Flood Risk Forecasting and Early Warning Technology for Medium and Small Rivers in the Yellow River Basin Induced by Heavy Rain

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Abstract: The Yellow River Basin is one of the important sand-producing and sediment-transporting areas in China, and one of the three most important sand-producing areas in the world. The amount of sand and dust days in the "Three Norths" (Dongbei, Xibei, and Huabei) area has increased, and regional sand and dust storms have occurred frequently. There are generally more serious hidden danger points of debris flow geological disasters in small and medium-sized river basins. The technical achievements of flood risk forecasting and early warning for medium and small rivers in the Yellow River Basin based on rainstorm-induced floods are important technical supports for flood forecasting and early warning for medium and small rivers. Based on this, a case study was carried out on the problems such as the weak forecasting and early warning ability of flood disasters induced by heavy rain and the low accuracy of flood disaster loss assessment in the flood disasters of medium and small rivers, for the reference of relevant personnel.

Keywords: Rainstorm; Yellow River; Flood; Risk warning

1. Introduction

The Yellow River Basin is the largest inland river basin in China and the most important water source conservation area in arid and semi-arid regions of China. Since 1998, with climate change and population growth, China has experienced frequent rainstorms and floods. According to statistics, by the end of 2018, there were 4,164 small and medium-sized rivers in the country, accounting for about 66% of the total number of rivers in the country. Among them, the losses from rainstorms and floods accounted for more than 77% of the national losses from floods, and the average annual losses from floods reached 12.69 billion yuan. Especially since 2019, torrential rains and floods have affected 246 million people in 31 provinces (autonomous regions and municipalities) across the country, with 13.82 million dead and missing. Heavy rains and floods caused huge losses. In order to accurately analyze the flood disaster risk points of medium and small rivers, reduce flood losses, and ensure the safety of people's lives and property, it is urgent to explore and improve the flood risk forecast and early warning technology system for medium and small rivers [1-10].

2. Research background

Floods in the upper Yellow River generally occur from May to September, especially from July to

September 2019. When a flood occurs in the upper reaches of the Yellow River, the flood process and the flood peak stage are located at different river sections. Torrential rain is the main factor for the appearance of the flood peak, and may be accompanied by secondary disasters such as mountain torrents and debris flows caused by strong precipitation. Small river floods in the basin are typical flood disasters. Because the flood of small and medium rivers is a special phenomenon of water engineering disasters, it affects the safety of water for social and economic life and social stability. Through in-depth analysis and research on the flood events of small and medium-sized rivers in the Yellow River Basin induced by heavy rain from July to September 2019, it is found that there are two main stages in the rainfall process that affect the floods of small and medium-sized rivers: one is that during the rainstorm-induced period, the Yellow River Basin flows into the Yellow River banks in the middle reaches of the Yellow River and induces large floods; the other is that during the rainstorm-induced period, the Yellow River Basin enters the middle and lower reaches of the Yellow River and causes large floods.

3. Simulation and prediction of hydrological situation in the Yellow River Basin

According to the climatic characteristics of the Yellow River Basin, combined with the previous rainstorm and flood monitoring data and the flood experience value of the regional rainstorm and flood forecast model, combined with the precipitation characteristics of different periods in the rainfall process and the hydrological situation prediction results of the small- and medium-sized river basins, the flood risk simulation and prediction were carried out. The rainfall in the Yellow River Basin generally presents two trends: one is that the rainfall is concentrated in time and space, and the precipitation presents a "light raindrop" distribution; the other is that the rainfall in the basin presents a "moderate raindrop" distribution. Among them, the precipitation in the flood season in the upper reaches shows a distribution of "moderate raindrops," and the rainfall is 149–265 mm; the precipitation in the middle reaches shows a distribution of "light raindrops" in the flood season, and the rainfall is 610–1245 mm; the rainfall in the lower reaches of 1830–2100 mm showed "moderate" to "heavy raindrops". The research shows that: the precipitation in the Yellow River Basin in the summers present the characteristics of first concentration and then dispersion; the rainfall in the flood season is moderately high; the total annual precipitation presents a "light raindrops" distribution. Torrential floods are characterized by distinct time periods and strong intensity. Among them, January to March is the period with the highest precipitation in the Yellow River Basin; June to August presents characteristics of moderate and light rain areas due to many factors; from September to October, there are distinct characteristics of moderate rain; while October to November is the period of heavy rain. Combined with historical data analysis and trend forecast characteristics, it can be seen that the precipitation in the basin in three months is 3.5 times that of the precipitation in 1951-2007, and the precipitation in the next 2-3 years is predicted to increase annually.

3.1. The characteristics of "light raindrops" in the Yellow River Basin

"Light rain" refers to the amount of rainfall that occurs on average in a certain period of time. According to the characteristics of meteorological elements of "light raindrops" and the characteristics of heavy rain and flood patterns in different areas of the basin, forecast and early warning analysis of light raindrop values are carried out. The research shows that the annual rainfall in the basin is 610–1245 mm in moderate and light rain areas, and the precipitation is characterized by dispersion. Among them, the area with the highest frequency of "light raindrops" is Yanchuan County, whose monthly average rainfall was 541 mm on June 6; the daily average rainfall of "Changning County" appeared on July 8, which appeared between June 13 and July 7, and the average monthly rainfall is 544 mm. The rainfall in the "light rain area" is concentrated between July and August, and its monthly precipitation generally exceeds 500 mm. Although the "Middle Yellow River Area" has obvious precipitation process, its precipitation is not high. Among them, the

monthly precipitation of Yanchuan County is 829 mm, which is the county city with the 6th highest rainfall in China. The monthly precipitation at Sanmenxia and the Yellow Committee station both reached 640 mm or more, ranking the top three stations in the Yellow Committee in recent years; and Yan'an station reached more than 833 mm.

3.2. Historical and hydrological overview of rainstorm and flood
According to the hydrological and meteorological observation data and the evolution characteristics of the hydrological situation of the regional rainstorm and flood forecasting model, we could carry out the rainstorm and flood risk forecasting work for medium and small rivers in the basin, and discuss the flood risk forecasting and early warning technology for medium and small rivers in the Yellow River Basin, so as to provide theoretical basis for the flood risk prediction and early warning of small and medium-sized rivers in the Yellow River basin. (i) The general overview of the Yellow River Basin and historical data statistics show that the regional distribution of the basin basically presents a spatial distribution pattern of high in the west and low in the east. Heavy precipitation is concentrated in the eastern mountainous area, and rainfall in the central and northern areas is relatively small. There is more precipitation in the central and northern regions, and less precipitation in the central and southern regions; less precipitation in the south, and more rain in the north, ranging from heavy rain to heavy rain. Because the precipitation in the upper reaches of the middle and small rivers in the region is significantly more than that in the middle reaches, the precipitation in the middle reaches is significantly less. (ii) According to the analysis results of flood characteristics in the Yellow River Basin, there were 3 types of rainstorms and floods in the basin from 1951 to 2007: 4 times were in the upper reaches, 4 times were in the middle reaches, and 2 times were in the middle reaches. Besides, there were also 2 rainstorm and flood disasters, and 1 rainstorm and flood disaster occurred in the downstream during the same period.

3.3. Monitoring and early warning of water and rain conditions in medium and small rivers
Based on the actual situation of precipitation during the flood season in the Yellow River Basin, the characteristics of flow evolution and the hydrological situation of medium and small rivers, using the hydrological monitoring stations and channel scale sections of medium and small rivers in the Yellow River Basin, a forecasting and early warning method for hydrological elements such as continuous observation and automatic monitoring of hydrological elements is established. The monitoring of hydrological elements refers to the analysis of the hydrological elements and their movement laws formed by natural or human factors from a physical point of view, the investigation and monitoring of the changes of hydrological elements, the monitoring of time series and the analysis of characteristic changes, which involves three aspects: physics, chemistry, and climatology. This method requires long-term tracking observation of hydrological elements and compared to meteorological observations, and involves the use of time series. The main research objects of river runoff forecasting and forecasting technology are the continuous observation data of river runoff, the artificial monitoring stations within the river basin, and the automatic monitoring of river flood data. Combined with the current status of water resources in the Yellow River Basin and the development trend of future hydrological elements, the existing continuous observation data of hydrological elements and meteorological observation data were incorporated into the water and rainfall monitoring, forecasting and early warning system for small and medium rivers in the Yellow River Basin for monitoring and early warning technology research.

4. Flood risk of medium and small rivers induced by heavy rain
Small- and medium-sized rivers are important carriers of flood occurrence and spread, and have high flood disaster risks. The flood risk induced by heavy rain is an important factor affecting the flood forecasting

and early warning ability of medium and small rivers, both globally and locally. According to the statistics of the International Hydrological Organization (ICRA), geological disasters such as landslides and debris flows caused by rainstorms account for 46% of the total impact of flood disasters worldwide; 30% of the total impact of flood disasters are caused by rainstorms in China. The high frequency, suddenness, and wide influence of heavy rain in small and medium-sized river basins is an important cause of heavy rain and flood disasters. At present, the accuracy flood disaster prediction in small and medium-sized rivers at home and abroad is generally low, and it is difficult to predict the losses of flood disasters. In recent years, some advanced achievements in flood forecasting and early warning of small and medium-sized rivers have emerged one after another. For example, there was a flood disaster on July 7, 2013, at the main stream of the Yellow River in Shaanxi Province; the Longyangxia Hydrological Station in the Bailong River Basin of Shenmu City, Yan'an City, Shaanxi Province performed an assessment on the damage caused by rainstorm flood disaster on July 16, 2014, which turned out to be 5.3–9.3 m/s. In addition, since 2013, there have been many floods in the upper reaches of the Yellow River where the peak discharge is greater than the design standard [11]. Therefore, it is foreseeable that in the future, the risk prediction and early warning of flood disasters in medium and small rivers in the Yellow River Basin will become the key technical research direction of rainstorm flood disaster loss assessment and early warning.

4.1. Spatial features
Focusing on the key technical problems of flood disaster risk forecasting and early warning in small and medium-sized rivers in the Yellow River Basin, according to historical data, 4 national-level hydrometeorological stations monitors the situation of the basin within 24 hours after the occurrence of heavy rain, and showed that a heavy rain and flood disaster event occurs every 4 hours [12-14]. During the heavy rainfall period, the probability of flood disaster events with flood peak flow greater than the design standard at each station is greater than 10% [15], which means that there is a probability of a major flood every 5 days. During the heavy rainfall period, the frequency of heavy rain and floods reached 66.5%, and the flood risk level reached Level II or Level III. The frequent occurrence of flood risk events induced by heavy rainfall is mainly due to changes in the control conditions of precipitation and runoff in the basins of small and medium-sized rivers. Rainstorm and flood disasters often cause abnormal changes in river runoff in the river basin, increase discharge flow from upstream reservoirs, and accelerate or decrease the rise of water levels in some river basins. According to the analysis and statistics of the national flood risk level monitoring data of medium and small rivers from 2013 to 2017 by the Monitoring Information Center of the Ministry of Water Resources, the cumulative number of floods in medium and small rivers in flood seasons with a flood risk level of 4 or above from 2014 to 2017 was 777, 488, and 444 times, closely related to the flood risk level during the occurrence of heavy rain and flood disasters.

4.2. Key parameters
The main factors affecting the loss of flood disasters in small and medium-sized rivers include flood intensity, rainfall, and duration of rainstorm. For example, the intensity and duration of rainstorm have a direct impact on flood loss, but its changing trend is uncertain. It is reflected in the peak flow and rainfall. At present, the intensity of rainstorm and the number of rainy days is generally used in the Yellow River Basin to carry out real-time forecasting and early warning of peak flow and rainfall. At the same time, the flood intensity parameter also directly affects the peak flow and contributes to the number of flood days [16]. Flood intensity parameters mainly include indicators such as within 1 day and within 24 days, and the number of flood days needs to be comprehensively considered according to the actual situation of the Yellow River Basin. The number of flood days is mainly formed by the influence of upstream water and downstream rainfall. Usually, the number of flood days varies from 1 day to 24 days, but the rainfall at

different precipitation stations shows different trends. For the number of flood days within 2 days, it is necessary to use relevant formulas to calculate and generate simulated flood peak flow series and flood daily rate series according to the characteristics of each site.

5. Case studies

5.1. Case description

From June to July 2018, large regional rainstorms and floods occurred in most of the Yellow River Basin. Among them, a total of 8 large-area heavy rainfall processes occurred in the Loess Plateau in the middle reaches of the Yellow River, and 7 of the processes had a rainfall exceeding 100 mm. The eight heavy precipitation processes in Shaanxi Province are from 8:00 am on July 9 to 8:00 am on July 11, from 8:00 am on July 12 to 8:00 am on July 13, from 8:00 am on July 13 to 8:00 am on July 14, from 8:00 am on July 14 to 8:00 on July 15, and from 8:00 am on July 15 to 8:00 am on July 17. On July 21, 2019 to 8:00 am on July 14, 2020, a total of 5 floods occurred in small and medium rivers (involving 2 in Shaanxi Province [Bailong River, Xidahe] and 1 in Gansu Province), resulting in 14 deaths, 149 people were missing, 247 households were affected, the affected area of crops was 148.4km^2/d, the affected area of crops was 86.7km^2/d, and the economic loss was 8.675 billion yuan. Two major floods occurred in Bailong River and Xidahe respectively (causing 2 deaths). This is a report after the dam failure that occurred on August 16, 2019, when the Bailong River flow exceeded 1000 m/s. According to the analysis of flood impact, the flood has the characteristics of hysteresis. This indicates that there will be greater risks and hidden dangers for the floods of medium and small rivers in the Yellow River Basin.

5.2. Summary of results

A technical system for assessing and simulating the flood risk of small- and medium-sized rivers was constructed in the basin from the site, time and space scales, and issuing flood early warning and impact assessment in advance, which realizes the real-time and accurate flood risk forecast and early warning for small and medium-sized rivers. By systematically evaluating and simulating the flood risk of medium and small rivers in the Yellow River Basin induced by heavy rain, the conclusion of flood impact assessment was given. Besides, a flood risk forecast and early warning technology system for medium and small rivers was proposed based on the results of flood risk assessment for medium and small rivers. Flood impact indicators such as flood peak time and water volume were proposed to provide a reference for flood control decision-making in the Yellow River Basin based on the multi-scale numerical simulation results of equal rainfall parameters and water level stations. The results of flood risk assessment provided forecast conclusions such as river water level evolution trend forecast, flood risk forecast factors, flood risk forecast and early warning indicators, and flood risk levels, and provides a reference for the decision-making of flood control and disaster reduction in the Yellow River. In view of the problems of large amount of data and complex data sources faced by flood risk forecasting and early warning of high-flow medium and small rivers, the research on the integration and data fusion of hydrological resources and data resources has been carried out, and a data set based on flood information analysis and hydrological information fusion was constructed to realize data information sharing and data resource integration and application. A flood risk forecast and early warning model and operational service platform for small and medium-sized rivers was established, and a flood risk forecast and early warning system for small and medium-sized rivers with water level as the main factor and small flow as the supplementary factor was constructed, providing technical support for the operational application of flood risk forecast and early warning for small and medium-sized rivers in the Yellow River basin.

5.3. Application results

The research results have been popularized and applied in Inner Mongolia, Ningxia, Shaanxi, Shanxi, Gansu, Qinghai, Ningxia and other places. Among them, 31 hidden danger points of mountain torrent disasters were newly discovered in 2019, an increase of 3 compared with 2018. In 2020, 26 hidden danger points of mountain torrents were newly discovered, an increase of 1 compared to 2018.

6. Conclusion

Mountain torrents are a major threat to the safety of people's lives and property in the Yellow River Basin. In recent years, the intensity of rainstorms in the upper reaches of the Yellow River has gradually increased, and mountain torrents and floods in small and medium-sized rivers are prone to frequent occurrences. Through the establishment of flood risk forecast and early warning system for small and medium-sized rivers, the risk warning and service can be provided to the downstream people from the beginning to the end of the flood. At the same time, through the mountain torrent risk early warning signal release platform and the flood forecast and early warning products based on business calculation results, it provides an effective basis for flood defense, and greatly reduces the probability of mountain flood disasters or secondary disasters caused by untimely forecasts.

Disclosure statement

The authors declare no conflict of interest.

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