Environment, Development and Sustainability (2021) 23:3673–3695
https://doi.org/10.1007/s10668-020-00738-6

High-resolution monitoring of inland water bodies across China in long time series and water resource changes

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Received: 11 December 2019 / Accepted: 15 April 2020 / Published online: 5 May 2020

Abstract

The accurate examination of inland water body distributions, types, areas and sizes is critical for global water cycling, while water resources and the diagnosis of utilization problem are essential to sustainable water management. Therefore, there remain less well-studied in China, especially for the accurate examination of long time series. Based on high-resolution satellite imagery from the late 1970s, statistical water resource data and precipitation data, this study identifies inland rivers, lakes, reservoirs and ponds larger than 0.001 km^2, examines the regularity of different water distributions; analyzes area, perimeter and water resource changes for ten basins from long time series, quantitatively and qualitatively analyzes determinants, and illustrates main characteristics and water use problems affecting each basin and presents a number of suggestions. The results show that inland water body areas increased from 1980 to 2015 and that reservoir and pond areas increased considerably, while lake and river areas changed little. Land surface water resources and precipitation declined slightly from 1997 to 2015. Climatic conditions determine basic water body and resource distributions and volumes at the macroscopic scale, and human activities have greatly altered spatial patterns. Basin with rivers in the southwest includes highly exploitable water resources. Basin with rivers in the northwest faces considerable water shortages and fragile environmental conditions. The Yellow River, the Haihe River and the Songhua and Liaohe River Basins suffer from water shortages and pollution. The other four basins are experiencing eutrophication and frequent meteorological and geological hazards. Sustainable water management must be based on basin characteristics and major problems.

Keywords Inland water body · Water resources · Temporal-spatial · High resolution · Long time · Precipitation · China

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1 Introduction

Inland water, which primarily includes streams, rivers, lakes and reservoirs, plays a key role in global water cycling. Although the total area of inland water only accounts for a small percentage of the global land surface (Cole et al. 2007), it can strongly affect regional climatic changes through the exchange of heat and water with the atmosphere (Tranvik et al. 2009). Inland water also constitutes an important carbon source by releasing carbon dioxide and methane into the atmosphere (Raymond et al. 2013; Verpoorter et al. 2014) with amounts nearly equivalent to those of ocean and land sinks globally (Borges et al. 2015), playing a substantial role in the global carbon cycle and thus potentially affecting climate as well. According to field observations, carbon flux velocities vary considerably with water body types, water body sizes and geographic positions (Barros et al. 2011; Hu and Cheng 2013). The distribution of water bodies and associated changes can directly determine the volume of regional water resources, thereby affecting water supplies available for industrial, residential and agricultural use (Daher et al. 2019). Water resources are essential to both vegetation and animal life and are fundamental for the development of the economy, society and the physical environment (Zhang et al. 2011). Although human beings have a high capacity to cope with changes in physical conditions, water is still critical in many respects in shaping anthropogenic activities. Thus, an examination of inland water bodies is very critical both for carbon flux at the water-atmosphere interface and for sustainable water resource planning and management.

Currently, inland water body monitoring and extraction has widely been executed globally. Satellite images and statistical extrapolations have both been used. For example, based on digitized inventories, registers, archives and remote sensing data, the Global Lake and Wetland Database (GLWD) has been compiled, and most large lakes with areas of larger than 10 km^2 are included in this dataset (Lehner and Döll 2004). With the rapid development of remote sensing technologies, spatial resolutions continue to improve, and data for all lakes greater than 0.002 km^2 have been extracted based on high-resolution imagery drawn from the Enhanced Thematic Mapper Plus (ETM+) sensor aboard the Landsat 7 satellite (Verpoorter et al. 2014). Most studies of high-resolution inland water body extraction and monitoring have focused on a certain water body type. Water resources change and the influence of climatic change and human activities have also been widely discussed in recent years (Voerosmarty et al. 2010; Chen et al. 2018). And, water resource deterioration has been observed in many studies across the globe (Rouholahnejad et al. 2014; Shevah 2014). For sustainable water resource utilization, it is therefore essential to analyze changes in water resources both spatially and temporally and to discuss their main determinants.

As the third largest country in the world, China has a land area of 9.6 million km^2 with annual total runoff volumes ranked sixth in the world. While China has the largest population and is experiencing a booming economy (Zhang et al. 2011), per capita water consumption is low and industrial water demands are increasing. China is also primarily an agricultural country, and its agricultural industry greatly depends on irrigation (Cui et al. 2009). It has been reported that China is home to approximately 20% of the world's population but accounts for only approximately 5–7% of global freshwater resources. It is therefore no surprise that water shortages are serious in China (Qiu 2010). Water bodies in China are found in extremely unbalanced distributions, and precipitation in southern and eastern China is abundant, while vast areas of northern and western China are characterized by arid and semiarid climatic conditions. Aside from water shortages, water utilization in China presents other major problems. Heavy precipitation in southern China always causes flooding while precipitation in vast areas of northern and western China is rare and water resources are very scarce, which has resulted in drought, desertification and low land productivity (Liu et al. 2018). To feed industrial development, agricultural irrigation and the country's growing population, more water resources have been consumed and, especially in China's large northern cities, and excessive water use has resulted in ground water decline (Hanjra and Qureshi 2010; Dalin et al. 2017; Ren et al. 2018). Water resource studies of China have mainly focused on individual basins or certain regions (Wang et al. 2009; Ma et al. 2010; Hu et al. 2014), and especially for the Yangtze River, Yellow River and Pearl River basins (Piao et al. 2010; Zhang et al. 2011). Some scholars have studied China overall and have also analyzed the influence of precipitation, but the time series need to be updated to reflect recent changes. By river distribution, China is divided into 10 basins, each of which presents different physical characteristics and anthropogenic activities that can greatly affect water resource utilization and water body distribution. An examination of inland water within basins can diagnose regional water statuses and major problems, reveal determinants of water body and water resource change and help to alleviate the negative influence of climate change and anthropogenic activities. In regard to water body monitoring, most previous studies have focused on the regional scale and on certain types of water bodies (Shen et al. 2015; Song et al. 2019; Yao et al. 2015), while few studies have been conducted over long time series for China's entire land area, including all inland water bodies and especially for the monitoring at high spatial resolution.

This study addresses the gaps discussed above, and our research objectives include the following: (1) to determine the distribution regularity and characteristics of inland water bodies; (2) to examine water body changes from 1980 to 2015 at a high resolution of 30 m grids for each basin, including changes in area and perimeter; (3) to analyze main driving forces that determine inland water change in each basin; and (4) to illustrate water resource changes occurring from 1997 to 2015 and to analyze responses to precipitation. The present study is necessary and meaningful, as it not only offers basic high-resolution data support for further studies of carbon flux in inland water bodies but can also help reveal main characteristics and problems related to water resource utilization for each basin and thus facilitate sustainable water resources management.

2 Materials and methods

2.1 Basin distribution

By major river distribution, China is divided into ten basins at the first classification level (Fig. 1). The Huaihe River Basin, the Yangtze River Basin, the Pearl River Basin and Basin with rivers in the southeast are operating under better hydrothermal conditions, covering more than 90% of China's coastline. The region has experienced rapid economic development, and the coastline area is heavily populated. Basin with rivers in the southwest also experience heavy levels of precipitation, while population density and economic development levels are much lower than those of the former four basins. Precipitation levels in the Yellow River Basin and Haihe River Basin are lower relative to those of the former, and the area also presents a weaker economy but a high population density, and China's capital Beijing is located in the Haihe River Basin. In northeastern China, precipitation in the Liaohe and Songhua River Basins is similar to that of the Haihe and Yellow River Basins, but levels of economy development and population density are lower. Basin with rivers in

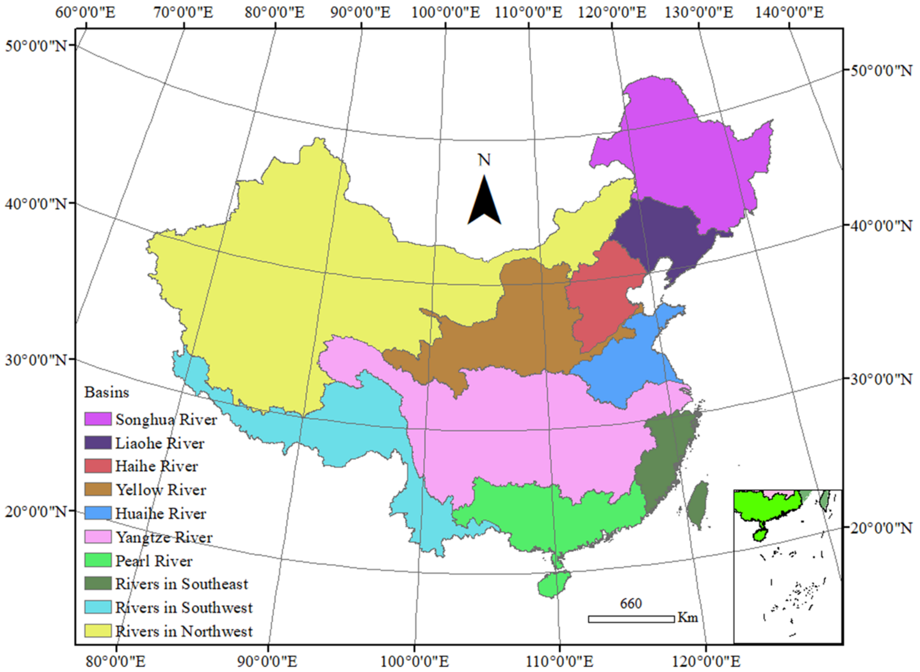


Fig. 1 Distribution of ten basins in China

the northwest are subject to arid and semiarid climatic conditions, and levels of population density and economic development are low.

2.2 Data and method

The water body dataset used for this study covers rivers, lakes, reservoirs and ponds for 1980 (the late 1970s), 1990 (the late 1980s), 1995, 2000, 2005, 2010 and 2015, with a spatial resolution of 30 m. Water body extraction was conducted using Landsat satellite imagery, data for the 1970s were derived from Landsat-MSS, and other data were drawn from Landsat-TM (Thematic Mapper) and Landsat-ETM (the Enhanced Thematic Mapper) sensors. Using a high-resolution remote sensing–Unmanned Aerial Vehicle (UAV)–ground survey observation system, land use-type data, including extracted water body data, were collected, nationwide subgroup field trips were taken for investigations, and a large number of field investigation records, photographs and UAV aerial images were obtained. The quality of the data has much improved, and the comprehensive valuation accuracy of the first level of land use is $>93\%$ and that of the second level is $>90\%$ (Ning et al. 2018). Based on this dataset, water body changes, including changes in area, perimeter and number, were analyzed with ArcGIS software. A spatial correlation analysis was conducted on water body volumes and precipitation for the studied basins, and the correlation coefficient was calculated to determine the correlation extent. Precipitation data from 1980 to 2015 were provided by Data Center of Resources and Environment Science, Chinese Academy of Sciences, with the initial data from more than 2400 meteorological stations in China, the ANUSPLIN software (Hutchinson 1998) was used to generate grid precipitation maps. Statistical water resource data for 1997–2015 are provided by the Annual Water Resources Bulletin published by the Ministry of Water Resources of China. Linear fitting equations were produced to measure the relationship between land surface water resources and precipitation and China's mean changes in precipitation levels. Dispersion was used to measure area and perimeter fluctuations for the 7 years, the equation is shown as:

$$V = \frac{\sum_{i=1}^{7} b_i - \overline{b}}{\overline{b}} \tag{1}$$

V is the dispersion degree, b_i is the water area or perimeter in year i, and $\overline{b}$ is the mean value of the area or perimeter of the 7 time intervals.

To analyze changes in precipitation from 1980 to 2015 for each grid, a simple linear regression analysis model of the slope was used:

$$\text{slope} = \frac{n \times \sum_{i=1}^{n} i \times \text{precipitation}_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} \text{precipitation}_i}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \tag{2}$$

where slope is the precipitation changing trend; n is the number of studied time intervals (years); precipitation_i is the annual precipitation for year i; and slope > 0 and slope < 0 represent increasing and decreasing tendencies of precipitation, respectively.

3 Results

3.1 Spatial distribution of inland water bodies

We selected the year 2015 to measure the inland water distribution (Fig. 2). The total area of inland water in 2015 is 15.68×10^4 km^2, accounting for 1.74% of China's total land area, and the area of rivers, lakes and reservoirs and ponds are 3.74×10^4 km^2, 7.67×10^4 km^2 and 4.27×10^4 km^2, respectively. Rivers are widely distributed across China, but river network density levels are considerably higher in the south and east of China (Fig. 2a). Lakes

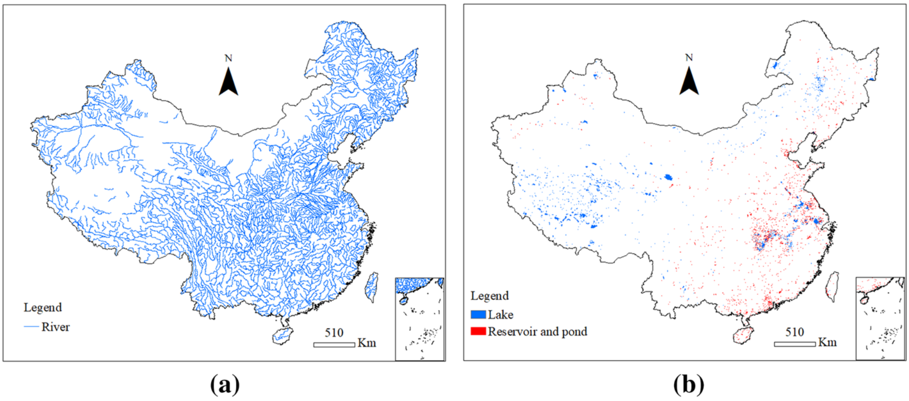


Fig. 2 Spatial distribution of rivers (**a**), lakes and reservoirs and ponds (**b**) across China in 2015

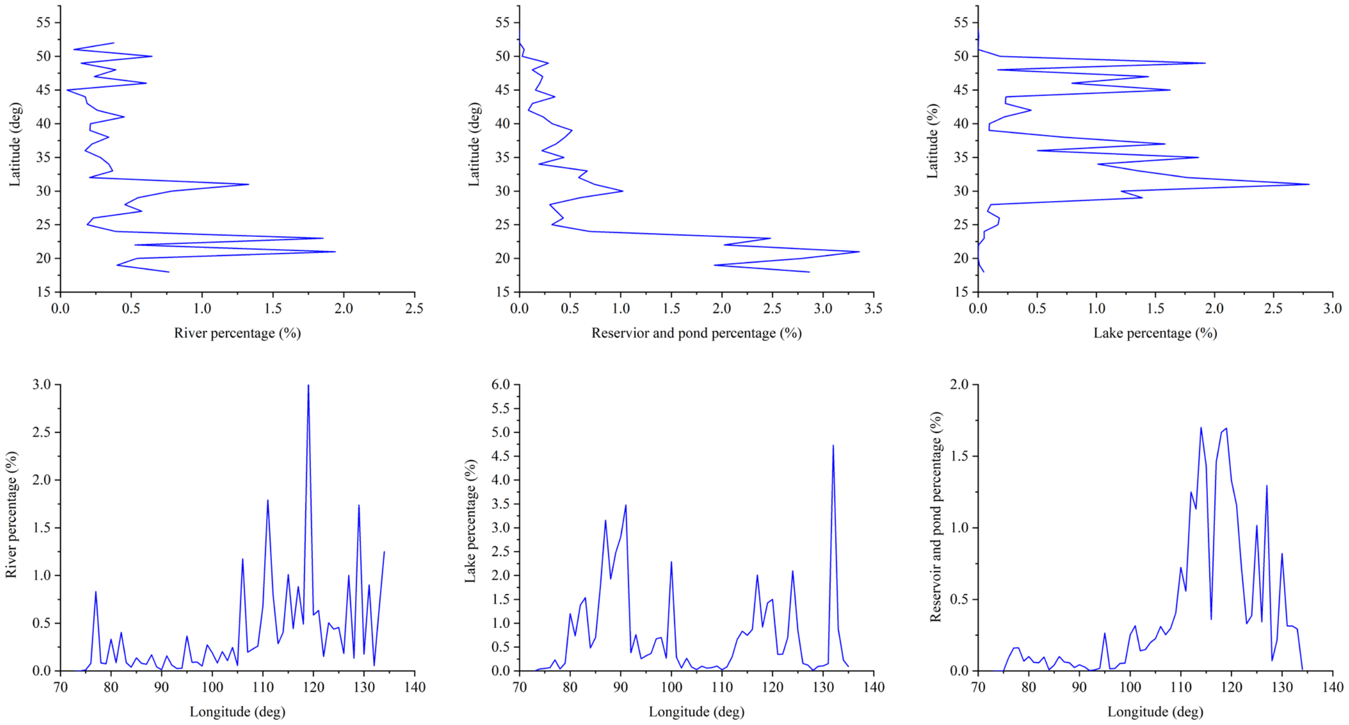


Fig. 3 Latitudinal and longitudinal abundance distributions of inland water bodies in China

Table 1 Water body numbers of different sizes

Area level	Lake		Reservoir and pond	
Km^2	Number	Percentage (%)	Number	Percentage (%)
> 500	25	0.05	0	0.00
100–500	100	0.18	28	0.02
10–100	519	0.96	511	0.37
1–10	2537	4.67	4807	3.50
0.01–1	25,342	46.69	93,944	68.48
0.001–0.01	25,756	47.45	37,895	27.62

and especially larger ones are mainly concentrated in the west, the central eastern area and the northeast. Most reservoirs and ponds are located in the east and especially in the central eastern and southeastern regions of China (Fig. 2b).

Water abundance statistics for different basins show that the Huaihe River Basin has the highest abundance, with a total water area accounting for 3.79% of the basin area. The Yangtze River Basin presents the second highest level with a percentage of 2.36%, and the Pearl River Basin, the Haihe River Basin and Basin with rivers in the southeast present a medium abundance of approximately 2%. The Yellow River Basin and Basin with rivers in the southwest present the lowest levels of 1.07% and 0.73%, respectively. We also analyzed changes in the abundance of inland water bodies along with longitude and latitude where abundance was evaluated from the percentage of water area accounting for the whole land area within a certain longitude or latitude (Fig. 3). Rivers, reservoirs and ponds present high abundance distributions in low latitude areas and especially for the region at approximately 20°N. For rivers, abundance levels present another peak at approximately 30°N, but considerably decrease as the latitude increases. The same is found for reservoirs and ponds, which show a decrease at between 20°N and 30°N, a second peak at approximately 30°N, and fluctuations with decreasing trends and with latitude increase, though declines are more obvious than those found for rivers. In terms of longitude, the abundance of rivers, reservoirs and ponds fluctuates, high values mainly appear from 110°E to 130°E, and the western region of China within low longitudes presents relatively low abundances. However, lakes do not show obvious signs of regularity by longitude and latitude, but values clearly fluctuate.

Table 1 shows the number of water bodies of different sizes. Water bodies of < 1 km^2 account for more than 90% of lakes, reservoirs and ponds. There are 25 lakes larger than 500 km^2, but no reservoirs or ponds are of this size. The number of water body with area between 100 and 500 km^2 is much higher for lakes compared with reservoirs and ponds. Water bodies of 10 to 100 km^2 for lakes are found in similar quantities among lakes, reservoirs and ponds. However, the number of reservoirs and ponds with area of less than 1 km^2 is much more than that of lakes, especially for those ranging from 0.01 to 1 km^2.

3.2 Temporal changes in inland water bodies in different basins

Table 2 summarizes area and perimeter changes of different inland water body types for China. The table shows that the total water area and perimeter increased from 14.25×10^4 km^2 in 1980 to 15.68×10^4 km^2 in 2015 and from 64.51×10^4 km in 1980 to 74.33×10^4 km in 2015, at rates of 10.03% and 15.23%, respectively. Reservoirs and

Table 2 Area and perimeter changes of inland water body among different years

Year	Area (Km^2)				Perimeter (Km)			
	Lake	Reservoir and pond	River	Total	Lake	Reservoir and pond	River	Total
1980	76,900.34	28,333.43	37,307.86	142,541.62	122,495.44	228,508.63	294,097.13	645,101.19
1990	75,453.36	32,879.14	36,372.62	144,705.13	121,389.85	252,051.36	291,713.66	665,154.86
1995	75,566.44	34,233.46	35,791.44	145,591.34	118,238.13	250,885.63	283,983.02	653,106.78
2000	75,801.08	36,037.54	36,370.03	148,208.65	115,007.47	259,173.78	292,999.63	667,180.88
2005	76,400.07	39,059.04	36,872.37	152,331.49	118,864.84	276,947.33	296,009.83	691,822.01
2010	75,713.26	41,048.78	38,708.95	155,470.98	117,362.96	284,931.94	312,943.71	715,238.61
2015	76,748.37	42,696.94	37,394.71	156,840.02	128,644.51	302,189.98	312,511.51	743,346.00
1980–1990	−1446.98	4545.71	−935.24	2163.51	−1105.59	23,542.73	−2383.47	20,053.67
1990–1995	113.08	1354.32	−581.18	886.21	−3151.72	−1165.73	−7730.64	−12,048.08
1995–2000	234.64	1804.08	578.59	2617.31	−3230.66	8288.15	9016.61	14,074.10
2000–2005	598.99	3021.50	502.34	4122.84	3857.37	17,773.55	3010.20	24,641.13
2005–2010	−686.81	1989.74	1836.58	3139.49	−1501.88	7984.61	16,933.88	23,416.60
2010–2015	1035.11	1648.16	−1314.24	1369.04	11,281.55	17,258.04	−432.20	28,107.39
1980–2015	−151.97	14,363.51	86.85	14,298.40	6149.07	73,681.35	18,414.38	98,244.81

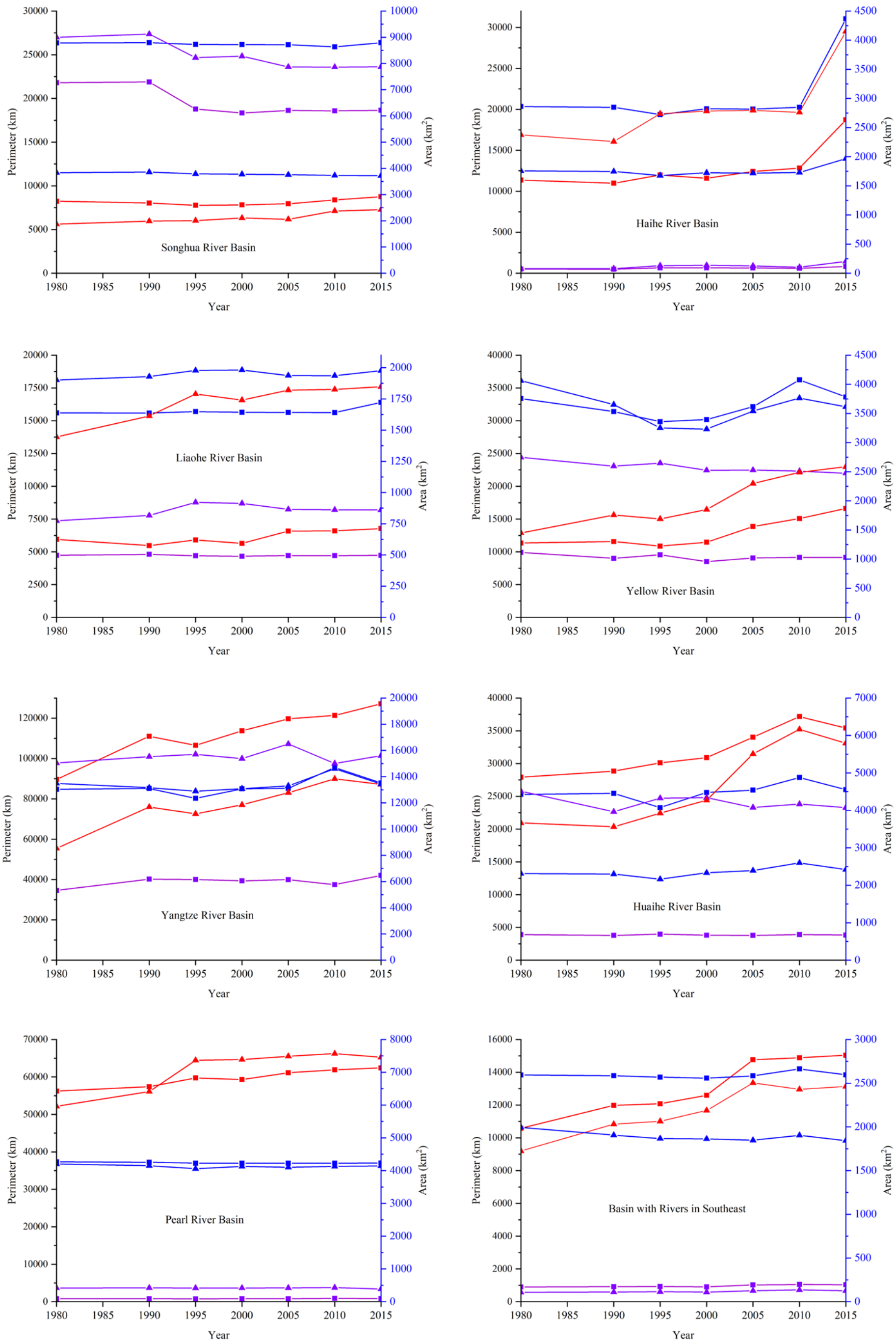


Fig. 4 Area and perimeter changes of different inland water bodies of the ten basins

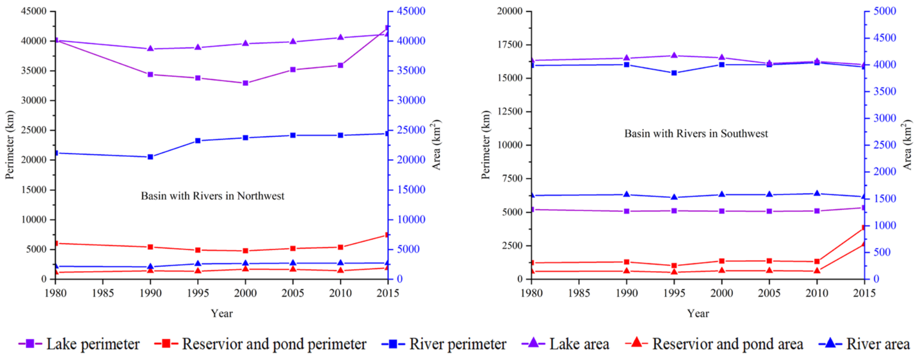


Fig. 4 (continued)

ponds are the only water bodies that expanded without fluctuations, with areas increasing by 50.69% and perimeters by 32.24%. From 1980-1990, reservoirs and ponds increased the most, reaching 4545.17 km^2 for area and 2354.73 km for perimeter. Lakes present a slight decreasing trend of 0.2%. Lakes decreased the most from 1980 to 1990 of 1446.98×10^4 km^2, and 2005–2010 also presents a decreasing trend of 686.81×10^4 km^2. All of the other periods show an increasing trend, where 2010-2015 presents the highest level of 1035.12×10^4 km^2. Rivers expanded by 0.23% from 1980 to 2015, where 2010-2015 presented the most obvious decreasing trend of 1314.23×10^4 km^2. The periods 1980–1990 and 1990–1995 also show decreasing trends of 935.24×10^4 km^2 and 581.18×10^4 km^2, respectively. Perimeter changes do not fully correspond to changes in area and even present a reversed trend (e.g., 1990–1995 and 1995–2000 show an increase in lake area with a decline in perimeter values).

Figure 4 illustrates area and perimeter changes for three inland water bodies of different basins. This figure shows that changes in the three water body types present more similarities than heterogeneities among the basins, with lakes changing little, with reservoirs and ponds clearly expanding, and with rivers changing little in most of the basins. Areas and perimeters under similar changes in most periods, but the reverse trend is found for some periods. From 1980 to 2015, reservoirs and ponds were the only inland water bodies to clearly expand among the basins, while both increasing and decreasing trends appear during different periods in different basins for lakes and rivers, and no obvious trends of the different basins are found in time series.

For lakes, areas and perimeters fluctuated among the basins. On the whole, the Songhua, Huaihe, Yellow and Pearl River Basins had their areas decreased, and Basin with rivers in the southwest remained relatively stable with limited changes in area and perimeters. Except for the above basins, lake areas presented increasing trends. Areas covered roughly 100 km^2 for Basin with rivers in the southeast and the Haihe River Basin in most years, and approximately 400 km^2 and 800 km^2 for the Pearl and Liaohe River Basins, respectively, which are considerably lower values than those of the other basins. Less significant changes in area are observed than those for the other basins, the most obvious increase appeared in the Haihe River Basin from 2010 to 2015, with its lake area measuring nearly twice that of 2010. Another pronounced increase in lake area is found for the Liaohe River Basin from 1990 to 1995 (104.78 km^2), but perimeters decreased by 114.22 km. The lake area of the Yellow River Basin is roughly 2500 km^2 and it is 4000 km^2 for the Huaihe River Basin and Basin with rivers in the southwest. A pronounced decreasing trend is found for the Yellow and Huaihe River Basins from 1980 to 1990 (with areas of 549.67 km^2 and 152.07 km^2, respectively), and perimeters decrease by 114.17 km and 896.48 km, respectively. Lake areas of the Songhua River Basin decreased from 9000.32 km^2 in 1980 to 7870.21 km^2 in 2015, representing a decrease of 12.56%, and perimeters also decreased by 14.49%. Lakes in basin with rivers in the northwest decreased dramatically during 1980–1990 from 40135.44 km^2 to 38689.57 km^2, and perimeters also decreased by 5765.63 km, while from 1990 the area expanded, causing the total area to increase by 2.52% in 2015 relative to 1980. The Yangtze River Basin has the largest lake area. This basin's lake area and perimeter values increased by 3.75% and 21.48%, and the most dramatic decrease appeared from 2005 to 2010, of 1488.01 km^2 and 2483.54 km, respectively.

Areas and perimeters of reservoirs and ponds increased among the basins overall, but decreasing trends also appeared in some periods for most basins. Basin with rivers in the southwest present the highest increases in reservoir and pond percentages of 343.1% and 212.3% for areas and perimeters, respectively, and dramatic increases occur from 2010 to 2015, of 501.52 km^2 and 2533.51 km. Increasing percentages found for the other basins are less than 100%. The Haihe and Yellow River Basins undergo similar rates of area increase of 74.66% and 78.41%, with areas increasing to 1773.28 km^2 and 1136.2 km^2, and with perimeters increasing to 7364.65 km and 5263.75 km, respectively. Reservoir and pond areas in Basin with rivers in the southeast, the Huaihe River Basin and the Yangtze River Basin increased by 42.82%, 58% and 57.14%, respectively, and perimeters increased by 42.16%, 26.85% and 41.86%, respectively, and changes occurring in different periods vary across the basins. The Liaohe River Basin, the Songhua River Basin and the Pearl River Basin show similar area increase rates of 25%–30%. Basin with rivers in the northwest also present obvious area increases of 65.6% and 23.46%, respectively, and increases in perimeter of 758.26 km and 1416.23 km, respectively.

Similar to lakes, rivers changed little. Basin with rivers in the southeast, the Yellow River Basin, the Yangtze River Basin, the Pearl River Basin, the Songhua River Basin and Basin with rivers in the southwest show slight decreasing trends of 7.59%, 11.04%, 0.46%, 1.42%, 3.03% and 1.42%, respectively. The former four basins present a pronounced decrease in river area from 1980 to 1990 and 1990 to 1995, and the more recent period of 2010 to 2015 presents declines in river areas, except for the Songhua River

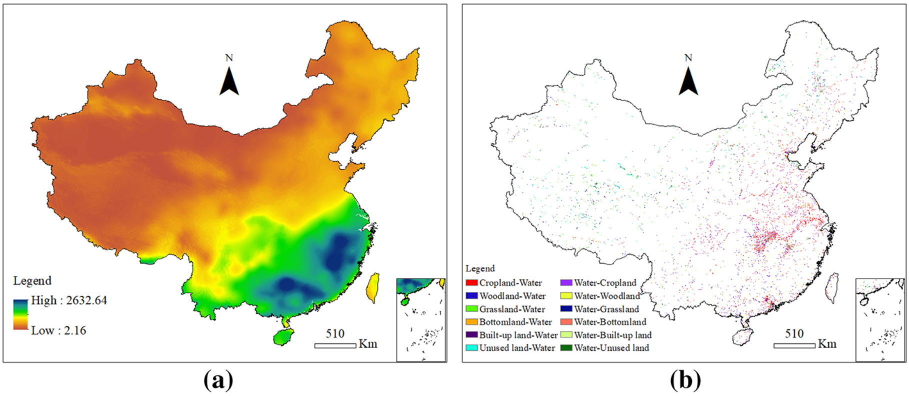


Fig. 5 Precipitation distribution for 2015 (**a**) and transfer of inland water with other land use types for 1980 to 2015 (**b**)

Basin. This basin does not undergo considerable fluctuations, and from 1980 to 1990, the area increases by 19.52 km^2, while in the other periods, a continuous slight decline was observed. The other four basins present an increasing trend, and Basin with rivers in the northwest expand the most obviously, with an expanded area of 556.8 km^2, and perimeters increase by 3265.02 km, with an increase of 15.54%, the only decline appears from 1980 to 1990. The Haihe River Basin presents the second highest increasing rate in terms of river area of 11.88%, and the perimeter presents a much stronger increasing rate of 52.56%. The Huaihe and Liaohe River Basins present similar area increases of 4.59% and 3.93%, and similar increases in perimeter of 718.66 km and 805.41 km, respectively.

3.3 Determinant analysis of inland water body distributions and changes

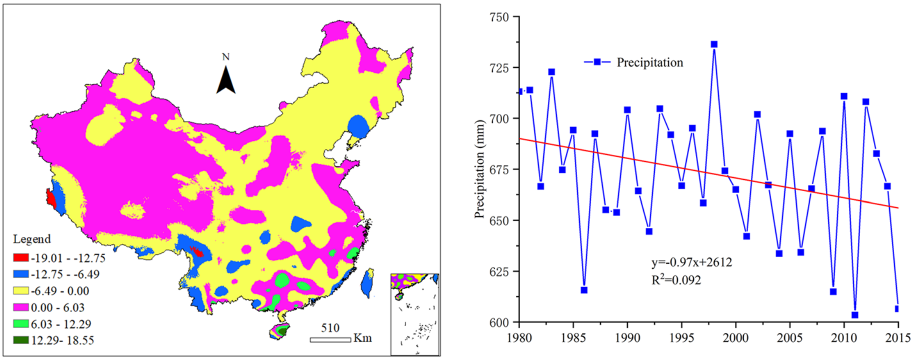
First, effects of precipitation were examined for different inland water bodies. Precipitation in 2015 was used to measure the spatial distribution (Fig. 5a), which presents an obvious decline from the southeast to the northwest. We conducted a spatial correlation analysis of inland water body area abundance and average annual precipitation. Results show that a significant correlation is only found for reservoirs and ponds with $R=0.7$, passing the significance test at the $P<0.05$ level. The correlation coefficient for rivers is $R=0.55$. For lakes, we find a negative correlation coefficient of -0.42, showing that precipitation can affect area distributions of reservoirs and ponds and can moderately determine river area distributions, while the distribution of lakes is also affected by other determinants.

In addition to climatic conditions, water areas are greatly disturbed by anthropogenic activities; thus, we also analyzed the transfer between water areas and other land types. Figure 5b illustrates the spatial distribution of the transfer of inland water with other land use types for 1980–2015. Transfer with cropland mainly occurring in central, southern and northeastern China, while the vast west of China presents sporadic distributions. The transfer with bottomland is observed across China and is especially intensive in the east. A considerably narrower distribution is found for the transfer of water and built-up land and mainly in eastern China along the Haihe River Basin, the Huaihe River Basin, the Yellow River Basin, the Yangtze Basin, the Pearl River Basin and Basin with rivers in the southeast. As most of China's unused land is located in northwestern and northern China, the transfer of water and unused land is concentrated in these areas. Transfer with woodland areas mainly appears in central, southern and northeastern China but at much lower density levels. Transfer with grassland is widely distributed across China and is especially obvious in the southwest and north.

Table 3 calculates the amount of transferred area between water areas and other land use types. The table shows that cropland is the main source of water area expansion. The 2010–2015 period is the only period presenting a net decrease of 1007.6 km^2 to be occupied by cropland. Reversely, built-up land expansion is observed in inland water areas and is especially obvious from 2000 to 2005, with net transfer-out to built-up land covering 532.71 km^2. Another form of transfer observed for large areas involves unused land. From 1980 to 1995, water areas transfer to unused land in net at two successive periods with the volume of 910.35 km^2 and 237.78 km^2, respectively, while the other periods show a net increase in water area from unused land. Although obvious differences exist across periods for the transfer of inland water body and bottomland, bottomland is another important source of inland water body area increase, and this is especially obvious for 1990–1995 and 2000–2005. For transfers with woodland and grassland, 1980-1995 presents a net area

Table 3 Inland water body transfer with other land use types (Km^2)

Period	Transfer with other lands	Cropland	Woodland	Grassland	Bottomland	Built-up land	Unused land	Total change
1980–1990	Transfer-out	17,934.9	8295.21	7700.58	4908.33	2315.7	5236.29	46,391.04
	Transfer-in	21,424.8	7955.55	7688.07	5141.07	2127.51	4325.94	48,662.91
	Net increase	3489.84	−339.66	−12.51	232.74	−188.19	−910.35	2271.87
1990–1995	Transfer-out	3572.28	887.58	1873.71	1877.94	298.53	1799.19	10,309.23
	Transfer-in	4184.46	829.62	1642.95	2783.43	159.93	1561.41	11,161.8
	Net increase	612.18	−57.96	−230.76	905.49	−138.6	−237.78	852.57
1995–2000	Transfer-out	2316.51	569.25	958.59	2336.4	208.98	919.26	7308.99
	Transfer-in	3488.85	884.7	1979.19	1633.32	179.19	1763.1	9928.35
	Net increase	1172.34	315.45	1020.6	−703.08	−29.79	843.84	2619.36
2000–2005	Transfer-out	881.82	62.19	532.44	1048.86	621.54	1518.3	4665.15
	Transfer-in	3013.74	421.38	816.57	2680.38	88.83	1804.05	8824.95
	Net increase	2131.92	359.19	284.13	1631.52	−532.71	285.75	4159.8
2005–2010	Transfer-out	1327.14	245.25	719.73	3185.19	712.8	704.7	6894.81
	Transfer-in	3349.98	782.1	1462.41	2512.71	528.66	1379.07	10,014.93
	Net increase	2022.84	536.85	742.68	−672.48	−184.14	674.37	3120.12
2010–2015	Transfer-out	23,834.3	10,407.15	8778.24	4754.52	4719.15	5094	57,587.4
	Transfer-in	22,826.7	10,436.31	9242.91	4706.37	5200.74	5942.79	58,355.82
	Net increase	−1007.6	29.16	464.67	−48.15	481.59	848.79	768.42



(a) (b)

Fig. 6 Precipitation changing trend in 1 km grid across China (mm/year) (**a**) and the fluctuations of mean annual precipitation for whole China (mm) (**b**) from 1980 to 2015

loss for inland water bodies, but water areas have subsequently occupied woodland and grassland.

Major determinants differ across basins according to regional characteristics. Northwestern and northern China are subject to arid and semiarid climatic conditions and are sparsely populated. Climate change in these regions plays a key role, causing the main form of transfer here to involved unused land. Central, southern and eastern China are characterized by heavy precipitation and dense populations, and with the exception of effects of climate change, water area changes are greatly shaped by human activities (e.g., reservoir construction, fish pond excavation, and water body reclamation to cropland). Thus, inland water body changes may not correspond well with precipitation levels, as shown in Fig. 6, as total water areas increased from 1980 to 2015, while mean precipitation slightly declined. This phenomenon occurs because area changes may not reflect the same changes in water resources. For example, coercive land use measures such as water body reclamation for cropland do not greatly reduce water resource. To better understand the effects of precipitation, we also analyzed water resource changes and responses to precipitation.

3.4 Water resource changes and responses to precipitation

Due to limited data available on land surface water resources, we selected the 1997–2015 period for our analysis. During this period, China's water resources amount ranged from 2221.36 to 2837.33 billon m^3 with a mean value of 2638.71 billion m^3. Both precipitation and water resources underwent a slight decline. For different basins, water resource abundances (densities) were compared, and Basin with rivers in the southeast and the Pearl River Basin present the highest land surface water resource abundances of 86.66×10^4 m^3/km^2 and 83.74×10^4 m^3/km^2. Basin with rivers in the southwest and the Yellow River Basin present values of 65.24×10^4 m^3/km^2 and 53.12×10^4 m^3/km^2, and water resource abundance levels of the Huaihe River Basin and the Songhua and Liaohe River Basins are valued at 21.27×10^4 m^3/km^2 and 12.17×10^4 m^3/km^2. Water resource abundances for all other basins are much lower at 6.53×10^4 m^3/km^2, 4.05×10^4 m^3/km^2, and 3.89×10^4 m^3/km^2 for the Yellow River Basin, the Haihe River Basin and Basin with rivers in the northwest, respectively.

Figure 7 shows fluctuations in land surface water resources and precipitation, and a linear fitting equation shows their relationship. The figure shows that both water resources and precipitation fluctuated and that fluctuations in water resources for the Huaihe River Basin, the Yangtze River Basin, the Pearl River Basin and Basin with rivers in the southeast correspond well with precipitation levels. The R^2 values of their fitting equation also reach high values of 0.98, 0.94, 0.97 and 0.91, respectively, showing that precipitation indeed contributed to land surface water resource variations. R^2 values for the Songhua and Liaohe River Basins, the Haihe River Basin, the Yellow River Basin, and Basin with rivers in the southwest are 0.52, 0.67, 0.64 and 0.71, respectively. For Basin with rivers in the northwest, R^2 is only valued at 0.18, which is considerably lower than those of other basins, showing that precipitation is not the main determinant of surface water resources.

4 Discussion

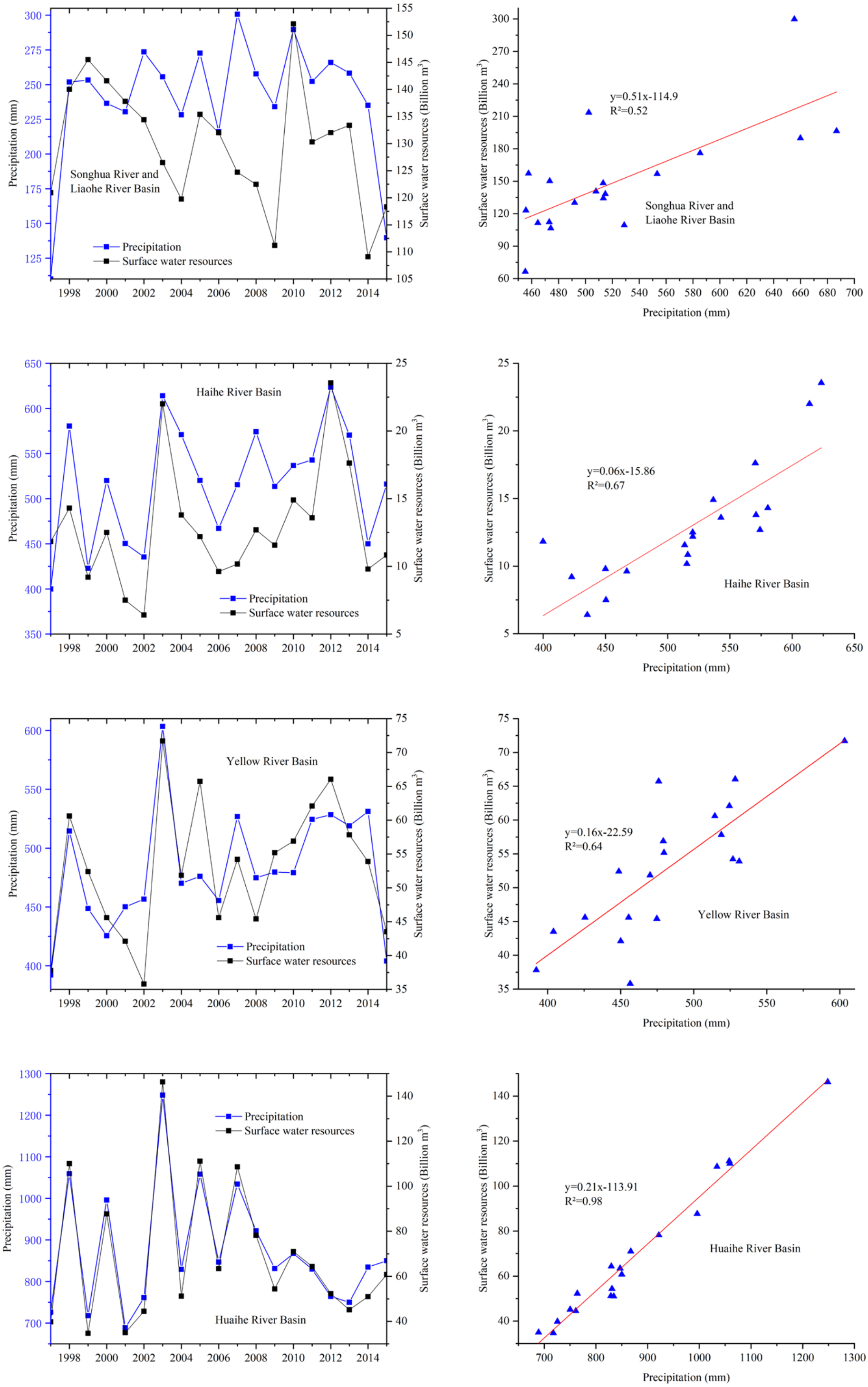
Spatially, water body distribution is affected by precipitation, which is obvious for reservoirs, ponds and rivers. Alternatively, large lakes are distributed in the west under arid and semiarid climate conditions, and large water bodies are found in and around the Qinghai-Tibetan Plateau (Fig. 2b). High elevations cause these areas to concentrate in China's glaciers, and the plateau is known as the "Water Tower of Asia," serving as an important source of freshwater resources from glacial meltwater (Deng and Zhang 2018). Water changes have been driven by both climate warming and precipitation (Fang et al. 2018), and studies show that temperatures in this region have increased most relative to other regions (Chuai et al. 2018). Thus, land surface water resources are weakly correlated with precipitation in the west, including in the northwestern and southwestern basins. Another factor weakening the correlation coefficient between water body area and precipitation is that of water consumption and irrigation particularly exhausts water resources. This finding is especially obvious in dry cropland areas of the northwest. For example, although the upper reaches of the Tarim River in the northwest have gained runoff due to increasing volumes of meltwater running from the mountainous region, its lower reaches have been suffering from persistent drought as a direct result of agricultural irrigation (Thevs et al. 2015). In other basins under relative dry climate conditions such as the Yellow, Haihe, Songhua and Liaohe Basins, with increasing irrigation and more water directed to industrial and residential demand, water deficits have grown more serious (Zhang et al. 2009), which not only directly affects surface water but which also results in the decline of groundwater levels (Döll et al. 2012; Mi et al. 2016). It has also been reported more than 60% of streamflow decline in the Yellow River Basin is attributable to human activities. Thus, the correlation coefficient between water resources and precipitation is weaker than that for basins receiving heavy precipitation. Luckily, cross-regional water diversion projects such as the South-to-North Water Diversion Project have begun to alleviate water shortages in the north (Yang et al. 2018). Other human activities also greatly affect China's water distribution and water resources, and China is experiencing rapid urbanization and land use changes. Especially in economically developed regions, such as the three coastal economic circles of the Bohai Rim, the Yangtze River Delta and the Pearl River Delta, built-up land has expanded rapidly, and large areas of ecological land including water areas have been occupied (Chuai et al. 2015). Agricultural activities such as water reclamation for cropland can also change water areas, but as more serious environmental problems manifest in China, the government has begun to realize the importance of environment protection, and the conversion

Fig. 7 Changes in land surface water resources and precipitation levels of different basins for 1997–2015 ▶ (left figures) and the linear fitting of the relationship between precipitation and water resources on the scatter plot (right figures)

of farmland to water areas has been strongly encouraged (Chen et al. 2016a). Thus, land transfers between water and cropland frequently occurred from 1980 to 2015. Increases in reservoir and pond areas results from vigorous hydroelectric facility constructions, and more and more reservoirs are being built. In 2011, China overtook the USA as the world's largest electricity producer and consumer (Hu and Cheng 2013). Although reservoirs constitute an important source of carbon (Giles 2006; Barros et al. 2011), they can contribute significantly to greenhouse gas reductions as an alternative to thermal power generation in China. Overall, climatic conditions shape basic water bodies and resource distributions at the macroscopic scale, and human activities have altered spatial patterns considerably. The effects of human activities have grown more pronounced with technological improvements and stricter government management.

Affected by physical conditions and human activities, the ten basins studied present different characteristics and face unique problems. A summary of basin features is given in Table 4, and classifications are made for the four groups.

Water abundance does not correspond well with water resources, as the terrain causes water basements and water depths to vary. Although water abundances are lowest in Basin with rivers in the southwest, precipitation and water resources are relatively abundant, and area and perimeter dispersion is not high as the population in this basin is not large and fewer human activities cause disturbances. Although precipitation fluctuates yearly, meltwater from glaciers can weaken this effect to some extent. The basin is characterized by complex terrain, severe drops in elevation and water power. Thus, a large proportion of China's hydropower stations are established in this basin. While water resources present a rather unbalanced distribution, the exploitation of water resources presents great difficulties (Jiang 2009; Tu et al. 2016), and with the improvement in infrastructure construction, the basin can be used for water resource exploitation and usage. Basin with rivers in the northwest present the lowest levels of water resource density, and high evaporation levels render most of the lakes in the area salty (Zhou et al. 2006). Ecological environments in this region are fragile, which is especially true for Xinjiang (Chen et al. 2016b), given its large desert area. While meltwater from surrounding mountains serves as freshwater, it cannot serve the local population or support physical environment improvements. Meanwhile, formidable natural conditions have led to lower levels of human disturbance in most areas, and water bodies changed less than those of other basins. Water shortages constitute the main issue faced in this basin, and environmental protection, especially for vegetation and plantations, must be improved. The Haihe River Basin, the Yellow River Basin and the Songhua and Liaohe River Basins present similar annual precipitation levels of roughly 500 mm, which is not sufficient to support regional economic development, and Fig. 6a shows that precipitation in most of these basins has declined from 1980 to 2015. The basins provide much of China's irrigation, support much of China's heavy industrial activity and high population density and especially for the Haihe River Basin, as Beijing and Tianjin are located within this basin. Human disturbances caused water bodies to fluctuate from 1980 to 2015, with water area and perimeter dispersion levels being considerably higher than those for basins supporting smaller populations. Water shortage and water pollution issues are serious in these basins and are a major cause of inhibited regional development


Songhua River and Liaohe River Basin
Precipitation
Surface water resources
Precipitation (mm)
Surface water resources (Billion m^3)
y=0.51x-114.9
R²=0.52
Haihe River Basin
y=0.06x-15.86
R²=0.67
Yellow River Basin
y=0.16x-22.59
R²=0.64
Huaihe River Basin
y=0.21x-113.91
R²=0.98
1998
2000
2002
2004
2006
2008
2010
2012
2014

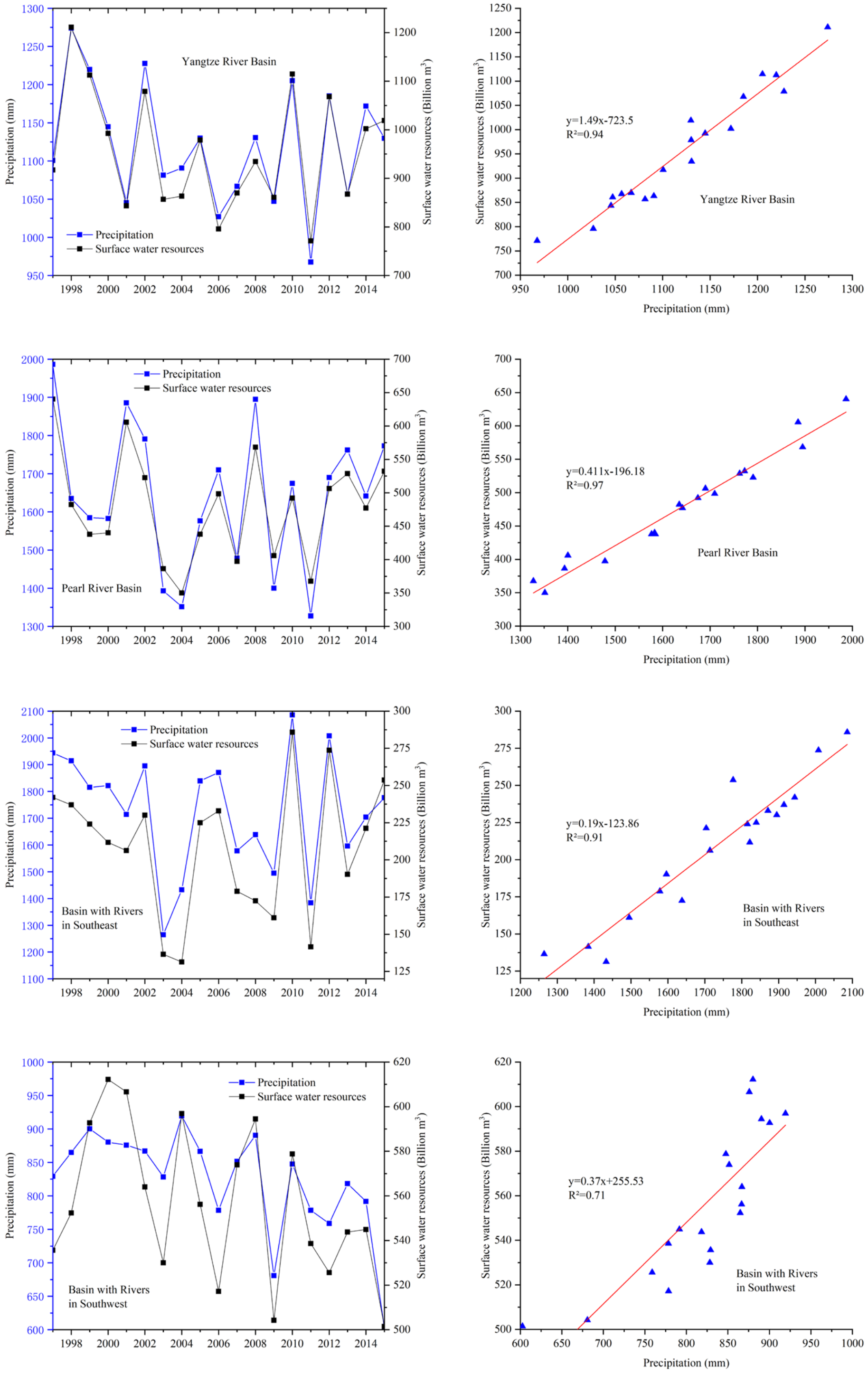


Fig. 7 (continued)

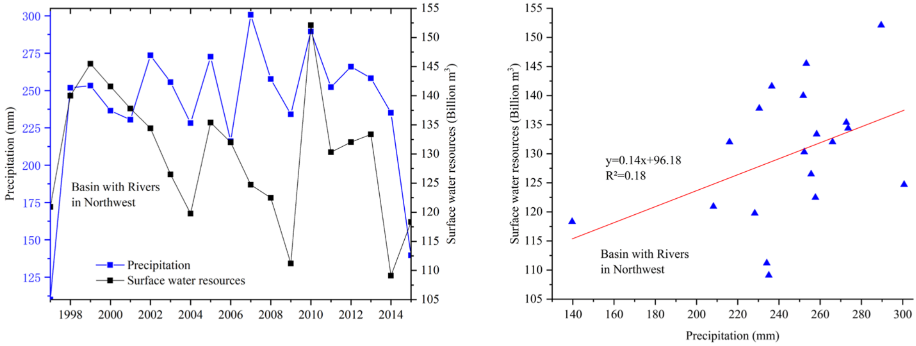


Fig. 7 (continued)

Table 4 Main indexes comparison of the ten basins and classification group

Basins	2015	1997–2015		1980–2015	
	Water abundance (%)	Water resources density (10^4 m^3/km^2)	Precipitation (mm)	Area dispersion degree (%)	Perimeter dispersion degree (%)
Basin with rivers in southwest	0.73	65.24	822.63	5.51	10.34
Basin with rivers in Northwest	1.37	3.89	245.23	9.86	22.52
Yellow river basin	1.07	6.53	482.12	26.79	32.58
Haihe river basin	1.99	4.05	517.04	33.85	44.18
Liaohe river basin	1.49	12.17	517.49	22.56	9.95
Songhua river basin	1.52	12.17	531.64	16.05	18.16
Basin with rivers in southeast	1.84	86.66	1725.13	30.36	34.74
Pearl river basin	2.10	83.74	1638.89	26.37	9.76
Yangtze river basin	2.36	53.12	1121.18	25.02	27.40
Huaihe river basin	3.79	21.27	874.41	51.17	37.24

(Eliasson 2015; Lu and Yu 2018). Regarding sustainable development, in addition to cross-regional water diversion projects that increase water supplies, water saving measures must be encouraged (e.g., sprinkler and drip irrigation, water transportation by pipeline, enhanced water use efficiency for industrial and residential purposes), and industrial structure adjustments and sewage treatment technologies are urgently needed. The other basins receive high levels of precipitation, and inland water body changes are also significant, especially for the Huaihe River Basin, with area dispersion levels reaching 51.17%. This phenomenon is also driven by human activities as discussed above. The basins also face water pollution and especially that related to eutrophication, which can cause cyanobacteria outbreaks, a major issue for water ecosystems (Zhou et al. 2014; Yu et al. 2017). Furthermore, heavy precipitation spurs such phenomena as soil erosion, flooding, debris flows and landslides (Shi et al. 2018; Zheng et al. 2018). Thus, water conservancy projects must be improved to dredge floods and waterlogged areas and to conserve soil and water, and sources of pollution causing eutrophication must be controlled, especially through the control of chemical fertilizer use. Finally, the improper disposal of industrial waste and sewage must be punished.

Findings and suggestions derived from this study can facilitate sustainable water management. There also exist some limitations. First, resolution of the remote sensing data may still need to be improved for more accurate examination, this is especially important for study at small scale. Second, time series need to be updated when data are available, which will help new problem diagnosis.

5 Conclusions

This study comprehensively examined China's main inland water body distribution at a high resolution of 30 m and for a long time period of 1980 to 2015. Changes in land surface water resources were also analyzed from 1997, and determinants were analyzed quantitatively and qualitatively. The conclusions are drawn below:

Spatial distribution pattern shows difference for different water bodies. Rivers are widely distributed across China. Lakes and especially larger lakes are mainly concentrated in the west, the central eastern area and the northeast. Most reservoirs and ponds are located in the east. Abundance of Rivers, reservoirs and ponds have obvious latitudinal and longitude zonality, with high abundance distributions in low latitude areas, and high values mainly appear from longitudes 110°E to 130°E, while neither latitudinal nor longitude zonality for lakes is obvious.

Between 1980 and 2015, areas and perimeters of reservoirs and ponds increased among the basins overall. Basin with rivers in the southwest presents the highest increases. Increasing percentages found for the other basins are $< 100\%$. Lake and river areas changed little. Basin with rivers in the southeast, the Yellow River Basin, the Yangtze River Basin, the Pearl River Basin, the Songhua River Basin and Basin with rivers in the southwest show slight decreasing trends, the other four basins present an increasing trend.

Land surface water resources and precipitation declined slightly from 1997 to 2015. Climatic conditions determine basic water body and resource distributions and volumes at the macroscopic scale, and human activities have greatly altered spatial patterns. For different water bodies, precipitation can affect area distributions of reservoirs and ponds and can moderately determine river area distributions, while the effect to lakes is not obvious. Human activities greatly change land surface and thus determine water body and resources; this effect is especially obvious in area with high population density, such as area along China's coastline.

Generally, Basin with rivers in the southwest includes highly exploitable water resources. The Yellow River, the Haihe River and the Songhua and Liaohe River Basins suffer from water shortages and pollution. Basin with rivers in the northwest face considerable water shortages and fragile environmental conditions. The other four basins are experiencing eutrophication and frequent meteorological and geological hazards.

Acknowledgement This research is funded by the Ministry of Education, Humanities and Social Science Fund of China (19YJAZH008) and the National Natural Science Foundation of China (41871135, 41971241).

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