

Article

Driving Force Exploration for Flash Flood Based on Mann–Kendall Test and Geographical Detector: A Case Study of Hainan Island, China

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Abstract: Flash floods are among the deadliest hazards in China and have led to substantial casualties and losses, especially on Hainan Island. Therefore, it is of great significance to explore the main driving force behind them. Nevertheless, research on the driving force of flash floods is limited here. This study explores the driving force of flash floods on Hainan Island from 14 factors involving three categories: natural, social, and rainfall factors. Two quantitative methods, like the Mann–Kendall test and the geographical detector method, are applied. The Mann–Kendall test is usually used for time series trend analysis and is introduced to divide the flash flood periods into D95 (years from 1980 to 1995) and D14 (years from 1996 to 2014) through the results of reported flash flood trend analysis. The geographical detector is applied to analyze the driving force of flash floods. There are several key findings from this study that help better understand the driving force about flash floods. Firstly, the results show that the main driving forces of flash floods are natural factors like Elevation and Soil in both periods, and they are on the rise. Secondly, the influence of short-term heavy rainfall on flash floods is becoming more and more serious. Thirdly, even though the driving forces from social factors to flash floods are small, the impact of population density on that is significantly increasing.

Keywords: flash flood; driving force; Mann–Kendall test; geographical detector



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1. Introduction

Flash flooding refers to the sudden surface runoff caused by rainfall in small drainage basins in hilly areas and is one of the most serious natural disasters around the world [1–3]. It is particularly true for China, where 560 million residents are threatened throughout areas prone to flash floods [4]. Therefore, it is significant to recognize the driving force behind flash floods, which will help better understand the causes of them and reduce losses.

In recent years, research on flash floods has gradually become a hot spot [5–8]. Extensive research points out that flash flooding is a complex problem caused by various factors [9]. Wang et al. (2022) suggested that unusual rainfall is the primary cause of the failure of the tailing dams, which is easy to cause a flood disaster [10]. Zhou et al. (2022) announced that lakes are an important component of the terrestrial hydrosphere and have a strong influence on the regional hydrological cycle [11]. Xie et al. (2022) proposed that situational states, meteorological factors, emergency activities, decision makers' emotions, and emergency targets are the key factors for flood control and disaster reduction [12]. In addition, Embankment Dam Break is defined as a key scenario causing flash floods, as many dams around the world withhold large quantities of water. Floods caused by their failures have historically resulted in catastrophic life losses [13]. In summary, flash flooding

is an interface dynamic between geoterrain system factors such as geology, geomorphology, soil, drainage density, slope, and flood, rather than only water movement from higher to lower elevation [14].

Gradually, a large number of methods (qualitative and quantitative) have been developed to explore the underlying causes of flash floods, and substantial and meaningful results have been achieved. Monsoon winds, rainfall, land use, land cover, steep topography, and physical features are regarded as the underlying causes of flash floods by Mahmood et al. (2016) [15]. These factors are tested by applying questionnaire-based household surveys, structured interviews, and geographic information systems (GISs). Diakakis et al. (2016) studied the impacts of various factors (total accumulated rainfall, soil sealing, the distance from the river network, slope, altitude, and flow accumulation factor) on flash floods in urban areas based on logistic regression, statistical significance, and other metrics [16]. In order to further explore the formation mechanism of flash floods, some scholars have developed integrated methods to analyze the driving forces of flash floods. Mahmood et al. (2017) applied a combination of seven approaches, including rainfall analysis, drinking water quality analysis, and so on, to identify the chief causal factors (natural and social) for the increasing level of flash flood risk, and the results have great significance for disaster reduction in the local area [17].

Gradually, some scholars have begun to pay attention to the research on the changing law of the driving force of flash floods. Liu et al. (2017) studied the driving force evolution of flash floods in two subjectively divided periods of Sichuan Province and argued that human activities and precipitation are the main reasons for the flash floods in the local [18]. Billi et al. (2015) explored the relationship between the evolution of flash floods, rainfall intensity, and land use change in the town of Dire Dawa [19]. Špitalar et al. (2014) adopted an interdisciplinary approach to aid in the interpretation of the results given that flash flooding had strong influences from meteorological, hydrological, and societal factors in the period of 2006 to 2012 [20]. Llasat et al. (2014) explored the relationship between the evolution of flash floods and the various factors (precipitation, population density and socio-economic factors) in Catalonia and argued that changes in population density, and land use are the primary reasons for the trend of flash floods [21].

However, most of these studies contain certain subjectivity, such as time stage division, index weight identification, or the process of data processing. In this study, two quantitative and objective methods, like the Mann–Kendall test and the geographical detector, are applied to identify the main driving force of flash floods on Hainan Island. The Mann–Kendall test is one of the most widely used distribution-free tests of trend in time series, which has the advantage that its power and significance are not affected by the actual distribution of data [22–24]. In this study, the Mann–Kendall test is used to divide historical flash floods into two periods, namely D95 (years from 1980 to 1995) and D14 (years from 1996 to 2014).

Hydrological connectivity indicators are usually adopted to detect spatial heterogeneity and reveal the driving force behind a hydrologic phenomenon [25]. However, presently there is confusion around the definition of hydrological connectivity because it has been interpreted and measured differently by researchers, which may lead to different driving force identification results for the same phenomenon. In consequence, this study attempts to introduce a method to identify flash flood driving forces based solely on spatial and geographic relations. Geographical detection is another powerful tool for driving force and factor analysis. The geographical detector method was first proposed by Wang et al. (2010) [26] and used to assess the relationship between risk factors and the distribution of human diseases. It is a new statistical method to detect spatially stratified heterogeneity and reveal the driving factors behind one phenomenon. Meanwhile, the method has the advantage that it has no linear hypothesis. Meanwhile, the method has the advantage that it has no linear hypothesis in the process of calculating the driving force [27], which can identify the relationship between two variables from a scientific objective point of view, whether it is a qualitative indicator or a quantitative indicator. Consequently, a geographi-

cal detector is introduced to compute the driving force of flash floods from various factors in this study.

The paper is devoted to exploring three categories of factors (natural, social, and rainfall) and their interactions to understand flash flood patterns on Hainan Island during two distinct periods. It has the potential to contribute to the development of effective flood prevention and mitigation strategies on Hainan Island. The use of both the Mann–Kendall test and the geographical detector provides a robust and comprehensive approach to analyze flash flood trends and identify the driving forces. These methods are well-suited for the study's objectives and are commonly employed in time-series trend analysis and geographical research.

The paper is organized as follows: Firstly, flash flood periods are divided into D95 and D14 based on the Mann–Kendall test. Secondly, three categories (natural, social, and rainfall) of a total of 14 factors related to flash floods are selected for main driving force identification. Thirdly, the main driving force results of flash floods from different factors at two periods are expressed and analyzed based on the geographical detector method. Finally, the direction and challenges of flash flood prevention and management are discussed.

2. Study Area

Hainan Island (Figure 1) is located at the southernmost tip of China, between $18^{\circ}10' \text{ N}$ and $20^{\circ}10' \text{ N}$ and $108^{\circ}37' \text{ E}$ and $111^{\circ}03' \text{ E}$. The area of the island is about $33,900 \text{ km}^2$, which makes it the second-largest island in China after Taiwan. The elevation of Hainan Island varies from high to low, from the middle area to all sides. The mountainous area of Hainan Island accounts for 38.7% of the total area. Hainan Island has abundant rainfall, and the average annual rainfall is about 1750 mm [4]. The island is one of the districts most frequently affected by flash floods in China, and there had been 2032 flash floods reported by the end of 2014. The flash floods occurred frequently in catchments, which has caused serious casualties and property losses in Hainan Island. Therefore, it is urgent to explore the driving force of flash floods here, providing a scientific basis for disaster prevention and reduction.

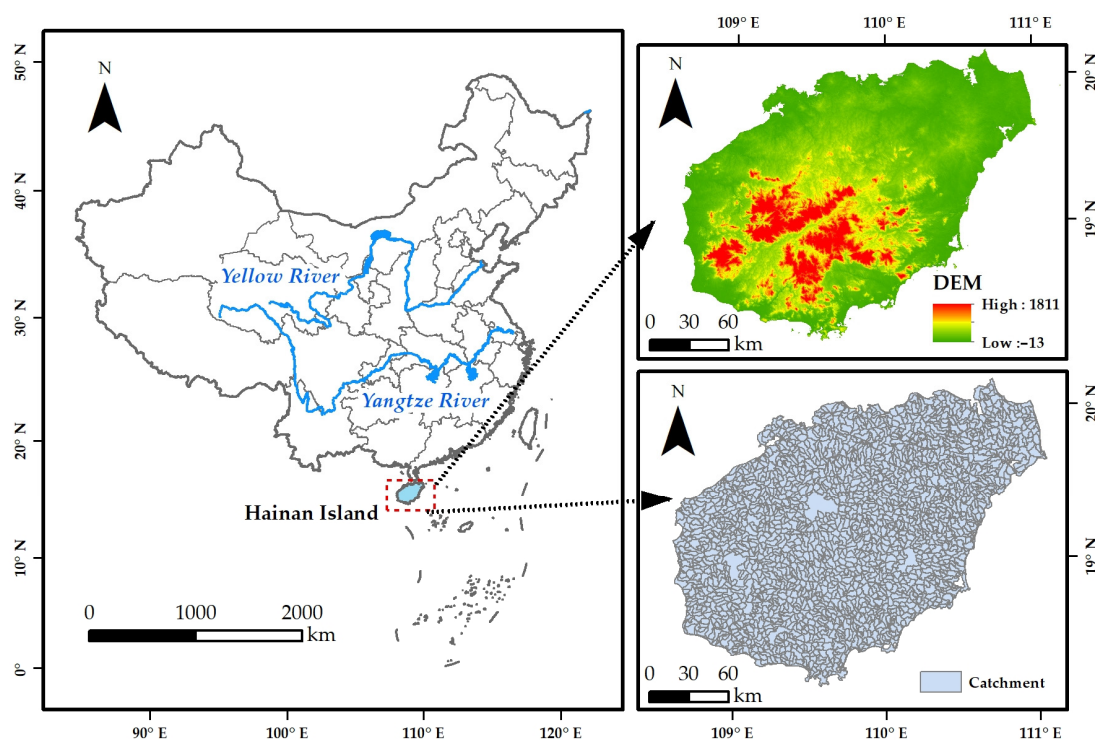


Figure 1. Location map and characteristics of the study area.

3. Materials and Methods

The Mann–Kendall test and the geographical detector method are introduced in this study. The Mann–Kendall test is used to perform the flash flood trend analysis, obtaining the period division. The geographical detector is applied to analyze the driving force of flash floods here (Figure 2).

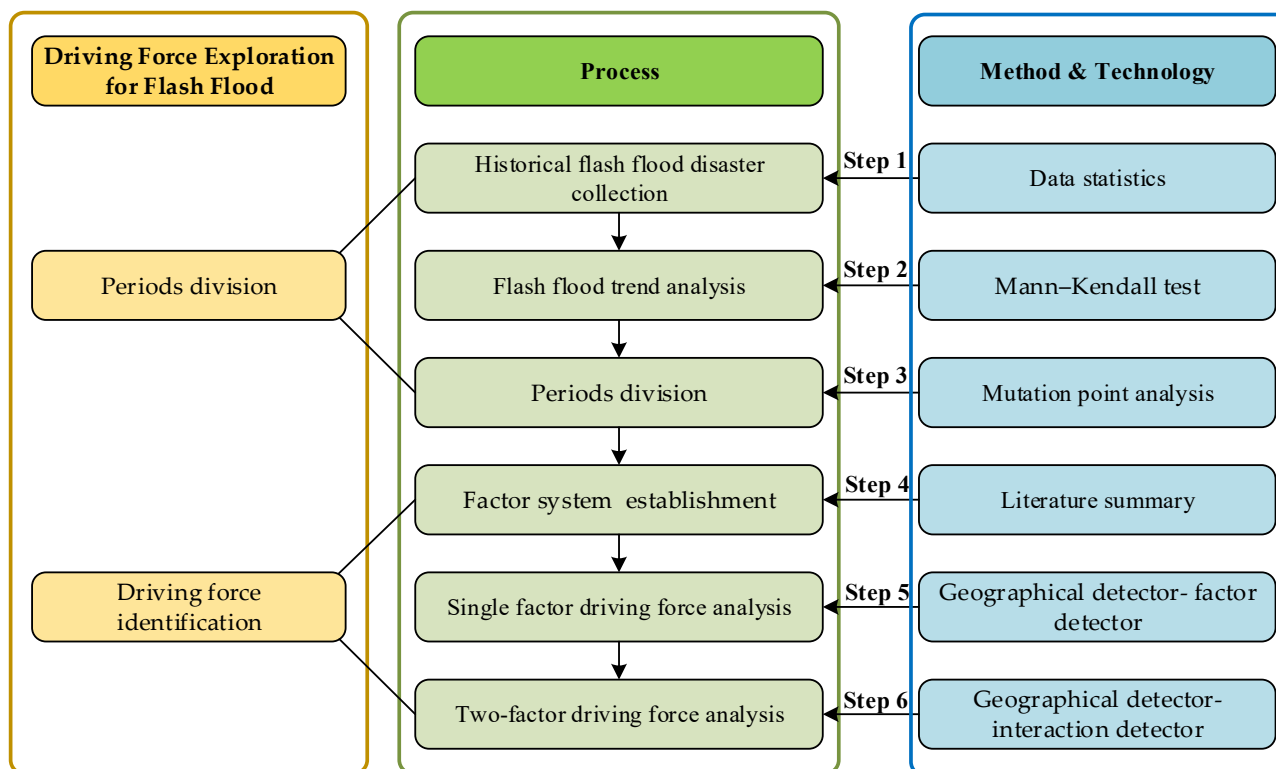


Figure 2. Technology roadmap of driving force exploration for flash floods.

3.1. Mann–Kendall Test

The Mann–Kendall test (MK test) was first developed by Kendall and Mann [28,29]. The test has been widely applied to evaluate the significance of trends in meteorological time series [30]. The test does not assume any distribution form for the data source, and it has similar power as parametric competitors. Goossens and Berger (1986) further developed the method, which was able to roughly identify the starting position of various trends [31]. Cao et al. (2013) then applied this method to the reverse sequence, resulting in a new method for detecting abrupt points of climate change [32]. In this study, the MK test for detecting abrupt change is applied to historical flash floods in the study area for period division. The process is as follows:

$$d_k = \sum_{i=1}^k m_i, (k = 2, 3, 4 \dots n) \quad (1)$$

$$E(d_k) = k(k-1)/4 \quad (2)$$

$$Var(d_k) = k(k-1)(2k+5)/72 \quad (3)$$

$$UF_k = \frac{d_k - E(d_k)}{\sqrt{Var(d_k)}} \quad (4)$$

where d_k and UF_k are statistical variables, m_i represents the number of flash floods in the i th year greater than that of the j th year, $E(d_k)$ is the mean value of d_k , and $Var(d_k)$ is the variance of d_k .

Repeat the process for the inverse sequence of time series samples, and then define as follows:

$$UB_k = -UF_k \quad (5)$$

The UB_k and UF_k curves can be drawn in the same coordinates. If the two curves' intersection appears in the confidence lines, the intersection is the abrupt site. Then the time at the abrupt site will be the partitioning point for periods.

3.2. Geographical Detector

Geographic detection is a new statistical method that can detect spatial heterogeneity and reveal the driving force behind a phenomenon. It is a spatial variance analysis tool first developed by Wang et al. (2010) [26]. It is first used to assess the relationship between risk factors and human diseases. The tool's core idea is based on the assumption that if one variable has a significant effect on a dependent variable, then the two variables will have a similar spatial distribution. Factor detectors and interaction detectors are two tools in the geographical detector. The factor detector can be used to detect the driving force of flash floods from each factor. The principle is to compare the sum of the dispersion variance from every sub-region with that of the entire region. While the interaction detector is able to identify the total contribution of two variables to the distribution of the dependent variable.

In this study, the factor detector and interaction detector are applied to analyze the driving force of flash floods at two periods on Hainan Island, China. Here, we give the process based on our present context as follows:

Define X as a layer of data representing the factors that may have an impact on the spatial distribution of Y . In this study, Y represents flash flood intensity. Based on the calculation principle of the geographic detector, X should be a categorical layer. If the factor is not a categorical layer, it needs to be classified according to certain principles (e.g., average rainfall can be classified into several categories as very high, high, moderate, low, and very low). Then the driving force from X to Y is measured by the potential driving force (PD) as follows:

$$PD = 1 - \frac{1}{N\sigma^2} \sum_{h=1}^L N_h \sigma_h^2 \quad (6)$$

$$\sigma_h^2 = \frac{1}{N_h - 1} \sum_{i=1}^{N_h} (N_{h,i} - \bar{N}_h)^2 \quad (7)$$

$$\sigma^2 = \frac{1}{N - 1} \sum_{j=1}^N (N_j - \bar{N})^2 \quad (8)$$

where PD indicates the driving force from X to the distribution of flash flood intensity. PD is a value between 0 and 1, where $PD = 0$ means that there is no relationship between X and Y , and $PD = 1$ means that Y is completely determined by X . N is the number of all samples in the entire study area; σ^2 is the global variance of Y in the Hainan island; N_h is the samples' number of Y in zone h ; σ_h^2 is the variance of Y in zone h ; L is the number of zones; $N_{h,i}$ is the value of Y in the i th sample of zone h ; $\bar{N}_h$ is the average value of Y in zone h ; N_j is the value of the j th sample unit in the whole study area; and $\bar{N}$ is the global average value of Y in the entire Hainan island.

In order to indicate the interactive influence on Y from X_1 and X_2 , the interaction detector in the geographical detector can be employed. $PD(X_1 \cap X_2)$ indicates the potential driving force from both X_1 and X_2 to the distribution of flash floods. The calculation principle is the same as that of the factor detector. Through the results of the factor detector and interaction detector, we can explore the main driving force to the distribution of flash floods from the factors selected.

3.3. Input Data and Classification

In this study, a factor system for driving force analysis is established according to the concept of risk. Risk is the combination of hazards, exposure, and vulnerability [33]. Hazard refers to extreme weather events. Exposure refers to the factors that may affect stress or disturbance. Vulnerability refers to the degree to which a system may be affected. According to the definition of risk and the literature review in the introduction part, 14 layers of factors are selected to analyze their driving force for flash floods at the catchment scale in Hainan Island. All factors are grouped into natural factors (factors related to catchment morphology), social factors (factors related to population economy), and rainfall factors (factors related to rainfall intensity). These three groups reflect the exposure, vulnerability, and hazard aspects of the risk definition, respectively.

The details of the input data are shown in Table 1. All factors should be classified into categorical layers according to the principle of the geographical detector. The meaning and classification of different factors are explained as follows:

- (1) Soil, Veg, and LU

Table 1. Factors selected for analysis.

Category	Factors	Factor Code	Time	Resolution	Data Sources
Natural factors	Elevation (m)	Ele	2014	30 m × 30 m	FFIEDC ¹
	Slope (°)	Slp	2014	30 m × 30 m	FFIEDC ¹
	Soil	Soil	2014	30 m × 30 m	FFIEDC ¹
	River density (1/km)	RD	2014	30 m × 30 m	FFIEDC ¹
	Vegetation type	Veg	1995, 2010	1 km × 1 km	RESDC ²
Social factors	Gross domestic product (yuan/km)	GDP	1995, 2010	1 km × 1 km	RESDC ²
	Land use	LU	1995, 2010	1 km × 1 km	RESDC ²
	Population density (person/km ²)	POP	1995, 2010	1 km × 1 km	RESDC ²
	Small reservoir density	SRD	2014	30 m × 30 m	FFIEDC ¹
Rainfall factors	Annual rainfall (mm)	P	1980–2014	30 m × 30 m	HNHWB ³
	Maximum 10 min rainfall (mm)	P10	1980–2012	30 m × 30 m	HNHWB ³
	Maximum 1 h rainfall (mm)	P1	1980–2012	30 m × 30 m	HNHWB ³
	Maximum 6 h rainfall (mm)	P6	1980–2012	30 m × 30 m	HNHWB ³
	Maximum 24 h rainfall (mm)	P24	1980–2012	30 m × 30 m	HNHWB ³
Flash flood intensity	Recorded flash flood intensity	FFI	1938–2014		FFIEDC ¹

¹ Flash Flood Investigation and Evaluation Dataset of China (FFIEDC). ² Resources and Environmental Sciences Data Center (RESDC), Chinese Academy of Sciences (<http://www.resdc.cn>). ³ Hainan Province Hydrology and Water Resources Investigation Bureau (HNHWB).

These three factors are already categorical layers. The type of catchment for the three factors is characterized by the type that occupies the maximum percentage of the catchment.

- (2) Ele and Slp

The value of the two factors in a catchment is represented by their mean value. Ele and Slp are classified according to the criteria of elevation and slope classification in the geomorphology.

- (3) RD

RD in a catchment is the mean river density of the area and is classified by the natural breaks method, which is designed to determine the best arrangement of values into different intervals and seek to reduce the variance within intervals and maximize the variance between intervals [33].

- (4) GDP, POP, P, P10, P1, P6, and P24

GDP, POP, P, P10, P1, P6, and P24 are the mean values in a catchment, respectively. They are all classified according to the natural break method as well.

(5) FFI and SRD

To evaluate the intensity of flash floods, the Getis–Ord's G_i^* statistic of hot spot analysis is employed. Getis–Ord's G_i^* can both express the presence of local clustering and indicate the clustering of locations and intensity [34–36]. In this paper, an optimization hot spot analysis tool based on the Getis–Ord G_i^* algorithm is adopted to quantify flash flood intensity. The z-score (standardization of G_i^*) of flash flood points is converted into grid data using the optimized hot spot analysis tool in the Geographic Information System (ArcGIS) 10.2, and then the grid data are converted into $1 \text{ km} \times 1 \text{ km}$ raster data to characterize the flash flood intensity of a unit. The mean value of the z-score is used to represent the flash flood intensity in a catchment. The quantization method of SRD is the same as that of FFI. The classification of SRD is based on the natural break method as well.

4. Results

4.1. Periods Division Results for Flash Floods

Based on the recorded flash floods in 1938–2014 on Hainan Island, the MK test is applied to detect the time of the abrupt site. The result of the MK test is shown in Figure 3. It is obvious that the intersection of the UF(r) and UB(r) lines is point P (1995, 1.52), which is in the 95% confidence interval. UF(r) and UB(r) are the statistical variables for reported flash floods in the MK test, calculated as Equations (4) and (5). The result indicates that a sudden change in the trend of flash floods happened in 1995. Consequently, the two periods about the flash floods on Hainan Island are divided. The years 1938–1995 are divided into the first period, while 1996–2014 are the second period. Moreover, since 1995, the value of UB(r) has been basically above zero, which indicates that flash floods show a significant upward trend. Considering that the rainfall data in driving force analysis is only from 1980 to 2014, here we choose flash floods from 1980 to 1995 as the D95 period and 1996 to 2014 as the D14 period for the driving force exploration of flash floods.

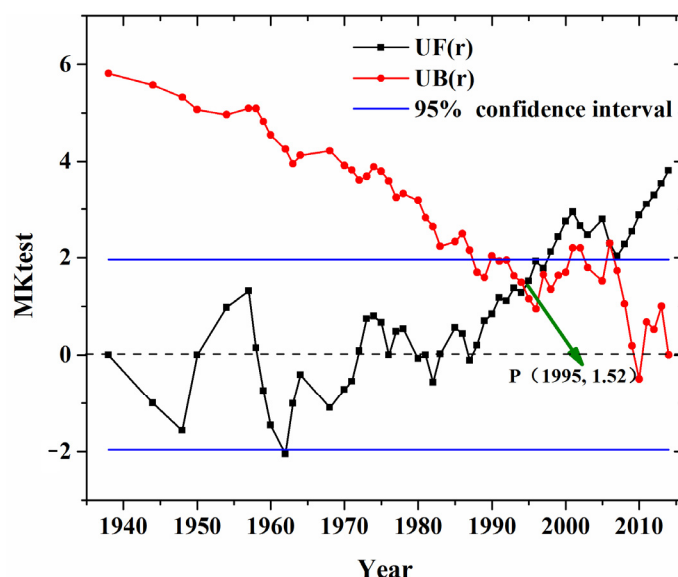


Figure 3. The MK test about the recorded flash floods on Hainan Island.

4.2. Results of Flash Flood Intensity and Factors in D95 and D14

Based on the results of the period division about the reported flash floods in Hainan Island, the spatial distribution of FFI and factors will be discussed in periods D95 and D14. Then they will provide the basis for a two-period driving force analysis of flash floods on Hainan Island.

4.2.1. Flash Flood Intensity

There are 146 flash floods in D95, and the spatial distribution of them is shown in Figure 4a. Then the flash flood intensity of D95 is obtained through the optimized hot spot analysis tool in ArcGIS 10.2. As shown in Figure 4b, areas with very high FFI are concentrated in the southeast of the island, while areas with very low FFI are mainly located in the northeast of the island. In D14, there are 1822 flash floods shown in Figure 4c, and the distribution of FFI in D14 is obtained in Figure 4d by the same method as that of D95. It is obvious that the distribution pattern of FFI in D95 and D14 has changed. The areas with very high FFI in D14 have transferred to the northeast of the island, while areas with very low FFI appear in the central and southern parts of the island.

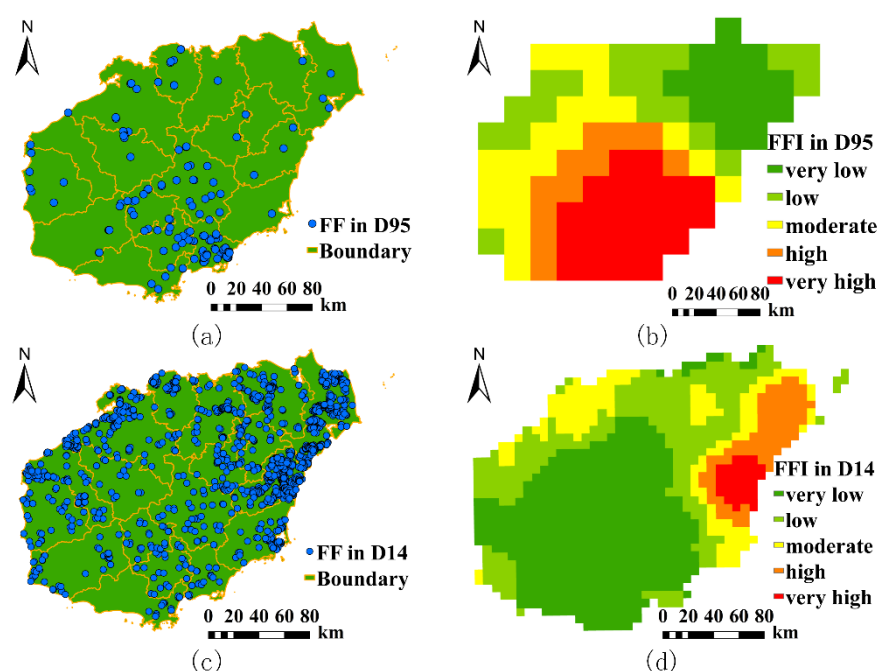


Figure 4. Spatial distribution of flash floods: (a) flash flood points in D95; (b) flash flood intensity in D95; (c) flash flood points in D14; and (d) flash flood intensity in D14.

4.2.2. Natural Factors

The natural factors adopted in this study are regarded as static factors in D95 and D14, mainly including elevation, slope, soil, river density, and vegetation type. The overall distribution pattern of elevation on the island is that the middle area is high, and the surrounding area is decreasing step by step. Meanwhile, the slope distribution pattern is similar to that of elevation. There are a total of 28 soil types, such as laterite, latosolic red soil, paddy soil, etc. The river density is mainly concentrated in the 0.2 to 16 range. There are a total of 26 vegetation types, such as coniferous forest, broad-leaved forest, bushwood, etc. The spatial distribution and categories of natural factors are shown in Figure 5.

4.2.3. Social Factors

The social factors considered in this study include GDP, land use, population density, and small reservoir density. The former three factors vary from D95 to D14, and here we use the data from 1995 to represent the whole situation for D95 and 2010 for D14 of the three factors, considering the possibility of data collection. The distribution patterns of GDP in different periods are shown in Figure 6. High-GDP districts are mainly in coastal areas of the two periods. The areas with high population density are mainly in the northern and coastal areas of the island, in both D95 and D14. In terms of LU, forest and meadow occupy most of the island, and the next is plough. Additionally, the small reservoir (SR) in this study is regarded as a static factor in D95 and D14, and the data are from 2014. The

SRD layer can be obtained by the same method as FFI. The high SRD is mainly located in the northeast and southwest of the island. The spatial distribution and categories of social factors in D95 and D14 are shown in Figure 6.

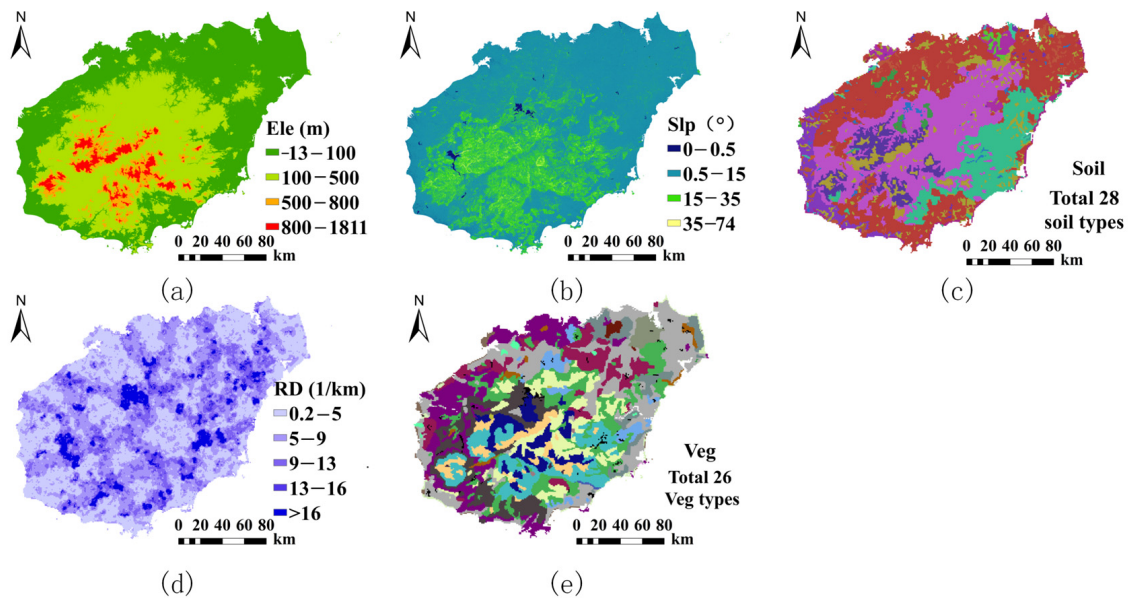


Figure 5. Spatial distribution and categories of natural factors: (a) elevation; (b) slope; (c) soil; (d) river density; and (e) vegetation type.

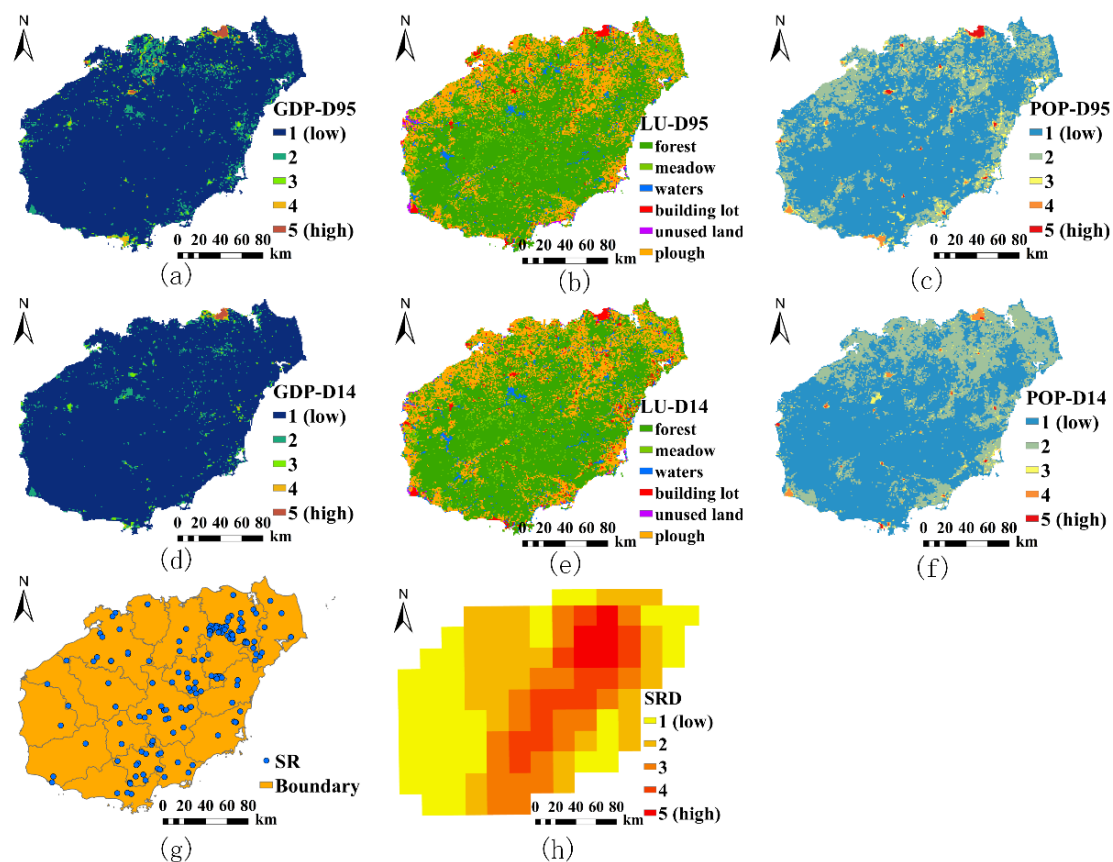


Figure 6. Spatial distribution and categories of social factors in D95 and D14: (a) GDP-D95; (b) LU-D95; (c) POP-D95; (d) GDP-D14; (e) LU-D14; (f) POP-D14; (g) SR; and (h) SRD.

4.2.4. Rainfall Factors

P, P10, P1, P6, and P24 are selected as rainfall factors in this study. Data for P10, P1, P6, and P24 of D95 and D14 are from 1980 to 2012, limited to available materials, while data for P is from 1980 to 2014. As shown in Figure 7, it is easy to find that the distribution patterns of all rainfall factors vary from D95 to D14. The distribution pattern of P in the two periods presents a similar situation as a whole. The areas with high P10 and P1 in D14 both transfer to the southeast compared with those in D95. In terms of P6, areas with a high value of D95 are in a strip of east to west direction, while those in D14 present two belts in the direction of southwest to northeast. The distribution pattern of P24 is overall similar to that of D95 and D14. Changes in all rainfall factors between the two periods may result in different flash flood intensities, and the driving force from them will be discussed through the geographical detector next.

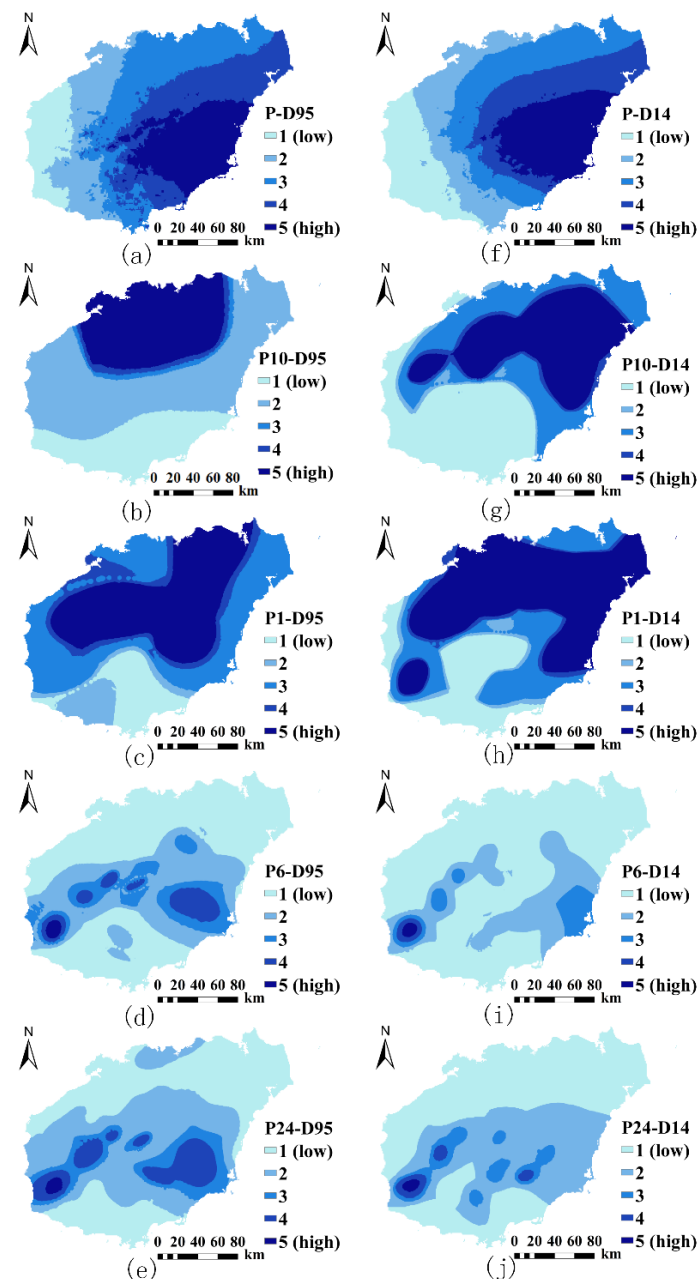


Figure 7. Spatial distribution and categories of rainfall factors in D95 and D14: (a) P-D95; (b) P10-D95; (c) P1-D95; (d) P6-D95; (e) P24-D95; (f) P-D14; (g) P10-D14; (h) P1-D14; (i) P6-D14; and (j) P24-D14.

4.3. Main Driving Force Identification Results in D95 and D14

According to the spatial distribution of FFI and factors in D95 and D14, all factors' PD values at the catchment scale can be obtained. The results are shown in Figure 8. The PD value is the driving force of different factors in flash flooding.

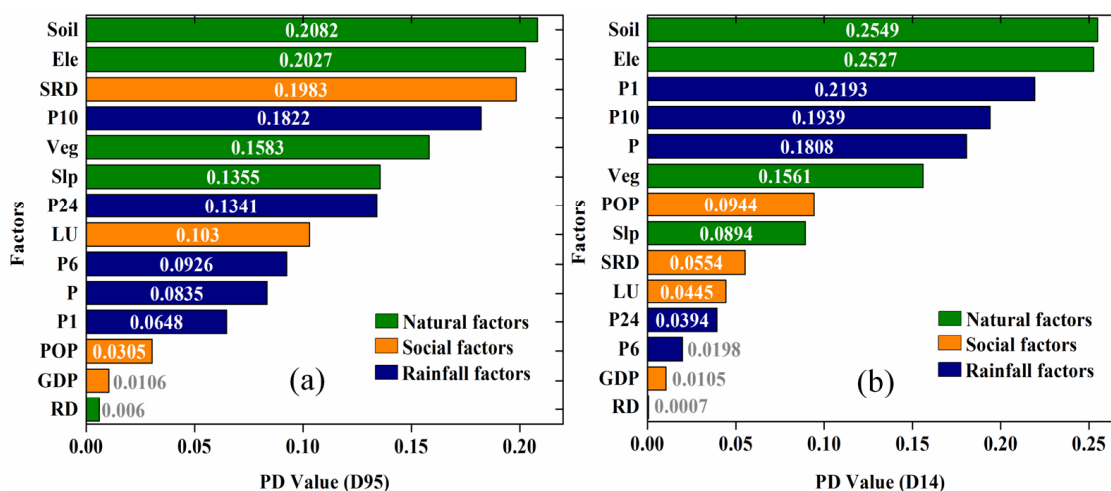


Figure 8. Driving force from different factors to flash floods in D95 and D14: (a) D95; and (b) D14.

In D95, all factors' driving forces for flash floods are shown in Figure 8a. Soil is the main driving factor for flash floods with the maximum PD value, while RD is the factor with the minimum PD value. The infiltration capacity of soil directly determines the amount of runoff, and rapid runoff production is a significant feature of flash floods, explaining their main driving force. Ele is the maximum driving force factor after Soil. Flash floods often distribute in the second level of elevation classification (100–500 m) here. This elevation level mainly occupies the hilly areas of Hainan Island, which are catchment areas and extremely vulnerable to flash floods. Flash floods are not caused by overflow from rivers but are caused directly by heavy rain on Hainan Island, which explains why RD has a low PD value. Other natural factors, such as Veg and Slp, also hold a relatively larger driving force for flash floods. Among all social factors, SRD is the factor with the largest PD value, indicating that the overflow from mountain ponds may bring about a number of flash floods at this stage. The driving forces of GDP and POP in flash floods are weak, as the overall economic level of Hainan is poor and population density is low at this stage, resulting in less interference in the distribution of flash floods. In terms of rainfall factors, P10 is the factor with the largest PD value of the five rainfall factors, which meets the fact that short-term heavy rainfall causes rapid runoff. Other rainfall factors have an overall small PD value, and we consider that the climate with abundant total rainfall here is not good for the visualization of the rainfall factors' influence on the distribution of flash floods.

All factors' driving forces for flash flooding in D14 are shown in Figure 8b. Similarly, Soil and Ele are the main driving factors, while RD is the factor with minimum driving force. The reasons are the same with those in D95. Other natural factors, such as Veg and Slp are the medium-level driving forces. Among rainfall factors, P1 and P10 are the two main driving factors with the largest PD values, which is consistent with the fact that flash floods are often caused by short-term heavy rainfall. P is also with a larger PD value and we consider that with global warming, the annual rainfall in Hainan has increased and contribute to the possibility of flash floods. In terms of social factors, POP has the strongest correlation with the distribution of flash floods. This phenomenon likely occurs because the ecological system may be damaged and flash floods expand to more areas as the population increases. Other social factors have lower PD values and their relationship

with the distribution of mountain torrents is weak, explaining that the influence of human activity on the distribution of flash floods in Hainan island is still relatively small.

The *PD* value of the interaction of pair factors can be obtained through the interaction detector, which expresses the driving force of pair factors in flash floods. The results in D95 and D14 are shown in Figure 9. The dominant interaction in D95 is $P10 \cap SRD$. It suggests that the majority of flash floods are caused by the overflow of a small reservoir (in a hilly area) due to short-term heavy rainfall in D95. In D14, the dominant interaction is $P10 \cap Soil$. It shows that the infiltration of soil due to short-term heavy rainfall may have a great relationship with flash floods during this period. The variety of dominant interactions from D95 to D14 also suggests that the flood caused by the overflow of the small reservoir is gradually decreasing.

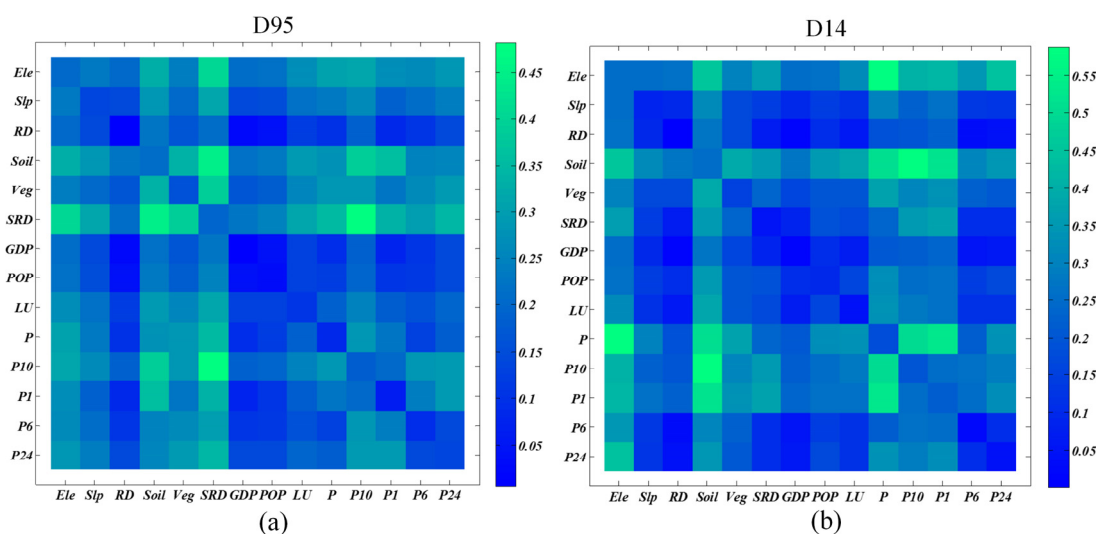


Figure 9. The *PD* value of the interaction of pair factors: (a) in D95 and (b) in D14.

In conclusion, the main driving forces of flash floods in both D95 and D14 are Soil and Ele from a single factor view, which indicates that natural factors are the dominant driving forces of flash floods here. The main dominant interactions in D95 and D14 are $P10 \cap SRD$ and $P10 \cap Soil$, respectively, expressing the important role of short-term heavy rain in the formation of flash floods.

4.4. Changes in Different Factors' Driving Forces for Flash Floods from D95 to D14

In order to further analyze the changes in driving force from factors in the time dimension, this study explores the driving force evolution from D95 to D14, and the results are shown in Figure 10. The average flash flood intensity (AFFI) of each level of factors is used to assist in the analysis of driving force changes. Here, we focus on the factors that are increasing the driving force to the distribution of flash floods.

In terms of natural factors, the driving forces of Ele and Soil to flash floods show a growing trend. We can find that high AFFI in the five elevation levels moves from the second level to the first level (Figure 11a) in the two periods, indicating that the first elevation level contributes to the increase in driving force. The AFFI of most soil types is increasing (Figure 11b), which may explain the reason for the growth of Soil's driving force to flash floods. In terms of social factors, POP's driving force is increasing. Nevertheless, Figure 11c shows that the AFFI of the fifth level of POP is decreasing from D95 to D14. We interpret the phenomenon as follows: the areas with the greatest population density often have developed economies, and they have sufficient funds for disaster prevention measures, which contribute to reducing flash floods. In terms of 2nd and 3rd population levels, AFFI continues to increase as a result of the fact that population is growing but disaster prevention measures fail to follow up, which may result in the increasing POP's

driving force from D95 to D14. On rainfall factors, the driving forces of P10, P1, and P are growing. As Figure 11 shows, AFFI of the three rainfall factors' 5th level precipitation is all increasing, indicating that there are more flash floods in places with short-term heavy rainfall or more annual rainfall, which may explain the reasons for their driving forces' expansion.

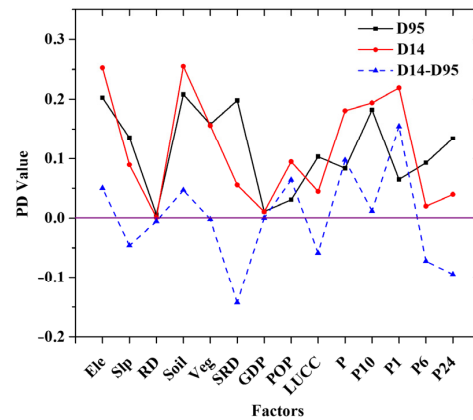


Figure 10. Changes in a single factor's driving force from D95 to D14.

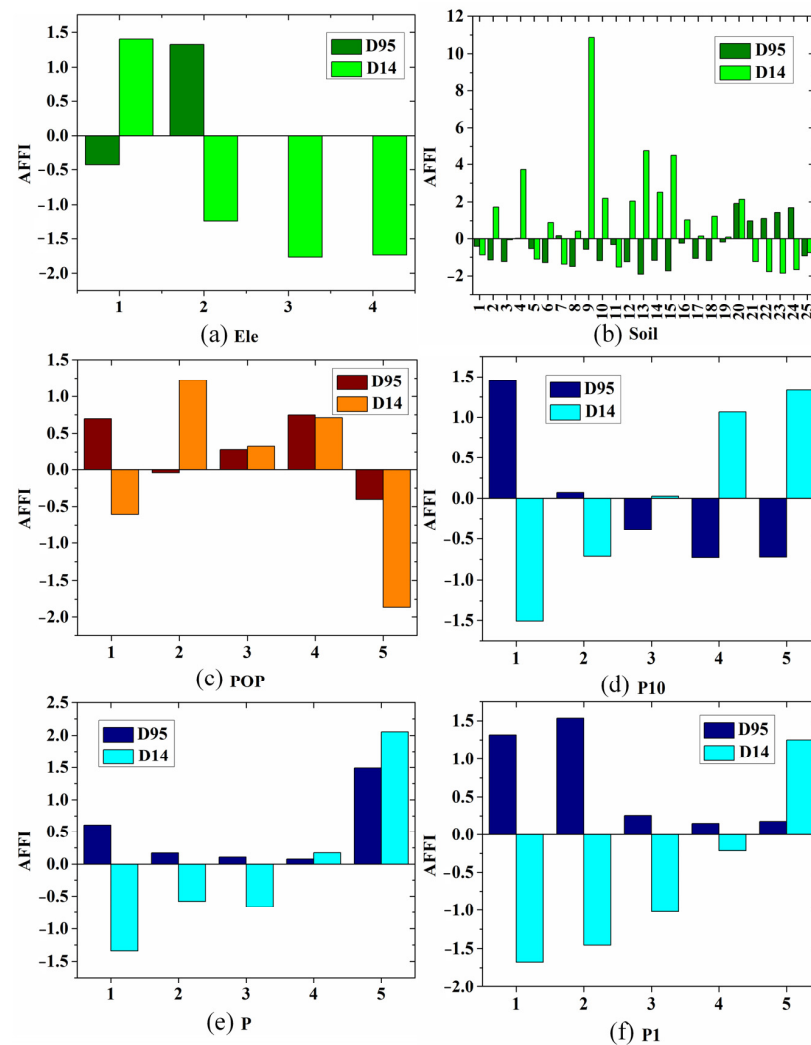


Figure 11. Average flash flood intensity (AFFI) of each level of factors: (a) AFFI of Ele; (b) AFFI of Soil; (c) AFFI of POP; (d) AFFI of P10; (e) AFFI of P and (f) AFFI of P1.

In summary, natural factors like Soil and Ele are the main driving factors in the two periods, and their driving forces are on the rise. The driving forces of rainfall factors such as P10, P1, and P have a growing trend, and more early warning measures should be established. Among social factors, areas with the 2nd and 3rd POP levels should receive adequate attention and increase the construction of disaster prevention measures.

5. Discussion

5.1. Driving Force Analysis of the Interaction between Rainfall Factors and Other Factors

According to the dominant interaction results, there is a rainfall factor in the dominant interaction of both D95 and D14, indicating that rainfall has a great influence on the distribution of flash floods. Consequently, the driving force of the interaction between different rainfall factors and other factors is analyzed, and the results are shown in Figure 12. In D95, the interaction driving force between P10 and other factors occupies a higher position than that of other rainfall factors. It indicates that local policymakers need to pay particular attention to the short-term heavy rainfall. In addition, P6 has a lower interaction driving force compared with other rainfall factors this period. In D14, P6 and P24 both have a lower interaction driving force, while P, P10, and P1 process a higher interaction driving force, which still suggests that short-term heavy rainfall has a great relationship with flash floods. Compared with D95, the interaction driving force between P and other factors in D14 has a notable upward trend. It indicates that the increasing rainfall caused by climate change is leading to more and more flash floods.

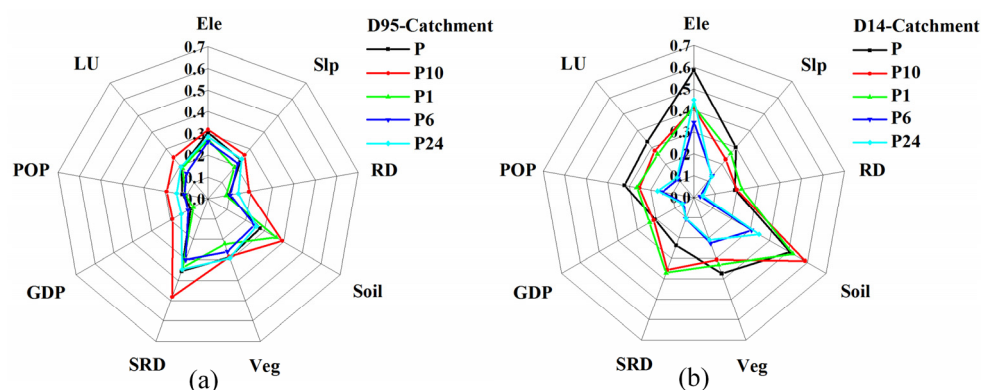


Figure 12. Driving force analysis of interactions between different rainfall factors and other factors: (a) in D95 and (b) in D14.

5.2. The Application of Driving Force Results for Flash Flood Prevention and Management

This study explores the main driving force of flash floods that occurred during the years 1980–2014 in Hainan Island. The results will aid in the determination of the direction for local flash flood prevention and management in the future.

Based on the driving force results from single factors, we find that natural factors like Soil and Ele are the main driving factors in both periods, and their driving force is on the rise. It suggests that local decision makers should pay particular attention to the areas with high AFFI in the specific factors' levels, such as the areas covered by 4, 9, 10, 13–15, and 20 soil types (Figure 13a) and with first level elevation (−13 to 100 m, Figure 13b) in D14. Among social factors, areas with the 2nd level POP (Figure 13c) process the highest AFFI and should receive adequate attention. In particular, these regions should strengthen residents' ability to take refuge and move to safety. From the driving force results of both the single factor and pair factors, we can find that rainfall factors are the key factors. The results show that driving forces from rainfall factors such as P10, P1, and P are having a growing trend, which indicates that the areas with high AFFI in the rainfall factors' level (5th rainfall level, Figure 7f–h) should establish more rainfall monitoring facilities and early warning measures.

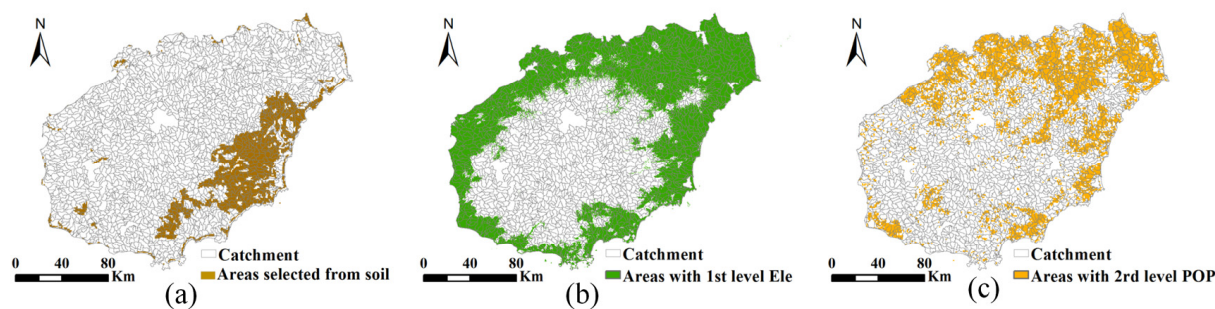


Figure 13. Areas requiring special attention based on the driving force results: (a) areas selected from Soil; (b) areas selected from Ele and (c) areas selected from POP.

Through the above discussions, local decision-makers can identify areas that will need priority assistance in the future. Through the identification of small catchments, local governments can accurately find the corresponding place names based on the ID of small catchments and carry out necessary disaster prevention and mitigation measures.

However, the management of flash floods on Hainan Island is likely to have many challenges in the future. The MK test about the recorded flash floods in Section 4.1 indicates that flash floods are still on a significant upward trend. It means that the local government needs to deal with more problems caused by flash floods. How to minimize losses, further explore the relationship between various elements and flash floods, and provide comprehensive countermeasures are the challenges to be faced for a long time in the future.

Of course, several limitations still exist. First, the selection of factors for driving force exploration still needs refinement. The establishment of a more comprehensive factor system for driving force analysis will require further improvement. Second, given the data limitations, GDP, LU, and POP data for D95 and D14 are represented by data from 1995 and 2010, respectively. They have some impacts on the driving force of the three factors contributing to flash floods, though the data used can illustrate some of the driving force issues to a certain degree. Thirdly, how to apply the study results of the driving force of factors to disaster risk reduction activities and give a concrete and reasonable plan still needs to be further studied in the future.

6. Conclusions

This study explores the driving force of three types of factors (natural, social, and rainfall) in a total of 14 flash floods at two periods on Hainan Island, China. The results help us better understand the changes or trends in flash floods and provide a basis for scientific disaster prevention and mitigation work.

The major findings are summarized as follows: (1) Ele and Soil are the main factors in flash floods in Hainan Province, and their impact on disasters is also increasing. (2) The top interactions between factors are $P10 \cap SRD$ in D95 and $P10 \cap Soil$ in D14, showing that the combined effect of different indicators will aggravate their respective impacts on flash floods. (3) The use of both the Mann–Kendall test and geographical detector provides a robust and comprehensive approach to analyzing flash flood trends and identifying the driving forces, which is expected to be extended to other areas. (4) The improvement of the index system affecting flash floods and the determination of the quantitative method of the multi-factor combined effect on it can be taken as future research work.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Item	Abbreviation
Annual rainfall	P
Average flash flood intensity	AFFI
Elevation	Ele
Flash Flood Investigation and Evaluation Dataset of China	FFIEDC
Gross domestic product	GDP
Geographic information system	GIS
Hainan Province Hydrology and Water Resources Investigation Bureau	HNHWB
Land use	LU
Mann–Kendall	MK
Maximum 1 h rainfall	P1
Maximum 10 min rainfall	P10
Maximum 6 h rainfall	P6
Maximum 24 h rainfall	P24
Population density	POP
Potential driving force	PD
Recorded flash flood intensity	FFI
Resources and Environmental Sciences Data Center	RESDC
River density	RD
Slope	Slp
Small reservoir density	SRD
Soil	Soil
Vegetation type	Veg
Years from 1980 to 1995	D95
Years from 1996 to 2014	D14

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