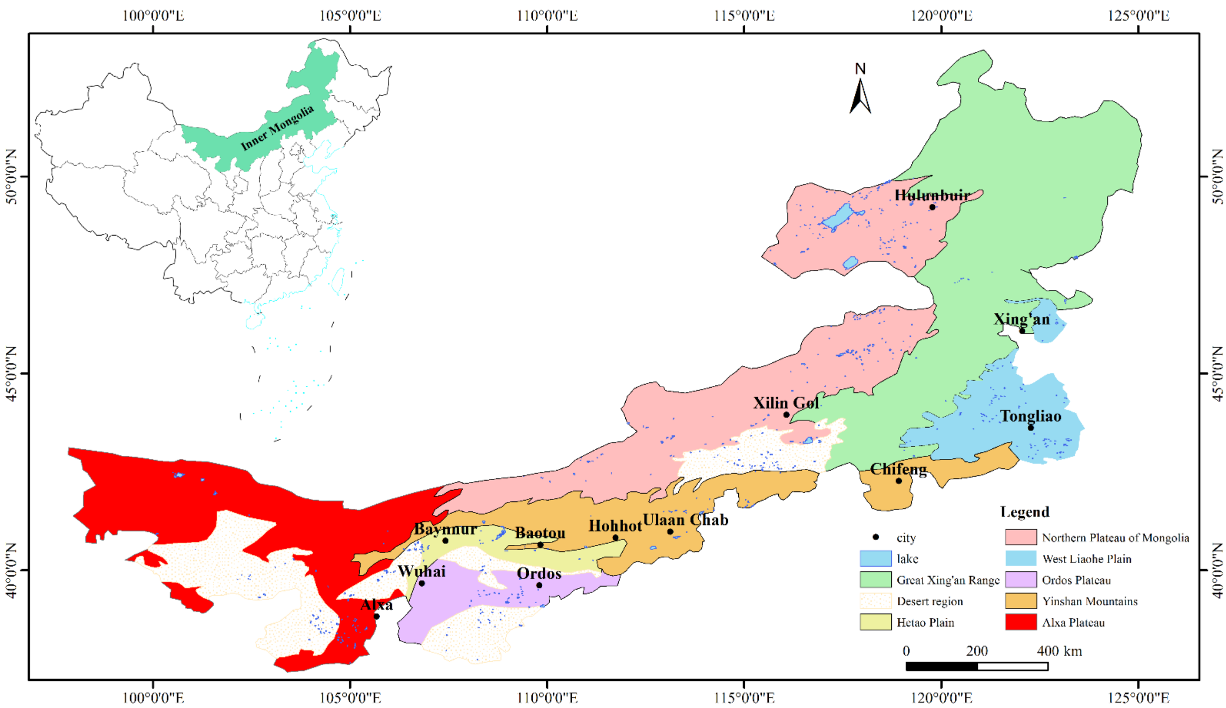

Figure 1. Distribution of lakes in the different geomorphological units in Inner Mongolia.

As for the temporal variations in the number of lakes within the different geomorphic units (Table 3), during 1990–2018, the number of lakes with individual areas of >1 km^2 decreased in the northern Inner Mongolian Plateau region, the desert zone, the West Liaohe Plain, the Yinshan Mountains, and the Daxinganling Mountains. Among these regions, the number of lakes in the West Liaohe Plain experienced the most significant decrease of 79 to 36 (54.43%), followed by that on the northern Inner Mongolian Plateau, which declined from 149 to 117 (21.47%). The temporal trend associated with the number of lakes within the desert zone consisted of two stages. Stage 1 involved an annually increasing trend during 1990–2000, with an overall increase of eight in the entire desert region, four of which occurred in the Mu Us Desert. Stage 2 was characterized by an annually decreasing trend during 2000–2018, with an overall decrease of 17 throughout the entire desert region, where the greatest decrease (of four lakes) occurred in the Hunshandake Desert. The overall trend associated with the number of lakes within the Yinshan Mountains also consisted of two stages. In Stage 1, the number of lakes increased during 1990–2005; in stage 2, it decreased during 2005–2018. The number of lakes on the Hetao Plain, the Ordos Plateau, and the

Alxa Plateau all increased, with the Alxa Plateau experiencing the largest gain of seven lakes (87.5%), from eight in 1990 to 15 in 2018.

Table 3. Number of lakes with individual areas of >1 km^2 in the different geomorphological units.

Year	Daxinganling Mountains	West Liaohe Plain	Northern Inner Mongolian Plateau	Yinshan Mountains	Hetao Plain	Ordos Plateau	Alxa Plateau	Deserts
1990	15	79	149	23	16	27	8	67
1995	14	78	141	26	20	28	10	74
2000	14	67	158	25	19	27	12	75
2005	13	56	131	26	19	27	12	74
2010	11	40	128	24	18	25	11	66
2015	12	47	136	21	18	26	10	65
2018	11	36	117	19	17	28	15	58

As is shown by the temporal distribution of the lake areas throughout the different geomorphological units (Table 4), the total area of the lakes with individual areas of >1 km^2 decreased during 1990–2018, except for that on the Hetao Plain and the Ordos Plateau, where the total area remained generally stable. In particular, the lake area on the West Liaohe Plain decreased most significantly, by nearly 50% (i.e., 49.18%). During 1990–2010, the total area of the lakes with individual areas of >1 km^2 decreased by different degrees depending on the geomorphological units, with the greatest reduction occurring on the northern Inner Mongolian Plateau, where the lake area decreased from 3121.81 km^2 to 2527.85 km^2 (19.03%). During 2010–2018, the lake area continued to decline in the Daxinganling Mountains, the West Liaohe Plain, the Yinshan Mountains, and the desert zone. Specifically, the Yinshan Mountains experienced the largest decrease of 54.98 km^2 (24.41%), from 225.25 km^2 to 170.27 km^2. Contrastingly, on the northern Inner Mongolian Plateau, the total lake area increased by 189.09 km^2 (7.48%), from 2527.85 km^2 to 2716.94 km^2.

Table 4. Total area of lakes with individual areas of >1 km^2 in the different geomorphological units.

Year	Daxinganling Mountains	West Liaohe Plain	Northern Inner Mongolian Plateau	Yinshan Mountains	Hetao Plain	Ordos Plateau	Alxa Plateau	Deserts
1990	72.58	238.36	3121.81	286.75	367.72	167.73	228.97	422.33
1995	70.85	250.35	3090.62	288.14	399.19	187.91	161.76	470.67
2000	62.88	215.67	3255.58	262.13	379.43	170.60	68.41	451.60
2005	61.14	168.51	2592.80	255.56	378.29	153.70	219.79	450.78
2010	57.41	129.57	2527.85	225.25	362.44	142.56	157.41	412.48
2015	59.00	154.94	2773.17	197.37	366.75	130.04	114.65	391.49
2018	52.83	120.63	2716.94	170.27	388.55	170.84	197.36	370.03

4.4. Changes in Lakes in Different Climatic Zones

According to the climate zoning scheme for China, Inner Mongolia is divided into five climate zones: mid-temperate arid, mid-temperate semi-arid, mid-temperate semi-humid, mid-temperate humid, and cold temperate humid zones [26]. The studied lakes were mainly distributed in the mid-temperate arid, mid-temperate semi-arid, and mid-temperate semi-humid zones (Figure 2); the temporal variations in the number and area of the lakes exhibited different trends depending on the climate zones (Table 5).

In the mid-temperate arid zone, the number and area of the lakes displayed increasing trends. During 1990–1995, the number of lakes increased rapidly from 106 to 119 (10.9%), and the area of the lakes increased from 627.86 km^2 to 642.80 km^2. Conversely, during 1995–2010, the number of lakes fluctuated, diminishing slightly from 119 to 116, and the total area of the lakes decreased from 642.80 km^2 to 583.82 km^2. During 2010–2018, the number of lakes increased from 116 to 125 (7.2%), and the area of the lakes grew by 25.13% or 146.71 km^2, from 583.82 km^2 to 730.53 km^2.

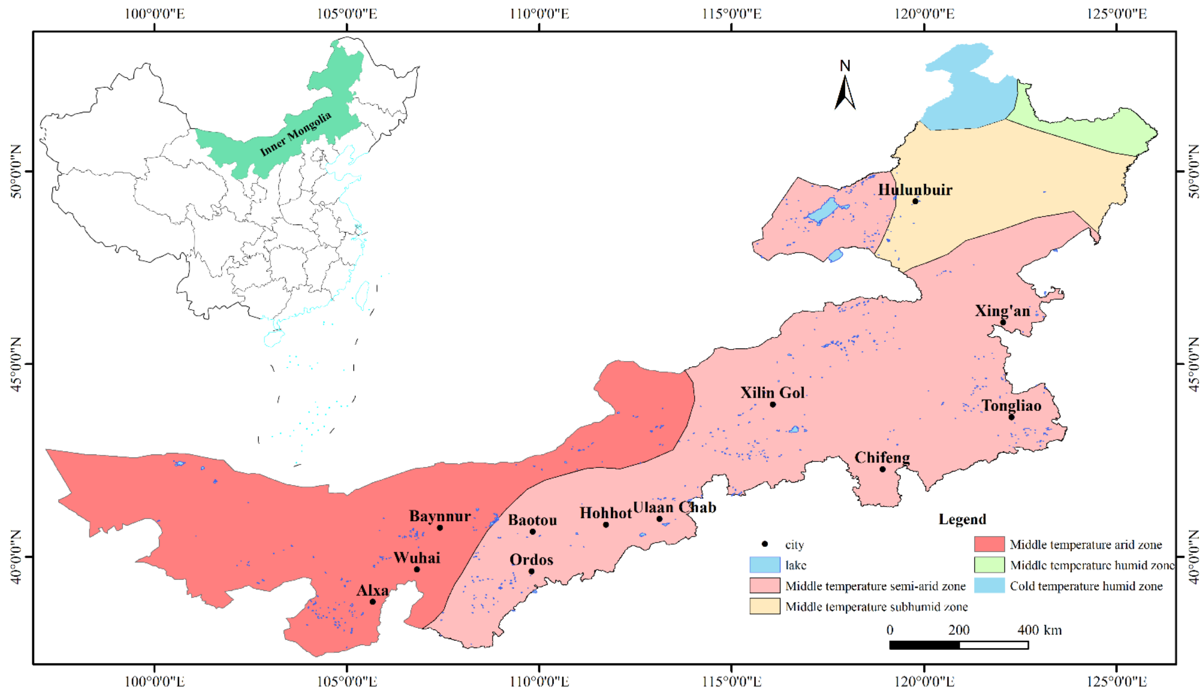

Figure 2. Distribution of lakes in the different climatic zones in Inner Mongolia.

Table 5. Number and area of lakes in the different climatic zones.

Year	Mid-Temperate Semi-Arid Zone		Mid-Temperate Arid Zone		Mid-Temperate Semi-Humid Zone	
	Number of Lakes	Area of Lakes/km^2	Number of Lakes	Area of Lakes/km^2	Number of Lakes	Area of Lakes/km^2
1990	389	4292.06	106	627.86	18	45.43
1995	383	4298.68	119	642.80	17	39.75
2000	390	4366.05	117	520.13	18	44.69
2005	389	3630.16	120	683.26	18	45.10
2010	385	3484.81	116	583.82	18	37.29
2015	386	3673.67	117	549.57	17	47.48
2018	384	3515.46	125	730.53	18	46.38

In 1990, the number and area of the lakes in the mid-temperate semi-arid zone accounted for 75.8% and 91.4%, respectively, of those in the entire region. During 1990–2000, the number of lakes remained relatively stable, decreasing from 389 to 390, while the area of lakes increased from 4292.06 km^2 to 4366.05 km^2. During 2000–2010, both the number and area of the lakes declined, with the number of lakes decreasing from 390 to 385 and their total area shrinking by 20.2% (881.24 km^2), from 4366.05 km^2 to 3484.81 km^2. After 2010, the number and area of the lakes gradually steadied, with the number stabilizing at a lower value of 384 and the area at a slightly higher value of 3515.46 km^2.

Both the number and area of the lakes in the mid-temperate semi-humid zone varied only slightly. The number of lakes remained at 18 for each year, except in 1995 and 2015 when the number was 17. The area stabilized between 40 and 50 km^2 in each year, except for 2010, which had a low value of 37 km^2.

5. Discussion

5.1. Impact of Climatic Conditions on Lakes

5.1.1. Precipitation

Over the past 50 years, the precipitation inclination rates at 69 meteorological stations in Inner Mongolia (Figure 3) were positive in the western region and in parts of northeast, indicating increased precipitation in these areas. In contrast, the precipitation inclination rate was negative in central Inner Mongolia and in the Hailar district in the northeast, indicating decreased precipitation in these areas. The specific rates of increase or decrease in the precipitation varied among the areas.

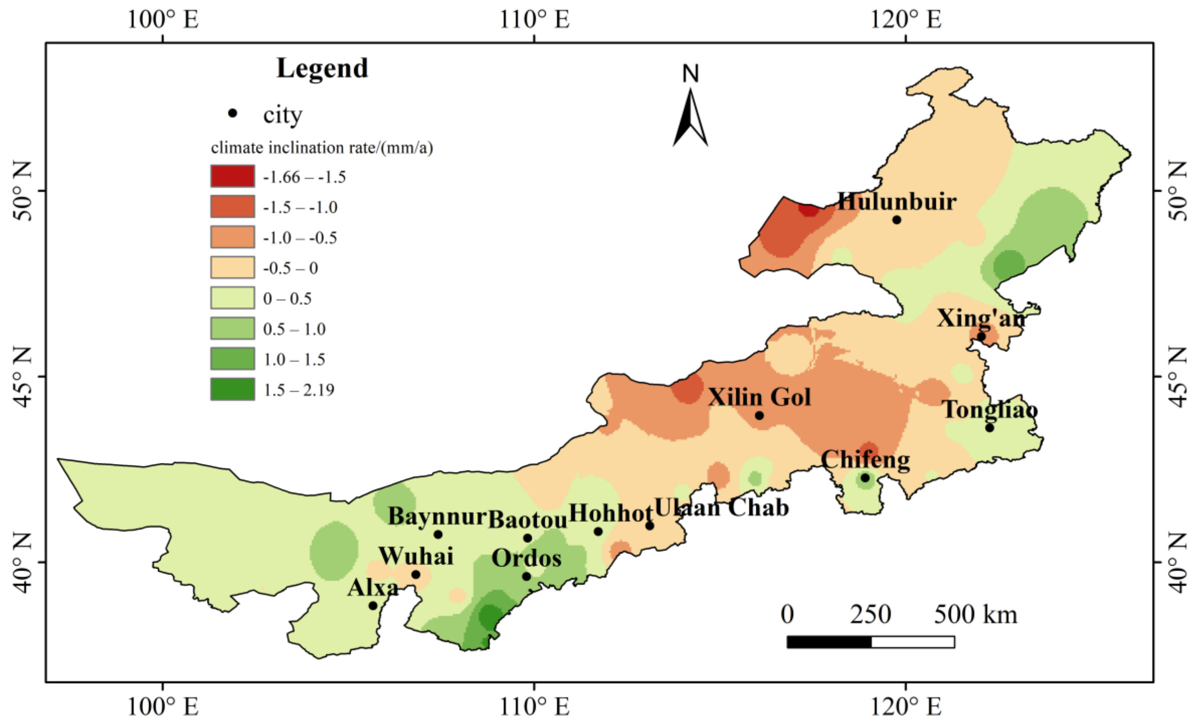

Figure 3. Precipitation inclination rate in Inner Mongolia during 1970–2017.

An interdecadal analysis of the precipitation measured by all the meteorological stations in Inner Mongolia over the past 40 years (Figure 4) revealed that the precipitation trends in the entire region were as follows: (1) Compared with the 1970s, the 1980s saw a precipitation decrease throughout most of Inner Mongolia, except for an increase at five stations in the northeast. (2) Compared with the 1980s, in the 1990s, the precipitation increased throughout most the region (by 0–50 mm), except for some areas in northeastern Inner Mongolia. (3) Unlike in the 1990s, in the 2010s, the precipitation declined throughout most the region to varying degrees, especially in the eastern region where the decrease was as large as 100–161.5 mm; however, a limited number of areas experienced a slight increase in precipitation. (4) After 2010, the precipitation increased (to varying degrees) throughout most of the region, except for a limited number of areas. This trend in precipitation is consistent with the dynamics in the number and area of the lakes during the 1990–2018 period.

5.1.2. Temperature

The temperature inclination rates in Inner Mongolia over the last 50 years (Figure 5) were positive across all the meteorological stations, indicating that, throughout the entire region, the temperature continuously increased over the nearly 50-year period from 1970–2017. Notably, the temperature increased at an average rate of 0.043 °C/a, and it increased by more than 2 °C in some areas. The slope of the increasing temperature trend varied among the regions. It was relatively high (0.3–0.5 °C/10 a) in central and western Inner Mongolia, where the temperature increased rapidly, whereas in the northeastern region, the slope of the increasing trend was relatively small, and the temperature rose slowly.

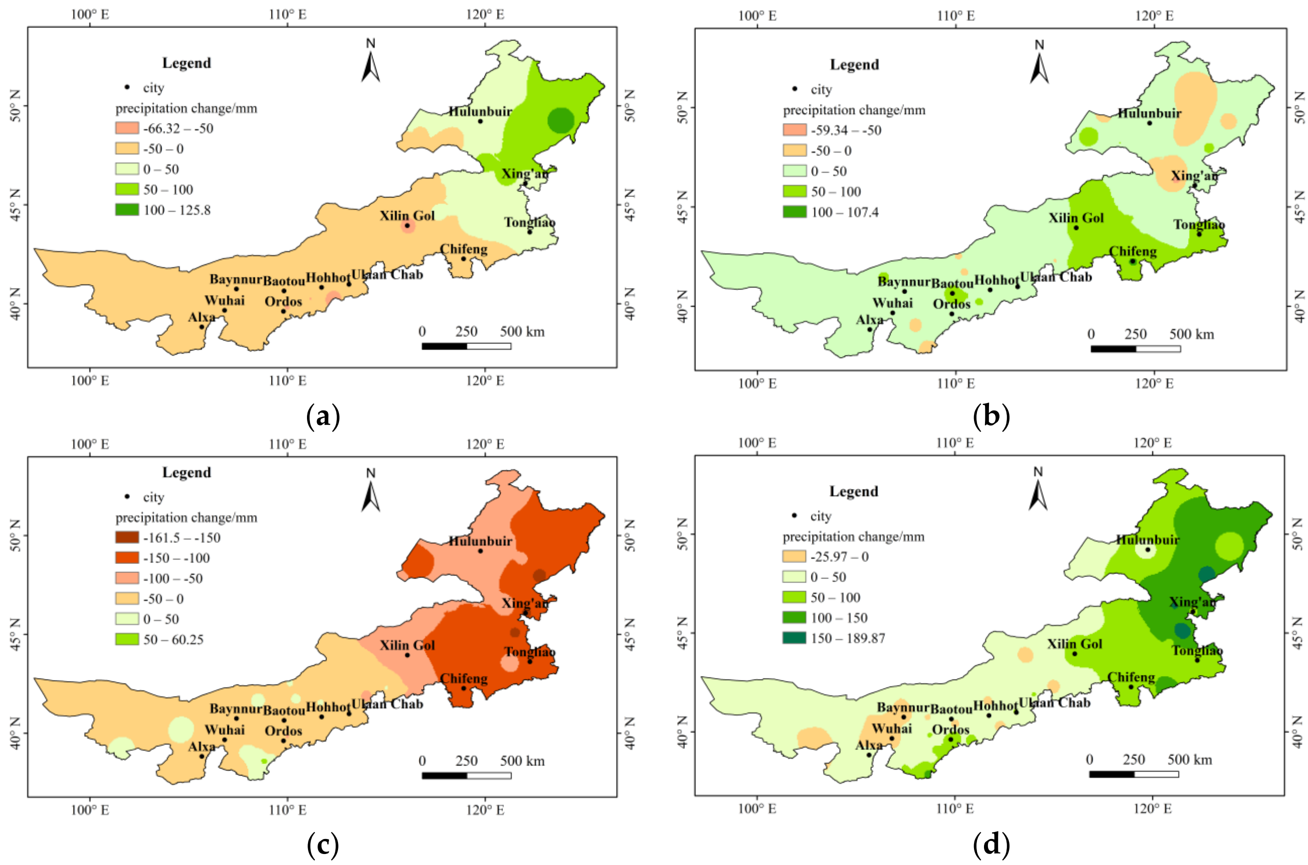

Figure 4. Precipitation changes in Inner Mongolia during different periods. (**a**) Description of precipitation changes in Inner Mongolia in the 1980s and 1970s; (**b**) Description of precipitation changes in Inner Mongolia in the 1990s and 1980s; (**c**) Description of precipitation changes in Inner Mongolia in the 2000s and 1990s; (**d**) Description of precipitation changes in Inner Mongolia from 2011–2017 and in the 2000s.

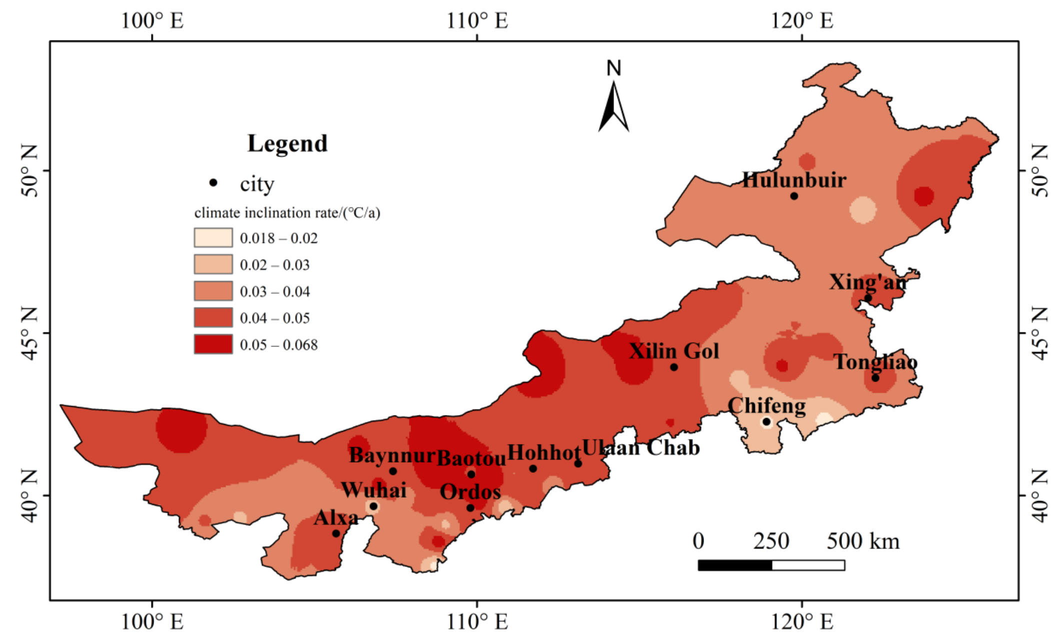

Figure 5. Temperature inclination rate in Inner Mongolia during 1970–2017.

The decade-average temperature was calculated for each meteorological station in Inner Mongolia, and the differences between the average values for two successive decades were calculated to compare the trend in temperature changes within each region over the different decades (Figure 6). Compared with the 1970s, the 1980s saw temperature increases throughout most of Inner Mongolia, with an average increase of less than 0.5 °C; however, some of the meteorological stations recorded temperature decreases. Compared with the 1980s, in the 1990s, the temperature increased throughout the entire Inner Mongolia, with an average increase of more than 0.75 °C. This phenomenon was more pronounced in Hailar, Manzhouli, Xinbaerhuzuoqi, Xinbaerhuyouqi, and other areas in the northeast, where the increases were large (>1 °C). Unlike in the 1990s, in the 2000s, the temperatures continued to increase throughout most areas in Inner Mongolia; however, the increase was relatively small (mostly below 0.5 °C). After 2010, western Inner Mongolia experienced a slight increase in temperature, whereas the temperature decreased in both central and northeastern Inner Mongolia. In general, the temperature in Inner Mongolia has continuously risen in almost all areas of the region since the 1980s, with particularly drastic increases in the 1990s, yet some areas experienced a certain temperature decrease after 2010.

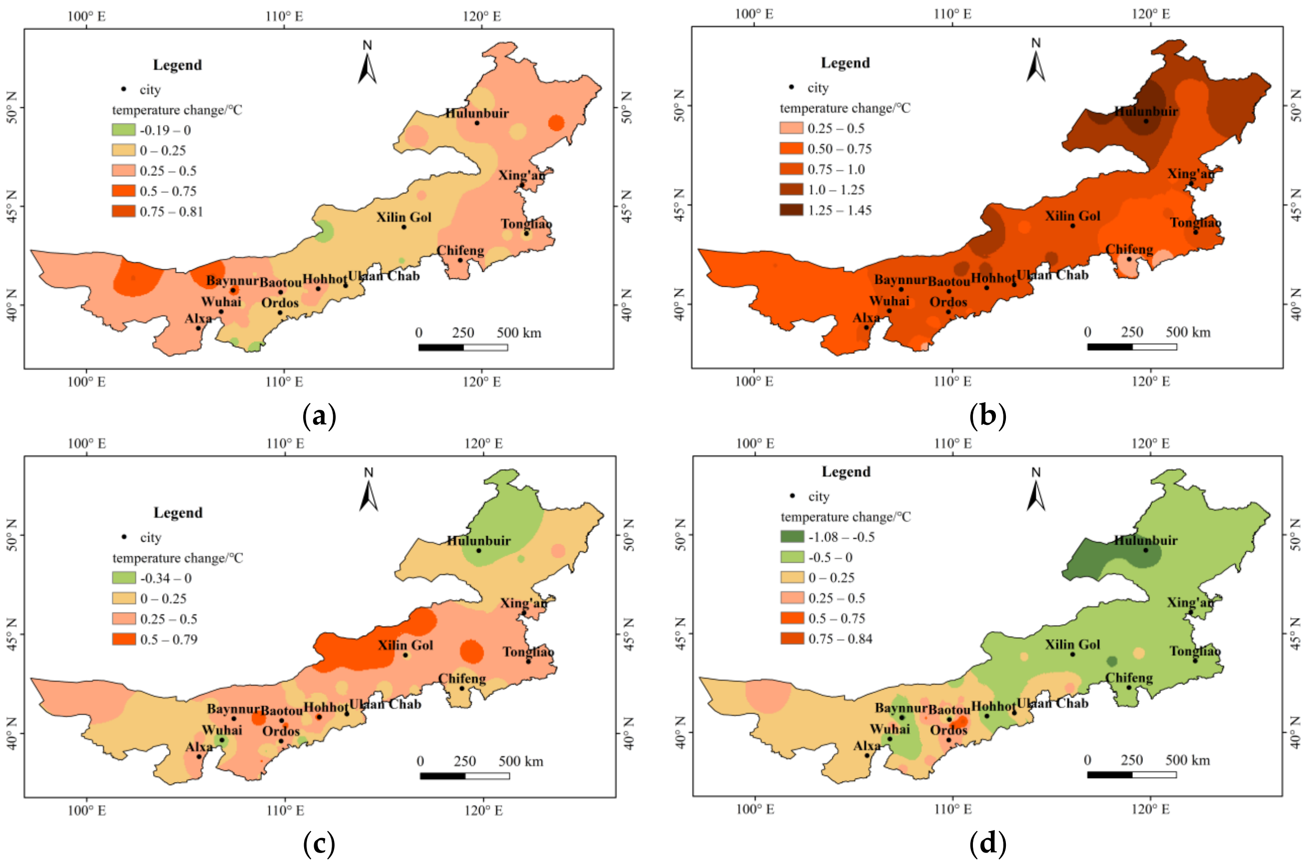

Figure 6. Temperature changes in Inner Mongolia during different periods. (**a**) Description of temperature changes in Inner Mongolia in the 1980s and 1970s; (**b**) Description of temperature changes in Inner Mongolia in the 1990s and 1980s; (**c**) Description of temperature changes in Inner Mongolia in the 2000s and 1990s; (**d**) Description of temperature changes in Inner Mongolia from 2011–2017 and in the 2000s.

As described above, a warm–dry climate trend characterized by significant and sustained increases in temperature and decreases in precipitation was typical post 1990s and served as the main driver of the lake changes [27]. The climate change pattern coincided with the overall pattern of the lake changes. (1) The number and area of the lakes reached minimum values during 2000–2010, when the region experienced the warmest and driest weather. (2) The lake area rebounded to some extent from 2010–2015 and during subsequent years when the region experienced increases in precipitation and decreases in temperature. The extreme events caused by climate change may cause future deterioration of the area of the lakes [28–34].

5.2. Impact of Human Activities on Lakes

Human activities are one of the important drivers of lake changes in arid and semi-arid regions; the main activities inducing the lake decline in Inner Mongolia include the high scale of water conservancy projects (such as reservoirs), increased water consumption, excessive industrial water consumption (such as coal mining), and increased water consumption for irrigation [12]. This study discusses the impact of these activities on lake changes from three perspectives.

5.2.1. Water Resource Regulation

Water regulation has both positive and negative impacts on lakes [35,36]. For example, there have been successful examples of anthropogenic interventions maintaining lake ecology; however, ecological problems associated with severe lake shrinkage after reservoir construction have also been reported. In Inner Mongolia, water regulation has become a powerful intervention measure for the artificial regulation of storage for most lakes. Based on field investigation, relevant national policies and news reports, and analysis of the driving factors of typical lake changes, we concluded that the seven large lakes with individual areas of >100 km^2 are mainly regulated artificially, except for Dalinuoer Lake, which is still chiefly controlled by natural factors (Table 6).

Table 6. Changes in and the major controlling factors of the lakes with individual areas of >100 km^2.

Year	Hulun Lake	Wuliangsuhai Lake	Wulagai Gobi Lake	Dalinuoer Lake	New Dalai Lake	West Juyanhai Lake	Daihai Lake
1990	2107.15	309.53	257.91	219.70	170.53	158.52	113.79
1995	2109.11	338.61	234.40	220.30	171.35	110.91	104.44
2000	2102.31	318.01	365.21	218.71	170.17	6.23	92.20
2005	2039.90	315.04	5.53	212.76	100.96	128.65	89.90
2010	1871.28	300.31	174.93	197.80	35.36	39.61	77.50
2015	2074.40	308.01	143.87	195.17	9.95	3.41	63.96
2018	2083.67	322.30	152.74	191.12	5.73	60.36	54.53
Amplitude of variation (%)	−1.11	4.13	−40.78	−13.01	−96.64	−61.92	−52.08
Main controlling factors	Diverting river water to the lake, controlled by the water conservancy project	Diverting irrigation water of the Yellow River, dam and enclosure	Regulated by the reservoir	Affected primarily by climate change	Blocked by the people	Controlled by Heihe River drainage	Irrigation agriculture, power plants, climate change

The construction of reservoirs in endorheic basins imparts an important impact on the lakes. As of 2007, there were 61 large reservoirs in Inner Mongolia, including 10 reservoirs in endorheic basins. In 1990, the Wulagai Gobi Lake had a water area of 257.91 km^2; however, by 2005 it had completely dried up due to the construction of the Wulagai reservoir. The lake area was maintained at about 140 km^2 after the construction [37,38]. Water conservancy projects in the upper reaches of the Heihe River in the Gansu Province caused the East Juyanhai Lake and West Juyanhai Lake on the Alxa Plateau to disappear in 1992 and 1961, respectively [39]. In 2000, the national inter-provincial water diversion policy was implemented for the Heihe River and led to a significant increase in the areas of these two lakes [40]. The East Juyanhai Lake has maintained a near constant water area since August 2004. Notably, by 2016, its water area was stable at about 40 km^2 [41]. The area of West Juyanhai Lake reached 128.65 km^2 in 2005 and has been maintained at 60.36 km^2 since 2018. In the 1950s, the Huangqihai Lake was a natural freshwater lake with an area of 130 km^2. After 37 reservoirs with a total storage capacity of 51.18 million m^3 were built on the inflowing rivers in the 1960s and 1970s, the surface water supply to the

Huangqihai Lake was basically cut off. Combined with the decrease in precipitation, this led to the lake's disappearance in 2008. This dried-up state lasted until 2012, when the lake water area recovered to 26.75 km^2 due to heavy precipitation [42]. However, the salinity increased to more than 7.79 g/L, turning the one freshwater lake into a saltwater lake [43].

The Hasuhai Lake, Wuliangsuhai Lake, and Hulun Lake are all maintained through water diversion projects. Both the Hasuhai Lake and Wuliangsuhai Lake are oxbow lakes of the Yellow River. The Hasuhai Lake is replenished using the Minsheng Canal to divert water from the Yellow River. The Wuliangsuhai Lake is maintained using key water control projects of the Hetao Irrigation District, which divert the ice-melt flood water of the Yellow River and intermittent irrigation water. Alternately, the Hulun Lake is refilled through a water resource allocation and water environment management project (which diverts river water to the lake). Notably, these efforts have restored the wetlands and improved the ecological environment surrounding the lake.

5.2.2. Groundwater Extraction and Agricultural Irrigation

The groundwater distribution is extremely uneven in Inner Mongolia [44]. The West Liaohe Plain and the Hetao Plain are the richest in groundwater resources and also have the highest degree of groundwater exploitation. In contrast, the northern Inner Mongolian Plateau and the Alxa Plateau are the areas with the poorest groundwater resources.

The lakes on the Hetao Plain are mainly located in the Yellow River Diversion Irrigation Zone, where the extent of groundwater exploitation is limited, and thus, groundwater extraction has a small impact on the plain's lakes. Conversely, the Hubao area is subject to a high degree of groundwater exploitation. In this area, the number of lakes is small, and the hydraulic link between the lakes and groundwater is weak. Therefore, groundwater extraction has a minimal impact on the lakes.

The West Liaohe Plain contains a large number of lakes, and its groundwater is the main source of drinking water for humans and animals. Furthermore, the plain's groundwater is the primary source for agricultural irrigation, with agricultural water consumption accounting for about 81% of the total groundwater extraction [45]. Notably, there is a close hydraulic link between the groundwater and surface water on the West Liaohe Plain. Additionally, as the surface water runoff gradually declined over the years, the exploitation of groundwater increased. This groundwater extraction has impacted the plain's lakes, but the degree varies among lakes.

In addition to the continuous temperature increases and precipitation decreases (i.e., natural factors) [46], the severe shrinkage of Daihai Lake is largely attributed to the development of irrigated agriculture within the area (an anthropogenic factor). Irrigation water consumption was once as high as 40 million m^3/a or more, which is nearly the multi-year average natural runoff recharge received by the lake. This resulted in severe water imbalance within the Daihai Lake and rapid shrinkage of the lake area.

5.2.3. Water Consumption for Mining and Power Plants

Coal mining has the following major impacts on lakes [47,48]. (1) Coal mining drains groundwater, and the subsequent decline in the groundwater table may lead to lake water leakage in areas where the lakes have close hydraulic links with the groundwater. (2) Coal mining causes surface subsidence and/or fractures throughout the lake area, thereby leading to lake water leakage. (3) Mine drainage pollutes the lake water.

Analysis of the lakes' spatial distribution in relation to the coal mining zones (Figure 7) revealed that the average distance between coal mines and lakes was only 43.72 km, with 54 lakes located less than 10 km from the nearest mining sites. Furthermore, 132 lakes were within 5 km of nationally planned mining zones, and 166 lakes were within 10 km (Table 7). The Hulun Buir Plateau, the northern Inner Mongolian Plateau, the Ordos Plateau, and the West Liaohe Plain all contain a large number of coal mines, as well as the largest number of lakes within 5 km and 10 km of these mining zones.

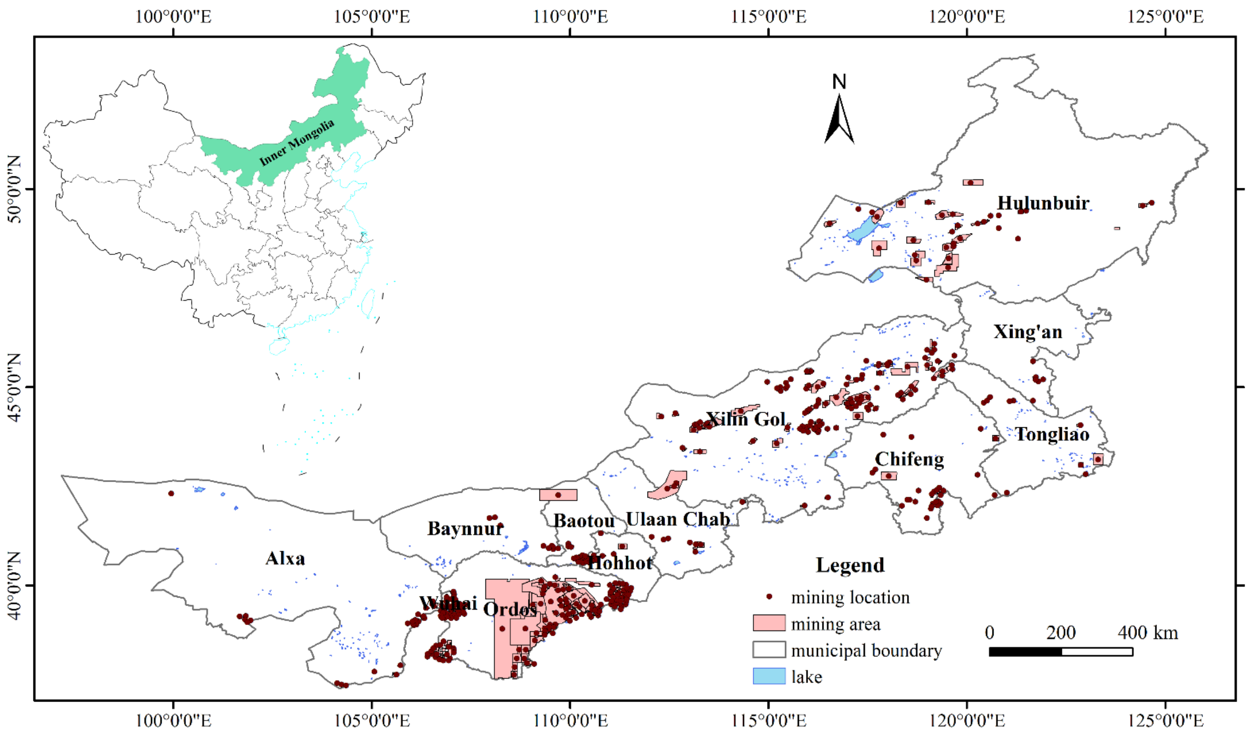

Figure 7. Distribution of lakes, mining sites, and planned mining zones throughout Inner Mongolia.

Table 7. Number of lakes within 10 km and 5 km of mining sites within the different geomorphological units.

Geomorphological Units	Number of Lakes within 5 km of Mining Zones	Number of Lakes within 10 km of Mining Zones
Ordos Plateau	27	27
Hulun Buir Plateau	22	36
Northern Plateau of Inner Mongolia	46	58
West Liaohe Plain	14	21
Kubuqi Desert	4	4
Mu Us Desert	17	17
Hunshandake Desert	0	1
Daxinganling Mountains	1	1
Yinshan Mountains	1	1
Total number	132	166

According to the annual statistical bulletins on national economic and social development in Inner Mongolia during 2000–2018 [49], the amount of coal mined in Inner Mongolia increased continuously during 2002–2012, and then decreased after 2014 (Figure 8). The areas of the lakes within 10 km of the mining zones on the Hulun Buir Plateau, the Northern Plateau of Inner Mongolia, the Ordos Plateau, and the West Liaohe Plain (Figure 9) decreased to various extents after 2000, though this decreasing trend slowed or even slightly reversed after 2010. This indicates that, to some degree, the lake area within 10 km of mining zones coincided with the fluctuations in the amount of coal mining.

The impact of a coal mining zone on a nearby lake is closely related to the hydrogeological conditions of both the lake and the mining zone. Thus, there is a need to conduct investigations and research on these coal mining zones. Regarding the use of water by power plants, as an example, the Daihai power plant uses water from Daihai Lake as the cooling circulating water, which consumes 10 million m^3 per year and has become one of the main drivers of the shrinkage of Daihai Lake [46].

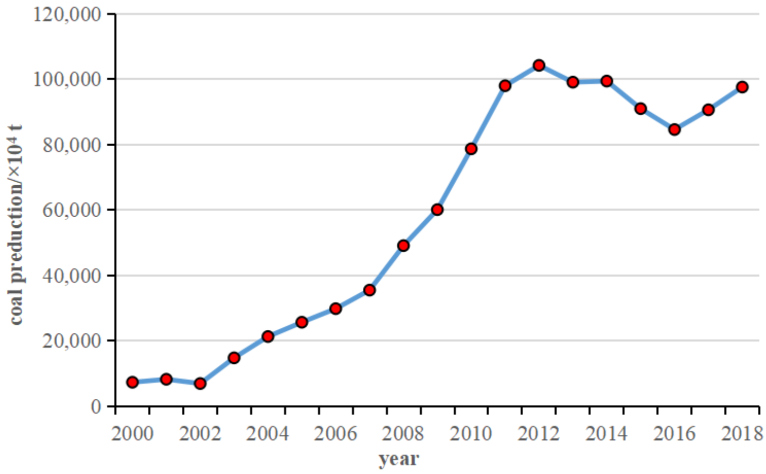

Figure 8. Changes in the amount of coal mining in Inner Mongolia.

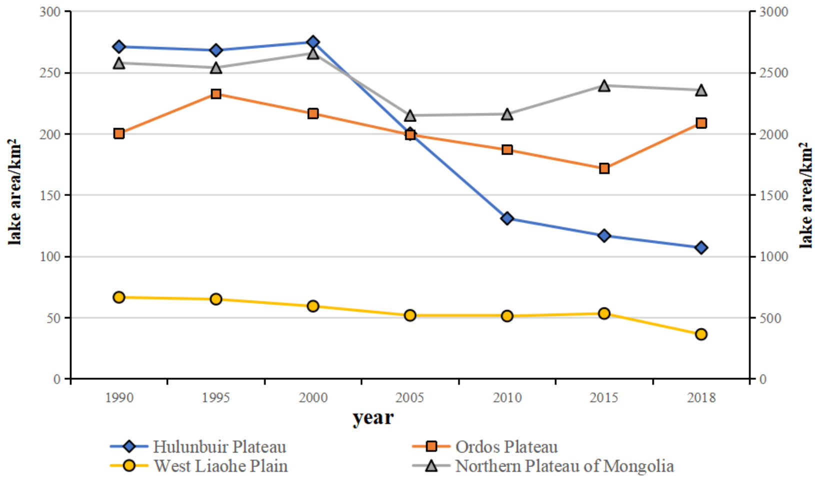

Figure 9. Changes in the lake area within 10 km of mining zones throughout the different geomorphological units.

6. Conclusions

1. From 1990–2018, the number and area of the lakes in Inner Mongolia significantly decreased, reaching minimums by 2010. Specifically, from 1990 to 2018, the total lake area exhibited a net decrease of 672.97 km^2 (13.55%), and the number of lakes with individual areas of >1 km^2 decreased by 83 (21.61%). This decreasing trend in lake area has slowed in recent years; however, the long-term decreasing shifts in both the number and area of the lakes are still apparent.
2. With respect to the distribution of the lakes throughout the different geomorphological units, lake shrinkage mainly occurred on the northern Inner Mongolian Plateau, in the desert zone, on the West Liaohe Plain, in the Yinshan Mountains, and in the Daxinganling Mountains. Among these regions, the lake shrinkage was the most severe on the West Liaohe Plain, where the number and area of the lakes decreased by 54.43% and 49.18%, respectively, followed by the northern Inner Mongolian Plateau, where the number and area of the lakes decreased by 21.47% and 19.03%, respectively.
3. With respect to the distribution of the lakes within the different climatic zones, the lake shrinkage was primarily seen in the mid-temperate semi-arid zone, decreasing by 776.6 km^2 (18.09%). In contrast, the number and area of the lakes in the mid-temperate arid zone increased by 19 lakes and 102.67 km^2, respectively. The lakes in the mid-temperate semi-humid zone remained relatively stable, with only small changes in both the number and area of the lakes.

4. The combined effects of the natural conditions and anthropogenic disturbances were the main causes of the lake shrinkage. The warm–dry climate trend characterized by increasing temperatures and decreasing precipitation was the main driver of the lake changes; however, the additional impacts of water regulation projects, agricultural irrigation, mining development, and population growth cannot be ignored. The factors associated with the lake shrinkage varied geographically, and thus there is a need to conduct more detailed lake-specific analysis and research.

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