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ORIGINAL RESEARCH ARTICLE

Advances in flash flood research based on dendrogeomorpholog

Jiazhi Qie[1,2], Yong Qie[1*]

[1] *Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China. E-mail: zhangyong@igsnrr.ac.cn*

[2] *University of Chinese Academy of Sciences, Beijing 100049, China.*

ABSTRACT

Flash flood is one of the major natural hazards in China. It seriously threatens the lives of people and property in mountainous areas. Various methods have been developed for flash flood study, but most of them focused on the past few decades. As one of the effective methods of historical flash flood events reconstruction, dendrogeomorphology has been used worldwide. It can provide hazard information with long temporal scale and high temporal resolution, sometimes at the seasonal level. By comparing tree ring width and other growth characteristics between disturbed and undisturbed trees, growth disturbance signals can be found in the disturbed trees. Using the growth disturbance in tree rings, flash flood events can be dated, and then the frequency, size, and spatial distribution characteristics of flash floods that have no or little documentary records can be reconstructed. The discharge of flash flood can be reconstructed quantitatively according to the height of scars or by using hydraulic models. With the development of dendrogeomorphology, research tends to probe into the meteorological driving mechanism of flash floods and the pattern of flash floods on a larger spatial scale. In the practical application of dendrogeomorphology, more instrumental data and historical records are applied in the studies. This makes the method increasingly more widely used around the world. But work based on dendrogeomorphology has not been reported in China. In this article, we reviewed the development of the study on flash floods based on tree ring, briefly summarized the research progress, and discussed the advantages, limitations, and potential of this approach, so as to provide some reference information for relevant work in China.

Keywords: Flash Floods; Tree Ring; Dendrogemorpholog

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1.Introduction

Flash floods in mountainous areas occur in a short time and are hard to prevent, usually with heavy precipitation events or infrastructure damage in most cases[1,2]. China has a mountainous terrain and the mountainous area accounts for about 2/3 of the national land area. Rainstorms occur frequently in the eastern monsoon area. Besides, the snow melts into water in the western mountains brings abundant water sources, and the height difference between the three steps is huge. These factors make flash floods occur frequently and affect a wide range in China[3]. At present, China has carried out a lot of systematic research on flash flood disasters, including analysis of flash flood causes[4–6], characteristics of temporal and spatial distribution[7–9], application of early warning indicators[10–12], the risk analysis and prediction of flash flood disaster[13–17] and so on. From the previous field survey to the application of "3S" technology, from the analysis based on historical records and measured data to the combination with meteorological forecast data, the research on flash flood disaster has been gradually deepened. However, most of these studies need to rely on historical flash flood data or instrumental measurement data. These data have a short recording period, especially in mountainous areas, which are limited by terrain and sparsely populated, and often lack historical data such as precipitation and flow, so it is difficult to find the historical law of flood. In recent years, dendrogemorpholog has been widely used in the dating and characteristic analysis of flash floods on a long time scale. Trees with clear annual rings will retain growth interference signals in the tree rings after being affected by flash floods. With the support of large sample size, such growth interference events can be dated with the help of cross-dating technology, so as to determine the year of flash floods. According to the number and intensity of growth disturbance, the number and spatial distribution of trees affected by flash floods, we can explore the temporal and spatial characteristics of flash floods and reconstruct the history of flash floods in areas with no or little data[18]. This method can provide alternative or supplementary data for flash flood event dating[19]. Compared with other alternative indicators, this method has accurate dating, high resolution and even up to seasonal scale[20]. A lot of work has been carried out all over the world and the research prospects are very broad. Flash floods occur frequently in China, especially in recent years, extreme precipitation events occur frequently[21–23]. Therefore, it is necessary to strengthen the research on the temporal and spatial characteristics and causes of flash floods under the background of longer time scale, so as to provide necessary background information for the prediction and prevention of flash floods in the region. Unfortunately, the relevant work has not been carried out in China. Therefore, this paper systematically introduces the development history, research methods and the latest progress of flash flood research based on dendrogemorpholog, and further discusses the problems and potential of this new research direction in China.

2. History and methods of flash flood research with using tree rings

2.1 The history of flash flood research

The study of historical dendrochronology of flash floods is a science that studies the annual growth layer of tree xylem and uses the annual growth layer for dating. It was founded by American astronomer Douglas in the early 20th century[24]. With the development of the discipline, many branches of the dendrochronological school have emerged, and dendrogemorpholog is one of them. Alestalo systematically expounded dendrogemorpholog and defined it as a discipline that uses tree rings to study geomorphic processes in historical periods and predict geomorphic processes in the future. Later, tree rings played an important role in the study of geomorphic processes such as avalanche, debris flow and rockfall[25–28].

In the early 20th century, Hardman realized the great potential of using tree rings for hydrological research[29]. However, it was not until Sigafoos studied the tree differences before and after the Potomac flood event in 1961 that he preliminarily pointed out the relationship between riparian vegetation and flood frequency[30]. Sigafoos then put forward the theoretical basis of using tree rings to study floods. His research has played a great role in the field of paleohydrology[31]. The great potential of flood botanical evidence in paleohydrology proposed by him has been repeatedly demonstrated[32] and widely used. In recent years, the study of flash flood events under the background of long-time scale by using tree rings has been widely carried out in Northern America, Eastern Europe and Mediterranean mountain basin and other areas[18,33–38]. The relevant research gradually starts from the dating of flood events and the analysis of their cycle, frequency and intensity to analyze the driving mechanism of flash floods and the changes of tree ring anatomical characteristics after being affected by flash floods.

2.2 Sampling and recognition of growth disturbance signals

Growth disturbance signals, such as scars or bent branches of trees should be captured when doing wide sampling. Generally speaking, priority is given to disturbed trees at the exposed location of the river bank or on the inner side of the river[39,40]. For the disturbed tree, the growth sample core can be collected, and the sampling position can be as close to the scar as possible, or the wedge wood can be collected directly at the injured position[41]. For European conifers, growth cores are generally collected at the upper part of the injured position, because the radial extension of the traumatic resin channel generated by the tree response after interference is the largest above the wound[42,43]. In addition, dead tree discs or branches and exposed roots can also be collected to make cross-sectional samples. For curved trees, growth cores are collected at the curved position. For trees with damaged crown or abnormal stem morphology, growth cores shall be collected at the lower part of the injured area. When sampling, pay attention not to collect samples at other positions of the stem or in the area where scars are formed due to other factors (surrounding tree dumping, etc.)[37]. Besides these, we also should record the sampling height, DBH and the growth of surrounding trees, and take photos of the sampling trees. In addition, it is necessary to collect cores of healthy growth of the same tree species not affected by flash floods around the study area, and take one growth core on both sides of a tree to establish a local reference chronology, so as to provide basis for cross-dating. After the samples are collected back to the laboratory, the sample core is fixed on the sample slot with glue, and then the sample core or tree disc is dried and polished until the tree ring is clearly visible. The tree ring width is measured by the ring width meter. Before establishing the reference chronology, COFECHA program can be used to control the accuracy of dating and measurement[44].

Flood will hinder the normal radial growth of trees in the affected area and induce growth interference that can indicate the geomorphological process, including growth inhibition or release, deformed trees, abnormal growth, callus, scar or traumatic resin channel.

Among them, scar is the most widely used because it has a strong ability to provide flood time and water level information in historical periods[45,46]. **Figure 1** shows a variety of growth interference response types. During the flood, the water flow and its carriers may break the crown of shorter trees, which will cause a sudden slow-down of tree ring growth[31]. After the broken trees died, they will no longer compete with the surrounding trees, and the wheel width of the remaining trees will become wider, which is manifested as sudden growth and release. If the trees are bent due to the flood, the tree rings will show abnormal growth, and the wheel width on one side will be narrowed and the wheel width on the other side will be relatively widened. If the damage suffered by the tree is not enough to make it die, the tree will form scars in the next few years[34]. When the river bank is eroded by flood, the roots of trees beside the river bank will be exposed[47], which will not only change the wheel width, but also lead to significant changes in the anatomical structure of trees, usually including the reduction of early wood tracheid size and the increase of late wood cells[48,49], the reduction of lumen area and the increase of cell wall thickness resulting in the increase of the proportion of cell wall in early wood tracheids. The increase of cell wall thickness also leads to the decrease of radial length and tangential width of tracheids in early wood, and the increase of the number of wound resin channels in early wood and late wood[36]. However, when Pinusdensi-floraSieb is eroded by flood for a long time, the lumen size of plant cells will not change[50]. Moreover, the changes of anatomical characteristics of different tree species are different, and there are obvious tree species differences. For example, when analyzing the changes of anatomical characteristics of Almsglutinosal, Fraxinus Angustifolia Vahl and Quercus Pyrenaica Willd in the Mediterranean region after flash floods, it is found that the lumen area of the three tree species decreases after flash floods and the results of nonparametric test are significant, but the area changes of early wood fibers and parenchyma cells vary with different tree species, and the degree of change is not obvious. Therefore, flash floods cannot be identified only based on this[37].

In short, by comparing the ring width and other characteristics of disturbed and undisturbed trees, we can find the sudden growth change of disturbed trees[51], so as to determine the occurrence time of growth disturbance, and then provide the flash flood event sequence with annual resolution and even seasonal resolution on a long time scale, and provide basic information for flood model simulation in small watersheds.

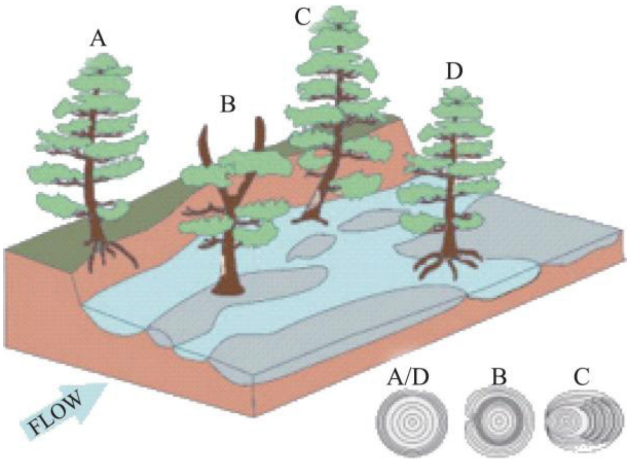

Figure 1. Predominant dendrogeomorphic macro-evidence in trees affected by flash floods and associated responses in tree-ring width and cell structure.

2.3 Dating and analysis of flash floods

The dating of flash floods often depends on the number of samples showing growth interference in the same year, the signal intensity of growth interference[52,53] and the spatial distribution of damaged trees in the river area[54]. When growth interference signals appear in tree rings for many years, only the first year of growth interference is often considered as the exact year of flash floods[55]. In practical application, it is generally necessary to define the index to determine the flash flood event. In individual years, the strength of flash flood signal can be expressed by the index I_t[56,57]. At first, the index was applied to the determination of avalanche disaster events. Afterwards, Šilhán[58] cited this index in the analysis of flash floods:

$$I_t = (\sum R_t / \sum A_t) \times 100\% \quad (1)$$

In this formula: R_t is the number of trees showing growth disturbance affected by flash floods in year t, and A_t is the number of all live trees collected in year t.

When the index is applied, a large number of samples need to be collected to avoid overestimation of recent interference events. The weight index W_t defined by Kogelnig Mayer *et al*., comprehensively considers the type, quantity and intensity of growth interference and the sample size that can be used for reconstruction[52]. This index was first used to analyze avalanche and debris flow events, and then cited in the analysis of flash floods:

$$W_t = [(\sum T_i \times 7)+(\sum T_s \times 5)+(\sum T_m \times 3)+\sum T_w] \times (\sum R_t / \sum A_t) \quad (2)$$

In this formula: T_i represents the number of trees with scars, and T_s, T_m and T_w represent the number of trees with strong, medium and weak growth interference respectively. Compared with index I_t, W_t takes into account the difference of growth interference intensity in tree rings. There may be many types of growth interference in trees, and the intensity is $T_i > T_s > T_m > T_w$. The strongest interference type should be selected for calculation during analysis. The application of this index has different standards in different study areas. Ballesteros-c á novas *et al*., reconstructed the flash floods in Guadalama Mountains of Spain[19]. When the weight index $W_t > 1$, it can be considered that a flash flood event occurred in that year. Ruiz Villanueva *et al*., also graded the weight of growth disturbance when reconstructing flash floods on the Perayo River in Spain and defined the weight index (WGD: weights of growth disturbances) with a value of 0.1 ~ 1 to distinguish the growth disturbance caused by flash floods to trees in different degrees[35]. In the end, they comprehensively considered the weight value of growth disturbance WGD, the ratio of the number of damaged trees to the analyzed trees in the same year (%DT: the percentage of damaged trees) and the spatial distribution of damaged trees in the river area (SD: spatial distribution of affected trees). The year of occurrence of flash floods is determined by the product of these three parameters (WGD×% DT×SD).

3 Advances in flash floods research based on tree rings

3.1 Single point and regional flash flood event reconstruction

Flash flood reconstruction can be divided into single point reconstruction and regional reconstruction, and most of the early work was single point reconstruction. Ballesteros-Cáno-Vas *et al*., collected 287 tree ring cores from 178 Scotch pine trees disturbed by flash floods, obtained 212 growth disturbance information related to flash floods, and reconstructed twenty-five flash floods in guadalama mountains of Spain from 1748 to 2011[19].

Ruiz-Villanueva *et al*., comprehensively used archival records, instrumental survey data and dendrogemorpholog methods to reconstruct 41 flash floods in Iron Tale River Basin in Spain since the end of the 19th century, and analyzed the frequency, intensity, seasonality and driving factors of flash floods. Among them, 60% of the 36 reliable flash floods occurred in autumn and winter, while the remaining 40% occurred in spring and summer Season[59].

Casteller *et al*., collected tree samples of Chilean Austrocedrus chilensis, Pseudotsuga menziesii and Nothofagus dombeyi with interference characteristics when analyzing flash floods in the Andes[55]. Disturbance features include scars, exposed roots, sloping, broken or buried stems. According to the characteristics of scar, eccentricity, sudden growth inhibition and release of reaction wood and tree rings, and tangential wound resin channels in tree rings, 21 flash floods in this area from 1890 to 2009 were reconstructed. It was found that the average recurrence cycle of flash floods was 37.4 years. Further analysis showed that 58.2% of flash floods occurred in dormant period, 29.1% and 12.7% of the events occurred in the growth period of early wood and late wood. It can be seen that using dendrogemorpholog can reconstruct the historical flash flood event information on a seasonal scale, and the occurrence of flash flood events has certain commonalities in the region. For example, the flash flood event in 1936 was found in many study areas in Spain.

With the development and deepening of flash floods reconstruction in a single watershed, the research tends to a larger spatial scale, that is, the flash floods in multiple watershed historical periods in a region. For example, Ballesteros-Cá novas *et al*., collected the sample cores of more than 1,100 injured trees affected by flash floods on the north slope of Tatra mountain in Poland and reconstructed the flash flood activities in the past 148 years with the method of dendrogemorpholog, and then discussed the temporal and spatial patterns of floods in the historical period of four rivers on the north slope of Tatra mountain[60]. He also analyzed the hydro meteorological driving factors of flash floods, including the indicators of total precipitation in 1, 3 and 5 days from April to October. By calculating the difference coefficient of effective precipitation data in the study area, he found that when the total precipitation in 3 days exceeds 100 mm, the water level will be higher than the usual 150%. Rodri-Guez morata *et al*., reconstructed 8 flash floods that were not recorded by historical data in the 20th century and early 21st century by analyzing 117 samples of 63 European Pinus sylvestris Linn affected by flash floods, so as to fill the gap of flash floods in seven rivers on the north slope of guadalama in central Spain in the past 200 years[61]. And Š ILHán collected 446 sections of injured tree roots and 192 sample cores in 10 watersheds around the highest peak of lishola mountain in the eastern Czech Republic, reconstructed the local historical flood, and obtained 64 flood events in 28 flood years from 1883 to 2012, and pointed out that most watersheds (90%) were affected by the flood in 1997[58].

3.2 Assessment of flash flood flow

The method of dendromorpholog can be used to evaluate the flow of flash floods, and the scar height is often used. The scar height can represent the lowest water level of the flood in that year[62]. When the flood inundates the trunk, it does not necessarily cause scars, but the existence of scars proves that the flood must have reached this height in that year. Some scholars hold different views on this. For example, McCord and Gottesfeld believe that the scar height represents the maximum water level of the river when flash floods occur[45,63]. Using Manning's equation, the height of scars in trees can be transformed into flood peak flow in the field[64].

Ballesteros-Cánovas *et al*., measured the slope of main rivers and the maximum height of scars in sampling trees in Gulu District, Himachal Pradesh, northwest India, and reconstructed the flood peak discharge in this area by using Manning equation[65].

When studying the flash flood situation of a river without historical records on the North slope of Tagus River Basin in Spain, Ballesteros-Cánovas *et al*., reconstructed a flash flood event on December 17, 1997 by using the information of the height and size of scars in trees a2ffected by flash flood, combined with two-dimensional hydraulic model and ground laser scanning technology[39]. The reconstructed peak flow was 79 ± 14 m^3/s, and the average deviation between flood level and scar height is -0.09 ± 0.53 M. Through further analysis, it is found that the geographical location of trees is the main factor to control the error, and the trees growing in exposed locations such as bedrock have the smallest evaluation error.

There is a certain error in evaluating flood peak discharge with scar height. When transported by flood, some materials such as wood debris forming scars can be located below the water surface, which can explain the reason for the error[66]. Of course, if the scar is formed before or after the flood peak, rather than when the flood peak comes, the flood peak flow assessed by the scar height may be smaller than the actual value. The possible reasons why the scar is higher than the actual water level are: when the flood breaks out and the local ultra-high water level exists, the material around the stem is deposited to form the scar[67,68]; the longitudinal propagation of cambium tissue and fiber damage can make the scar longer, so that the scar exceeds the position corresponding to the actual peak flow.

The flood peak discharge is reconstructed by scar height. The uncertainty of scar caused by debris carried by flood will increase with the increase of flood volume. Roughness can be used to quantitatively describe the uncertainty. In addition, sampling should be as far away from the bottom of the river as possible. And selecting scarred trees that can indicate large flash flood events can minimize the uncertainty[69].

In addition to the peak discharge analysis based on scar height, other methods can be used to analyze the flood size. Ballesteros-Cánovas *et al*., analyzed the relationship between stem inclination and flood size of trees affected by flood, and also tried to analyze the feasibility of using stem inclination to reconstruct flood size in historical period. They established a conceptual model of tree inclination[70]. Then they parameterized the model and compared the difference between observation data and simulation data. In the end, they analyzed that the inclination of tree stem base was correlated with flood size, which proved that the method was reliable.

3.3 Study on flash flood driving mechanism

The research on the driving mechanism of flash floods based on tree rings has also been carried out gradually in recent years. Casteller *et al*., reconstructed the temporal and spatial pattern of flash floods in a small watershed in the Andes mountains of Patagonia in the historical period with the method of dendromorpholog[55]. They also analyzed the possible flood driving factors in combination with climate data, and found that flash floods will occur when there is a large amount of precipitation in 1–3 days and the temperature of the whole watershed exceeds the rain / snow threshold (2 °C). Ballesteros-Cánovas *et al*., reconstructed the spatio-temporal pattern of flood in a river on guadalama mountains in central Spain from 1748 to 2011, analyzed the meteorological driving factors of flood in this region. Finally they found that there are great differences in rainfall thresholds of 1, 3 and 5 days during flood occurrence in different seasons, and flash flood events often occur in wet season (autumn and winter)[19].

Rodriguez-Morata *et al*., reconstructed the flash flood data of 7 rivers on the north slope of guadalama mountains in central Spain in the past 200 years based on scars and abnormal growth[61]. Through analysis, it was found that the total rainfall in 1, 3 and 5 days may be the factor driving the occurrence of flash floods. Ferrio *et al*., used isotopes in tree rings for the first time to analyze flash floods in the Tagus River Basin in Spain[38]. They collected samples of four tree species in the forest area affected by flash floods and obtained their data α Cellulose, and then the oxygen isotopic composition in tree rings and meteorological data, as well as the oxygen isotopic composition in rainfall $\delta^{18}O$ comparison to investigate the possible meteorological drivers of flash floods. After removing the spring signal of oxygen isotope in tree ring cellulose, it was found that the late wood $\delta^{18}O$ is related to heavy rainfall events, but the correlation between $\delta^{18}O$ in tree rings of different tree species and the meteorological elements will be different.

A series of studies on the driving factors of flash floods show that there is a great correlation between continuous heavy precipitation and flash floods. However, flash floods are often not driven by a single factor, and their occurrence is usually the result of the comprehensive action of a variety of meteorological elements. It can be seen that the tree ring dendrogemorpholog method provides more valuable information for understanding the driving mechanism of flash floods in the context of longer time scale, and is of great significance to the early warning and protection of flash floods.

4. Advantages, limitations and potential of flash flood research based on tree wheel

Compared with other flash flood research data, tree ring index has the advantages of accurate dating, high spatial resolution, sometimes time-resolved over seasonal resolution, long recording age and easy access to copies. In a typical flash flood prone area with large trees, trees can record multiple flash floods, recover the frequency and size of flash floods in the basin, and provide more data for exploring the climate driving mechanism of flash floods and also provide more background information for the prediction and prevention of flash floods.

In addition, the method is easy to implement and there are many available tree species. And analyzable samples are also easy to find. We can not only use single point tree samples to restore flash flood history, but also use regional multi-point samples for integrated analysis. Therefore, it has great advantages in obtaining the temporal and spatial variation characteristics of flash flood events under the background of long-time scale. Of course, this method also has some limitations. First of all, flash flood prone areas are often areas with high incidence of disasters such as landslide, debris flow and rockfall, which leads to the mixing of different types of disaster signals.

In addition, the scars of the trees affected by the flood can indicate the flood event, but the period without scars in the tree rings does not mean that they are not affected by the flood. The flood may have occurred, but its size is not enough to form scars. When trees are affected by floods for a long time, scars may not form in tree rings.

In addition, most of the scarred trees are distributed in or around the river. When a strong flood occurs, it is likely to cause the scarred trees to be cut off and die, and carry the tree stumps to the downstream area, which means that the reconstructed flood time series may not be complete, that is, it is difficult to reconstruct flash floods with a long time scale by dendrogemorpholog. The years with a large number of scars can indicate high-intensity flood, but the flood intensity of the remaining years with scars is difficult to define.

There may be flash flood events after the last flash flood event covered up. For example, it is often difficult to distinguish the events that occur continuously in one year or the next year, resulting in signal loss. The limitations listed above often vary with different regions. Therefore, in different regions, targeted sampling schemes need to be designed to minimize the impact of adverse conditions in order to obtain the most flash flood information. A large number of flash flood reconstruction work based on dendrogemorpholog has been carried out abroad, but there is no report of relevant work in China. China's Qinghai Tibet Plateau Sichuan Basin transition zone, the border between Sichuan and Yunnan, the Loess Plateau, the eastern coastal area and North China are prone to flash floods, and most areas are covered with forests. Therefore, using tree ring geomorphology to carry out flash floods research has great potential, opportunities and challenges[71].

(1) The development of dendrogemorpholog in China is relatively late, and the existing work is mainly concentrated in the field of dendroclimatology and dendroecology[72–76]. In recent years, the method of dendrogemorpholog has been slowly carried out in China, starting from a few early studies on ancient earthquakes using tree ring analysis to specific mountain disasters[77–80].

For example, Hong Ting *et al*., studied the years of landslide activity in Jiufang mountain in southern Gansu, the disaster assessment work carried out by Tie Yongbo *et al*., and Malik *et al*., in Moxi River Basin, Sichuan, and a series of research work on glacier activity in Southeast Tibet and along the Himalayas by means of dendrogemorpholog[81–87]. And Zhang *et al*., used the abnormal growth characteristics of Sabina przewalskii and It and Wt indexes to reconstruct the historical landslide work in the past 300 years for the first time in the Qilian Mountains[88]. These works show the great potential of dendrogemorpholog in domestic mountain disaster research, but the domestic flash flood reconstruction has not been carried out, which is a new research direction with great potential.

(2) Flash floods occur frequently in China. When using dendrogemorpholog to study flash floods, first of all, it is necessary to determine suitable tree species even though coniferous trees are widely used in dendrochronology. To carry out flash floods research, we must also start from the foundation, explore the appropriate sampling location of conifers and identify their response characteristics to disaster events. In fact, at present, most of the vegetations in flash flood prone areas in China are trees or shrubs, which need to be sampled and evaluated to explore the potential of disaster research. Therefore, the response characteristics of different shrubs and trees to mountain disasters are one of the important directions that need to be broken through in the future. In addition, due to regional differences, there are many means to define flash floods, but there is a lack of reliable standards, which need to be verified with the help of historical data or instrumental records. When I_t and W_t indexes are introduced into domestic research, including the definition of the intensity of flash flood events and so on, the appropriate threshold range should be determined according to the actual situation. In the end, when analyzing the characteristics of flash floods, according to the evaluation of peak discharge we need to build a small watershed flood model and determine the reasonable value of parameters in the conversion equation. It is also an important direction in the future to systematically build a flash flood event definition method suitable for domestic conditions and a small watershed flood simulation system.

In short, using dendrogemorpholog to study flash floods in China has a long way to go. We need to combine international experience and base on China's actual situation, start from the foundation and systematically carry out relevant research work.

Conflict of interest

The authors declare that they have no conflict of interest.

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References

1. Collier CG. Flash flood forecasting: What are the limits of predictability? Quarterly Journal of the Royal Meteorological Society 2007; 133: 3–23.
2. Georgakokoskp. On the design of a national real-time early warning system with site-specific lightning flood forecasting capability. Bulletin of the American Meteorological Society 1986; 67(10): 1233–1239.
3. Zhao S. Preliminary study on the overall characteristics and risk zoning of flash flood disaster system in China. Journal of Natural Disasters 1996; 5(3): 93–99.
4. Gao Y, Xing J, Wang C, *et al*. Cause and forecast of flash flood from rainstorm. Journal of Natural Disasters 2006; 15(4): 65–70.
5. Zhou C, Jin S. Damage cause and control measures

of flash flood hazard in Henan Province. Journal of Natural Disasters 2008; 17(3): 148–151.
6. Liu C, Miao T, Chen H, *et al*. Basic feature and origin of the"8·8" flash flood- debris flow disaster happened in Zhouqu County, Gansu, China, Aug. 8, 2010. Geological Bulletin of China 2011; 30(1): 141–150.
7. Zhang P, Ren H, Hu W, *et al*. An elementary study on Chinese flash floods disaster prevention regionalization. Journal of Soil and Water Conservation 2006; 20(6): 196–200.
8. Li Z, Yang D W, Hong Y, *et al*. Characterizing spatiotemporal variations of hourly rainfall by gauge and radar in the mountainous three gorges region. Journal of Applied Meteorology and Climatology 2014; 53(4): 873–889.
9. Liu Y S, Yuan X M, Guo L, *et al*. Driving force analysis of the temporal and spatial distribution of flash floods in Sichuan Province. Sustainability 2017; 9: 1527. doi: 10.3390/su9091527.
10. Jiang J, Shao L. Standard of flash flood warning based on the precipitation observation data. Journal of Hydraulic Engineering 2010; 41(4): 458–463.
11. Cheng W. A review of rainfall thresholds for triggering flash floods. Advances in Water Science 2013; 24(6): 901–908.
12. Li Q, Wang Y, Li H, *et al*. Rainfall threshold for flash flood early warning based on flood peak modulus. Journal of Geo-information Science 2017; 19(12): 1643–1652.
13. Tang C, Shi Y. Approach to mutil-objectives assessment for urban torrent hazard. Progress in Geography 2006; 25(4): 13–21.
14. Tang C, Zhu J. A GIS based regional torrent risk zonation. Acta Geographica Sinica 2005; 60(1): 87–94.
15. Chen H, Yang D W, Hong Y, *et al*. Hydrological data assimilation with the ensemble square-root-filter: Use of streamflow observations to update model states for real-time flash flood forecasting. Advances in Water Resources 2013; 59: 209–220.
16. Huang W, Cao Z, Qi W J, *et al*. Full 2D hydrodynamic modelling of rainfall-induced flash floods. Journal of Mountain Science 2015; 12(5): 1203–1218.
17. Cui P, Zou Q. Theory and method of risk assessment and risk management of debris flows and flash floods. Progress in Geography 2016; 35(2): 137–147.
18. George S, Nielsen E. Palaeoflood records for the Red River, Manitoba, Canada, derived from anatomical tree ring signatures. The Holocene 2003; 13(4): 547–555.
19. Ballesteros-Cánovas JA, Rodríguez-Morata C, Garó-fanoGómez V, *et al*. Unravelling past flash flood activity in a forested mountain catchment of the Spanish Central System. Journal of Hydrology 2014; 529: 468–479.
20. Stoffel M. Dating past geomorphic processes with tan-gential rows of traumatic resin ducts. Dendrochronologia 2008; 26(1): 53–60.
21. Wang Z, Qian Y. Frequency and intensity of extreme precipitation events in China. Advances in Water Science 2009; 20(1): 1–9.
22. She D, Xia J, Zhang Y, *et al*. The trend analysis and statistical distribution of extreme rainfall events in the Huaihe River Basin in the past 50 years. Acta Geographica Sinica 2011; 66(9): 1200–1210.
23. Ren Z, Zhang M, Wang S, *et al*. Changes in precipitation extremes in South China during 1961–2011. Acta Geographica Sinica 2014; 69(5): 640–649.
24. Fritts HC. Tree rings and climate. London, UK: Academic Press; 1976.
25. Alestalo J. Dendrochronological interpretation of geomorphic processes. Fennia 1971; 105: 1–139.
26. Butler DR. Snow avalanche path terrain and vegetation, Glacier National Park, Montana. Arctic and Alpine Research 1979; 11(1): 17–32.
27. Hupp CR. Dendrogeomorphic evidence of debris flow frequency and magnitude at Mount Shasta, California. Environmental Geology and Water Sciences 1984; 6(2): 121–128.
28. Stoffel M. A review of studies dealing with tree rings and rockfall activity: The role of dendrogeomorphology in natural hazard research. Natural Hazards 2006; 39(1): 51–70.
29. Hardman G. The relationship between tree growth and stream runoff in the Truckee River Basin, California-Nevada. Transactions, American Geophysical Union 1936; 17(2): 491–493.
30. Sigafoos RS. Vegetation in relation to flood frequency near. Washington DC, USA: United States Government Printing Office; 1961.

31. Sigafoos RS. Botanical evidence of floods and floodplain deposition. Washington DC, USA: United States Government Printing Office; 1964.
32. Baker VR. Palaeoflood hydrology and extraordinary flood events. Journal of Hydrology 1987; 96: 79–99.
33. Bégin Y. Tree-ring dating of extreme lake levels at the subarcticboreal interface. Quaternary Research 2001; 55(2): 133–139.
34. Zielonka T, Holeksa J, Ciapala S. A reconstruction of flood events using scarred trees in the Tatra Mountains, Poland. Dendrochronologia 2008; 26(3): 173–183.
35. Ruiz-Villanueva V, Díez-Herrero A, Stoffel M, *et al*. Dendrogeomorphic analysis of flash floods in a small ungauged mountain catchment (Central Spain). Geomorphology 2010; 118(3-4): 383–392.
36. Ballesteros JA, Stoffel M, Bodoque JM, *et al*. Changes in wood anatomy in tree rings of Pinus pinaster Ait following wounding by flash floods. Tree-Ring Research 2010; 66(2): 93–103.
37. Ballesteros JA, Stoffel M, Bollschweiler M, *et al*. Flash flood impacts cause changes in wood anatomy of Alnus glutinosa, Fraxinus angustifolia and Quercus pyrenaica. Tree Physiology 2010; 30(6): 773–781.
38. Ferrio JP, Díez-Herrero A, Tarrés D, *et al*. Using stable isotopes of oxygen from tree-rings to study the origin of past flood events: First results from the Iberian Peninsula. Quaternaire 2015; 26(1): 67–80.
39. Ballesteros-Cánovas JA, Eguibar M, Bodoque JM, *et al*. Estimating flash flood discharge in an ungauged mountain catchment with 2D hydraulic models and dendrogeomorphic palaeostage indicators. Hydrological Processes 2011; 25(6): 970–979.
40. Ballesteros-Cánovas JA, Stoffel M, Guardiola-Albert C.XRCT images and variograms reveal 3D changes in wood density of riparian trees affected by floods. Trees 2015; 29(4): 1115–1126.
41. Grissino-Mayer HD. A manual and tutorial for the proper use of an increment borer. Tree-Ring Research 2003; 59(2): 63–79.
42. Schneuwly DM, Stoffel M, Dorren LK, *et al*. Three-dimensional analysis of the anatomical growth response of European conifers to mechanical disturbance. Tree Physiology 2009; 29(10): 1247–1257.
43. Schneuwly DM, Stoffel M, Bollschweiler M. Formation and spread of callus tissue and tangential rows of resin ducts in Larix decidua and Picea abies following rockfall impacts. Tree Physiology 2009; 29(2): 281–289.
44. Grissino-Mayer HD. Evaluating crossdating accuracy: Amanual and tutorial for the computer program cofecha. Tree-Ring Research 2001; 57: 205–221.
45. Gottesfeld AS. British Columbia flood scars: Maximum flood-stage indicator. Geomorphology 1996; 14: 319–325.
46. George SS. Tree rings as paleoflood and paleostage indicators. Tree Rings and Natural Hazards 2010; 41: 233–239.
47. Stoffel M, Wilford DJ. Hydrogeomorphic processes and vegetation: Disturbance, process histories, dependencies and interactions. Earth Surface Processes and Landforms 2012; 37: 9–22.
48. Stoffel M, Casteller A, Luckman B H, *et al*. Spatiotemporal analysis of channel wall erosion in ephemeral torrents using tree roots: An example from the Patagonian Andes. Geology 2012; 40(3): 247–250.
49. Stoffel M, Butler DR, Corona C. Mass movements and tree rings: A guide to dendrogeomorphic field sampling and dating. Geomorphology 2013; 200: 106–120.
50. Yamamoto F, Kozlowski TT. Effects of flooding, tilting of stems, and ethrel application on growth, stem anatomy and ethylene production of pinus densiflora seedlings. Journal of Experimental Botany 1987; 38: 293–310.
51. Friedman JM, Vincent KR, Shafroth PB. Dating floodplain sediments using tree-ring response to burial. Earth Surface Processes and Landforms 2005; 30(9): 1077–1091.
52. Kogelnig-Mayer B, Stoffel M, Schneuwly-Bollschweiler M, *et al*. Possibilities and limitations of dendrogeomorphic time-series reconstructions on sites influenced by debris flows and frequent snow avalanche activity. Arctic, Antarctic, and Alpine Research 2011; 43(4): 649–658.
53. Stoffel M, Corona C. Dendroecological dating of geomorphic disturbance in trees. Tree-Ring Research 2014; 70(1): 3–20.
54. Schneuwly-Bollschweiler M, Corona C, Stoffel M.

Howto improve dating quality and reduce noise in tree-ring based debris-flow reconstructions. Quaternary Geochronology 2013; 18: 110–118.

55. Casteller A, Stoffel M, Crespo S, *et al*. Dendrogeomorphic reconstruction of flash floods in the Patagonian Andes. Geomorphology 2015; 228: 116–123.
56. Shroder JF. Dendro-geomorphological analysis of mass movement on Table Cliffs Plateau, Utah. Quaternary Research 1978; 9(2): 168–185.
57. Butler DR, Malanson GP. A reconstruction of snow-avalanche characteristics in Montana, USA using vegetative indicators. Journal of Glaciology 1985; 31: 185–187.
58. Šilhán K. Frequency, predisposition, and triggers of floods in flysch Carpathians: Regional study using dendrogeomorphic methods. Geomorphology 2015; 234: 243–253.
59. Ruiz-Villanueva V, Diez-Herrero A, Bodoque J M, *et al*. Characterisation of flash floods in small ungauged mountain basins of Central Spain using an integrated approach. Catena 2013; 110: 32–43.
60. Ballesteros-Cánovas JA, Czajka B, Janecka K, *et al*. Flash floods in the Tatra Mountain streams: Frequency and triggers. Science of the Total Environment 2015; 511: 639–648.
61. Rodriguez-Morata C, Ballesteros-Cánovas JA, Trappmann D, *et al*. Regional reconstruction of flash flood history in the Guadarrama range (Central System, Spain). Science of the Total Environment 2016; 550: 406–417.
62. Harrison SS, Reid JR. A flood-frequency graph basedon tree-scar data. Proceedings of the Northern Dakota Academy of Sciences 1967; 21: 23–33.
63. McCord VA. Fluvial process dendrogeomorphology: Reconstructions of flood events from the southwestern United States using flood-scarred trees. Dean JS, MekoDM, Swetnam TW. Tree rings, environment and humanity. Tucson, USA: University of Arizona; 1996. p. 689–699.
64. Jarrett RD, England J. Reliability of paleostage indicators for pale of lood studies. House PK, Webb RH, Baker VR, *et al*. Ancient floods, modern hazards: Principles and applications of paleoflood hydrology. Water science and application Vol. 5.Washington DC, USA: American Geophysical Union; 2002. p. 91–109.
65. Ballesteros-Cánovas JA, Trappmann D, Shekhar M, *et al*. Regional flood-frequency reconstruction for Kullu district, Western Indian Himalayas. Journal of Hydrology 2017; 546: 140–149.
66. Webb RH, Jarrett RD. One-dimensional estimation techniques for discharges of paleofloods and historical floods. House PK, Webb RH, Baker VR, *et al*. Ancient floods, modern hazards: Principles and applications of paleoflood hydrology. Water Science and Application, vol. 5. Washington D C, USA: American Geophysical Union; 2002. p. 111–125.
67. Darby S. Effect of riparian vegetation on flow resistence and flood potential. Journal of Hydraulic Engineering 1999; 125(5): 443–454.
68. Carling PA, Hoffman M, Blatter AS. Initial motion of boulders in bedrock channel. House PK, Webb RH, Baker VR, *et al*. (editors). Ancient floods, modern hazards: Principles and applications of pale of lood hydrology. Water Science and Application, vol. 5. Washington D C, USA: American Geophysical Union; 2002. p. 147–160.
69. Ballesteros JA, Bodoque JM, Díez-Herrero A, *et al*. Calibration of floodplain roughness and estimation of flood discharge based on tree-ring evidence and hydraulic modelling. Journal of Hydrology 2011; 403(1-2): 103–115.
70. Ballesteros-Cánovas JA, Márquez-Peñaranda JF, SánchezSilva M, *et al*. Can tree tilting be used for pale of flood discharge estimations? Journal of Hydrology 2015; 529: 480–489.
71. Guo L, Zhang X, Liu R, *et al*. Achievements and preliminary analysis on China national flash flood disasters investigation and evaluation. Journal of Geo-information Science 2017; 19(12): 1548–1556.
72. Shao XM, Xu Y, Yin ZY, *et al*. Climatic implications ofa 3585-year tree-ring width chronology from the northeastern Qinghai-Tibetan Plateau. Quaternary Science Reviews 2010; 29: 2111–2122.
73. Yang B, Qin C, Wang JL, *et al*. A 3,500-year tree-ring record of annual precipitation on the northeastern Tibetan Plateau. PNAS 2014; 111(8); 2903–2908.
74. Zhang QB, Evans MN, Lyu LX. Moisture dipole over the Tibetan Plateau during the past five and a half centuries. Nature Communications 2015; 6:

8062. doi: 10.1038/ncomms9062.
75. Liang EY, Wang YF, Piao SL. Species interactions slow warming-induced upward shifts of treelines on the Tibetan Plateau. PNAS 2016; 113(16): 4380–4385.
76. Liu Y, Cobb KM, Song HM, *et al*. Recent enhancement of central Pacific EI Niño variability relative to last eight centuries. Nature Communications 2017; 8: 15386. doi: 10. 1038/ncomms15386.
77. Han T. The dendrochronological method: A new method for determining the ages of seismic deformational belts in Damxung of Xizang (Tibet). Journal of the Chinese Academy of Geological Sciences 1983; (6): 95–110.
78. Han T. Discussion on epicentral locations for the Tibet M=8 earthquake on 29, September 1411. Seismology and Geology 1984; 6(4): 6–12.
79. Yang B, Liu B, Zhou J. Tree seismological study of active Gulang and Jingtai fault in Gansu Province. Seismology and Geology 1995; 17(2): 139–147.
80. Lin AM, Lin SJ. Tree damage and surface displacement: The 1931 M 8.0 Fuyun earthquake. The Journal of Geology 1998; 106: 751–757.
81. Hong T, Bai S, Wang J, *et al*. Reconstruct the activity years of Jiufangshan landslide by means of tree-rings. Journal of Mountain Science 2012; 30(1): 57–64.
82. Tie Y, Malik I, Owczarek P. Dendrochronological dating of debris flow historical events in high mountain area: Take Daozao debris flow as an example. Mountain Research 2014; 32(2): 226–232.
83. Malik I, Wistuba M, Tie YB, *et al*. Mass movements of differing magnitude and frequency in a developing highmountain area of the Moxi Basin, Hengduan Mts, China: A hazard assessment. Applied Geography 2017; 87: 54–65.
84. Yang B, Bräuning A, Dong ZB, *et al*. Late Holocene monsoonal temperate glacier fluctuations on the Tibetan Plateau. Global and Planetary Change 2008; 60: 126–140.
85. Xu P, Zhu H, Shao X, *et al*. Tree ring-dated fluctuation history of Midui glacier since the Little Ice Age in the southeastern Tibetan Plateau. Science China: Earth Sciences 2012; 42(3): 380–389.
86. Zhu HF, Shao XM, Zhang H, *et al*. Trees record changes of the temperate glaciers on the Tibetan Plateau: Potential and uncertainty. Global and Planetary Change 2019; 173: 15–23.
87. Zhu HF, Xu P, Shao XM, *et al*. Little Ice Age glacier fluctuations reconstructed for the southeastern Tibetan Plateau using tree rings. Quaternary International 2013; 283: 134–138.
88. Zhang Y, Stoffel M, Liang E Y, *et al*. Centennial-scale process activity in a complex landslide body in the Qilian Mountains, northeast Tibetan Plateau, China. Catena 2019; 179: 29–38.