The relationship of human activities and rainfall-induced landslide and debris flow hazards in Central China

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Abstract

Human activities have been recognized as one of the significant influencing factors on flash flood, yet studies of quantitative relationship between human activities and flash flood have been limited. The relations of human activities and hazards (landslide and debris flow) induced by flash floods are quantitatively analyzed in this study and suggestions are provided for the integrated flash flood mitigation management in the study area of Central China. The results show that human activities index (*HAI*) is an effective indicator to characterize spatio-temporal changes of human activities. The relations of landslide, debris flow and human activities are significant as shown in spatial distribution. The probability of both landslide and debris flow is highly correlated with *HAI* and its changes. However, in terms of temporal relations, human activities have more direct impact on landslide than on debris flow, as the landslide frequency showed a 2-year delay with *HAI* changing, in general, according to the cross-wavelet transform analysis. In comparison no significant correlating period is shown between the changing human activities and debris flow frequency. Specifically, there are three types of time relationship between the changing human activities and landslide, debris flow in the flash flooding affected counties: i) concurrent changing, accounting for 30% of landslide and 18% of debris flow; ii) lagging relationship, accounting for 54% of land slide and 30% of debris flow; iii) no direct relationship, accounting for 16% of landslide and 52% of debris flow. The results in this study suggested that *HAI* is a simple and effective index for the local governments to manage human impacts on landslide and debris flow induced by flash floods, and integrated flash flood management is suggested to be executed when *HAI* reaches 0.072. In addition, the types of human activities also impact landslide, as the ratio of Economy factor to Land use factor (E/L) is significantly ($P < 0.05$) higher in counties with concurrent relationship of changing human activities and landslide. The results should assist the policy-making for integrated flood mitigation at local/regional level, while balancing economic development and flooding hazard.

Keywords: Human activities index; Flash flood; Landslide; Debris flow; Lagging relationship; Spatio-temporal variation

1. Introduction

Flash flood has become one of the deadliest natural disasters in the world, which has caused extremely high property damage, infrastructure destruction and human casualty due to its extremely high runoff velocity in mountainous areas and fast rising water carrying a large amount of sediments (Jonkman and Kelman, 2005; Kleinen and Petschel-Held, 2007; Marchi et al., 2010; Creutin et al. 2013; Śpitalar et al., 2014; Ballesteros-Cánovas et al., 2015; Rodriguez-Morata et al., 2016; Mahmood et al., 2017; Liu et al., 2018; He et al., 2018). Flash flood ranked top two causes to property losses by a range of natural disasters in 105 out of 139 countries worldwide (He et al., 2018). Flash flood includes river floods, landslide and debris flow caused by heavy rainfall in mountain areas, which outburst abruptly with strong and intense destruction (He et al., 2018). Flash flood in China has occurred widely in mountain areas in more than 2050 counties, involving 30 provinces (autonomous regions and municipalities) with a total area of 3.86 million km^2, high frequencies of occurrence and costs (Guo et al., 2018; Liu et al., 2018). The death toll caused by flash floods could reach 67,000 since 1950, averaging at 984 deaths per year, and the related economic losses could reach 139 billion since 1990 (He et al., 2018). During serious flood events, the number of missing and dead people reached 3887 in 2010, contributing to 92% of the total human losses by flood disasters in that year (Guo et al., 2018; He et al., 2018). It is reported that more than 28 billion RMB has been invested in the integrated prevention of the Flash hazard, due to its extremely high destructiveness (Liu et al., 2018). Extensive efforts such as research and infrastructure projects have been implemented in China, and the National Flash Flood Control Planning (NFFCP) was compiled during the period of 2003-2006 (Sun et al., 2012).

It is commonly recognized that physical factors such as rainfall, topography and geology, are the main causes of flash flood. Intense rainfall is the most important factor influencing flash floods, which are mostly induced by local high-intensity rainfall events (Cao et al., 2010). Cao et al. (2010) also indicated that the threshold rainfall may be less than 100 mm or even 50 mm with durations from 1 h to 6 h. Moreover, the occurrence of flash flood is significantly depending on the terrains, which may amplify the functions of precipitation, trigger large erosion and result in sediment transportation or even slope failures and debris flows (Marchi et al., 2009; Borga et al., 2011; Destro et al., 2018). Therefore, the intense flooding may occur simultaneously with landslides and debris flows, and the simultaneous occurrence of these different hazards will enhance the destruction (Tao and Barros, 2014; Destro et al., 2018). For example, landslides triggered by the flood may form dams to block river flow and magnify the flood hazard, or even destroy the infrastructure and change the channel landform by falling trees in the debris flow or significant sediment transportation (Comiti et al., 2016; Ruiz-Villanueva et al., 2017; Destro et al., 2018). Debortoli et al. (2017) reported that there is a tendency of increasing frequency and intensity in extreme events since the 1990s. It is assumed that heavy precipitation events are increasing at both regional and global scale due to the intensified global hydrological cycle under global warming (Groisman et al., 2004, 2005; Huntington, 2006; Borga et al., 2011; Velasco et al., 2013; 2014). Accordingly, the flash flood hazard is anticipated to increase in both frequency and severity due to the global warming impacts on precipitation (Kleinen and Petschel-Held, 2007; Beniston et al., 2011).

In addition, increasing concerns are given to the impacts of human activities on flash floods, due to the economic developments in mountain areas to conquer poverty (Ruin et al., 2008; Śpitalar et al., 2014; Billi et al., 2015; He et al., 2018). Efforts have been made in interdisciplinary work by co-consideration of social sciences and physical sciences in the field of flash flood assessment (Śpitalar et al., 2014). For example, Ruin et al. (2008) conducted a first trial to combine both natural and human factors to understand the relations between hydro-meteorological conditions and casualties. Bill et al. (2015) tried to identify whether rainfall intensity or land use change is the dominant contribution to the flash floods in Dire Dawa, Ethiopia. An integrated approach was developed by Creutin et al. (2013) to incorporate numerous layers that are evaluating various parameters considering the interdisciplinary sciences relating to flash flooding. Śpitalar et al. (2014) also tried to cross-correlate the spatiotemporal variations of both flash flood parameters and human impacts. They indicated that analysis and correlation of various flash flood parameters may help better understand the contribution of each parameter to the casualties. In China, the investigation of human impacts on natural hazards is at its early stage and most of the studies are qualitative analysis, due to the high complexity of human activities and variable terrains (Chen et al., 2005; Huang et al., 2007).

This study therefore attempts to assess the inter-relationship between human activities and serious natural hazards, like landslide and debris flow hazards caused by flash flooding in central China; to conduct quantitative analysis of both spatial and temporal impacts of human activities on flash flood; and to provide suggestions for reasonable human activities in mountain areas susceptive to flash floods.

2. Study area and data sources

2.1 Study area

The study area is selected in Hunan Province in Central China, where is located in the south of Jianghan Plain of the middle reaches of Yangtze River (30°08′~24°38′ N; 108°47′~114°15′ E) with more than 82% of the total area located in mountain areas. The distance from the east to west is 667 km and the distance from north to south is 774 km. The total area is 211,800 km^2, accounting for 2.2% of the total land area in China. Hunan Province has 13 prefecture-level cities and one autonomous prefecture. Hunan Province is surrounded by mountains on three sides, open to the north as a horseshoe shape. The average precipitation in Hunan Province is 1427 mm, dominated by the subtropical monsoon in high value zone of the national rainstorm and concentrated in the spring and summer seasons. The river density in Hunan Province is high and the main rivers are Xiangjiang River, Zijiang River, Yuanjiang River and Lishui River. The types of rock and soil are complex and diverse, dominated by sandy rock, mudstone, slate, carbonate rock, red rock, Quaternary loose accumulation and other rocks e.g. metamorphic rocks and magmatic rocks. Soil erosion resistance is weak and water storage capacity is poor. Due to such physical conditions, flash flood in Hunan Province is frequent, abruptly outburst and widespread. The flash floods in Hunan have caused extreme high casualties and economic costs, which make Hunan Province in the top 5 in China in terms of death toll by flash floods (He et al., 2018). For example, in the 1990s, the direct economic loss caused by flash floods in the province exceeded 100 billion RMB, accounting for 63.1% of the direct economic losses and 97.7% of the death toll by floods. Debris flows and landslides are frequently happened in the mountainous areas of Hunan Province, due to its special terrain geological conditions.

<**Fig. 1 is here**>

2.2 Data sources

All data related to the human activities are from Hunan Province Statistical Yearbook, involving 104 counties with complete statistical data in Hunan province during1994-2014 (data in 2010 are missing). Data related to flash flood are from Flash Flood Prevention and Control Planning in Hunan Province. The data of land slide and debris flow are obtained for years 1994-2003, due to the limitation of the data availability.

In this study, the debris flow and landslide caused by flash flood were particularly focused on. According to the collected data (Table 1), there are 51 debris flows and 320 landslides, respectively, during years 1994-2003. For debris flows caused by flash floods, they happened 13 times during years 1994-1996, 12 times during years 1997-1999 and 26 times during years 2000-2003. For landslides caused by flash floods, they happened 60 times during years 1994-1996, 113 times during years 1997-1999 and 147 times during years 2000-2003.

<**Table 1 is here**>

3. Methods

3.1 Human activities index (*HAI*)

According to previous studies (Sigamani et al., 2015; Huang et al., 2016; Ursu et al., 2017) and the current social and economic situation of Hunan Province, 10 indices were selected for the evaluation of human activities index (*HAI*) of flash floods, following the principles of objectivity, systematisms and feasibility. As shown in Table 1, the 10 *HAI* are closely related to the vulnerability of human to flash floods and its related hazards. Three sub-indices are classified, namely Economy factor, Land use factor and Managing factor. Accordingly, 3-layer index system was used to evaluate *HAI* (Table 2). The Economic includes 5 sub-indices, which correlated with the economic indicator with direct influences on both the occurrence and the consequences of landslides and debris flows related with flash flood. The land use factor includes 3 sub-indices, i.e. sown area, forestry output value and mechanized cultivation area, which affecting the runoffs during flash floods. The managing factor includes 2 sub-indices, i.e. number of reservoirs and embankment length, involving the prevention of flash floods, which are both negative indices to the *HAI*.

<**Table 2 is here**>

3.2 Evaluation of *HAI*

According to previous studies (Satty, 1980; Sun et al., 2010; Huang et al., 2016), analytic hierarchy process (AHP) was used to determine the weight of each index (Table 2). The result of hierarchical total sorting met the requirement of consistency with consistency ratio (*CR)* which is 0.08 (< 0.10). In the index system of human activities, each index has different dimensions and orders of magnitude. Modified min-max normalization is used to standardize each basic indicator ($HAI_{m,n}$) of *HAI* as equations (1) and (2):

$$HAI_{m,n}(C_t)=\frac{HAI_{m,n}(C_t)-\mathrm{HAI_u(C)}}{\mathrm{HAI_u(C)-HAI_l(C)}} \quad (1)$$

$$HAI_{m,n}(C_t)=\frac{\mathrm{HAI_u(C)}-HAI_{m,n}(C_t)}{\mathrm{HAI_u(C)-HAI_l(C)}} \quad (2)$$

where $HAI_{m,n}(C_t)$ is the basic indicator of *HAI* in county *t*, HAI_u and HAI_l are the upper and lower values of basic indicators in all counties. The maximum and minimum values of $HAI_{m,n}$ are not used here to reduce the side effects of the extremely high or low values. HAI_u and HAI_l are determined by the maximum value and minimum value of 98 counties (except 2% counties with extreme high for HAI_u and 2% counties with extreme low for HAI_l), respectively. Positive indicators are transformed by equation (1) and negative indicators are transformed by equation (2).

HAI was then calculated in different counties based on the allocated weight and normalized data of each index according to equation (3):

$$HAI_{m-1,n} = \sum_{j=1}^{k} W_j \, HAI_{m,j} \quad (HAI_{m,j} \in C_{m,n}) \qquad (3)$$

where $HAI_{m,j}$ are sub-indices of $HAI_{m-1,n}$ and $C_{m,n}$ is the corresponding group of sub-indices ($HAI_{m,j}$).

3.3 Methods for analysis of spatio-temporal variations of *HAI*

3.3.1 Average *HAI*

The temporal variations of human activities were analyzed by calculating the average *HAI* (HAI_a) as:

$$HAI_{aj} = \frac{1}{x}\sum_{t=1}^{x} HAI_{tj} \qquad (4)$$

where HAI_{aj} is the average value of *HAI* of the total counties in year *j*; HAI_{tj} is the value of *HAI* in county *t* of year *j* (t=1,2,…,x； j=1,2,…,m; x=104, m=20).

Specifically, the average *HAI* in counties encountered flash floods (HAI_{ad}) is calculated for the cross-analysis of human activities and flash flood, as:

$$HAI_{adj} = \frac{1}{y}\sum_{d=1}^{y} HAI_{dj} \qquad (5)$$

where HAI_{adj} is the average value of counties with flash flood in year *j*; HAI_{lj} is the value of *HAI* in flash flood county *d* in year *j* (d=1,2,…,y； j=1,2,…,k; y=33 for landslide and y=23 for debris flow, k=10).

3.3.2 Standard deviation of *HAI*

The spatial variations of human activities could be analyzed by calculating the static standard deviation and dynamic standard deviation of *HAI* in different counties. Among them, the static standard deviation reflected the difference of human activities in a certain period of time, while the dynamic standard deviation reflected the changes of human activities with time. The static standard deviation (σ_s) can be calculated as:

$$\sigma_{sj} = \sqrt{\frac{1}{x}\sum_{t=1}^{x}(HAI_{tj} - HAIa_j)^2} \tag{6}$$

where σ_{sj} is the standard deviation of *HAI* in county *j*; HAI_{tj} is the value of *HAI* in county *t* of year *j* (t=1,2,…,x; j=1,2,…,m; x=104, m=20), HAI_{aj} is the average *HAI* of total counties in year *j*.

The dynamic standard deviation (σ_d) can be calculated as:

$$\sigma_{dt} = \sqrt{\frac{1}{m}\sum_{j=1}^{m}(HAI_{tj} - HAIa_t)^2} \tag{7}$$

where σ_{dt} is the dynamic standard deviation of *HAI* in county *t*; HAI_{tj} is the value of *HAI* in county *t* of year *j* (t=1,2,…,x; j=1,2,…,m; x=104, m=20), HAI_{at} is the annual average of *HAI* in county *t*.

3.4 Spatial distribution map of human activities intensity

The calculated results of *HAI* were overlayed with administrative division of Hunan Province using ArcGIS software (version 9.0) to create the spatial distribution map of human activities intensity. Also, the natural breaks method in ArcGIS was used for the classification of the intensity of human activities. The distribution map of human activities intensity could be compared in different periods for the analysis of the temporal variation of human activities.

The calculation results of σ_{dt} are overlaid with administrative division of Hunan province using ArcGIS (9.0) software to create the spatial distribution map of human activities changing. The natural breaks method in ArcGIS was used for the classification of human activities changes.

3.5 Cross-wavelet transform

Cross-wavelet transform was used for the analysis of the time-frequency relationship between human activities and flash floods, as it has proved to be a useful tool to examine the degree of interaction and the time-frequency relationship between multiple time-period elements by previous studies (Frick et al., 1997; Grinsted et al. 2004; Soon et al., 1999; Soon et al., 2016). Cross-wavelet transform can be defined as (Hudgins et al., 1993; Torrence and Webster 1999):

$$W_n^{XY}(s) = W_n^X(s) W_n^{Y*}(s) \tag{8}$$

where $W_n^X(s)$ and $W_n^Y(s)$ are continuous wavelet variations of two time series $X = \{x_1, x_2, \cdots, x_n\}$ and $Y = \{y_1, y_2, \cdots, y_n\}$, $W_n^{Y*}(s)$ denotes complex conjugateion of $W_n^Y(s)$ and s denotes time shift. The power spectrum of cross wavelet transform is defined as $|W_n^{XY}(s)|$. The larger the value of $|W_n^{XY}(s)|$ is, the higher the energy region is between two time series, and the higher correlation degree between two time series is. The complex angle of $W_n^{XY}(s)$ was used to describe the local relative phase relationship of time series *X* and *Y* in time-frequency.

4. Results and discussion

4.1 Spatio-temporal changes of human activities

4.1.1 Temporal variations of human activities

The temporal variations of HAI_a can reflect the average changes of human activities during the study period. As shown in Fig. 2, HAI_a kept stable during years 1994-2000 (0.038-0.044), fluctuated with increasing trend in years 2000-2009 (0.037-0.060) and increased sharply after 2009 up to 0.990 in 2013 with a slight drop in 2014. As for the sub-indices, the gross output value of heavy industry output value ($HAI_{3,1}$) and the fixed asset investment ($HAI_{3,5}$) in 14 cities in Hunan Province have increased by 22 times and 98 times, respectively. Also, the number of employed workers in the urban collective economic mining industry ($HAI_{3,4}$) has increased three-fold, and the population ($HAI_{3,3}$) has increased by 44,000 people. In addition, the area of mechanized cultivation area ($HAI_{3,8}$) has increased by 5.7 kha and the forestry output value

($HAI_{3,7}$) has increased sevenfold. Hence, the variations of human activities mainly include the rapid development of coal, metallurgy and other heavy industries, combined with the rapid increase of social fixed assets, population, and the change of land use pattern, which lead to the great changes in the economy factor ($HAI_{2,1}$) and changes in the land use factor ($HAI_{2,2}$) of *HAI*.

<Fig. 2 is here>

4.1.2 Spatio-temporal variations of human activities intensity

The spatial distribution of human activities in Hunan Province during 1994-2014 is shown in Fig. 3. The five classes are extreme low human activity (≤0.042), low human activity (0.043-0.071), medium human activity (0.072-0.112), high human activity (0.113-0.222) and extremely high human activity (≥0.223).

The number of counties and their area percentage in different types of human activity intensity in Hunan Province is shown in Table 3. Combined with data in Fig. 3 and Table 3, the intensity of human activities in most counties was low and extreme low (61-94%). Up to 2007, the area with high and extreme high human activities occupied no more than 3%, which means the development of human activities in Hunan Province was relatively slow at that period. Since 2007, human activities have gradually expanded to central hilly areas and the eastern mountainous areas of Hunan Province. Extreme high human activities initially occurred since 2007 (3%) and presented increasing trend with the area percentage at 7% in 2014, mainly distributed in Yiyang City, Chengzhou City, Hongjiang City, Liuyang City and Changsha City. The number of counties with medium human activities also increased gradually from 8-10% before 2007 to 18-19% after that. Accordingly, the area of low and extremely low human activities decreased since 2007, from 80-90% to 61%, mainly in the western mountainous area, northern Dongting Lake plain and part of southern mountainous areas.

<Fig. 3 is here>

<Table 3 is here>

4.1.3 Regional distribution of changing human activities

The variations of static standard deviation of HAI_a (σ_s) with time represented the temporal variation of regional differences in human activities. σ_s has the similar changing curve with HAI_a (Fig. 2), which implied that the uneven development of human activities began in 2000 and resulted in the dramatic increase of HAI_a after 2009.

Moreover, the spatial distribution of dynamic standard deviation of HAI (σ_d) reveals the regional differences of changing human activities during 1994-2014. According to the calculated values σ_d among counties, the changing human activities are classified into five grades using the natural breaks in ArcGIS (Fig. 4), namely extremely low changing human activities (0.003-0.010), low changing human activities (0.011-0.021), medium changing human activities (0.022-0.036), high changing human activities (0.037-0.093) and extremely high changing human activities (0.094-0.194). Changes in human activities in low and extreme low level occupied 51% counties (Table 4), mainly distributed in areas with low and extreme low human activities, in western mountainous area, northern Dongting Lake plain and part of southern mountainous areas with the overlap ratio at 75% in 2014 (Fig. 4). The development of these areas is restricted due to the harsh natural conditions. 18% of counties experienced medium changing human activities, with a scattered distribution pattern. Extreme high and high changing human activities occurred in 31% of counties, with similar distribution of high and extreme high intensity of human activities. For example, the overlap ratio could reach up to 70% in areas of counties with high and extreme high intensities of human activities in 2014, mainly distributed in highly developed cities of central and eastern hilly areas (Fig. 4). These results indicate that the changes of human activities have close relations with intensity of human activities, driven by the rapid development of cities in central hilly areas and the eastern mountainous areas.

<**Fig. 4 is here**>

<**Table 4 is here**>

4.2 Spatio-temporal changes of landslide and debris flow in Hunan Province

As shown in Figs. 5a-c, the spatial distribution of landslide did not change much during years 1994-2003, mainly distributed in the North central, west and east mountain areas, including cities like Xiangtan City, Changde City, Hengyang City, Shaoyang City, Yongzhou city and Chengzhou city with total 33 counties. Similarly, the spatial distribution of debris flow did not change much during years 1994-2003 (Figs. 5 d-f), scattered in mountain areas, including cities like Shaoyang City, Changsha City, Chengzhou City, Yongzhou City and Yiyang City, with total 23 counties. The spatial distribution is mainly determined by the natural factors, like terrain, storm and geology characteristics, which would not change easily in short term. It is noticeable that 23 counties with debris flow are totally included in those 33 counties with landslide hazards. This means where there is high probability to suffer debris flow may suffer landslide. However, places suffer landslide may not suffer debris flow. The occurrence of debris flow in Hunan Province needs more strict conditions than that of Landslide. The spatial distribution of landslide and debris flow is mainly determined by natural factors, which would not change in short term.

However, the frequency of both landslide and debris flow increased with time. As shown in Figs. 5a-c and Table 1, the landslide occurred approximately 20 times/year during years 1994-1996. After 1997, the landslide frequency increased to approximately 38 times per year, which is almost twice as that before 1997. The debris flow showed similar increasing trend with landslide (Figs. 5d-f and Table 1), however, the turning year is 2000 for debris flow. Debris flow occurred nearly 4 times/year before 2000, however, increased to approximately 6 times per year during years 2000-2003. The increasing frequency of both landslide and debris flow suggested the influence of human activities on the natural hazards. It is also noticeable that the frequency of landslide is much higher (5-6 times) than that of debris flow, suggesting that the occurrence of debris flow is more limited than that of landslide.

<**Fig. 5 is here**>

4.3 Spatial relations of landslide and debris flow with human activities

Due to the unavailability of data after 2003, the probability of landslide and debris flow in relation to human activities intensity was calculated for years 1994-2003, based on different degree of human activities intensity (Table 5). Here, the probability (shown in percentage) is referring to 33 counties with landslide and 23 counties with debris flow to the total numbers of counties with different intensity levels of human activities. As shown in Table 5, both landslide and debris flow show an increasing trend with the intensity of human activities, most likely occurred in counties with high and extreme high human activities, with higher average probability than other regions at 60%-64% and 37-40%, respectively. For example, landslide happened in approximately 70% of years 1994-2003 in Leiyang County, where the intensity of human activities is high in 60% of those years, averaged at 2.2 times of occurrence of landslide per year. Thus, it can be summarized that the occurrence of landslide and debris flow induced by flash flood is highly impacted by the intensity and dynamics of human activities.

<**Table 5 is here** >

4.4 Temporal relations of landslide and debris flow with human activities

According to the analysis results of cross-wavelet transform, there is a correlated period cycles of significant in-phase resonance oscillation between landslide and average human activities ($P < 0.05$; Fig. 6a). The correlated period cycle occurred in years 2000-2004, during which landslide lagged behind human activities, on average, by 1/2 period cycle,of, i.e. 2 years. Fig. 6b shows that there is no significant ($P < 0.05$) correlated cycle of debris flow and average human activities, which demonstrate that human activities have more direct impacts on landslide than on debris flow.

<**Fig. 6 is here**>

Specifically, the time relationships between the changing frequency of landslide, debris flow and human activities are examined in 33 counties suffering from landslide and 23 counties suffering from debris flow during 1994-2003. Three types of time relationships were observed as concurrent relationship, lagging relationship and no direct relationship. The concurrent relationship indicates that the changing landslide or debris flow frequency happened around the same time with the changes of human activities. The lagging relationship indicates that the changing landslide or debris flow frequency lagged behind the changes of human activities. No direct relationship indicates that the changing landslide or debris flow frequency showed no regular trend in association with the changes of human activities. For landslide hazard (Fig. 7a), the concurrent relationship accounted for 30%, lagging relationship accounted for 54% and no direct relationship accounted for 16% of the 33 counties suffering from landslide in 1994-2003. The lagging relationship between the changing landslide frequency and human activities is dominant, which is consistent with the results showing in Fig. 6a. As for debris flow hazard (Fig. 7b), the different relationships accounted for 18% (concurrent), 30% (lagging) and 52% (no direct relationship), of the 22 counties suffering from debris flow during 1994-2003. No direct relationship occurred in more than half counties suffering from debris flow, which is also an explanation of why no correlated cycle of debris flow and average human activities in Fig. 6b.

<Fig. 7 is here>

4.5 Managing landslide and debris flow induced by flash flood

In order to predict and manage landslide and debris flow induced by flash flooding, appropriate scientific tools are needed. Here, we think that *HAI* is a simple and effective index for the local governments to manage human impacts on hazards (landslide and debris flow) induced by flash floods. As discussed above, the probability of flash floods is higher when human activities intensity is increasing, averaging at 51% for landslide in areas of medium intensity of human activities (Table 5). Thus, *HAI* of 0.072 is a supposed to be a reasonable value for the implementation of integrated flash flood management in Hunan Province. When *HAI* reaches medium level (0.072-0.112), low level of flash flood mitigation measures on landslide and debris flow should be considered. When *HAI* reaches high level (0.113-0.222), medium level of flash flood mitigation measures on landslide and debris flow should be considered. When *HAI* reaches extreme high (⩾ 0.223), high level of flash flood mitigation measures on landslide and debris flow should be adopted. Considering the close relationship between the intensity of human activities and human activities changes, it is important that local governments control the changing rate of human activities, by maintaining the dynamic standard deviation of *HAI* to be lower than 0.022 in Hunan Province.

Compared with the concurrent relationship between changing between landslide and human activities, the lagging relationship may provide potential time for the government to take effective preventive measures for landslide mitigation before or during the lagging period. Thus, we try to find potential rules by analyzing the sub-indices of *HAI*, as it is assumed that the different human activities may have various impacts on the occurrence of landslide even with the same *HAI* value. In other words, the ratios of sub-indices to *HAI* may affect the human impacts on landslide. Economy factor ($HAI_{2,1}$) is closely related to the occurrence and suffering of the landslide, Land use factor ($HAI_{2,2}$) is closely related to the runoffs flash flood, and Managing factor ($HAI_{2,3}$) is closely related to the mitigation capacity of the flash flood. As shown in Table 5, we figure out that the ratio of Economy factor ($HAI_{2,1}$) to Land use factor ($HAI_{2,2}$), in lagging relationship of changing human activities and landslide is significantly different with other two kinds of relationships between changing human activities and landslide. Accordingly, we define the ratio of Economy factor ($HAI_{2,1}$) to Land use factor ($HAI_{2,2}$) ratio as *E/L*, which is assumed to potentially have impact on the time relationships between changing human activities and landslide. The average *E/L* ratio in counties with concurrent relationship between changing human activities and landslide is significantly ($P < 0.05$) higher (2 times) than other counties. Thus, we suppose that *E/L* might be used as a managing indicator to minimize the probability of concurrent occurrence of changing human activities and landslide. Based on results in this study (Table 6), it is suggested that the *E/L* ratio should be lower than 4.0 in Hunan Province.

<**Table 6 is here**>

5. Conclusions

This study quantitatively assessed the spatial and temporal relations of human activities and natural hazards (landslide and debris flow) induced in flash floods in Hunan province, Central China. *HAI* is an effective indicator for both characterizing the changing human activities and managing the integrated prevention of natural hazards (landslide and debris flow) induced by human activities. The spatial distribution landslide and debris flow was highly dependent on human activities intensity, with a higher probability in counties with higher *HAI*. Accordingly, different levels of mitigation measures for flash flood related natural hazards are suggested to be taken when *HAI* reaches medium level (≥ 0.072) and the dynamic standard deviation of *HAI* should be controlled at lower level (≤ 0.022). The changing human activities have more direct impacts on temporal relations with land slide frequency than that of debris flow, as a significant correlate period (2-year time delay) presenting between the changing human activities and landslide frequency. Specifically, three time relationships between changing human activities and landslide, debris flow frequency, namely concurrent relationship, lagging relationship and no time relationship, with the dominant lagging relationship for landslide and dominant no time relationship for debris flow. The types of human activities are also revealed to have different impacts on landslide frequency, as *E/L* is significantly ($P<0.05$) higher in counties with concurrent relations of changing human activities and landslide, which is suggested to be controlled to a certain value in Hunan Province. The scientific approach adopted here is feasible for the quantitative analysis of the cross-link between human activities and natural hazards induced by flash floods. The results should assist the integrated flood mitigation at local/regional level, when the economic development in mountain areas with potential flash flood risk is carefully planned and managed.

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Tables

Table 1. The frequency of landslide and debris flow in Hunan Province during years 1994-2003

Table 2. Indices, data sources and weight allocation for human activities index (HAI) of flash flood

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Fig. 1. The location of Hunan Province, China

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Fig. 3. Spatial distribution of human activity intensity in different years

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Fig. 6. Cross wavelet transform between human activity index and frequency of landslide and debris flow, Hunan. Period cycles of significant (P<0.05) in-phase resonance

oscillation between landslide and human activity; Right-pointing arrows indicate the isotropic relationship; Downward arrows indicate a phase difference of 90^{o}, with a lagging of 1/4 period cycle; Left-pointing arrows indicate a phase difference of 180^{o}, with a lagging of 1/2 period cycle; Upward arrows represent a phase difference of 270^{o}, with a lagging of 3/4 period cycle.

Fig. 7. Spatial distribution of three types of time relationship between changing human activities and flash flood frequency (1994-2003)