Scenario Analysis Technology for Flood Risk Management in the Taihu Basin

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ABSTRACT: The Taihu Basin is located in the east coast of China, where the threats of frequent floods have induced construction of massive, complex, hierarchical flood defense systems over the interconnected river networks. Digital modeling of flooding processes and quantitative damage assessment still remain challenging due to such complexity. The current research uses an integrated approach to meet this challenge by combining multiple types of models within a GIS platform. A new algorithm is introduced to simulate the impacts of the flood defense systems, especially the large number of polders, on floods distributions and damages.

1 INTRODUCTION

In recent years, the occurrence of extreme events such as floods has been on the rise almost worldwide. Some researchers speculated the prospect of increases in hydrological extremes in relation to climate change. The variability of precipitation and runoff is particularly high for sensitive climates, e.g., a higher percent change in runoff resulting from a small change in precipitation, especially in the high-urbanized area due to rapid development of economics and society. It is very important for water authorities to know and prepare to deal with the effects of climate change and human activities on the changes of hydrological cycles and stream flow regimes. The better understanding on the relationships among climate change, human activities and the flood occurrence will allow water authorities to make more rational decisions on flood control and management.

The Taihu Basin is located in delta region of the Yangtze River in East China with total area of 36,895 km^2 involving south part of Jiangsu province, North part of Zhejiang province and the continental part of Shanghai Municipality. The big floods that occurred in the Taihu Basin in 1991 and 1999 have received significant attention by both local and central government in China. The government gets more and more concerned about the problem of flood risk. Will the flooding risk continue to increase and how large the risk will be in the future 10 years, 20 years, and 50 years? Whether this increased risk will affect the sustainable development of economics and society, and how the flood regime will change due to the effect of human activities under climate change? If this long-term trend continues, what kind of new flood prevention policy should be adopted? It is, therefore, important to investigate the changes of flood regimes due to the rapid development of economics and urbanization and the effect from climate change, and understand the causes resulting in big floods and on the basis of this investigation to formulate a new vision for the future flood control in the Taihu Basin.

2 OVERVIEW

The research applies scenarios analysis technologies in flood risk management and aims at getting better understanding of how flood risk is affected by the following problems:

- Land subsidence caused by over pumping of ground water that deteriorated due to the water pollution.
- Along with the expanding of urbanized area and changes of land use, more water surface decreased and more plain area are being protected by dike, water gates and pump stations, resulting in flood risk being transferred from protected urban areas to rural areas intensifying the regional conflicts in flood fighting.
- Due to the increasing demands of water supply, many dams shift their function of flood control and irrigation to water supply.
- Hidden troubles in security of flood control works due to the aging of materials, land subsidence and other causing.
- Increasing of population and properties in the flood prone areas that require a higher standard of the flood protection but hardly to meet by structural measures alone.
- Incomplete social system for disaster mitigation.

To satisfy the requirements of objectives above, the whole system is divided into eight work packages, which carry out their own functionalities respectively:

1. Qualitative analysis
2. Climate scenarios
3. Set up hydrological models
4. Socio-economic scenarios
5. Set up flood damage data and models
6. Set up hydraulic model
7. Set up dyke reliability analysis
8. Set up quantitative risk model

3 WP1.Qualitative analysis

The objective of Work Package 1 is identifying, describing and ranking the relative importance of drivers of flood risk and responses to changes in flood risk that are in future likely to affect the flooding system in the Taihu Basin.

By assessing the impact and importance of drivers and responses, WP 1 will allow experts and non-specialist stakeholders to develop a common understanding of the factors responsible for determining future levels of flood risk under a range of possible scenarios for climate and socio-economic change. It will also provide narrative descriptions and rankings of drivers and responses that will be informative for the experts involved in constructing quantitative models as part of other Work Packages.

4 WP2.Climate scenarios

The objective of Work Package 2 is using global and regional climate model data to develop scenarios of boundary conditions to the flooding system in the Taihu Basin.

This work package includes the tasks listed below:

- Collection and quality control of rainfall data.
- Precipitation and temperature data over the Taihu basin from CAAS Precis simulations for China.
- Rainfall extremes in the naturally varying climate and projected future changes.
- Mean sea level rise scenarios.

5 WP3.Set up hydrological models

The objective of this Work Package is establishing rainfall and hydrological boundary conditions for the quantified risk analysis. An appropriate hydrological model has been established. Methods for parameterization of future changes have also been established.

This work package includes the tasks listed below:

- Runoff generation at the boundaries of the floodplain.
- Generation of direct net rainfall input to the floodplain.
- Parameterization of non-climate hydrological drivers and responses.

6 WP4.Socio-economic scenarios

The objective is providing socio-economic storylines for the Taihu Basin that are consistent with the current socio-economic position of China and the SRES scenarios.

This work package includes the tasks listed below:

- Generation of the socio-economic scenarios A2 and B2 for the Taihu Basin.
- Generation of the National Planning socio-economic scenarios.
- Development of a rule based GIS model for change in population, land use and assets.

7 WP5.Set up flood damage data and models

The objective of this work package is developing a system for assessing potential flood impacts to economic assets, economic activity and the people of the Taihu Lake Basin. This system is able to characterize the flood damage and loss that the Basin faces now, and is amenable to user-adaptation so that different future climate change and socio-economic scenarios can be explored in terms of the additional (or less) flood damage potential that they create. The system is based on UFDEM model

This work package includes the tasks listed below:

- Decide the level of detail with which the flood damage assessment is undertaken, based on the whole Taihu Lakes Basin project team's views.
- Review the methodology and operation of the UFDEM flood damage estimation model.
- Up-date the flood damage data files.
- Review and incorporate data on the social impacts of floods and potential for loss of life.

8 WP6.Set up hydraulic model

The objective of the hydraulic modeling is generating flood depth data covering the study area for the baseline and scenario analyses that take into account the effects of relevant drivers and structural responses, using broad-scale hydraulic model that represents the important hydraulic features of the Basin in rational way consistent with fulfilling the functional requirements.

The flood depth data has prescribed probabilities and feeds into the risk calculation of impacts (covered in Work Package 8). The hydraulic model has been set up and validated for the current management system. Application of the model for future drivers and responses has been undertaken.

This work package includes the tasks listed below:

- Assembly of data for hydraulic model and plan model updating.
- Transfer existing data to modeling system.
- Set up a tool for efficient calculation of flood depths.
- Parameterization of hydraulic model to represent hydraulic drivers and responses.

9 WP7.Set up dyke reliability analysis

The chance of flooding within the floodplains of the Taihu Basin is heavily influenced by the presence and operation of flood control structures including a significant length of dikes, numerous large sluice gates and pumping stations as well as many smaller local gates and pumps. This Work Package provides an analysis of the baseline and future changes in the reliability of the dikes and associated flooding.

The dike reliability analysis enables:

- The reliability of the linear dikes and their influence of flooding.
- The impact of both climate and deterioration processes on dike performance.
- The impact of management responses, such as raising and strengthening, on dike performance.

The reliability analysis is completed for selected flood areas protected by raised defenses. Undefended flood areas are excluded from the reliability analysis. The reliability analysis is completed for the linear dike system only. Point assets (such as pumps, gates and barriers) are assumed to operate to rule. Interventions to such point assets are made through WP 6.

The outputs of WP7 are used in WP8 to provide an approximate identification and attribution of risk between those defenses contributing most to it.

10 WP8.Set up quantitative risk model

Work Package 8 is the focal point of the quantified analysis as it brings together inputs from each of the preceding work packages in a probabilistic structure in order to calculate risk estimates now and under scenarios of change. The overall objectives are:

- Establishing a GIS tool that can be used to combine probabilities, flood depths and consequences to calculate flood risks
- Establishing a framework so that the tool can conveniently be used to test scenarios of change, drivers and responses in future
- Demonstrating the feasibility of the approach with an approximate quantified analysis of flood risk in the Taihu basin.

The workflow of system is as below:

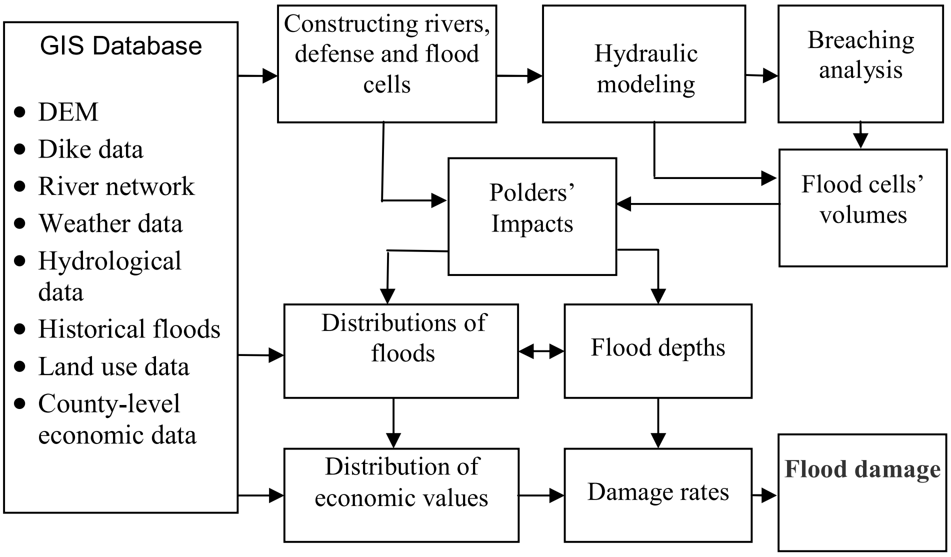

Fig. 1. Workflow of system

11 HISTORICAL FLOOD

We use the hydraulic model to simulate the flow processes of the 1999 flood event in the river network, because the major projects of the defense systems had almost been finished by 1999. After 1999, further construction of the defense systems has been kept going, but the main structure of the defense systems has kept no change. Figure 2 shows the simulated daily water levels of six gauges in the 1999 flood event from June 1st to August 31st by using the hydraulic model. The main dynamic input data include the daily rainfalls, the tide levels in the East Sea and the Yangtze River, as well as the modeled incoming flows from the west upland (i.e. the output data of hydrological model). The results in Figure 2 indicate that the average deviation of the modeled water levels in the hydraulic model from the observed data is about 15.2 cm. For the Taihu Lake, the difference between the modeled and observed peak water level is less than 6 cm. Considering the extent and complexity of the river networks of the entire plain area, we believe that our hydraulic model can simulate the water flowing process in the entire river network of the plain areas very well.

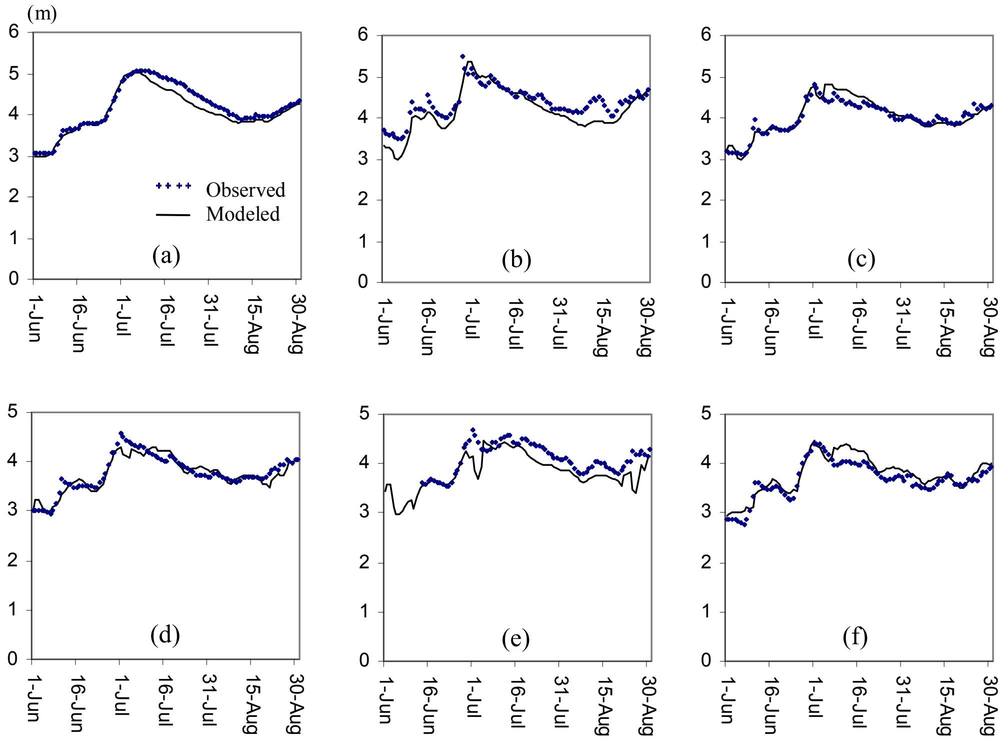

Fig. 2. Calculated water level of 1999 flood (line—simulated, dot—recorded value)

12 SCENARIO SIMULATION

The hydraulic model also outputs the total volumes of floodwater for the plain areas, which include the volumes of overtopping and the residues of direct rainfall. The expected breaching water volumes are derived via analyzing the output water levels and dike conditions on the specific river sections. As such, the total flood volume for each plain cell in a flood event can be calculated. Once the flood volumes for the cells are known, the flood distributions and damages can be calculated. We used this hydraulic approach to simulate the flood distributions using the 1999 flood event as an example, but could not use the same model to simulate the 1991 and 1954 floods. This is because the hydraulic model is built based on the recent environmental status, but the flooding environment has been fundamentally reshaped by human activities, especially after 1991. In addition, there are no data available to describe these historical changes of the defense systems and the flooding processes.

To understand the effectiveness of the current defense systems in reducing flood damages if the same amounts of floodwaters in historical events reoccur, as mentioned previously, we use another approach to directly derive the floodwater depths and volumes from the maps. We combine the DEM data with the historical flood boundaries in the maps, and then estimate the floodwater levels according to the elevation contour lines. Using the estimated water levels, it is possible to calculate the flood depth on each DEM grid cell, and then compute the total flood volume for each flood cell. These derived water-level values are calibrated with the historical water-level records; the derived flood volumes from the map in the 1999 events were tested with the recorded data; and the results can approximately match the records. Using such map-derived flood depth values, we can directly calculate the damages and compare that with the historical records, so as to examine the feasibility of the damage ratios. Using the map-derived flood volumes in each flood cell and combining that with WP5, we can evaluate the effectiveness of the defense systems, especially the polders, in reducing the economic losses. To make the damage assessment comparable, we used the same economic and land-use data for all the historical events of 1954, 1991, and 1999. The economic values are from the records of the 1999, and land use is based on the 2000 data.

The results of damage assessments are shown in Table 1. A widely accepted record for the total damage in the 1999 flood was 14.13 billion Yuan (RMB), which was issued by the Taihu Basin Authority. This record was derived from a survey right after the flood event, including the damages on agriculture, forest, fish farming, industry, transportation, and dikes. We can use this record to compare our modeling results.

Table1. The results of flood damages under different scenarios

	Historical Record	Calculation methods for deriving floodwater volumes						
		Directly from the static maps						Model
Events	1999	1999		1991		1954		1999
Current polders	\	No	Yes	No	Yes	No	Yes	Yes
Damage(billion)	14.13	11.97	9.44	34.23	16.87	46.12	22.82	10.27

Using the flood depths directly derived from the map without using the impacts of the current polder data, the calculated damage is 11.97 billion Yuan in the 1999 flood, by using the 1999 economic data, the 2000 land use data, and the damage ratios. Comparing this value with the recorded 14.13 billion Yuan, we believe that our calculation result is in a reasonable range, because our indicators are not exactly same as that used by the Taihu Basin Authority. This means that the ratios are feasible for our damage assessment. Similarly, the calculated damages in the 1991 and 1954 maps are 34.23 and 46.12 billion Yuan respectively. The rainfall in the 1999 event was the worst, but the flood damage value was the smallest, which means that the overall defense systems by 1999 had efficiently reduced almost three quarters of damage since 1954.

If the same amount of floodwater volumes in the historical floods are generated and the current polder data is also considered in the calculation, the spatial distributions of the 1954, 1991, and 1999 floodwaters will be significantly changed. In this case, although there are multiple polders flooded, most of the floodwater is relocated to the unprotected areas, outside of the polders. The calculated damages of these three events are reduced from 46.12, 34.23, and 11.97 to 22.82, 16.87, and 9.44 billion Yuan respectively. This means that the current polder systems can effectively reduce half of the damage if the same amount of floodwater in 1991 and 1954 is generated in the Taihu Basin. In the 1999 situation, the ratio of damage reduction is smaller than those in the other two events.

If we use the floodwater volume from the outputs of hydraulic modeling and integrate that with breaching analysis and the impact of polders, the modeled flood damage under the 1999 rainfall is 10.27 billion Yuan. We understand that it is very difficult to generate a modeling result to be same as the historical map. This is because (i) the exact data for all the variables of the 1999 flooding environmental are not available, (ii) the defense systems in the entire basin have been kept changing after 1999, and (iii) it is challenging to simulate that the dikes would breach in the model exactly same as that happened in the history (instead of setting deterministic breaches in the model, we use a probability-analysis approach for calculating expected breaching volumes).

13 DISCUSSION

Flood management has gradually been shifted from earlier emphasis on control and defense towards a more holistic risk management (Harvey 2009, Bohm et al. 2004). This requires a development of more comprehensive approaches to technically support such a shift. It is no doubt that GIS can provide an important platform to integrate multi-disciplinary modeling for better assessment of risks. The flooding processes in the Taihu Basin are complex. The involvement of human activities and their great impacts make it more difficult to model such processes. GIS in this research is used as a tool to resolve the "where" issue by developing a new algorithm for modeling these human-intertwined processes. GIS also links multiple types of models to perform in an integrated way. As such, it is possible to simulate the processes of rainfall, water flows in the river-lake networks, the floodwater exchanges between the rivers and the lands, human responses, as well as human impacts on the distributions of floodwaters and damages. Quantitative assessment of the consequences of the past, current, and future floods, therefore, becomes practical. Using this GIS platform, this paper reveals the quantitative changes of flood damages before and after the development of the defense systems through analyzing the historical flood events. These change values had been unknown previous to the current research. In the project, GIS platform has been applied to analyze the change of flooding risks in the next 50 years under different scenarios, such as climate change, sea-level rising, and socioeconomic development (Harvey et al. 2009, Evans et al. 2004).

The results show that the defense systems developed in the Taihu Basin could significantly reduce flood damages, in comparison with 50 years ago. The defense systems, especially the polders, could also substantially change the spatial distribution of flood. This also indicates the transferring process of flood risk. The traditional flood-prone areas have become safer under the protection of the hierarchical defense systems, but many unprotected areas are exposed to flood. The spatial shift of flood risk and the fast urbanization may inevitably result in further competition among local communities on building dikes and sluice gates. Could such competition end up with positive feedback from the natural systems? Imagine one day, the entire plain in the Taihu Basin is full of polders, the interconnected river networks are blocked with gates, all the floodwater is pumped into the rivers channels, but the walled rivers and lakes are too small to store and detain an ordinary monsoon rain, and a normal local short-term storm immediately causes chaos. Such unmanaged competition may eventually lead the flood risk back to a very high level again. Making an optimal strategy for developing the defense systems and balancing the cost and benefit among the local communities will become critical for keeping the defense systems within a rational extent. More importantly, it needs to take proactive actions, such as land-use planning, to reserve flood pathways and make space for flood (Defra 2005).

A main constraint of the research presented in the paper is the availability of data, especially the dynamic state of the historical defense systems. This makes it difficult to use the model with the current environmental parameters to simulate historical events. The algorithm in the project is based on an assumption that the floodwater will flow to the place with the lowest elevation without considering natural barriers. In reality, however, it may not always be true. This assumption nevertheless has effectively reduced the running time on simulating the micro-level flow mechanism, so that the overall integrated flood-process modeling for the entire Taihu Basin becomes achievable.

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