ARTICLE

Chinese Built-up Land in Floodplains Moving Closer to Freshwaters

Yongqiang Fang[1,2] · Shiqiang Du[2,3] · Jiahong Wen[2] · Min Zhang[2] ·
Jiayi Fang[1] · Min Liu[1]

Abstract Human proximity to water and its dynamics are important to understanding the socio-hydrological dilemma between using floodplains and avoiding flood risk. However, previous studies have not distinguished between the water proximity of built-up land in floodplains (BLF) and the water proximity of built-up land outside floodplains (BLOF). This article provides a new and spatiotemporal perspective of the BLF water proximities for understanding the changing flood risk in China. The results show that China's BLFs had an average water proximity of 5.41 km in 2014. Most of the BLFs (62%, 25.88×10^3 km^2) were located within 3 km of waterbodies. From 1990 to 2014, China's BLFs increased rapidly by 81% from 23.06×10^3 km^2 to 41.74×10^3 km^2, of which a large portion (57%) was concentrated in water surroundings ($\leq$3 km), shortening the distance between BLFs and waterbodies by 169 m. The BLF growth concentrated in water surroundings even in areas where BLFs have an overall increasing distance from waterbodies. Both the increases in the BLFs and their proximity to waterbodies can increase flood exposure and exacerbate flood risk. The scientific community and policymakers should pay attention not only to the volume of BLF growth, but also its spatial relationship with waterbodies.

1 Introduction

Freshwater is vital to humans. People have inhabited places close to rivers and lakes to ensure water supply and navigation since ancient time (Bertuzzo et al. 2007; McCool et al. 2008; Best 2019; Viero et al. 2019). However, close water proximity is not always a positive factor and can cause devastating flooding, which forces human settlements to keep a certain distance from waterbodies (Di Baldassarre, Kooy et al. 2013; Alfieri et al. 2017). Socioeconomic development promotes the implementation of engineering measures, such as dams and levees, to control floods. However, the reduced flood frequency and a sense of safety because of the engineering measures will likely boost floodplain development and increase flood exposure surrounding waters—the so-called "levee effect" (White 1945; Di Baldassarre, Viglione et al. 2013; Jongman 2018; Du et al. 2019). The distance between human settlements and waterbodies is vital to understanding the choices of society in facing the socio-hydrological dilemma between using waters and floodplains and avoiding flood risk (Loucks 2015; Sivapalan 2015).

The proximity of human activities to water has drawn increasing attention (Becker and Grunewald 2003; Fang, Ceola et al. 2018; Ceola et al. 2019). Kummu et al. (2011) examined the distance from human settlements to freshwater and found that over 50% of the world's population

✉ Shiqiang Du
shiqiangdu@shnu.edu.cn

✉ Min Zhang
zhangmin@shnu.edu.cn

1 Key Laboratory of Geographic Information Science, Ministry of Education, School of Geographic Sciences, East China Normal University, Shanghai 200241, China

2 School of Environmental and Geographical Sciences, Shanghai Normal University, Shanghai 200234, China

3 Institute for Environmental Studies, Vrije Universiteit Amsterdam, 1081 HV Amsterdam, Netherlands

lived within 3 km of freshwater and only 10% lived in areas farther than 10 km away from freshwater. Based on nightlight data as a proxy for human activities, Ceola et al. (2014) analyzed the increase in nightlight digital numbers (DN) along river networks from 1992 to 2012 and revealed a strong correlation between increasing nightlights and intensifying flood damages. Ceola et al. (2015) observed a high human concentration in the vicinity of rivers during 1992–2013. Mård et al. (2018) analyzed the dynamic proximity of total nightlight DN values to main rivers during 1992–2013 in 16 countries with different flood protection levels. The results showed that settlements tend to move farther from rivers in countries with higher flood fatalities and lower flood protection levels. Fang and Jawitz (2019) analyzed the dynamic relationships between settlements and water in the United States and found that people moved closer to major rivers during 1790–1870 but farther from major rivers thereafter.

However, none of these studies considered the differences between human settlements in floodplains and those outside floodplains. In contrast to human settlements in floodplains, the water proximity of human settlements outside floodplains is not directly related to flood exposure and risk. The indicators of human activities in these studies—population density or nighttime light intensity—are also characterized by uncertainties, particularly when they are compared over time. Population distribution is a result of dasymetric mapping methods that disaggregate the population numbers from census units to pixels using proxies like built-up land, whose uncertainties originate from both the dasymetric mapping methods and the proxy data (Hay et al. 2005; Smith et al. 2019). The nighttime light DNs have difficulties for interannual comparisons (Liu et al. 2012), reducing the usefulness of the data in analyzing water proximity of human settlements. Therefore, we used built-up lands as a direct representation of human activities and employed the built-up land in floodplains (BLF) proxy to investigate the spatiotemporal patterns of human proximity to rivers and their implications for flood risk management.

We chose China as the study area as the proximity of BLFs to rivers may be more complicated and significant than in other countries. China is one of the countries that suffer from devastating floods (Han and Kasperson 2011; Wallemacq and House 2018; Du et al. 2019). From 1990 to 2014, a total of 157 riverine floods occurred in China, annually resulting in 952 fatalities, affecting 69 million people and causing direct economic losses of USD 7.78 billion per year (Guha-Sapair et al. 2016). But China has also developed rapidly during recent decades (Chen et al. 2019). The gross domestic product (GDP) increased 34-fold, from USD 270 billion in 1990 to USD 9,212 billion in 2014 (in 2014 prices); the urban population increased from 3.0×10^8 in 1990 to 7.5×10^8 in 2014, more than doubling the urban proportion of the total population from 26.4% to 54.8% (National Bureau of Statistics 2015). Therefore, in the context of China's severe flood damages and rapid socioeconomic development, the spatial relationship between people and waterbodies may be changing dramatically, which is a key to understanding the flood risk in the world's second largest economy (Du et al. 2018).

However, the relationship between BLFs and waterbodies in China needs to be clarified. Previous studies mainly focused on the regional-scale impact of urban expansion on waterbodies, such as reclaiming lands from rivers and lakes for croplands, aquaculture ponds and built-up areas (Chen et al. 2013; Fu et al. 2014; Xie et al. 2017). Du et al. (2018) assessed the spatiotemporal changes in Chinese BLFs from 1992 to 2015 and Han et al. (2020) analyzed the BLF growth modes in the Yangtze River Economic Belt during 1990–2014. Neither of these studies mentioned the spatial relationship of BLFs with waterbodies. Little is known about the dynamic proximity of BLFs to waterbodies in China. To fill this research gap, this study examined the dynamic relationships between BLFs and waterbodies in China and discussed their implications for flood risk management. Such an assessment is of great significance for understanding the changes in the socio-hydrological system and flood risk in China.

2 Data and Methods

The following subsections present the employed datasets and their validations, followed by the methods to calculate the BLF and its water proximity dynamics.

2.1 Data

We used three datasets to examine the proximity of BLFs to waterbodies: built-up lands, freshwaters and floodplains. Built-up lands were derived from the Global Human Settlement Layer (GHSL) data packages—produced by the European Commission Joint Research Centre as free access data—for the years 1990, 2000 and 2014. The built-up land in the GHSL dataset is defined as building surfaces of human settlements—which include buildings, associated structures and civil works (Pesaresi et al. 2015)—with a resolution of 38 m. In order to evaluate the quality of the GHSL built-up land data in China, a sample of 1,000 random built-up points and 1,000 random non-built-up points was selected for each of the three years 1990, 2000 and 2014. These random points were then interpreted using high-resolution remote sensing images of Google Earth to evaluate the accuracy. The evaluation showed that the

Table 1 Accuracy assessment of built-up land data in China (n=1,000)

Global Human Settlement Layer (GHSL) Data		Reference from Google Earth		Total (Overall) Accuracy (%)
		Built-up	Non-Built-up	
1990	Built-up	878	122	91.25
	Non-Built-up	53	947	
2000	Built-up	884	116	89.45
	Non-Built-up	95	905	
2014	Built-up	897	103	91.05
	Non-Built-up	76	924	

overall accuracy of the built-up land data is 91.25% in 1990, 89.45% in 2000 and 91.05% in 2014 (Table 1).

The freshwater bodies refer to the major lakes and rivers, which exclude seawaters following Kummu et al. (2011). The data were obtained from the China National Basic Geographic Information Center.[1] The 100-year riverine flood depth map was provided by the Centro Internazionale in Monitoraggio Ambientale (CIMA) foundation (Rudari et al. 2015). The data are produced based on regional runoff frequency analysis and hydrodynamic model simulation and are verified based on historical records. This map has been used for analyzing global flood risk (UNISDR 2015) and studying floodplain urbanization in China (Du et al. 2018).

Floodplains are defined as the maximum extent (flood depth>0 cm) of the 100-year riverine flood depth map, following the flood risk assessment by Shi et al. (2015) and the flood exposure analyses by Jongman et al. (2012), Du et al. (2018) and Fang, Du et al. (2018). The total area of floodplains in China is $1,131.65 \times 10^3$ km^2, accounting for 12.11% of China's total land area. A large proportion of the floodplains (36.10%, or 408.57×10^3 km^2) is located in southeast China. Northeast, northwest and southwest China contain 29.91%, 21.12% and 12.87% of the floodplains, respectively (Du et al. 2018; Fang, Du et al. 2018).

2.2 Methods

The BLF was calculated by overlaying the floodplains and the built-up land datasets using ArcGIS 10.4 (Han et al. 2020). Two major indices were then examined to represent the dynamic spatial relationships between BLFs and waterbodies: (1) water proximity, in terms of distance between built-up lands and waterbodies; and (2) BLF growth within different distances to waterbodies. The analyses were conducted at multiple scales.

2.2.1 Distance between Built-up Lands and Waterbodies

We calculated the water proximity based on BLF patches, which is a basic component of the BLF landscape and refers to a spatial entity of BLF that is qualitatively different from its surrounding environment (that is, non-built-up land) (Turner et al. 2001; Han et al. 2020). The water proximity of a BLF patch is defined as the Euclidean distance from its gravity center to waterbodies (D_i). Regarding a spatial unit z (that is, the country, a region, a basin, or a subbasin) that has n BLF patches, its water proximity (D_z) is defined as the weighted average of the water proximities of its BLF patches, which can be expressed as Eq. 1:

$$D_z = \sum_n^{i=1} D_i A_i \left/ \sum_n^{i=1} A_i \right. \qquad (1)$$

where A_i refers to the area of the patch i.

2.2.2 Measuring Built-up Land in Floodplains Growth by Different Distances to Waterbodies

We also examined how BLFs were distributed across the water proximity classes. Following Kummu et al. (2011), we divided the water proximity into three classes: low distance (<3 km), moderate distance (3–6 km) and high distance (>6 km). For each proximity zone, we calculated the BLF area (BLF_d) and its proportion (r_d) to the total BLF, using Eq. 2:
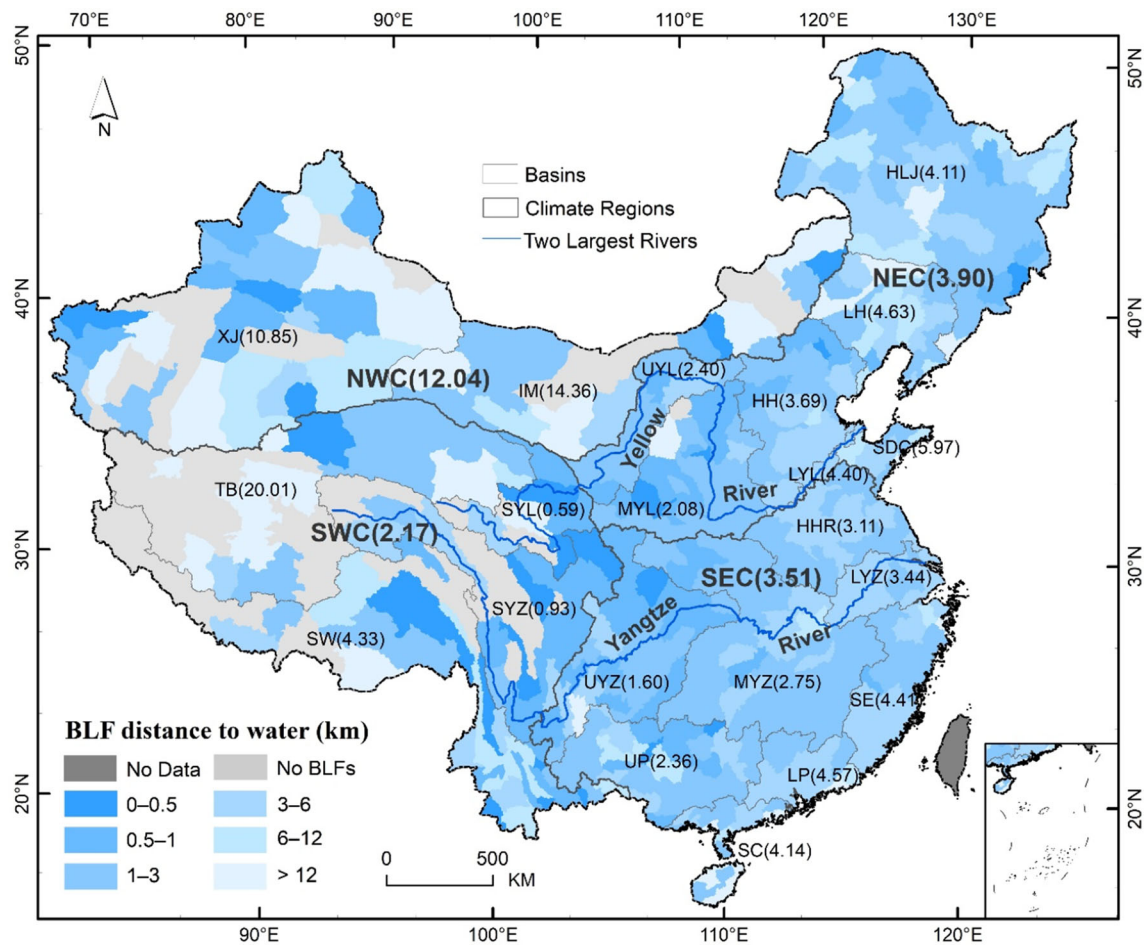
$$r_d = \frac{BLF_d}{BLF_{TOT}} \times 100\% \qquad (2)$$

where BLF_d is the BLF area in the water proximity class d and BLF_{TOT} is the total BLF area in the spatial unit z.

In addition, the change of BLFs during 1990–2014 was calculated following Eq. 3:

$$CR_d = \frac{BLF_d(t_2) - BLF_d(t_1)}{BLF_d(t_1)} \times 100\% \qquad (3)$$

---

[1] http://www.ngcc.cn/.

Fig. 1 Built-up land in floodplains (BLF) proximity to waterbodies in 2014. Value unit of numbers in brackets after basin/region abbreviations indicates kilometers. Notes: Climate regions: NWC (Northwest China), NEC (Northeast China), SWC (Southwest China), SEC (Southeast China). Basin abbreviations: HLJ (Heilongjiang River), LH (Liaohe River), IM (Inner Mongolia Rivers), XJ (Xinjiang Rivers), HH (Haihe River), LYL (Lower Yellow River), MYL (Middle Yellow River), UYL (Upper Yellow River), SYL (Source of Yellow River), TB (Tibetan Rivers), SDC (Shandong Coastal Rivers), HHR (Huaihe River), LYZ (Lower Yangtze River), MYZ (Middle Yangtze River), UYZ (Upper Yangtze River), SYZ (Source of Yangtze River), SW (Southwest Rivers), SE (Southeast Coastal Rivers), LP (Lower Pearl River), UP (Upper Pearl River), and SC (South Coastal Rivers)

where $BLF_d(t_1)$ and $BLF_d(t_2)$ represent the area of BLF in distance class d in years t_1 and t_2, respectively.

2.2.3 Multiple-Scale Analysis

We analyzed the spatial and temporal changes of the distance between BLFs and waterbodies at four scales—subbasin, basin, region and country. The study area contains 529 subbasins and 21 basins. These subbasins and basins were first derived from the Food and Agriculture Organization (FAO) and then the delineations were rectified based on datasets of rivers and elevation (Du et al. 2018) that were obtained from the National Geomatics Center of China. The 21 basins were aggregated into four regions according to the climate zonation of China (Zheng et al.

2010)—southwest, northwest, northeast and southeast China (Fig. 1).

3 Results

The following subsections present the spatiotemporal dynamics of the BLF water proximity in China, including the water proximity of BLFs in 2014, the proximity dynamics during 1990–2014 and the distribution of new BLFs relative to waterbodies during the study period.

3.1 Built-up Land in Floodplains is Concentrated near the Waterbodies in 2014

In 2014, the total area of China's BLFs was 41.74×10^3 km^2 and the average distance of BLFs to

waterbodies was 5.41 km. Most of the BLFs (62.00%, 25.88×10^3 km^2) were located within 3 km from the waterbodies; only 19.40% (8.10×10^3 km^2) and 18.60% (7.76×10^3 km^2) of the BLFs had a distance of 3–6 km and >6 km from waterbodies, respectively.

At the regional scale, BLFs in southwest China had the closest proximity to waterbodies on average, at only 2.17 km (Fig. 1), which was much closer than the national average (5.41 km). A majority (87.38%, or 668.02 km^2) of the BLFs in southwest China was located within 3 km of waterbodies (Table 2). In southeast and northeast China, the average water proximity was 3.51 km and 3.90 km, respectively, which were both closer than the national average (5.41 km). Over half of the BLFs, about 62.85% (16.16×10^3 km^2) and 59.37% (9.01×10^3 km^2) in southeast and northeast China, respectively, were located within 3 km of waterbodies. The BLFs of northwest China had the farthest distance to waterbodies, with an average distance of 12.04 km, much higher than that in the other three regions.

At the basin scale, the distance between BLFs and waterbodies increased from the headwaters to the lower basins in China's three major rivers—the Yangtze River, the Yellow River and the Pearl River. The BLFs in the headwater areas of the Yangtze River (SYZ) and the Yellow River (SYL) had the closest proximity to waterbodies, 926 m and 588 m, respectively, across all the basins and an overwhelming majority of the BLFs (99.29%, or 74.58 km^2 in the SYL and 94.82%, or 392.90 km^2 in the SYZ) was located within 3 km from waterbodies. The average distance from the BLFs to waterbodies increased to 1.60–2.75 km in the upper and middle reaches of the three major rivers, where the majority (77.27%, or 5.99×10^3 km^2) of the BLFs was located within 3 km from waterbodies. In the lower basins of the three major rivers, the average distance between BLFs and waterbodies was 4.40 km, farthest among all the basins in the three major rivers.

In the Xinjiang (XJ), Inner Mongolia (IM) and Tibetan (TB) river basins, the BLFs were farthest from

waterbodies, reaching 10.85 km, 14.36 km and 20.01 km, respectively. The average proximity of BLFs to waterbodies in other basins was in a range of 3–6 km.

At the subbasin scale, most (71.64%, or 379) of the 529 subbasins had a majority (>50%) of their BLFs within 3 km of waterbodies. In contrast, only in a small portion (10.59%, or 56) of the subbasins the majority (>50%) of the BLFs was at least 6 km away from waterbodies.

## 3.2 Increasing Water Proximity of Built-up Land in Floodplains during 1990–2014

The average distance between China's BLFs and waterbodies decreased by 169 m during 1990–2014. In western China, particularly, the water distance decreased by 926 m in the northwest and by 198 m in the southwest. In contrast, the average distance of the BLFs to waterbodies increased by 426 m in northeast China and by 23 m in southeast China (Fig. 2, Table 3).

At the basin scale, most (15, or 71.43%) of the 21 basins experienced a moderate increase (less than 1000 m) in the average distance between BLFs and waterbodies. In the Upper Yellow River (UYL), the distance of the BLFs to waterbodies increased by 571 m. In the Lower Yangtze River (LYZ), Source of Yellow River (SYL) and Source of Yangtze River (SYZ), the distances appeared essentially stable (the variation range was only 3–30 m). The largest increase in average distance was 857 m in the Heilongjiang River (HLJ). In contrast, the BLF distance to waterbodies in the basins of Upper Yangtze River (UYZ), Southwest Rivers (SW), Lower Pearl River (LP) and South Coastal Rivers (SC) decreased by 51 m, 178 m, 307 m and 410 m, respectively, especially in the Tibetan Rivers (TB) and the Xinjiang Rivers (XJ) in western China, the distance of BLFs to waterbodies sharply decreased by 6842 m and 1784 m.

At the subbasin scale, the average distance from the BLFs to waterbodies increased in 50.66% (268) of the subbasins by an average of 868 m, while it decreased in 35.16% (186) of the subbasins by an average of 857 m.

Table 2 Built-up land in floodplains (BLF) proximity to waterbodies in China in 2014

Region	BLF area (10^3 km^2) and proportion (%, in brackets)			Average distance (km)
	0–3 km	3–6 km	>6 km	
Southeast	16.16 (62.85)	5.06 (19.67)	4.50 (17.48)	3.51
Northeast	9.01 (59.37)	3.01 (19.82)	3.16 (20.81)	3.90
Southwest	0.67 (87.38)	0.03 (2.72)	0.08 (9.90)	2.17
Northwest	0.03 (45.31)	0.06 (10.46)	0.03 (44.22)	12.04
China	25.88 (62.00)	8.10 (19.40)	7.76 (18.60)	5.41
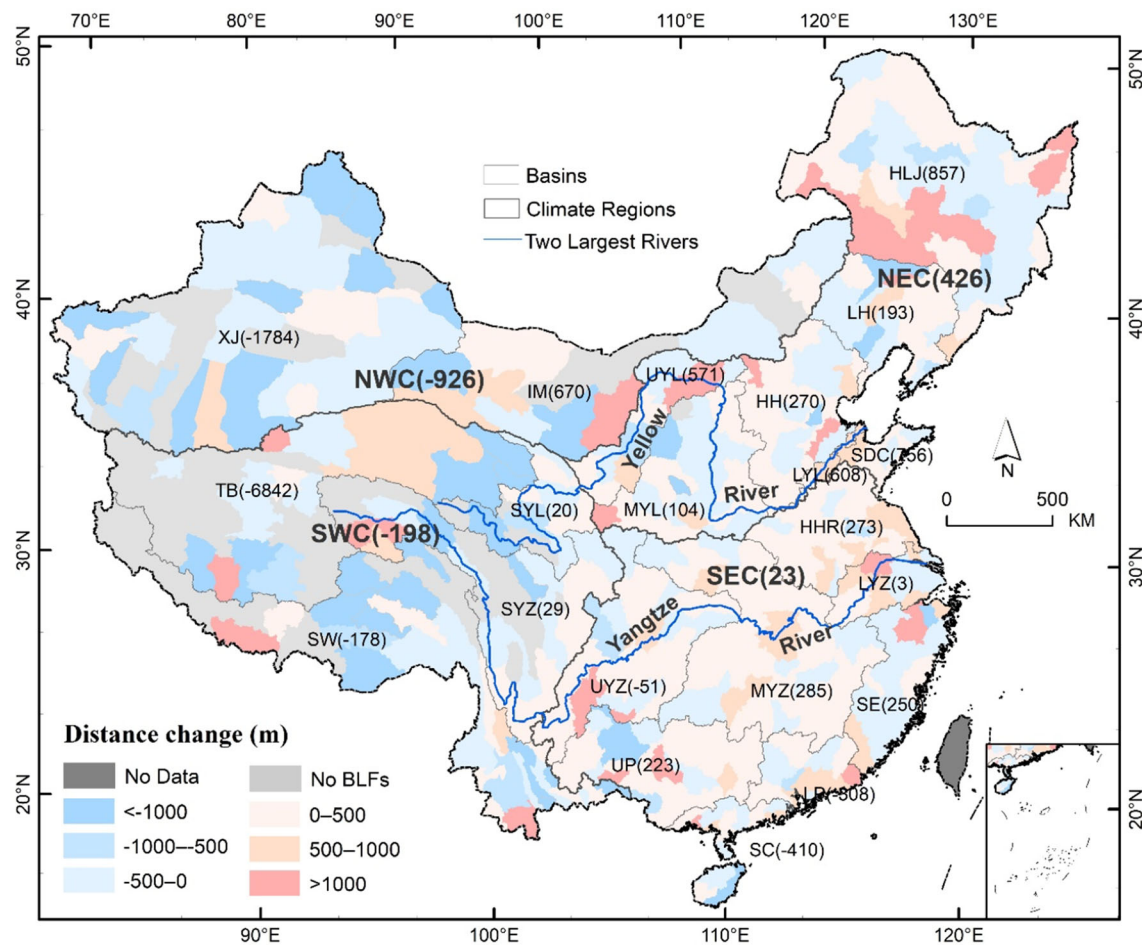
Fig. 2 Changes of built-up land in floodplains (BLF) proximity to waterbodies during 1990–2014 (Negative value indicates moving closer to waterbodies; positive value indicates moving farther from waterbodies. Value unit of numbers in brackets after basin/region abbreviations indicates meters. Abbreviations see Fig. 1 notes)

Table 3 Changes in built-up land in floodplains (BLF) proximity to waterbodies and BLF growth in different water-proximity classes in China during 1990–2014

Region	Distance Change (m)	BLF Changes (10^3 km^2) with the Proportions (%) in Brackets			
		0–3 km	3–6 km	>6 km	Total
Southeast	23.11	6.92 (58.62)	2.72 (23.01)	2.17 (18.36)	11.80 (100)
Northeast	425.85	3.55 (53.40)	1.45 (21.76)	1.65 (24.84)	6.64 (100)
Southwest	− 197.87	0.20 (91.38)	0.006 (2.63)	0.01 (5.99)	0.22 (100)
Northwest	− 925.54	0.01 (69.06)	0.002 (9.86)	0.003 (21.09)	0.02 (100)
China	− 168.61	10.68 (57.16)	4.17 (22.32)	3.83 (20.53)	18.68 (100)

The remaining 14.18 % (75) of the subbasins showed relatively constant water proximity of the BLFs between 1990 and 2014.

Over the three data years—1990, 2000, 2014—the increased water proximity of the BLFs mainly occurred during 2000–2014. The average distance between China's BLFs and waterbodies decreased by 198 m during

2000–2014; in contrast, it increased by 30 m during 1990–2000. At the regional scale, the BLF water proximity increased in the northwest and southwest during 2000–2014 compared with the period 1990–2000. In contrast, the BLFs of northeast China consistently moved farther away from waterbodies in the two periods while those of southeast China witnessed a transition from an

increasing water proximity during 1990–2000 to a decreasing one during 2000–2014.

3.3 New Built-up Land in Floodplains is Concentrated in the Vicinity of Waterbodies

In the 25 years between 1990 and 2014, China's BLFs increased by 81%, or by a total area of 18.68×10^3 km^2. More than half (57.16%, or 10.68×10^3 km^2) of the BLF growth occurred within 3 km from waterbodies; only 22.32% and 20.53% of the new BLFs were located within 3–6 km and more than 6 km away from waterbodies (Table 3). The BLF growth decreases with the increasing distance from waterbodies, following the law of negative exponents (Fig. 3a).

At the regional scale, 58.62% (6.92×10^3 km^2) and 53.40% (3.55×10^3 km^2) of the new BLFs were located within 3 km from waterbodies in southeast and northeast China, with an increase rate of 74.82% and 64.92%, respectively. A higher concentration of the new BLFs in waterbody surroundings was found in southwest and northwest China, with 91.38% (0.2×10^3 km^2) and 69.06%

(0.01×10^3 km^2) of the new BLFs within 3 km from waterbodies, respectively.

At the basin scale, more than 50% of the new BLFs were located within 3 km from waterbodies in 18 of the 21 basins. In terms of the proportion of the total new BLFs in the waterbody surroundings (≤ 3 km), the results generally showed a decreasing trend from inland to coastal areas. An average of 78.80% of the new BLFs were located in the waterbody surroundings in the 13 inland basins, while it was only 54.05% in the eight coastal basins. This trend was more obvious in China's three major river basins—the Yangtze River, the Yellow River and the upper basin of the Pearl River. The average proportion of the new BLFs in the waterbody surroundings in the source area of the rivers was as high as 96.81%, while it was only 78.84%, 71.86% and 50.4% in the upper, middle and lower basins, respectively. In terms of growth rate, however, the average growth rate of the BLFs in the eight coastal basins was 89.41% within 3 km of the waterbodies, which was higher than the average in the inland basins (63.48%).

The concentration of new BLFs in the water surroundings was consistent over the two periods: 1990–2000 and 2000–2014. The water surroundings witnessed 59.48% and

Fig. 3 Built-up land in floodplains (BLF) growth in different water-proximity classes in China (**a**) and the four regions (**b**), from 1990 to 2014
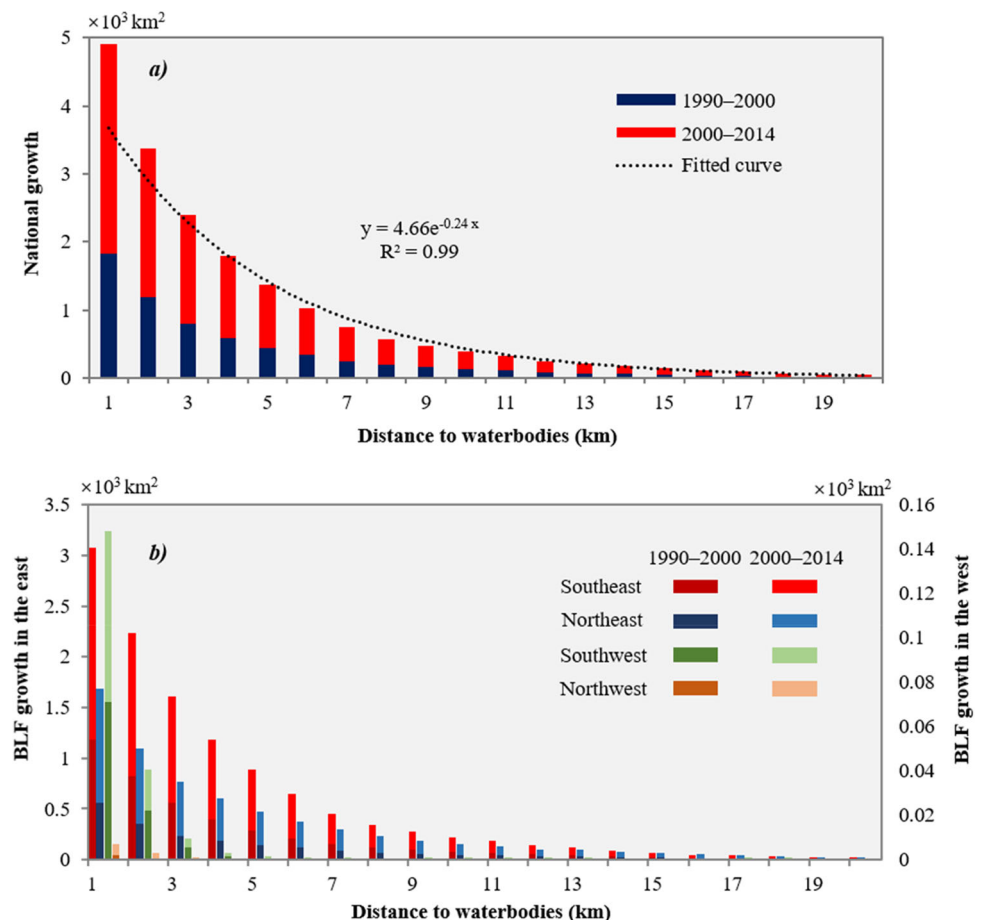
55.94% of the Chinese total BLF growth over the two periods, respectively. The principle held across the four regions and 21 basins (Fig. 3b). More than half (52.74%–74.25%) of the new BLFs in the different regions were located within 3 km of waterbodies over the two periods. The proportion was more than 90% during both periods in Southwest China (SWC).

4 Discussion

In this section, the differences of water proximity dynamics between BLFs and the built-up lands outside floodplains (BLOFs) are compared. The challenges of increasing BLF water proximity to flood risk management are discussed, followed by policy implications. The strengths and limitations of the study are also assessed.

4.1 Built-up Lands in Floodplains Have Different Water Proximity than Built-up Lands outside Floodplains

The BLFs and the BLOFs were different in terms of water proximity dynamics during 1990–2014, in addition to an obvious closer water proximity of the BLFs (5.41 km) than the BLOFs (10.44 km). At the national scale, the average distance of the BLOFs to waterbodies decreased by 223 m, more than that of the BLFs (169 m). At the regional scale, the average water distance of the BLOFs in northeast and southeast China decreased by 424 m, compared to an increasing distance of the BLFs to waterbodies in the two regions. In the northwest, both the BLFs and BLOFs moved towards waterbodies, but the decrease of distance to water of the BLFs (925 m) was significantly larger than that of the BLOFs (210 m). The average distance of the BLOFs to waterbodies in southwest China increased by 378 m, while the average distance of the BLFs to waterbodies decreased by 199 m. At the basin and subbasin scales, the distance changes of the BLOFs to waterbodies were also significantly different from that of the BLFs.

Water proximity is different between BLFs and BLOFs and so are the water proximity dynamics of the two types of built-up land, which had not been investigated in previous studies. As the BLOFs and their water proximity are not directly related to flood exposure, it is reasonable and important to distinguish the BLFs and BLOFs in evaluating human settlement water proximity and its dynamics.

4.2 Built-up Land in Floodplains' Close Proximity to Waterbodies Challenges Flood Risk Management

In addition to the increasing exposed assets and infrastructures caused by the amount of BLF growth (Du et al. 2018), the increase in water proximity of the BLFs may aggravate flood risk in three ways. First, deeper floodwater is associated with the BLFs that are closer to waterbodies (Fig. 4). The average water depth of a 100-year flood is 2.9 m within 3 km of waterbodies, while the depth decreases to 2.5 m and to 2.1 m in the areas of 3–6 km and >6 km from waterbodies, respectively.

Second, the proximity of BLFs to waterbodies is associated with the arrival time of floodwaters and the readiness of people to evacuate and their other emergency responses. The closer the BLFs are to waterbodies, the sooner the floodwaters arrive, which decreases the lead time and readiness of people to receive early warnings and evacuate (Han and Coulibaly 2017; Alcántara-Ayala and Oliver-Smith 2019).

Third, the increasing water proximity of the BLFs may be associated with floodplain development occupying waterbodies and wetlands, decreasing their capacity to regulate and discharge floodwaters (Veldkamp et al. 2017; Fang, Ceola et al. 2018; Du et al. 2019). The rapid BLF growth in the middle reaches of the Yangtze River caused lakes to shrink rapidly (Xie et al. 2017). Therefore, the water proximity of the BLFs should be an important factor to be considered in flood risk management.

The challenge of BLF water vicinity may be more serious in western China. Western China is characterized by mountainous landscapes and a considerable number of cities are located in valleys that are relatively flat, fertile and have better access to water resources. As a result, water surroundings are attractive to people. Since 1998, large-scale ecological migration has been implemented in western China, relocating people from ecologically fragile mountains to the relatively flat areas that are typically close
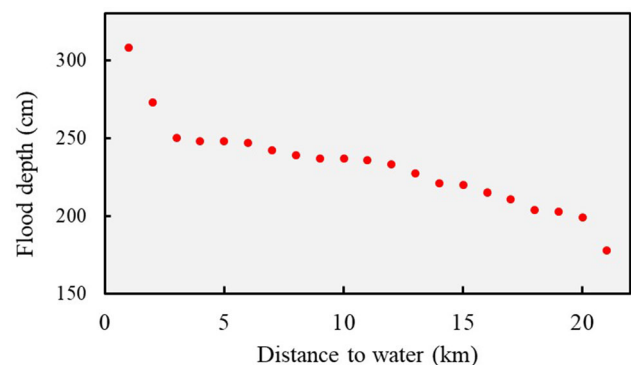
Fig. 4 Changes in average flood depth along water distances in China

to waterbodies (Fang, Du et al. 2018; Du et al. 2019). Such an ecological migration may decrease the distance from the BLFs to waterbodies in this region. However, the flood protection level is relatively low in western China and flood adaptation measures are rarely considered in urban and rural planning in this region, in part because of a low population density and a false sense of safety (Cheng and Li 2015). These medium- and small-sized basins disproportionally suffer flood fatalities (Du et al. 2019). A local-scale mudslide catastrophe in Zhouqu, western China in 2010 caused 1765 deaths, in part because of improper urban planning and the occupation of river spaces (Fang et al. 2010; Zhang et al. 2012). Moreover, this region is expected to experience increasing extreme precipitation events (Zhou et al. 2014), which will probably exacerbate the flood risk of the BLFs surrounding waterbodies in this region. Therefore, increased water proximity of the BLFs would dramatically challenge the flood risk management and regional sustainability in western China.

The BLFs in eastern China moved farther away from waterbodies during 1990–2014—as a result of some new BLF patches being located farther from the waterbodies, but this does not mean a reduction of the total BLFs near waterbodies. On the contrary, a large portion (58.62%, 6.92×10^3 km^2 and 53.40%, 3.55×10^3 km^2 in southeast and northeast China, respectively) of the BLF growth was concentrated in areas ≤ 3 km from the waterbodies. Therefore, although the BLFs are generally moving farther away from waterbodies, the new BLFs are still concentrated in the vicinity of waterbodies (≤ 3 km) in eastern China, which can directly increase the flood exposure and exacerbate the flood risk.

4.3 Policy Implications

Humans traditionally prefer to live in the vicinity of waterbodies as water proximity facilitates the water supply, transportation and military defense (Du et al. 2018). Many cities in China have traditionally been close to rivers (Gu 1997). However, the human dependence on water proximity has greatly decreased with the continuous advancement of technology (Fang and Jawitz 2019), which opens a window to controlling BLFs and their water proximity. In China, the Urban Planning Law[2] and the National Comprehensive Disaster Reduction Plan[3] do not take into account the water proximity of BLFs, although they have stipulated that BLF growth should comply with certain flood control standards (Du et al. 2019; Han et al. 2020). In

this context, BLF sprawls at the expense of shrinking waterbodies (Xie et al. 2017; Xie et al. 2018). Therefore, the water proximity of BLFs should be monitored from two aspects: (1) the distance from the BLFs to waterbodies; and (2) the BLF dynamics in waterbody surroundings, using remote sensing technologies. Recently, China has nominated millions of "river chiefs" and "lake chiefs" to protect waterbodies from possible reclamation (Du et al. 2019). This policy could be more effective for flood risk management if the BLFs were to be forbidden from reclaiming land from waterbodies and their near surroundings.

Flood risk is expected to increase rapidly in China because of climate change and socioeconomic development (Xia 2019). However, it is impossible for society to heavily invest in mega engineering projects to completely eliminate flood risk. A consensus in the flood risk research tells us that we have to learn to live with the residual flood risk that cannot be completely avoided by flood protection structures. To live with the residual flood risk, household-level adaptation measures can play a key role (Attems et al. 2019), such as elevating (Leandro et al. 2020) and wet-proofing buildings (Aerts et al. 2018). These measures are more urgently needed in the near surroundings of waterbodies, as our findings suggest that these areas are expected to have more flood depths and narrower windows for preparing for coming floodwaters. Household-level adaptation measures could be encouraged through tools like subsidies for flood insurance premiums. Advances in flood monitoring and early warning (Megharaj Bhosale and Mahesh Chavan 2018) and training in flood evacuation (Liu et al. 2017; Wu et al. 2019) should also help people to live with floods.

Water proximity should be given particular attention in western China. Settlements and BLFs are typically located in valleys in the mountainous areas in this region, rendering it impossible to avoid floodplain development and BLF growth. Moreover, the flood protection level is low in this region. First, a semiarid or arid climate is characterized by less precipitation, which can result in a false sense of safety. However, this does not mean that there is no flood risk in this region. Variability is high and unexpected extreme precipitation can cause surprises and serious impacts, as suggested by devastating floods in recent years in this region (Du et al. 2019). Second, population and economic densities in this region are significantly lower than in eastern China. Thus, expensive high-level flood protections do not make sound economic sense in western China. Therefore, keeping the BLFs at a safe distance from waters through proper land use planning is vital in this region. Elevation, wet-proofing and other flood-proofing building codes should be encouraged particularly for new buildings.

---

[2] http://www.npc.gov.cn/wxzl/gongbao/2015-07-03/content_1942844.htm

[3] http://www.gov.cn/zhengce/content/2017-01/13/content_5159459.htm

4.4 Strengths and Limitations of the Study

Previous studies have demonstrated that BLF growth can increase flood exposure and exacerbate flood risk (Du et al. 2019; Han et al. 2020). This study provides new insights in terms of the BLF water proximity and the BLF dynamics in different water proximities for understanding the changes in flood exposure in China. It reveals the divergent water proximity between BLFs and BLOFs, suggesting the importance of distinguishing BLFs and BLOFs in the evaluation of human settlement water proximity and its dynamics. It extends our understanding about Chinese BLFs from a high concentration of build-up lands in floodplains (Du et al. 2018) to a high concentration of the BLFs in the vicinity of waterbodies and from a rapid BLF growth to a concentration of the BLF growth in waterbody surroundings.

The study, however, has several limitations that require further analyses. First, the water data used in this study only cover the large and medium-sized rivers and lakes in China, excluding small rivers because detailed data are unavailable. However, small rivers generally lag behind in flood protection and urban planning both in China (Wang 2018) and globally (Jongman et al. 2012). Therefore, BLF expansion near small rivers may mean a higher risk of flooding.

Second, the shape of rivers and lakes may be instable due to diverse factors including human activities and climate change (Xie et al. 2017). The spatiotemporal evolution of the relationships between BLFs and waterbodies can be further revealed given the availability of spatially explicit BLF and waterbody data over long time periods. This kind of study might be more interesting in China than in other countries because of China's long history of civilization, during which the relationship between settlements and waterbodies has evolved over time.

Third, the reasons for the distance changes between the BLFs and waterbodies are complicated and outside of the scope of this article, which only provides a brief explanation. Future research needs to investigate the underlying mechanisms using more case studies and a mixed quantitative and qualitative approach. However, the study of the relationship between BLFs and waterbodies not only helps to reveal the changes in flood exposure, but also provides an enhanced understanding of the socio-hydrological process in terms of floodplain development and flood risk adaptation.

5 Conclusion

This study examined the spatiotemporal dynamics of BLFs in different water proximities at a national scale in China to provide new insight for understanding the changes in flood exposure and resulted in three major findings. First, the water proximity and its dynamics are divergent between the BLFs and BLOFs. From 1990 to 2014 the BLFs moved towards waterbodies by an average of 169 m, less than the BLOFs (223 m). Second, a large proportion of the Chinese BLFs (62.00%, or 25.88×10^3 km^2) are distributed within 3 km from the waterbodies. The proportion is highest in southwest China (87.38%), making this the region with the closest proximity between the BLFs and waterbodies, at only 2.17 km. Third, the BLFs increased rapidly by 81% or 18.68×10^3 km^2 from 1990 to 2014. The BLF growth decreases with the distance from waterbodies, following the law of negative exponents. A large portion (57.16%, or 10.68×10^3 km^2) of the newly developed BLFs are concentrated in waterbody surroundings (≤ 3 km). The BLF growth concentrates in waterbody surroundings even in areas where the BLFs have an overall increasing distance from waterbodies.

Both the increase of BLFs and their proximity to waterbodies can increase flood exposure and exacerbate flood risk. This relationship should be verified by further studies and evidence to uncover the underlying mechanisms between the water proximity of BLFs and flood risk. Such an analysis can be extended to an integrated assessment of the BLF impacts on the three components of flood risk—flood exposure, vulnerability and hazard. In urban planning and flood risk management, policymakers should pay attention not only to the volume of BLF growth, but also to its spatial relationship with waterbodies.

References

Aerts, J.C.J.H., W.J.W. Botzen, K. Clarke, S.L. Cutter, J.W. Hall, B. Merz, E. Michel-Kerjan, and J. Mysiak et al. 2018. Integrating human behaviour dynamics into flood disaster risk assessment. *Nature Climate Change* 8(3): 193–199.

Alcántara-Ayala, I., and A. Oliver-Smith. 2019. Early warning systems: Lost in translation or late by definition? A FORIN approach. *International Journal of Disaster Risk Science* 10(3): 317–331.

Alfieri, L., B. Bisselink, F. Dottori, G. Naumann, A. De Roo, P. Salamon, K. Wyser, and L. Feyen. 2017. Global projections of river flood risk in a warmer world. *Earths Future* 5(2): 171–182.

Attems, M.S., T. Thaler, E. Genovese and S. Fuchs. 2019. Implementation of property-level flood risk adaptation (PLFRA) measures: Choices and decisions. *WIREs Water* 7: Article e1404.

Becker, A. and U. Grunewald. 2003. Disaster management – Flood risk in central Europe. *Science* 300(5622): Article 1099.

Bertuzzo, E., A. Maritan, M. Gatto, I. Rodriguez-Iturbe and A. Rinaldo. 2007. River networks and ecological corridors: Reactive transport on fractals, migration fronts, hydrochory. Water Resources Research 43(5): Article W04419.

Best, J.L. 2019. Anthropogenic stresses on the world's big rivers. *Nature Geoscience* 12(1): 7–21.

Ceola, S., F. Laio, and A. Montanari. 2014. Satellite night-time lights reveal increasing human exposure to floods worldwide. *Geophysical Research Letters* 41(20): 7184–7190.

Ceola, S., F. Laio, and A. Montanari. 2015. Human-impacted waters: New perspectives from global high-resolution monitoring. *Water Resources Research* 51(9): 7064–7079.

Ceola, S., F. Laio, and A. Montanari. 2019. Global scale human pressure evolution imprints on sustainability of river systems. *Hydrology and Earth System Sciences* 23(9): 3933–3944.

Chen, K., X. Wang, D. Li, and D. Xue. 2013. The morphological evolution of river and water body in urban area of Guangzhou City in 1990–2010. *Scientia Geographica Sinica* 33(2): 223–230 (in Chinese).

Chen, Y., W. Xie, and X. Xu. 2019. Changes of population, built-up land and cropland exposure to natural hazards in China from 1995 to 2015. *International Journal of Disaster Risk Science* 10(4): 557–572.

Cheng, X.T., and C.C. Li. 2015. The evolution trend, key features and countermeasures of urban flood risk. *China Flood and Drought Management* 25(3): 6–9 (in Chinese).

Di Baldassarre, G., M. Kooy, J.S. Kemerink, and L. Brandimarte. 2013. Towards understanding the dynamic behaviour of floodplains as human-water systems. *Hydrology and Earth System Sciences* 17(8): 3235–3244.

Di Baldassarre, G., A. Viglione, G. Carr, L. Kuil, J.L. Salinas, and G. Blöschl. 2013. Socio-hydrology: Conceptualising human-flood interactions. *Hydrology and Earth System Sciences* 17(8): 4515–4536.

Du, S., X. Cheng, Q. Huang, R. Chen, P.J. Ward, and J.C.J.H. Aerts. 2019. Brief communication: Rethinking the 1998 China floods to prepare for a nonstationary future. *Natural Hazards and Earth System Sciences* 19(3): 715–719.

Du, S., C. He, Q. Huang and P. Shi. 2018. How did the urban land in floodplains distribute and expand in China from 1992–2015? *Environmental Research Letters* 13(3): Article 4018.

Fang, H., G. Cai, Q. Li, L. Sun, and J. He. 2010. Causes and countermeasures of giant flash flood and debris flow disaster in Zhouqu County in Gansu Province on August 7, 2010. *Science of Soil and Water Conservation* 8(6): 14–18 (in Chinese).

Fang, Y. and J. Jawitz. 2019. The evolution of human population distance to water in the USA from 1790 to 2010. *Nature Communications* 10(1): Article 430.

Fang, Y., S. Ceola, K. Paik, G. McGrath, P.S.C. Rao, A. Montanari, and J.W. Jawitz. 2018. Globally universal fractal pattern of human settlements in river networks. *Earth's Future* 6(8): 1134–1145.

Fang, Y.Q., S. Du, P. Scussolini, J. Wen, C. He, Q. Huang and J. Gao. 2018. Rapid population growth in Chinese floodplains from 1990 to 2015. *International Journal of Environmental Research and Public Health* 15(8): Article 1602.

Fu, Y., X. Xu, L. Tong, and S. Li. 2014. Spatial-temporal variation and driving forces of surface water in Beijing over one hundred years. *Resources Science* 36(1): 75–83 (in Chinese).

Gu, C. 1997. *China's urban geography*. Beijing: The Commercial Press.

Guha-Sapair, D., R. Below and P. Hoyois. 2016. *EM-DAT: International disaster database—*www.emdat.be. Brussels, Belgium: Université Catholique de Louvain.

Han, G., and R.E. Kasperson. 2011. Dilemmas and pathways to dealing with flood problems in twenty-first century China. *International Journal of Disaster Risk Science* 2(3): 21–30.

Han, S., and P. Coulibaly. 2017. Bayesian flood forecasting methods: A review. *Journal of Hydrology* 551: 340–351.

Han, Y., Q. Huang, C. He, Y. Fang, J. Wen, J. Gao and S. Du. 2020. The growth mode of built-up land in floodplains and its impacts on flood vulnerability. *Science of the Total Environment* 700: Article 134462.

Hay, S.I., A. Noor, A. Nelson, and A. Tatem. 2005. The accuracy of human population maps for public health application. *Tropical Medicine & International Health* 10(10): 1073–1086.

Jongman, B. 2018. Effective adaptation to rising flood risk. *Nature Communications* 9(1): Article 1986.

Jongman, B., P.J. Ward, and J.C.J.H. Aerts. 2012. Global exposure to river and coastal flooding: Long term trends and changes. *Global Environmental Change* 22(4): 823–835.

Kummu, M., H. Moel, P. Ward and V. Olli. 2011. How close do we live to water? A global analysis of population distance to freshwater bodies. *PloS One* 6(6): Article e20578.

Leandro, J., K.-F. Chen, R.R. Wood and R. Ludwig. 2020. A scalable flood-resilience-index for measuring climate change adaptation: Munich city. *Water Research* 173: Article 115502.

Liu, D., Y. Li, S. Fang, and Y. Zheng. 2017. Influencing factors for emergency evacuation capability of rural households to flood hazards in western mountainous regions of Henan province, China. *International Journal of Disaster Risk Reduction* 21: 187–195.

Liu, Z., C. He, Q. Zhang, Q. Huang, and Y. Yang. 2012. Extracting the dynamics of urban expansion in China using DMSP-OLS nighttime light data from 1992 to 2008. *Landscape and Urban Planning* 106(1): 62–72.

Loucks, D.P. 2015. Comment on "Debates-perspectives on sociohydrology: Simulating hydrologic-human interactions" by M. Sivapalan. *Water Resources Research* 51(6): 4789–4794.

Mård, J., G. Di Baldassarre, and M. Mazzoleni. 2018. Nighttime light data reveal how flood protection shapes human proximity to rivers. *Science Advances* 4(8): 5779–5801.

McCool, S.F., R.N. Clark and G.H. Stankey (eds.). 2008. *Water and people: Challenges at the interface of symbolic and utilitarian values*. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Megharaj Bhosale, M., and M. Mahesh Chavan. 2018. Review on flood monitoring and early warning system. *International Journal for Research in Applied Science and Engineering Technology* 7: 455–461.

National Bureau of Statistics. 2015. *China statistical yearbook 2014*. Beiijing, China: China Statistics Press (in Chinese).

Pesaresi, M., D. Ehrlich, A. Florczyk, S. Freire, A. Julea, T. Kemper, P. Soille and V. Syrris 2015. *GHS built-up grid, derived from Landsat, multitemporal (1975, 1990, 2000, 2014),* version R2015. Brussels, Belgium: Joint Research Centre (JRC), European Commission.

Rudari, R., F. Silvestro, L. Campo, N. Rebora, G. Boni and C. Herold. 2015. *Improvement of the global food model for the GAR 2015.* Geneva, Savona and Arendal: United Nations Office for Disaster Risk Reduction (UNDRR), Centro Internazionale in Monitoraggio Ambientale (CIMA) and United Nations Environment Programme Global Resource Information Database (UNEP GRID).

Shi, P., J. Wang, W. Xu, T. Ye, S. Yang, L. Liu, W. Fang, and K. Liu et al. 2015. *World atlas of natural disaster risk*. Berlin: Springer.

Sivapalan, M. 2015. Debates-perspectives on sociohydrology: Changing water systems and the "tyranny of small problems"—Sociohydrology. *Water Resources Research* 51(6): 4795–4805.

Smith, A., P. D. Bates, O. Wing, C. Sampson, N. Quinn and J.C. Neal. 2019. New estimates of flood exposure in developing countries using high-resolution population data. *Nature Communications* 10(1): Article 1814.

Turner, M.G., R.H. Gardner, and R. O'Neill. 2001. *Landscape ecology in theory and practice: Pattern and Process*. New York: Springer.

UNISDR (United Nations International Strategy for Disaster Reduction). 2015. *Making development sustainable: The future of disaster risk management.* Global assessment report on disaster risk reduction. Geneva: UNISDR.

Veldkamp, T.I.E., Y. Wada, J.C.J.H. Aerts, P. Döll, S.N. Gosling, J. Liu, Y. Masaki, T. Oki, et al. 2017. Water scarcity hotspots travel downstream due to human interventions in the 20th and 21st century. *Nature Communications* 8(1): Article 15697.

Viero, D., G. Roder, B. Matticchio, and A. Defina. 2019. Floods, landscape modifications and population dynamics in anthropogenic coastal lowlands: The Polesine (northern Italy) case study. *Science of the Total Environment* 651: 1435–1450.

Wallemacq, P. and R. House. 2018. *Economic losses, poverty and disasters 1998–2017.* Brussels, Belgium: Centre for Research on the Epidemiology of Disasters (CRED), United Nations Office for Disaster Risk Reduction (UNDRR).

Wang, J. 2018. Problems existing in small and medium rivers and countermeasures in mountainous areas. *Technology Innovation and Application No.* 2: 81–82 (in Chinese).

White, G.F. 1945. *Human adjustment to floods: A geographical approach to the flood problem in the United States*. Chicago, IL, USA: The University of Chicago.

Wu, J., C. Huang, M. Pang, Z. Wang, L. Yang, G. FitzGerald and S. Zhong. 2019. Planned sheltering as an adaptation strategy to climate change: Lessons learned from the severe flooding in Anhui Province of China in 2016. *Science of the Total Environment* 694: Article 133586.

Xia, J. 2019. New concepts of urban flood control in China. *China Flood & Drought Management* 29(8): 2–3 (in Chinese).

Xie, C., X. Huang, H. Mu, and W. Yin. 2017. Impacts of land-use changes on the lakes across the Yangtze floodplain in China. *Environmental Science & Technology* 51(7): 3669–3677.

Xie, C., X. Huang, L. Wang, X. Fang, and W. Liao. 2018. Spatiotemporal change patterns of urban lakes in China's major cities between 1990 and 2015. *International Journal of Digital Earth* 11(11): 1085–1102.

Zhang, Z., Q. Zhang, J. Tao, Y. Sun, and Q. Zhao. 2012. Climatic and geological environmental characteristics of the exceptional debris flow outburst in Zhouqu, Gansu Province, on 8 August, 2010. *Journal of Glaciology and Geocryology* 34(4): 898–905 (in Chinese).

Zheng, J., Y. Yin, and B. Li. 2010. A new scheme for climate regionalization in China. *Acta Geographica Scinica* 65(1): 3–12 (in Chinese).

Zhou, B., Q. H. Wen, X. Ying, L. Song and X. Zhang. 2014. Projected changes in temperature and precipitation extremes in China by the CMIP5 multimodel ensembles. *Journal of Climate* 27(17): Article 6591.