Dynamic Assessment of Spring Snowmelt Flood Hazard in Xinjiang: A Postprint Study

Authors: Zhou Gang

Date: 2021-08-11T00:00:00+00:00

Abstract

Based on the mechanism of spring snowmelt flood occurrence in Xinjiang, three evaluation factors—snow depth, elevation, and distance to the drainage network—were selected. Combined with historical disaster data, a quantitative assessment of spring snowmelt flood hazard in Xinjiang was conducted using the highly objective information content model and GIS technology, yielding a hazard zoning map for spring snowmelt floods in Xinjiang. By employing dynamic hazard-inducing factors of daily positive accumulated temperature and daily precipitation to drive the static hazard zoning of spring snowmelt floods in Xinjiang, a dynamic assessment system for spring snowmelt flood hazard was established, enabling dynamic evaluation of spring snowmelt flood occurrence across the entire Xinjiang region at a daily scale. The results indicate that: (1) High-hazard zones for spring snowmelt floods in Xinjiang are primarily distributed in the Ili River Valley, Bortala, northern slopes of the Central Tianshan Mountains, northern Tacheng, and Altay Region in Northern Xinjiang. (2) Verification through dynamic assessment of the snowmelt flood disaster in the Ili region of Xinjiang during early to mid-March 2005 demonstrates that the dynamic assessment results for snowmelt flood hazard exhibit relatively high accuracy and can be applied to dynamic assessment of snowmelt floods throughout the entire Xinjiang region. This study can provide support for spring snowmelt flood prevention and control as well as water resources management in Xinjiang.

Full Text

Dynamic Evaluation of Spring Snowmelt Flood Risk in Xinjiang

ZHOU Gang[12], CUI Manyi[12], LI Zhe[12], ZHANG Shiqiang[12]

[1]Shaanxi Key Laboratory of Earth System and Environmental Carrying Capacity, Northwest University, Xi' an 710127, Shaanxi, China

[2]College of Urban and Environmental Sciences, Northwest University, Xi' an 710127, Shaanxi, China

Abstract

Based on the mechanisms of spring snowmelt flood formation in Xinjiang, this study selected snow depth, elevation, and distance to water systems as evaluation factors. Combined with historical disaster data, we conducted a quantitative assessment of spring snowmelt flood risk using an objective information model and GIS technology to obtain a risk zoning map for Xinjiang. By employing dynamic hazard factors—daily positive accumulated temperature and daily precipitation—to drive the static spring snowmelt flood risk zoning, we established a dynamic evaluation system that assesses flood risk across Xinjiang at a daily temporal resolution. The results indicate that: (1) High-risk areas for spring snowmelt floods are primarily distributed in the Ili River Valley, Bortala Mongol Autonomous Prefecture, the northern slope of the central Tianshan Mountains, northern Tacheng, and the Altay region of northern Xinjiang; (2) Dynamic evaluation testing of the March 2005 snowmelt flood disaster in the Ili region demonstrated high accuracy, suggesting that this approach can be applied to dynamic snowmelt flood assessment across Xinjiang. This study provides scientific support for spring snowmelt flood prevention and water resource management in Xinjiang.

Keywords: snowmelt flood; risk assessment; flood forecast; information model; Xinjiang

---

1. Introduction

Snowmelt floods, defined as floods formed by rapid snowmelt, frequently occur in northwestern China during spring, causing annual damage to transportation infrastructure, downstream reservoirs, irrigation channels, and threatening human lives and property [?]. Under global warming, accelerated ice and snow melting and earlier melt periods have advanced the timing of snowmelt flood seasons and peak runoff [?], while the frequency and intensity of snowmelt floods have increased significantly [?], leading to greater disaster losses. As one of China' s three major snow-covered regions, Xinjiang experiences substantial snowmelt flood hazards. Severe snowmelt flood disasters occurred in 2005 in Wusu, Manas, Hutubi, and other areas of northern Xinjiang. For example, during mid-to-late March in the Ili River Valley, rapid temperature increases combined with heavy rainfall events caused rapid snowmelt, triggering frequent snowmelt flood disasters that affected 468,000 people, inundated 32,670 hectares of crops, destroyed 7,960 hectares of farmland, and killed 1,500 head of livestock [?].

Risk assessment of snowmelt floods forms a critical foundation for disaster prevention and response. With the development of GIS technology, multi-criteria evaluation methods combining spatial analysis with statistical approaches such as Analytic Hierarchy Process, principal component analysis, fuzzy logic, and expert scoring have been widely applied to flood risk assessment [?]. For instance, Tang et al. [?] used GIS-based spatial analysis with AHP to evaluate mountain flood hazards in the Honghe River Basin of Yunnan; Jiao et al. [?] applied fuzzy evaluation to assess flood risk in Laoshan District, Qingdao; Wang et al. [?] used logistic regression to analyze correlations between evaluation indices and flood occurrence for risk zoning in the Han River Basin of Hubei; Li et al. [?] developed a national flood risk map for China using causal analysis and AHP with factors including precipitation, climate zoning, slope, elevation, and river buffer zones.

For snowmelt flood prediction and early warning, previous studies have primarily used meteorological indicators or hydrological models. Tian et al. [?] identified key predictors for Xinjiang snowmelt floods: average temperature transitioning from negative to positive, maximum temperature exceeding 0°C, and significant precipitation following warming periods. Wu et al. [?] determined that temperature increases of 1.5–2.5°C $\cdot$ d^{-1} sustained for 3–6 days at mountain pass stations, with average temperatures reaching 0–5°C, could serve as flood warning indicators. Adamowski [?] used wavelet and cross-wavelet analysis of runoff and meteorological time series to achieve stable 1–2 day advance forecasts. Chen et al. [?] developed an ANFIS-based flood forecasting model for Taiwan' s Zhuoshui River, while Ma et al. [?], Liu et al. [?], and Qiao et al. [?] applied SRM snowmelt runoff models to various watersheds. Fang et al. [?] constructed a distributed snowmelt runoff model in the Jungtang Lake Basin that coupled atmospheric models to improve forecast lead times.

However, traditional methods like AHP and expert scoring are highly subjective, making regional-scale risk assessment difficult. Meteorological indicators for snowmelt flood prediction show large threshold variations, limiting practical application. Hydrological models focus on long-term runoff simulation with complex spatial parameterization, hindering large-scale dynamic risk evaluation. This study addresses these limitations by selecting snow depth, elevation, and water system distance as evaluation factors, combining historical disaster data with an objective information model and GIS technology for quantitative risk assessment. We further incorporate dynamic hazard factors (daily positive accumulated temperature and precipitation) to drive static risk zoning, enabling daily-scale dynamic evaluation across Xinjiang.

2. Data and Methods

2.1 Data Sources   2.1.1 Disaster Data

Historical snowmelt flood disaster data for Xinjiang from 2001–2013 were compiled from flood control bulletins, hydrological newsletters, and meteorological department records. Disaster occurrences were counted at the county level, with each event in different counties or at different times counted separately. Data from Ablimitjan et al. [?] were also integrated.

2.1.2 Snow Depth Data

Snow depth data were obtained from the "China Long-Term Series Snow Depth Dataset (1979–2019)" from the National Earth System Science Data Center (http://www.geodata.cn/). This dataset, derived from passive microwave remote sensing using the Chang algorithm adapted for China, provides snow depth data in WGS84 geographic coordinates at 0.25° spatial resolution and daily temporal resolution. The study utilized data from 2001–2013, defining end-of-February maximum snow depth for each year.

2.1.3 Elevation Data

Digital Elevation Model (DEM) data were obtained from the SRTM DEM (V3) dataset on Geospatial Data Cloud (http://www.gscloud.cn/), processed from radar topography data collected by the Space Shuttle Endeavour. The data use WGS84 coordinate system with 90 m spatial resolution.

2.1.4 Water System Data

River network data at 1:1,000,000 scale were obtained from the Resource and Environmental Science Data Center (www.resdc.cn/). Using ArcGIS, buffer zones of 3000 m, 6000 m, 9000 m, and 14000 m were created to calculate distance to water systems.

2.1.5 Meteorological Data

Daily temperature and precipitation data from 102 meteorological stations in Xinjiang and surrounding areas were obtained from the China Meteorological Data Network (http://data.cma.cn/). The Gradient plus Inverse Distance Squared (GIDS) interpolation algorithm [?] was used for spatial interpolation at 3 km $\times$ 3 km resolution.

2.2 Methods 2.2.1 Selection of Risk Assessment Factors

Regional natural disaster risk assessment typically considers multiple factors including disaster-forming environments and hazard-inducing factors. Previous studies have identified key controls on snowmelt floods: stable winter snow accumulation provides the material basis [?]; maximum snow depth >25 cm serves as a criterion for floods in the Ningjia River of the Tianshan Mountains [?]; snow depth in early spring and thermal conditions affect flood formation [?]; snow depth >10 cm by late February can trigger floods, with sustained or rapid warming and post-warming rainfall as critical forecast factors [?]; Xinjiang snowmelt floods primarily occur in low mountain areas and piedmont plains below 1500 m elevation in the Altay, Tacheng, Ili, and northern Tianshan regions, as well as in mid-low mountain rivers [?]; areas near rivers show higher flood probability [?].

Based on these findings, this study selected three static risk factors: end-of-February maximum snow depth, elevation, and distance to water systems. Dynamic hazard factors (daily positive accumulated temperature and daily precipitation) were incorporated to drive the static risk zoning for dynamic evaluation.

2.2.2 Information Model

The information model, originally proposed by Yin [?], calculates information content of disaster-related indices. This model offers advantages for cases with numerous evaluation units [?]. In this study, snowmelt flood risk is influenced by snow depth, elevation, and water system distance, with each factor playing a different role. The information model quantitatively calculates each factor' s contribution to snowmelt flood probability. The total information content, obtained by superimposing individual contributions, serves as the quantitative risk index.

The information value of each factor is calculated as:

$$I(X_i) = \ln\left(\frac{S_i/S}{R_i/R}\right)$$

where $I(X_i)$ is the information value of factor X_i, S is the total study area, S_i is the area containing factor X_i, R is the total number of historical snowmelt flood events, and R_i is the number of events in areas containing factor X_i.

The total information value for each evaluation unit is:

$$P = \sum_{i=1}^{n} I(X_i)$$

where P is the total information content and n is the number of factors. Higher P values indicate higher snowmelt flood probability. Using 3 km × 3 km grid cells as basic evaluation units, information values were calculated (Table 1) and summed using map algebra in ArcGIS. Natural breaks classification was applied to categorize risk levels: high, medium, low, and very low.

2.2.3 Dynamic Evaluation Index System

Static risk assessment reflects multi-year average distributions, while dynamic evaluation better serves future flood prevention and water resource management. This study introduces dynamic hazard factors—daily positive accumulated temperature and daily precipitation—to drive the static risk zoning.

Drawing from snowmelt models using degree-day factors [?] and Wu et al.' s [?] criteria (temperature increase of 1.5-2.5°C$\cdot$d^{-1} sustained for 3-6 days, with average temperatures of 0-5°C), we improved these indicators by using continuous 3-day positive accumulated temperature to reflect temperature effects on snowmelt. Rainfall significantly accelerates snowmelt, with 0.125 mm of rain capable of melting equivalent snow [?]. Spring rain-on-snow events have increased, amplifying peak flows. Using Xinjiang Meteorological Bureau rainfall standards and analyzing historical precipitation characteristics (2001–2013), we selected light, moderate, and heavy rain as dynamic evaluation indicators (Table 3).

The dynamic evaluation system combines static risk zoning with dynamic factors (Tables 2 and 3) to predict daily risk levels (Table 4).

2.2.4 Spatialization of Daily Temperature and Precipitation

Accurate spatialization of daily positive accumulated temperature and precipitation is crucial for dynamic evaluation. The GIDS algorithm performs multiple linear regression of climate variables against geographic coordinates (longitude, latitude, elevation) using nearby station data, with inverse distance squared weighting. This approach effectively captures spatial variations in meteorological elements:

$$T = \frac{\sum_{i=1}^{n} \left[T_i + T_{\mathrm{alt},m}(E - E_i) + T_{\mathrm{lat},m}(L - L_i) + T_{\mathrm{lon},m}(\mathrm{Lo} - \mathrm{Lo}_i)\right] / d_i^2}{\sum_{i=1}^{n} 1/d_i^2}$$

$$P = \frac{\sum_{i=1}^{n} \left[P_i + P_{\mathrm{alt},m}(E - E_i) + P_{\mathrm{lat},m}(L - L_i) + P_{\mathrm{lon},m}(\mathrm{Lo} - \mathrm{Lo}_i)\right] / d_i^2}{\sum_{i=1}^{n} 1/d_i^2}$$

where T and P are predicted daily temperature and precipitation at grid points; T_i and P_i are observed values at neighboring stations; E, L, and Lo are elevation, latitude, and longitude of prediction points; E_i, L_i, and Lo_i are station coordinates; d_i is distance between station and prediction point; $T_{\mathrm{alt},m}$, $T_{\mathrm{lat},m}$, $T_{\mathrm{lon},m}$ and $P_{\mathrm{alt},m}$, $P_{\mathrm{lat},m}$, $P_{\mathrm{lon},m}$ are temperature and precipitation gradients; n is number of neighboring stations (set to 8).

3. Results

3.1 Spatial Characteristics of Risk Factors Spatial analysis of risk factors with historical disaster data (2001–2013) reveals that multi-year average end-of-February maximum snow depth in Xinjiang ranges from 0–32.5 cm, showing a pattern of greater depth in northern Xinjiang than southern Xinjiang, with maximum depths in the Altay and Tianshan high-elevation areas. Flood frequency generally increases with snow depth, with areas having >10 cm snow depth accounting for 40% of disasters. Floods predominantly occur at elevations of 500–1500 m, representing 70% of events. Xinjiang' s numerous rivers, mostly originating in mountains, are more abundant in the west and north. Flood probability increases near rivers, with 96% of disasters occurring within 14,000 m of rivers and the highest density within 3,000 m (Table 5).

3.2 Spring Snowmelt Flood Risk Zoning in Xinjiang The risk zoning map (Figure 5) shows high-risk areas concentrated in: Habahe, Burqin, Altay City, Qinghe, northern Fuhai and Fuyun counties in northern Altay; Tacheng City, Yumin, and Emin counties in northern Tacheng; Bole, Wenquan, and Jinghe counties in Bortala; Huocheng, Yining, Gongliu, Nikle, and Xinyuan counties in the Ili River Valley; and Wusu, Kuitun, Shawan, Manas, Shihezi, Hutubi, Jichang, and Urumqi cities on the northern Tianshan slope. These areas are densely populated and economically developed, requiring prioritized prevention. High-risk zones are characterized by valley locations with dense river networks, low elevation, gentle slopes, and substantial end-of-February snow depth. Medium-risk areas occur adjacent to high-risk zones and in eastern Junggar Basin (with relatively large snow depth), as well as near rivers in southern Tianshan and southern Xinjiang (Kashgar, Akto, Wuqia, and Hotan counties). Low-risk areas are found in western Junggar Basin and parts of southern Xinjiang, while very low-risk areas cover the Taklamakan Desert and mountainous areas above 3500 m.

Validation using historical disaster data shows that 52.9% of events occurred in high-risk areas (10.6% of total area), 30.9% in medium-risk areas (13.1% of area), 6.2% in low-risk areas (23.4% of area), and no events in very low-risk areas (52.9% of area), demonstrating that the zoning effectively reflects spatial disaster patterns. However, static assessment alone cannot capture the risk magnitude and probability of individual flood events.

3.3 Dynamic Evaluation Validation In March 2005, extensive snowmelt floods caused major economic losses across Xinjiang. We selected this event for validation. The flood process was characterized by: (1) Late February temperatures 2–4°C below normal with snow depth 10–40% above normal; (2) March 11–20 sustained warming of 0.7-3.2°C $\cdot$ d^{-1} across Ili, northern Tacheng, and northern Tianshan slope; (3) Heavy precipitation on March 18–19 in Ili, accelerating snowmelt and creating rain-on-snow floods with higher peak flows.

Dynamic evaluation results show: - **March 11**: Most of Xinjiang at very low/low risk due to low temperatures. Small high-risk areas appeared in southern Tianshan rivers, with medium risk emerging in Ili. - **March 15**: Continuous warming created extensive very high-risk zones along the Ili River Valley (Kokdala, Huocheng, Yining, Qapqal, Yining County, Gongliu), extending to Tekes County. Large high-risk areas emerged in Tacheng City along the Emin River, with very high-risk zones in Habahe County along the Irtysh River. - **March 18**: Very high-risk zones in Ili River Valley persisted and expanded eastward to Xinyuan County. Very high-risk areas in Wenquan County (Bortala) and Baicheng County (southern Tianshan) began receding. - **March 20**: Ili River Valley very high-risk zones started retreating, though local heavy rain created new rain-on-snow very high-risk areas around Yining City. Wenquan County' s very high-risk zone disappeared. - **March 22**: Continued warming and March 21 heavy rain accelerated snowmelt. Snow depth data indicated complete snowmelt in Ili, ending the flood risk. Small very high/high-risk areas appeared in Wusu, Karamay, Shawan, and Manas.

The dynamic evaluation process aligns well with actual conditions, demonstrating the feasibility of daily-scale dynamic risk assessment across Xinjiang. Ili River Valley showed the highest risk, followed by northern Tacheng and Wenquan County, with lower risk in southern Tianshan rivers.

4. Discussion

This study combined historical disaster data with the objective information model for dynamic snowmelt flood risk assessment in Xinjiang, yielding results consistent with reality. However, uncertainties in parameterization schemes for driving data (daily snow depth, temperature, precipitation) may introduce bias. The dynamic evaluation index system also involves subjective component selection, where different indicators could produce varying results. Future research should test high-resolution meteorological products and integrate snowmelt runoff models [?] with predicted high-risk areas for more accurate flood process estimation.

This study focused primarily on warming-induced spring snowmelt floods, with only preliminary treatment of rain-on-snow floods. The simple combination of heavy rainfall and warming to define mixed floods requires further investigation of rain-on-snow mechanisms to develop more accurate risk classification indicators.

5. Conclusions

By investigating spring snowmelt flood formation mechanisms in Xinjiang, we developed a method that combines information model-based risk factor analysis with dynamic evaluation indicators to generate a spring snowmelt flood risk zoning map and achieve daily-scale dynamic assessment. Main conclusions are:

1) High-risk areas for spring snowmelt floods are mainly distributed in the Ili River Valley, Bortala, northern slope of central Tianshan, northern Tacheng, and Altay region of northern Xinjiang. These zones feature dense river networks in valleys with low elevation, gentle slopes, and substantial end-of-February snow depth. Medium-risk areas occur near high-risk zones, in eastern Junggar Basin, and near rivers in southern Tianshan and southern Xinjiang. Southern Xinjiang is predominantly low and very low risk. The zoning objectively reflects spatial disaster patterns.

2) Using dynamic hazard factors (daily positive accumulated temperature and precipitation) to drive static risk zoning, we validated the method against the March 2005 flood event. The dynamic evaluation results matched actual conditions, demonstrating that this approach can support refined snowmelt flood forecasting and water resource management in Xinjiang.

References

[1] Yang Jinming, Li Chengzhi, Fang Shifeng, et al. A review of seasonal snow melt flood simulation and forecast in Xinjiang[J]. Journal of Xinjiang University (Natural Science Edition), 2019, 36(1): 80-88.

[2] Chen Yaning, Li Zhi, Fan Yuting, et al. Research progress on the impact of climate change on water resources in the arid region of Northwest China[J].

Acta Geographica Sinica, 2014, 69(9): 1295-1304.

[3] Wang Hui. Study on Three-dimensional Visualization of Snowmelt Flood[D]. Shihezi: Shihezi University, 2016.

[4] Fang Shifeng. A Study on Snowmelt Runoff Forecasting and Its Uncertainty Analysis in Xinjiang[D]. Urumqi: Xinjiang University, 2010.

[5] Li Qiong. The Research and Improvement of Risk Analysis and Evaluation Method on Flood Disaster[D]. Wuhan: Huazhong University of Science and Technology, 2012.

[6] Tang Chuan, Zhu Jing. A GIS-based regional torrent risk zonation[J]. Acta Geographica Sinica, 2005, 60(1): 87-94.

[7] Jiao Junchao, Ma Anqin, Li Fujian. Fuzzy evaluation of flood risk rating in Laoshan district based on GIS[J]. Bulletin of Soil and Water Conservation, 2010, 30(5): 161-164.

[8] Wang Peng, Liu Zhihui, Ye Zhaoxia. Establishment and validation of early warning model for snowmelt flood in North Xinjiang[J]. Arid Land Geography, 2009, 32(4): 552-557.

[9] Li Lintao, Xu Zongxue, Pang Bo, et al. Flood risk zoning in China[J]. Journal of Hydraulic Engineering, 2012, 43(1): 22-30.

[10] Tian Hua, Yang Xiaodan, Zhang Guoping, et al. The possible weather causes for snowmelt flooding in Xinjiang in Mid-March 2009[J]. Meteorological Monthly, 2011, 37(5): 590-598.

[11] Wu Sufen, Liu Zhihui, Qiu Jianhua. Analysis of the characteristics of snowmelt flood and previous climate snow condition in North Xinjiang[J]. Journal of China Hydrology, 2006, 26(6): 90-93.

[12] Adamowski J F. Development of a short-term river flood forecasting method for snowmelt driven floods based on wavelet and cross-wavelet analysis[J]. Journal of Hydrology, 2008, 353(3): 247-266.

[13] Chen S H, Lin Y H, Chang L C, et al. The strategy of building a flood forecast model by neuro-fuzzy network[J]. Hydrological Processes, 2006, 20(7): 1525-1540.

[14] Ma Hong, Yang Jing, Cheng Guodong. Application experiment of SRM snowmelt runoff model in Gongnaisi River Basin of west Tianshan[J]. Chinese Science Bulletin, 2003, 48(19): 2088-2093.

[15] Liu Junfeng, Yang Jianping, Chen Rensheng, et al. The simulation of snowmelt runoff model in the Dongkemadi River Basin, headwater of the Yangtze River[J]. Acta Geographica Sinica, 2006, 61(11): 1149-1159.

[16] Qiao Peng, Qin Yan, Liu Zhihui. A spatially distributed snowmelt model based on energy balance[J]. Advances in Water Science, 2014, 25(1): 53-59.

[17] Zhao Q D, Liu Z H, Ye B S, et al. A snowmelt runoff forecasting model coupling WRF and DHSVM[J]. Hydrology and Earth System Sciences, 2009, 13(10): 1897-1906.

[18] Ablimitjan Ablikim, Chen Chunyan, Yusup Abdula, et al. The temporal and spatial distribution features of snowmelt flood events in Xinjiang from 2001 to 2012[J]. Journal of Glaciology and Geocryology, 2015, 37(1): 226-232.

[19] Liu Xin, Zhao Luqiang, Ma Hong, et al. Study on distribution features of spring snowmelt flooding in Xinjiang[J]. Journal of Anhui Agricultural Sciences, 2016, 44(30): 165-168.

[20] Che T, Li X, Jin R, et al. Snow depth derived from passive microwave remote sensing data in China[J]. Annals of Glaciology, 2008, 49(1): 145-154.

[21] Zhao Q D, Ding Y J, Wang J, et al. Projecting climate change impacts on hydrological processes on the Tibetan Plateau with model calibration against the glacier inventory data and observed streamflow[J]. Journal of Hydrology, 2019, 573: 60-81.

[22] Price D T, Mckenney D W, Nalder I A, et al. A comparison of two statistical methods for spatial interpolation of Canadian monthly mean climate data[J]. Agricultural & Forest Meteorology, 2000, 101(2-3): 81-94.

[23] Lin Zhonghui, Mo Xinguo, Li Hongxuan, et al. Comparison of three spatial interpolation methods for climate variables in China[J]. Acta Geographica Sinica, 2002, 57(1): 47-56.

[24] Liu Xin, Zhao Luqiang, Liu Na, et al. Risk evaluation of the spring snowmelt flood in Ili River basin and its mapping[J]. Advances in Meteorological Science and Technology, 2016, 6(6): 35-41.

[25] Wang Zhijie, Dilimulati, Li Conglin. Study on the spring floods caused by snow melt water in low mountain and hill regions of the northern piedmont of the Tianshan Mountains: A case study in the paleochannels of Sangong River[J]. Arid Land Geography, 2002, 25(4): 302-308.

[26] Liang Chuncheng, Yang Naikang, Chen Yaning. A preliminary study on snowmelt flood of Ninjia River, Tianshan Mountains[J]. Arid Land Geography, 1993, 16(3): 75-79.

[27] Yu Yongwang, Xu Bing, Bai Dongming, et al. Analysis on the cause of spring melted snow flood in Qiurgou River[J]. Arid Zone Research, 1995, 12(3): 15-20.

[28] Shen Yongping, Su Hongchao, Wang Guoya, et al. The responses of glaciers and snow cover to climate change in Xinjiang(II): Hazards Effects[J]. Journal of Glaciology and Geocryology, 2013, 35(6): 1355-1370.

[29] Jiang Yuanan, Liu Jing, Shao Weiling, et al. Climatic characteristics and historical evolution of precipitation in different time scales in Xinjiang from 1961 to 2013[J]. Journal of Glaciology and Geocryology, 2014, 36(6): 1363-1375.

[30] Yin K L. Statistical prediction model for slope instability of metamorphosed rocks[C]// Proc 5th International Symposium on Landslides, Lausanne, 1988.

[31] Huang Runqiu, Xu Xiangning, Tang Chuan, et al. Geological Environment Assessment and Geological Disaster Management[M]. Beijing: Science Press, 2008: 151-179.

[32] Vijith H, Madhu G. Application of GIS and frequency ratio model in mapping the potential surface failure sites in the poonjar sub-watershed of meenachil river in western ghats of kerala[J]. Journal of the Indian Society of Remote Sensing, 2007, 35(3): 275-285.

[33] Meng Qinghua, Sun Weifeng, Wang Tao. Study on the landslide susceptibility assessment in Feng County, Shaanxi Province[J]. Geological Survey and Research, 2013, 36(2): 136-145.

[34] Lee M J, Park I, Won J S, et al. Landslide hazard mapping considering rainfall probability in Inje, Korea[J]. Geomatics Natural Hazards and Risk, 2016, 7(1): 424-446.

[35] Akbar T A, Ha S R. Landslide hazard zoning along Himalayan Kaghan Valley of Pakistan by integration of GPS, GIS, and remote sensing technology[J]. Landslides, 2011, 8(4): 527-540.

[36] Cheng Weishuai. A review of rainfall thresholds for triggering flash floods[J]. Advances in Water Science, 2013, 24(6): 901-908.

[37] Yan Baowei, Liu Yu, Jiang Huining, et al. Study on dynamic critical rainfall warning index considering spatial heterogeneity of rainfall[J]. Journal of Hydraulic Engineering, 2020, 51(3): 342-348.

[38] Zhang Shicai, Chu Jianhua, Zhang Tongze. Calculation of critical rainfall amounts and risk area partition of flood disaster in QiLian Mountain Area[J]. Journal of Soil and Water Conservation, 2007(5): 196-200.

[39] Shen Yongping. Snow Disaster[M]. Beijing: China Meteorological Press, 2009: 1-200.

[40] Zhang Junlan, Luo Ji, Wang Rongmei. Combined analysis of the spatiotemporal variations in snowmelt(ice) flood frequency in Xinjiang over 20 years and atmospheric circulation patterns[J]. Arid Zone Research, 2021, 38(2): 339-350.

[41] Zeng Ziyue, Xu Jijun, Wang Yongqiang. Advances in flood risk identification and dynamic modelling based on remote sensing spatial information[J]. Advances in Water Science, 2020, 31(3): 463-472.

[42] Marinec J, Rango A. Parameter values for snowmelt runoff modelling[J]. Journal of Hydrology, 1986, 84(3-4): 197-219.

[43] Zheng Ning, Liu Qiong, Huang Guan, et al. Temporal and spatial distribution characteristics of total precipitable water vapor in three mountain areas of Xinjiang[J]. Arid Land Geography, 2019, 42(1): 77-84.