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RESEARCH ARTICLE

Land use/cover change effects on floods with different return periods: a case study of Beijing, China

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Abstract In this study, an approach integrating digital land use/cover change (LUCC) analysis, hydraulic modeling and statistical methods was applied to quantify the effect of LUCC on floods in terms of inundation extent, flood arrival time and maximum water depth. The study took Beijing as an example and analyzed five specific floods with return periods of 20-year, 50-year, 100-year, 1000-year and 10000-year on the basis of LUCC over a nine-year period from 1996 to 2004. The analysis reveals that 1) during the period of analysis Beijing experienced unprecedented LUCC; 2) LUCC can affect inundation extent and flood arrival time, and floods with longer return periods are more influenced; 3) LUCC can affect maximum water depth and floods with shorter return periods are more influenced; and 4) LUCC is a major flood security stressor for Beijing. It warns that those cities having experienced rapid expansion during recent decades in China are in danger of more serious floods and recommends that their actual land use patterns should be carefully assessed considering flood security. This integrated approach is demonstrated to be a useful tool for joint assessment, planning and management of land and water.

Keywords inundation extent, flood arrival time, maximum water depth, shallow flow model

1 Background

In the last few decades, more and more disastrous floods have occurred in China, especially in urban and peri-urban areas, causing serious human and economic losses. Research has been carried out to determine the reasons behind this increased number of floods. Land use/cover change (LUCC) is one of the suspected causes [1–3]. LUCC and its effects on water and the environment have thus been extensively studied [4–10]. The effects of LUCC on flooding attracts attention at the basin and lake level using hydrological models [11–23]. LUCC can be also studied with hydraulic models due to the fact that LUCC changes surface roughness, which subsequently influences overland flow velocity and routing [24,25]. The models derived from 2D shallow water equations have been used for simulating flood velocity, route and extent [26–29].

In the past three decades, Beijing has experienced major LUCC in association with rapid economic development, with large amounts of cultivated land having been changed to urban land, forest and heavy brush. Focusing on a nine-year period from 1996 to 2004 and considering various flood return periods from 20 to 10000 years, this study assesses the LUCC effect on flood security in terms of inundation extent, maximum water depth and flood arrival time by means of a 2D shallow flow model.

2 Study area

The study area is the Chaobai River shown in Fig. 1, which is one of the most important rivers in Beijing. It originates in the Yanshan mountains in the north of China, and flows from north to south in eastern Beijing. The basin totals 19354 km^2, covering 16810 km^2 of upstream mountainous area and 2544 km^2 of downstream plain. The upstream valley is narrow and deep, connected with an open downstream plain. This features of the terrain makes this area vulnerable to flooding. The river channel was rebuilt in order to control mountain torrents and prevent associated disasters. There are 47 towns and 875 villages, with a population of approximately one million living in the river basin. In this study, the inflow cross-section is set at the dam of the Miyun Reservoir.

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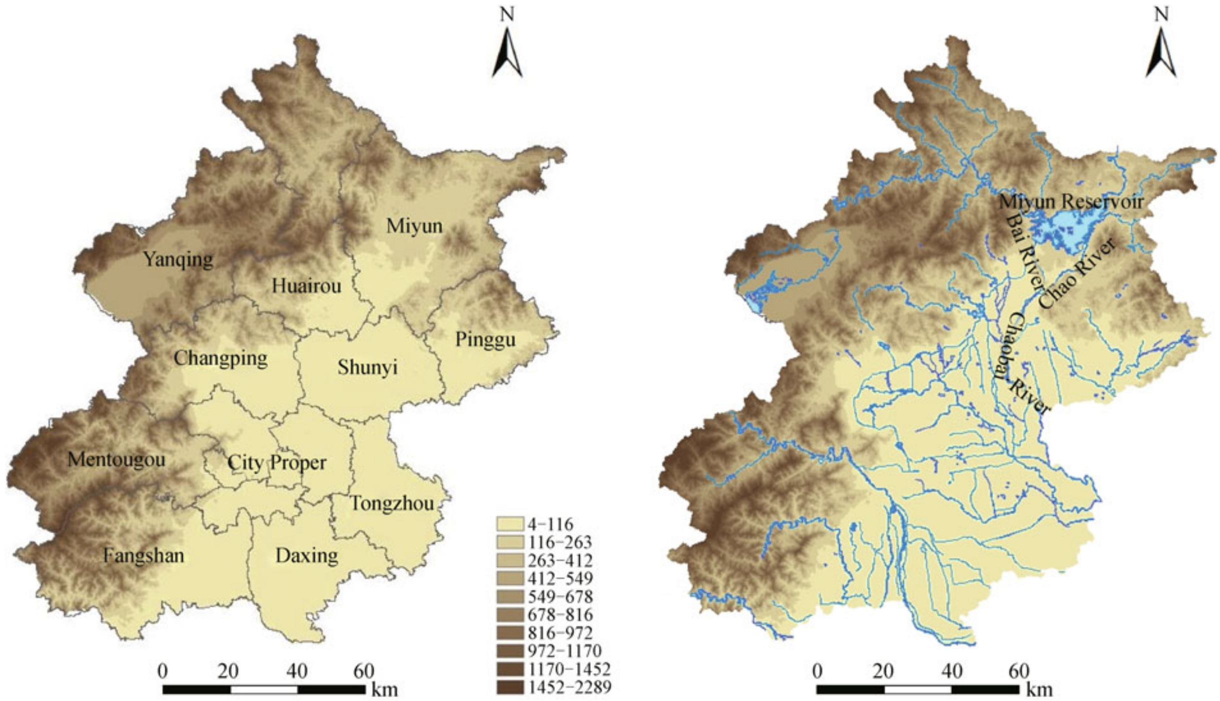

Fig. 1 The topographic elevation of Beijing

3 2D shallow flow model

A 2D shallow flow model (SFM), based on fully 2D shallow water equations (SWEs), has been developed and verified by [30–32] to solve complicated hydrodynamic problems. In a matrix form, the hyperbolic SWEs are generally written as

$$\frac{\partial \mathbf{q}}{\partial t} + \frac{\partial \mathbf{f}}{\partial x} + \frac{\partial \mathbf{g}}{\partial y} = \mathbf{s}, \tag{1}$$

where $\mathbf{q}$ is the vector containing the conserved flow variables, $\mathbf{f}$ and $\mathbf{g}$ denote the flux vectors in the x and y-direction, respectively, $\mathbf{s}$ is the source term vector, t is the time and x and y are the Cartesian coordinates. The vectors are given by

$$\mathbf{q} = \begin{bmatrix} \eta \\ uh \\ vh \end{bmatrix} \quad \mathbf{f} = \begin{bmatrix} uh \\ u^2h + \frac{1}{2}g\left(\eta^2 - 2\eta z_b\right) \\ uvh \end{bmatrix}$$

$$\mathbf{g} = \begin{bmatrix} vh \\ uvh \\ v^2h + \frac{1}{2}g\left(\eta^2 - 2\eta z_b\right) \end{bmatrix} \quad \mathbf{s} = \begin{bmatrix} 0 \\ -\frac{\tau_{bx}}{\rho} - g\eta\frac{\partial z_b}{\partial x} \\ -\frac{\tau_{by}}{\rho} - g\eta\frac{\partial z_b}{\partial y} \end{bmatrix} \tag{2}$$

where η is defined as the water level, z_b is the bed elevation above datum, h is the water depth ($h = \eta - z_b$), u and v are the depth-averaged velocity components in the x and y-direction, g is the acceleration due to gravity, ρ is the water density, $-\frac{\partial z_b}{\partial x}$ and $-\frac{\partial z_b}{\partial y}$ are the bed slope in the Cartesian directions and τ_{bx} and τ_{by} denote the bed friction stresses, which can be calculated by the following formulae

$$\tau_{bx} = \rho C_f u\sqrt{u^2 + v^2} \text{ and } \tau_{by} = \rho C_f v\sqrt{u^2 + v^2}, \tag{3}$$

in which the bed roughness coefficient C_f can be evaluated by $C_f = gn^2/h^{1/3}$ and n is the Manning coefficient. When $h < 1.0 \times 10^{-6}$, C_f is directly set to zero (a cell is assumed to be dry when $h < 1.0 \times 10^{-6}$).

As depicted in Fig. 2, the pre-balanced formulation of the 2D shallow water equation is solved by employing an explicit finite volume Godunov-type scheme. The interface fluxes are evaluated using an HLLC approximate Riemann solver. The wet-dry problem is solved by a non-negative water depth approach, incorporated within a simple local bed modification method, in order to avoid the spurious oscillation at the wet-dry interface. The friction source term is discretized and controlled by a limited implicit scheme. The second order accuracy is achieved using a Runge-Kutta integrated method in time and a slope limited linear reconstruction scheme in space. For the explicit numerical scheme, the Courant-Friedrichs-Lewy criterion-based adaptive time step is implemented to maintain the computational stability.

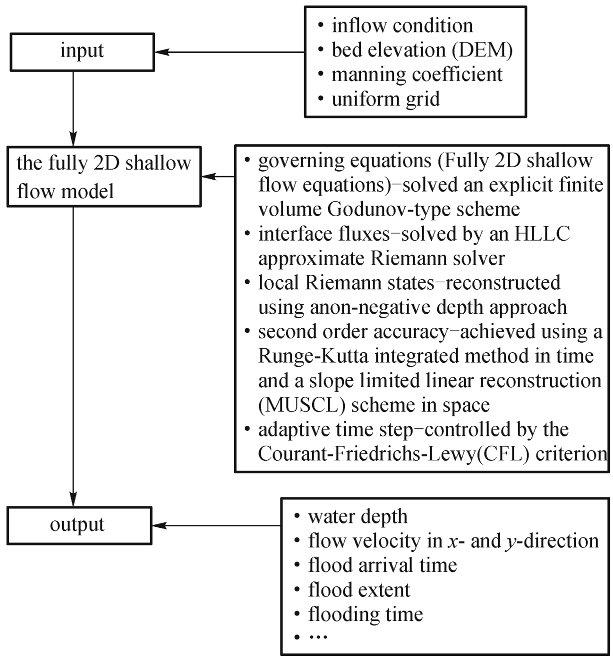

Fig. 2 Framework of the 2D SFM

4 Data treatment

4.1 Land use/cover and manning coefficients

The cross tabulation matrix of LUCC in 1996 and 2004 in Beijing is presented in Table 1. It shows that 1,053 km^2 of cultivated land was transferred to forest (327.55 km^2), heavy brush (191.77 km^2) and urban land use (533.71 km^2) during the period of analysis. The LUCC is classified into seven main types of hydraulics, each corresponding to a Manning roughness coefficient [33,34] as listed in Table 2.

4.2 Flood scenarios

Five flood return periods–20-year, 50-year, 100-year, 1000-year and 10000-year–are considered in this study (hereafter shorted to “the five floods”). The hydrographs, reproduced by [35], are illustrated in Fig. 3.

4.3 Grid cell

The computational area is 19354 km^2. DEM data are developed from Shuttle Radar Topography Mission

Table 1 Cross tabulation matrix of LUCC in Beijing 1996–2004

from 1996	to 2004							
	1	2	3	4	5	6	7	total 1996
1	**1199.92**	47.41	31.72	37.26	252.66	82.42	138.02	1789.41
2	45.16	**167.02**	4.1	30.04	29.77	8.33	83.9	368.32
3	34.51	6.95	**37.83**	2.96	39.14	6.52	12.33	140.24
4	67.1	92.3	5.14	**636.36**	114.84	73.75	598.06	1587.55
5	533.71	82.92	83.16	173.1	**1936.94**	191.77	327.55	3329.15
6	110.94	27.25	7.53	74.56	152.98	**421.83**	221.32	1016.41
7	116.12	216.88	5.04	538.46	189.97	218.46	**4782.37**	6067.3
total 2004	2107.46	640.73	174.52	1492.74	2716.3	1003.08	6163.55	
C	0.18	0.74	0.24	−0.06	−0.18	−0.01	0.02	
A	318.05	272.41	34.28	−94.81	−612.85	−13.33	96.25	
B	35.34	30.27	3.81	−10.53	−68.09	−1.48	10.69	

Note: *Data source: developed based on Landset5-TM data. 1: Urban land; 2: Bare land; 3: Ponds; 4: Grassland; 5: Cultivated land; 6: Heavy brush; 7: Forest; C: Changing rate (%); A: Changing gross (km^2); B: Annual changing gross (km^2·a^{-1}).

Table 2 Manning roughness coefficients corresponding to land use/cover (summarized from [27] and [28])

land use/cover	manning roughness coefficient
urban land (incl. rural road, town land, rural residence and mining land, railway, highway, airports, ports and wharfs)	0.016
bare land (incl. saline alkali land, swamp, sand land, bare rock, threshing ground specially designated land and unutilized land)	0.025
ponds (incl. aquaculture)	0.027
grassland (incl. reed and mudflat)	0.03
cultivated land (incl. pasture, irrigation and water conservancy works, ridge, river, lake, reservoir, confined feeding operations, green house and aquatic operations)	0.035
heavy brush	0.075
forest	0.15

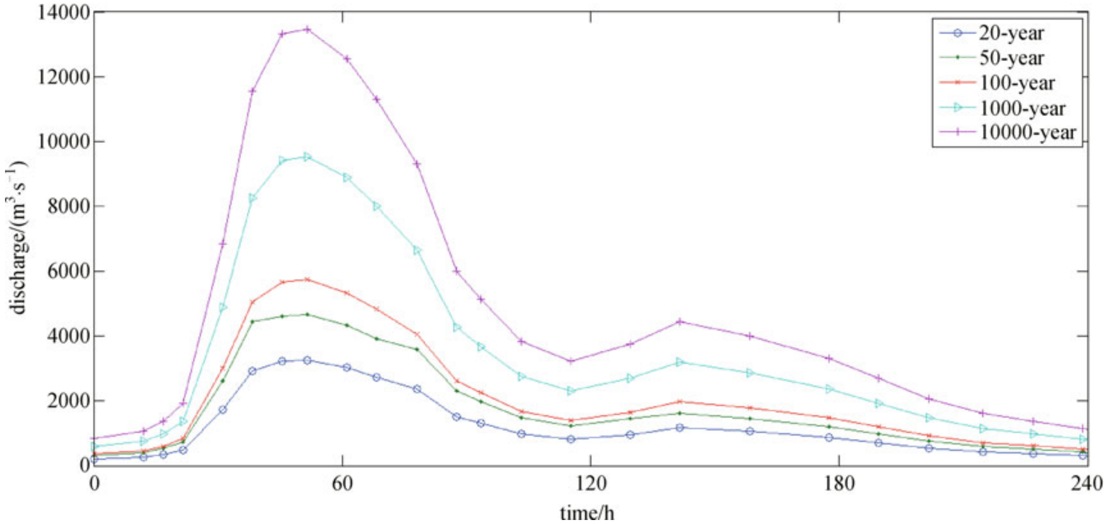

Fig. 3 The flood hydrographs with different flood return periods upstream from Beijing

(STRM) data and resampled to 183.3 m × 183.3 m resolution. A uniform grid of 870 × 955 is adopted with a grid size of 183.3 m. Each grid cell covers an area of about 0.0336 km^2.

4.4 Hypothesis

Two hypotheses are made for simplifying computation: 1) no significant infiltration during flooding time and 2) no human influence on floods.

5 Effect analysis

5.1 Effect on inundation extent

Figure 4 depicts inundation extents for the five floods in 1996 and in 2004 and reveals that the inundation extents of the five floods in 2004 are all larger than their counterparts in 1996. Figure 5 demonstrates variation in time of the extent differences of the five floods between the two years in question, and reveals that floods with longer return periods correspond to larger inundation extents.

5.2 Effect on maximum water depth

Focusing on the overlapped area that is inundated both in 1996 and 2004, Fig. 6 shows the cumulative areal distribution of the difference of maximum water depth at grid cells between the two years. It reveals that every flood is affected by LUCC, and that floods with shorter return periods receive more influence, corresponding to a larger difference.

5.3 Effect on flood arrival time

In the overlapped area, cumulative areal distributions of flood arrival time at grid cells of the five floods between 1996 and 2004 are shown in Fig. 7. It can be seen that each flood is influenced by LUCC and that floods with longer return periods receive more influence, corresponding to a larger difference.

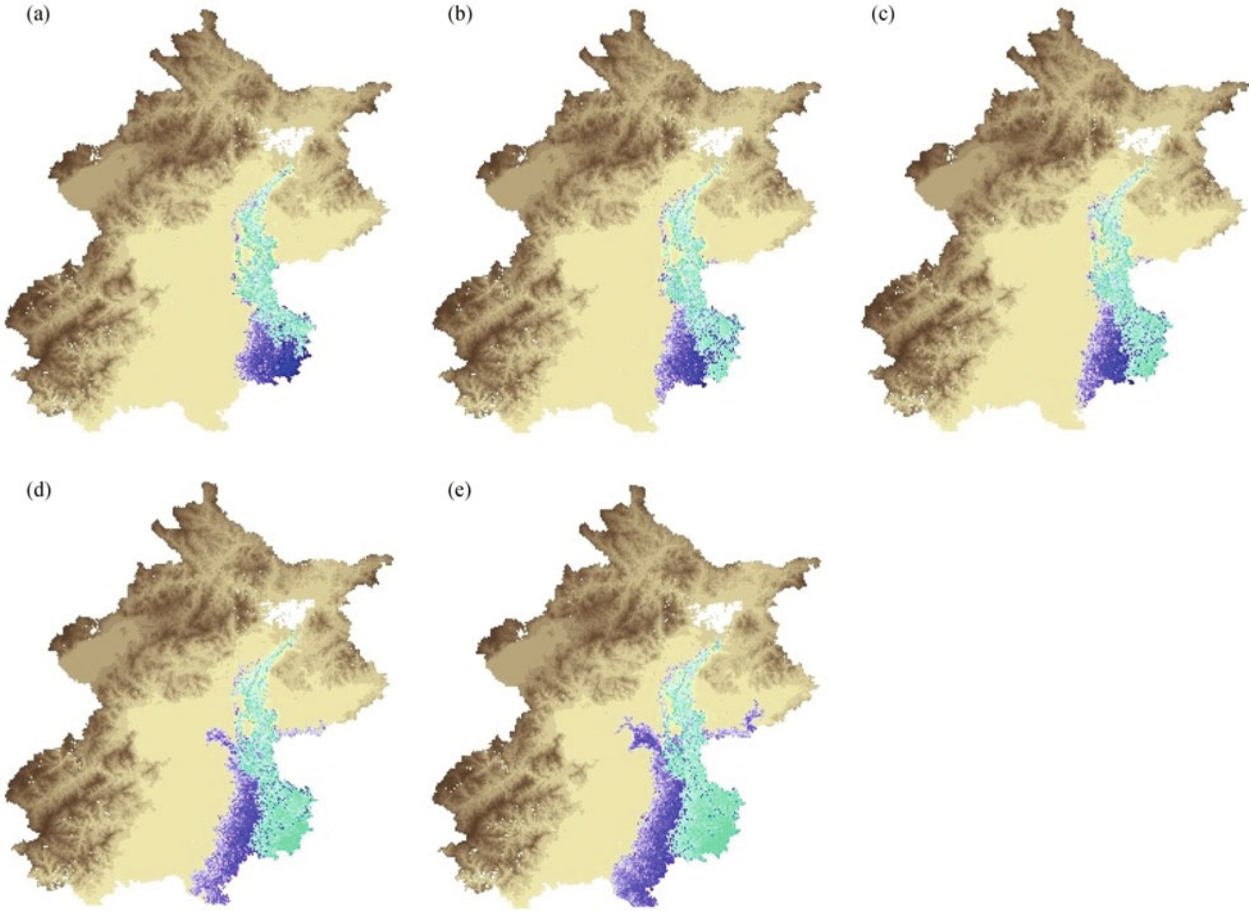

Fig. 4 Flood extent of the five floods: (a) 20-year; (b) 50-year; (c) 100-year; (d) 1000-year; (e) 10000-year (Green–flooded in both 1996 and 2004; Blue–flooded in 2004)

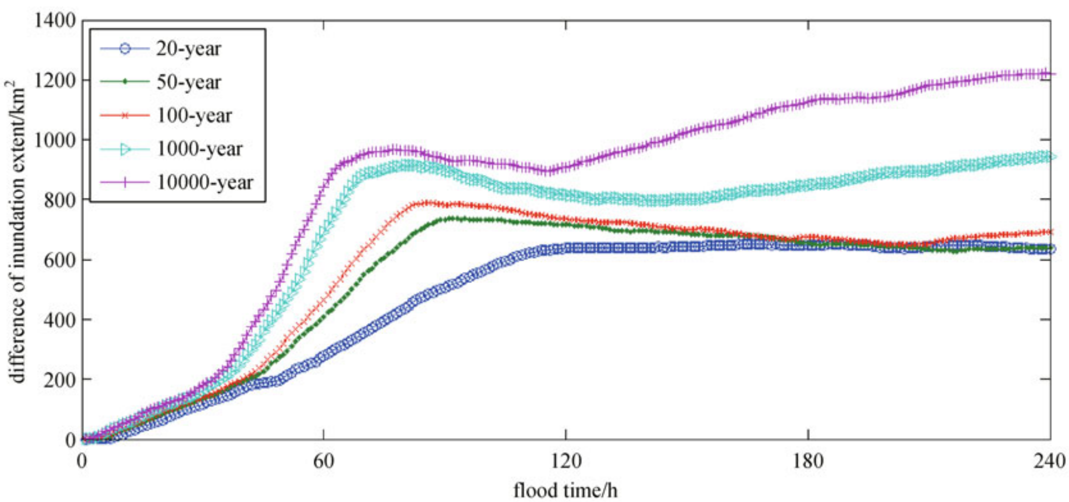

Fig. 5 Inundation extent differences of the five floods between 1996 and 2004 along flooding time

6 Conclusions

Effects of LUCC on the floods in Beijing were evaluated using a combination of land use data analysis, hydraulic modeling and statistical methods. The LUCC effect on the floods with various return periods were identified and quantified for the time period from 1996 to 2004.

We summarize our conclusions as follows;

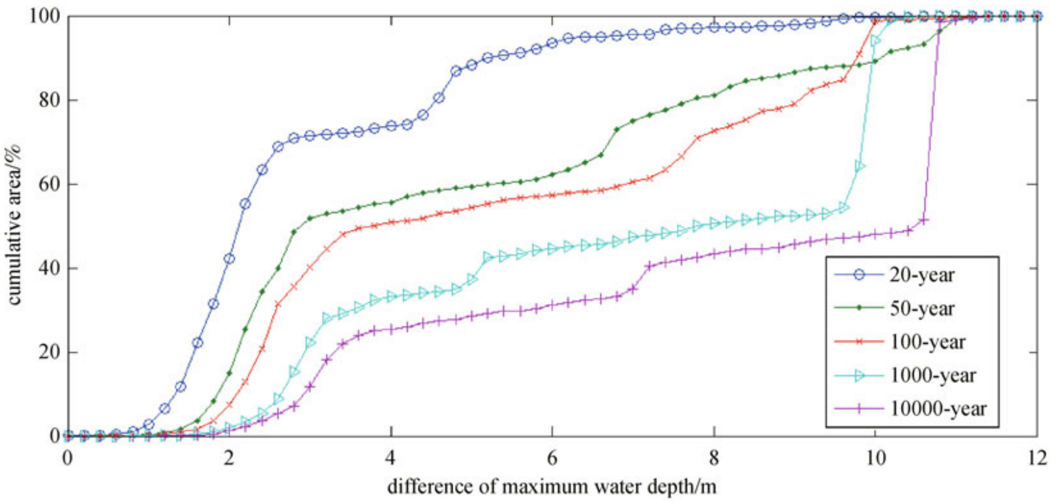

Fig. 6 Cumulative areal distribution of the difference of maximum water depth at grid cells between 1996 and 2004

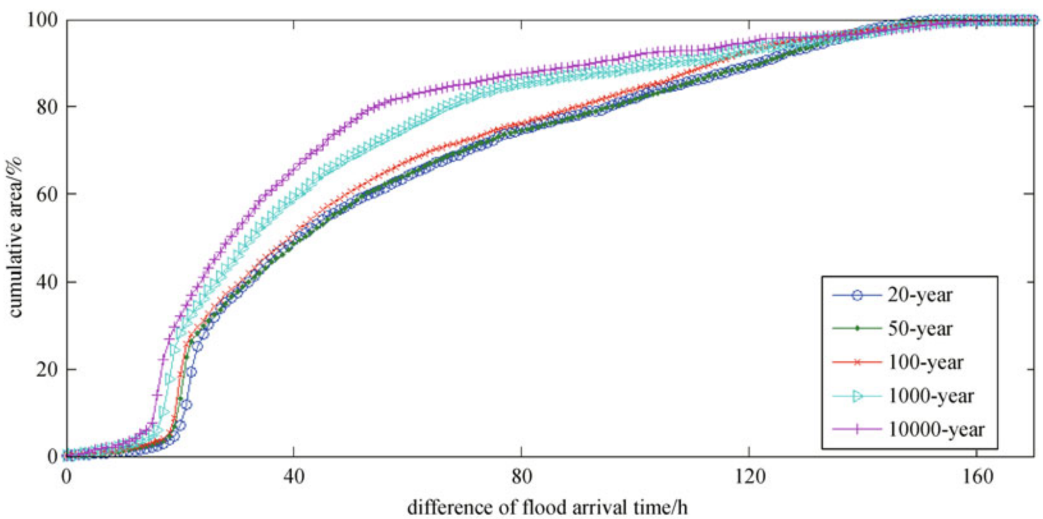

Fig. 7 Cumulative areal distribution of the difference of flood arrival time of the five floods between 1996 and 2004

1) Land use/cover experienced major change during the period from 1996 to 2004, i.e. 1053 km^2 of cultivated land was transferred to forest (327.55 km^2), heavy brush (191.77 km^2) and urban land use (533.71 km^2) during the period of analysis. Among these changes, urbanization is the most significant. Beijing has never in its history experienced such LUCC.

2) This LUCC affected inundation extent and flood arrival time, and floods with longer return periods were more significantly influenced.

3) This LUCC affected maximum water depth, but floods with shorter return periods were more influenced.

LUCC is considered to have a negative effect on flood security in Beijing. It generates larger inundation extents, deeper maximum water depths and shorter flood arrival times. LUCC can thus be considered a major flood security stressor for Beijing. During recent decades almost all cities in China have expanded rapidly in association with fast economic growth. This study warns that these cities are facing more dangerous floods than those experienced previously. Importantly, the actual land use patterns across all of China should be assessed, and joint management of land use and flood security should be enforced in urban and peri-urban areas. This study provides an example of integrating digital LUCC analysis, hydraulic modeling and statistical methods to understand the potential effect of LUCC on flood security. It can be widely applied to a variety of LUCC areas, where time-sequenced digital land use/cover is available, to predict hydrological consequences of LUCC.

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