Chin. Geogra. Sci. 2022 Vol. 32 No. 1 pp. 174−188
https://doi.org/10.1007/s11769-021-1252-2

Springer Science Press
www.springerlink.com/content/1002-0063

Spatial and Temporal Dynamics of Surface Water in China from the 1980s to 2015 Based on Remote Sensing Monitoring

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Abstract: Climate change and human interference play significant roles on dynamic of water body abundance, and drive related hydrological, biochemical and social/economic processes. Documenting and monitoring surface water area with high resolution multi-temporal satellite imagery provide new perspective to evaluate the dynamics of surface water area, especially in continental and global scale. In this study, based on the Landsat images from 1980s to 2015, we surveyed the spatial and temporal variation of surface water area, including rivers, lakes and reservoirs, in 10-yr temporal slice across China. Furthermore, the driving forces of the variation has been identified to reveal the interaction of water bodies and the changing environment. The results show that, the water surface area expanded over all three decades with strong spatial and temporal difference, despite the drier and warmer climate background; although lakes comprise the largest portion of the surface water area, the highest contributor of surface water expansion was new constructed reservoir located in the densely populated region; climatic parameters alteration, like precipitation and temperature, resulted in the water surface expansion in the northwestern basin by growing water input linked with rain and glacier melting; in the rest part of China, rise of water surface area was predominately attributed to human relocation of water resource, which yielded more new water storage area than the disappeared water body caused by less precipitation and stronger evapotranspiration. The conclusions highlight the integrative water resource management, especially in water conservation and restoration.

Keywords: temporal dynamics; spatial variation; surface water area expansion; driving forces

Citation: SONG Song, CAO Zheng, WU Zhifeng, CHUAI Xiaowei, 2022. Spatial and Temporal Dynamics of Surface Water in China from the 1980s to 2015 Based on Remote Sensing Monitoring. *Chinese Geographical Science*, 32(1): 174−188. https://doi.org/10.1007/s11769-021-1252-2

1 Introduction

Surface water actively participate in the hydrological and biochemical processes, and influence many aspects of ecology, economy, and human welfare by retaining, storing, cleaning, and providing water resource, although it occupies little proportion of global surface (Lehner and Döll, 2004; Verpoorter et al., 2014; Pekel et al., 2016). Nowadays the water body have been increasingly affected by the anthropological activity and climate change, and the intensive temporal-spatial variation of the surface water area cause a series of environ-

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Received date: 2021-05-06; accepted date: 2021-09-01

Foundation item: Under the auspices of Natural Science Foundation of Guangdong Province (No. 2020A1515011065), Guangdong Province Universities and Colleges Pearl River Scholar Funded Scheme (2019), the Key Special Project for Introduced Talents Team of Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou) (No. GML2019ZD0301), the NSFC (National Natural Science Foundation of China)-Guangdong Joint Fund Key Project (No. U1901219)

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mental problems (Biemans et al., 2011; Tshipa et al., 2017; Busker et al., 2019). Besides the water cycle processes, the associated carbon, energy, pollutant and sediments fluxes can be quite responsive to the water body change (Adrian, R. et al., 2009; Immerzeel et al., 2010; MacDonald, 2010; Czekalski et al., 2015; Khandelwal et al., 2017). Despite the importance knowledge of the spatial-temporal variations and long-term trends in surface water area, the current understanding in global and continental scale with high resolution is still rather limited (Pekel et al., 2016; Khandelwal et al., 2017; Nitze et al., 2017; Zhang et al., 2017b).

The monitoring of surface water area at a sufficiently accurate spatial and temporal resolution, is crucial for understanding the underlying processes driving surface water area change (Crétaux et al., 2015; Mueller et al., 2016). With the rapid development of computer science and remote sensing technology, a massive of local and global Landsat imagery archive has accumulated particularly for environmental monitoring purposes in various temporal scales recent years (Hansen et al., 2013; Zhou et al., 2015; Pekel et al., 2016). Widely used multispectral Landsat indices allows refined dynamics detection of rivers, lakes and reservoirs respectively (Verpoorter et al., 2014; Allen and Pavelsky, 2015; Nitze et al., 2017). The comparison research revealed good performance of various products, like MODIS (Moderate Resolution Imaging Spectroradiometer) data (MOD09A1) and Landsat data (Multispectral Scanner, MSS; Thematic Mapper, TM; Enhanced Thematic Mapper Plus, ETM+; and Operational Land Imager, OLI) in water area mapping (Zhang et al., 2017a). Globally study estimated a severe decline of water area over the past 30 yr, including a total 1.15×10^5 km^2 of land converted into water, but more water area, 1.73×10^5 km^2, lost by transforming into non-water area (Donchyts et al., 2016).

Previous studies focusing on the China inland water area provided insightful view in the statistics characteristics and long term variation of the water bodies (Ma et al., 2010; Yang and Lu, 2014). However, the data source of the previous research involved only remote sensing images over short term, published data and digitalized map, integrated long term satellite image archive were in shortage. In addition, earlier research focusing separately on rivers, lakes or reservoirs, illustrated abundant indices of each water body but fragmented the integrity of the hydrological system. Comprehensive study scanned the entire inland surface water body dynamics with systematically high spatial resolution are in urgent need.

In this study, we mapped the surface water distribution in China, including rivers, lakes and reservoirs from 1980s to 2015 with a time interval of 10 yr, based on remoting sensing images with 30 m spatial resolution. The spatial and temporal dynamics of the surface water area has been analyzed, and the driving mechanism of the variation was investigated, in order to achieve a comprehensive understanding of the water area dynamics under climate change and human interferences. The aims of this study are to identify the surface water area distribution characteristics, to clarify the spatial and temporal variation of rivers, lakes and reservoirs, and to figure out the causing factors of the surface water dynamics.

2 Material and Methods

2.1 Study area

The study area is the whole China, including Hong Kong, Macao and Taiwan. South China Sea Islands are not included because of the resolution limitation of the satellite images. The morphology and landscapes vary significantly across the vast continent. Qinghai-Tibetan Plateau known as 'the Roof of the World', forms the top gradient at the height over 4000 m. Extensive and densely populated alluvial plains on southern and eastern China with elevation lower than 1000 m comprises the third Gradient. The second Gradient covers the broad area of central and northwestern China, with altitude in-between 1000 and 2000 m. Most rivers in China flow from west to east due to the gradient condition. In general, ten main basins were divided across the continent. China's two major rivers, the Yellow River (YR) and the Yangtze River (YZ), originate from Qinghai-Tibetan Plateau, flow across the two largest basins of China, and empty into Bohai Sea and East China Sea, respectively. Other exorheic basin include Songhuajiang River Basin (S) connected with Okhotsk Sea, Liaohe River Basin (L) and Haihe River Basin (Ha) flowing into Bohai Sea, Huaihe River Basin (Hu) emptying into East China Sea, while Pearl River Basin (P) and Southeastern (SE) Basin flowing in to South China Sea. Southwestern Basin (SW) is mainly dominated by the Upper Reach of Mekong River. Northwestern Inland Basin (NW) extends over the vast endorheic region. Apart from river systems, lakes and reservoirs share high portion of the total surface water area. The climate of China is mainly influence by the combination of monsoon system and complex topography. Overall, a gradual decreasing trend of precipitation is witnessed from southeastern shore to the northwestern inland. The longitudinal and latitudinal distribution of the surface water area have been shown in Fig. 1. The southeastern China is relatively more concentrated with surface water compared with the rest part. A second region intensively covered by water body is Qinghai-Tibetan Plateau. Around 1.67% of the land surface of China is covered by water area in 2015, relatively low compared with the global data.

The regional disparity and imbalance characteristics of the water resource in China are remarkable. The precipitation and surface water depth in SE region are 10 and 30 times higher than that of NW region (The Ministry of Water Resources of the People's Republic of China, 2020). The main supply of surface water is precipitation, except NW region, where the glacier melt water plays more important role. As the largest consumer of water resources in the world, China supported 22% of the world's population and the explosive economic growth with only 6% of the world's fresh water resource in the last decades. Due to the rapid aggregation of human, resources and economy, the entire country is confronted with unprecedent conflict between supply and demand of water resource, especially in the northern and northwestern China. Meanwhile, various

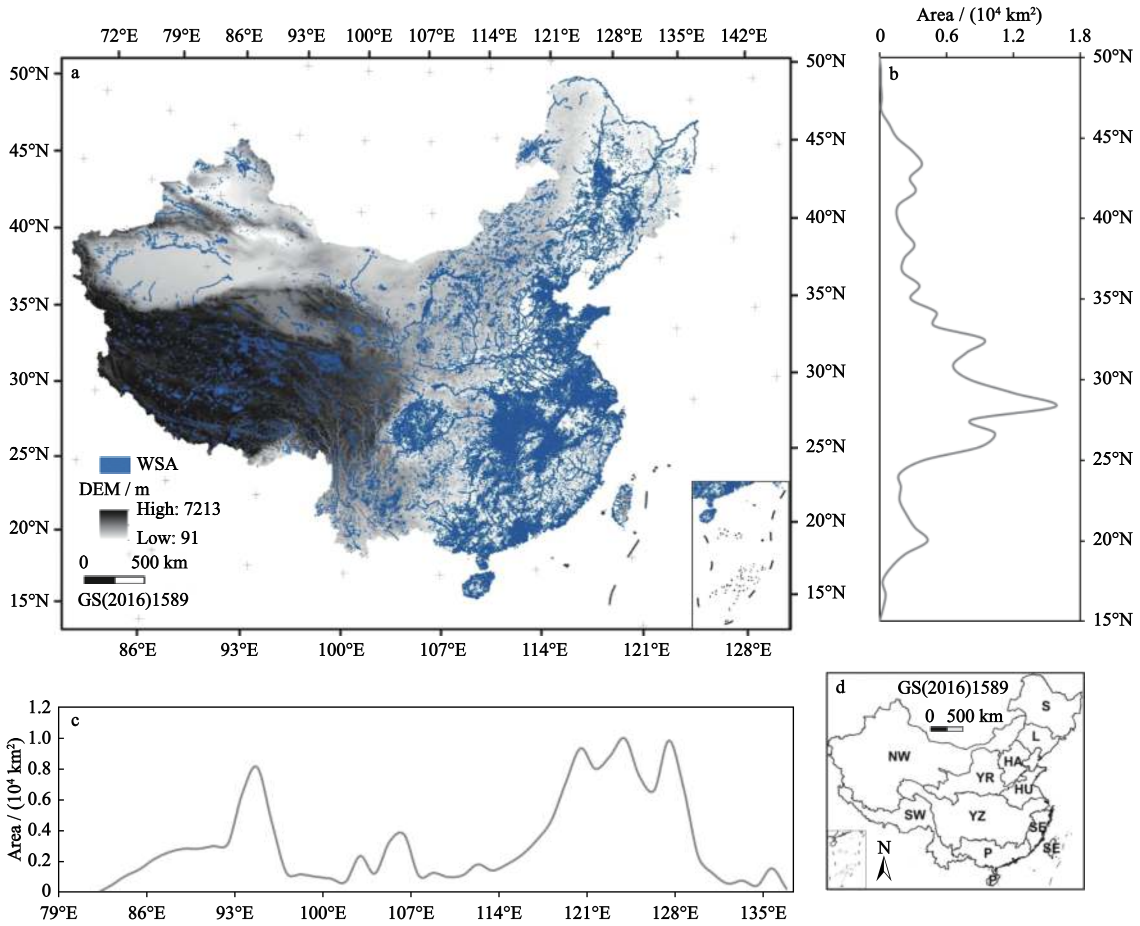

Fig. 1 Spatial distribution (a) and area at different latitudial (b) and longitudial (c) of water surface area (WSA), and main basins (d) in China. WSA generated by the remote sensing images in 2015; The ten main basins of China is given in the small map in the right bottom corner; NW, SW and SE represent the northwestern inland basin, southwestern basin and southeastern basin, respectively; S, L and P are the abbervations referging Songhua River Basin, Liaohe River Basin and Pearl River Basin; HA, YR, YZ and HU symbolize Haihe River Basin, Yellow River Basin, Yangtze River Basin and Huaihe River Basin, individually

water-related crisis severely threatens the local sustainable development, such as water pollution, drought, flooding, rainstorm waterlogging, *etc*.

2.2 Data acquiration and processing

The multi-temporal satellite image data from Landsat-MSS/TM/ETM were collected and interpreted with human-PC interpretation technologic (Table 1). Together with the field survey data, thematic maps, statistics material and geographic maps, the water area interpreted process was carried out. The national land use land cover map of 2015 with the scale of 1∶10 were integrated in the water surface mapping. A series of preparation was essential before interpretation process, including false color composite, geometric correction, images cutting and georeferencing (Fig. 2). It's a critical step to set up unified interpretation symbols for the participated experts. The symbols of rivers, lakes and reservoirs were as follows:

Rivers, naturally or artificially generated streamways with obvious geometric features and boundary, stretched from upstream to downstream with free cultivation and local flatness, light to dark blue in color, represented by high uniformity in image structure;

Lakes, natural permanent water logging area, with distinct geometric features and natural shapes, in blue to green color, shown uniformed image structure;

Reservoirs, artificially constructed water storage area with regular form or remarkable human modification, in color of light blue, blue or dark blue, and exhibited relatively even image structure.

As shown in Table 1, the study period spanned from the early 1980s till 2015. The water surface data of the 1980s based on the Landsat MSS/TM images from 1979 till 1982, while the images of other periods were mainly concentrated in the corresponding year.

The quality of the remote sensing data was influenced strongly by air visibility, which is highly related

Table 1 The data source of this study

Study period	1980s	1995	2005	2015
Time	1979–1982	1995–1996	2004/2005	2015
Satellite source	Landsat MSS/TM	Landsat TM	Landsat TM	Landsat 8 OLI, GF-2
Amount of Scenes	650	–	–	767

Notes: – meas no data. MSS and TM refer to the images from Multispectral Scanner and Thematic Mapper, while OLI and GF-2 mean remote sensed image taken by Operational Land Imager and Gaofen-2 satellite

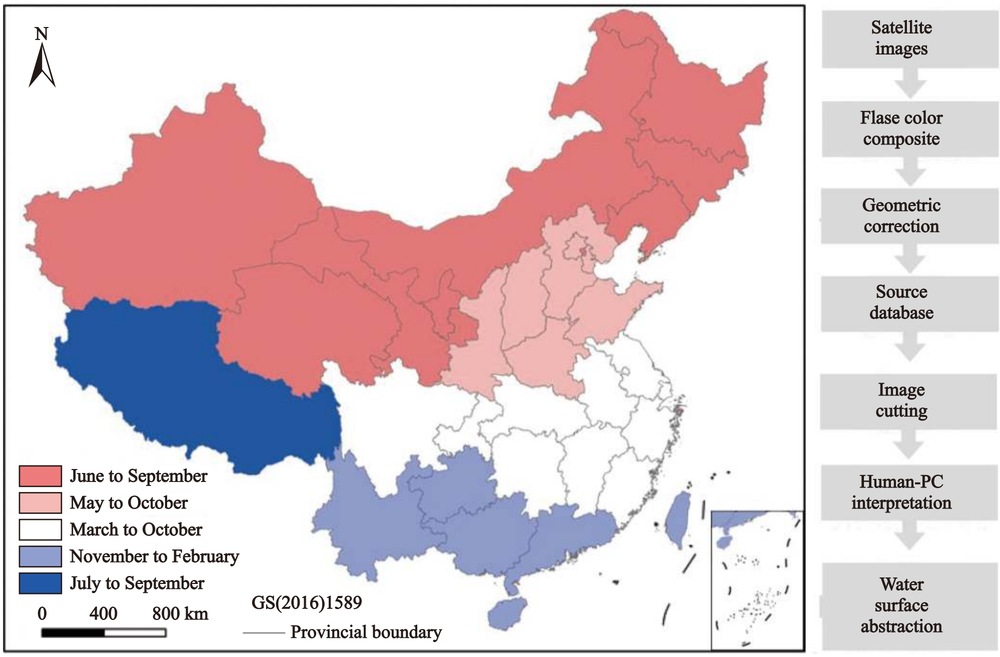

Fig. 2 The selection and processing of satellite image. UAV is Unmanned Aerial Vehicle

to the local climate and weather. Images from days of high air visibility with relatively low humidity and cloud coverage degree were selected for interpretation. In general, the season of images we adopted across the entire China were illustrated in Fig. 2.

2.3 Precision validation

The quality of the interpretation was validated with random sampling inspection of field survey points. We first classified the accuracy level into 11 grades, from $L0$ to $L10$ level. Here $L10$ represents all the sampled grids fit the interpreted results, and the accuracy rate reach 100%. In contrast, $L0$ meant the interpreted image is totally incorrect. The overall precision was calculated using the following equation,

$$P = N_{L10}/N \times 100\%$$

where P is overall precision, N_{L10} means the number of the 100% precise grids, and N refers to the total amount of the sampled grids.

In general, 434 sampled points were sampled, the overall precision for river, lake and reservoir are 96%, 93% and 88%, respectively.

3 Results

3.1 Surface water area change

3.1.1 Water surface area change in total

Fig. 3a showed the total water area has been increasing from 14.67 × 10^4 to 15.89 × 10^4 km^2 since the 1980s to 2015. The total surface water area grew only 0.61% from the 1980s to 1995, while dramatic increase occurred in the latter two periods, with increment of 4.57% and 2.93% during 1995–2005 and 2005–2015, respectively. From the perspective of water body, the river area decreased from the 1980s to 1995, while area of lakes and reservoirs rise slightly during the same period (Fig. 3b). The area of rivers, lakes and reservoirs all increased distinctly in the latter two periods. Lakes occupied nearly half of the total water area in all periods. Reservoirs contributed highest portion to the surface water area expansion. The area ratio of reservoir increased from 23.77% to 28.15% in the past three decades.

3.1.2 Numbers and area of lakes and reservoirs

The vast majority of lakes and reservoirs are in small size (≤ 1 km^2). Around 93% of lakes were smaller than 1 km^2, which comprised only 5.3%–5.4% of the total lake area during study period. The large portion of lake area was contributed by lakes with size ranging from 100–1000 km^2, accounting for 40% of the lake surface area. One third of the reservoir area was contributed by the small sized ones (≤ 1 km^2). Reservoirs with area range of 1–10 km^2 and 10–100 km^2, constituted one quarter of the reservoir surface area individually. Approximately, 10% of reservoir surface area was dedicated by reservoirs larger than 100 km^2. The following tables show the dynamics of the amount, average area and total area of lakes (Table 2) and reservoirs (Table 3) in the last three decades. Although the total area of lakes and reservoirs were on growing in all periods, the amount of small lakes and reservoirs decreased significantly from the 1980s to 1995. The surface ratio of small reservoirs decreased from 31.76% to 28.58% from the 1980s till 2015.

3.2 Surface water area of the main basins

The water surface area is unevenly distributed among basins (Fig. 4a). Northwestern inland basin had the highest portion of the surface water, followed by the Yangtze Basin, accounting for 30% and 25% of the total surface water area respectively. Southeastern, Haihe River and Liaohe River basins weakly contributed to the

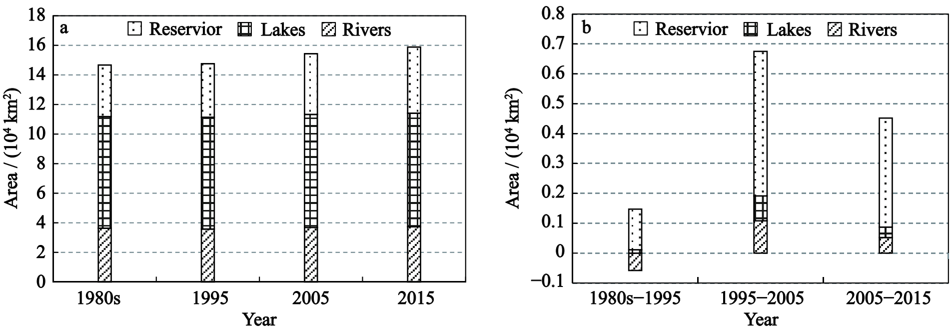

Fig. 3 The area (a) and increase range (b) of rivers, lakes and reservoirs in China from the 1980s to 2015

Table 2 The dynamics of lakes with different size range in China from the 1980s to 2015

Size / km^2	Amount				Averaged area / km^2				Total area / km^2			
	1980s	1995	2005	2015	1980s	1995	2005	2015	1980s	1995	2005	2015
≤1	41671	33779	36386	51068	0.06	0.07	0.07	0.05	4075.54	4000.38	4033.01	4182.15
1–10	2481	2419	2376	2536	2.89	2.86	2.85	2.83	7166.51	6918.75	6768.99	7182.07
10–100	534	538	522	519	31.77	31.23	31.11	30.53	16967.08	16802.92	16239.41	15843.99
100–1000	109	113	110	116	272.81	266.99	273.82	277.94	29735.95	30169.46	30120.21	32241.11
>1000	9	9	10	9	1945.37	1963.88	1923.84	1922.12	17508.29	17674.93	19238.45	17299.05
Total	44804	36858	39404	54248	0.59	0.49	0.52	0.71	75453.36	75566.44	76400.07	76748.37
Change / %	–	–17.74	6.91	37.67	–	–17.86	5.74	37.05	–	0.15	1.10	0.46

Table 3 The dynamics of resevoirs with different size range in China from the 1980s to 2015

Size / km^2	Amount				Averaged area / km^2				Total area / km^2			
	1980s	1995	2005	2015	1980s	1995	2005	2015	1980s	1995	2005	2015
≤1	128507	96049	100978	131732	0.09	0.11	0.12	0.10	11075.16	10996.72	12015.76	12777.63
1–10	3754	3909	4507	4803	2.52	2.55	2.54	2.55	9463.13	9954.30	11470.05	12230.76
10–00	336	382	458	511	26.78	25.31	24.99	24.45	8996.90	9668.07	11444.63	12494.69
>100	15	21	23	28	222.93	172.11	179.50	185.49	3343.96	3614.37	4128.60	5193.86
Total	134602	102356	107971	139089	3.86	2.83	2.63	3.11	34869.14	36228.46	41064.04	44711.94
Change / %	–	–23.96	5.49	28.82	–	–26.81	–6.94	18.31	–	3.90	13.35	8.88

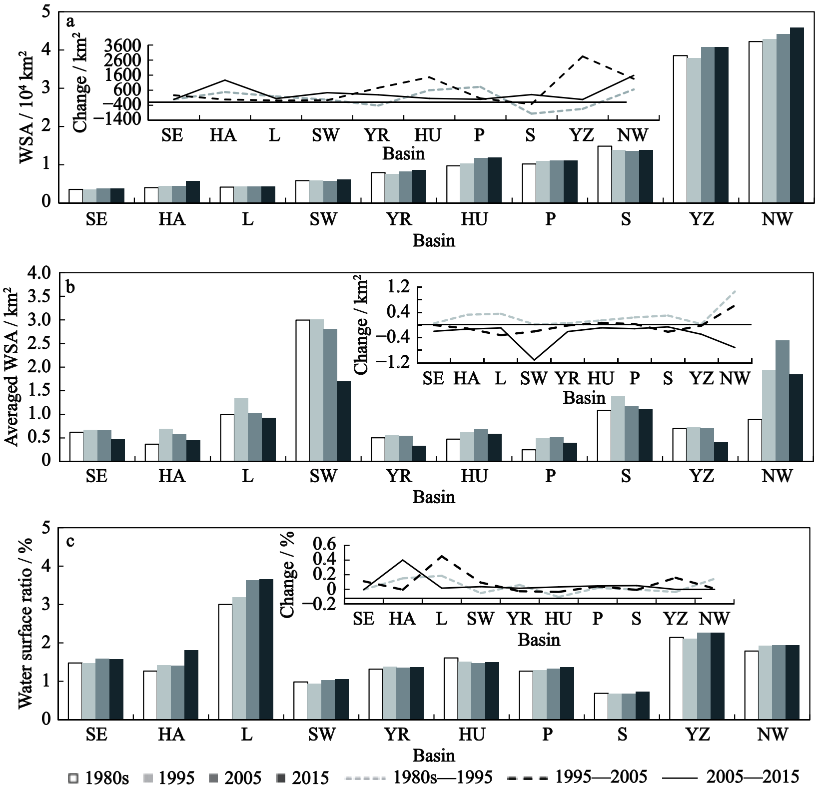

Fig. 4 The distribution and its variations (smaller window) of surface water in ten main basins in China from the 1980s to 2015. WSA is water surface water. Meaning of the abbreviation is the same with that of Fig. 1

total surface water area. Net increase of surface water area can be recognized in nearly all basins, except Songhua River Basin. Yangtze River, Northwestern, Huaihe River and Hahai River basins showed high net growth from the 1980s to 2015 (Fig. 4a).

An overall decline trend is revealed in the averaged water surface area (WSA) of water bodies, especially in Southwestern, Yangtze River, Southeastern and Yellow River basins. Although most basins showed increase trend from the 1980s till 1995 in extent, nearly all basins started to shrink in averaged WSA in the following periods. Distinct decrease of WSA occurred to all the basins from 2005 to 2015 (Fig. 4b). In 1980s, the averaged area of surface water in the southwestern basin was as high as 3.00 km^2, which dropped to 1.70 km^2 in 2015. Although there were high growth of averaged WSA from the 1980s till 1995 in Liaohe River, Haihe River and Songhua River basins, distinct shrinkage in the following periods offset the previous growth. Sharp net increase of the averaged WSA was observed only in northwestern basin, despite the large degradation in averaged WSA from 2005 to 2015 (Fig. 4b).

Slightly growth of water surface ratio was specified in basin scale, except Huaihe River Basin (Fig. 4c). The averaged surface water ratio across China in the 1980s was 1.55%, which increased with accelerated rate in each period and finally reached 1.73% in 2015. Liaohe River and Haihe River basins reported the highest increment in water surface ratio among all basins. With a strong increase from 3.00% in the 1980s to 3.65% in 2015, Liaohe River Basin had the highest water surface ratio, while its geographical neighborhood basin, Songhua River Basin was the lowest in water surface ratio, 0.73% in 2015. Yangtze and northwestern basins are the second and third highest in water surface ratio.

3.3 Surface water in different elevation

Overall, the rivers, lakes and reservoirs distributed mainly in the low land area. According to the altitude statistics given in Fig. 5, nearly one third of the surface water located in the area with altitude lower than 30m, and nearly half of the surface water lay in the region lower than 300 m elevation. Around 18% of the surface water area was found in the elevation rang of 4500–5000 m. Temporally, sharp growth and decrease of surface water area within altitude lower than 30 m and in between 100–300 m was identified from the 1980s to 1995. Slightly decrease of the surface water extent in the region with elevation range of 1500–4500 m was also recognized in the same period. An overall increase of surface water with all elevation range occurred during 1995 to 2005, while the highest increase located in the area lower than 30 m elevation. Compared with the former two periods, surface water area increases from 2005 till 2015 was relatively moderate in all elevation range. The similar growth extent exhibited in the elevation range of 500–1000 m, 2500–3000 m and 4500–5000 m. The water area expansion in these three elevation ranges equaled to 45% of the net increase of surface water between 2005 and 2015.

3.4 Spatial-temporal dynamics of the rivers, lakes and reservoirs

3.4.1 Rivers

As shown in Fig. 6a, rivers unevenly distributed across China. The density of rivers decreased from southeastern to northwestern region. Although slightly increase of the river area in the northwestern border of China have been witnessed from the 1980s to 1995, the total river area decreased in the same period, mainly caused by the river decreasing of Yangtze River and Huaihe

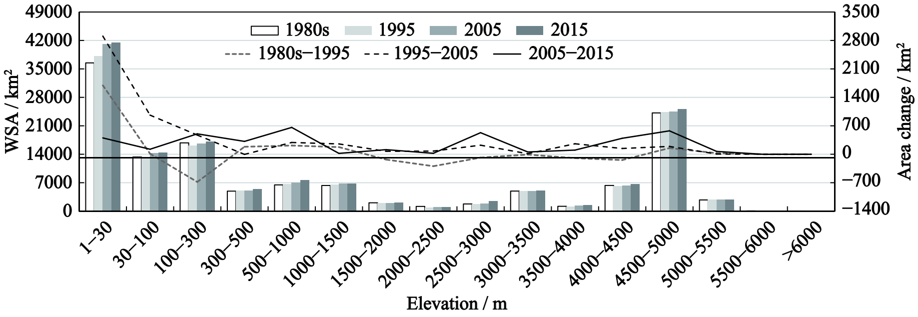

Fig. 5 The water surface area (WSA) distribution in different elevation in China from the 1980s to 2015

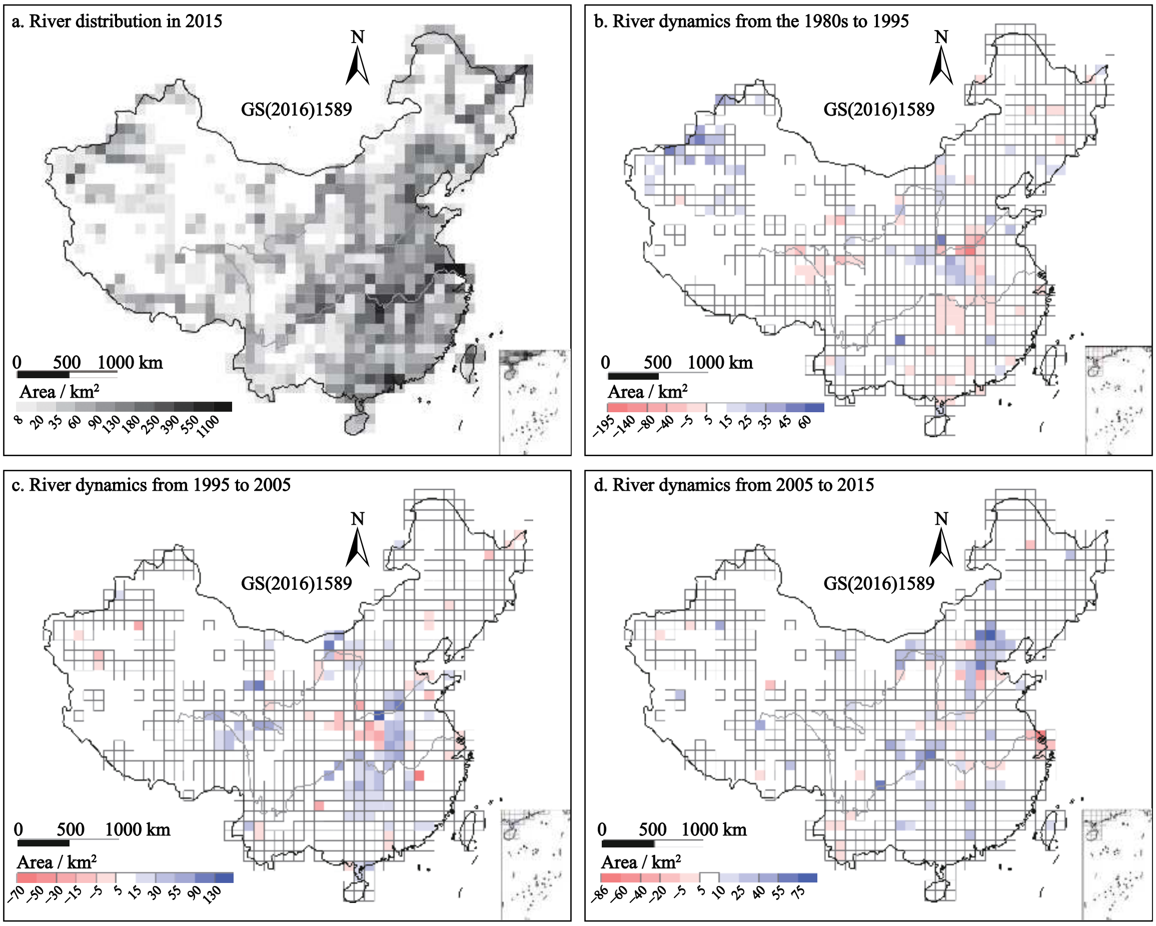

Fig. 6 The distribution of area and its change of rivers in 2015 and its spatial-temporal dynamics in China. Resolution of each grid is 100 km × 100 km, the following figures share the same grid

River basins (Fig. 6b). Two hot spots of river area growth have been identified from 1995 to 2005, seated in the upper and middle- lower Yangtze and Yellow basins, and middle-lower Yangtze basin, respectively (Fig. 6c). The Haihe Rvier Basin, covering Beijing rim region, represented distinct increase in the third periods, from 2005 to 2015 (Fig. 6d). In general, the dynamic of river area primarily happened in the upper, middle-lower reach of Yangtze River and Huaihe River basins in the first two periods, and in Beijing Rim Region in the last period.

3.4.2 Lakes

Three main lake regions were clearly exhibited in Fig. 7a, knowing as Qinghai-Tibet Plateau Lake Region (QTP), Northeastern Lake Region (NLR), and Lower Yangtze River Lake Region (LYR). QTP is the largest Lake Region globally, accounting for 50% of the lake area all over China. The lake area in QTP grew during the study period, especially from 1995 to 2005, during when the lake area rose sharply along the middle part of the Plateau north edge (Figs. 7b–7d). Lake area growth in the vast plateau region with lower growing rate dominated the lake dynamics from 2005 to 2015. The NLR was shrinking from the 1980s to 2015. Remarkable lake degradation during the recent decades related to intensive human activities and climate changes have been reported in Mongolian Plateau, especially in Inner Mongolian region (Tao et al., 2015). Lakes in LYR played considerable role in hydrological regulation and flood protection. Lake area represented growing trend in LYR from the 1980s to 1995, and this trend continued in the following decade, despite the obvious widespread decline in most region (Fig. 7c). Since 2005, the lake area in LYR started to decline. In general, QTP contributed most significantly both in the distribution and the increase range of the lake area (Fig. 7d).

3.4.3 Reservoirs

The distribution of reservoirs was similar with that of

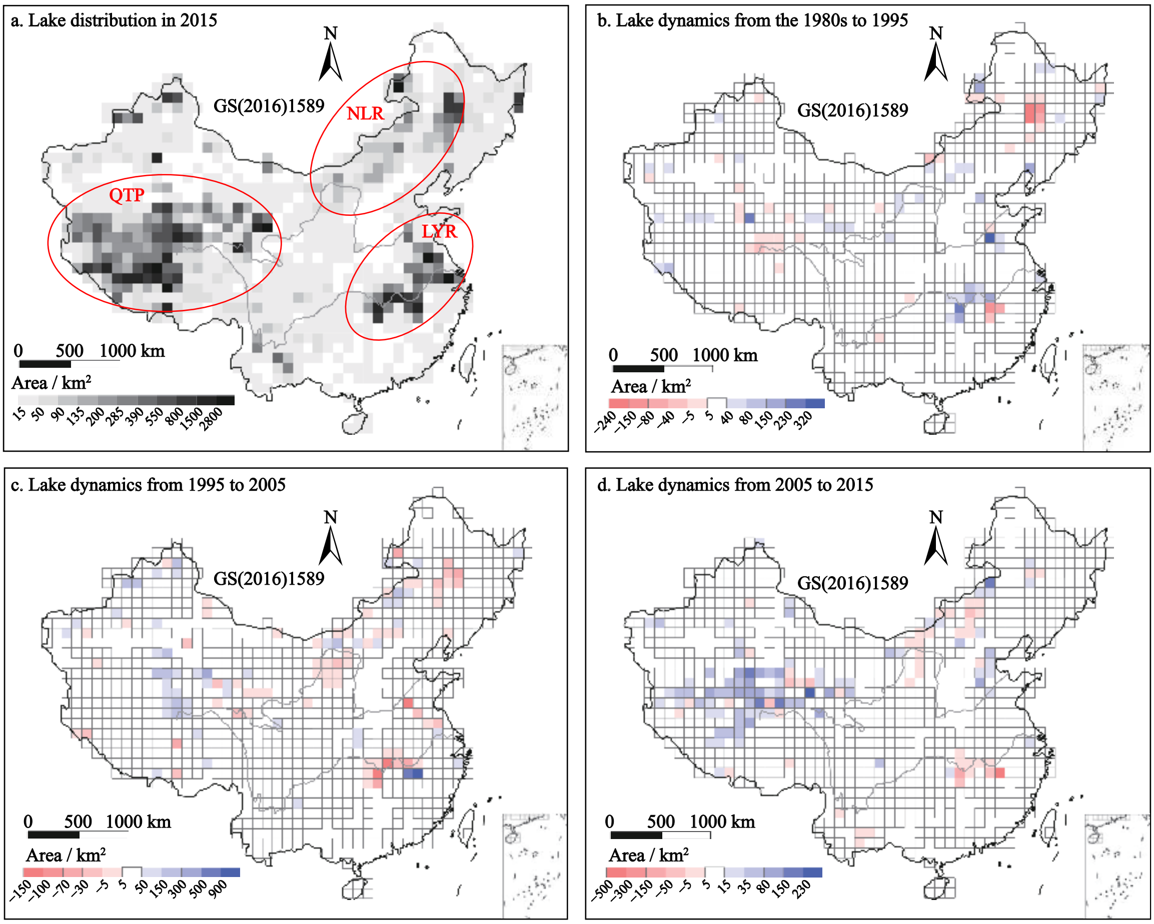

Fig. 7 The distribution of area in 2015 and its spatial-temporal dynamics of lakes during different peroids in China. Qinghai-Tibet Plateau Lake Region (QTP), Northeastern Lake Region (NLR), and Lower Yangtze River Lake Region (LYR)

rivers, but more concentrated in the southeastern part and along the coast, especially in the deltas of Yangtze River, Yellow River and Pearl River. The spatial reservoir area divider was identical with the demarcation line, 'Heihe-Tengchong Line' (Hu Line) (Fig. 8a). To the east of the line, lies the densely populated area with high economic power and plenty of reservoirs. While to the west of the line is a vast territory with a sparse population, weak economy and scare reservoirs. This expressed the strong anthropogenic influence on the development of reservoirs. The spatial dynamics of reservoirs become decentralized in the three periods. The increase of reservoirs area clustered in Huaihe River and Haihe River basins (Fig. 8b), which expanded to a wider area covering middle-lower basin of Yangtze River from 1995 to 2005 (Fig. 8c). In the last period, the increased area of reservoir distributed all over the mainland extensively, especially in the middle and southwestern China (Fig. 8d). Earlier research has highlighted a steady increase of reservoir storage from 350 km^3 in 1970s to 725 km^3 in the 2010s, and implied an accelerating storage growth rate after 2000 (Yang and Lu, 2014).

4 Discussion

4.1 Land use cover change and water area change

4.1.1 Change between water and non-water area

Based on the land use/cover map of the studied four stages, the land use sources of the increased water area change were analyzed. As shown in Table 4, strong interaction between agricultural land and water area was clearly revealed. The increased river and reservoir area were mainly from agricultural land. The dominate land source of increased lake area was agricultural land from the 1980s to 1995, while in the latter two periods, lakes expanded mainly to grass land and unused land. Apart from grass and unused land, lakes and wetland presented high transition flux.

Construction land played dual role in water area change. Expansion of construction land, for one thing

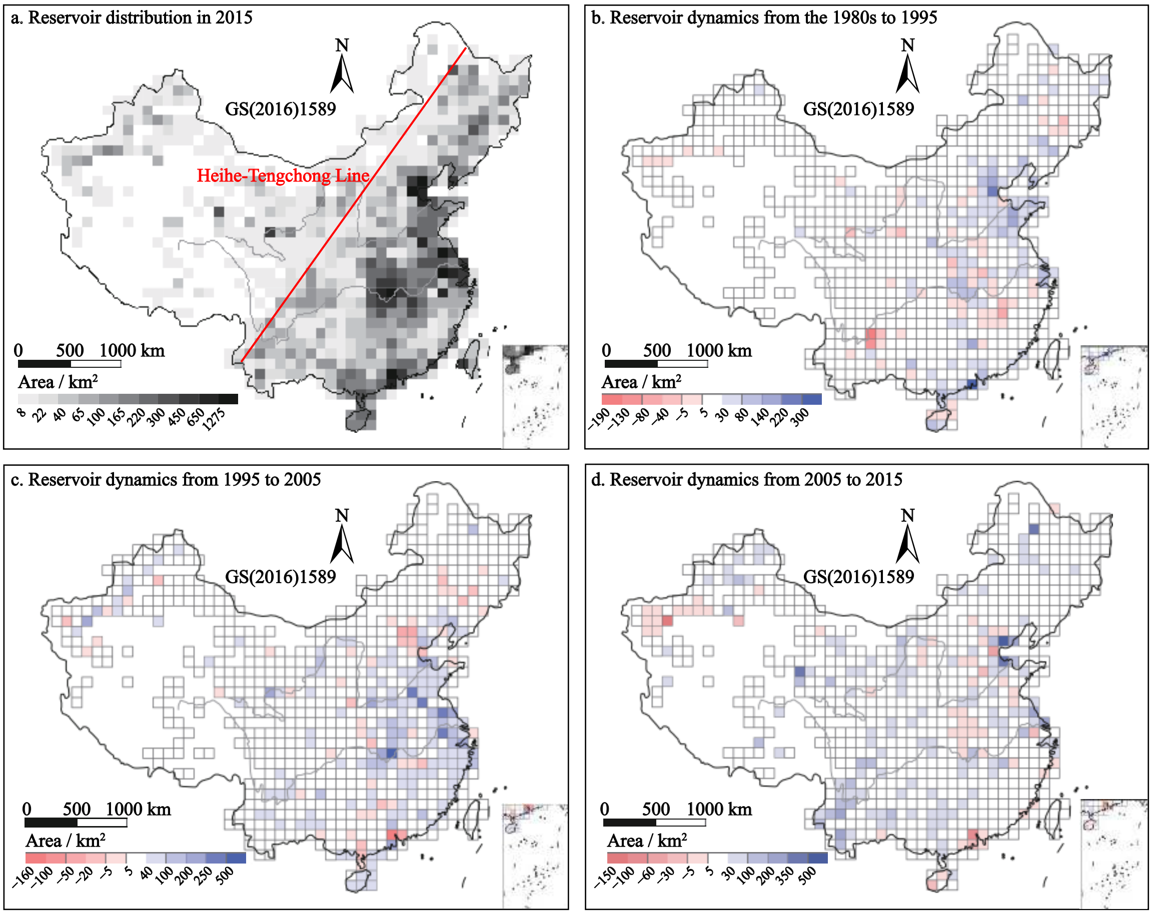

Fig. 8 The distribution of area in 2015 and its spatial-temporal dynamics of reserviors during different peroids in China

Table 4 The sources of the increased water area in different periods in China

Water type	Period	Agriculture	Forest	Grass	Wetland	Construction	Unused	Ocean	Sum
Rivers	1980s–1995	–751.83	6.14	166.35	–15.98	–26.94	–4.50	–7.49	–634.25
	1995–2005	819.35	164.13	353.23	105.11	–16.26	84.64	3.40	1513.61
	2005–2015	475.33	101.10	–11.55	182.97	–117.92	64.56	-2.07	692.41
Lakes	1980s–1995	210.79	–17.43	11.64	51.22	–14.64	–206.00	2.84	38.43
	1995–2005	–314.88	16.21	471.95	451.53	–63.06	814.30	-0.02	1376.02
	2005–2015	–3.90	29.32	895.96	–1335.93	–75.52	783.27	0.04	293.25
Reservoirs	1980s–1995	1142.59	46.43	–432.14	862.60	–112.15	–37.22	16.92	1487.04
	1995–2005	3469.53	521.56	643.10	–710.40	–588.71	502.65	22.77	3860.50
	2005–2015	1526.75	496.44	401.44	172.55	388.37	546.77	0.54	3532.87

Notes: positive number means where the increased rivers, lakes and reservoirs area came from, the negative number represented the rivers, lakes or reservoirs transferred into other land use type. The data set of land use cover change is provided by Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn)

has seized space which belonged to rivers and lakes before. For another, the infiltration rate decline caused by the rapid growth of paved area in construction land, would have accelerated the runoff generation and confluence rate, and intercepted more water on land surface. In addition, growing need of urban water management and waterscape planning might have caused the abrupt change of construction land to human controlled city water landscape.

4.1.2 Area transferred within rivers, lakes and reservoirs

With the increasing need of agriculture irrigation, urban water usage and industry water demand, enormous rivers and lakes have been regulated by water engineered facilities. Rivers transferred to reservoirs has happened in all three periods, which delineated the increasing human control on rivers. From 1995 to 2005, large amount of lakes has been transformed into reservoirs, while in other two periods, a small portion of reservoirs were changed into lakes. Very seldom occurred that lakes and reservoirs transferred into rivers (Table 5).

4.2 Driving factors of the water area change

4.2.1 Climate change

The two main climate parameters, precipitation and evapotranspiration, influence the surface water dynamic by alteration of water input and output in basin and continental scale. The annual averaged precipitation from the 1980s to 2015 showed slightly declining trend or remained steady in most of basins, except Northwestern basin, where the precipitation was rising remarkably (Fig. 9). Evapotranspiration is proportional to temperature. Distinct growing trend has been revealed by the annual averaged temperature in all ten basins (Fig. 9). The evapotranspiration was correspondingly ascending over the study period. On the background of drying and warming weather, the total water surface area in basin scale was broadening, which suggested that the water surface area expansion in basin scale was not driving by climate parameter, except Northwestern basin.

Considering the relatively weak human activity in the northwestern basin, climate change played dominate role in the surface water expansion. Large scale atmospheric circulation changes associated with climate warming in the middle of 1990s resulted in statistically significant water area changes. In response to this climate shift, increased precipitation and cryospheric contributions to lake expansion have been detected in Qinghai-Tibet Plateau (Zhang et al., 2017b). While the adjacent Inner-Mongolian Plateau experienced strong lake shrinkage due to the same climate shift. Simulation analysis suggested a contribution of 10.6% and 9.9% snow and glacier melting to the total runoff over the Upper Brahmaputra River in the southern Qinghai-Tibet Plateau, with the emergency of the glacier melting inflection points in some rivers (Chen et al., 2014; Chen X et al., 2017). Satellite monitoring illustrated that the glaciers in the alpine region of China have decreased by 886.63 km^2 over the past three decades. The melting rate reached 57.21 m^2/yr, during 1995 and 2005, much higher than the earlier and latter period, which were 13.98 and 17.07 m^2/yr, respectively. The contribution of glacial meltwater to lake storage in different regions of the Qinghai-Tibet Plateau from 2000 to 2013 varied 22.2%–100.0%, while the total lake surface area expanded around 4000 km^2 during the same period in northern and central Qinghai-Tibet Plateau (Qiao et al., 2019; Qin et al., 2020). In addition, the recent glacial lake expansion observed connected not only to the direct glacial melt water, but also to the hydrogeomorphic process of glacier thinning and retreat (Song et al., 2016). It is essential to link the responses of hydrologic processes to both climate change and shrinking glaciers in glacierized catchments for the future hydrological and water resource research (Chen Y N et al., 2017). In addition to Qinghai-Tibet Plateau, another major distribution region of glacier is the northwestern border of China, where the increased water surface area would highly correlated with glacier dynamics.

Table 5 The transferred area between rivers, lakes and reservoirs in China from the 1980s to 2015 / km^2

Period	Rivers to lakes	Rivers to reservoirs	Lakes to reservoirs
1980s–1995	–0.19	9.77	–75.11
1995–2005	82.27	115.94	416.17
2005–2015	–14.13	172.18	–87.24

Note: the negative number indicated the transferred area is in opposite direction

4.2.2 Human activity

Human activity severely interfered the hydrological process, especially in the relocation of the water resource on land surface, by reservoir storage, irrigation, urban construction *etc*. Reservoir contributed the biggest portion of the water surface expansion (Fig. 3b), while the new constructed reservoirs were widespread across the southeastern China (Figs. 8b–8d). The expansion of reservoirs was in highly accordance with the intensity of the human interference. As shown in Fig. 10, the abundance of the new constructed reservoirs was identical with the increased population density and the Grand National Production (GDP) over the study period.

Human induced water surface extent growth overpassed the climate induced water surface loss. We can consequently conclude that the surface water area rises distinctly despite the loss of net water input, due to the interference of human activity. The increase of construction area, water engineering facilities and water storage area resulted in an efficiency growth of surface

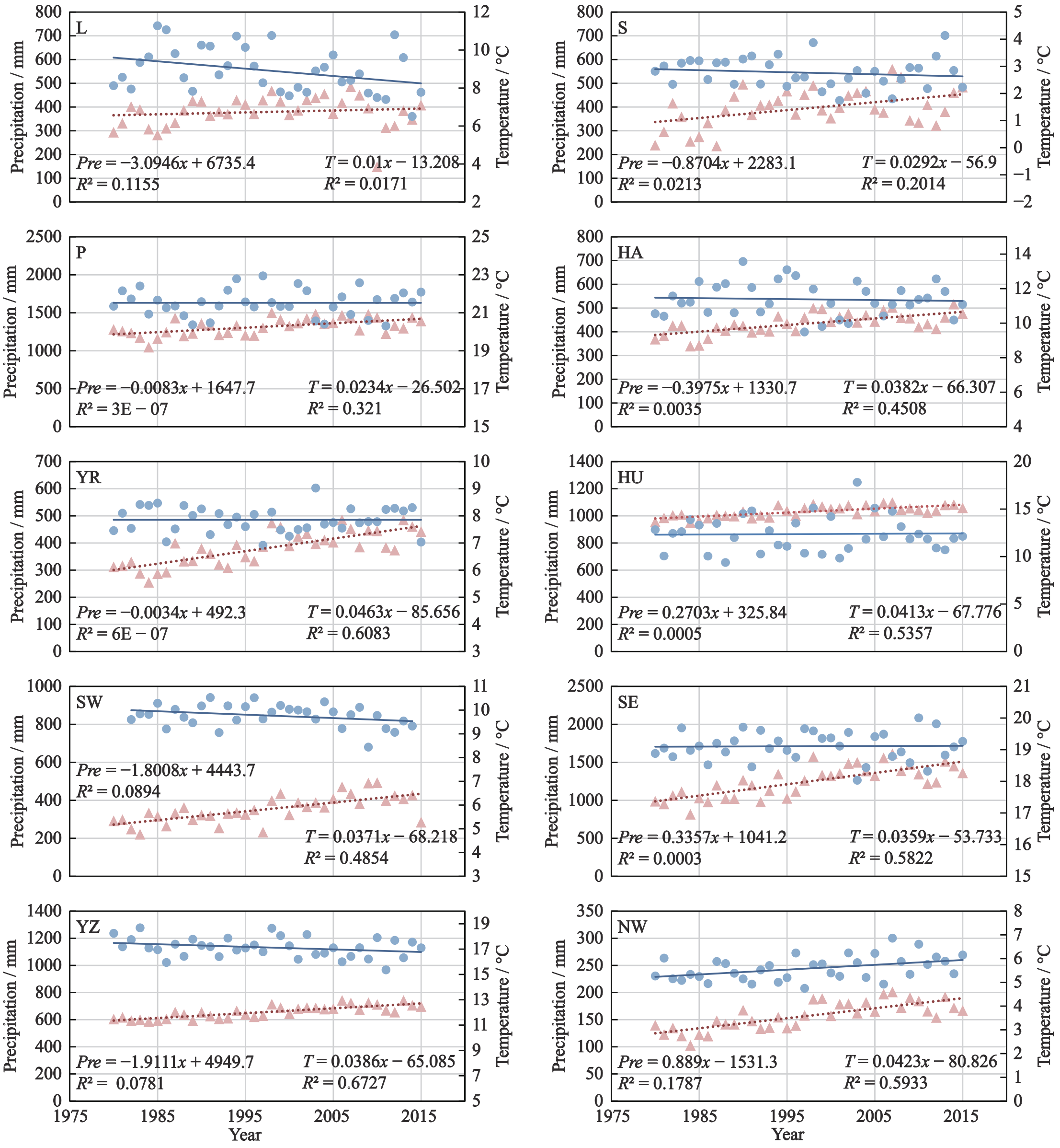

Fig. 9 The distribution of reservoirs in 2015 in different basins in China. *Pre* represents precipitation and *T* means temperature. Blue dot and line mean the annual precipitation and its changing trend; red triangle and dotted line represent averaged temperature and the corresponding trend line. NW basin is the only basin where the surface water expansion is dominated by climate change due to the growing precipitation and glacier melting. Meaning of the abbreviation is the same with that of Fig. 1

water retaining, but a decline of water outflow in to the ocean. Instead of absorption by soil or drained out of the catchment, higher portion of water was collected and regulated by the new emerged dams, channels, reservoirs, irrigation ponds, artificial lakes, *etc*. Impounding by the decay of precipitation, the decline of flow discharge has been reported in the major basins of China. Quantifying analysis presented the decline of the Yangtze River discharge, mainly attributed to decreased precipitation (60%–70%), while the remainder was owing to human activity, such as construction of Three Gorges Dam (Yang et al., 2015). Besides the decline of discharge, the sediment flux of Yangtze River decreased by more than two thirds due to the dam trapping effect (Chen et al., 2016). Human activities were the major causes of the significant decline of Yellow River stream flow since the 1990s. The 17.0%–45.0% reduction was contributed by climate change and human activities contributed the rest 55.0%–83.0% in the streamflow reduction (Wei et al., 2016). Hydrological record revealed the declining of Pearl River annual outflow into the sea from 1994 till 2011, and pointed out

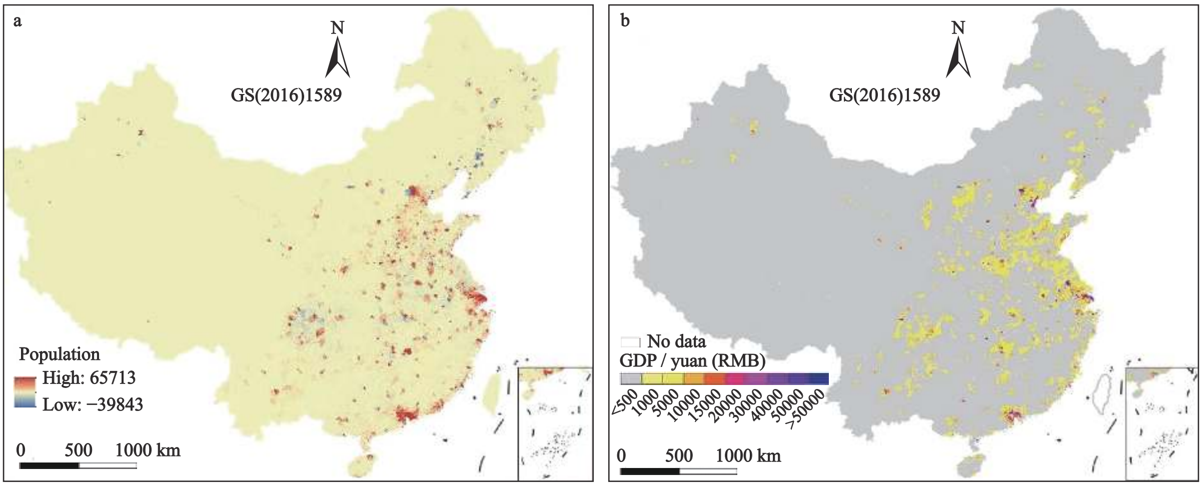

Fig. 10 Population (a) and GDP (Gross Domestic Product) (b) change of China from the 1980s to 2015. Population data of the 1980s and 2015 were from http://www.resdc.cn/data.aspx?DATAID=25, GDP data of 1995 and 2015 were from http://www.resdc.cn/data.aspx?DATAID=252 (no data available in Taiwan, China). Last visit date of the both links were 2019-05-14

that the construction of Longtan Reservoir in the Upper Reach of Pearl River cased a reduction of 14% in river runoff (Wu et al., 2014).

4.3 Consequences of the water area change

The main influence of reservoir construction is the impoundment of water and sediment, which will then lead to the decreasing river runoff and sediment flux. Especially in Yangtze River, the mean annual sediment load at Yichang Station, 44 km downstream of the Three Gorges Dam (TGD), decreased drastically by 84% of that in the pre-TGD period (1986–2002) (Hu et al.,

Table 6 The changes of annual river runoff and sediment load in major river basins of China

Item	Basin	Long-term averaged	Recent 10 yr	2018	Change trend
Annual runoff / 10^8 m^3	Yangtze River	8391	8852	8028	Decreasing
	Yellow River	336	259	415	Decreasing
	Haihe River	38	14	14	Decreasing
	Pearl River	2821	2737	2447	Decreasing
	Liaohe River	31	25	11	Decreasing
	Qiantang River	221	240	148	Decreasing
	Minjiang River	573	600	344	Decreasing
	Huaihe River*	32.7	29.3	–	Decreasing
	Songhua River*	2014	1535	–	Decreasing
	Rivers in northwest*	–	–	–	Increasing
Annual sediment load / 10^4 t	Yangtze River	36800	12200	8310	Decreasing
	Yellow River	97800	16600	37300	Decreasing
	Haihe River	2540	58	21	Decreasing
	Pearl River	6720	2170	1010	Decreasing
	Liaohe River	1420	156	51	Decreasing
	Qiantang River	289	370	79	Decreasing
	Minjiang River	599	263	49	Decreasing
	Huaihe River*	–	–	–	–
	Songhua River*	–	–	–	–
	Rivers in northwest*	–	–	–	–

Notes:* indicate that the data were collected from Qin et al (2020). The rest data were from The Ministry of Water Resources of the People's Republic of China (2019). Last visit date of the link were 2019-09-25

2009). As shown in Table 6, nearly all the big rivers declined both in water and sediment discharge, except rivers in Northwestern China, which showed increasing trend due to the glacier melting.

Surface water is a crucial component in the global water cycle. The dynamics of surface water can greatly interfere the water budget. Globally, an extra water flux of 30.38 ± 15.51 km^3/yr is omitted in global evaporation calculation caused by a net increase of global surface water area between periods of 1984–1999 and 2000–2015 (Zhan et al., 2019). It was estimated that the evapotranspiration rise by 0.1–1.0 km^3/yr across China, caused by the water extent expansion (Zhan et al., 2019).

5 Conclusions and Outlook

Based on the high resolution multi temporal satellite image, the database of surface water area, including rivers, lakes and reservoirs, of China was constructed. The distribution trend, statistics features and spatial temporal dynamics of the entire surface water and each water body were analyzed separately. Furthermore, combing the climatic parameters and China social/economic data, the driving forces of the water surface variation was revealed. It can be concluded that,

1) Spatially, water bodies unevenly distributed across China. Southeastern China was relatively more abundant in rivers and reservoirs. Lakes concentrated in Qinghai-Tibet Plateau, northeastern region and middle-lower Yangtze River Basin.

2) The water surface area expanded distinctly over the last three decades. Lakes shared the highest portion of the water surface area, while the new construction reservoirs contributed mostly to the water surface expansion. Temporally, all water bodies increased with highest range from 1995 to 2005.

3) Climate change dominated the water surface area increase in the northwestern basin of China. Climatic parameters triggered surface water area growth by increasing precipitation and accelerating glacier melting connected to rapid temperature rising.

4) Human activity, like water facility, agriculture abandon and urban construction, was the major driving force of the water area expansion in other area of China. Human driven water area increase has exceeded the climate induced water area loss caused by precipitation reduction and evapotranspiration increase.

The analysis and results of this study indicate the growing significance of water resources monitoring for sustainable development of urban and agriculture. An increasing water surface area, caused by artificial water storage, reallocation and distribution, promoted the water resource availability for social/economic system and led to the water surface expansion, although the climate was getting drier and warmer. It however implies sever pressure to the hydrological circulation, because the water captured by the surface storage would have diminished the subsurface water and outflow discharge, and hindered the connection between various water systems. Current patterns of water resource utilization and exploitation will finally cause a series environmental problem in the long run. Water regulation strategies emphasizing conservation and restoration of hydrological cycle should be involved to prevent ecological and environment crisis caused by the imbalance of water resource.

Acknowledgments

The authors would like to thank Resource and Environment Center of Chinese Academy of Sciences for providing the water surface distribution data and the social/economy data of China.

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