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Rural area flooding digital prediction based on TELEMAC-2D

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Abstract – **In 2020, the Wuqiangxi Watershed, located near Hangzhou, suffered severe financial damage due to an extreme rainfall. The likelihood of such events has recently been increasing due to global warming and climate change. To address these issues, the local water conservation bureau demanded a study to dynamically forecast flood risks of the Wuqiangxi Watershed, and thus to assist in early warning as well as intervention to ensure civil protection.**

In this study, an integrated solution was proposed to fulfil the needs of the local bureau. Flood risks prediction calculation is performed by TELEMAC-2D coupled with a lumped hydrological model named Xin'anjiang (XAJ). Once heavy rainfall is detected in the weather forecast of the next 24 hours, the following simulation process is triggered: (1) The XAJ model is firstly applied to calculate the flow discharges from the upstream sub-watersheds; and (2) The computed discharges are then taken as inflows of the 2D hydrodynamic model. The rainfall-runoff process in the 2D hydrodynamic domain is simulated by the built-in SCS-CN model available in the open TELEMAC system.

This paper presents a technical focus on the process of hydraulic models deployed in flood risk prediction.

Keywords: TELEMAC-2D, Xin'anjiang model, hydrology, dynamic flood risk maps.

I. INTRODUCTION

Flash floods intensively occur during June to August in Hangzhou because of severe downpours. Chun'an County lies in a hilly area in the west of Hangzhou, and is famous for the sceneries of Qiandao Lake. The later, also known as Xin'anjiang Reservoir, is an artificial lake built for the Xin'anjiang hydropower station to retain the upper reaches of Xin'anjiang River. In July 2020, Chun'an suffered the strongest rains throughout history and the water level of Qiandao Lake reached a record-breaking point of 108.43 meters. Wuqiangxi Watershed in Chun'an County (see Figure 1), the interest area of this project, was subjected to serious flood event (see Figure 2) as a consequence of torrential flood, superimposed to the backwater effect induced by the high stage of Qiandao Lake.

The focus of this study is to demonstrate how a hydrological model namely Xin'anjiang model and TELEMAC-2D (version V8P3R1 of the open TELEMAC system) are coupled in the study to dynamically predict flood risks.

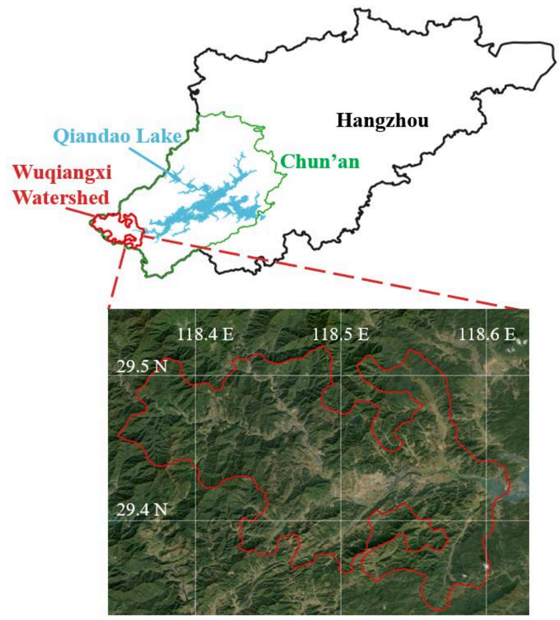

Figure 1. The location of Wuqiangxi Watershed

Figure 2. Flood event in Wuqiangxi Watershed

The first part of this article presents how the data was gathered for the study. A second part describes the model setup with the data while a third part details the calibration process and the model results.

II. DATA COLLECTION

A. *Topographic data*

Topographic data for Wuqiangxi Watershed consists of Digital Elevation Model (DEM) data and river cross-section data. The obtained DEM data describes the terrain with a 12.5 m resolution and consists in the ALOS PALSAR RTC

Digital Elevation Model (DEM), which was downloaded through the official website of NASA EARTH DATA [1]. The local bureau provided surveyed river cross-section data in the Wuqiangxi Watershed. The topographic data was processed as an ASCII file including three columns of data, which are longitude, latitude, and bottom elevation.

B. *Precipitation and evaporation data*

There are two forms of precipitation data depending on the functionality designed in the study. For the in-time forecasting, precipitation data is obtained through access to real-time weather forecast. In terms of recurrence of extreme floods, a formula recommended in a local hydrological manual [2] is implemented to reproduce, for instance, once-in-20-year, once-in-50-year, or once-in-a-century rainstorm data:

$$H_p=\overline{H}(\Phi_p * C_v + 1), \tag{1}$$

where H_p is the designed precipitation, $\overline{H}$ is the average rainfall listed in the manual, Φ_p is the coefficient of deviation of Pearson-III curve, C_v is the coefficient of variation.

The evaporation data was provided by local evaporation gauging stations.

III. MODEL DESCRIPTION

The main goal of the study is to cyclically forecast flood risks every 3 hours in order to demonstrate how simulation can be used to better assist municipalities manage flood risks. Once rainfall occurs in the weather forecast, the Xin'anjiang model (referred to as the XAJ model in the rest of this article) will be initiated to compute the runoff discharges in the upstream of Wuqiangxi Watershed. Then, the computed discharges are processed as the input of the TELEMAC-2D model. The TELEMAC-2D model performs the hydrodynamic simulation inside Wuqiangxi Watershed, subsequently a risk rating function is carried out based on output water depth and velocities [3]. This procedure will be looped every 3 hours if it rains in the next 24 hours. For other types of applications, for instance the reproduction of extreme rainstorms, the same procedure will be launched. A detailed description is presented in the following content.

A. *The XAJ model*

The XAJ model was applied to model the hydrological process in upstream sub-catchments of the Wuqiangxi Watershed. It is a conceptual model put forward by Professor Zhao Renjun of Hohai University in 1963 [4]. The model describes hydrological phenomena through four different levels of calculation, which are:

- evapotranspiration calculation at the first level,
- runoff generation calculation at the second level,
- runoff separation at the third level,
- flow concentration at the fourth level.

In evapotranspiration calculation, according to the characteristics of soil storage, the soil can be divided into the top, intermediate and deep layers. Those three layers are computed separately. The runoff generation calculation is based on Stored-full Runoff Theory [4], which means that runoff is not produced until the soil is saturated and thereafter runoff equals the rainfall excess without further loss. The total runoff, generated in the previous step, must be separated into its three components, *RS* surface runoff, *RG* the ground water contribution, and *RI* a contribution to interflow. In the final flow concentration level, according to the difference of flow characteristics between the hillslope and the river network, it is divided into two different processes: hillslope runoff and river network runoff.

Figure 3 shows the flow chart of the XAJ model. The inputs to the model are *P*, the measured areal mean rainfall depth (mm) and *EM*, the measured pan evaporation in the same unit. *E* is the total evapotranspiration in the watershed and Q is the discharge at the water outlet of a watershed. *E* and *Q* are the model outputs.

As previously mentioned, the XAJ model includes four processes. Each process introduces its conforming state variables, indicated in the black rectangular boxes in Figure 3. *R* is the total runoff generated by a rainfall, and *FR* is the runoff contributing area factor. *W* is the tension water storage, and consists of *WU*, *WL* and *WD*. *WU* is the top layer tension water storage; *WL* is the intermediate layer tension water storage; *WD* is the deep layer tension water storage. *EU*, *EI* and *ED* are the corresponding evapotranspiration state variables. *S* is the free water storage; *RS* is the surface runoff; *RI* is the interflow runoff; *RG* is the ground water runoff. *QS, QI* and *QG* are the respective routing flow.

In addition to those input and state variables, there are 15 parameters for a watershed when using the lag-and-route method [4]. The 15 parameters can be grouped as follows:

- Evapotranspiration parameters *K*, *UM*, *LM*, *C*.
- Runoff generation parameters *WM*, *B*, *IM*.
- Parameters of runoff separation *SM*, *EX*, *KG*, *KI*.
- Routing parameters *CG*, *CS*, *CI*, *L*.

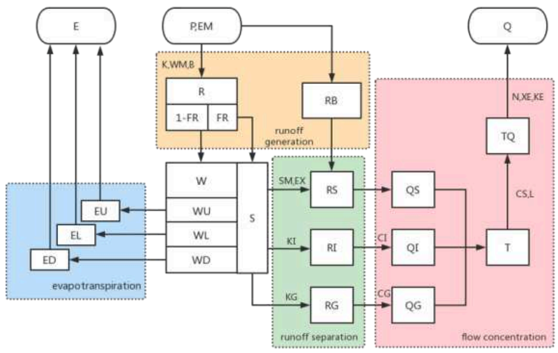

Figure 3. Flow chart of the XAJ model

1) Study area

19 rivers in Wuqiangxi Watershed were taken into account in the TELEMAC-2D model, hence 19 sub-catchments upstream were delineated based on the obtained DEM data, shown as green-shadowed areas in Figure 4.

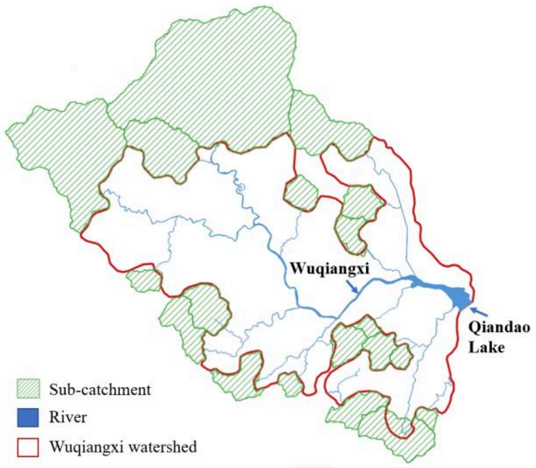

Figure 4. Layout of sub-catchments

2) Model output

The output of the XAJ model is a sequence of discharges as Table I shows. It will be converted to a liquid boundaries file for the TELEMAC-2D model. It should be noted that if the hydrological output was directly applied as the boundary file, a deviation of the input flow rate would be introduced. The output discharge per hour is an average flow rate over the time span, while TELEMAC-2D assumes a linear interpolation in time of the flow rates at each time step. It would lead to discrepancy at flood peak arrival time and consequently results in failure to timely decision-making.

Table I . Output of XAJ model

Time (h)	Q (m^3/s)
1.0	3.78
2.0	5.62
3.0	8.65
4.0	7.21
5.0	5.97
6.0	4.52

To address this issue, the corresponding time step for discharge is shifted to half hour earlier, as can be seen through the green line in Figure 5. The adjusted line is more appropriate than the original one (the red line in Figure 6). A sensitivity analysis shall be operated with regards to the adjusted time length in future work, in order to accurately characterize inflows.

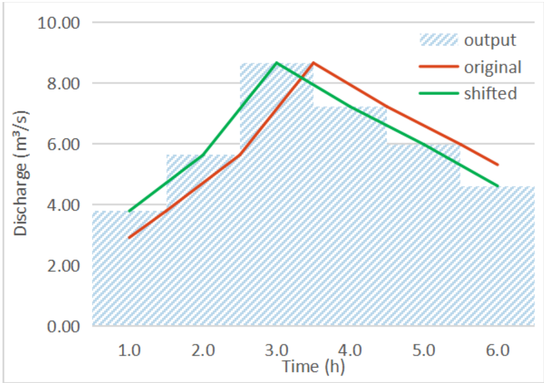

Figure 5. Adjustment of time-varying discharges as hydrodynamic input

It barely rained this summer in Hangzhou (2022); therefore, a once-in-50-year rainstorm was designed in this study and the finalized discharge time series for one branch is shown in Figure 6.

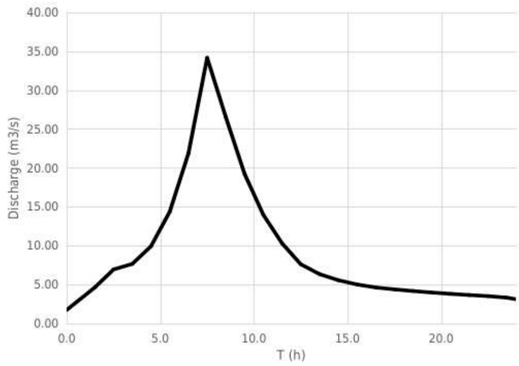

Figure 6. Finalized discharge time series for one small branch

B. *Hydrodynamic model*

1) Computational Mesh

The study area of the TELEMAC-2D model in Wuqiangxi Watershed is around 348 km^2. The mesh resolution ranges from 4 m in the river channel to 150 m at the outline, containing around 233,834 elements and 117,844 nodes, see Figure 7.

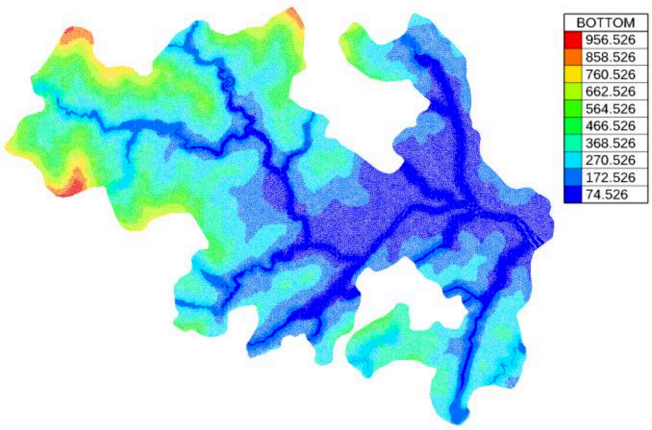

Figure 7. Computational mesh for Wuqiangxi watershed (Bottom elevation unit: m)

2) Boundary conditions

River bottom varies greatly in Wuqiangxi Watershed, as mentioned before it is a mountainous area. To tackle the potential supercritical entry warning, around 20 meters long at the inlets of 19 streams were pre-processed as flat bottom. Furthermore, test runs suggested that at least 4 nodes are required for each boundary segment to better maintain subcritical flow.

3) Initial conditions

Monthly average runoffs of sub-catchments were evaluated by the XAJ model, and then were applied as boundary conditions to spin-up the model. 48 hours of model computation were sufficient to reach a steady state. Thereafter, the last record was extracted as the initial condition for further simulations.

4) Parameters

a) Bottom friction coefficient: The land type of Wuqiangxi Watershed can be characterized as town, cropland, forest and stream. Manning friction coefficients are set with respect to land use type. The friction coefficients served in the TELEMAC-2D model are listed in Table II [5].

Table II Friction coefficient

Friction coefficient	**Land Use Type**			
	Town	***Cropland***	***Forest***	***Stream***
Manning Coefficient	10	0.075	0.18	0.04

b) Curve Number (CN): The rainfall-runoff process within the TELEMAC-2D model is modelled by the built-in Soil Conservation Service Curve Number (SCS-CA) model. In SCS-CA model, Curve Number (CN) is used to describe infiltration capacity of different soil types. By referring to the Hydrology National Engineering Handbook [6], CN values are determined according to the land use type, as shown in Table III.

Table III CN value

Curve number	**Land Use Type**			
	Town	***Cropland***	***Forest***	***Stream***
CN	95	85	73	95

IV. Calibration & Results

A. Calibration of the XAJ model

The original source codes of the XAJ model in this study was further developed by scientists in Yuansuan. It was calibrated with the help of historic data of two flood events in 1993 and 1994 in Chengcun, Anhui Province. The hydrologic data in Chengcun is relatively sufficient and frequently selected for verification [7]. As shown in Figure 8 & Figure 9, the hydrograph (red dash line) calculated by the XAJ model shows a good agreement with the observed data (black line), which ensures the reliability of the XAJ model used in this project.

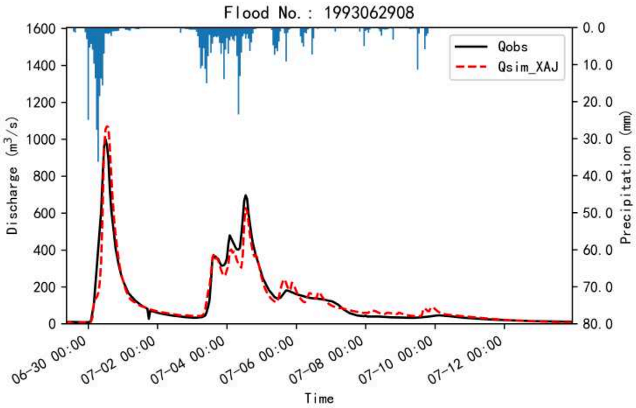

Figure 8. Results comparison for flood event in 1993

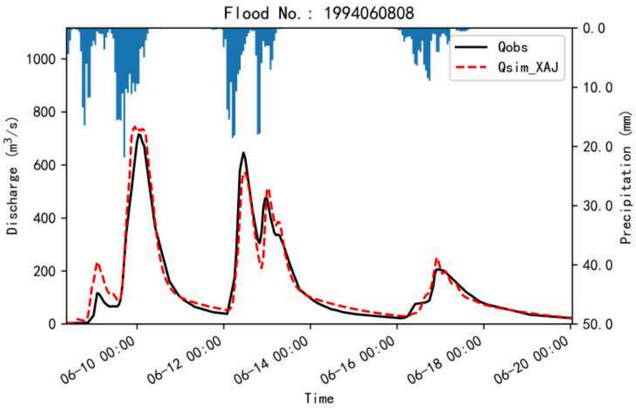

Figure 9. Results comparison for flood event in 1994

B. Hydrodynamic results

In order to compare the backwater effect induced by the high-water level of Qiandao Lake at the downstream location of Wuqiangxi Watershed, 3 scenarios were simulated and compared. For the once-in-50-year flood event, the TELEMAC-2D model was launched 3 times with different downstream water level namely:

- 104 meters - scenario 1: normal water level
- 106 meters - scenario 2: intermediate water level
- 108 meters - scenario 3: high water level

By looking into the towns adjacent to Qiandao Lake, the submerged area was evidently affected by the high stage at the Wuqiangxi outlet (see Figure 10, Figure 11 & Figure 12). The differences of water depth at one village (red dot in Figure 10, Figure 11 & Figure 12) for different scenarios are depicted in Figure 13. The hydrodynamic model took around 1.3 hours to spin-up from initial condition (104 m) to the conforming high water level condition. The water depth difference at the point of interest reached 1.3 meters between scenario 2 and scenario 1, not to mention the 2.5 meters dissimilarity between scenario 3 and scenario 1. This is aimed to demonstrate the potential danger for civilians living adjacent to Qiandao Lake and hence to suggest Qiandao Lake may not operate at high water level.

Figure 10. Water depth at Wuqiangxi downstream, outlet water level 104 m

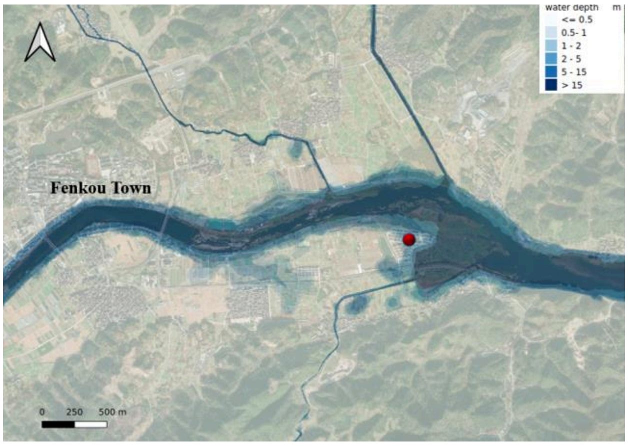

Figure 11. Water depth at Wuqiangxi downstream, outlet water level 106 m

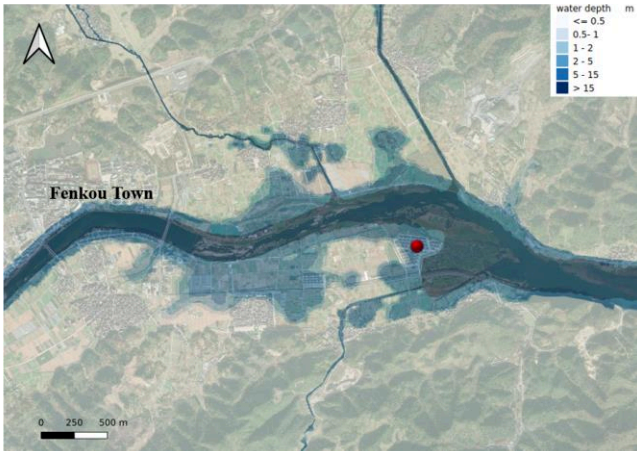

Figure 12. Water depth at Wuqiangxi downstream, outlet water level 108 m

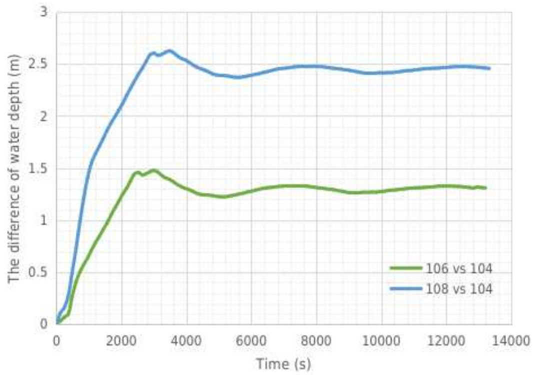

Figure 13. The difference of water depth at one village for high stage scenarios (green line: 106 m vs 104 m, blue line: 108 m vs 104 m)

V. CONCLUSION & PERSPECTIVES

It is the first time that the XAJ model and a TELEMAC-2D model are coupled to forecast flood risks in China. The results demonstrates that it is qualified to model the general flood hazard tendency in Wuqiangxi Watershed and capable to be used as a core engine dynamically forecasting flood risk and reproducing extreme flash floods.

The sensitivity analysis for shifted time step of input flow rates and the validation for hydrodynamic model have not been carried out at this stage. In the next phase of this work, the installation of water gauges in vulnerable villages in Wuqiangxi Watershed will proceed to serve the verification and validation data for both the XAJ and the TELEMAC-2D model.

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