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A GIS-supported impact assessment of the hierarchical flood-defense systems on the plain areas of the Taihu Basin, China

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The Taihu Basin is located in the east coast of China, with a total area of 36,895 km². Low-lying floodplain areas occupy about 83% of the basin. The threat of frequent floods to this economically important area has stimulated construction of enormous flood-defense projects along the complex system of rivers and lakes. Digital modeling of flooding processes and quantitative assessment of flood damages in this basin remain challenging due to the complexity. This article reports on an approach to simulate the flooding processes, which integrates hydrological and hydraulic modeling with dike-reliability analysis and socioeconomic information within a GIS platform. A new algorithm is introduced to calculate the influence of the flood-defense systems on spatial distributions of floodwater and consequential damages. Scenario analysis indicates that the modeling is particularly sensitive to the assumed rainfall, dike reliability, and the pump capacities within local polders. The model is validated by comparison with observations from historical flood records. The analysis reveals that the defense systems have significantly reduced the basin-wide flood risk and changed the spatial distributions of floodwater. Such a GIS-based approach can be potentially used to assess the benefit from construction of flood defenses and to avoid unintended spatial redistribution of flooding.

Keywords: the Taihu Basin; flooding; hydraulic modeling; polders; GIS; damage assessment

1. Introduction

GIScience is progressing from its traditional focus on form to an emphasis on processes (Goodchild 2004). Understanding, representing, and analyzing the mechanisms of how natural and social components interact within a geographic system are essential in the analysis of processes (Yu and Peuquet 2009). This inevitably leads to interdisciplinary collaborations among GIScience and many other fields in Earth Science for developing more holistic representation of context-oriented (e.g., flood, drought, and urbanization)
geographic processes. This article demonstrates an example of integrating GIS with hydrological and hydraulic modeling for representing the human-interwoven flooding processes and assessing flood risks over the complex flood-defense systems in the Taihu Basin, China.

The Taihu Basin is located in the Yangtze River Delta region, with a total area of 36,895 km² in the east coast of China (Figure 1a). It includes the south of Jiangsu Province, the north of Zhejiang Province, the mainland of Shanghai Municipality, and a small portion of Anhui Province. Economically, Taihu Basin is a well-developed region in China. Although its area only takes 0.4% of the nation’s territory, it contributes about 12% to the total gross domestic product (GDP) in 2005 (The Taihu Basin Authority; TBA 2007). The rapid socioeconomic development has made this region sensitive to environmental hazards. Flooding is one of the most frequent and threatening hazards and has resulted in a series of human responses, including construction of multilevel flood-defense systems over a complex interconnected river network (Figure 1b). The TBA, the provincial authorities, and the main cities have built major dikes, water gates, and discharging channels to meet the basin- and regional-level protection standards. Small cities and villages have constructed numerous local river dikes and polders (Figure 1c) in the plain areas to protect local communities.

Understanding and evaluating the impacts of such hierarchical flood-defense systems on flooding processes and potential damages are key to flood-risk assessment in this region. Quantitative modeling of such impacts, however, remains challenging, due to the large number of engineering projects, the complicated river–lake networks, the dynamic human interactions with floods, and the spatial variations in economic values. Especially, modeling the effect of thousands of local polders on the flood distribution and damages in a basin on this scale exceeds the complexity of previously reported model studies. The current research digitizes the record of historical flooding areas, establishes hydrological and hydraulic models in the current research to represent the flooding processes in the river network, develops a new algorithm to integrate the models with GIS to simulate impacts of the defense systems on spatial distributions of floodwater, and evaluates flood risks in different situations.

The main purposes of this article are to introduce the complex flooding processes in the Taihu Basin, demonstrate an integrated approach to flood-risk assessment, and evaluate the impacts of the defense systems on flood distributions and damages using the information of historical floods. Section 2 provides a brief background of this basin and the relevant research. Section 3 discusses the overall methodology, a new hydraulic model, and the new GIS-based algorithm for simulating the impacts of the defense systems on flood

Figure 1. (a) The location of the Taihu Basin in the mainland of China. (b) The light lines represent the main rivers and the thick lines represent some of the major flood-defense and drainage projects constructed after the 1991 flood. (c) The known 2374 polder polygons in the basin.
distributions and damages. Section 4 analyzes the sensitivity of the modeling and reports the calculation results. Finally, Section 5 summarizes the findings and discusses the spatial transfer of flood risks and the constraints of this research.

2. Background

In the plain areas of the Taihu Basin, the river networks are formed under the monsoon climate, with an average annual precipitation of 1177 mm. The Tai Lake (or Taihu), 2338 km$^2$, is located in the center of the basin. It accepts the upstream flows from the west uplands and the surrounding plain areas and redistributes the water through the interconnected river network northward to the Yangtze River and southeastward to the East Sea. Individual local storms in the plain areas usually do not generate basin-wide flood disasters because the river network can effectively spread water outward from storm centers. Intensive and long-lasting monsoon rains (e.g., 30-, 60-, and 90-day periods of rainfalls, also called plum rains) in summer, however, can cause widespread floods. In the twentieth century, there were three major basin-level flood events, which occurred in 1954, 1991, and 1999 (Figure 2).

The low elevations (averagely 2–5 m) of the plain areas and the frequent flood events have stimulated human responses in this economically important area. There are many polders that have been in existence for hundreds of years for protecting local communities. Systematic construction of the flood-defense systems for the entire basin (Lin 2002), nevertheless, did not happen until the serious damage caused by the 1991 flood. Since then, the national and provincial governments have invested heavily on constructing and enhancing major dike systems to improve their protection standards, and expanding drainage systems to increase discharging capacities (Figure 1b). Cities and villages have hastened the development of local river dikes and polders (Figure 1c). These new projects were soon tested in the 1999 flood. The resulting flooding showed that such human activities had fundamentally changed the flood environment and reshaped the flooding patterns. While the rainfall in the 1999 flood was more intensive than that in the 1954 and 1991 events, the total flooded areas in 1999 were much smaller. The flood pattern had changed from large continuous flooding areas (Figure 2a–b) to small scattered spots (Figure 2c). To understand the changes of flood risks in the past and future, it is necessary to develop tools to simulate the flooding processes and the spatial changes of the flood patterns.


![Figure 2. The shaded areas indicate the flooded areas recorded in (a) 1954, (b) 1991, and (c) 1999.](attachment:image)
increasing our understanding of how various natural and social elements, including climate change, sea-level rise, economic development, urbanization, flood-defense systems, and policy options, would interactively affect the changes of flood risks in the next 50 years. Quantitative modeling of the interactions among these elements in the flooding processes was central to meeting the project goals. It required building a set of models to simulate dynamic flow behaviors and flood distributions and to evaluate the potential damages of socioeconomic assets.

Hydraulic modeling (Abbott 1979, Prudovskii 1982, Bradbrooke et al. 2005, Merz et al. 2008, Erpicum et al. 2010, Khuat Duy et al. 2010) is a key approach for digital simulation of flow behaviors and flooding processes of the river networks in floodplains. The most commonly developed and used models for flood-risk analysis are one-dimensional (1D) hydraulic models (e.g., Sorensen et al. 1996, Correia et al. 1998, Merz et al. 2008). There are a few 1D hydraulic models being previously developed for simulating water flowing in the rivers of the Taihu Basin. For example, the HOHY model, initially programmed by Cheng (see Liang and Cheng 1993, Cheng et al. 2006) in the 1980s, is one of the earliest hydraulic models for the Taihu River network and has become an operational tool for forecasting water levels and flood-management planning after continuous improvement of its functionality and usability (e.g., Lin and Yang 1999). Wang et al. (2000) presented another river network model to evaluate the impacts of sea-level rise on water levels in the basin with consideration of river flows, water gates, and floodwater pumping. These models, however, are purely one-dimensional and intended for prediction of water levels in the channel, not in the floodplain. The crests of river embankments in the models are set with unlimited heights, without allowing water flowing out from the river network. It is therefore difficult to use such models to dynamically calculate and balance the volumes of water exchange between the river channels and the floodplain. These existing hydraulic models, in addition, have not been tightly coupled with GIS for modeling the two-dimensional (2D) spatial distributions of floods in the Taihu Basin, so that quantitatively assessing flood depths and damages over space cannot be achievable using these models.

Research on integrating GIS with hydrological and hydraulic models has been conducted in the past decades (Sorensen et al. 1996, Correia et al. 1998, Sui and Maggio 1999, Al-Fuagara et al. 2008, Edwards et al. 2009, Ernst et al. 2010). The development and use of 2D hydraulic models with the support of GIS have gained increasing attention (Bishop and Catalano 2001, McCowan et al. 2001, Aureli et al. 2006, Lindenschmidt et al. 2008, Van der Knijff et al. 2010), such as using quadtree-based raster data (e.g., Liang et al. 2006), and triangular irregular network (TIN) or mesh data (e.g., Cobby et al. 2003, Mandlburger and Briese 2007, Schubert et al. 2008). Using 2D hydraulic models, it is possible to simulate floodwater flow velocities, directions, depths, and extents of the inundation areas beyond the 1D river channels. The availability of high-resolution digital elevation model (DEM) data derived from LiDAR (Light Detection and Ranging) in recent years allows very accurate 2D hydraulic simulation of flooding processes (e.g., Marks and Bates 2000, Cobby et al. 2003, Erpicum et al. 2010). Using high-quality data in 2D hydraulic models for simulating urban flooding has been frequently addressed in recent literatures (e.g., Bishop et al. 1995, Brown et al. 2007, Sanders et al. 2008, Schubert et al. 2008, Gallegos et al. 2009, Abderrezzak et al. 2009, Tsubaki and Fujita 2010). One of the latest research directions of developing hydraulic modeling is coupling 1D and 2D models for integrated representation of flooding processes of river channels and inundation areas (Bates and De Roo 2000, Barnard et al. 2007), such as for detailed simulation of urban flooding (e.g., Phillips et al. 2005, Li et al. 2009).
For numerical inundation simulation over large-scale river basins, however, the fully coupled 1D and 2D modeling approaches may commonly encounter the difficulties of data scarcity, complexity for establishing channel–floodplain connections, high cost in computational time, long duration of floods, and the need to represent precipitation and evapotranspiration processes (Paz et al. 2010). A more realistic approach is to integrate a full 1D hydraulic model with a simplified 2D flood-distribution model, with careful consideration of balanced water exchanges between the river channels and the floodplains. Examples of such an approach can be seen in modeling the inundation dynamics in the Pantanal of Brazil (Paz et al. 2010), and the use of LISFLOOD-FP for modeling inundation of Amazonian wetlands (Wilson et al. 2007). In addition to those difficulties mentioned by Paz et al. (2010), for the Taihu Basin, the complex defense systems and the interconnected river networks make it difficult to simulate the inundation processes. In such a river system, the sources of floodwaters may come from any of the surrounding rivers and direct rainfalls, so that the flow directions are highly uncertain. Therefore, simplification of 2D inundation modeling is particularly necessary to reduce the computational complexity in order to carry out the heavy tasks of calculation in scenario analysis.

The hierarchical flood-defense systems, including the major dikes and local polders, as well as the human-manipulated water exchanges between channels and floodplains make it even more challenging to simulate 2D flood distributions in Taihu Basin. While modeling the impacts of polder systems on flooding is not a new research task (e.g., De Roo 2003, Hesselink et al. 2003, Yulianti and Lence 2007), these research efforts mostly are focused on studying limited number of polders. For example, Huang et al. (2007) integrated a 2D hydraulic model with several polders to simulate the control strategy for polders and flood distributions in a small catchment. Nevertheless, it would become difficult if all of such detailed controlling behaviors are considered when there are thousands of polders that affect the very complex flooding processes over a large plain area. This article proposes a GIS-supported approach that couples a full 1D hydraulic model and a simplified new algorithm for simulating 2D flood distributions with consideration of the polders as many as that shown in Figure 1c.

Quantitatively assessing flood damages often involves nontrivial investigation of spatiotemporal variations of economic assets and their vulnerabilities (e.g., Jonkman et al. 2003, Penning-Rosswell et al. 2005, Scawthorn et al. 2006, Rose 2007). There are no universal damage assessment rules that can be applied to all flood events. In addition, most research on damage assessment is focused on direct economic losses. Estimations of indirect losses (e.g., business interruption caused by the broken supply chains because of the failures of transportation systems) remain challenging due to the uncertainty and complexity. For the Taihu Basin, there has been some research on evaluating the impacts of the major river defense systems on economic damages. For example, Ou and Wu (2001) applied the HOHY model to estimate potential changes in flooding areas under different water levels. Such estimates largely relied on individuals’ expertise, rather than a systematic approach to calculate the spatial distributions of both flooding areas and economic losses. In addition, there is no holistic tool that is able to perform flooding simulation and damage assessment for the entire plain area of the Taihu Basin.

This article presents a new tool, ‘Taihu Basin Flood Risk Analysis System (TBRAS),’ which integrates hydrological and hydraulic models, GIS, and damage assessment to allow quantitative impact assessment of the flood-defense systems, especially the polders, on flood distribution patterns and economic damages. It is intended to answer the following questions: (1) If the floodwaters are directly derived from the historical flood maps (as shown in Figure 2) without considering the rainfall and hydrological processes, how
much would the current defense systems affect the flood damages and distributions?

(2) If using the hydrological and hydraulic models to simulate the flood processes based on the historical rainfall data, under the current defense systems, what are the expected flood distributions and risks?

3. Methods

To address the first question above, the method is to derive flood volumes and depths directly from historical flood maps, by matching the flood boundaries and the elevation contour lines to estimate floodwater levels on the maps, and then using the DEM data to calculate the flood depth for each DEM grid cell. As such, a digital representation of the floods as shown in Figure 2 can be generated to allow the assessment of the flood damages in different events.

To address the second question, hydrological and hydraulic modeling is integrated with the GIS for dynamic simulation of the rainfall, water levels, floodwater volumes, as well as the distributions of damages. The following sections focus on introducing the conceptual design, the hydraulic model, the new algorithm, the spatial distribution of economic values, and the approaches of damage assessment.

3.1. Conceptual design

Figure 3 shows the data flow for modeling the flooding processes and calculating damages. The main tasks include hydrological modeling, hydraulic modeling, dike-reliability analysis, socioeconomic and vulnerability analysis, flood-depth analysis, and damage assessment. The hydrological model is used to simulate runoff from the uplands in the western areas of the basin and to calculate the net rainfalls in the plain areas. Both the upland inflows and the effective rainfalls are input into the 1D hydraulic model to simulate the flow processes, including the changes of flow velocities and water levels within the floodplain river network. The outputs of the hydraulic modeling are combined with dike-reliability analysis to derive breaching volumes and probabilities. The flood volume for a particular place is calculated with consideration of direct rainfall, breaching, and spillover. Combining the defense systems and the flood volumes with the DEM data, it is possible to compute the flood distributions and flood depths for each place. For economic values, the finest resolution of the original data is based on the county-level information from yearbooks. Such county-level economic values can be downscaled according to different land-use types. The damage rates of different flood depths for each land-use type can be evaluated for calculating the flood damage in each flooded area.

To spatially match the flood-depth data with economic values and damage rates, the calculations are performed on a raster dataset (Figure 4). The plain areas of the Taihu Basin are divided into 198 smaller regions, called flood cells (Figure 5), according to the natural river networks. These flood cells are used for accepting rainfalls, exchanging water between lands and the surrounding rivers, and calculating the volumes of floodwater. Each flood cell may include multiple polders that can significantly affect the spatial distribution of the floodwater. The information of flood cells and polders is encoded into the raster dataset that matches the political boundaries, the land-use types, and the economic values (Figure 4). As such, the flood-depth and damage values can be calculated for each grid cell, each county, each province, as well as the entire study area of the Taihu Basin. The resolution of the grid cell used for calculation is 500 × 500 m². The detailed calculation methods are described in the following sections.
Figure 3. The main steps and data flow to evaluate the flood damages.
Figure 4. The relationships between a county, a flood cell, and multiple polders (p1–p3). These data are converted to raster data to allow grid-cell-based damage assessment.

Figure 5. (a) The hydraulic model built in the current research; it includes 795 rivers, 2394 river sections (i.e., the black dots), and 111 water gates (i.e., the unconnected river sections in the map); (b) the 198 flood cells that are associated with the rivers; and (c) a zoomed-in flood cell from the black polygon in (b), with multiple polders included.

3.2. Modeling the flooding process

3.2.1. One-dimensional hydraulic modeling

To simulate the flow in the river networks and lakes, a 1D hydraulic model is built for the entire plain areas of the Taihu Basin. This model consists of 795 rivers, 2394 river sections,
and 111 water gates (Figure 5a). Each river in the model may represent one particular real river in the world, or a combination of several small streams (see Figure 1b) with consideration of their actual total drainage capacities and protection standards. According to the river networks of the model, 198 flood cells are constructed to represent the plain areas (Figure 5b). Each of the flood cells is linked with the surrounding river sections in hydraulic modeling for representing water exchange between the rivers and lands (Figure 6). Within a flood cell, it may include many polders (Figure 5c) that have different standards of protections or crest levels. The boundary conditions of the hydraulic model include the net rainfall, the water levels of the Yangtze River in the north, the tide levels of the East Sea, and the incoming flows from the rivers in the western uplands (i.e., also the outputs of the hydrological model). A commercial software tool, ISIS (http://www.halcrow.com/isis/), is used to perform the calculations of the hydraulic modeling. The outputs of the hydraulic modeling include the dynamic (e.g., with a 30-minute time step) water levels and flow volumes for each river section, and a volume of floodwater for each flood cell during a flood event. According to the available data, the recent river conditions, water gates, and polders are encoded in this hydraulic model.

In this hydraulic model, a whole flood cell is abstracted as a single point. It focuses on representing the total volumes of water exchange between a flood cell and its surrounding rivers, but does not consider how the floodwater will be spatially distributed within the flood cell. As previously mentioned, instead of using 2D hydraulic models, the current research simplifies the calculation with a GIS approach to simulate how the defense systems, especially the polders, affect flood distributions.

3.3. Modeling 2D flood distributions within flood cells

Figure 6 shows a conceptual flooding process within a flood cell, which consists of dikes along the surrounding major rivers, inner polders, small streams linking the water flows between lands and the main rivers, as well as sluice gates and pumps for human control of the flows. In normal conditions, the sluice gates are open, and most of the water from

![Figure 6](image-url)
the direct rainfall will flow into the main river channels via natural (gravity-driven) runoff. In flood seasons, if the water in the main river channel rises to a level higher than the local water level, the gates along the major rivers and the polder dikes will be closed, and the water in flood cells will be pumped into the surrounding rivers. If the water level is beyond the limits of river’s capacity, pumping to the main rivers will be constrained, overtopping and breaching may occur, and the water in the main river channels can flow into the flood cell. The hydraulic model simulates the flowing process (e.g., flow directions, flow velocities, flow volumes, and water levels) in the river channels, as well as the water exchange between the river channels and the flood cells.

Breaching analysis of the major river dikes in this research is performed using the approaches of dike-reliability analysis developed previously for broad-scale flood-risk analysis in the United Kingdom (Hall et al. 2003a). The analysis of dike reliability considers breaching sizes, volumes (see Visser 1998, Wahl 1998, Wallingford 2004a, Buijs et al. 2007), and probabilities. Breaching probabilities are derived from generic fragility curves that describe the relationships between breaching probabilities and water levels according to the design, materials, lengths, and conditions of the dikes (Casciati and Faravelli 1991, Wallingford 2004b, Dawson and Hall 2006, Buijs et al. 2007, 2009). The breaching volumes, ideally, are calculated in the modeling according to the water levels and the dike data. The uncertain information is propagated through the volume calculation using a Monte Carlo procedure, which generates probability distributions of volumes for each defense section in different water levels. To reduce computational cost, in practice, an expected breaching volume (i.e., a combination of probability and volumes) at the maximum water level is used to represent the breaching volume of a flood cell. The detailed methods for evaluating breaching probabilities and volumes, as well as the issue of uncertainties, are discussed in Gouldby et al. (2008); and more information relevant to fragility curves can be seen in Buijs et al. (2007) and Simm et al. (2008).

The total floodwater volume within a flood cell includes the overtopping water from the main rivers, pumping water from polders, breaching water from the major river dikes, and the residual direct rainfall (after pumping). For distributions of the floodwater within a flood cell, as shown in Figures 5c and 6c, it is assumed that the floodwater will first flow or be pumped into the unprotected areas outside the polders. If the floodwater level outside the polders keeps rising, the floodwater will then flow into the polder with the lowest dike-crest level, and then the outside water level will stop rising until this polder is full. Breaching of small local polder dikes is not considered because the detailed condition data for the numerous dikes are not available, and it is supposed that local people will try their best to protect these small dikes from breaching when floods happen.

Within a unit area (i.e., an unprotected area, or a polder) without dike barriers, an assumption is that the floodwater always flows to the places with the lowest elevations. It is therefore possible to combine the defense system with the DEM data to model the flood distributions within a flood cell. Figure 7 shows the GIS-based new algorithm for computing the flood distribution and flood depth within a flood cell with multiple polders (i.e., p1–p3 in Figure 7, also see, e.g., in Figure 5c). This algorithm includes the following major steps:

1. Data sorting: The GIS data are sorted with two steps: sorting the unit areas and then sorting the grid cells within the unit areas. Since it is assumed that floodwater will first go to the unprotected areas outside the polders, and then flow into the polder-protected areas with lowest dike-crest levels, the algorithm therefore
sorts these unit areas according to the dike-crest levels (Figure 7a). The unprotected area (i.e., (u) in Figure 7) will be first flooded. Within a unit area (i.e., in a polder or an unprotected area), because the floodwater is assumed to flow into the lowest place, it is necessary to sort the grid cells from low to high within this area according to their elevation values in the DEM data (see the DEM curves in Figure 7a and c).

(2) Building relationship curves between water levels and flood volumes: According to the sorted unit areas and the DEM grid cells, it is possible to generate a relationship between the floodwater volume (V) and floodwater levels (WL) for each flood cell. Figure 7b shows that if the volume (V) increases, the floodwater level (WL) will first increase in the unprotected area (u). When the floodwater level reaches the lowest dike-crest level of the first polder (p1), the water level within the polder (p1) increases, but the water level outside the polder does not change until this polder is full. Once this polder (p1) is filled, the overall water level will increase until reaching the second lowest crest level of the polder (p2). Similarly, the flooding areas will expand to other polders (e.g., p3) if the flood volume keeps increasing. As such, the relationship curve for a flood cell is generated if all the grid cells below the water level of the surrounding major river dikes are visited.

(3) Determining flood distributions and depths: For each flood event, the floodwater volume in a flood cell will be calculated by considering the direct rainfall, the pumping process, the flows in the river network, and dike-reliability analysis. If a flood cell receives a volume (V1) of floodwater, the algorithm checks the volume-level relationship curve and determines the positions of the flooded polders and the DEM cells on the curve. For example, in Figure 7b, once the algorithm identifies V1 interacting with the water-level curve of polder (p2), it can determine that all grid cells in (u) and (p1) will be flooded if their elevations are below the crest level of polder (p2). The flood depths for these grid cells in the unprotected area (u) and the polder (p1) are the differences between their elevations and the crest level of polder (p2), as shaded in Figure 7c. Within the polder p2, only a part of area below its crest level is flooded, and its water level is the elevation level on the intersecting point between its DEM curve and V1, and the flood depth for each grid cell therefore can be derived by comparing the water level and the DEM data.
3.4. Flood damage assessment

3.4.1. Distributions of economic values

To assess flood damages, the current project only takes direct economic losses into account, without considering indirect losses. The direct economic losses are mainly related to flood duration and depth in the plain areas, as well as the business categories of the economic data. The economic data used in the current research include: agricultural, urban housing, urban housing goods, industrial fixed assets, industrial stock, commercial fixed assets, commercial stock, rural housing, rural housing goods, and infrastructure (Table 1). These data are derived from the county-level records (Figure 8a) in yearbooks relevant to the study area. In this article, there are 46 counties involved in calculation of the direct economic losses.

The spatial distributions of the economic values for each category (Table 1) within a county are unknown from the original data. A land-use dataset is used to downscale the county-level data and allocate the economic values for each category to specific locations in a raster map, with a 500 m spatial resolution. The original land-use types include agriculture, forest, grass, water body, urban, rural housing, and unused lands (Figure 8b). For flood-damage assessment, the current research only considers agriculture, urban, and rural housing, without calculating the damages on grass land, forest, unused land, and the properties within the water bodies (e.g., fish farming). Table 1 demonstrates the relations between the land-use and the county-level economic categories. Within a county, it is assumed that the grid cells with the same type of land use will have the same value in each economic category. Therefore, the value for an agricultural grid cell, for example, is determined by the total number of agriculture grid cells and the total agricultural values within a county.

<table>
<thead>
<tr>
<th>Land use</th>
<th>Economic categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Built-up: urban</td>
<td>Urban housing, urban housing goods, industrial fixed assets, industrial stock, commercial fixed assets, commercial stock</td>
</tr>
<tr>
<td>Built-up: others</td>
<td>Infrastructure</td>
</tr>
<tr>
<td>Rural residential</td>
<td>Rural housing, rural housing goods</td>
</tr>
<tr>
<td>Agricultural</td>
<td>Cropland</td>
</tr>
</tbody>
</table>

Figure 8. (a) The polygons are the county boundaries; the points indicate the locations of the water level gauges for Figure 11; (b) The raster data for land use; red: urban; blue: water; light green: agricultural; dark green: forests; yellow: other types; and (c) the calculated economic values in a raster dataset from the county-level information, lighter colors indicating less economic values.
As such, all grid cells in the land-use dataset have economic values attached after data processing (Figure 8c).

3.4.2. Damage rates

A main task for damage assessment is to build a relationship among flood, land-use type, and economic values. In the current research, flood depth is used as the only indicator for estimating damages, because a limitation of the new algorithm shown in Figure 7 is the lack of consideration on flood directions and velocities. Table 2 shows the damage ratios for each economic category in different flood depths. These values are derived from investigation of the existing insurance records and household surveys (i.e., conducted by the current research team members) after particular flood events. While flooding durations are also relevant to damages, the information about durations of historical floods is not well recorded, and it is difficult to quantify the damage values caused by durations from the existing investigation and survey data. In the current research, therefore, both flood durations and velocities are not specifically considered in damage assessment. For the urban areas, only the economic values in the ground floor are taken into account because the floodwater level in the floodplain areas usually spreads out widely so cannot be very high. Using this table, the damage on each grid cell can be calculated if its flood depth (Figure 7) and economic values (Figure 8) are determined.

The new algorithm in Figure 7, the calculations on distributing economic values, and the damage assessment are connected with the hydraulic model and implemented in a software system, entitled TBRAS. All the 198 flood cells, the known 2374 polders, and the 46 counties have been encoded into the system to allow computations of flood depths and damage assessment.

4. Results

4.1. Map-derived flood damage assessment

To understand the effectiveness of the current defense systems in reducing flood damages if the same amounts of floodwaters recorded in historical events reoccur, floodwater depths and volumes have been directly derived from the maps. The method is to combine the DEM data with the historical flood boundaries in the maps and then estimate the floodwater levels according to the elevation contour lines and the historical records on water levels. 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 as shown in Figure 5b.

Table 2. The damage ratios between flood depths and economic categories.

<table>
<thead>
<tr>
<th>Economic category (land use)</th>
<th>Flood depth</th>
<th>&lt;0.5</th>
<th>0.5–1.0</th>
<th>1.0–1.5</th>
<th>1.5–2.0</th>
<th>2.0–2.5</th>
<th>2.5–3.0</th>
<th>&gt;3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential (urban, rural)</td>
<td>Housing (%)</td>
<td>2</td>
<td>5</td>
<td>8</td>
<td>12</td>
<td>16</td>
<td>19</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Housing goods (%)</td>
<td>3</td>
<td>8</td>
<td>16</td>
<td>23</td>
<td>27</td>
<td>31</td>
<td>41</td>
</tr>
<tr>
<td>Industry (urban)</td>
<td>Fixed assets (%)</td>
<td>2</td>
<td>6</td>
<td>9</td>
<td>13</td>
<td>17</td>
<td>21</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Stock (%)</td>
<td>4</td>
<td>10</td>
<td>16</td>
<td>24</td>
<td>27</td>
<td>31</td>
<td>33</td>
</tr>
<tr>
<td>Commercial (urban)</td>
<td>Fixed assets (%)</td>
<td>2</td>
<td>6</td>
<td>9</td>
<td>12</td>
<td>15</td>
<td>18</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Stock (%)</td>
<td>4</td>
<td>10</td>
<td>18</td>
<td>26</td>
<td>30</td>
<td>34</td>
<td>38</td>
</tr>
<tr>
<td>Infrastructure (urban-other)</td>
<td>(%)</td>
<td>3</td>
<td>7</td>
<td>12</td>
<td>17</td>
<td>22</td>
<td>27</td>
<td>30</td>
</tr>
<tr>
<td>Agriculture (%)</td>
<td>(%)</td>
<td>12</td>
<td>25</td>
<td>60</td>
<td>80</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
Using such map-derived flood depth values, it is possible to directly calculate the damages and compare that with the historical records, so as to examine the feasibility of the damage ratios in Table 2. Using the map-derived flood volumes in each flood cell and combining that with the algorithm in Figure 7, the effectiveness of the defense systems, especially the polders, in reducing the economic losses can be evaluated. To make the damage assessment comparable, the same economic and land-use data are used for all the historical events of 1954, 1991, and 1999.

A widely accepted record for the total damage in the 1999 flood (Figure 2c) was 14.13 billion Yuan (RBM), which was determined by the TBA. This record was derived from a survey right after the flood event, including the damages on households, agriculture, forestry, fish farming, industry, transportation, and the broken dikes. Using the flood depths directly derived from the map (Figure 2c) without using the current polder data, the calculated damage is 11.97 billion Yuan (Table 3) in the 1999 flood, by utilizing the 1999 economic data, the 2000 land-use data, and the damage ratios in Table 2. Compared with the recorded 14.13 billion Yuan, the calculated damage value is slightly different. This is because the indicators for damage assessment used in the current research are not exactly the same as that used by the TBA. In light of the scale and complexity of the study area, the overall calculation result is in a reasonable range (i.e., 84% similarity). Similarly, the calculated damages in the 1991 and 1954 maps (Figure 2a and b) are 34.23 and 46.12 billion Yuan, respectively (Table 3). 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 in Figure 2 are generated, and the algorithm using the current polder data (as shown in Figure 7) is also considered in the calculation, the spatial distributions of the 1954, 1991, and 1999 floodwaters will be significantly changed, as shown in Figure 9. In this case, although multiple polders are flooded, most of the floodwaters are 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 defense systems can effectively reduce half of the damages if the same amounts of floodwaters in the 1991 and 1954 are regenerated in the Taihu Basin. In the 1999 situation, the modeled flood damage is smaller than the recorded value too, because there were many new local defense systems that have been constructed after 1999. For example, the cities of Huzhou, Jiaxing, and Wuxi were seriously flooded in the 1999 event (see the recorded floods in Figure 10). Since then, these cities have decided to build more dikes to increase the protection area and improve the protection standards. Using the current data of flood-defense systems, the modeled results (in Figure 10) show that these cities are protected if the same amount of floodwater reoccurred in these regions.

<table>
<thead>
<tr>
<th>Events</th>
<th>Recorded 1999</th>
<th>Calculated damages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corresponding flood Maps</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Corresponding flood Maps</td>
<td>Figure 2c</td>
<td>Figure 2c</td>
</tr>
<tr>
<td>Damages (billion Yuan)</td>
<td>14.13</td>
<td>11.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.44</td>
</tr>
</tbody>
</table>

Table 3. The flood damages derived from the historical flood maps.
Figure 9. With consideration of the current dike data and the algorithm in Figure 7, (a), (b), and (c) are the redistributions of the floodwaters that are directly derived from the maps for the events of 1954, 1991, and 1999, respectively (Figure 2).

Figure 10. Comparing the recorded 1999 floods with the modeled floods with the current dike data: (a) the Huzhou City, (b) the Jiaxing City, and (c) the Wuxi City; red: urban area; green: agricultural lands; blue: floodwater; dark lines: river or polder dike boundaries in current data of defense systems.

4.2. Hydraulic modeling and sensitivity analysis

Beyond the static historical flood maps, simulating dynamic flooding processes and performing flood-risk assessment in different scenarios need to use the integrated approach as shown in Figure 3. The 1D hydraulic model (Figure 5) and dike-reliability analysis are incorporated with the new algorithm of 2D flood-depth analysis (Figure 7) for evaluating
flood damages in different scenarios. These analyses are based on the 1999 flood event, because the major flood-defense projects had almost been finished by the 1999 event. While further construction of the defense systems has been kept going after 1999, the main structure of the defense systems has not been changed. The hydraulic model has not been used to simulate the 1991 and the 1954 floods, because there are no data available to describe the historical changes of the defense systems and the flooding processes beyond the static flood maps (Figure 2).

Figure 11 shows the observed and simulated daily water levels of six gauges (see their locations in Figure 8a) in the 1999 flood event from 1 June to 31 August. The main dynamic input data include the observed initial water levels before the flood event, 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 the hydrological model). The results in Figure 11 indicate that the average deviation of the modeled water levels in the hydraulic models from all of the observed data in Figure 8 is about 15.2 cm. For the Tai Lake (Figure 11a), the difference between the modeled and observed peak water level is less than 6 cm. Considering the scale and complexity of the river networks of the entire plain area, the hydraulic model can reasonably represent the water-flowing process in the entire river network of the plain areas.

The hydraulic model also outputs the volumes of floodwater for the flood cells (Figure 5b), which include the volumes of overtopping and the residues of direct rainfall. The expected breaching volumes are derived through dike-reliability analysis. The total

![Graphs showing observed and simulated water levels for six gauges in the 1999 flood event.](image)
flood volume for each flood cell in a flood event, as shown in Figure 3, can be calculated from net rainfall, overtopping, and breaching. Once the flood volumes for the flood cells are known, the flood distributions and damages can be derived by the method demonstrated in Figure 7 and Table 2. The integrated risk analysis tool is tested with different drivers to evaluate the sensitivity of the modeling by changing the input parameters of rainfalls, economic values, breaching, and pumping capacities.

In the 1999 event, the water levels rose from a normal state to the peak level within 30 days (i.e., from June to July, see Figure 11). The total rainfall in these 30 days was 614 mm, which was equivalent to a 200-year flood (i.e., 610 mm of rainfall). The GDP value of the Taihu Basin in 1999 was 910.6 billion Yuan and increased to 2024.9 billion Yuan in 2005. The values of damage changes are compared using the 1999 and 2005 economic values with the same land-use dataset in the 2-, 10-, 20-, 50-, 100-, 200-, 500-, and 1000-year events, based on the space–time pattern of the 1999 rainfall. To understand the role of dike reliability, the damage assessment is performed in nonbreaching and breaching scenarios. In the nonbreaching scenario, all dikes are assumed not be breach; in the breaching scenario, the expected breaching volumes are used based on the reliability analysis and the breach volume calculations for each flood-defense section. Pumping is also an important factor in flood management, but the data of pumping capacities were not available. The solution has been to refer to the designed pumping capacities (e.g., 10-, 20-, or 50-year standards in different places) in the official flood-defense plan for 2020 issued by the TBA. Given the sensitivity to these pumping capacities, the flood damage values are calculated under the scenarios of using full and half of the designed pumping capacities.

Table 4 shows the calculated flood risks under these different scenarios. The results demonstrate that the overall flood damages in 2005 are about 1.5 times of that with the 1999 economic values in different return periods, although the GDP value in 2005 was more than 2 times of that in 1999. One reason is that many areas with high economic values are protected by the defense systems. Improving the pumping capacities or increasing dike reliabilities can significantly reduce flood risks; especially it can reduce the damages in the 2- and 10-year flood events to very small values. This is because the discharging capacities of the main drainage channels are limited. In small flood events, the drainage channels are able to contain the increased pumping volumes and the reduced breaching volumes, and therefore the flood risks can be effectively reduced. Rainfall is another main driver

<table>
<thead>
<tr>
<th>Return period (year)</th>
<th>30-day rainfall (mm)</th>
<th>Breaching</th>
<th>Nonbreaching</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30-day</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>rainfall (mm)</td>
<td>Econ. 1999</td>
<td>Econ. 1999</td>
</tr>
<tr>
<td>1000</td>
<td>720</td>
<td>22.88</td>
<td>31.2</td>
</tr>
<tr>
<td>500</td>
<td>700</td>
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</tr>
<tr>
<td>200</td>
<td>610</td>
<td>10.21</td>
<td>17.6</td>
</tr>
<tr>
<td>100</td>
<td>560</td>
<td>4.77</td>
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<tr>
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<td>517</td>
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<td>20</td>
<td>450</td>
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<td>10</td>
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<tr>
<td>2</td>
<td>265</td>
<td>0.038</td>
<td>0.055</td>
</tr>
</tbody>
</table>

Table 4. Sensitivity analysis of the modeling results in different scenarios (the 200-year event with bold values is equivalent to the 1999 flood).
that causes changes in flood damages. Table 4 shows the changes of the basin-wide risk values under different return periods. These risk values in different return periods also have different patterns in spatial distributions. Figure 12, for example, shows the expected flood depths and damages in the 20-, 200-, and 1000-year rainfalls. The rainfall center of the 1999 flood is in the west of the basin. As shown in Figure 12, in the plain area, both flood depths and damages in the rainfall center will significantly increase if rainfall becomes more intense. In small flood events, unprotected rural areas have higher damage values than urban areas. In extreme floods beyond the protection standards, however, many large municipal areas are expected to have much higher risk than rural areas.

These outputs indicate that the modeling is sensitive to different input values and can generate rational results in different scenarios. The expected damages in the 200-year event (equivalent to the 1999 flood), in the scenarios as shown in Table 4, range from 7.44 to 17.6 billion Yuan using the 1999 economic data. These values are reasonable in comparison with the 14.13 billion Yuan recorded in the 1999 event. The GIS tool developed in the current research, therefore, can be used to quantify how the environmental drivers and people responses could affect the space–time changes of flood risks in the Taihu Basin.

5. Discussion

Flood management has gradually been shifted from earlier emphasis on control and defense toward more holistic risk management (Sayers et al. 2002, Hall et al. 2003b, Bohm et al. 2004, Harvey et al. 2009). This requires a development of comprehensive approaches to technically support risk management. GIS can be used as an important platform to integrate multidisciplinary modeling for simulating complicate flooding processes and performing quantitative risk assessment. This article demonstrates an example of using a GIS-based approach for analyzing flood risks in a broad-scale river basin.
Using the GIS approach, this article presents a quantitative impact assessment of the hierarchical defense systems on the space–time changes of flood risks. These new findings can be potentially used to quantitatively evaluate the cost and benefit of the flood-defense systems constructed in the past. In the China–UK Scientific Cooperation Project ‘Scenario Analysis Technology for River Basin Flood Risk Management in the Taihu Basin,’ this GIS-based platform has also 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 (Evans et al. 2004, Harvey et al. 2009).

The complexity of the modeling brings a great range of uncertainties in the research. Such uncertainties lie in the following aspects. First, the availability and quality of the data for such a large river basin causes a variety of uncertainties that need to be handled with assumptions and simplifications. Second, it is unknown where and how dikes are to breach when calculating floodwater volumes. Fragility curves thus are adopted to estimate the breaching probabilities. Third, the uncertainty of how human would respond to flood risks is very high. This research therefore evaluated the changes of risk values with different pumping capacities and dike reliabilities to understand the range of flood risk changes. Fourth, the indices and the data used for damage assessment in the current research are not exactly same as the damage being officially reported by the TBA. It is difficult to obtain a very objective appraisal of both the reported damage and the calculated results.

While the current research scope covers rainfall, pumping, dike breaching, floodwater distributing, land use, economic changes, and damage assessing, there are a number of limitations exiting in the modeling. First, the unavailability of the historical data makes it difficult to address the changing flooding system. The historical flood events, such as the 1954 and the 1991 floods, cannot be well applied to calibrate the models with current defense systems. Second, the algorithm of 2D flood distribution does not fully consider the flood velocities and durations, which are always important in damage assessment. Velocities could be estimated using a full 2D hydraulic model, but in such a large-scale basin it would be necessary to overcome the barriers of data quality, the high cost of computational time, and the uncertainty of breaching volumes. Third, the algorithm in Figure 7 is based on an assumption that the floodwater will flow to the places with the lowest elevations. In reality, however, this may not always occur, when there are barriers within a polder. This assumption nevertheless has effectively reduced the run-time for simulating the micro-level flow mechanism, so that using the integrated modeling to analyze flood risks in many different scenarios for the entire Taihu Basin becomes achievable. Fourth, the current algorithm does not consider breaches of the local polders, whilst there were several local polder breaches reported in the 1999 event. Evaluating the impacts of the polder-dike reliabilities on flood risks needs a survey of these local polders to obtain the detailed data for the construction materials and conditions. Fifth, the current research only takes direct economic losses into account in damage assessment, although indirect damages, especially in long-lasting flooding areas, can be significant. Evaluating indirect losses needs to establish a new set of indices for damage assessment and survey methodologies. Finally, the spatiotemporal patterns of rainfall can substantially affect the distributions of flood risks. The rainfall center was in the west in 1999, the northwest in 1991, and the southwest in 1954. A given amount of rainfall intensively concentrated in a short term can generate different flooding processes than that being evenly distributed in a longer time. However, analyzing the spatial distribution of rainfall would add considerable computational expense. The modeling results demonstrated in this article show that the defense systems developed in the Taihu Basin have significantly decreased flood. In extreme events (see Figure 12f), nevertheless, flood damages can be still very high even with the significant enhancement of
the defense projects after the 1991 flood. This indicates that the measures of flood control cannot fully prevent the damaging floods from happening. The modeling results also show that the defense systems, especially the polders, could substantially change the spatial distributions of floods. This indicates a spatial transferring process of flood risks. The traditionally flood-prone areas have become safer under the protection of the hierarchical defense systems, but many unprotected areas, often called ‘high-lands,’ are now exposed to floods. Such spatial shifts of flood risks and the fast urbanization may inevitably result in further competitions among local communities building dikes and sluice gates. Imagine one day, the entire plain area in the Taihu Basin is full of polders; the interconnected rivers are blocked with gates; all the floodwater is pumped into the rivers channels; the walled rivers and lakes are too small to store and detain an ordinary monsoon rain; and a normal local short-term storm could immediately cause chaos. Such unmanaged competitions may eventually lead flood risks back to a high level again.

Overall, the current research developed a GIS-based integrated approach to model the flooding processes, and quantifying the impacts of the complex flood-defense systems on flood risks over the Taihu Basin. The quantitative results indicate that human activities in this region have fundamentally changed flood patterns, reduced the basin-level flood risks, but cannot fully avoid flood damages. Making an optimal strategy for developing the defense systems and balancing the cost and benefit among the local communities become critical for keeping the defense systems within a rational extent. Developing plans for centralizing high-value properties in safer places, reserving flood pathways, making space for water (Defra 2005), and enhancing adaptation capacities should be better considered in future flood-risk management.

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