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Flood Forecasting with Merged Satellite Precipitation and Hydrologic Model

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Abstract. Flood forecasting has been an effective way to reduce the potential flood hazards for a sustainable socio-economy. However, the lack of in-situ precipitation records has limited the applicability of flood forecasting with hydrologic models in poorly gauged basins. To address this problem, we aim to develop a flood forecasting framework based on the merged satellite precipitation and a hydrologic model. The framework was then applied to a small basin in the upper Lequan River Basin, Hainan, China for flood forecasting experiments. Results indicate that the combination of merged satellite precipitation and hydrologic model can generally well reproduce the past major flood events occurred in the basin. Our approaches are expected to provide new insights into the flood forecasting in small and poorly gauged basins and can be used to support the sustainable development of the socio-economy.

1 Introduction

The massive advantages of hydrologic simulation in floods, droughts and other water hazards forecasting have been well acknowledged for a rather long time [1-2]. However, the model has not been widely used until recent decades due to the computational burden. Current development in the computational efficacy has allowed the hydrologic models to be used in real-time flood forecasting, which has the potential to reduce the flood hazard before it arrives [3-4]. Nowadays, state-of-art hydrological models are considered able to depict the runoff generation, runoff routing and many other hydrologic components in a relatively accurate way [5-7]. With the use of hydrologic models, multiple studies have reported increasing benefits in protecting the downstream area from inundation and guiding the dam operation for flood control [6-7].

Despite the hydrologic model has brought many advantages to the flood forecasting, the lack of in-situ observed precipitation data have limited the use of hydrologic model in flood forecasting. Normally, flood forecasting by hydrologic models require meteorologic forcing data such as precipitation and temperature for calibration and validation [8]. However, in areas with sparse population or inhabitable environment, gauged meteorological stations were rarely built, and historic meteorologic data are often unavailable. This is particularly the case for the upper Lequan River Basin in the Hainan Island, China. The basin is surrounded by mountains, and meteorologic stations were sparsely constructed. On the other hand, the need for flood forecasting has been increasing for the past years because the population and economy are growing in the downstream areas, which are prone to flood disasters. That being said, the lack of observed precipitation has posed a challenge to flood forecasting with hydrologic models due to the difficulty in calibrating and validating the model [9].

To address this problem, in this study we develop a flood forecasting framework based on the merged satellite precipitation and a hydrologic model. The merged satellite precipitation was originally developed by the National Meteorological Center and was employed in this study to drive the Xin'anjiang hydrologic model to reconstruct the flood events in the recent years. The simulated flood events are then compared with observed streamflow records for an extensive validation. Results indicate that the combination of the merged satellite precipitation and the Xin'anjiang hydrologic model can well reproduce the flood events in the past and can be used in real-time flood forecasting. Our approaches can support the government to prevent flood hazards, and to achieve the sustainable development of the socio-economy.

2 Materials and methods

2.1 Study area

The upper Lequan River Basin has a drainage area of 508 km^2 and its outlet is the Fucai hydrologic station (see Fig. 1). The basin is climatologically affected by the East Asia monsoon and sees a large temporal variability of precipitation. Historically, the basin experienced a

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large amount of floods that brought significant economic losses to the downstream areas.

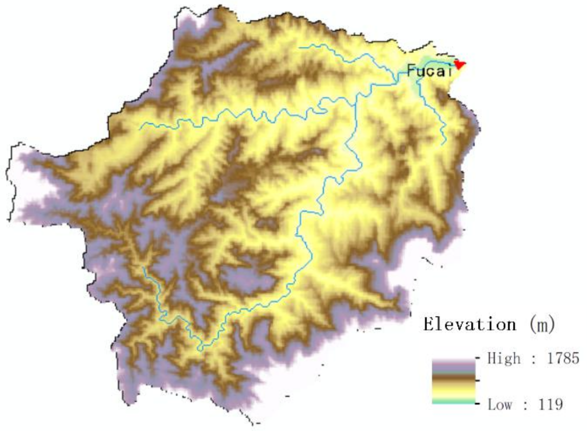

Fig. 1. The map of the upper Lequan River Basin.

2.2 Merged CMORPH satellite precipitation product

The merged CMORPH satellite precipitation product was developed from China's automatic stations and CMORPH precipitation products with a two-step data merging algorithm of probability density matching + optimal interpolation (PDF+OI), and the date product was developed at a resolution of 1 hour and 0.1°, covering the land area of the country since 2008. Its temporal and spatial resolution is high, which can meet the calibration and validation requirements of the flood forecasting model in the upper Lequan River Basin.

The merging steps of this dataset are as follows:

Step 1: Obtain hourly precipitation data from ground observations: extract the hourly precipitation data from the real-time database every hour after quality control at the national automatic station, and interpolate them into an hourly grid with a spatial resolution of 0.1°×0.1°.

Step 2: Obtain precipitation products retrieved by CMORPH satellite: Through FTP transmission, the CMORPH precipitation products developed by the Climate Prediction Center of the US Environmental Prediction Center are obtained (the original CMORPH data has a spatial resolution of 8km and a time resolution of 30 minutes) and resampled to derive a 1-hour, 0.1°×0.1° satellite precipitation product.

Step 3: Use the probability density function matching (PDF) error correction method to correct the systematic errors of the precipitation products retrieved by the CMORPH satellite in China based on the hourly ground observation precipitation data in China.

Step 4: Correct the initial estimation field from the satellite product obtained in Step 3 with the Optimal Interpolation (OI) method based on the observation-based product obtained in Step 1, thereby achieving the effective combination of the two datasets and obtaining the final merging results of hourly precipitation data products.

Step 5: Quantitative evaluation and analysis of product spatial distribution, error characteristics, etc.

2.3 Evaporation and streamflow data

The Xin’anjiang hydrologic model requires evaporation as an input in addition to precipitation. Due to no evaporation gauging stations within the basin, here we select two meteorological stations of Danzhou and Qiongzhong near the basin as the data source of potential evapotranspiration within the basin. The data is at a daily scale, and are processed by the weighted Tyson polygon method to calculate the daily evaporation, before downscaling to every hour.

The daily streamflow data of the Fucai station was collected from the Hydrologic Yearbook to calibrate and validate the hydrologic model.

2.4 Xin’anjiang hydrologic model

In this study, the Xin’anjiang hydrologic model is used as the base model for flood forecasting in the upper Lequan River Basin. Its concept is briefly introduced as follows:

In the 1970s, Professor Zhao Renjun of Hohai University designed the first complete watershed hydrological model in China—Xin’anjiang Two Water Source Model [10]. In the mid-1980s, drawing on the concept of hillside hydrology and research results at home and abroad, he proposed the Xin’anjiang Three Water Source model. The Xin'anjiang model is reliable for streamflow simulation in both humid and semi-humid areas, and has good simulation performance and a high forecast accuracy in most cases. Its application is not only limited to rainfall runoff simulation and flood forecasting, but also water-related fields such as water resources planning and management, disaster prevention, and agricultural development. It has also made a major contribution to the development of the national socio-economy.

The structure of this model is simple and clear and easy to realize through computer programming. Therefore, it is widely favoured in scientific research and engineering applications. However, due to the looped structure of the model, it is not possible for the model to comprehensively describe the flow generation and routing of the hydrological system, and it also cannot simulate the land surface process in the changing environment (such as land use, soil erosion, non-point source pollution, climate change impact assessment, etc.).

The model divides the watershed into many unit watersheds, and calculates the sink term of each unit watershed to obtain the outgoing flow process of the unit watershed. The model then performs the runoff and flood routing along the unit watersheds towards the basin outlet. The main purpose of dividing the unit basin is to deal with the spatial variability of rainfall, so the unit basin should be of appropriate size so that the rainfall distribution on each area is relatively uniform. If there are large and medium-sized reservoirs in the basin, the catchment area above the reservoir should be regarded as a unit basin.

The Xin’anjiang model can be divided into two parts: the runoff generation module and the routing module. The runoff module employs the Three Water Source runoff generation module. The module itself consists of three parts, namely the evapotranspiration calculation, the runoff calculation, and the water source division. Similarly, the Xin'anjiang model divides the flow routing processes into three parts: the land surface routing, the river network routing, and the groundwater routing. The land surface routing is calculated through unit hydrograph method, the river network routing is calculated through the Muskingum method simplified from the St. Venant equations, and the groundwater routing is calculated through the simple, effective linear reservoir method.

2.5 Particle Swarm Optimization Algorithm for Model Parameter Calibration

In this study, the parameters of the Xin'anjiang model are calibrated automatically by the Particle Swarm Optimization (PSO) algorithm [11]. The particle swarm optimization is an algorithm based on intelligence optimization, similar to the genetic algorithm derived from the perspective of biological evolution. This method was first produced when people observe the predation behaviour of birds/fish schools. This method is mainly based on the process of collaboration and competition with individuals to find the optimal solution in the space. The difference between the PSO and another parameter optimization algorithm of genetic algorithm is that the PSO mainly relies on the cooperation between individuals to find the optimal solution, while genetic algorithm seeks the optimal solution based on the survival of the best mutation noted in Darwin's evolution theory.

The PSO algorithm assumes the following scenario: a group of birds are randomly distributed in a certain natural space. They don't know where the food is, but they can feel how far the food is from them. All the birds are searching randomly for food, and the optimal strategy depends on two aspects: search for the area closest to the food, and search based on your own flight experience.

A major concept of the PSO algorithm is that when people make decisions, the main effect is people's own experience and group experience. In other words, people always make their own decisions based on their own experience and group experience. The particle swarm algorithm is simple to apply based on the above principles, and the algorithm is easy to implement.

3 Results and discussion

3.1 Parameter sensitivity analysis

There are in all 16 parameters that can be calibrated (see Table. 1). To reduce the equifinality of parameters, a model parameter sensitivity analysis is first performed to identify the sensitivity analysis to reduce the number of calibrated parameters.

Table 1. Parameters of the Xin'anjiang model

Parameter	Abbreviation	Unit	Values
Soil water cappacity, upper	WM0(1)	mm	5~60
Soil water cappacity, lower	WM0(2)	mm	10~140
Soil water cappacity, deeper	WM0(3)	mm	10~120
Evaporation factor	K		0.3~1.8
Deep evaporation factor	Cd		0.1~0.5
Impermeable area ratio	IMP		0.01~0.5
Storage capacity curve parameter	B		0.2~0.8
Mean free water storage capacity	SM	mm	3~65
Free water storage capacity curve	EX		1~1.5
Free water groundwater discharge parameter	KG		0.1~0.85
Free water soil water discharge parameter	KSS		0.1~0.85
Groundwater parameter	KD		0.3~0.8
Soil flow subsidence parameter	KKSS		0.1~0.999
Fast groundwater subsidence parameter	KKGF		0.7~0.999
Low groundwater subsidence parameter	KKGS		0.7~0.999
Unit hydrograph parameters 1~5	UH1~5		sum = 1

We randomly sample the above 20 parameters, and obtain 10,000 parameter groups. These parameters were input into the model to carry out flood simulation of typical flood events at Fucai Station. The results show that the upper, lower and deep soil water storage capacity WM0, the mean free water storage capacity of the basin SM, the free water groundwater discharge parameter KG, the free water soil discharge parameter KSS, the soil flow subsidence parameter KKSS, the fast groundwater subsidence parameter KKGF, slow groundwater subsidence parameter KKGS, and unit hydrograph parameters UH (1~5) are more sensitive, and the other parameters are not sensitive. Therefore, we select the above 14 parameters for calibration.

3.2 Flood forecasting with the calibrated model

This study selects 10 typical flood events that occurred in the upper Lequan River basin, and divided them into the calibration group and the validation group to calibrate and validate the parameters of the Xin'anjiang flood forecasting model. The calibration and validation results of the flood simulation are presented in the form of the percentage bias (PB) and the determination of coefficient (DC) Table 2.

Table 2. Calibration and validation of flood simulations

Flood event	RB	DC	Note
20081011	-10.5%	0.88	calibration
20091008	-9.6%	0.95	validation
20101001	0.0%	0.83	calibration
20101014	-21.8%	0.76	calibration
20130801	18.3%	0.83	calibration
20131109	-7.4%	0.85	validation
20140715	11.1%	0.66	calibration
20140914	20.6%	0.92	validation
20160816	33.0%	0.82	validation
20161012	-15.7%	0.91	validation

The results indicate that the model can well reproduce the selected flood events, as the RB are fewer than 20% and the DC are higher than 0.8 for most of the flood events, indicating the model and the merged precipitation have a good capability of simulating and forecasting floods. Here, we further present a few representative flood events that were caused by severe storms and typhoons for illustration.

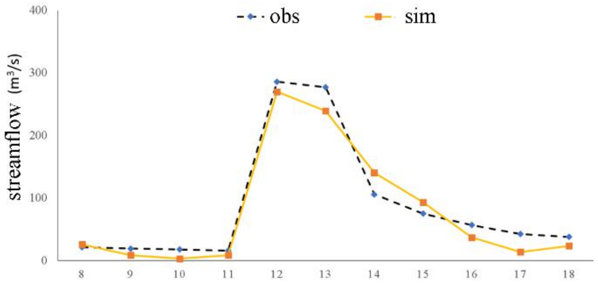

Fig.2. The observed and simulated flood event during Oct.8 and Oct. 18, 2009, where the Typhoon Bama passed by. Obs means observed streamflow, and Sim means simulated streamflow, same for all figures.

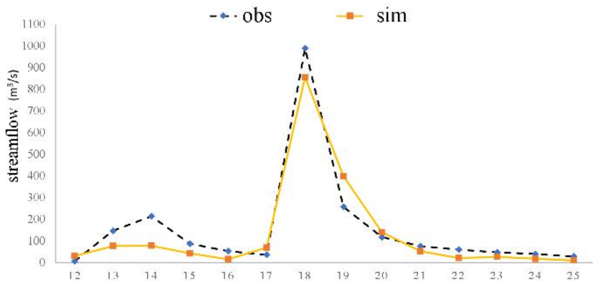

Fig. 3. The observed and simulated flood event during Oct.12 and Oct. 25, 2016, where the Typhoon Sarika passed by.

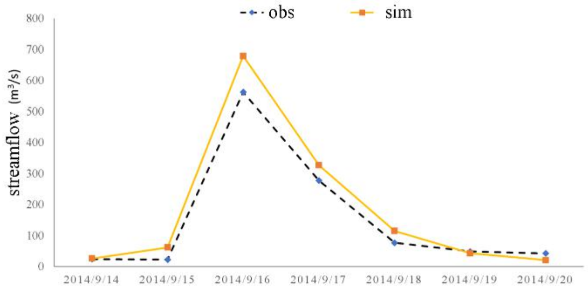

Fig. 4. The observed and simulated flood event during Sep.14 and Sep. 20, 2014, where the Typhoon Kalmaegi passed by.

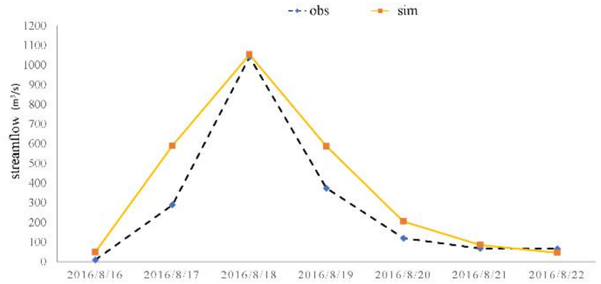

Fig. 5. The observed and simulated flood event during Aug.16 and Aug. 22, 2016, where the Tropical Storm Dianmu passed by.

As is shown in Fig.2, 3, 4, and 5, the flood forecasting model well captures the flood peak and the flood processes for the flood events. This again confirms that the merged satellite precipitation is a reliable data source and can serve as a substitute of in-situ precipitation in case that the gauged precipitation is unavailable. Our results also confirm the applicability of Xin'anjiang model in the flood forecasting in the upper Lequan River Basin and similar basins that are affected by strong storms and typhoons.

4 Conclusions

In this study, we develop a flood forecasting framework based on the merged satellite precipitation and a hydrologic model. The framework was then applied to a small basin, namely the upper Lequan River Basin, Hainan, China for validation of flood forecasting. Results indicate that the combination of merged satellite precipitation and hydrologic model can generally well reproduce the past major flood events occurred in the basin in terms of both the flood peak and flood volume. This confirms the applicability of merged precipitation and Xin'anjiang model in flood forecasting for basins that are of small size and are often affected by storms and typhoons. Our approaches and findings are expected to provide new insights into the flood forecasting in these basins, and can be used to support the sustainable development of the socio-economy.

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