AN INSTRUCTURAL SYSTEM MODEL OF COASTAL MANAGEMENT TO THE WATER RELATED HAZARDS IN CHINA

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KEY WORDS water-related hazard; hazard-management system; interpretation structure model

ABSTRACT Coastal lowlands have large areas of hazard impact and relatively low capacity of prevention to the water related hazards, which have been indicated by the wide-spread flood hazards, high percentages of land with high flood vulnerability. Increasing population pressure and the shift of resources exploitation from land to sea will force more and more coastal lowlands to be developed in the future, further enhancing the danger of water-related hazards. In this paper, the coastal lowlands in the northern Jiangsu province, China, were selected as a case study. The Interpretation Structural Model (ISM) was employed to analyze the direct and indirect impacts among the elements within the system, and thereby, to identify the causal elements, middle linkages, their expressions, and relations.

1 Introduction

The north Jiangsu coastal lowlands are located in the mid-section of the east China, the lower reach of the Yangtze River and the Huai River. It is in the north part of Jiangsu province, which is one of the well-developed administrative units in China. With an area of about 1% of the national total, it supports 6% of the nation's population and a population density of 654 persons/km², the highest in the nation and about 5 times of the nationwide average. It also produces 11% of the national GDP (Lu Yurong, 1991). As the global economic activities gradually shift to the Pacific Rims, Jiangsu province has increasingly significant location advantages. However, since 69% of its area are plains and located in the 30° ~ 35° north latitudes where the frequency of natural hazard occurrence is the highest in the world, water-related natural hazards become one of the major limiting factors for economic growth in the north Jiangsu Lowlands. Based on 42 years’ records (1949 ~ 1990), 28% of the province can be categorized as flood-prone land. The land with high flood vulnerability is closely related to surface conditions and mostly found in the northern part of Jiangsu province, with the Lixiahe lowlands being the most typical. Widespread flood hazards and high percentages of land with high flood vulnerability indicate the fact that the north Jiangsu region has large areas of hazard impact and low capacity of prevention.

According to 1:50 000 digital elevation models in Fig. 1 (Chen Xiaoling, 1996, 1998), surface elevation in the north Jiangsu lowlands is 2 ~ 3 m above sea level on average, with a maximum regional relief of 5 m. The relief is very low, with gradients of 0.02 ~ 0.2 per thousand. Ground water table is mostly higher than the stages of nearby streams. Channel gradients are small, about 0.005 per thousand on average and the flow velocity is very slow. Additionally, flood stage heights are normally lower than the mean high tide level, but higher than the
mean low tide level. Therefore, most streams can only discharge floodwater intermittently during the low tides. All above factors reduce the capacity of floodwater discharge and, thereby, cause flood hazards in the region (Chen Xiaoling, 1996).

On the basis of the analysis of precipitation and water level data from 1951 to 1988, annual maximum stage, duration of high stage, and the impacted area of water-related hazards are all correlated with precipitation. Most precipitation occurred during the June-September flooding season, with the four-month total as 61.85% of the annual total. During this period, more than half of the rainfall was produced by the Plum Rain and typhoon weather systems. For years with severe flooding, the Plum Rain and typhoon rainfall made more than 80% of the total precipitation (e.g., 1965 and 1991). In north Jiangsu region, annual hazard impacted area is significantly correlated with total amount of Plum Rain \[(r = 0.71, N = 38, \text{confidence level} = 0.999).\] Thus, the precipitation during flooding season is a major cause of water-related hazards in the study area, while the Plum Rain and typhoons are major hazard-causing weather systems. The Plum Rain weather condition mostly occurs in June and July, producing about 35% of the total June-September rainfall. On the basis of the data from 1951 to 1994, the mean duration of the Plum Rain events was 22 days. The Plum Rain events with longer than 30 days was 3.4 years. The longest event occurred in 1954, with 63 days, and the one that caused the severe water-related hazards in 1991 lasted for 56 days. In general, those events with longer duration tended to produce more rain. Table 1 summarizes the precipitation characteristics for 13 years of severe flood hazards during 1951–1988. For extreme years (e.g., 1954 and 1991), the Plum Rain alone may generate more than 80% of the June-September total precipitation. Ten out of those 13 years of severe water-related hazards were related to Plum Rain events.

### Table 1 Characteristics of precipitation for 13 years of severe water-related hazards during 1951–1988

| Characteristics                        | Amount during 1951-1988 | Amount in 13 years | Parent of long-term averages/ % |
|----------------------------------------|--------------------------|-------------------|---------------------------------|
| Annual precipitation/mm                | 1 022.9                  | 1 206.0           | 117.9                           |
| June-September precipitation/mm        | 640.4                    | 818.4             | 127.8                           |
| Plum Rain amount/mm                    | 220.0                    | 366.0             | 166.4                           |
| Plum Rain duration/d                   | 22.8                     | 33.1              | 145.1                           |
| Plum Rain (% of June-September total)  | 34.4                     | 44.7              | 127.7                           |

Another major hazard-causing mechanism is typhoons or tropical storms, producing extreme heavy rainfall events covering large area. For example, the 3-day precipitation at Chaoqiao Town (Rudong County of Jiangsu province along the coastal China) during August 3–5, 1960 and Dafengzha (Dafeng County) during August 19–21, 1965, reached 934 mm and 917 mm respectively (Weather Forecasting Group in the Meteorological Bureau of Jiangsu province, 1988), and caused significant
damages. The typhoon in August, 1965 caused flooding in 44% of Yancheng and Yangzhou cities, and 35% of the impacted area had a water depth of 0.3 m. Just the cost to drain the flood water reached 18 million RMB (Shi Zhoucen, 1991).

2 System design

Systematic management of hazards involves complex natural, socio-economical, and technical issues. It is the key to better understand the system on the basis of the systems links. In this study, The Interpretation Structural Model (ISM) was employed to analyze the direct and indirect impacts among the elements within the system, and thereby, to identify the causal elements, middle linkages, their expressions, and relations. The systematic concept becomes the basis to establish the hazard-management system, the related hazard-causing environment system, and the hazard-mitigating system. The ISM model was also used to specify the structural relations within the systems (Chen X L et al., 1997).

Considering $S$ as a system to be established, it contains $n$ elements to form a set of $n$-dimensional vectors:

$$S = (s_1, s_2, \cdots, s_n)$$

The structural matrix of the interaction among the $n$ elements is defined as:

$$S = (S_{ij})_{n \times n}$$

where $S_{ij} = 1$ if $s_i$ and $s_j$ have a direct relation and $S_{ij} = 0$ if $s_i$ and $s_j$ have not a direct relation.

The transfer characteristics of the matrix vectors can be expressed as: if $S_{ij} = 1$, and $S_{ik} = 1$, then $S_{jk} = 1$; and if $S_{ij} = 1$, but $S_{ik} = 0$, then $S_{jk} = 0$. All elements that influence $S_j$ are from a leading set, $L(S_j)$, while all elements being impacted by $S_j$ are from its derived set, $D(S_j)$. The union $L(S_j) \cup D(S_j)$ creates a hierarchical group. Then, by constructing a hierarchical structure diagram (Fig. 2), the basic characteristics of the system can be examined.

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Fig. 2 Structural diagram of the hazard management system for the coastal lowlands
As to the water-related hazard management system (M-ISM) for the coastal lowlands, its behavior is determined by the hazard-causing environment system (E-ISM) and hazard-mitigating system (D-ISM). The M-ISM affects the E-ISM and the D-ISM through various management measures, while the latter two systems reflect the effect of management through system feedback.

3 System analysis

3.1 Hazard management system M-ISM

This system is defined as \( M = (M_1, M_2, \ldots, M_{10}) \), where

- \( M_1 = \) land use pattern;
- \( M_2 = \) protection capacity of the levees;
- \( M_3 = \) pumping/drainage capacity;
- \( M_4 = \) retention storage capacity;
- \( M_5 = \) legislation and insurance policies;
- \( M_6 = \) investment;
- \( M_7 = \) hazard monitoring and forecasting;
- \( M_8 = \) contingency plans and hazard-reducing planning;
- \( M_9 = \) economic production structure;
- \( M_{10} = \) hazard awareness.

Hazard management is a combination of structural and non-structural measures. Currently, the focus is that various structural measures should be taken frequently to reduce the damages caused by hazards as various construction plans have been proposed and implemented on the basis of comprehensive studies. In the meantime, however, the impacts of hazards have been ignored in economic development, resulting in widespread improper land use patterns in the hazard-prone regions. Large amount of money has been spent on construction and maintenance of the hazard-reducing structures. This, in fact, increases the economic losses caused by hazards.

Among the complex relations within the hazard-management system, the ISM model identified the key elements as hazard (\( M_{10} \)) and hazard monitoring and forecasting (\( M_7 \)). These two elements directly influence hazard-reduction contingency plans and planning (\( M_8 \)). The latter is the linkage to structural measures (protection capacity of levees, \( M_2 \), and pumping/drainage capacity, \( M_3 \)) and non-structural measures (changes in land use pattern, \( M_1 \), and the related changes in retention storage capacity, \( M_4 \)). \( M_8 \) also indirectly influences the processes of legislation and insurance policies (\( M_5 \)). All the above elements have impacts on the economic production structure (\( M_9 \)) and investment (\( M_6 \)) in the region, which affect each other. The effect of hazard management is finally expressed in land use pattern (\( M_1 \)).

3.2 Hazard-causing environment system (E-ISM)

This system is defined as \( E = (E_1, E_2, \ldots, E_{13}) \), where

- \( E_1 = \) ground surface elevation;
- \( E_2 = \) ground surface gradient;
- \( E_3 = \) soil type;
- \( E_4 = \) vegetation and crop type;
- \( E_5 = \) precipitation amount;
- \( E_6 = \) runoff;
- \( E_7 = \) groundwater table depth;
- \( E_8 = \) surface water level;
- \( E_9 = \) tidal level;
- \( E_{10} = \) atmospheric conditions;
- \( E_{11} = \) background of Quaternary geology;
- \( E_{12} = \) storm surge;
- \( E_{13} = \) astronomic factors.

These elements represent the hazard-causing mechanisms in two aspects. One is precipitation related to atmospheric conditions and storm surge associated with astronomic factors as well as atmospheric conditions. The other is the flat lowland surface condition, determined by gradual ground subsidence related to the Neotectonics, which can be considered as the very root of hazard occurrence, but also as relatively stable factor to be treated as the hazard-causing background.

The structural diagram (Fig. 2) indicates that the hazard-environment system has four hierarchies. There are three key environmental elements that produce flood/waterlogging hazards in the coastal lowlands: Quaternary geology (\( E_{11} \)), atmospheric condition (\( E_{10} \)), and astronomic factors (\( E_{13} \)).
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$E_{11}$ directly determines ground surface elevation ($E_1$) and gradient ($E_2$). The latter two elements form a character group for landforms, which dictate surface and ground water levels ($E_7$ and $E_8$), and runoff ($E_6$). $E_{10}$ causes the occurrence of storm surge ($E_{12}$) and also influences $E_7$, $E_8$, and $E_6$ through precipitation ($E_5$). Astronomic factors ($E_{13}$) influence tidal levels along the coast, which combining with atmospheric condition eventually determines the severity of storm surge hazards. Ground water table, as a linkage, affects soil condition ($E_3$) and vegetation/crop characteristics ($E_4$). Flooding, waterlogging, and storm surge are the expressions of the above elements. The grouping of surface water level and runoff represents the characteristics of regional flood hazards, while the grouping of soil and plants reflects the characteristics of waterlogging hazards. The storm surge hazards, based on frequency of occurrence and mean annual damages, are considered less significant than the other two types of hazards and, therefore, are placed at a lower hierarchy in the system.

3.3 Hazard delimiting system (D-ISM)

This system is defined as $D = (D_1, D_2, \cdots, D_9)$, where

- $D_1$ = ground subsidence;
- $D_2$ = sea level rise;
- $D_3$ = storm surge influx;
- $D_4$ = heavy and long-duration precipitation processes;
- $D_5$ = water levels;
- $D_6$ = hazard duration;
- $D_7$ = hazard-impacted area;
- $D_8$ = future climate warming;
- $D_9$ = water surface gradient.

From the viewpoint of system theory, flooding and waterlogging are natural phenomena caused by excessive water influx from precipitation and storm surge to the coastal plain lowlands system. The magnitude of events is controlled by water influx processes and regional characteristics. Hazards become more serious only when such natural phenomena interact with human activities. Therefore, the hazard-delimiting system reflects a type of human-centric phenomena mainly expressed as the threat and damages to human kind caused by natural processes.

According to the analysis on the hazard-delimiting matrix $D = (d_{ij})_{9\times9}$, this system has been determined to be four hierarchies. The key elements are ground subsidence ($D_1$) and future climate warming ($D_8$). $D_1$ influences water levels ($D_5$) and water surface gradient ($D_9$) through its impact on sea level rise ($D_2$). Its effects are expressed as hazard-impacted area ($D_7$) and hazard duration ($D_6$). $D_7$ and $D_6$ affect each other, forming a group characterizing the hazards and reflecting the regional hazard severity. Future climate warming will cause sea level rise ($D_2$) and increase storm surge influx ($D_3$), and influence the precipitation processes ($D_4$). The latter three elements belong to the same hierarchy at the bottom of the hazard-delimiting subsystem and their effects are expressed as hazard severity through hydrologic factors, $D_5$ and $D_9$.

And they interact with each other forming the group of hydrologic characteristics.

4 Conclusions

Coastal plains, with high concentration of population and wealth, have been constantly plagued by water-related hazards. Coastal lowlands in the coastal plains have large areas of hazard impact and low capacity of prevention, which has been indicated by the wide-spread flood hazards, high percentages of land with high flood vulnerability.

It is important to build an appropriate system for the water-related hazard management. Systematic management of hazards involves complex natural, socio-economic, and technical issues. The concept of the system becomes the basis to establish the hazard management system, the related hazard-causing environment system, and hazard-delimiting system. The ISM model was used to specify the structural relations within the systems. As to the flood/waterlogging hazard management system (M-ISM) for the coastal plain lowlands, its behavior is determined by the hazard-causing environment system (E-ISM) and hazard-delimiting system (D-ISM). The hazard-management system affects the hazard-causing environment system and hazard-delimiting
system through various management measures, while the latter two systems reflect the effect of management through system feedback. By implementing these strategies in hazard management, the impact of hazards can be minimized.

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