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Evaluation of the effect of land use/cover change on flood characteristics using an integrated approach coupling land and flood analysis

Xiaoliu Yang, Huili Chen, Yueling Wang and Chong-Yu Xu

ABSTRACT

Land use/cover change (LUCC) is one of the crucial factors influencing the hydrological process, thus the flood characteristics in time and space. Therefore the evaluation of the change of flood characteristics implies an integrated analysis of LUCC and hydraulic simulation. In this study, the effect of LUCC on flood is examined based on an approach composed of three parts: (1) reproduction of spatially explicit LUCC; (2) application of a 2D hydraulic modelling for flood simulation; (3) demonstration of results for Beijing. The approach is applied to a flood-prone area in Beijing. The results show that 8% and 21% of the study area experienced LUCC during 1991–2001 and 2001–2011, respectively, and these changes greatly influenced the characteristics of the 20-year flood, i.e.: (1) the flood zone is doubled during 1991–2001 and about four-fold during 2001–2011; (2) the water depth is increased for most of the study area; and (3) the flow velocity becomes faster. It indicates that flooding still exists within Beijing and is even more dangerous than 40 years ago and suggests that actual land use pattern and existing flood protection works should be re-evaluated regarding the flood characteristics change due to LUCC.

Key words | 2D hydraulic model, Beijing, flood characteristics, land use/cover change

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INTRODUCTION

The temporal and spatial pattern of floods is attributed to several factors of global change. The relentless land use/cover change (LUCC) can affect flood propagation (Di Baldassarre *et al.* 2009), flood volume (Miller *et al.* 2014), flood frequency (Brath *et al.* 2006; Chu *et al.* 2013), flood peak (Deasy *et al.* 2014), streamflow regime (Priess *et al.* 2011; Niehoff *et al.* 2002; Dixon & Earls 2012), etc. It therefore poses challenges to the existing flood emergency and disaster management and planning efforts. Undoubtedly, an effective planning and implementation of flood disaster management and mitigation system requires and can benefit from a greater understanding of the effect of LUCC. However, determining the relationship between flood and LUCC is not an easy task. Detecting the effects of changing land use/cover on flood characteristics can be complicated by collection and interpretation of LUCC over a sufficiently long time period, selection and implementation of a suitable flood analytical tool at basin level and the linkage between the above two.

Recent development of 2D hydraulic modelling at large scale basins (e.g., Di Baldassarre *et al.* 2009; Andreadis & Schumann 2014) catalyses this study. The scientific literature addresses the exercise of applying 2D hydraulic models for large river basins to help in formulating flood mitigation strategies (Castellarin *et al.* 2011), identifying wetlands' effects on flooding (Javaheri & Babbar-Sebens 2014), assessing extreme weather event changes (Chau *et al.* 2013) and mapping flood

doi: 10.2166/nh.2016.108

risk (Suriya & Mudgal 2012). These works were boosted by the technical progress made for topographical survey, for increasing availability of geographic information system (GIS) tools, and for growing computational capabilities of personal computers. These techniques can provide sufficiently high planimetric resolution data and can be effectively exploited in hydraulic analyses for describing flood-prone river basins (see, e.g., Castellarin *et al.* 2009; Koora *et al.* 2014; Andreadis & Schumann 2014; Schellekens *et al.* 2014).

Most of China's cities have greatly expanded during the last decades and this increasing trend is foreseen for the future. In the areas of these cities, major changes have been observed in the land-intensive sectors like housing, road building, as well as crop production, grazing, forestry and mining. Simultaneously, more disastrous urban floods have also been observed in these cities in recent years, for example, the floods in June 2011 and July 2012 in Beijing in northern China, that in May 2010 in Guangzhou city in southern China, and that in July 2010 in Anqing city in eastern China. There is no doubt that LUCC has altered the flooding characteristics in these cities, but due to the complexity of the processes involved, the magnitude of their effect on flood characteristics and the spatial and temporal variation of these effects are still highly uncertain. This paper is a follow-up to the earlier work of the authors (Wang & Yang 2013) who have examined the effect of land use change on floods with various frequencies and pointed out that a 20-year flood can be affected the most. This is why the paper especially focuses on such a flood.

The work presented in this paper focuses on three main questions, always accounting for the cross-cutting issues between land and water sciences:

1. Which kind of land use changes have been observed in the past, and what was their spatial distribution in the landscape?
2. Which flood characteristics (e.g., flood zone, water depth and flow velocity) were affected by LUCC and how can they be quantified?
3. What is the related significance for urban development and flood protection?

We demonstrate the advantages of a coupling approach representing land and water in a common framework to study LUCC consequences to floods. Furthermore, we discuss new insights about urban development generated from this coupled analysis. The investigation does not address the influences of infiltration and hydraulic infrastructures.

STUDY AREA AND MATERIAL

Beijing, the capital of the People's Republic of China, is governed as a direct-controlled municipality under the national government with 16 urban, suburban and rural districts. It is located in northern China, covers a total area of 16,807.8 km^2 and had a total population of 21.5 million in 2013 (BMBS 2015). Several major rivers, including the Chaobai, Yongding, Juma and Wenyu flow through Beijing. The Chaobai River, flowing through northern and eastern Beijing, is 467 km long and covers a basin area of 19,545 km^2, of which 83.4 km and 5,613 km^2 are in Beijing (BMBWR 1999). Our study area is situated downstream of the Zhangjiafen hydrological station and inside of the above-mentioned 5,613 km^2, as shown in Figure 1. Precipitation over the Chaobai River basin during 1961–2000 averaged around 418 mm annually, with close to two-thirds of that total falling from June to October (Zhang & Wang 2010). The upstream valley of the Chaobai River is narrow and deep and therefore poses a high flood risk to Beijing. Connected with the upstream valley, northern and eastern Beijing are situated in an open floodplain for the most part covered by urbanized area, water surface, bare land, grassland, cultivated land, heavy brush and forestry. Their spatial and temporal distribution and combination affect flood characteristics.

Historically available hydrological data are constituted by hourly discharges that have been observed for 55 years in the Zhangjiafen station (see Figure 1) in the northwest of Beijing. A 20-year flood is reproduced using the hydrological series by Gao (2011). The hydrograph, given in Figure 2, is used as the input to the 2D hydraulic model to be presented in the following section.

METHODS AND MODELS

Land use and flood analysis are connected by means of the generation of grid cells, determination of altitude, interpretation of land use/cover information and assignment of Manning's roughness coefficients. On such a basis, the

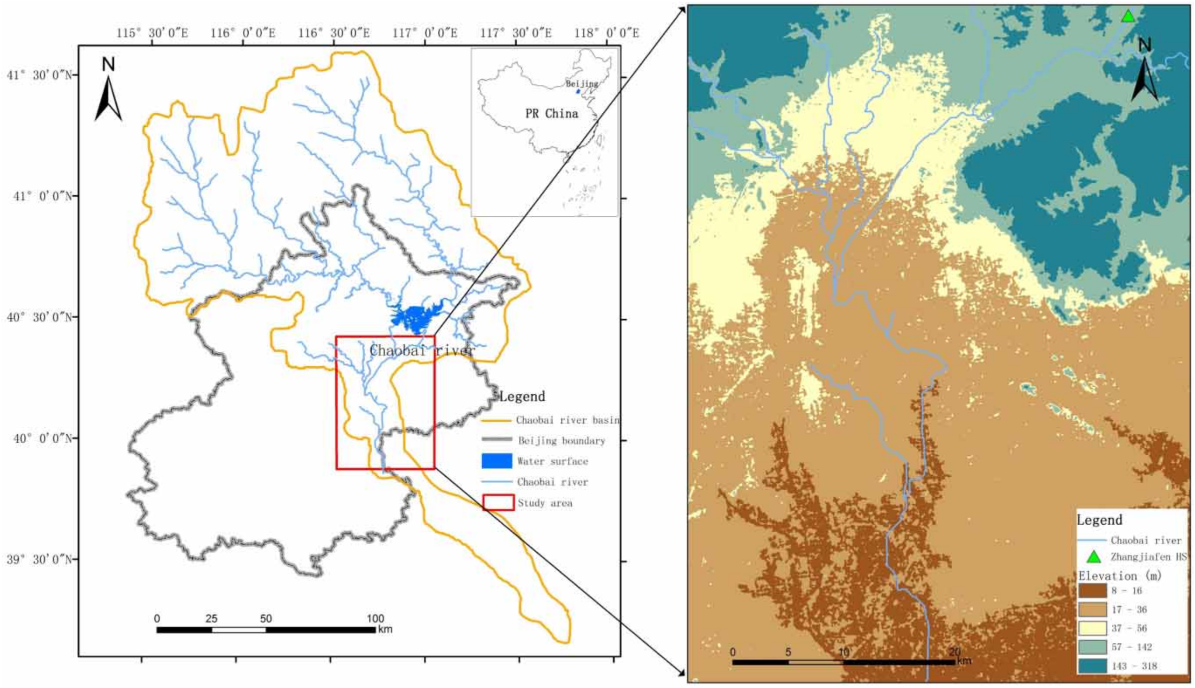

Figure 1 | Beijing, the Chaobai River and the study area.

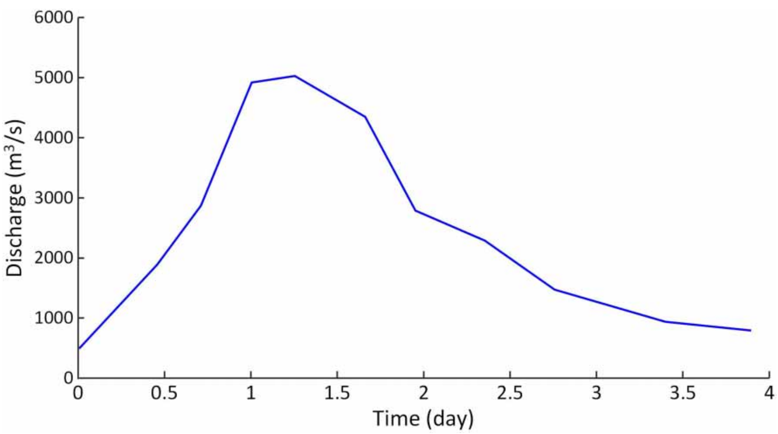

Figure 2 | The hydrograph of a 20-year flood reproduced by Gao (2011).

propagation of flood over the study area is simulated by a 2D hydraulic model to enable the provision of flood characteristics, i.e., flood zone, water depth and flow velocity.

Determination of time scale

There are two considerations related to setting the time span of the analysis of LUCC and flood characteristics: (a) what time span is reasonable both for LUCC and flood characteristics' analysis and (b) whether remote sensing data are available. In order to compare results, the time periods should be chosen regarding specific stages of LUCC. For this reason three analytical years are especially focused on in this study, namely, 1991, 2001 and 2011. The two decades between 1991 and 2011 are recognized as the period when most of China's cities experienced ever increasing LUCC in association with economic boom. Additionally, the remote sensing data are available and have identical accuracy for these analytical years.

Grid cell generation and determination of altitude and land use/cover

The remote sensing images at 30 × 30 m pixels are the multiple band TM images at 1:50,000 scale and are available at Geospatial Data Cloud (http://www.gscloud.cn/). Correspondingly, the study area was described with a uniform grid containing 6,654 × 9,038 grid cells. The altitude at the central place of a grid cell is taken to represent the grid cell's altitude. From the same data source, the altitude data of ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model) were downloaded and used for defining grid cell slope. The produced altitude for each grid cell is shown in Figure 1. It is found that the slopes of the study area are gentle. In fact, 70% of the contributing area has a slope comprising between 1 and 3%. In order to get land use/cover information for each grid cell, the multiple band TM images were processed with Environment for Visualizing Images software at grid cell basis and a geometric adjustment to the images of 1991 and 2001 was made referring to the images of 2011 with the binary quadratic polynomial method, and the nearest neighbour method was applied for resampling. The processing was accepted if the verification shows that the adjustment error is less than half a pixel. Based on the accepted images, the land use/cover was interpreted for each grid cell by the supervised classification method and maximum likelihood classification method. The Normalized Difference Vegetation Index was adopted for classifying vegetation.

Hydraulic model

The 2D hydraulic model used has been developed for solving shallow flow hydrodynamic problems of complex flood flows. The reader is referred to Pan *et al.* (2006), Liang *et al.* (2007), Zhang *et al.* (2007), Gallegos *et al.* (2009), Liang *et al.* (2010), Wang *et al.* (2011), Wang & Yang (2013) and Hou *et al.* (2015), among others, for a comprehensive description of the modelling techniques and numerical methods used. In this model the well-balanced fully 2D shallow water equations have been solved by using a finite volume Godunov-type scheme (Liang & Marche 2009; Liang *et al.* 2010). The HLLC Riemann solver is adopted to solve the interface fluxes. The second-order accuracy is achieved by using Runge–Kutta time integration method and the MUSCL slope limiter in space. A non-negative water depth reconstruction approach is implemented to deal with the wetting and drying interfaces, incorporated with a local bed elevation modification method. A limited implicit scheme is implemented to discretize the friction source term to avoid spurious oscillation. For the explicit numerical scheme, the Courant–Friedrichs–Lewy criterion is adopted to limit the time step in order to maintain the computational stability. A local boundary modification method is applied to deal with the non-aligned domain boundary or the obstacles and structures in the computational domain. A more detailed description of the numerical scheme can be found in Wang *et al.* (2011).

This numerical model has been validated against several benchmark cases and real cases (Wang *et al.* 2011). The numerical model has presented accurate simulation of the tidal wave over the complex bed topography. Hydraulic jump corresponds closely to the theoretical solution, in which the velocity field is also predicted accurately. The numerical model is found to be able to correctly simulate the different flow regimes, e.g., transcritical flow and shock-like flow, and accurately capture the wet–dry interfaces over the complex bed topography. The reflection, interaction and transaction of the shock wave have been accurately reproduced in the applications. The numerical scheme is proved to be second-order accurately based on an analytical solution. The fully 2D shallow flow model has been verified to be a reliable numerical tool for the flooding simulation of different flow regimes over complex domain topography (Toro 2001; Marche *et al.* 2007; Liang & Borthwick 2009; Kesserwani & Liang 2010; Singh *et al.* 2011; Hou *et al.* 2013). Following the flood paths, from each grid cell to the basin outlet, the water depth and flow velocity over each grid cell can be identified with the above model and the flood zone is computed, for which all the boundaries among grid cells are set to be transmissive.

Determination of Manning's roughness coefficient

In order to apply the hydraulic model, energy or continuity and momentum equations should be solved numerically for the calculated area. This solution process requires Manning's roughness coefficients which are decided upon land use types. These empirical roughness coefficients are a vital determinant of connecting land and flood analysis. The coefficients were drawn from the available literature (Liu *et al.* 1998; Guo *et al.* 2010) and are summarized in Table 1. It is seen that these coefficients range from 0.016 to 0.15 with a difference of more than eight times with the greatest for forest and the smallest for urban area. Each grid cell was assigned a Manning's roughness coefficient dependent on its land use/cover type.

RESULTS AND DISCUSSION

LUCC

During the last decades, considerable LUCC has occurred all over China. In general, the cultivated land and forest, which characterized most areas around cities, decreased due to increasing urbanization and deforestation. A similar behaviour occurred in the study area. In order to investigate the land use change that occurred in the Chaobai River basin, historical land use maps for the analytical years were produced for the study area, which are comparable since they were derived by means of photo interpretation of remote sensing images carried out with same procedure as described in the previous section. As some of the 16 original land use/cover types adopted by land use analysts possess similar hydraulic features, such as roughness to water flow, they were merged into seven major types for hydraulic analysis, namely, urbanized area, bare land, water surface, grassland, cultivated land, heavy brush and forest. The land use/cover derived for each grid cell for the three analytical years of 1991, 2001 and 2011 are shown in Figure 3.

Table 2 shows that the urbanized area increased by 71 km^2 during 1991–2001 and by 119 km^2 during 2001–2011; heavy brush and bare land, respectively, increased by 61 km^2 and 52 km^2 during 2001–2011; however, grassland decreased by 57 km^2 from 1991 to 2001 and cultivated land and forest were sharply reduced by 128 km^2 and 117 km^2 from 2001 to 2011. The area where LUCC reached 191 km^2 and 490 km^2 during 1991–2001 and 2001–2011, accounting for 8% and 21% of the total study area, respectively.

The relative change of land use/cover is given by the bar diagram in Figure 4. The height of each bar segment is proportional to the relative areal extent of a given land use type so that the heights of the different types sum to 100%. The obvious increase in urbanized area as well as decrease in cultivated land and forest can be seen in Figure 4.

Based on the analysis of land use maps prepared and the changes shown in Table 2 and Figure 4, the following observations are made:

- The urbanized area, heavy brush, bare land and water surface had been continuously increasing during the 20 years (see Figure 4). Moreover, the urbanized area increased from 23.2% of the total study area in 1991 to 26.2% in 2001 and then to 31.3% in 2011, as did the heavy brush area from 6.9% in 1991 to 7.5% in 2001 and then to 10.1% in 2011. The increasing trend was accelerated during the second decade and the urbanized area and heavy brush, respectively, increased 8% and 3% during the 20 years.
- The changes in forest and cultivated land were in the opposite direction (see Figure 4). The forest area in the study area was reduced from 30.3% in 1991 to 29.8% in 2001 and then to 24.8% in 2011 and the cultivated area went down from 32.3% in 1991 to 31.4% in 2001 and

Table 1 | Manning's roughness coefficients corresponding to land use/cover (summarized from Guo *et al.* (2010) and Liu *et al.* (1998))

Land use/cover	Manning's roughness coefficient
Urban land (incl. rural road, town land, rural residence and mining land, highway)	0.016
Bare land (incl. saline alkali land, swamp, sand land, bare rock, construction site and threshing ground)	0.025
Water surface (incl. river, lake, reservoir, aquaculture)	0.027
Grassland (incl. reed and mudflat)	0.030
Cultivated land (incl. pasture, irrigation and water conservancy works, ridge, confined feeding operations and green house)	0.035
Heavy brush	0.075
Forest	0.150

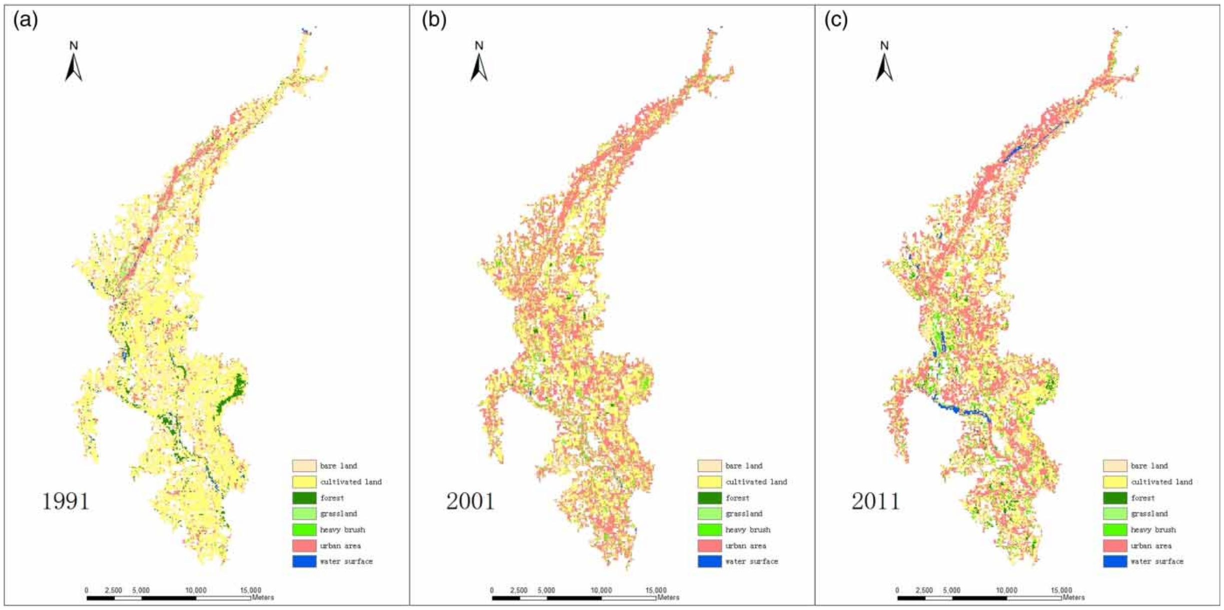

Figure 3 | Land use/cover maps of 1991, 2001 and 2011.

Table 2 | LUCC (in km^2)

	Analytical year		
Types of land use/cover	**1991**	**2001**	**2011**
Urban area	2,885	3,085	3,514
Bare land	1,252	1,575	1,691
Water surface	181	142	186
Grassland	2,064	1,436	1,449
Cultivated land	3,060	3,114	2,820
Heavy brush	2,738	3,354	3,039
Forest	7,174	6,648	6,655

then to 25.9% in 2011. The decreasing trend was maintained during the 20 years.

Flood zone mapping and comparative area

Application of the LUCC-based 2D hydraulic modelling provides the capability to simulate flood zone over a basin (e.g., Wang & Yang 2013). Flood zone maps were created and are shown in Figure 5 to denote the area inundated by the 20-year flood under the different land use/cover conditions of 1991, 2001 and 2011. From Figure 5, it is observed that the inundated area is expanded from 281 km^2 for the land use/cover condition of 1991 to 612 km^2 for 2001 and then to 1,070 km^2 for 2011, increasing by 2.2 times for 2001 and by 3.8 times for 2011. In addition, it is found that the 281 km^2 for 1991 are also inundated for 2001 and 2011. For comparison, this area (hereafter refer to as 'comparative area') is especially focused on in the following analysis.

Water depth mapping

The water depth can also be calculated for each grid cell using the approach, and the water depths averaged in each grid cell over the comparative area for the three analytical years are mapped in Figure 6. It is observed that water depth gets deeper and deeper during the 20 years and the grid cells in and adjacent to the river channels and urbanized areas are characterized as high water depth.

Statistics of water depth, as shown in Figure 7, were done by considering four ranges of water depth, i.e., [0, 2 m], [2 m, 4 m], [4 m, 6 m] and higher than 6 m (*X*-axis) versus the ratio of the grid cell number within a range to the total grid cell number (*Y*-axis).

Figure 7 shows that 84% of the grid cells are in a water depth lower than 2 m for the land use condition of 1991 and this percentage fell sharply to 35% for 2001 and then to 10% for 2011; 14% of the cells are in a depth between 2 and 4 m

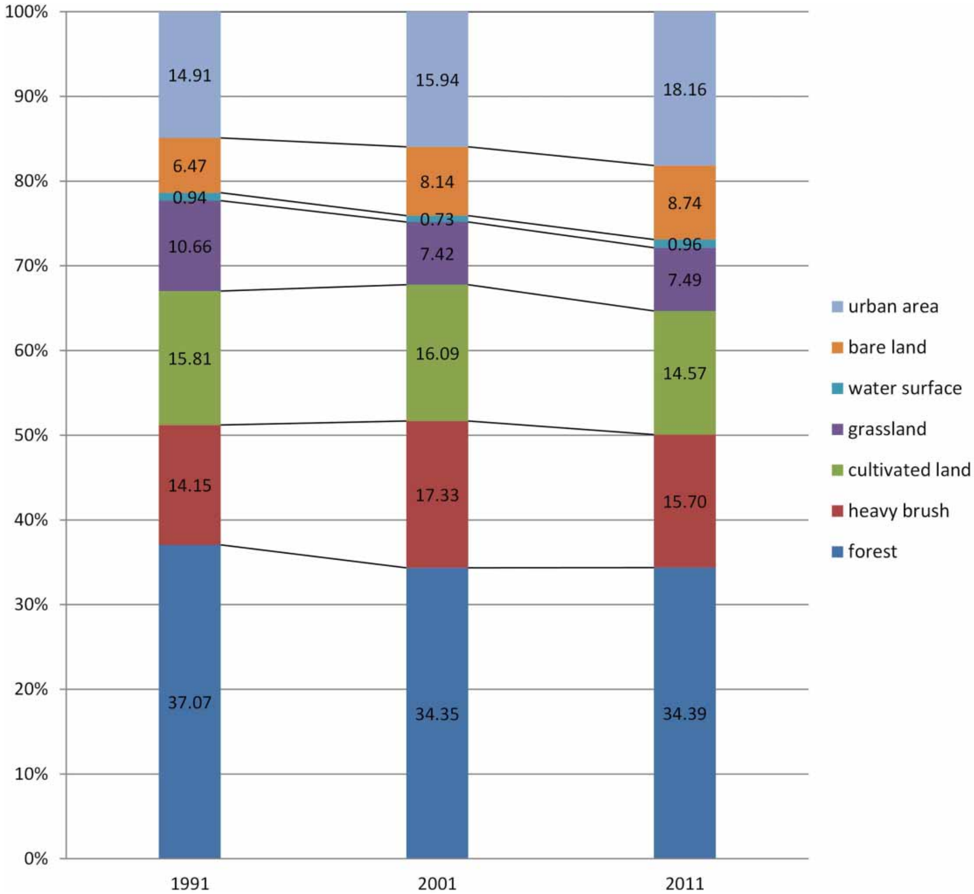

Figure 4 | Relative change of land use/cover in analytical years.

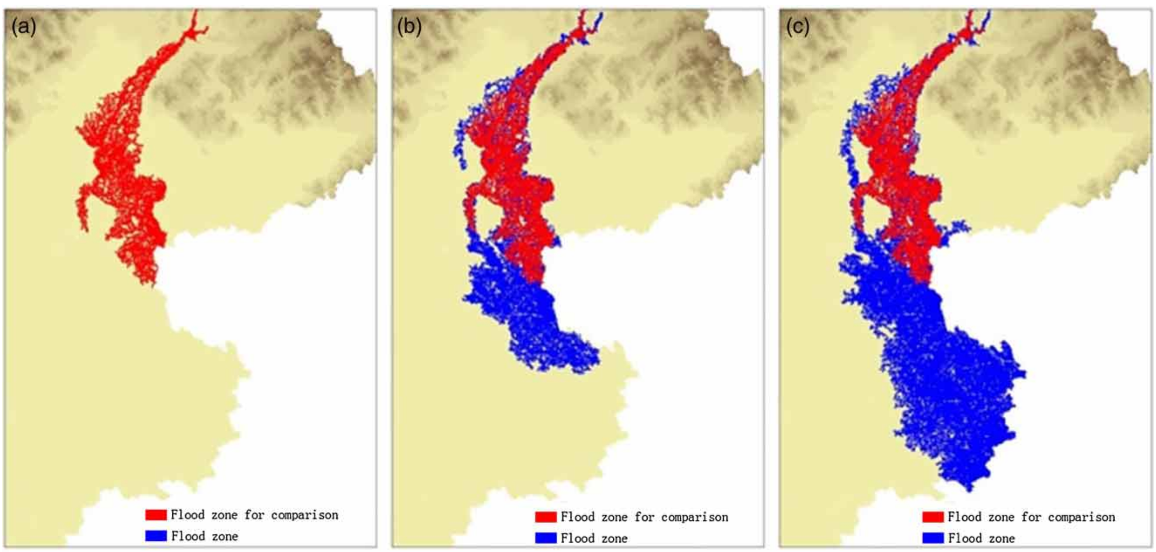

Figure 5 | Flood zone maps for (a) 1991, (b) 2001 and (c) 2011 and the comparative area.

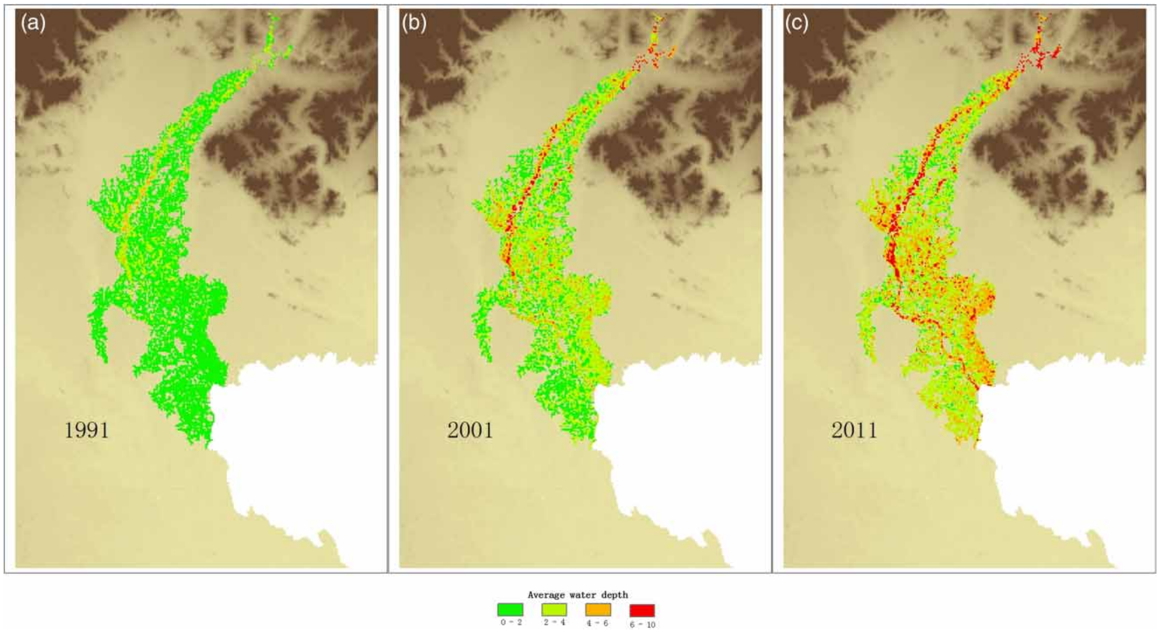

Figure 6 | Water depth maps for (a) 1991, (b) 2001 and (c) 2011.

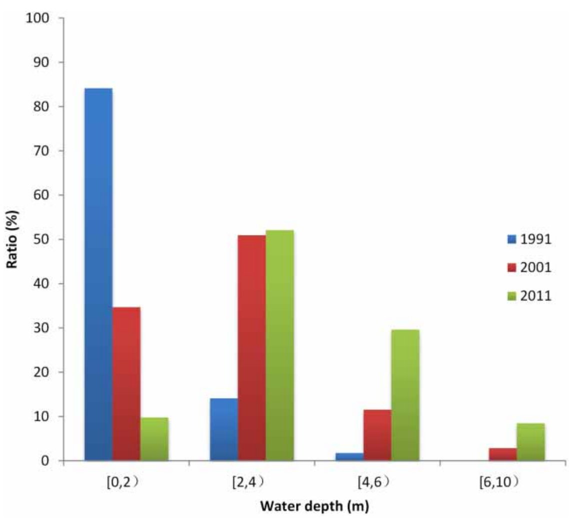

Figure 7 | Statistics of water depths for the three analytical years.

for 1991 and this figure rises significantly to more than 50% for 2001 and 2011; the cells in a depth within 4 and 6 m went up from 2% for 1991 to 12% for 2001 and then to 30% for 2011; the cells in a depth higher than 6 m increased to 3% for 2001 and then to 9% for 2011, up from zero for 1991. The results show an obvious increasing trend of water depth due to LUCC.

Flood velocity mapping

By using the above approach, flood velocity was calculated for each grid cell and the maps of the velocity averaged in time were created. Figure 8 presents maps for the area illustrating how the velocity becomes changed under the land use conditions of 1991, 2001 and 2011. As is seen in Figure 8, by the change of land use pattern during the 20 years, the velocity changes considerably in both magnitude and space.

Figure 9 displays the distribution of velocity for 1991, 2001 and 2011 within three ranges of velocity: [0, 1.5 m/s], (1.5 m/s, 3 m/s] and more than 3 m/s (X-axis) versus the ratio of the grid cell number in a range to the total grid cell number (Y-axis). It indicates that 67% of cells' average velocity is less than 1.5 m/s for the land use condition of 1991, but that percentage sharply decreased to 47% for 2001 and then to 38% for 2011; while the cells with the velocity ranging between 1.5 and 3 m/s went up from 32% for 1991 to 49% for 2001 and then to 56% for 2011. It indicates that floods moved faster and faster during the 20 years. With reference to Figure 5, it can be found that the urbanized area and water surface are at high velocity, but the areas of the other land use types are at lower velocity. The urbanized areas and water surface are smoother than the land surfaces covered by the

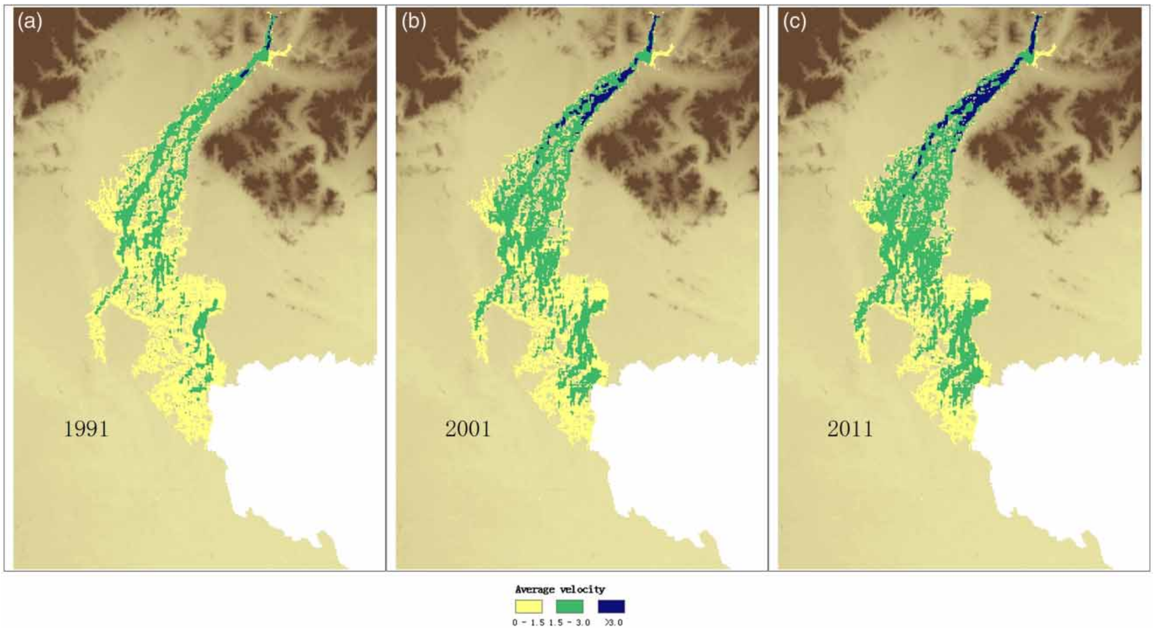

Figure 8 | Flow velocity maps for (a) 1991, (b) 2001 and (c) 2011.

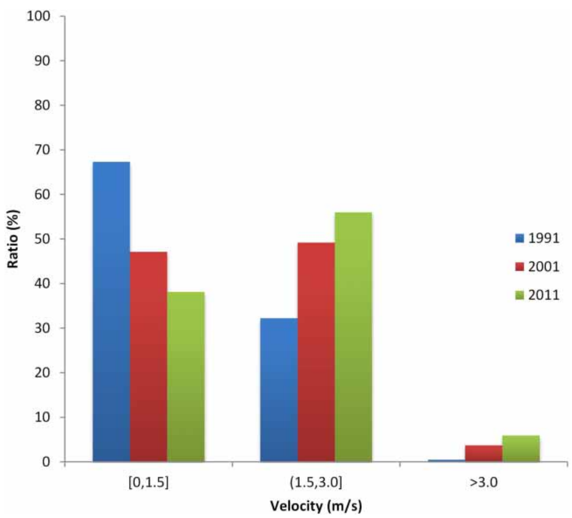

Figure 9 | Statistics of flow velocity for the three analytical years.

vegetation like forest, heavy brush, grass and crop which increase the ground roughness, thus the velocity is higher.

CONCLUSIONS

This study evaluated the land use/change and its effect on flood characteristics in Beijing based on an integrated approach composed of LUCC mapping and application of a 2D hydraulic modelling for flood simulation. The study was conducted for a flood-prone area in Beijing based on the reproduced historical land use maps of 1991, 2001 and 2011. The following is concluded:

- The proposed approach provides an efficient tool for mapping land use/change and evaluating its effect on city flood inundation. With the approach of integrating land use analysis and hydraulic modelling, the effect was quantified and maps of flood zone, water depth and flow velocity were produced for various land use patterns. These maps could be helpful in preparing appropriate urban and rural development planning. It is believed that the approach proposed in this study provides a useful reference for similar studies to be conducted in other regions of the world.
- The remote sensing data and GIS provide more opportunities to detail flood characteristics and allow people to understand more about a flood in space and time. This study highlights the importance of a close collaboration between land and water professionals.
- In the case of Beijing, due to the LUCC during 20 years from 1991 and 2011 and corresponding to a 20-year flood, the inundated area is expanded from 281 km^2 for

1991 to 612 km^2 for 2001 and further to 1,070 km^2 for 2011. In the comparative area, 16% of it was in a water depth higher than 2 m for 1991 and this percentage significantly increased to 65% for 2001 and then went up to 90% for 2011; 33% of it suffered from a flood velocity greater than 1.5 m/s for 1991, this percentage increased to 53% for 2001 and then went up to 62% for 2011. The results from this study provide further evidence that the change of land use pattern, i.e., transition of less impervious land use type to an impervious one, can adversely affect flood peak and flood propagation, leading to a larger flood zone, higher water depth and greater flash response.
- The study suggests that the land use pattern and flood protection works should be re-evaluated regarding the change in flood characteristics due to LUCC and their trade-offs should be identified and predicted while planning for urban development.

ACKNOWLEDGEMENTS

This work has been supported by the National Major Science and Technology Program for Water Pollution Control and Management (Grant No. 2014ZX07203008) and Natural Science Foundation of China (Grant No. 41171405). The authors also thank the reviewers for their valuable suggestions.

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First received 14 May 2015; accepted in revised form 11 December 2015. Available online 11 February 2016