Flood disaster monitoring and evaluation in China

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Abstract

China frequently experiences natural disasters, of which flooding is the most serious. How to monitor and control natural disasters, assess damage, and provide relief is the most urgent problem for the Chinese government and disaster experts. A national integrated system using remote sensing, geographic information systems, the Global Positioning System, and other technology for monitoring and evaluating flood disasters has been assembled and tried out for 3 years. The system has played an important role in flood mitigation during the trial and has become a key part of the flood management system at China’s National Flood Control Headquarters. This paper presents an overview of the system and its use in China.

Keywords: Integrated system; Image processing; Remote sensing; GIS

1. Introduction

The vast territory of China experiences frequent natural disasters, including floods, droughts, earthquakes, forest fires, snow, typhoons, and marine disasters. Flooding is the most serious. Almost every year, China is affected by severe flooding, which causes considerable economic loss and serious damage to towns and farms. The frequency of occurrence of flood disasters in China is higher than the world average (Zhang, 1995). History records more than 1000 floods, including the 1998 floods in the middle and lower reaches of the Yangtze River, Nenjiang (Nen River), and Songhua River (Ministry of Water Resources, 1999). Flooding seriously affects people’s lives and productivity (Wang, 1999).

Big floods are mainly concentrated in the lower reaches of the “seven big rivers”, which include the Yangtze River, the Yellow River, and the Huaihe. These areas are home to 50% of China’s population and produce 70% of its industrial and agricultural value. Over 8 million hectares are flooded every year. More than 100 medium to large cities in China have been affected by flooding in the past 30 years. Annual economic loss is about 100 billion yuan, almost a quarter of the world total (Zhang and Wei, 1995). It is evident that both the frequency and intensity of flooding are increasing.

Flooding greatly concerns the different levels of Chinese government. Although more than 86,000 reservoirs have been constructed and more than 200,000 km of dykes have been strengthened in the last 50 years and have played an important role in alleviating the impacts of floods, problems remain, including insufficient protection, serious soil and water losses, obvious reduction of water surface in lakes owing to reclamation, artificial obstacles in river courses, and numerous weaknesses hidden in flood control structures. Flood protection is decreased by low flood control standards and lack of maintenance and repairs. Economic losses caused by flooding have tended to increase in recent years with the development of the Chinese economy.

Early in the 1970s, the concept of nonstructural disaster control measures was first put forward in the USA. Losses due to flooding can be reduced by means of measures such as monitoring, forecasting, simulation, evaluation, and analysis (Chen, 1990; OAS, 1990; UNDRO, 1991). One nonstructural measure, the integrated use of geographic information systems (GIS) and remote sensing (RS), has been playing a very important role in monitoring, controlling, relieving, and assessing natural disasters, especially flood disasters.
With the fast development of RS and GIS applications, more and more practical GIS systems have been built (Zhou, 1993; Islam and Sado, 1998, 2000; Jiang and Cao, 1994; Zhang, 1995, 1997; Paudyal, 1996). It is imperative and possible to integrate those systems into more powerful and convenient forms (Li and Yin, 1995; Li, 1997; Zhang, 1998).

In 1995, with financial aid from the Ministry of Science and Technology of China, the National Professional and Operational Integrated System (NPOIS) for monitoring and evaluating serious natural disasters was created from five research units: the Remote Sensing Technology Application Center of the Ministry of Water Resources (RSTAC/MWR), the State Key Laboratory of Resources and Environment Information Systems, the Institute of Geography, the Chinese Academy of Sciences, and the Academy’s Space Center. The participating Chinese scientists have cooperated with several scientists from the European Space Agency and Japan in research on flood and drought monitoring technology. The system has now become operational after a 3-year trial. It focuses on serious disasters, especially floods. It can provide dynamic situation reports and loss assessment reports on disaster-hit areas to the National Flood Control Headquarters in Beijing. It has already become a key part of the flood mitigation system in China. This paper introduces the products, performance, and roles of the system.

2. The role of the NPOIS

RS images, which cover very large areas of the surface of the Earth, can be acquired at regular time intervals at relatively low cost. When these are supplemented with non-RS data, it is easy and efficient to survey the evolution of natural disasters (Dai, 1993; Zhu, 1996; Zhou et al., 2000). China has paid great attention to flood control and management. As the natural disaster monitoring department of China, RSTAC/MWR has used different kinds of RS data for flood monitoring since 1983 (Table 1). In addition to RS data, GIS databases and image processing methods have been accumulated. These data form the basis of the NPOIS.

<table>
<thead>
<tr>
<th>Year</th>
<th>Source of data</th>
<th>Year</th>
<th>Source of data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984</td>
<td>NOAA and airborne infrared</td>
<td>1996</td>
<td>ERS-1/2, Radarsat, FY-2 NPOIS</td>
</tr>
</tbody>
</table>

Table 1

Remote sensing data used for monitoring floods by RSTAC/MWR

Data are used only in very urgent cases, in limited areas, or where very detailed flood information is needed.

Outputs are flood information reports with flood images, land use maps of submerged areas, and corresponding statistics. The NPOIS makes it possible to use multiple sources of RS data for monitoring flood disasters efficiently and successfully. The main roles of this system cover three periods: before, during, and after flooding.

2.1. Before flooding

Before a flood, the system can be used to:

- calculate the distribution of areas at high risk by comparing historical flood heights with digital elevation model data;
- estimate social and economic losses under different alternatives for decision-making or flood routing based on social and economic databases and corresponding models;
- suggest the best alternative for population withdrawal from areas at risk; and
- suggest the best alternative for storing and transporting flood-prevention materials.

This information is important for several reasons. If people are aware of the risks, they can make more informed personal decisions regarding the purchase of insurance and other mitigative and adaptive options. Government at various levels can devise better policy tools to deal with flood disaster, in terms of prevention, response, and recovery. Industries (e.g. insurance) can base their cost–benefit analyses on the best available data.

2.2. During flooding

During a flood, the NPOIS is useful in the following areas:

- dynamic monitoring of flooded areas;
- estimating the expansion of flooded areas according to meteorological and hydrological forecasting; and
optimizing the transport of materials for disaster relief.

2.3. After flooding

When a flood is over, the system can be used to calculate the actual flood losses in different administrative areas. Such information allows government agencies to determine relief funds and for insurance companies to calculate payments. By providing comprehensive spatial information, the system supports various efforts in rebuilding, such as planning water conservation facilities and selecting locations of new towns. The flow chart in Fig. 1 shows the flow from input data (RS) to output data (disaster information).

3. Components of the NPOIS and technology flow

Sufficient and reliable RS data, sufficient background data, and effective and quick technology for image processing, information extraction, and analysis are basic conditions. The NPOIS has two main parts: flood disaster monitoring and flood disaster assessment.

3.1. Flood disaster monitoring

Floods can be monitored from three levels: from space, from the air, and from the ground.

3.1.1. From space

Many satellite sensors may be used to observe water extent, and in practical applications, several types of sensors may be used in combination. The disadvantage of satellite measurement in the visible and near-visible wavelengths is that useful data are obtainable only during daylight under cloud-free conditions. Satellites using radar transmitters and receivers, on the other hand, do not depend on sunlight and are largely independent of weather conditions. Satellites such as Radarsat can provide information on inundated areas even under cloud where it is not possible with optical data.

Table 2 compares several RS data sources used in China’s flood mitigation.

3.1.2. From the air (real-time transmission of airborne SAR image system)

The “airplane–satellite–ground” system arose from a research program on flood monitoring promoted by the Chinese government during the last decade. This system integrates RS, the Global Positioning System, data transmission, and image processing.

To reduce a disaster and control a flood quickly it is important to understand the water condition of flooded areas as soon as possible. To monitor the water condition, RS airplanes fly over the flooded areas and collect radar images. The image data are sent to a communication satellite, which relays them to a ground station. The data are enhanced and sent back to the satellite, which relays them to staff on the ground. Fig. 2 shows how it works.

Decision makers at the National Flood Control Headquarters can see the flood images and make appropriate decisions.

The system allows all-weather use, flexibility, real-time transmission of image data, and high spatial resolution (3m for 9km swath width and 6m for 18km swath width).

Airborne SAR can be used for flood disaster monitoring from an altitude of 10000–13000m. Because of the high cost, however, it is only used for monitoring serious natural disasters and evaluating urgent cases.

3.1.3. From the ground

Thousands of hydrology stations distributed throughout the country provide information on rainfall, runoff, and water elevation, which is very useful for flood mitigation. All of this information is transferred to the Ministry of Water Resources and the NPOIS.

3.2. Logic structure of flood disaster assessment system

Integration of the monitoring data sources mentioned above has allowed NPOIS to be established for flood disaster assessment. The integration of software, hardware, databases, and networks is the key to its successful establishment. The system uses a client/server GIS data integration platform and a GIS model integration platform. Fig. 3 shows the concept and framework of this system. The GIS data integration server and GIS model integration server are the two key components.
It is very difficult to integrate different kinds of GIS data into one database that is managed by commercial GIS or image processing software, such as ArcInfo (ESRI, Redlands, CA, USA) or ERDAS (Leica Geosystems, Atlanta, GA, USA). We divide the GIS data into four categories: RS image data (raster), RS classification data (vector), digital map data (vector), and relational data (attribute). Each GIS data set registers its meta-data information in the data integration platform. Through a meta-database management system we can link those data by the RS image serial number and a foreign attribute key. The platform provides GIS information retrievals, GIS model data requests, and a mapping function in an integrated, visual, interactive way.

For model integration, we have established a database management system to create, add, delete, or modify GIS models by decomposing each model into three levels: model, function, and variable. Items in each table are standard 3NF-compatible. The database management system links those relational tables together and provides those functions through relational operation in real time. A visual model construction tool is necessary in complex GIS applications, since specific models may be unavailable. We provide such a tool based on the client/server system architecture and relational-model-based management systems.

### 3.3 Technology flow

The main operational procedures of this system can be divided into three parts: preprocessing; extracting inundation information and estimating flood disaster;
and assessing flood disaster and analyzing decision-making.

3.3.1. Preprocessing

A flow chart of the system’s preprocessing module is shown in Fig. 4. There are two main tasks in the module. The first is to make all data sets from a variety of data sources register exactly with each other via precision geometric correction, so that they can be used together in a GIS environment for overlay analysis and dynamic monitoring of floods. Data sets used in this process include digital satellite images (such as Radarsat, Landsat, SPOT, and airborne SAR), digital elevation model data sets, social economic data, and topographic maps. In this registration process, each kind of data set has its own degree of difficulty. Registration of radar images proves to be the most difficult and time consuming. Factors that increase the time for registration include Doppler shift effects, high noise levels, and mosaic image (for airborne SAR). The time required to register the image can be significantly improved by stockpiling a set of registered images. These geo-registered images can then be used for image-to-image registration of any new data sets. The accuracy of the registration can be improved if the stockpiled images are of high resolution. The second task is to make image interpretation much easier through image enhancement and composites, so that flood information can be extracted from enhanced images.

3.3.2. Extracting inundation information and estimating flood disaster

A flow chart of this module is shown in Fig. 5. It has two main tasks. One is identification of flood information and extraction from the preprocessed image. The other is to estimate the degree of severity of the flood, in terms of the sizes and types of the flooded areas (roads, cities, fields).

Optical and radar images are analyzed for detection, classification, and modeling of features. Interferometric processing of complex-signal radar images is used to discriminate the water region (Zhang et al., 1999). To differentiate between water and non-water, unsupervised and supervised classification methods are used on the flood images. To estimate the inundated area and the extent of damage, we constructed a model by using a spatial analysis tool of ERDAS IMAGE software (Model Maker). The model has two parts. In one, water and non-water areas are differentiated. In the other,
Inundated areas are computed after “flooded images” and “non-flooded” images are matched. For example:

- if a pixel is “non-water” on both flooded and non-flooded images then it is identified as “land”;
- if a pixel is “water” on both flooded and non-flooded images then it is identified as “normal water” or
- if a pixel is water on flooded images but non-water on non-flooded images then it is identified as “inundated area.”

By using interactive interpretation, plenty of flood information can be extracted from the enhanced images. The accuracy of the inundated area from images depends on how to define the area of the normal water surface. Therefore, the concept of “warning water extent” is introduced as a standard for measuring the real submerged area.

The contents of flood information output from the module are as follows:

- location, extent, and total area of real submerged districts in images and tables;
- real submerged images with county boundaries and tables of submerged area in various counties; and
- land use map of submerged districts with county boundaries, and tables of submerged area in various counties and types of land use.

3.3.3. Assessing flood disaster and analyzing decision-making

When serious floods occur in China, local government must report the loss to the Central Government. However, to get more disaster relief, local government usually inflates its figures. This makes it hard for the Central Government to make the correct decision.

In order for decision makers to plan flood control, disaster relief, and reconstruction, the damage and losses caused by a flood have to be measured or assessed quickly and accurately. The procedures for assessment are shown in Fig. 6. The main methods are time series analysis and integrated analysis of data sets from various sources. The priorities are:

1. area of homes submerged and population;
2. area of crop land submerged and losses;
3. damage to infrastructure, such as roads, bridges, and pipe lines; and
damage to flood control works, such as dykes and dams.

3.4. Products and performance of the NPOIS

The main outputs from the system are flood information reports with flood images, maps of land use of submerged land, and corresponding tables. These outputs can show the location, extent, and time of submergence; the degree of severity; flood dynamics; failures or weak points in the flood control system; and suggestions for flood control and mitigation works. The required system response and information accuracy specifies the performance of the system. The system response specifications are as follows:

- 2–3 h for general flood information report after AVHRR data input;
- 8 h for preliminary report after Radarsat SAR data input;
- 24 h for detailed report after Radarsat SAR data input; and
- 2 days for detailed report (mosaic processing is difficult and time consuming) after airborne SAR data input.

The information accuracy specifications are as follows:

- interpretation accuracy for submerged objects is better than 95%;
- area accuracy for submerged district is 90–95%; and
- position accuracy for flood boundaries is 1 or 2 pixels.

4. Application of the integrated system

In the summer of 1998 the Yangtze River (Fig. 7) suffered one of its worst floods in decades. Many people were killed and countless more were made homeless. The flooding was caused by torrential rains occurring in the center of China around the end of July. The disaster attracted world attention. During that flood season, multi-temporal Radarsat ScanSar data, airborne SAR data, and other data were used to monitor the flood. Both the spatial and temporal extent of the flood were investigated.

From 20 to 31 July, as a result of the retreat of a subtropical high-pressure cell to the south, an unprecedented unbroken succession of storm rains fell along the middle reach of the Yangtze. As a result, water levels in the middle and lower reaches rose sharply.

On 26 July, the water level at Chenglingji hydrological gauging station (in the Dongting Lake area, Hunan Province) reached 35.48 m, exceeding the historical maximum record by 0.17 m. From 27 to 31 July 1998, the airborne SAR monitoring system was used to monitor floods in Dongting Lake area. Fig. 8 shows an airborne SAR image of the submerged areas. The image shows many large flooded areas. A detailed flood disaster assessment report based on those images and a GIS database was prepared within 30 h. The total inundated area was 1403.2 km², including 68 000 ha of cultivated land and 47.42 km² of residential land.

At the same time, the water levels at Wuhan, Jiujiang, and Hukou hydrological gauging stations exceeded their historical maximum records also. Wuhan city and its surrounds were inundated. Fig. 9 shows the distribution of flooding there. A detailed flood disaster assessment report based on those images and a GIS database was prepared within 30 h. The total inundated area was 1403.2 km², including 68 000 ha of cultivated land and 47.42 km² of residential land.

During the flood season of 1998, more than 100 images and about 100 disaster analysis reports were produced. These results were quickly circulated, giving prompt support to emergency services. Later, the data provided the basis for reconstruction, hydraulic planning, and construction for flood prevention.
Fig. 7. Location of the Yangtze drainage basin.

Fig. 8. Airborne SAR image of the submerged areas around Dongting Lake in July 1998.
5. Conclusions and prospects

Disaster relief is a major research subject for realizing sustainable social development. In the past several years, the NPOIS has provided many flood images and assessment reports to the State Council, Ministry of Water Resources, National Flood Control Headquarters, and other departments. The system has played a very important role in flood control and disaster mitigation, especially in the serious floods occurring along the middle and lower reaches of the Yangtze River in 1998. Through daily remote monitoring of floods in all or part of China, the NPOIS can quickly let decision makers know the exact extent and development of floods. This allows them to adopt effective measures for disaster relief. Through detailed assessment of damage and losses caused by floods, the system can help decision makers better understand the behavior of floods, related human activities, and their interaction. Since this system has been in service for 3 years, its products and performance have been improved year by year. Still, some considerations for future improvement follow.

Table 3
Assessment of flood damage (in ha) in Wuhan and adjacent regions in 1998

<table>
<thead>
<tr>
<th>County</th>
<th>Total submerged area</th>
<th>Dry land</th>
<th>Wetland</th>
<th>Forest</th>
<th>Grassland</th>
<th>Urban land</th>
<th>Rural residential land</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wuhan</td>
<td>169 750</td>
<td>30 422</td>
<td>89 644</td>
<td>53 35</td>
<td>11 749</td>
<td>82 38</td>
<td>38 09</td>
<td>20 552</td>
</tr>
<tr>
<td>Wuchang</td>
<td>136 975</td>
<td>37 408</td>
<td>81 329</td>
<td>81 93</td>
<td>23 65</td>
<td>15 1</td>
<td>14 80</td>
<td>60 48</td>
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<tr>
<td>Huangpi</td>
<td>170 045</td>
<td>55 23</td>
<td>70 13</td>
<td>15 0</td>
<td>29 31</td>
<td>8 6</td>
<td>23 53</td>
<td>10 89</td>
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<td>Xinzhou</td>
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<td>48 381</td>
<td>19 623</td>
<td>9 71</td>
<td>37 77</td>
<td>18 21</td>
<td>34 61</td>
<td>32 0</td>
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<td>1 45</td>
<td>9 43</td>
<td>0</td>
<td>2 012</td>
<td>2 02</td>
<td>0</td>
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<td>Dazhi</td>
<td>49 916</td>
<td>5 204</td>
<td>39 847</td>
<td>1 28</td>
<td>4 10</td>
<td>10 66</td>
<td>1 503</td>
<td>6 04</td>
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<td>67 230</td>
<td>9 083</td>
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<td>5 818</td>
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<td>5 799</td>
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<td>2 37</td>
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<td>Hanchuan</td>
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<td>6 280</td>
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<td>11 48</td>
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<td>0</td>
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<tr>
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<td>3 027</td>
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<tr>
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<td>23 107</td>
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<td>3 978</td>
<td>1 218</td>
<td>1 918</td>
<td>43 130</td>
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<tr>
<td>Total</td>
<td>1 146 031</td>
<td>314 202</td>
<td>469 287</td>
<td>78 816</td>
<td>47 798</td>
<td>24 659</td>
<td>32 816</td>
<td>178 454</td>
</tr>
</tbody>
</table>

Fig. 9. Distribution of flooded areas in Wuhan area during the flood of 1998.
China receives monsoon rains, and flood flows are normal. The distribution of precipitation is unequal in both time and area. Ground gauge data, hydrological modeling, weather satellites, and radar satellites (such as TRMM; National Space Development Agency of Japan, Tokyo, Japan) can provide useful precipitation information (Bellerby et al., 2000; Vincente, 1996; Xu et al., 1999). In combination with this information, NPOIS will no doubt increase the early warning time for flooding.

AVHRR/NOAA has been the major source of satellite data for many years. The ease of access to its data and its ease of use have made it very popular. MODIS (Moderate Resolution Imaging Spectroradiometer) is considered its successor, having 4 times the resolution and 7 times as many channels. Our next task is to work out how to use MODIS data for dynamic monitoring of flood disasters and to incorporate it into the NPOIS.

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