

# Measuring the past 20 years of urban-rural land growth in flood-prone areas in the developed Taihu Lake watershed, China

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**Abstract** There is growing interest in using the urban landscape for stormwater management studies, where land patterns and processes can be important controls for the sustainability of urban development and planning. This paper proposes an original index of Major Hazard Oriented Level (MHOL) and investigates the structure distribution, driving factors, and controlling suggestions of urban-rural land growth in flood-prone areas in the Taihu Lake watershed, China. The MHOL of incremental urban-rural land increased from M 31.51 during the years 1985–1995 to M 38.37 during the years 1995–2010 (M for medium structure distribution, and the number for high-hazard value). The index shows that urban-rural land was distributed uniformly in flood hazard levels and tended to move rapidly to high-hazard areas, where 72.68% of incremental urban-rural land was aggregated maximally in new urban districts along the Huning traffic line and the Yangtze River. Thus, the current accelerating growth of new urban districts could account for the ampliative exposure to high-hazard areas. New districts are driven by the powerful link between land financial benefits and political achievements for local governments and the past unsustainable process of “single objective” oriented planning. The correlation categorical analysis of the current development intensity and carrying capacity of hydrological ecosystems for sub-basins was used to determine four types of development areas and provide decision makers with indications on the future watershed-scale subdivision of Major Function Oriented Zoning implemented by the Chinese government.

**Keywords** urban-rural land growth, flood-prone areas,

major hazard oriented level, major function oriented zoning, Taihu Lake Watershed

## 1 Introduction

The United Nations reported that 54% of the world’s population lives in urban areas in 2014, a proportion that is expected to increase to 66% by 2050 (United Nations, 2014). The negative environmental impacts associated with urbanization such as loss of farmland and biodiversity, aesthetic degradation, and rising urban flooding are linked to the patterns of land use, specifically unwieldy and low-density urban sprawl (Pauleit et al., 2005; Chaves et al., 2009; Su et al., 2010) which has increased at alarming rates in many countries. Urban flooding is a major threat to many cities worldwide, with more significant impacts on developing countries and no improvement seen in the near future (Haase, 2009).

Urbanization impacts on runoff measures and flood damage and control are still important areas of research (Isidoro et al., 2012). Urban flood control includes both structural measures, such as detention or retention reservoirs, infiltration structures, reforestation actions, and channel enlargement or implementation and non-structural measures, such as urban drainage master plans, zoning of flood-prone areas, flood warning systems, flood insurance, and environmental education programs (Miguez et al., 2009). Initially, most studies focused on local hydraulic representation of floods of streets and pipes and sewer system designs in the early 1960s (Delleur, 2003; Brabec, 2009). The impervious threshold was used directly as a common and useful method for quantifying the effects on the hydrological process in the 1970s (Brabec, 2009) and benchmarks in watershed planning efforts (Shuster et al., 2005; Schueler et al., 2009). Many studies showed a

high correlation between imperviousness and increased run-off. Several qualitative studies have indicated that urban patterns in watersheds can play an important role and determine a number of changes in hydrologic function, such as flow rate (Mejía and Moglen, 2009). Later studies focused on the implementation of urban planning and design technologies, such as Low Impact Development (LID) to reduce the effects of urban growth on water resources (Coffmann, 2000; Mejía and Moglen, 2010; van Roon, 2011). Understanding the relationship between land use changes associated with urbanization in the context of climate change and land surface modeling studies has become a growing need, and is where the effects of urbanization on land processes can play an important role (Vörösmarty et al., 2000; Pielke, 2005). More studies have focused on the urban landscape for managing and controlling stormwater (Delleur, 2003; Mejía and Moglen, 2009). Moreover, the focus of urbanization effects on floods has gradually shifted from hydraulic channels to the imperviousness ratio and the pattern of urban land use control in urban areas or the urbanized basin. However, the spread of the use of the urban landscape for managing and controlling stormwater or urbanized basins has been rather slow.

Flood risk is constitutive of the current era of urbanization and must be linked to urban planning and management (Mentens et al., 2006; Nie et al., 2009; Ahmad and Simonovic, 2013). An improved understanding of the sustainability of urban development and planning must rely strongly upon available information on the causes, chronology, and effects of urbanization. Moreover, modeling impacts of urbanization on an ecological security pattern is an effective way to achieve sustainable urban growth (Yin et al., 2016), particularly by integrating development strategies with planning processes in the specified context. Miguez et al. (2015) discussed the need to integrate innovative stormwater drainage practices with the urban planning process in the metropolitan region of Rio de Janeiro by comparing a traditional drainage system approach with a distributed stormwater management approach. They considered land-use planning as a key element for urban flood control. Peng et al. (2015) proposed an effective approach to integrate urban land-use zoning with the possibility of land-use transformation. Urban land sprawl results from a bottom-up economic-driven consequence in the U.S. but is a powerful top-down government-driven process in China (Zhang, 2001). The Chinese government has launched sweeping reforms of the structure of institutions and urban development policies since the early 1980s, which led to a colossal engine of urban expansion around large cities and accounted for the high frequency of urban flood events since 2008 (Su et al., 2010).

Thus, this paper focuses the research on the structural distribution of urban-rural land in flood-prone areas in the Taihu Lake watershed, China and measures the evolution

of current urban growth patterns to verify how significantly they have amplified the exposure to flood prone areas. Their driving processes are explored from the perspective of local government policies and urban planning, and good options for the location of urban-rural activities were presented based on current development policies.

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## 2 Study area and methods

### 2.1 Study area

The Taihu Lake watershed occupies an area of 36,895 km<sup>2</sup> and lies at the southern end of the Yangtze River Delta. The watershed is adjacent to the Yangtze River, Hangzhou Bay, East China Sea, and has Mountain Tianmu immediately to its west. The key part of the whole watershed is Taihu Lake, the main sources of which include Stream Shao and Stream Nan and flow into the East China Sea through more than 70 channels. These channels also receive run-off from the western areas and finally flow into the Yangtze River and East China Sea through the Liu River and the Huangpu River (Fig. 1). The Taihu Lake watershed has experienced some of the greatest floods in the history of the People's Republic of China in the years 1954, 1991, and 1999. Average annual rainfall in the area is 1177 mm and is concentrated in the months from May to September. Current floods, especially frequent urban floods, are caused by heavy rainfall in rainy seasons, the shrinkage of drainage networks, and increasing impervious surfaces.

The Taihu Lake watershed is one of the largest metropolitan areas worldwide and is centered at Shanghai city with 21.76 million people. The area is listed as the fifth greatest city worldwide (Cox, 2013). The gross domestic product (GDP) of the watershed was  $4.29 \times 10^{13}$  CNY in 2010, representing 10.8% of the GDP of the entire country. However, the area of the watershed accounts for 0.4% of the area of the entire country. The Taihu Lake watershed has been in the forefront of the urbanization process countrywide and will become the largest megalopolis of China by the year of 2020 (Su et al., 2010). This projected growth raises the urgency of controlling the urban sprawl for flood management studies.

### 2.2 Methods and data

#### 2.2.1 Urban-rural land and development pattern

Land use classification with information on land cover and the types of human activity was extracted from the Bands 5, 4, and 3 of Landsat-MSS on April 10, 1985 and Landsat-TM on April 17, 1995 and April 22, 2010. The images were rectified using 1:100,000 topographic maps and the nearest neighbor method. The overall accuracy (OA) and kappa coefficient (Kappa), which were 86.22% and 0.844, 88.77% and 0.93, and 89.11% and 0.89, respectively, for

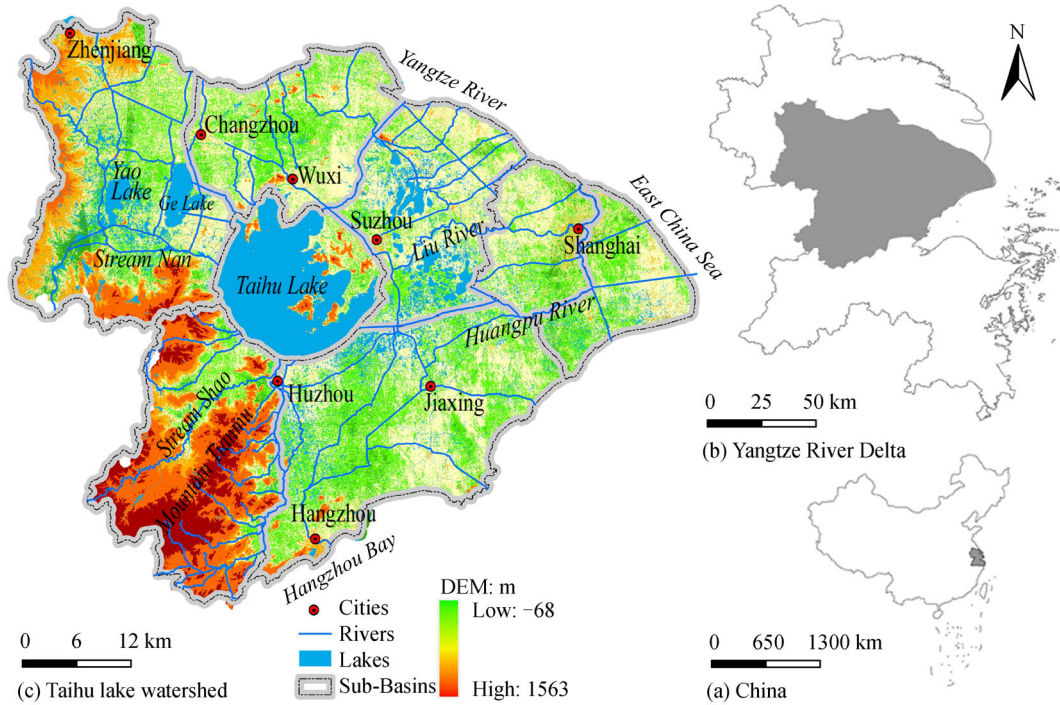


Fig. 1 Location of the Taihu Lake watershed.

images in 1985, 1995, and 2010, indicated satisfactory land classification results. Land use was divided into ten categories, including farmland, woodland, garden, grass, water (rivers and lakes), wetland (ponds, swamps, and beaches), urban, rural, industrial-mining, and unused land (Fig. 2). Urban and rural lands refer to urban and village settlements, respectively, which are more impervious and thus are crucial to flooding control. Urban development policies have focused on cities, resulting in rapid urban expansion around large cities since the early 1980s. The “New Urbanization Planning of China” was issued in 2014 and required future urban and land use planning to focus on the integration of urban and rural areas to control unsustainable urban and consumption patterns in fast growing urban agglomerations. Thus, the integration of urban, rural, and industrial-mining land (urban-rural land) is the object of this study.

Local spatial units are available to measure spatial differences of urban-rural land patterns. The Taihu Lake watershed was divided into eight sub-basins with respective independent drainage systems following natural flow lines (Gao and Gao, 2012). The eight sub-basins are called Huxi, Zhexi, Taihu, Wucheng, Yangcheng, Hangjia, Puxi, and Pudong. The southern Huxi, Zhexi, and southern Hangjia are located along the Ninghang traffic line (Ninghang high speed railway and expressway). The northern Huxi, Wucheng, Yangcheng, Puxi, and Pudong are located in the areas along the Huning traffic line and Along-Yangtze River.

### 2.2.2 Mapping flood-prone areas

The amount of rainwater that is converted into flow depends on catchment characteristics including size, shape, and land use. Once water begins flowing into a catchment, various factors such as slope and roughness of the terrain determine how much flows downhill into successively larger waterways and how quickly it moves. The key parameters for flood-prone areas are as follows: 1) Rainfall. This paper uses rainstorm data from 1980–2012 obtained from 14 meteorological stations as well as rainfall indices (intensity and frequency) which were obtained based on the average annual rainfall value in rainstorm days (24 hours rainfall  $\geq 50$  mm) and the average annual rainstorm days. Flooding problems are usually related to rainstorms. The maximum daily precipitation with a return period of 200 years is commonly used to reflect impacts of natural disaster weather on flooding on a regional scale. The average annual number of days in which rainfall surpassed 50 mm is used to reflect urban flooding based on surface drainage design criteria in urban planning (Zhou et al., 2000; Li and Cai, 2002; Yu et al., 2011). 2) DEM. Based on the 30-m resolution DEM and other studies (Zhou et al., 2000; Li and Cai, 2002), elevations, which indicate the degree of impact on flooding, were divided into nine levels. Elevation change is represented generally by slope, which is computed only by the neighboring grid. Thus, the standard deviation of elevations (DEM\_std) with  $3 \times 3$  neighboring grids is used to measure the elevation

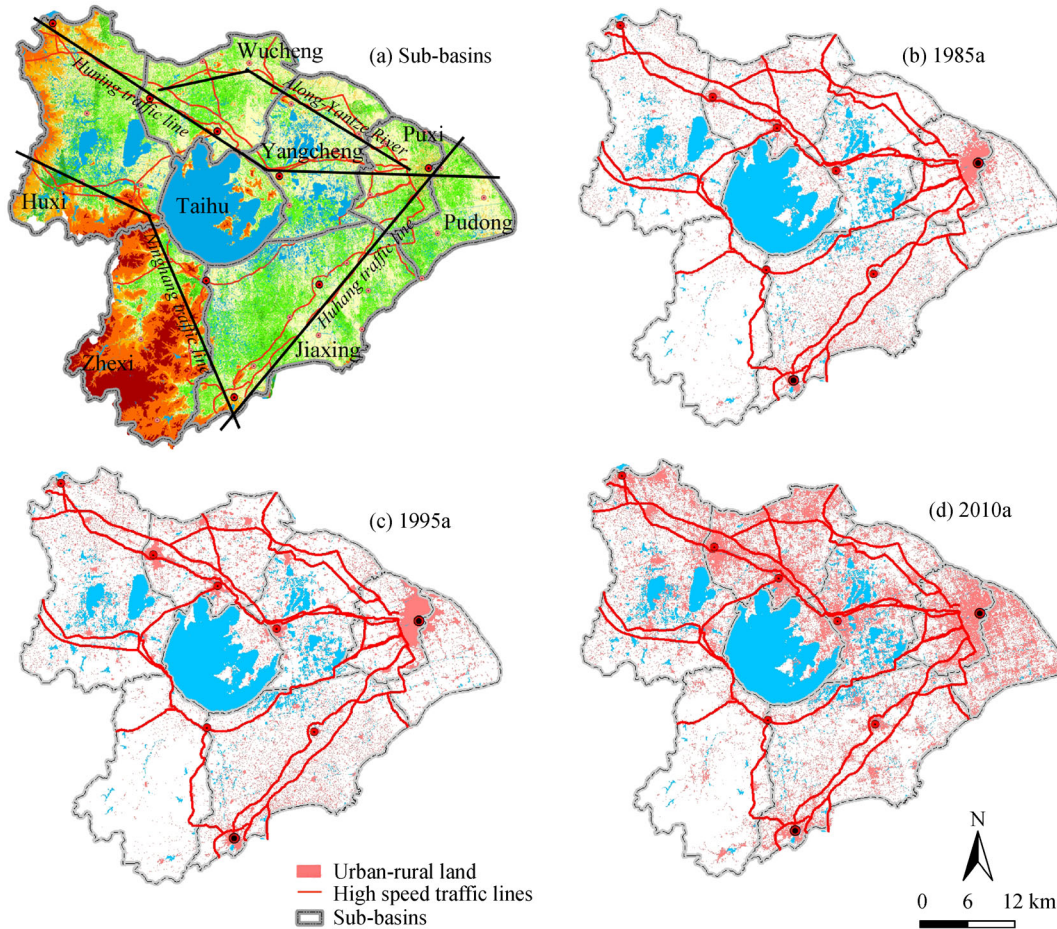


Fig. 2 Urban-rural land and sub-basins of the Taihu Lake watershed.

change of grids within a large spatial context. 3) Drainage. Drainage networks carry and drain off floodwater. The distance of the floodplain from the river, particularly for areas in which runoff is piped directly to the stream, has a significant effect on the flooding occurrence when the storm water in the river overtops the banks. If overtopping flows occur, floodplains will be occupied, with the number of flooded areas depending on the amount of overflow. The main rivers and water surfaces data are obtained from the Scientific Data Sharing Platform of Lake and Watershed (<http://lake.geodata.cn/>).

First, the mean value of two rainfall indices is categorized into five levels as the rainfall impact degree based on the Equal Interval method of ArcGIS. Second, the final DEM impact levels are shown in Table 1, and the distance of the floodplain from main rivers and water surfaces is categorized into three Drainage levels based on buffers with a radius of 1 km, 2 km, and 3 km. The classification matrix of DEM and Drainage results in terrain impact degree. Third and finally, the product of terrain impact degree and rainfall impact degree results in categories of flood-prone areas (flood hazard levels, FHL),

which include level 0 for water areas and five levels from I to V.

### 2.2.3 Distribution structure of urban-rural land in flood-prone areas

Five FHLs are further merged into three classes, such as low hazard (L, referring to I and II), moderate hazard (M, referring to III), and high-hazard (H, referring to IV and V) (Table 2 and Fig. 3(a)). The coefficients of  $L_r$ ,  $M_r$ ,  $H_r$  and  $W_r$  are the percentages of the areas of the L, M, H flood hazard levels and the water surface (W) in a spatial unit such as watershed or sub-basin. Thus, we propose an original index Major Hazard Oriented Level (MHOL) to represent the flood hazard degree of urban-rural land growth according to the coefficients analysis.

The MHOL expression is composed of two parts (Eq. (1)). One part represents the degree of flood hazard based on the use of L, M, H, and W (water surface oriented) levels. The other part is the value of high-hazard levels through the  $H_r$ . The dividing value uses the largest part of the coefficients of the all watershed FHLs. The coefficients

**Table 1** Classification matrix of terrain impact degree

DEM level/m	DEM_std level		
	I (< 1)	II (1–10)	III ( $\geq 10$ )
I (< 0)	10	9	8
II (0–2.5)	9	8	7
III (2.5–5)	8	7	6
IV (5–7)	7	6	5
V (7–10)	6	5	4
VI (10–30)	5	4	3
VII (30–200)	4	3	2
VIII (200–500)	3	2	1
IX ( $\geq 500$ )	2	1	0

**Table 2** Classification matrix of flood hazard levels

Drainage buffer/km	Terrain impact degree				
	0–3	4	5–6	7	8–10
Water surfaces	0	0	0	0	0
0–1	I	I	II	III	IV
1–3	I	II	III	IV	V
> 3	I	III	IV	V	V

of  $L_r$ ,  $M_r$ ,  $H_r$ , and  $W_r$  of the Taihu Lake watershed FHLs are 39.35, 14.58, 28.67, and 17.4, respectively. Thus, 40, which is the nearest integer larger than 39.35, is regarded as the final dividing value.

$$MHOL = \begin{cases} LH_r, & \text{If } L_r > 40\% \\ HH_r, & \text{If } H_r > 40\% \\ MH_r, & \text{If } L_r \leq 40\% \text{ and } H_r \leq 40\% \\ WH_r, & \text{If } W_r > 40\% \end{cases} \quad (1)$$

### 3 Results

The MHOL of the watershed FHLs is M28.67, indicating a medium structure distribution (Table 3). The FHLs spatially present a non-uniform pattern that varies considerably from the topographic features of the watershed, such as in the eastern and northern high-hazard plain and the southern low-hazard hilly areas (Figs. 3(b)–3(d)). MHOL sub-basins were divided into four categories. The first category includes the Huxi with M22.48 and the Yangcheng with M18.45, showing that the two sub-basins downstream and upstream of Taihu Lake have medium hazard structures because they cover vast low-hazard water or hilly areas and enormous high-hazard plains along the Huning traffic line and Along-Yangtze River. The second category with L5.67 is the low-hazard Zhexi sub basin, where vast low-hazard mountainous areas are widely

distributed. The third category is the high-hazard sub-basins, which include Pudong with H60.96, Wucheng with H50.62, Hangjia with H46.17, and Puxi with H43.97. They are considered high hazard because they cover vast plains along the Huning traffic line, the Huhang traffic line, and the Yangtze River. The last category is Taihu Lake with a water surface value W2.96.

We use the urban-rural land MHOL (e.g., urban-rural land 1985) to represent the flood hazard status of the total urban-rural land in a certain year, and the incremental urban-rural MHOL (e.g., incremental 1985–1995) to reflect the flood hazard degree of the increased urban-rural land during a certain timeframe. The values of the urban-rural land MHOL in 1985, 1995, and 2010 increased from M33.12, to M32.25, to M35.37 (Table 3). Incremental MHOL increased from M31.51 from 1985 to 1995, to M38.37 from 1995 to 2010 (Fig. 4). The growth of urban-rural land had a relatively uniform structure in flood hazard levels during the period from 1985 to 1995 but began to move toward high-hazard levels from 1995–2010.

The 1985 MHOL in Fig. 4 and green patches (low-hazard areas) around cities in Figs. 3(b)–3(d) show that most of the large cities and major towns were located in urban-rural lands and were situated mainly in low-hazard areas. Rural land was located in high-hazard areas, and was distributed uniformly in flood hazard levels. The growth in high-hazard areas changed slightly in 1995, with the exception of Yangcheng and Wucheng, where towns around large cities expanded rapidly in high-hazard

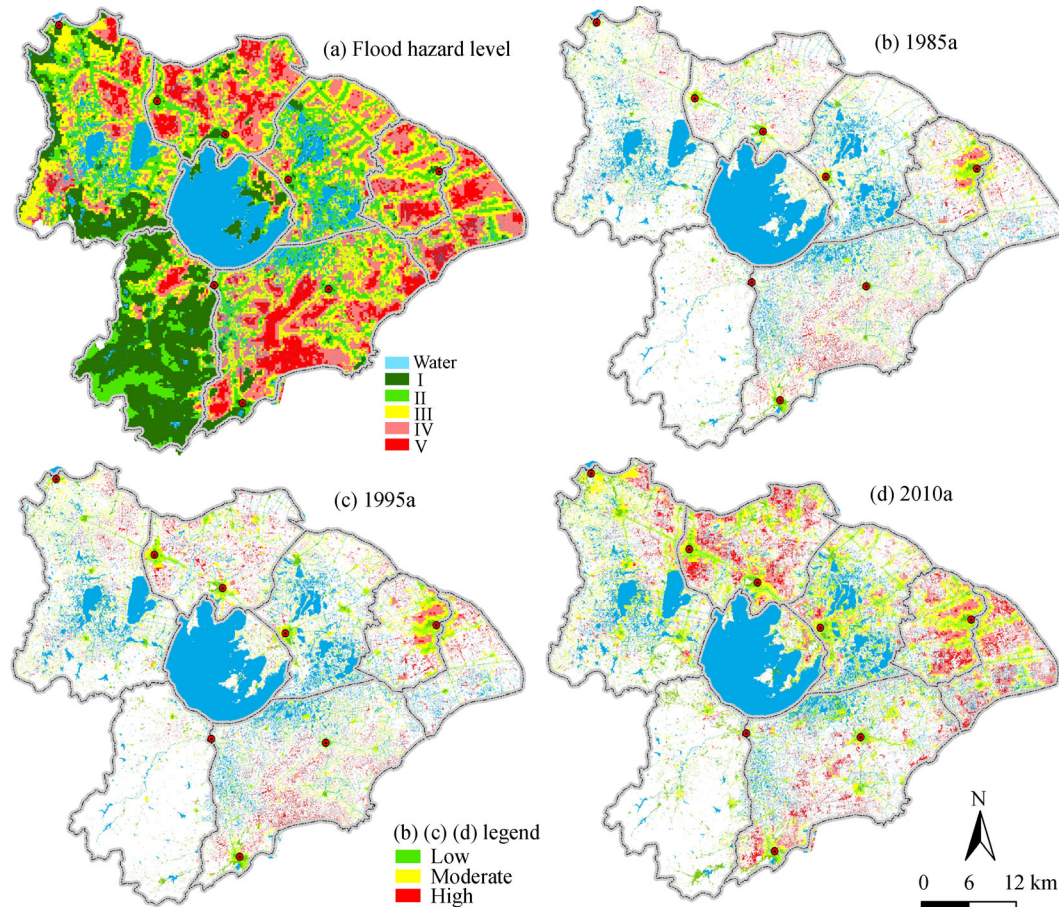


Fig. 3 Urban-rural land growth patterns in flood hazard levels.

areas. Urban growth patterns amplified significantly the exposure to high-hazard areas across the whole watershed, particularly in the Wucheng, Yangcheng, Pudong, Puxi, and northern Huxi sub basins due to new district development in 2010. However, urban patterns also have slightly increased in the III hazard areas far from the lowlands (Medium hazard level) in the rural areas of Hangjia. The peripheral urban-rural land started to grow in the upstream highlands along the valley in the Stream Nan of southern Huxi and Stream Shao of the Zhexi. Poor land resources and powerful profits pursued by estate stakeholders changed the natural cover in these areas into buildings clustered in the upstream mountainous valley with medium hazard levels.

## 4 Discussion

### 4.1 Spatial sources of incremental high-hazard urban-rural land

The area of urban-rural land and its percentage in the watershed in 1985, 1995, and 2010 increased from

3570.32 km<sup>2</sup> (9.69%) to 4637.46 km<sup>2</sup> (12.58%) to 9560.80 km<sup>2</sup> (25.93%), respectively. The area of incremental urban-rural land in high-hazard areas increased by 561.62% from 336.36 km<sup>2</sup> in 1985–1995 to 1889.09 km<sup>2</sup> in 1995–2010. The area of incremental urban-rural land rose by 461.36% in the same period. Figure 5 shows the sources of incremental urban-rural land, with which administrative boundaries of new urban districts, urban downtowns, and town areas were overlaid based on the ArcGIS analysis. Green patches and yellow patches in Fig. 5 refer to incremental low and medium hazard urban-rural patches. Red patches in Fig. 5(a) refer to high-hazard incremental urban-rural patches in new districts in 1985–1995 with high area ratios, such as 23.11% in Wucheng, 21.28% in Pudong, 17.56% in Puxi, and 16.12% in Yangcheng; moderate ratios in Hangjia and Huxi; and lower values in Zhexi and Taihu. Moreover, the incremental patches are aggregated significantly in the peripheral areas of large cities along the Huning and Huhang traffic lines and the small towns in the *Sunan* regions (i.e., Suzhou, Wuxi, and Changzhou), which resulted from the self-organized growth of large cities with good development conditions and the *Sunan* development model (Su et

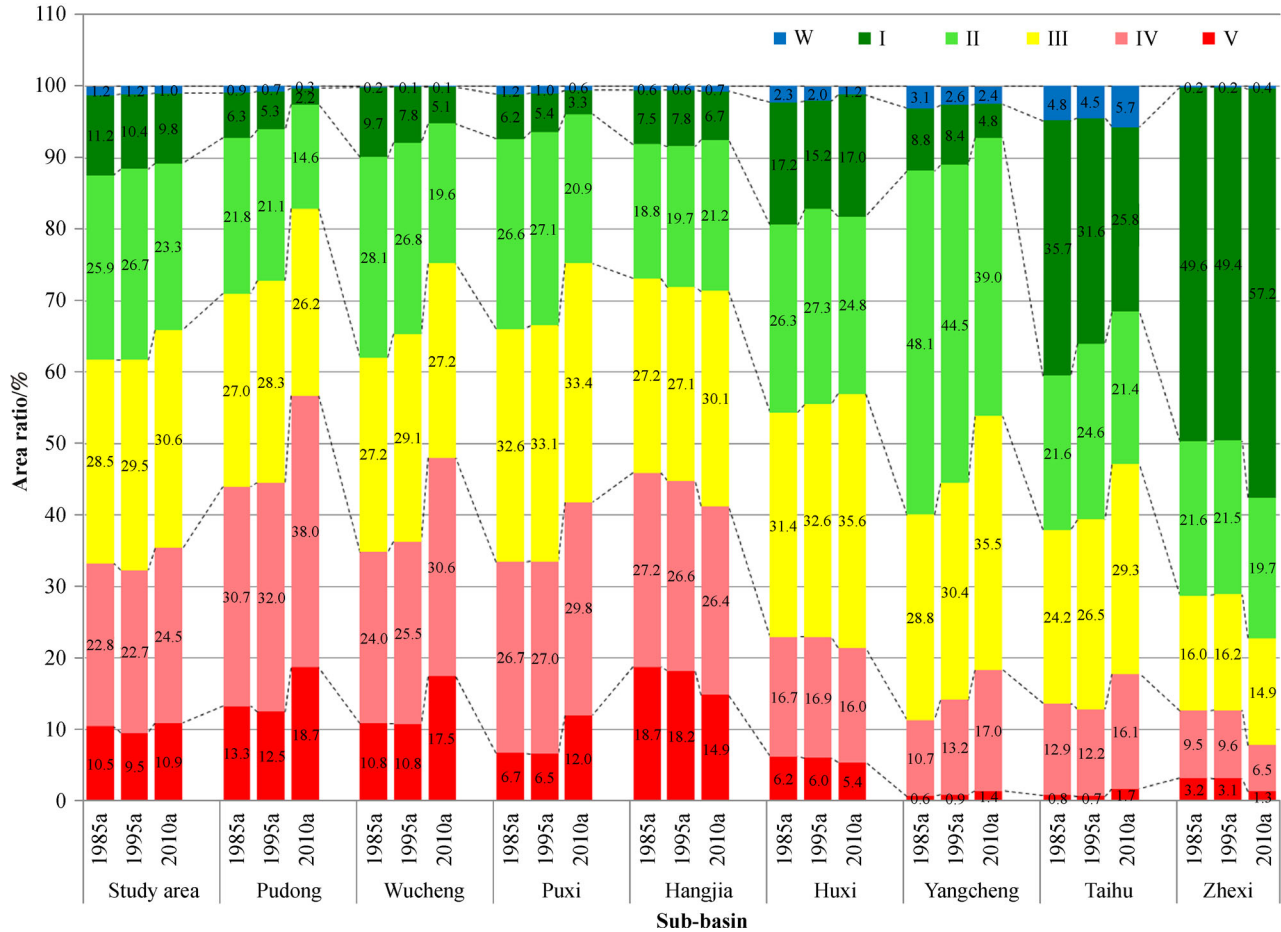


Fig. 4 Structure distribution of urban-rural land in flood hazard levels.

Table 3 MHOL of flood-prone areas and urban-rural land

Items	Study area	Hangjia	Pudong	Wucheng	Puxi	Huxi	Taihu	Zhexi	Yangcheng
Flood hazard levels	M28.67	H46.17	H60.96	H50.62	H43.97	M22.48	W2.96	L5.67	M18.45
Urban-rural land 1985	M33.12	H45.89	H43.97	M34.8	M33.43	L22.87	L13.66	L12.65	L11.32
Urban-rural land 1995	M32.25	H44.80	H44.54	M36.15	M33.49	L22.9	L12.86	L12.7	L14.11
Urban-rural land 2010	M35.37	H41.25	H56.67	H48.01	H41.79	L21.37	L17.81	L7.8	L18.36
Incremental 1985–1995	M31.51	M34.07	H47.59	H42.03	M37.55	L22.56	L12.21	L11.7	L18.57
Incremental 1995–2010	M38.37	M31	H62.05	H54.5	H51.4	L21.32	L19.1	L8.18	L20.62

al., 2010), respectively. Approximately 72.68% of red high-hazard patches in Fig. 5(b) in 1995–2010 were distributed in the new urban districts of Pudong, Puxi, Wucheng, Yangcheng, and the northern Huxi along Huning traffic line and Along-Yangtze River. Other areas were distributed relatively uniformly in the rural areas of Hangjia, the southern Huxi, Taihu, and Stream Shao of the Zhexi.

Thus, incremental high-hazard urban-rural land was aggregated maximally in new urban districts along the Huning traffic line and Along-Yangtze River and was distributed relatively uniformly in the Hangjia and the

southern Huxi along the Huhang and Ninghang traffic lines. The current new urban districts account for the ampliative exposure to high flood hazard areas. Much of the higher frequency of urban flood events occurred in these parts of the watershed.

#### 4.2 Driving policies of high-hazard incremental urban-rural land

Various urban development policies played a leading role in the accelerating growth and ampliative exposure to high flood hazard areas in the whole watershed. From 1984 to

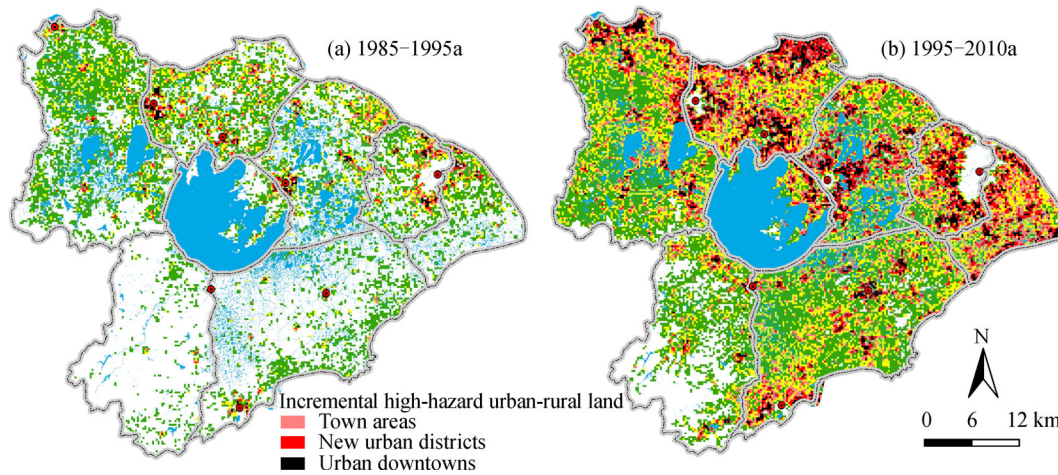


Fig. 5 Sources of high-hazard incremental urban-rural land.

1995, the *Control large cities' size and push small towns' development* policy was implemented as a national development strategy. The growth of urban-rural land in the whole watershed was slow and concentrated mostly on the low-hazard areas adjacent to large cities, such as Changzhou, Wuxi, Suzhou, Shanghai, and Pudong along the Huning traffic line at the 6–10 m elevation. However, the adjacent high-hazard areas of rural towns spread widely in the Sunan region, such as Wucheng, Yangcheng, and Taihu at the 2–3 m elevation under the *Sunan* development model, representing the development of township enterprises (Su et al., 2010). From 1995 to 2010, the government-driven establishment of land use rights and the commercialization of housing led to a low-cost, fast expansion of large cities. The development strategy had shifted from the *Sunan* model into the *New Sunan* model, that is, the accelerated development of large cities and economic development zones. The centrifugal tendencies of urban development have been reinforced by the top-down powerful government-driven processes in China unlike the direct bottom-up economic-driven consequence in the U.S. (Zhang, 2001; Song and Zenou, 2006; Aguayo et al., 2007). The Chinese local governments always gave exclusive priority to economic development for political benefit because the top-down administrative policy and low-cost expansion were linked to land financial benefits and the pursuit of the short-term GDP achievement. The increasing imbalance between urban land needs and supplies compelled urban-rural activities to move to high-hazard areas with poor land suitability, such as vast lowlands in the plain.

Urban and land planning have significant roles in the final decision on the growth patterns in flood-prone areas. Some irrational urbanized “hot areas,” which include roads and buildings constructed in flood-prone areas with inadequate drainage hydraulic efficiency, reflect the lack of rationality and authority in urban planning. Urban

drainage planning was only passively adapted to government needs, strategy, and land use organization. Moreover, urban drainage planning was difficult to coordinate with other planning subjects such as traffic, greenery, and landscape. Planners' scenarios were restricted from local governments because of their political achievement and economic needs, and hence were often considered as government-led wishful thinking. The values and paradigms of planners pertain to a rationalism under which planners may focus less on urban organism integration and more on economic and social planning through land suitability evaluation (i.e., urban construction investing funds on more ground buildings and less on invisible sewer pipes). Thus, planning sometimes becomes a single-objective oriented process rather than a comprehensive-objective oriented process, as well as an intervening-nature oriented process rather than a respecting-nature oriented process. Improved planning requires planners from various scientific sectors who can create regional strategies to sustain the development and integration of natural ecosystems. These factors are necessary to provide decision makers with indications on urban development and storm water management.

#### 4.3 Application of Major Function Oriented Zoning (MFOZ)

The *Urban drainage (rainfall water) comprehensive planning outline* was compiled in 2013. The outline requires identification of “hot areas” and flood risk areas during the pre-development and post-development stages. The Chinese government also proposed the massive project called MFOZ (Major Function Oriented Zoning), which will plan and determine the leading development direction of a certain spatial unit (e.g., watershed, sub-basin, and city region) in the future based on the carrying capacity for natural ecosystems and the current develop-

**Table 4** Indices of urban-rural land growth and flood hazard levels

Indices	Study area	Pudong	Wucheng	Puxi	Hangjia	Huxi	Yangcheng	Taihu	Zhexi
Hr_FHL	28.67	60.96	50.62	43.97	46.17	22.48	18.45	2.96	5.67
Hr1985	33.12	43.97	34.80	33.43	45.89	22.87	11.32	13.66	12.65
Hr1995	32.25	44.54	36.15	33.49	44.80	22.90	14.11	12.86	12.70
Hr2010	35.37	56.67	48.01	41.79	41.25	21.37	18.36	17.81	7.80
D1985	9.69	11.56	12.63	28.13	13.72	7.09	7.97	2.49	2.02
D1995	12.58	14.88	19.21	33.35	14.68	10.47	13.02	3.29	2.38
D2010	25.93	42.75	47.59	52.09	21.03	22.49	31.08	8.94	6.81
AI1985	87.89	91.15	89.84	95.25	87.89	86.94	89.60	87.77	87.12
AI1995	89.70	93.77	93.94	97.07	89.70	91.56	92.55	91.19	89.40
AI2010	85.97	89.67	91.44	92.36	81.97	81.22	88.46	89.37	81.27

**Table 5** Correlation coefficients between urban-rural growth and FHLs

	Hr_FHL	Hr1985	D1985	Hr_FHL	Hr1995	D1995	Hr_FHL	Hr2010	D2010	
Hr1985	.942**			Hr1995	.963**		Hr2010	.976**		
D1985	0.622	0.586		D1995	0.628	0.569	D2010	.746*	.777*	
AI1985	0.493	0.339	.870**	AI1995	0.434	0.271	AI2010	0.338	0.495	.713*

Notes: \*\* Correlation is significant at the 0.01 level (2-tailed). \* Correlation is significant at the 0.05 level (2-tailed).

ment intensity of human-made ecosystems. The major function in each zone involves four categories of development strategies, including optimizing development (e.g., low carrying capacity and current high-density development), permitting development (high carrying capacity and current low/moderate-density development), and restricting and prohibiting development (low carrying capacity).

Density (D) (D1985, D1995, and D2010) and aggregation index (AI) (AI1985, AI1995, and AI2010) values (McGarigal et al., 2002) of urban-rural land were selected to assess the current development intensity (Table 4) and apply the results to the MFOZ of the eight sub-basins. The urban-rural land Hr coefficients (i.e., Hr1985, Hr1995, and Hr2010) and watershed FHLs Hr coefficients (Hr\_FHL) for the eight sub-basins are used to assess carrying capacity. The correlation among these indices is discussed in Tables 4 and 5. The correlation between urban-rural land Hr and Hr\_FHL was significant and increased from 0.942 in 1985 to 0.976 in 2010, indicating a lack of significant

urban-rural development controls in high-hazard areas. The correlation between Hr and D of urban-rural land was not significant in 1985 and 1995 but became significant in 2010, highlighting that urban-rural land in some sub-basins grew less in high-hazard areas. The location of urban-rural land expansion was also affected by other factors such as traffic conditions, land demands, and control measures. The correlation between AI and D was significant, showing that greater urban-rural land intensity led to more clustered significant development.

A categorically analytic approach for four indices, including D, AI, Hr, and Hr\_FHL in 2010, is adopted to uncover the non-linear relationship between current land development intensity and the carrying capacity of hydrological ecosystems for sub-basins (Table 6). The high Hr results in low carrying capacity, and thus, the MFOZ of sub-basins from a perspective of hydrological safety are categorized into four types of areas as follows: 1) Area I, which refers to areas with low carrying capacity for hydrological ecosystems, has the highest density of

**Table 6** Classification matrix of sub-basins based on MFOZ

MFOZ areas	Hr_FHL/%	Hr2010/%	D/%	AI	Sub-basins
I: Optimizing development	High: 100 > FHL > 40	High: 100 > Hr > 40	High: 100 > D > 40	High: 100 > AI > 85	Pudong, Wucheng, Puxi
II: Optimizing or Permitting development	High: 100 > FHL > 40	High: 100 > Hr > 40	Low: 40 > D > 0	Low: 8 5 > AI > 0	Hangjia
III: Integrated development	Low: 40 > FHL > 0	Low: 40 > Hr > 0	Low: 40 > D > 0	Low: 85 > AI > 0	Huxi, Zhexi
IV: Optimizing or prohibiting development	Low: 40 > FHL > 0	Low: 40 > Hr > 0	Low: 40 > D > 0	High: 100 > AI > 85	Yangcheng, Taihu

urban development because of the tremendous urbanized land demand along the Huning traffic line and the Along-Yangtze River. For areas in Area I, the strategy of optimizing development should be adopted to improve current urban land productivity. Urban sprawl in flood-prone areas should also be controlled by use of planning urban growth boundaries. Water and permeable surfaces, such as soil and vegetation, should also be increased and connected into a network system; 2) Area II pertains to the area with low carrying capacity for hydrological ecosystems, which is located mostly in rural areas and has low-density urban development. Under this category, dispersed village settlements in high-hazard rural areas should be concentrated and optimized through land consolidation planning. However, the strategy of permitting development should be adopted to enable faster expansion of urbanized land into new urban districts and economic development zones of large cities along the Ninghang railway. 3) Area III refers to the mountainous area that has a moderate carrying capacity for hydrological ecosystems and moderate-density urban-rural development along the Ninghang traffic line. Thus, integrated strategies should be adopted in the different regions, including permitting future development of “hot areas in new urban districts and economic development zones along the Ninghang railway. These districts and zones should prohibit and restrict development in the plains of the large lakes (Yao Lake, Ge Lake) and their adjacent areas, and restrict the pottery industry and tourism development to a moderate degree in hilly areas. 4) Area IV refers to the plain area with moderate carrying capacity for hydrological ecosystems and has moderate-density urban development. For districts and zones in this area, booming tourist activities along Taihu Lake and the Huning line should be optimized through the “points-axis spatial development model. However, the protected buffer zone of major lakes should be broadened and regarded as prohibited development areas in future urban and land use planning.

## 5 Conclusions

First, the MHOL of incremental urban-rural land changed from M31.51 to M38.37, indicating that urban-rural land distributed uniformly at flood hazard levels in the watershed was not significantly inclined to the high-hazard areas during the 1985–1995 timeframe but tended to move rapidly to high-hazard areas during the 1995–2010 timeframe. The area of incremental high-hazard urban-rural land increased by 561.62% from 336.36 km<sup>2</sup> during 1985–1995 to 1889.09 km<sup>2</sup> during 1995–2010. 72.68% of the area was aggregated maximally in the new urban districts along the Huning traffic line and Along-Yangtze River. Thus, the current accelerating growth of new urban districts could account for the ampliative exposure to high-hazard areas.

Second, urban development policies in different phases and current planning processes have played significant roles on the structure and sources of incremental high-hazard urban-rural land. The 1984–1995 strategy of *Control large cities size and push small towns development* resulted in the slow growth of low-hazard areas of large cities along the Huning and Huhang traffic lines, and the rapid growth of high-hazard areas in small towns in the Sunan region. However, the ampliative exposure of new urban districts to high-hazard areas in 1995–2010 have been reinforced by the powerful link between land financial benefits and political achievements for local governments. This exposure also had a direct relationship with the single-objective-oriented planning process, which led to the increasing imbalance between urban land needs and supplies and irrational planned “hot areas”.

Third, the Chinese government completed the MFOZ works on the national scale in 2011 and determined optimizing development as the leading direction of the Taihu Lake watershed. The correlation and categorical analysis between the intensity of the current development and the carrying capacity of hydrological ecosystems for the eight sub-basins provide decision makers with indications on future MFOZ subdivision on a regional scale. Area I (optimizing area) has a low carrying capacity for hydrological ecosystems and is currently undergoing the highest density of development along the Huning traffic line and along the Yangtze River. Area II (optimizing or permitting area) has a low carrying capacity and low-density development. Area III (integrated development area) has a moderate carrying capacity and moderate-density development along the Ninghang traffic line. Area IV (optimizing and prohibiting areas) has a moderate carrying capacity and moderate-density urban development along the Taihu Lake, Huning line, and major lakes.

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