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SPECIAL ISSUE: HYDROLOGICAL CHANGE IN CHINESE RIVERS

Studies on changes in extreme flood peaks resulting from land-use changes need to consider roughness variations

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ABSTRACT
The impacts of changes in forest coverage on extreme floods have drawn much attention globally. This study quantifies the sensitivity of flood peaks to forest coverage and roughness changes. With this objective, a framework is first introduced that includes a variance-based sensitivity analysis approach and a water and energy budget-based distributed hydrological model with a vegetation module. The influence of forest coverage changes is simulated by altering land-use types that are based on physical parameters. A variance decomposition approach is used to quantify the contribution of influential factors, i.e. event size, forest coverage and roughness changes, to extreme flood peak variations. The results in a medium-sized river basin show forest coverage changes have little influence: variations in canopy interception, ground surface water retention, soil moisture and groundwater table resulting from changing forest coverage did not alter flood peaks considerably. In contrast, it is found that flood peaks are more sensitive to roughness variations.

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Introduction

Extreme floods could cause huge casualties and economic losses (Perron *et al.* 2016, Wells *et al.* 2016, Zhou *et al.* 2016, Qi *et al.* 2016b, 2018c, Blöschl *et al.* 2017, Qi 2017, Song *et al.* 2017, Qi and Liu 2018). There are many factors that can influence the regimes of extreme floods and their consequences, for example, climate change, human activities and forest coverage changes (Yang *et al.* 2016, Qi *et al.* 2016c). The influence of forest coverage changes is addressed in this study.

The impacts of forest coverage changes on extreme floods have long been recognized as very complex processes. There are several key issues that have been identified, for example, changes in canopy interception, ground surface water detention, soil moisture, groundwater table, runoff routing velocity (Jones 2000, Ouellet *et al.* 2012, Rogger *et al.* 2017, Song *et al.* 2017). When forest coverage varies, rainfall interception capacity could change, and therefore the volume of rainfall holding on the canopy changes. These changes could alter the timing of rainfall reaching ground. The altered rainfall volume reaching ground could later influence soil moisture and therefore change generations of surface runoff and subsurface runoff (Brown *et al.* 2005, O'Connell *et al.* 2007, Wahren *et al.* 2012, Rogger *et al.* 2017). Changes in forest coverage may also alter ground surface water retention capacity: decreasing forest coverage may leave more rainfall running off directly (Fazio 2012). The roughness influencing routing may become smaller when forest coverage decreases (Bathurst *et al.* 2011). When roughness decreases, routing velocity increases, and therefore more discharges can reach outlets of river basins at the same time, which could increase magnitude of flood peaks.

Influence of forest coverage changes on extreme floods is compound results of all the changes in canopy interception, ground surface water detention, antecedent soil moisture, groundwater table and runoff routing velocity on a river basin scale. Forest coverage change impacts on extreme floods are much more complex on medium sized (>1000 km^2)/large river basin (>10 000 km^2) scales than on plot or small river basin scales (<1000 km^2) (Rogger *et al.* 2017). Therefore, in medium-sized /large river basins, the understanding on the impacts of forest coverage changes on extreme floods and on the flood generation mechanism controlled by vegetation is not as good as on plot/ small river basins (Rogger *et al.* 2017). More studies are needed to conduct the research on the influence of forest coverage changes on extreme floods on medium sized/large river basins.

Because there is less experimental data in the entire area of medium sized/large river basins than in small river basins, modelling approaches are commonly implemented to conduct the research (Eisenbies *et al.* 2007, O'Connell *et al.* 2007, Kuraś *et al.* 2012, Rogger *et al.* 2017). For example, Crooks and Davies (2001) used a semi-distributed hydrological model to investigate changes of extreme floods in Thames catchment (10 000 km^2); De Roo *et al.* (2003) implemented a distributed hydrological model to investigate influence of land cover changes on floods in a river basin with catchment size being 60 000 km^2; Zhou *et al.* (2010) used a water balance calculation approach based on Penman-Monteith equation to investigate the influence of forest coverage changes on water yield in a region in a South China province (179 752 km^2).

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However, these models used do not have physical meaning, and it is difficult to assign physically based parameters, such as canopy interception, ground retention and evapotranspiration, to distinguish different land-use types.

Physically based models can be used to conduct the research on the impacts of forest coverage changes on extreme floods, such as the Liuxihe model (Chen *et al.* 2011) and the Geomorphology-Based Hydrological Model (GBHM) (Yang *et al.* 1997). Matheussen *et al.* (2000) implemented the variable infiltration capacity (VIC) model, which has physically based parameters for different land-use types, to study hydrological impacts of changing land cover; Saurral *et al.* (2008) also used the VIC model to investigate streamflow changes when converting a region area into different land-use types; Hurkmans *et al.* (2009) used a improved VIC model to investigate the impacts of changing land use on extreme floods; Kuraś *et al.* (2012) used the distributed hydrology soil–vegetation model to study forest harvesting effects on peak flows in a snow-dominated catchment. Although these prior studies used a physically based model, which facilitates the investigations of impacts of land-use changes on discharges, the influence of routing parameter variations resulting from land-use changes on extreme floods is not considered. With the changes of forest coverage, the roughness of river routing may vary (Jones and Grant 1996, 2001, Tonina *et al.* 2008, Kuraś *et al.* 2012). As pointed out by Zaitchik *et al.* (2010), discharge routing parameters have large impacts on discharges, and therefore it is very necessary to incorporate routing parameter influence when investigating impacts of forest coverage changes on extreme floods (Maske and Processes 2014, Zhang *et al.* 2016, Gao *et al.* 2017). However, only few studies have investigated the impacts of changing roughness, for example, Bathurst *et al.* (2011) used a surface runoff resistance coefficient to represent the influence. Although the study by Bathurst *et al.* (2011) considered the changes, the direct impacts of forest coverage changes, i.e. canopy interception, ground surface water detention, etc., are not quantitatively compared with impacts of roughness changes.

The overall objective of this study is to investigate the impacts of forest coverage changes on extreme flood peaks considering influence of roughness variations. For this purpose, a framework is introduced first which includes a water and energy budget-based distributed hydrological model with a vegetation module (V-WEB-DHM) and a variance-based sensitivity analysis approach (analysis of variance; ANOVA) (Bosshard *et al.* 2013). The V-WEB-DHM includes a biosphere hydrological model (Wang *et al.* 2009a, 2009b, 2009c) and a vegetation module (Qi *et al.* 2019). The biosphere hydrological model couples a land surface model (Simple Biosphere model 2; SiB2) with GBHM (Yang 1998), and used physically based morphological properties for each of the SiB2 land-use types (Sellers *et al.* 1996a, 1996b, Wang *et al.* 2009a, 2009b, 2009c). In the biosphere hydrological model, a kinematic wave approach is used to route discharges, which facilitates the study on the influence of roughness changes. In the framework, the respective influence of extreme flood event size, forest coverage changes, roughness changes and their combined effects can be explicitly quantified using ANOVA. The results can provide unique insights into the influence of forest coverage changes on extreme flood peaks and could be beneficial for flood management.

Study region and materials

The Biliu basin and datasets

Northeast China frequently suffers from floods which pose a threat to the regional sustainable development. Thus, this study is carried out in a river basin in northeast China, the Biliu basin (2814 km^2) (Fig. 1). The data used were collected from 11 raingauges, one hydrology station and three meteorological gauges (Fig. 1). Other data are also used, including a digital elevation model (DEM) with 30 m resolution (Rabus *et al.* 2003); the US Geological Survey's (USGS) SiB2 land-use type classification[1] (Fig. 1); Moderate Resolution Imaging Spectroradiometer (MODIS) MOD15A2 1-km 8-day leaf area index (LAI) and Fraction of Photosynthetically Active Radiation (FPAR) products (Myneni *et al.* 1997); and soil data of the Food and Agriculture Organization (FAO) (2003). This study region is the same as in the studies by Qi *et al.* (2015, 2019), and more detailed descriptions about the data used and their processes can be found in these papers.

Criteria for flood evaluation

Nash-Sutcliffe efficiency (NSE), relative bias (RB, %) of flood peaks and flood peak timing error (PT) are calculated as follows:

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}\left(Q_{pi} - Q_{ti}\right)^2}{\sum_{i=1}^{n}\left(Q_{ti} - \overline{Q_t}\right)^2} \tag{1}$$

$$\mathrm{RB} = \frac{\max\left(Q_p\right) - \max\left(Q_t\right)}{\max\left(Q_t\right)} \times 100 \tag{2}$$

$$\mathrm{PT} = i_{\max\left(Q_p\right)} - i_{\max\left(Q_t\right)} \tag{3}$$

where Q_{pi} and Q_{ti} are, respectively, the simulated and observed data at time i; and $\overline{Q_t}$ is the average of observed data. A perfect fit should have NSE values of one, while the lower the absolute values of RB and PT, the better the results.

Methodology

The floods are simulated using the V-WEB-DHM model while changing forest coverage, and then the ANOVA approach is used to attribute the contribution of influential factors to the changes in extreme flood peak values. The V-WEB-DHM simulates LAI on the basis of environmental resources limiting vegetation growth, such as precipitation, temperature, light, CO_2 and humidity, SiB2 vegetation type classification, and corresponding biomes dependent morphological properties in SiB2 lookup tables. The vegetation module was validated using MODIS LAI

[1]https://edcftp.cr.usgs.gov/project/glcc/globdoc2_0.html.

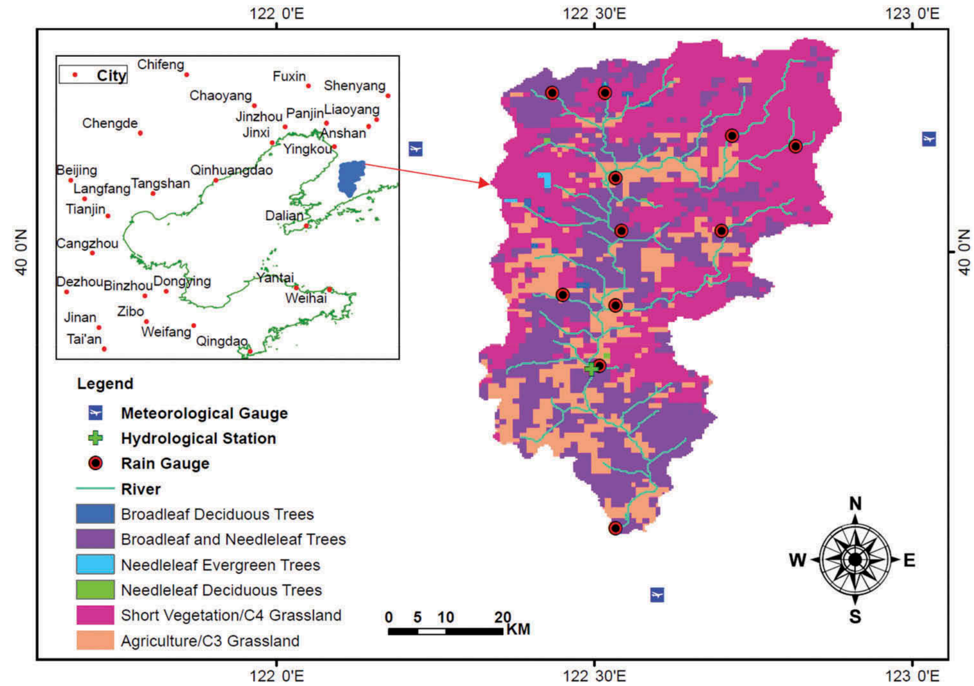

Figure 1. The Biliu basin.

(Myneni *et al.* 1997) data, showing good performance, which enables the study on forest coverage change impacts on extreme floods. The V-WEB-DHM model used is the same as in the study by Qi *et al.* (2019), and more details about the model (including calibration and validation of soil hydraulic parameters) can be found in Qi *et al.* (2015) and Qi *et al.* (2019).

The total changes M are the relative changes of extreme flood peak values:

$$M = \frac{\left|Q_{\text{max,sim}} - Q_{\text{max,obs}}\right|}{Q_{\text{max,obs}}}$$

where $Q_{\text{max,sim}}$ and $Q_{\text{max,obs}}$ are, respectively, the maximum values of simulated and observed flood peak values. To relate M to various contributions, the superscripts j, k and l in $M^{j,k,l}$ represent a combination of event size j, forest coverage change scenario k and roughness l. In this study, j varies from one to four representing four extreme flood events with different sizes, k varies from one to three and l varies from one to three.

The combination chain is shown in Fig. 2. The scenario settings are based on assumed forest coverage changes and changes in roughness value, which are analogous to the hypothetical sensitivity scenario methods used in previous studies (e.g. Rehana and Mujumdar 2011, Wu *et al.* 2012a, 2012b, Walling *et al.* 2017). Three land-use scenarios are used: 36% forest coverage, Agriculture/C3 grassland and Short vegetation/C4 grassland. The first scenario represents observed land use; while the other scenarios assume that all the land-use types are converted into one land-use type. The calibrated Manning's roughness parameter value based on observed data in the study by Qi *et al.* (2015) equals 0.25, and this roughness value is used when observed land-use type distribution is used in simulation. Because roughness values become smaller when forest coverage decreases, as indicated in the study by Bathurst *et al.* (2011), two smaller roughness values are used to investigate the sensitivity of flood peaks to roughness changes (0.1 and 0.05). The roughness values represent basin average values and, therefore, changed roughness values are applied to the entire river

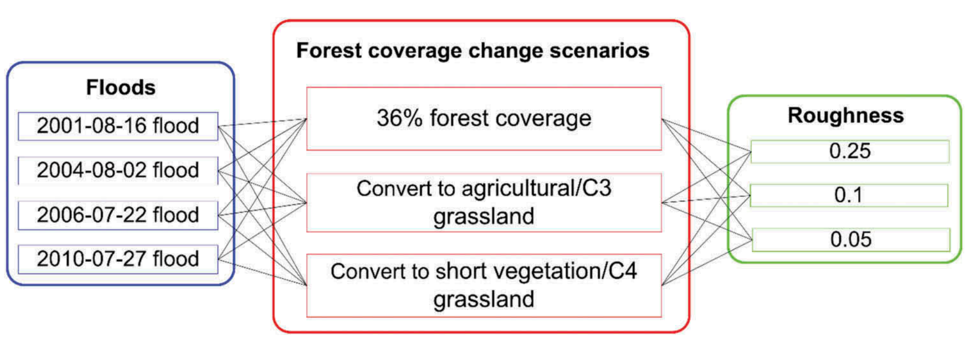

Figure 2. Combinations of extreme floods, forest coverage change scenarios and roughness values.

basin. The ANOVA approach used (Zwiers 1987, 1996) is the same as in the study by Qi *et al.* (2019), and more details may be found in that study.

Results

V-WEB-DHM evaluations using observed floods

Figure 3 shows flood simulation results with rainfall intensity on a daily time step. For the 16 August 2001 flood, it can be seen that the flood simulation results using MODIS data agree well with observed runoff, with NSE, RB and PT of 0.89, 11% and 0, respectively. The results using simulated LAI also perform well, with NSE, RB and PT of 0.93, 5% and 0, respectively. Similarly, for the other three flood events, the results using simulated LAI are acceptable. Overall, the V-WEB-DHM model shows good performance in replicating observed floods.

Forest coverage change impacts on extreme floods

The V-WEB-DHM model shows good capability in replicating observed floods and, therefore, it is implemented to investigate the influence of forest coverage changes on the flood peak. To consider the influence of antecedent soil moisture and groundwater table, the simulation starts from the beginning of every year to the beginning of every flood event; therefore, the antecedent soil moisture and groundwater table are different in different forest coverage scenarios. Table 1 shows the values of antecedent soil moisture and depth of groundwater table. It can be seen that the root zone soil moisture becomes larger when the land-use type is converted to Agriculture/C3 grassland or Short vegetation/C4 grassland. In addition, it can be seen that the depth of groundwater table becomes smaller when converting to Agriculture/C3 grassland or Short vegetation/C4 grassland land-use types. These results may be because the transpiration of forest mainly comes from deep soil, and when forest coverage reduces, more water is stored in the deep soil, increasing root zone soil moisture and groundwater levels.

The canopy interception capacity of the land-use types Broadleaf and needleleaf trees, Agriculture/C3 grassland and Short vegetation/C4 grassland are functions of their LAI values: the larger the LAI, the greater the canopy inception capacity (Sellers *et al.* 1996a). Therefore, the influence of canopy interception is considered through the changed LAI when converting land-use types. Ground surface water retention capacity is 15, 5 and 5 mm for Broadleaf and needleleaf trees, Agriculture/C3 grassland and Short vegetation/C4 grassland land-use types in the SiB2 lookup tables (Sellers

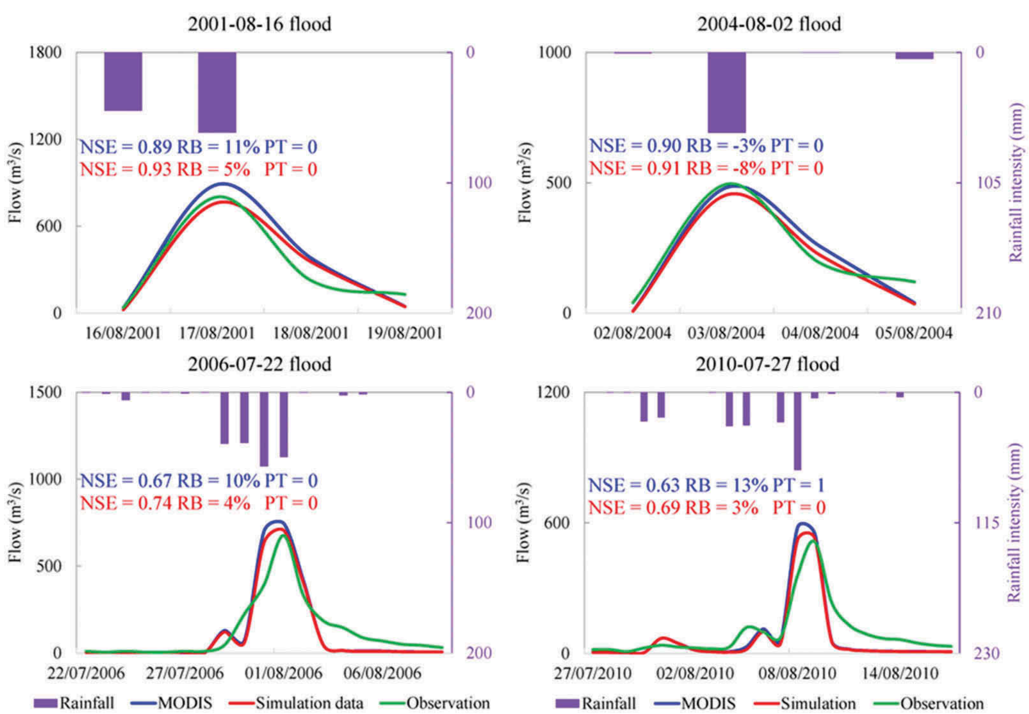

Figure 3. Evaluation of the V-WEB-DHM model in flood simulation. MODIS: results using MODIS vegetation data as input; Simulation: results using V-WEB-DHM simulated vegetation data as input.

Table 1. Basin average antecedent soil moisture and depth of groundwater table. Scenario 1: agriculture/C3 grassland land-use type; Scenario 2: short vegetation/C4 grassland land-use type. W_{sur}: top soil (5 cm) wetness; W_{root}: root zone soil wetness; G: depth of groundwater table.

	16 August 2001			2 August 2004			22 July 2006			27 July 2010		
	W_{sur}	W_{root}	G (m)	W_{sur}	W_{root}	G (m)	W_{sur}	W_{root}	G (m)	W_{sur}	W_{root}	G (m)
Original	0.88	0.77	1.57	0.58	0.79	1.56	0.47	0.72	1.56	0.48	0.71	1.56
Scenario 1	0.87	0.82	1.54	0.58	0.85	1.52	0.47	0.75	1.53	0.49	0.75	1.54
Scenario 2	0.88	0.77	1.54	0.57	0.8	1.53	0.49	0.74	1.54	0.51	0.72	1.54

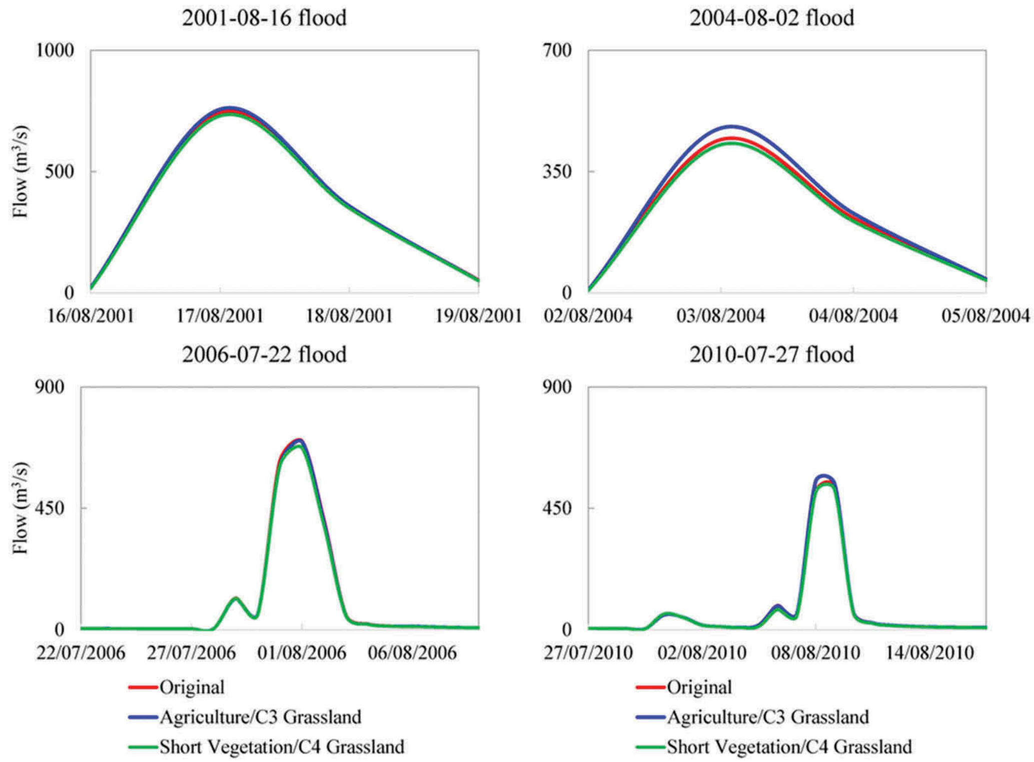

Figure 4. Flood simulation results using the V-WEB-DHM model when converting forest land-use type to Agricultural/C3 grassland or Short vegetation/C4 grassland without changing roughness.

et al. 1986, 1996a); therefore, ground surface water retention is also considered when changing land-use types.

Figure 4 shows the flood simulation results using the V-WEB-DHM model when converting forest land-use types to Agricultural/C3 grassland or Short vegetation/C4 grassland without changing roughness. For the 16 August 2001 flood, the Agriculture/C3 grassland scenario shows the flood peak increases, while the Short vegetation/C4 grassland scenario shows a decrease in the flood peak, although the differences are very small (<4%). Similarly, the 22 July 2006 and 27 July 2010 floods also show very small changes in flood peaks. In the case of the 2 August 2004 flood, the Agriculture/C3 grassland scenario shows an 8% increase in flood peak, whereas the Short vegetation/C4 grassland scenario shows a 3% reduction in flood peak. The differences between the 16 August 2001flood and other floods may result from the differences in their peak magnitude (Bathurst *et al.* 2011). In this study region, the Agriculture/C3 grassland land-use type has smaller LAI than the Broadleaf and needleleaf trees, which could result in less rainfall being intercepted. The reduced interception could decrease the time lag of rainfall on the canopy and, therefore, increase peak discharge. Short vegetation/C4 grassland has larger LAI than Broadleaf and needleleaf trees in this region and, therefore, results in smaller discharges. Overall, changes in the flood peak are less than 8% when replacing all the forest with Agriculture/C3 grassland or Short vegetation/C4 grassland without changing roughness.

Roughness impacts on extreme floods

Figure 5 shows flood simulation results using the V-WEB-DHM model when converting forest land-use type to Agricultural/C3 grassland or Short vegetation/C4 grassland with roughness reduced to 0.1. Regarding the 16 August 2001flood, it can be seen that the flood peak values increase a lot: 19% for the Agricultural/C3 grassland scenario and 16% for the Short vegetation/C4 grassland scenario. Similarly, the peak values of the other three flood events also increase. For example, the increase of the 2 August 2004 flood peak is up to 29%. Compared with the results in Fig. 4, it can be seen that the flood peak values with changes in roughness are larger than the results without roughness changes. The differences are because discharge is routed to the location of the discharge gauge more quickly when roughness is reduced. Thus, it is necessary to consider changes in roughness when investigating the influence of forest coverage changes on extreme floods. The timing of the 22 July 2006 and 27 July 2010 flood peaks also changed, which could also be attributed to the change in roughness.

Figure 6 shows the results when the roughness value is reduced to 0.05. It can be seen from Fig. 6 that the results are similar to those presented in Fig. 5, but flood peaks are even larger, which may be attributed to the smaller roughness value used. Figure 7 compares the flood peak values. It can be seen that the reductions in roughness when converting forest land use to other land-use types generally results in larger flood peak values.

Impacts on flood peaks

Figure 8 shows the contribution of various influential factors to the changes in flood peak when altering the forest coverage. The covariations refer to the simultaneous changes in forest coverage, event size and roughness. It can be seen that

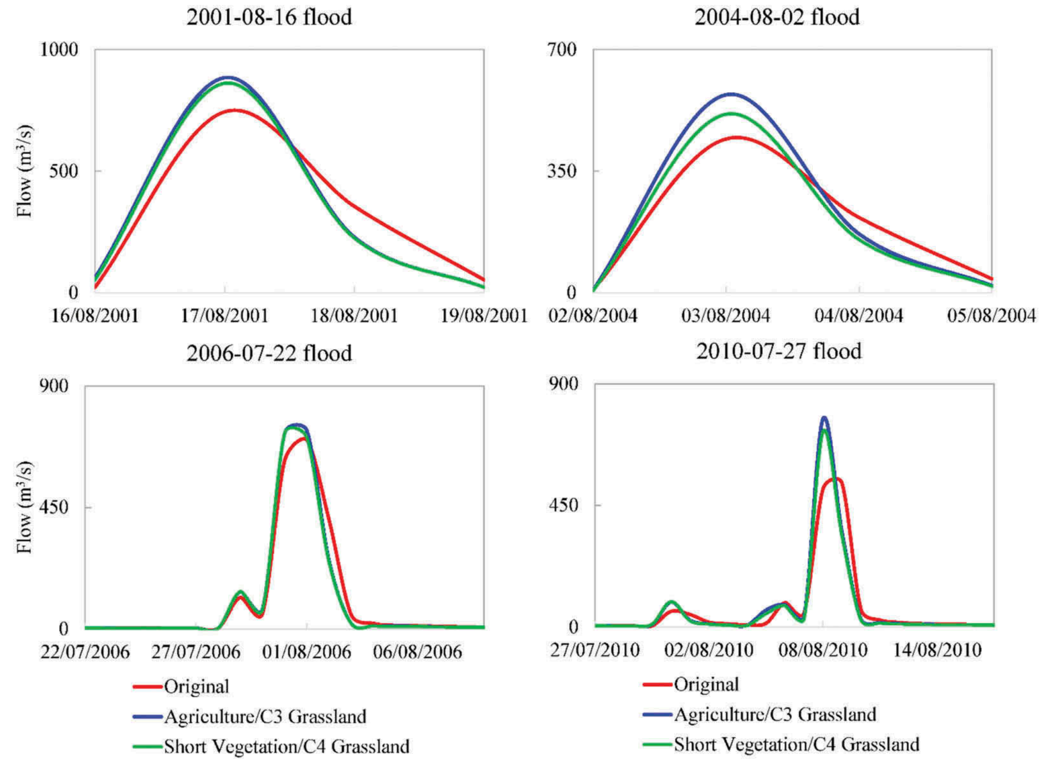

Figure 5. Flood simulation results using the V-WEB-DHM model when converting forest land-use type to Agricultural/C3 grassland or Short vegetation/C4 grassland with roughness reduced to 0.1.

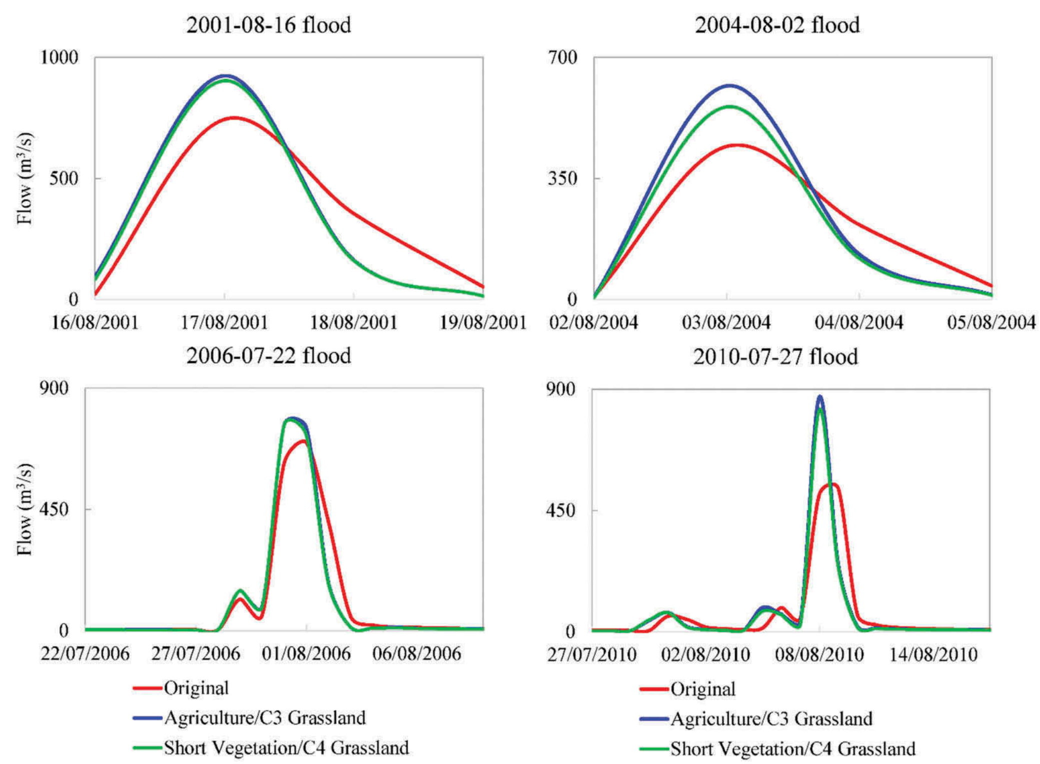

Figure 6. Flood simulation results using the V-WEB-DHM model when converting forest land-use type to Agricultural/C3 grassland or Short vegetation/C4 grassland with roughness reduced to 0.05.

roughness variations have the largest contribution, and the event size has the second largest influence, which is the same as the impact of covariations. Forest coverage changes have the least influence. Therefore, the changes in soil moisture, groundwater table depth, canopy interception and ground surface water detention are less influential than variations in roughness. It should be noted that the model uncertainty may have influence on the contribution quantification: the

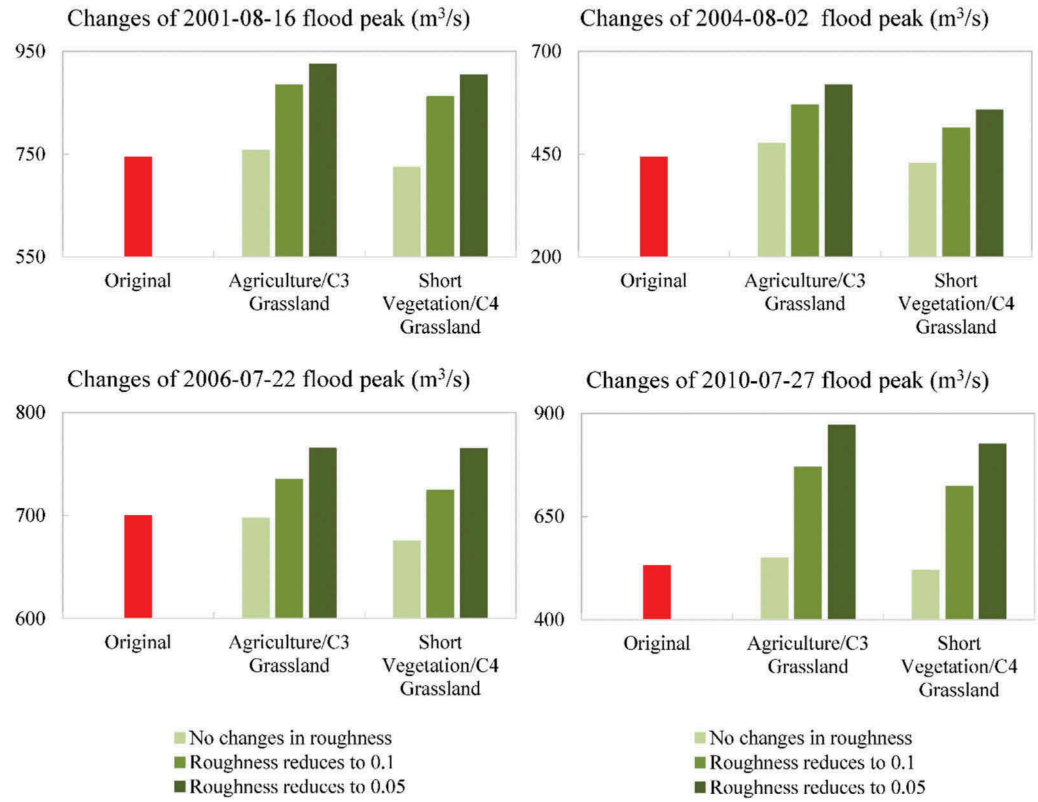

Figure 7. Comparison among flood peak values. Original: results using observed land-use data and calibrated roughness values based on observed floods.

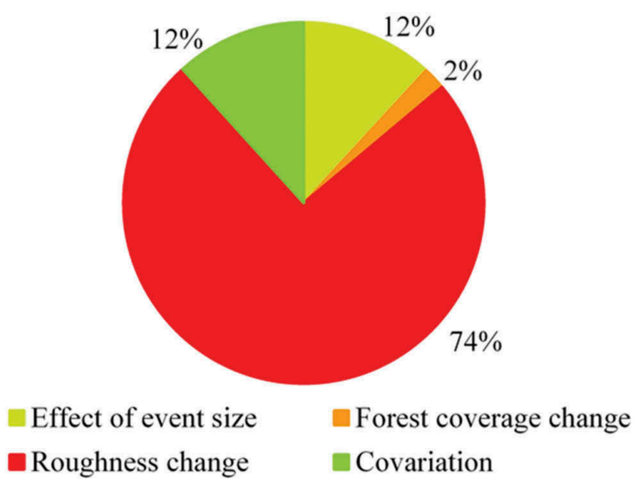

Figure 8. Contributions to the variations of extreme flood peaks.

maximum of the absolute values of RB is 8% (recall the results in Fig. 3). However, it can be seen that roughness still has the largest influence even when subtracting the maximum model uncertainty.

Discussion

Extreme floods mainly result from overland flow, and changes in roughness can alter the concentration time of overland flow. Therefore, roughness has the largest impact on extreme floods. Changes in soil moisture, groundwater table depth, canopy interception and surface water retention could influence discharge generation processes, but have little influence on overland flow concentration time. Thus, they contribute less to extreme flood variations than roughness. The results imply that increasing roughness along overland flow routing paths could be an effective way to reduce the magnitude of extreme floods, which could be beneficial for flood management. Previous research identified the impacts of roughness in flow channel (e.g. Jones and Grant 1996, 2001, Rogger *et al.* 2017), but did not quantitatively investigate the influence of roughness changes on extreme flood peaks when changing forest coverage. Compared with previous research, this study quantitatively investigates the relative importance of forest coverage changes and roughness changes.

The influence of climate change on extreme floods has been investigated in many studies. For example, Qi *et al.* (2016c) showed that the extreme floods could increase in the future under climate change; Blöschl *et al.* (2017) showed that the timing of floods in Europe has changed because of climate change; Thober *et al.* (2018) studied the variations of extreme floods in Europe under different degrees of global warming. However, as pointed out by Whitfield (2012) and Slater and Wilby (2017), land-use changes may also have large influence on floods, but the influence is not sufficiently addressed generally (Slater and Wilby 2017). The results in this study do contribute to the research on the impacts of land-use changes on extreme floods, and therefore provide important information on the role of land-use variations in extreme flood changes.

The study by Bathurst *et al.* (2011) indicates roughness values become smaller when forest coverage decreases, and therefore two smaller roughness values were used in this study. Barnes (1967) reported roughness values of 50 natural rivers in the United States, and the roughness ranges from 0.024 to 0.097. Engman (1986) suggested that the roughness values of grassland and cropland range from 0.05 to 0.2. Shit and Maiti (2012) reported roughness values in 33 rills based on their field investigations in a basin without trees, and their results show roughness values range from 0.01 to 0.1. Thus, the roughness values used in our study are within appropriate ranges. The roughness may change in the regions where forest coverage has been varied, which can change the average roughness of the entire region studied. The roughness values used in this study represent basin average roughness. Most of hydrological and/or hydraulic studies use an average roughness value of a region (Barnes 1967, Engman 1986, Maske and Processes 2014, Zhang *et al.* 2016), and therefore using the average roughness values in our study is acceptable.

This study was carried out in a medium sized river basin and four floods were used. The quantified influence may change when study regions or used data change. Nevertheless, the introduced framework is applicable when changing river basins and study data. The influence of soil erosion, the development of gullies after forest coverage changes and changes in paths of surface runoff is not considered in this study. Future studies could carry out such studies by implementing more sophisticated models including soil erosion processes and path development processes. The SiB2 land surface model is commonly used in hydrology and land surface process studies (Baker *et al.* 2003, 2017, Sellers *et al.* 2007, Wang *et al.* 2010a, 2010b, 2012, Shrestha *et al.* 2013, Xue *et al.* 2013, Hu *et al.* 2014, Qi *et al.* 2018a). Our previous studies in the same river basin also showed that model can simulate the hydrological process well (Qi *et al.* 2015, 2016a, 2018b, 2019). In addition, the flood simulation results show the model performs well in this study. Therefore, we believe the model and its parameter values used are suitable for the Biliu basin in this study.

Conclusions

Extreme floods have drawn much attention from policy maker and engineer throughout the world. Land-use management has been identified as one of the drivers of extreme flood changes. This study investigates the changes in extreme flood peaks when forest coverage is changed and quantifies the contributions of influential factors to the changes. The main contributions of this study are summarized as follows.

First, a framework combining a physically based biosphere hydrological model and a variance decomposition approach is introduced to quantify the influence of forest coverage changes on flood peaks.

Second, we found that forest coverage changes have little influence on the magnitude of flood peaks. The variations in soil moisture, groundwater table, canopy interception and ground surface water retention resulted from forest coverage changes could not alter flood peaks considerably.

Third, we also found that roughness changes have higher impacts on flood peaks than forest coverage changes. When forest coverage reduces, the runoff routing processes may be altered: overland runoff can concentrate more rapidly increasing flood peaks. Therefore, studies on changes in extreme flood peaks resulting from land-use changes need to consider roughness variations.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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