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Technical Note

Flood Disaster Monitoring and Emergency Assessment Based on Multi-Source Remote Sensing Observations

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Abstract: Flood disasters are one of the most serious meteorological disasters in China. With the rapid development of information technology, individual monitoring tools could not meet the need for flood disaster monitoring. Therefore, a new integrated air-space-ground method, based on combined satellite remote sensing, unmanned aerial vehicle remote sensing and field measurement technology, has been proposed to monitor and assess flood disasters caused by a dam failure in Poyang County, Jiangxi Province. In this paper, based on an air-space-ground investigation system, the general flooded areas, severely affected areas, and more severely affected areas were 53.18 km^2, 12.61 km^2 and 6.98 km^2, respectively. The size of the dam break gap was about 65 m and 34.7 m on 22 and 23 June. The assessment precision was better than 98%, and the root mean square error (RMSE) was 0.86 m. The method could meet the needs for flood disaster information at different spatiotemporal scales, such as macro scale, medium scale and local small scale. The integrated monitoring of flood disasters was carried out to provide the whole process and all-round information on flood evolution dynamics, the disaster development process for flood disaster monitoring and emergency assessment, and holographic information for emergency rescue and disaster reduction, as well as to meet the need for different temporal and spatial scales of information in the process of disaster emergencies.

Keywords: satellite remote sensing; UAV remote sensing; integrated air-space-ground remote sensing; flood disaster monitoring; emergency assessment

Citation: Lei, T.; Wang, J.; Li, X.; Wang, W.; Shao, C.; Liu, B. Flood Disaster Monitoring and Emergency Assessment Based on Multi-Source Remote Sensing Observations. *Water* **2022**, *14*, 2207. https://doi.org/10.3390/w14142207

Academic Editors: Yizi Shang, Yuchuan Wang, Akiyuki Kawasaki, Ling Shang and Yongping Wei

Received: 11 May 2022
Accepted: 21 June 2022
Published: 13 July 2022

1. Introduction

Floods are one of the most disastrous natural hazards and cause serious loss of life and economic damage every year in China. From 1950 to 2017, flood disasters of different degrees occurred almost every year [1,2]. Among them, the strong El Nino phenomenon caused frequent and serious flood disasters in 2016 in most areas of China [3,4]. According to the 2018 China flood and drought disasters bulletin, nationwide, flood disasters were generally light but in some areas heavy. The flood disasters in Sichuan, Guangdong, Shandong, Gansu, Inner Mongolia (autonomous regions), Yunnan and Jiangxi provinces were relatively serious and seriously affected economic and social development and the safety of people's lives and property; the direct economic loss accounted for 70.2% of the national total [5,6]. As disaster risks from floods and droughts continue to increase and affect communities, the relationship between disaster risk and human development has become increasingly important [7–9]. Therefore, it is necessary to establish a fast and precise method to monitor and assess flood disasters to ensure people's safety and decrease economic loss.

In recent years, remote sensing information has become an important means of flood monitoring and emergency assessment because of its strong dynamics, good regional macro coverage and low cost of data acquisition and processing [10–14]. The macro-scale disaster information obtained by remote sensing improved the timeliness and recognition accuracy of dynamic flood monitoring to a certain extent [15]. However, considering the increasingly severe flood disaster conditions, none of these methods can be singularly applied in China to meet the demands of the development of disaster reduction and disaster relief in terms of timeliness or specific understanding [16]. Thus, many methods of monitoring flood disasters based on satellite remote sensing systems have been widely used [17–20]. Nevertheless, some scholars have noted that satellite remote sensing technology has some limitations in acquiring refined flood disaster information, such as the location of disaster victims and the submerged conditions of houses [21]. To overcome these limitations, some scholars chose UAV remote sensing technology to monitor disaster conditions while assessing its accuracy [22]. UAV remote sensing technology could collect refined flood disaster information. However, this technology was incapable of monitoring large-scale flood disasters in the same way as that of satellite remote sensing technology [23–28]. To adequately use the advantages of these technologies in monitoring and assessing flood disasters, the best approach could be to combine them as an integrated air-space-ground remote sensing method to meet the needs for different temporal and spatial scales of information during disaster emergencies. Nevertheless, the monitoring results from both satellite remote sensing and UAV remote sensing have revealed a variety of errors caused by image acquisition and data processing [29,30]. Accordingly, a ground survey could be able to evaluate the accuracy of the results of the integrated air-space-ground remote sensing method.

Although most scholars had discussed the application of different means at different developmental stages of flood disasters, the whole link of a flood disaster was still separated from the disaster-causing event and disaster-relief process [31,32]. What we need is the whole link process of disaster monitoring and assessment, to carry out the disaster intervention and response at the different developmental stages of disaster situations and reduce flood losses with more precise interdiction. A monitoring and emergency evaluation technology system through the integration of air-space-ground means was proposed, and a three-dimensional spatial information pyramid of multiple space-time scales was constructed. The pyramid was implemented by the technology system of general investigation, detailed surveys and exploration, which was to realize the scientific division of different serious flood disaster areas, i.e., general flooded areas, severely affected areas and more severely affected areas. By using this data collaborative analysis method, the time series monitoring and analysis of flood inundation area were carried out, the quantitative relationship between the flood disaster risk index and social and economic loss was refined, and the rapid emergency assessment of disaster-affected areas was further carried out. However, the primary objectives of this paper were (1) to establish a method based on integrated air-space-ground remote sensing for the whole link process of flood disasters, (2) to form a multi-spatial-temporal scale and three-dimensional spatial information pyramid of flood disasters based on the integrated method, which aims to actualize the scientific division of different severe flood disaster areas, and (3) to estimate the effectiveness of the integrated method and spatial information pyramid in monitoring and assessing flood disasters. A roadmap of air-space-ground integrated monitoring and emergency assessment of flood disasters (as shown in Figure 1). The combination of different technologies could effectively meet the actual needs of monitoring and evaluating flood disasters on a large scale for rescue from local dike breaks, truly achieving air-space-ground integrated monitoring and emergency assessment of flood disasters. Moreover, this combination could achieve seamless monitoring and more accurate scientific and stereoscopic disaster relief, reducing the undetected areas for emergency rescues so that, to the maximum extent, limited manpower and material resources can be distributed to the most dangerous disaster areas to meet the needs of rescuing people's lives and property. Thus, the establishment of a real-time, complete risk monitoring and assessment system based on integrated air-space-ground remote sensing will be an important part of flood management in the future.

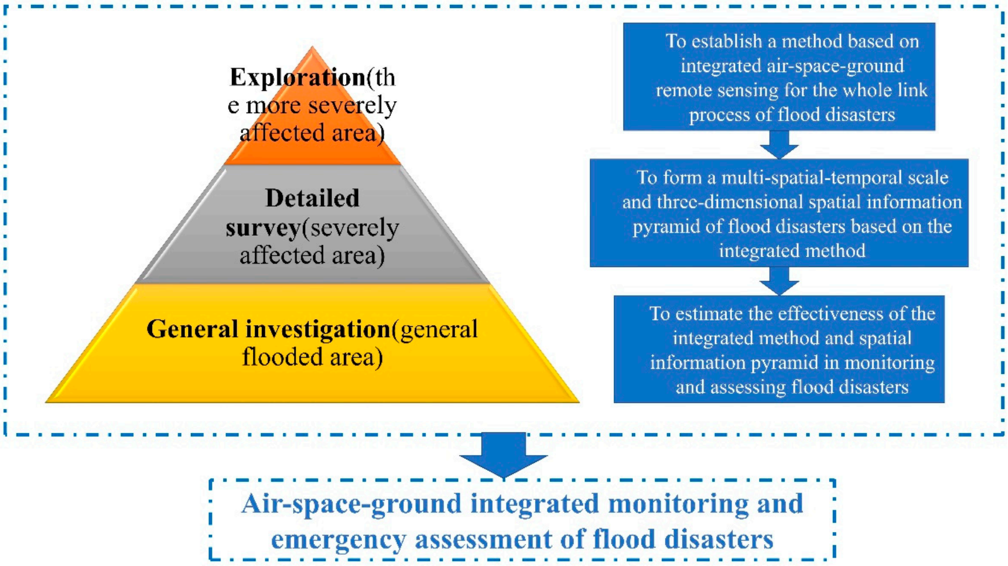


Figure 1. A roadmap of air-space-ground integrated monitoring and emergency assessment of flood disasters.

2. Study Area and Data

2.1. Study Area

From 18–19 June 2016, the northern part of Jiangxi Province suffered the heaviest rainfall caused by the El Niño phenomenon. In particular, the cities of Jiujiang and Jingdezhen as well as Yichun, Nanchang, and Shangrao in the northern part experienced general heavy rainfall to heavy rainfall, with local extra heavy rainfall (136 stations). Hukou County, Wushan Town recorded precipitation of 389.7 mm, the largest amount during a short-term period of rain intensity, with 1 h maximum rainfall of 118.7 mm and 3 h maximum rainfall of 216.3 mm, surpassing the daily rainfall, 1 h and 3 h rain intensity totals over the preceding year for Jiangxi Province. Affected by the heavy rainfall, the Changhe River basin, which flows through Jiangxi Province, suffered from severe flooding. The Changjiang River was flooded for the first time in twenty years, and Poyang Xiangyang Wei was breached, which led to the flooding of ten thousand mu of farmland and crop failures. The breach was located on the Bintian River, a tributary of the Changhe River. Figure 2 shows the locations and distributions of the study area, outburst, settlements and river.

2.2. Method

In this paper, an integrated air-space-ground method was proposed to monitor and assess flood disasters based on satellite remote sensing, unmanned aerial vehicle remote sensing and field measurement technology. To identify different seriously flood-affected areas, the flood monitoring and emergency evaluation technology system of the air-space-ground investigation system was established, i.e., for general investigation, detailed survey and exploration [33]. It was possible to realize the scientific division of different serious flood disaster areas, i.e., general flooded areas, severely affected areas and more severely affected areas. The technical roadmap of this paper is shown in Figure 3. The optimal monitoring scheme and evaluation system for space cooperation was constructed, which includes multi-satellite cooperation in high and low orbits, space and aviation cooperation, remote sensing and station cooperation, the combination of multi-temporal and spatial resolutions, and complementary advantages of multi-sensors.

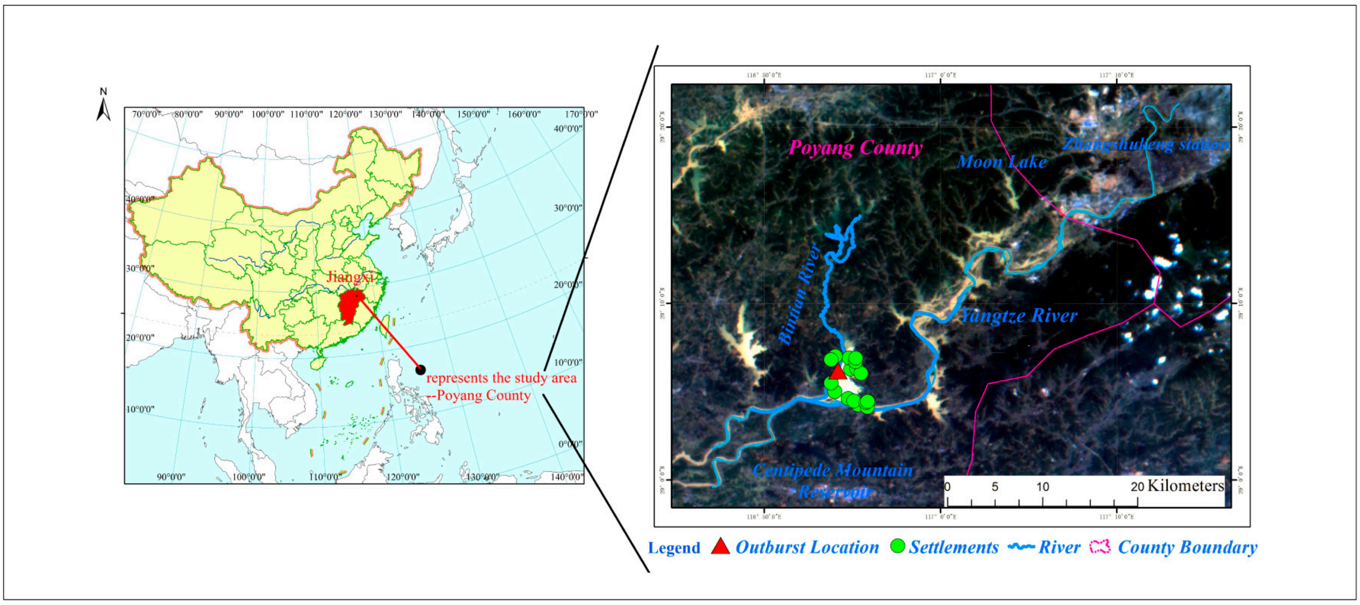


Figure 2. Locations and distributions of the study area, outburst, settlements and river.

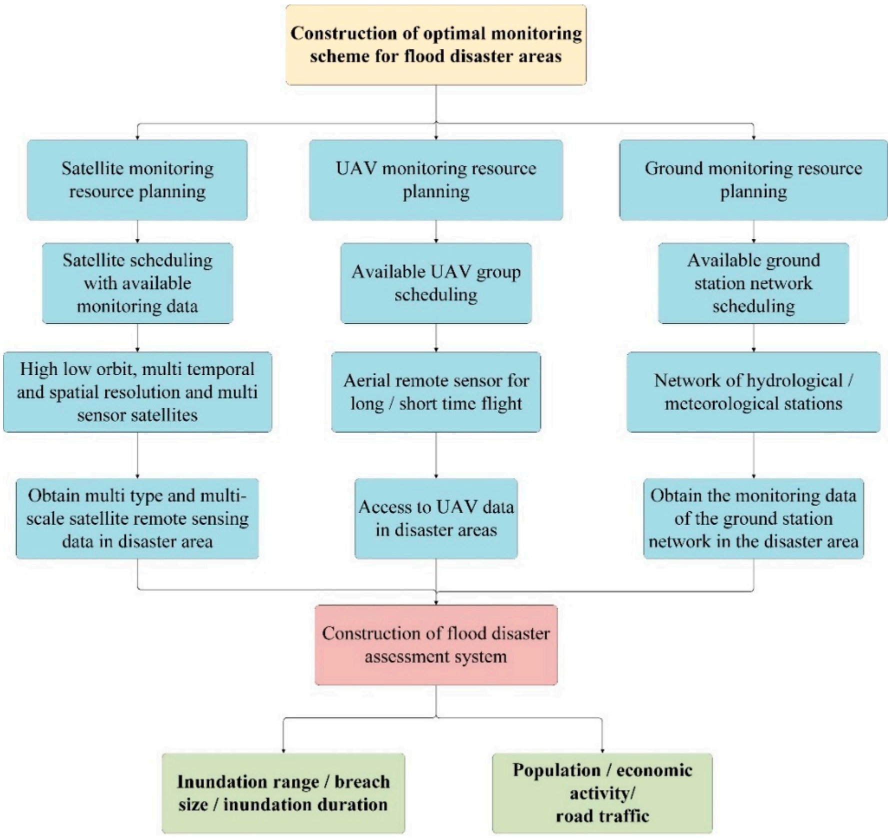


Figure 3. Implementation roadmap of collaborative planning technology of air-space-ground monitoring resources for flood disaster.

1. Satellite remote sensing data, such as high-resolution optical images, were employed to obtain a global panorama of a region on a large scale, highlighting these problematic flood areas and realizing the macro description of the general survey level of the

affected cultivated land and villages and towns. That is to say, after a flood disaster occurs, according to the specific conditions of the disaster, analyze and form the optimal joint scheduling and collaborative planning observation acquisition scheme for the aerial observation resources, carry out the coverage analysis and observation planning tasks for the satellite resources in the disaster area, and form the satellite observation data and satellites in the disaster area by analyzing the available high-low orbit, multi-temporal and spatial resolution and multi-sensor satellite resources satellite to earth observation common data products and other acquisition programs. In this process, targeted analysis and focus will be carried out according to the characteristics of flood disasters and the distribution characteristics of key observation targets. This is called the general investigation on macro-scale.

2. Detailed assessments can be performed through the development of UAV tilt photography data for elaborating high-resolution relief maps. UAV was used to carry out the detailed investigation of the local flood area and focus on the levee breaches, collapsed houses, roads and bridges and damaged lifeline engineering information. In the case that satellite and aerial remote sensing cannot effectively cover or disaster targets needed to focus on high-precision observation, focusing on the specific needs of on-site information such as emergency response, the detailed spatial information acquisition technology and methods for UAV monitoring of flood disasters were carried out. Combined with brief information on flood disaster mechanism, disaster location and disaster time, the delineation design of priority observation areas such as residential areas, important lifelines (roads), outburst location and severe disaster areas was carried out to form a fine monitoring space network, flight area and route design for UAV with plane and strip combination. It could effectively support the acquisition of monitoring disaster information in key areas and the assessment of disaster situations in severe disaster areas, and ensure the timeliness of large-scale emergency command, rescue and search and rescue operations. This was called the detailed survey on medium-scale. It could make up for the deficiency of satellite remote sensing technology due to the weather, terrain, spatial resolution, etc.
3. Third, with the development of a ground mobile disaster real-time verification system or equipment, a village will be a real-time disaster reported to the local flood control command center. This was called the exploration on local small-scale. As a consequence, the ground means were mainly used to accurately mark the flood location and confirm the disaster loss.

At present, the combination of air-space-ground investigation systems for flood disasters have sufficient scientific basis to divide the general flooded area, severely affected area and more severely affected area. At the same time, the pyramid information database of flood disaster situations was constructed to meet the needs of flood disaster relief in different stages and levels. A three-dimensional flood monitoring network based on integrated air-space-ground was carried out to obtain more comprehensive flood disaster monitoring information and provide flood monitoring results with different timelines and accuracy in pre-disaster assessment, mid-disaster rough assessment and post-disaster refined assessment, as shown in Figure 4.

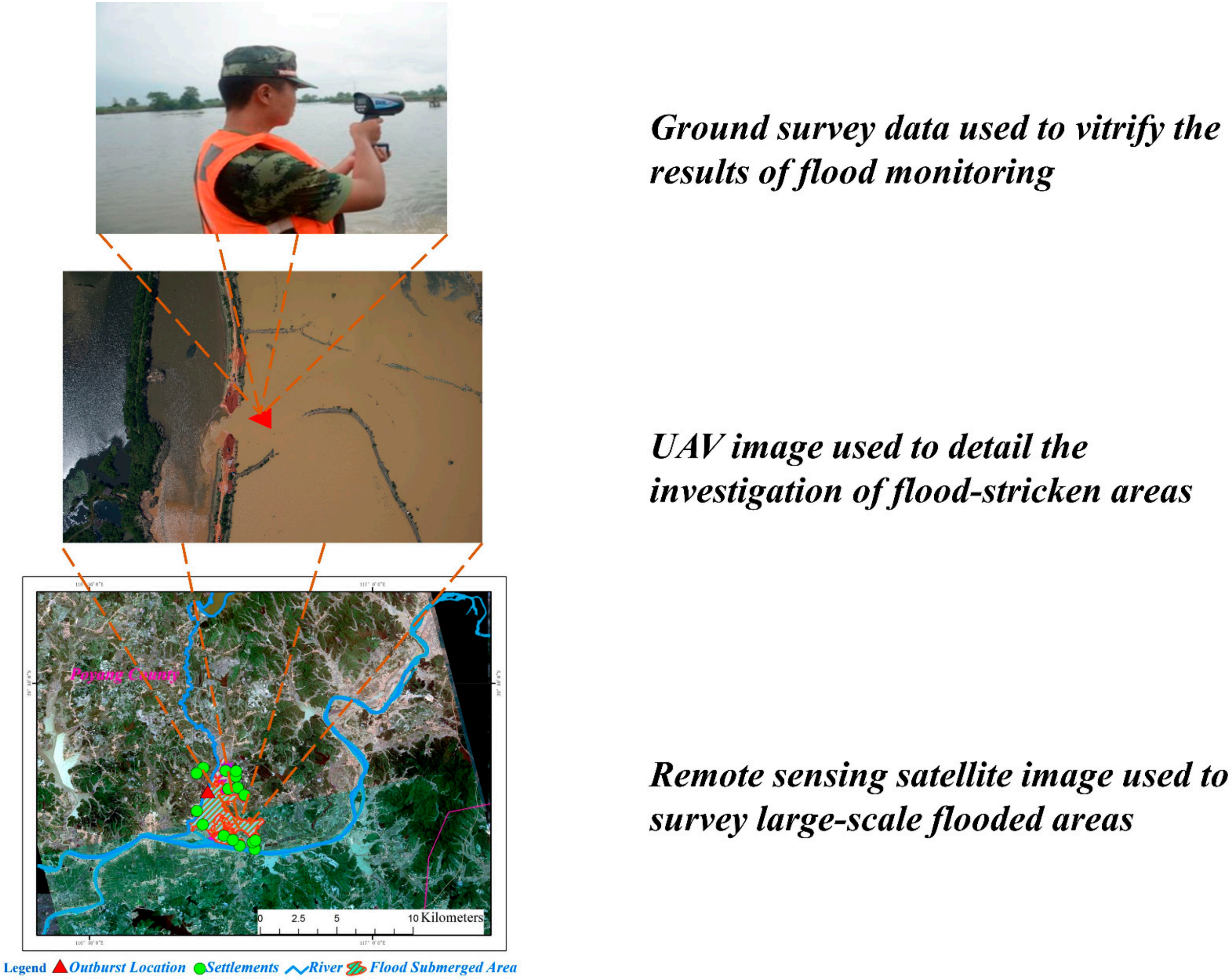


Figure 4. Data types and data purpose.

Then, it was necessary to verify the scientific validity of the integrated air-space-ground method proposed to monitor and assess flood disasters. In order to improve the efficiency and accuracy of the new method, we introduced relative error (μ) and root mean square error ($RMSE$) for analysis, as follows:

$$\mu = 1 - \sigma = \left(1 - \frac{\Delta}{L}\right) \times 100\% \tag{1}$$

$$RMSE = \sqrt{\frac{1}{N}\Sigma_{i=1}^{n}\left(X_{obs,i} - X_{model,i}\right)^2} \tag{2}$$

In the formulas, σ means actual relative error, generally expressed as percentage, Δ means absolute error, L means observed value. N is observed number, $X_{obs,i}$ is observed value, $X_{model,i}$ is model value.

2.3. Data Acquisition

From 18–19 June 2016, northern Jiangxi Province experienced the strongest rainfall process since the beginning of that year. Under the influence of heavy rainfall, the Yangtze River Basin flowing through Jiangxi Province caused large-scale flooding. The peak water level of Zhangshukeng station was 41.52 m, exceeding the warning level by 7.02 m; the flood peak water level of Dufengkeng station was 33.89 m, exceeding the warning level of 5.39 m; this was a flood with a return period of more than 20 years. Affected by the high-water level of the Yangtze River, a breach occurred in Xiangyangwei, Guxiandu Town, Poyang County, Jiangxi Province on the evening of the 20th. The breach was in the Bintian River, a tributary of the Yangtze River. The breach was about 100 m wide and the water level difference between the inside and outside the dike was 5 to 6 m. By the early morning of the 21st, 5600 people had been successfully transferred from the flood discharge dike.

The purpose of the study was to achieve the emergency monitoring and assessment of the flood disaster caused by the breach of Xiangyang dike in Poyang County. The high-resolution satellite image data from 12 May 2016 (spatial resolution: 16 m) and 21 June 2016 (50 m resolution) were provided by the China Resource Satellite Application Centre. The Beijing No. 2 satellite image of 22–23 June (1 m resolution) was provided by 21st Century Space Technology Application Co., Ltd. (Beijing, China), and UAV remote sensing images of 24 June (0.13 m resolution) were collected. Therefore, remote sensing data with different spatial and temporal resolutions were used to conduct all aspects of the whole process of monitoring and evaluating floods. Ground survey data were collected to evaluate the accuracy of the method. The details of these data are described in Table 1.

Table 1. Type, spatial resolution, time, resource and purpose of the experimental data.

Data Type	Satellite	Spatial Resolution	Time	Data Resource	Data Purpose
Remote sensing satellite image	GF-1	16 m	May 12	China Resources Satellite Application Centre	Large-scale survey of flooded areas
	GF-4	50 m	June 21		
	Beijing No.2 satellite	1 m	June 22 June 23	21st Century Space Technology Application Co., Ltd.	
UAV image	UAV remote sensing system	0.13 m	June 24		Detailed investigation of flood-stricken areas
Ground survey data			June 22–24	Field measurement	Verify the results of flood monitoring

3. Results

3.1. Gudu Town Flood Disaster Conditions

Influenced by heavy rainfall from 18–19 June 2016, the Changhe River, which flows through Jiangxi Province, suffered from heavy floods. The flood peak level of the Zhangshukeng station in the Changhe River was 41.52 m, exceeding the warning level by 7.02 m. The flood peak level of the Dufengkeng station in the Changhe River was 33.89 m, exceeding the warning level by 5.39 m. Affected by the flood of the Changhe River and the flood discharge of the Bintian Reservoir, the width of the dike breach was approximately 65 m, and the difference between the water level inside and outside of the levee was 5 to 6 m. The submerged areas of Gudu Town on 21, 22 and 23 June were 12.61 km^2, 8.85 km^2 and 6.98 km^2, respectively (Figure 5). By 9:00 am on 21 June, 13,000 people had been successfully transferred from the levee.

3.2. Integrated Air-Space-Ground Remote Sensing Monitoring of Flood Disaster

Satellite remote sensing images from GF-1 on 12 May and GF-4 on 21 June were selected to determine the overall flood submergence area after the Xiangyang dike break on 21 June 2016. As shown in Figure 6a,b, it was indicated that due to the impacts of large-scale, heavy rainfall in the early stage, the water level of the river, lake and reservoir generally rose, and the channel was densely covered. According to the statistics of monitoring results, the water area of the main channel of the Changhe River in the monitoring area was 24.67 km^2 on 12 May; however, the water area of the main channel increased by a general flooded area of 53.18 km^2 on 21 June, accounting for approximately 116% of the previous area (Figure 5). As shown in Figure 6a,b, on 21 June, the water surface width of the main channel of the Changhe River increased from 342 m on 12 May to approximately 700 m, and the maximum width was enlarged to approximately 1 km. The results of satellite remote sensing monitoring demonstrated that Zhangjialing, Zhengjia and Caojia villages were affected by the flood, and the severely affected area was 12.61 km^2. Because the spatial resolutions of GF-1 and GF-4 images were 16 m and 50 m, respectively, the location of the dike break could not be identified.

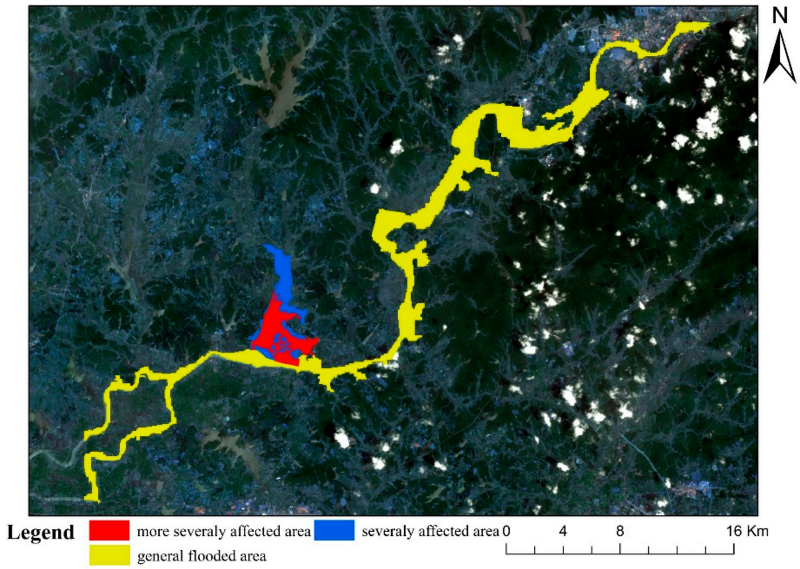
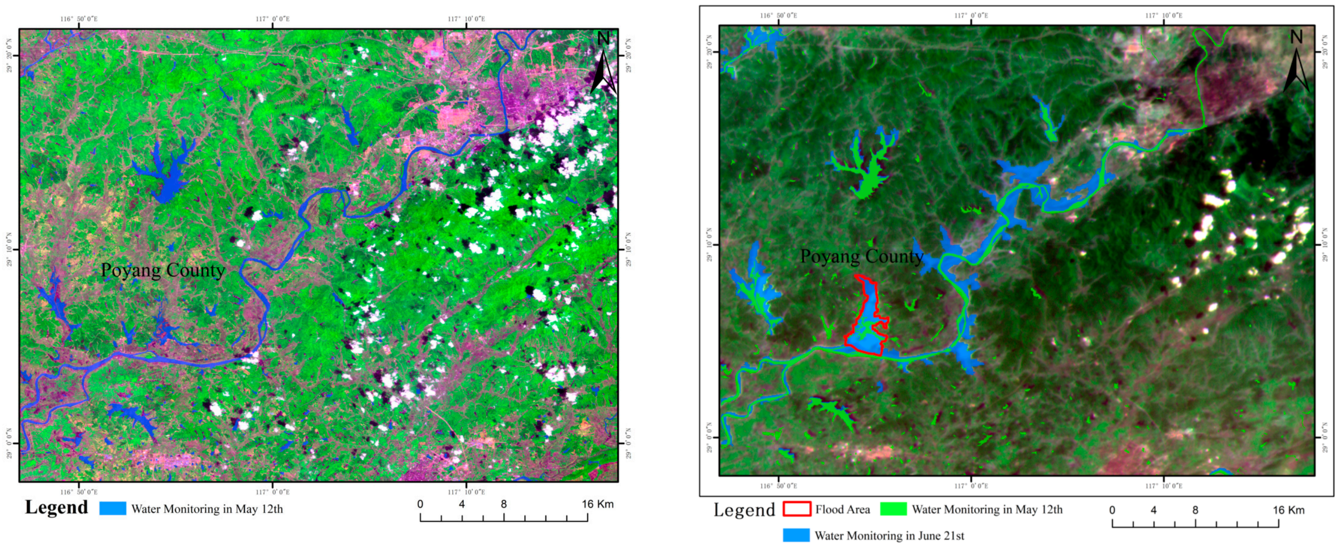


Figure 5. General flooded area, severely affected area and more severely affected area.



12 May 2016 (**a**) 21 June 2016 (**b**)

Figure 6. Thematic map of flood monitoring by GF satellite images in Poyang County.

To identify the location and size of the dike break, Beijing No. 2 satellite images on 22–23 June were selected. These images were used to analyze the flood inundation clearly and carry out emergency satellite remote sensing monitoring of the flood disasters caused by dike breaks in Poyang County, Jiangxi Province. On 22 June, the break of the Bintian River dike was identified based on remote sensing data, as shown in Figure 7. The shadow area in Figure 8a,b covers the flood-inundated area caused by the break of the Bintian River dike, corresponding to 22 June and 23 June, respectively. The current width of the breach was approximately 34.7 m (34m of ground survey data) based on the air-space-ground method, which was 30.3 m shorter than the 65 m before the closure on 22 June. The flood level of the inundation area began to decline, and some areas at higher elevations had begun to retreat by about 1.87 km^2. However, many villages were still surrounded by flood waters, and the more severely affected area of Gudu Town was 6.98 km^2 in scale (Figure 5).

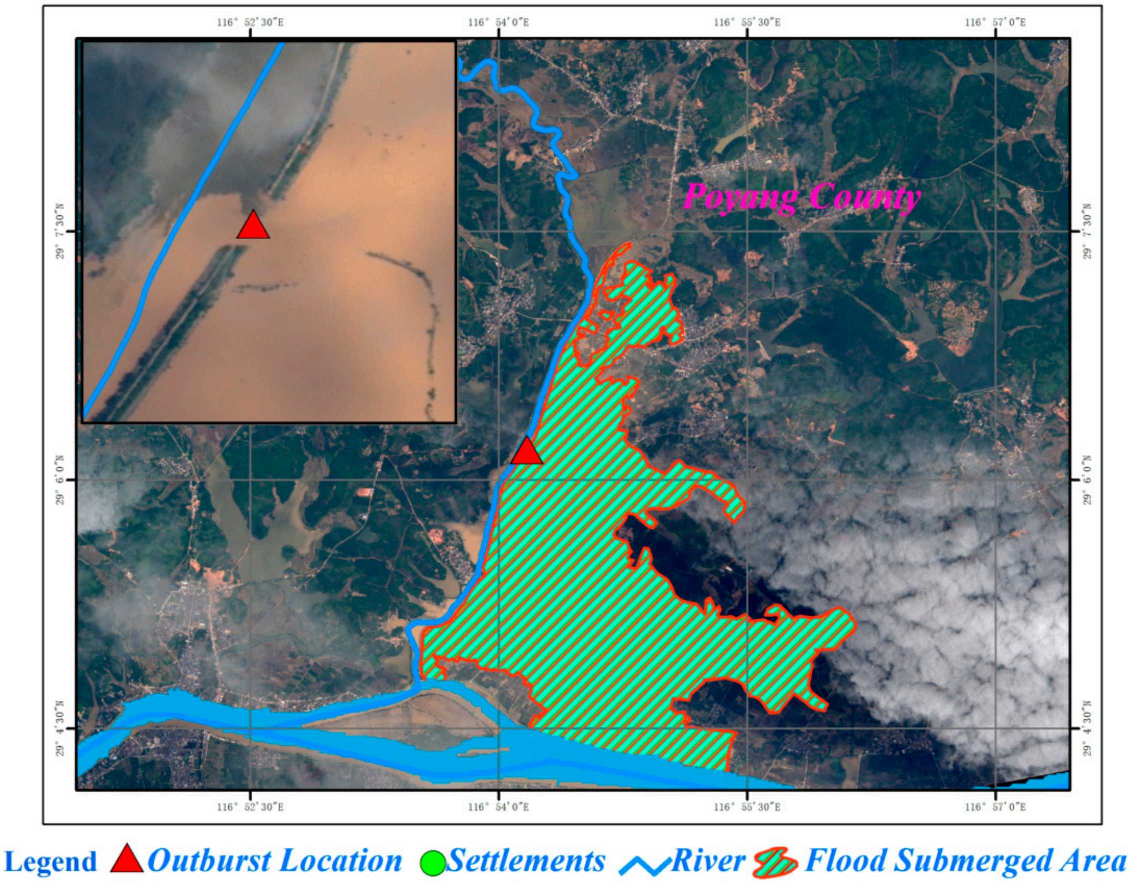
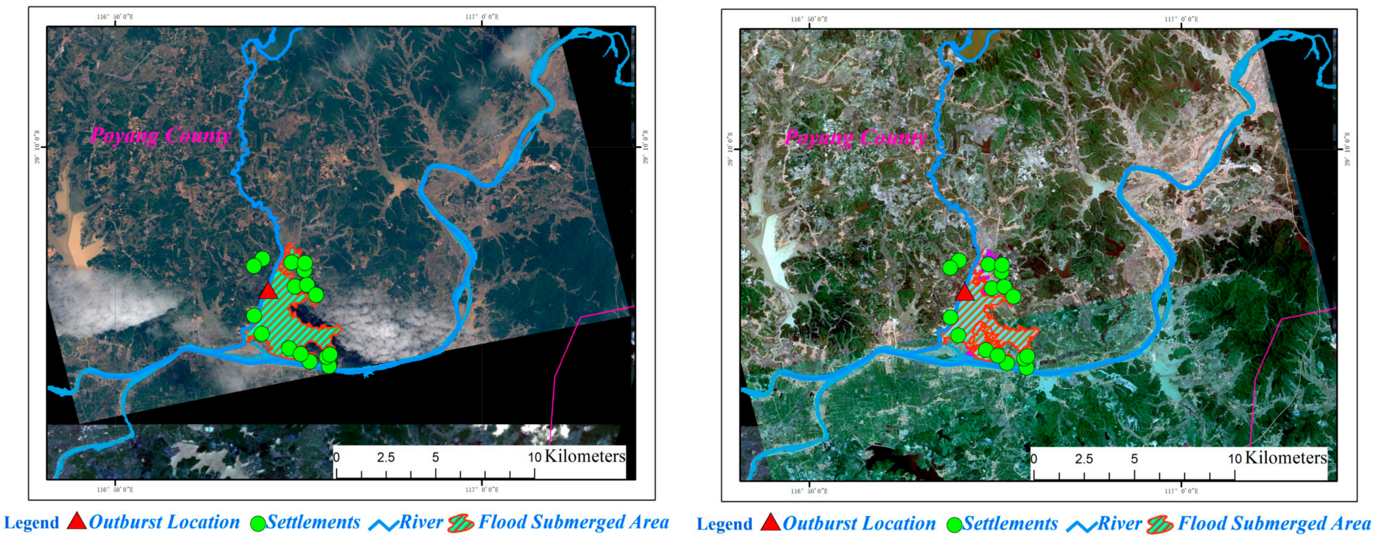


Figure 7. Thematic map of outburst location and flood area in Poyang County, based on GF-1 images.



(**a**) (**b**)

Figure 8. Thematic map of flood monitoring in Poyang County, by Beijing No. 2 satellite images.

To verify the flood monitoring results by satellite remote sensing, UAV remote sensing was an important supplementary means. At the same time, to meet the needs of rescue and disaster relief, UAV remote sensing was used on 24 June to conduct on-site monitoring of dike burst disaster scenarios [34]. As shown in Figure 9, UAV remote sensing images could reflect detailed information on every flood-stricken area. In addition, UAV remote sensing could provide more detailed dynamic information on the breach (Figure 10). Based on satellite and UAV remote sensing images, the width of the breach was estimated at approximately 65 m on June 22. According to ground survey data on June 2016, the breach gap was 64 m. The details are shown in Table 2; the monitoring precision of the air-space-ground method was 98.46%. In addition, due to the implementation of a manual construction enclosure on June 24, the optimal monitoring method proposed in this paper changed the gap length from 65 m to 34.7 m, and according to the ground measurement method, the gap length was changed from 64 m to 34 m, and the monitoring accuracy was 97.98%. The trace of the construction could be clearly identified from the UAV remote sensing images, and the progress of the construction could be grasped in real time. The results indicated that the combined satellite and UAV remote sensing technology could more accurately monitor the actual condition and size of the dam. Based on of the field observation data for evaluation of the accuracy of the method, the root mean square error of the method was 0.86 m. Therefore, the method had better effectiveness.

Figure 9. Disaster image map of Gudu Town based on UAV image.

Table 2. Comparison of the breach in the embankment between air-space-ground method and ground survey data.

Date	Air-Space-Ground Method	Ground Survey Data	Accuracy
22 June 2016	65	64	98.46%
24 June 2016	34.7	34	97.98%

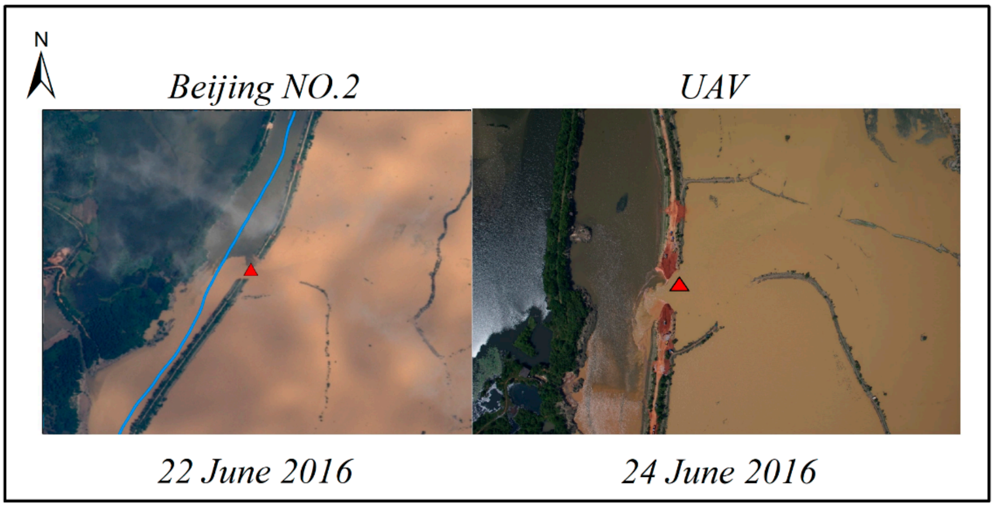


Figure 10. Comparison of the breach in the embankment based on monitoring with Beijing No. 2 and UAV remote sensing images.

4. Discussion

At present, an air-space-ground investigation system has been used to monitor other natural disasters such as catastrophic geohazards. However, few examples of research on air-space-ground investigation systems for floods have been reported [35]. The multi-source data from satellite remote sensing or the combination of space-ground data had been used to monitor flood disasters [36]. The research methods suitable for flood disasters still need to be further explored, due to great differences among the different types of natural disasters, especially in terms of cooperative monitoring and emergency assessment [37]. Thus, a new integrated air-space-ground method needed to be proposed to monitor and assess flood disasters based on satellite remote sensing, unmanned aerial vehicle remote sensing and field measurement technology [38]. It should be the focus in the whole link process of flood monitoring and assessment, to carry out the disaster intervention and response at the different developmental stages of disaster situations and reduce flood losses with more precise interdiction based on multi-source means [39,40].

The advantages of satellite remote sensing technology are that it can provide multiple data formats, including large-scale, multi-angle, multi-band and multi-temporal observation data, and it can also acquire surface feature information over time. From satellite remote sensing images, macro information of the disaster area can be obtained [41]. The results are authentic and objective and have many detection ranges, which can quickly respond to the dynamic changes in disasters and provide vital support for flood disaster monitoring and emergency rescue. However, whether sourced from optical remote sensing or microwave remote sensing, the flood information provided cannot fully meet the needs of disaster emergency management. The quality of satellite remote sensing monitoring data is greatly affected by atmospheric and topographic conditions and calibration, positioning and sensor factors, with low spatial and temporal accuracy. In addition, the coverage scope is generally inadequate to completely cover the affected areas and cannot fully meet the requirements of timeliness for emergency monitoring of flood and waterlogging disasters. Further, the current flood of remote sensing monitoring technologies based on experience and semi-quantitative methods has given priority to lower levels of automation, quantitative research and higher precision, more quantitative remote sensing monitoring models, and flood monitoring indicators that cannot meet the practical requirements of national disaster prevention and reduction of business, or the need to increase investment in manpower and material resources for in-depth research and extensive application of practice. The establishment of an automatic image management system, rapid preprocessing system, application analysis and product release system will facilitate remote sensing-based monitoring of floods and waterlogging operational capacity and improve the response to sudden flood events.

Thus, satellite remote sensing with the indispensable complement of manned aerial remote sensing methods and low-altitude aviation photographs taken by UAV remote sensing systems offers clear images with high resolution, strong real-time performance, flexibility and convenience, low environment impact, low cost, and low flight under the clouds nearly all day with advantages in working ability that can be used for resource investigation, environmental monitoring, disaster emergency relief, and other fields [42]. The system has good complementarity with satellite remote sensing and manned aerial remote sensing and can form a monitoring platform combining satellite-based, space-based and ground-based technologies. It is capable of emergency and repeated monitoring and monitoring of key hot spots. The three-dimensional monitoring of floods with satellite remote sensing provides information with improved accuracy, timeliness and targets for flood control departments to make decisions. Figure 6b shows the flooding of Xiangyang county of Poyang County in Jiangxi province on 23 June and the river embankment collapse, providing more accurate and detailed information on the collapse than satellite images.

In this paper, the monitoring precision of the air-space-ground method was better than 98%, and the RSME was 0.86 m. Some scholars have shown that the precision of monitoring and assessing flood disasters singularly based on satellite remote sensing technology was 73–97% [43,44]. Other studies indicated that the precision of monitoring and assessment of disasters based only on UAV remote sensing technology were approximately 75% and 91%, respectively [45]. Clearly, in disaster monitoring and assessment, the precision of the results obtained by using either satellite remote sensing or UAV remote sensing technology alone was not as high as that of the air-space-ground method. Consequently, the air-space-ground method could effectively meet the actual needs of flood disaster monitoring over a wide area and in emergency rescue from a local dike breach and truly realize the integrated air-space-ground monitoring and emergency assessment of flood disasters, greatly reducing the losses from flood disasters as well. In addition, the method can meet the comprehensive process information needs for rescue and disaster relief, whereas other methods only meet certain needs of the flood disaster response process [46].

Neither optical remote sensing nor microwave remote sensing can provide flood information that can comprehensively fulfill the requirements of disaster emergency management. The quality of satellite remote sensing monitoring data is greatly affected by atmospheric and topographic conditions, calibration and positioning and sensor factors, with low spatial and temporal accuracy. In addition, it is generally difficult to completely cover the affected areas and fully meet the timeliness requirements of the emergency monitoring of flooding and waterlogging disasters. Furthermore, the current priority flood remote sensing monitoring technology is based on experience and semi-quantitative methods with a low level of automation, quantitative research and higher precision, and flood monitoring indicators that cannot meet the practical requirements of national disaster prevention and mitigation. It is necessary to increase investment in manpower and material resources for in-depth research and the extensive application of practice.

Based on satellite remote sensing, UAV remote sensing and ground disaster investigation data, the integrated monitoring of a flood disaster was carried out to provide the whole process and all-round information of flood evolution dynamics and the disaster development process for flood disaster monitoring and emergency assessment, holographic information for emergency rescue and disaster reduction, and meet the needs of different time and space scale information in the process of a disaster emergency [47]. For the rapid acquisition of large-scale flood information, space-based satellite resources with different temporal-spatial resolutions were used to provide large-scale flood inundation scope, to identify the flood-affected areas and accomplish a general investigation of flood disasters. For the severely affected areas, UAV remote sensing images with higher temporal-spatial resolution were used to obtain more detailed information on the disaster areas in time, and to conduct a detailed survey of the flood disaster and the need for actual disaster relief

(DEM Generation from Fixed-Wing UAV Imaging and LiDAR-Derived Ground Control Points for Flood Estimations). For the more seriously impacted areas of disaster zones, the ground investigation was the main means to carry out the precise construction to obtain the point-to-point exploration data and achieve the largest scale capture of the flood disaster information. In order to realize the scientific division of different serious flood areas, the air-space-ground monitoring and emergency evaluation technology system was used to construct the three-dimensional spatial information pyramids of multiple spatiotemporal scales to apply the flood investigation technology system for general investigation, detailed surveys and exploration, which was to realize the scientific division of different serious flood disaster areas, i.e., general flooded area, severely affected area and more severely affected area. The air-space-ground investigation technology system for floods can meet the needs for seamless monitoring and more accurate, scientific, three-dimensional disaster relief and reduce the blind area of emergency rescue and meet the people's life and property rescue needs to the greatest extent, due to limited human and material resources that are most needed in the disaster area. Therefore, the integrated air-space-ground method can effectively meet the needs of flood monitoring and emergency assessment and rescue at different time stages and greatly improve the capability of flood monitoring. Additionally, this method may be also used in the monitoring and assessment of other disasters.

5. Conclusions

Because China had suffered flood disasters for decades, the integrated air-space-ground method was implemented to improve the accuracy of monitoring and assessing flood disasters and accelerating disaster response times. A new integrated air-space-ground method has been proposed to monitor and assess flood disasters based on satellite remote sensing, unmanned aerial vehicle remote sensing and field measurement technology. The method identified different serious flood-affected areas. Based on the air-space-ground investigation system, the identified general flooded area, severely affected area and more severely affected area were 53.18 km^2, 12.61 km^2 and 6.98 km^2 in scale, respectively. The integrated air-space-ground investigation system method can meet the need for flood disaster information at different spatiotemporal scales, such as macro-scale, medium-scale and local small-scale. The results indicated that the method can provide more comprehensive information on disaster areas. This information can be useful in developing disaster relief plans and in implementing relief efforts more effectively. Consequently, it is of great significance to realize integrated monitoring and assessment with remote sensing in the comprehensive process of flood management.

Hence, in terms of timeliness or the specific degree of understanding, the integrated air-space-ground remote sensing method should be constantly improved to meet the needs of the development of national disaster reduction and relief in the future. First, the development of professional satellites for water resources/cycle observation could become an effective means to improve the spatiotemporal accuracy of remote sensing monitoring products for floods. In the next 10 years, more than 200 earth observation satellites could be launched around the world, which would greatly enhance the earth observation capability, provide products and key parameters in flood remote sensing monitoring technology, and provide a continuous, stable, real-time and efficient data source for the operation of remote sensing monitoring for floods. Second, the low-altitude, fast, flexible and mobile UAV remote sensing platform, through regional UAV alliance networks with different types of sensors and high-precision terrain measurement, could provide flood disaster information on levee breaches, landslides, destroyed flood control works and river or lake engineering works, collapsed houses, roads and bridges, and damaged lifeline engineering information to compensate for the weather, terrain and spatial resolution of satellite remote sensing technology. Third, a ground mobile disaster real-time verification system or equipment could be developed. For example, the real-time disaster of a village could be reported to the local flood control command center immediately. Furthermore, a three-dimensional flood monitoring network combining space and sky could be constructed to obtain more comprehensive flood disaster monitoring information and provide flood monitoring results with different timeliness and accuracy in pre-disaster assessment, mid-disaster rough assessment and post-disaster refined assessment.

In conclusion, because of abundant remote sensing products, an important direction for flood remote sensing monitoring in the future is to establish real-time and integrated whole-process risk monitoring and assessment systems based on air-space-ground observations using data assimilation or mining technology. It is necessary to fully welcome the arrival of the new era of flood control and disaster reduction, particularly during the period of big data, for instance, making full use of and mining abundant data resources and further improving the scientific and technological benefits of flood control and disaster reduction.

Author Contributions: T.L. and J.W. contributed to the study's conception and design. T.L. de-signed the experiments, analyzed the data, and wrote the first draft. J.W. proposed key ideas and gave suggestions for the manuscript. X.L., W.W. and C.S. participated in the data curation. B.L. gave suggestions for modifications to the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This work was funded by the Agricultural Science and Technology Innovation Program of Chinese Academy of Agricultural Sciences (CAAS-ASTIP-2014-IEDA).

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

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