Improving flood monitoring and forecasting in High Mountain Asia using remote sensing of glacier lake outbursts

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ABSTRACT

A flood and drought monitoring and forecasting system with high spatiotemporal resolution (up to 500 m, 30 min) using satellite and climate model data has been developed for China. The system uses a combination of the Variable Infiltration Capacity (VIC) and Catchment-Based Macro-scale Floodplain (CaMa-Flood) models to simulate hydrologic-hydrodynamic processes over large basins. Satellite precipitation data such as NASA's Integrated Multi-satellitE Retrievals for GPM (IMERG) have been used to drive the models in near real time, enabling the implementation of the system over ungauged regions such as the transboundary Lancang-Mekong, Ganges-Brahmaputra-Meghna (GBM), and Aksu river basins. Although the system can monitor the rainfall and snow induced floods, it cannot predict the glacier lake outburst floods (GLOF) because the current framework does not take into account of the glacier lakes, which hinders its application in the High Mountain Asia where GLOF frequently occurs. A simple approach is therefore proposed to monitor glacier lake change and detect glacier lake outburst using remote sensing, and to simulate the downstream impacts of the glacier lake outburst floods. Glacial lake volume was estimated by combining lake area data derived from satellite imagery with the 1-meter resolution bathymetric data. When a decrease in glacial lake volume was detected, the suspicious GLOF warning was initiated and the GLOF simulation was triggered. An ensemble of water release processes of glacier lake outburst was formed using the water release processes in the historical periods, and the ensemble GLOF predictions are made by adding glacial lake outburst water release to the hydrological-hydrodynamic simulations. The system successfully detected the decrease of glacier lake storage in July 2024, enabling reliable nowcasting of GLOF risk for Aksu city. The improved flood monitoring and forecasting framework can greatly benefit flood assessment and early warning in other rivers with glacier lakes in High Mountain Asia.

KEYWORDS: Hydrological monitoring and forecasting; Glacier lake outburst floods; Satellite remote sensing; High Mountain Asia

1 INTRODUCTION

Large-scale hydrological monitoring and forecasting systems are essential for managing water resources and providing early warnings of floods and droughts. Satellite-based hydrological monitoring typically involves long-term hydrological simulations that provide a reference database. It also includes a hydrological monitoring component that processes real-time observations and a hydrological forecasting component that offers future predictions based on initial hydrological states provided by the monitoring component. Previous studies have developed long-term land surface hydrologic flux and state datasets for China (Zhang et al., 2014; Miao and Wang, 2020; Gou, et al., 2021). A probability mapping method was used to integrate real-time satellite precipitation into long-term, gauge-based retrospective products by matching cumulative probability functions. This enabled near-real-time hydrological monitoring consistent with long-term retrospective simulations (Zhang and Tang, 2015). Using initialization states from satellite-assisted hydrological monitoring, a hydrological forecast based on climate forecasts and ensemble streamflow predictions was developed (Zhang et al., 2017). This hydrological monitoring system has been applied in China and in various transboundary river basins surrounding China (Jia et al., 2020; Yang et al., 2020; Wang et al., 2021). However, these hydrological models did not account for glacial lake outburst floods (GLOFs). Although the hydrological monitoring system can capture floods induced by rainfall and snowmelt, it cannot predict GLOFs because the current framework lacks an explicit representation of glacial lakes. This hinders its application in High Mountain Asia, where GLOFs frequently occur. Remote sensing monitoring techniques for GLOFs could improve hydrological predictions for rivers in High Mountain Asia. This paper proposes an improved framework for monitoring and forecasting floods in High Mountain Asia by remotely sensing glacier lake outbursts. The Aksu River Basin, where GLOFs occasionally occur, was selected as the case study area. We tested the improved hydrological monitoring and forecasting system to predict GLOF risk in the Aksu River Basin.

2 SATELLITE-BASED HYDROLOGICAL MONITORING

2.1 Framework of Improved Monitoring and Forecasting System

The proposed framework is an improved ensemble GLOF prediction approach built on the ensemble streamflow prediction-based hydrological forecasting framework, with the addition of ensemble GLOF processes. It uses satellite remote sensing techniques to acquire information on glacier lake changes and glacier lake outbursts. Once a glacier lake outburst is detected, an ensemble of water-releasing processes is used to release the water from the glacier lake outburst into the river network. A hydrodynamic model is used to simulate flood propagation and assess the downstream impacts of GLOFs (Figure 1). The original, satellite-based, large-scale hydrological monitoring framework provides the platform, and the GLOF ensemble provides a range of possible water-releasing processes during a GLOF that cannot be observed by satellite remote sensing (Figure 1). The improved framework is described in details below.

The satellite-based hydrological monitoring system employs a combination of the Variable Infiltration Capacity (VIC) and Catchment-Based Macro-scale Floodplain (CaMa-Flood) models to simulate hydrological and hydrodynamic processes in large basins (Zhang and Tang, 2015; Wang et al., 2021). The system provides flood and drought monitoring and forecasting with high spatiotemporal resolution (up to 500 meters and 30 minutes). The models are primarily driven by near-real-time satellite precipitation data, such as NASA's Integrated Multi-satellitE Retrievals for GPM (IMERG) Early Run. This enables implementation of the system over ungauged regions (Tang and Lettenmaier, 2010).

To enable the system to predict GLOF in High Mountain Asia, where it frequently occurs, variations in glacial lakes are monitored using remote sensing. The minimum lake area prior to a GLOF event in historical records was used to determine the warning threshold. The lake area usually increases from winter to summer. When the lake area approaches the warning threshold, there is an increased risk of outburst, so the remotely sensed lake imagery is checked manually every day. Glacial lake volume is estimated by combining lake area data derived from satellite imagery with 1-metre resolution bathymetric data. When a sharp decrease in glacial lake volume is detected, suspicious GLOF warning is initiated and the GLOF simulation is triggered. An ensemble of glacier lake outburst water-releasing processes was formed using those in historical years, and ensemble GLOF predictions were made by adding the released water to hydrological-hydrodynamic simulations.

Although satellite remote sensing can detect GLOF events, it cannot capture the timing of the event or the process by which water is released due to the low revisit frequency of satellites, which is usually 2–5 days. Similar to ensemble streamflow prediction, an ensemble GLOF prediction approach was adopted. Firstly, the ensemble members of the GLOF water-release process were formed based on discharge records following GLOF events in previous years. Most GLOF water-release processes take about 70 hours, but some last less than 40 hours. The volume of water released by the GLOF is obtained from remote sensing estimates, and the total volume is redistributed across the time series in line with the water-release process. Climate sequences resampled from the past will be used as model inputs to perform the ensemble GLOF prediction. Secondly, ensemble GLOF predictions were made by adding glacial lake outburst water release to hydrological-hydrodynamic simulations.

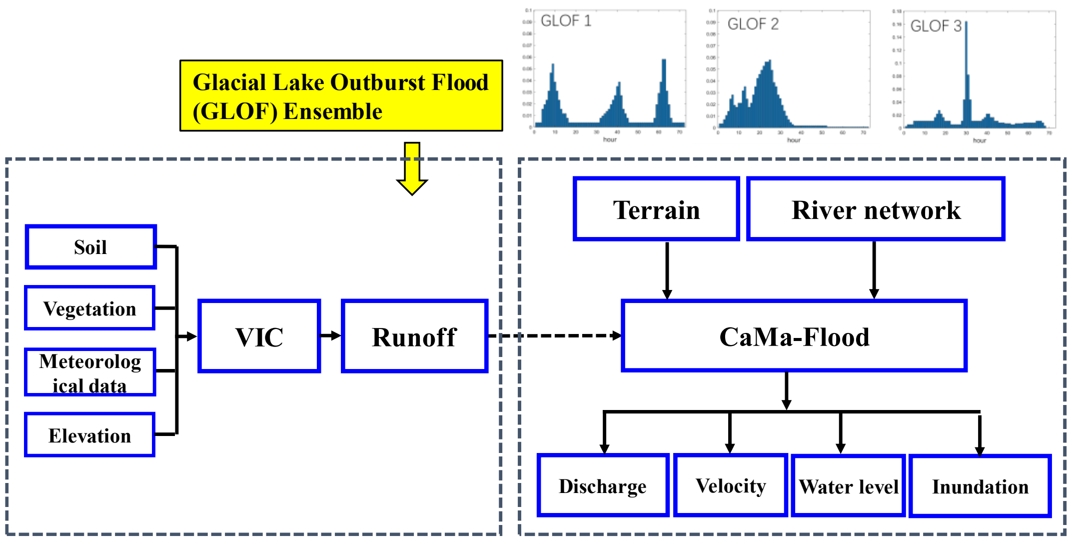

Figure 1: Framework of the improved flood monitoring and forecasting system using remote sensing of glacier lake outbursts

In summary, satellite remote sensing is used to detect the approximate timing and total volume of water released by GLOFs. Information about the water-releasing process, which cannot be obtained from satellite data, was obtained from an ensemble of past GLOF events. This approach involves generating multiple model simulations based on plausible GLOF water-release scenarios in order to produce a range of possible future river flows following a GLOF. This provides probabilistic forecasts rather than a single estimate. The uncertainty of GLOF impact prediction can therefore be quantified.

3 APPLICATION IN HIGH MOUNTAIN ASIA

The Aksu River Basin was chosen as the case study area in which to test the performance of an improved hydrological monitoring and forecasting system. The Merzbacher glacier lake, located upstream of the Aksu River, was monitored and the impact of a glacier lake outburst was predicted.

3.1 Aksu River Basin

The upper reaches of the Aksu River basin possess a complete set of cryospheric elements, with glacial lake outburst floods having a significant impact on the city of Aksu downstream (Figure 1a). Merzbacher glacial lake, located in the upper Sarez River, is a large-to-medium-sized glacial lake formed by the melting of the northern branch of the Irchek Glacier and the blockage of its southern branch by an ice dam (Figure 1b). Each year during spring and summer, as the glaciers melt, the lake gradually fills, generating hydrostatic pressure on the downstream ice dam and promoting the formation of subglacial drainage channels. Following significant accumulation of lake water, the southern ice dam lifts and bursts, causing flooding. This dynamic interplay between hydrostatic pressure and drainage channel adjustment (Figure 1c) makes Merzbacher Lake highly suspicious to outburst hazards.

Although the glacier is located in Kyrgyzstan, its outburst floods affect the Aksu oasis in China every year. In recent years, climate warming has accelerated glacial melt, continuously increasing the lake's volume. This has, in turn, heightened the frequency and peak intensity of downstream floods. An improved monitoring and forecasting system has been implemented to monitor changes in the Merzbacher glacial lake and predict the risk of GLOFs in Aksu city.

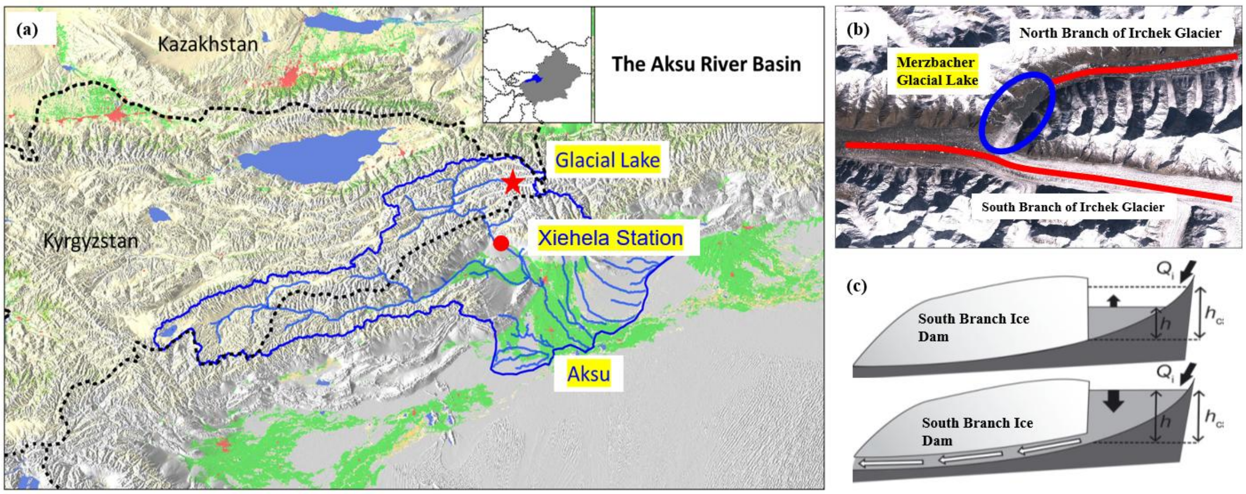

Figure 2: Merzbacher glacial lake and Aksu River basin (a), the two branches of the Merzbacher glacial lake (b), and an illustration of the dynamic interplay of these two branches (c).

3.2 Monitoring Glacial Lakes and Detecting GLOFs

Sentinel-2 satellite imagery with a resolution of 10 m and a revisit time of 2–5 days was used to extract the lake area (see Figures 3a and 3c). The minimum lake area prior to GLOFs in previous years, when satellite data was available, can be used to determine the lake area warming threshold. The estimated lake area was converted to lake storage volume using bathymetric data with a resolution of 1 metre (Figures 3b and 3d). Monitoring began in April 2024 and lasted for more than two months. Monitoring of the lake shows that the lake area increased to 2.5 km² by 30 June 2024, while the corresponding storage volume increased to 80×10^6 m³. Subsequently, the lake storage volume decreased sharply after 7 July 2024 and the GLOF impact simulation was triggered.

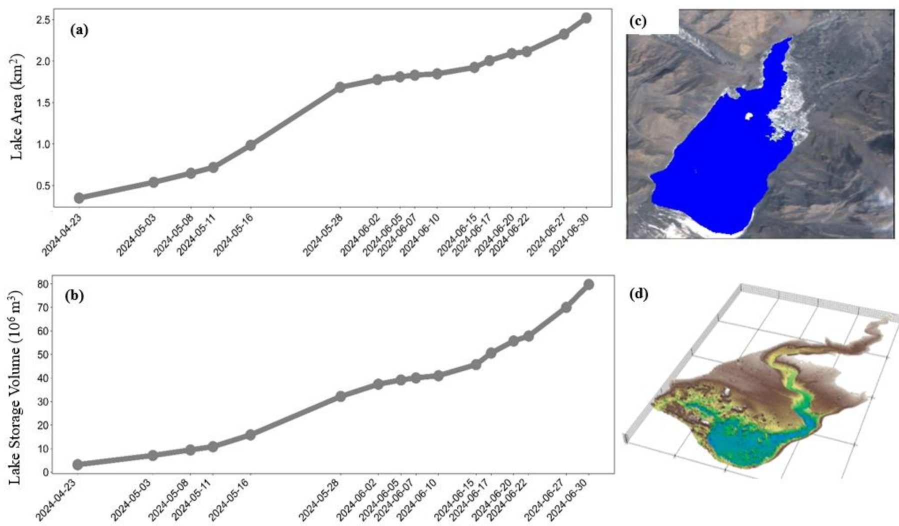

Figure 3: Panel (a) shows the lake area and panel (b) shows the lake storage volume of the Merzbacher glacial lake in 2024. Panel (c) shows the lake area on 7 July 2024 and panel (d) shows the bathymetry data at a resolution of 1 metre.

3.3 The GLOF Ensemble

Based on discharge records at the Xiehela hydrological station from previous years, an ensemble of GLOF water release processes has been formed for GLOF flow prediction in the Aksu river basin. Three ensemble members are shown as an example, and the flood volume is redistributed across the time series in line with the water-release process, resulting in different peak discharges. The ensemble members differ from each other greatly with different numbers of peaks and peaking time. The flood peak could be three times higher in some ensemble members than in others (Figure 4), suggesting significant uncertainty in GLOF flow predictions.

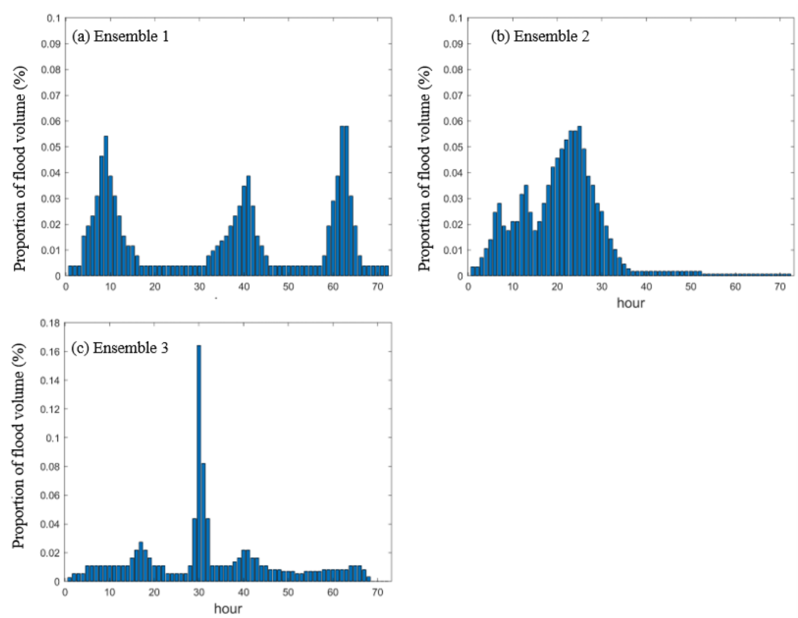

Figure 4: Ensemble of GLOF water release processes in the AKsu River

3.4 Nowcasting of GLOF Hazards

Figure 5 shows the ensemble GLOF forecast at the Xiehela hydrological station, including the simulated water elevation, river discharge and flow velocity. Although there is significant uncertainty regarding the timing of the peak, the forecasting system successfully predicted a flood peak that would not have been anticipated if GLOF had not been explicitly incorporated into the hydrological monitoring and forecasting framework. According to the forecast, the GLOF started on 7 July, with the release of the lake's stored volume taking place over a period of approximately three days, ending on 9 July. According to observations at the hydrological station, the peak discharge occurred on 8 July, which is quite close to the prediction. This suggests that the most likely forecasted GLOF process fairly agrees with the after-event report, except for the slightly overestimated flood volume.

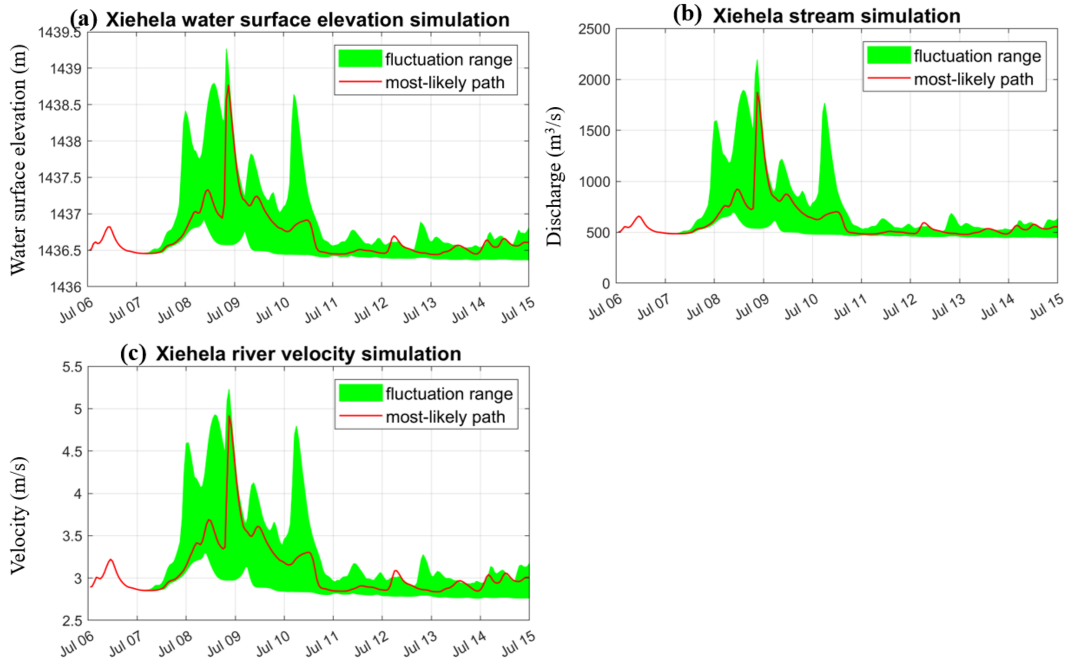

Figure 5: Ensemble GLOF forecast in 2024 at Xiehela Station (with all GLOF ensemble members)

4 CONCLUSION

This paper presents an improved satellite-based hydrological monitoring and forecasting system that uses remote sensing to detect glacier lake outbursts. The approach involves monitoring changes to glacier lakes and detecting outbursts using remote sensing, as well as simulating the downstream impacts of glacier lake outburst floods. Glacial lake volumes were estimated by combining lake area data derived from satellite imagery with 1-metre resolution bathymetric data. When a sharp decrease in glacial lake volume was detected, a GLOF warning was issued and a GLOF simulation was triggered. The system successfully detected a sharp decrease in glacial lake storage in July 2024, enabling reliable nowcasting of the GLOF hazard in the city of Aksu. This improved flood monitoring and forecasting framework could greatly benefit flood assessment and early warning systems in other rivers with glacier lakes in High Mountain Asia.

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