Social impact assessment of integrated flood risks based on Catastrophe Theory

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Abstract Owing to the natural and social attributes of floods, assessment of integrated flood risks should include both technical and social assessments. When considering social assessment of risks, three questions typically arise: (1) how high is the ability of humans to endure risk? (2) what risk level is acceptable for humans? and (3) to what extent can floods affect society? By considering the transient attribute of flood disaster risk both in nature and society, this paper analyses the basic composition of assessment of integrated flood risks, which consists of risk of casualties of people, economic risk, environmental risk, and potential risks. The paper establishes an assessment index system for the Yangtze River and presents an assessment method for integrated flood risks based on the Catastrophe Theory. By using an orthogonal formula, the calculation of each index is carried out from the lowest layer to the top layer according to the type of catastrophe to get a risk sequence of the Yangtze River basin during 1995–2000. The method offers an answer to the question: to what extent can floods affect society?

Key words Catastrophe Theory; flood disaster; integrated risk; social assessment

INTRODUCTION

In past decades, people have come to realize that human beings have to change nature on one hand and adapt to nature on the other hand. In flood control, peoples' attitude is changing from controlling all floods with technological means alone, to compromising by acknowledging the objective existence of floods and actively taking a certain flood risk. However, what kind of risk should human beings take actively in flood control? What is the flood risk value that a human being can accept? To what extent will a flood impact society? All these endeavours are aimed at a social assessment system of flood based on sustainable development (Pivot *et al*., 2002; Takeuchi, 2002; Vrijling & Jonkman, 2002; Li, 2004).

Huge amounts of rainfall in a short time result in flood hazards, which will destroy houses and farmland, ruin dams and dikes, threaten lives and property, and damage farm animals. At the same time, the trauma the flood hazard causes to people is beyond measure. These manifestations of the sudden shift of the nature of water resources range from benefits to disasters. There is also a sudden shift of flood hazards. This paper analyses the basic composition of social assessment of flood hazards from the perspective of sociology and presents an assessment method of integrated risks of flood hazards based on Catastrophe Theory.

THE BASIC COMPOSITION OF SOCIAL ASSESSMENT OF INTEGRATED FLOOD RISKS

The main impacts floods exert on human society are: (a) human casualties; (b) economic loss; (c) environmental loss (the deterioration of environment, such as proliferation of pollutants and spread of diseases); and (d) potential losses (damage to natural resources and social infrastructure, such as the ruin of farmland, breakdown of communication systems, etc.). Therefore, if floods are examined in the context of sociology, their integrated risks should include risk of human casualties, economic risk, environmental risk, and potential risks (whose effects can be stood for by foregoing risks). These risks cover not only the probability of human fatalities, but also injuries, mental anxiety and trauma, social disturbance and deterioration of the environment.

FUNDAMENTAL ASSESSMENT PRINCIPLES BASED ON CATASTROPHE THEORY

Catastrophe is a sudden change, or a jump, after smooth progress. The Catastrophe Theory is a mathematical theory that describes how catastrophes occur (Arnold, 1986; Zhou, 1990). The application of Catastrophe Theory falls roughly into two categories. One is theoretical application, mainly in mathematics, physics and chemistry, etc.; the other is in bioscience, social science and environmental science. The application in floods is the latter.

Primary models of assessment based on Catastrophe Theory

In essence, the Catastrophe Theory is concerned mainly with potential functions. It classifies the critical points according to potential functions, and studies the characteristic of discontinuity near the critical point. Zhou (2003) sums up seven types of primary catastrophe models: Fold, Cusp, Swallowtail, Butterfly, Hyperbolic umbilic, Elliptic umbilic, and Parabolic umbilic Catastrophe (Table 1). The first four models are widely used. By analysing equilibrium manifolds, singularity set and bifurcation set of different catastrophe models on the basis of potential functions, orthogonal formula and assessment values can be obtained for social assessment of floods based on the Catastrophe Theory.

Orthogonal formula for social assessment of integrated flood risks

The orthogonal formula is the basic calculation formula for integrated analysis and assessment based on Catastrophe Theory. By the orthogonal formula, the different states of control parameters in the assessment index system can be transformed into a comparable state of the same kind, so that recursive quantification of indices are calculated from the bottom layer upwards in the assessment system; and the value of the fuzzy membership function based on Catastrophe Theory can be obtained, which represents the state characteristic of the system and serves as the basis on which

Table 1 Seven primary Catastrophe models.

Catastrophe model	Control parameter dimension	State parameter dimension	Potential function
Fold	1	1	$V_a(x) = \frac{1}{3}x^3 + ax$
Cusp	2	1	$V_{ab}(x) = \frac{1}{4}x^4 + \frac{1}{2}ax^2 + bx$
Swallow tail	3	1	$V_a(x) = \frac{1}{5}x^5 + \frac{1}{3}ax^3 + \frac{1}{2}bx^2 + cx$
Butterfly	4	1	$V_{abc}(x) = \frac{1}{6}x^6 + \frac{1}{4}ax^4 + \frac{1}{3}bx^3 + \frac{1}{2}cx^2 + dx$
Hyperbolic umbilic	3	2	$V_{abc}(x, y) = x^3 + y^3 + axy + bx + cy$
Elliptic umbilic	3	2	$V_{abc}(x, y) = x^3 - xy^2 + a(x^2 + y^2) + bx + cy$
Parabolic umbilic	4	2	$V_{abcd}(x, y) = x^2y + y^4 + ax^2 + by^2 + cx + dy$

State parameters, *x, y*; Control parameters, *a*, *b*, *c*, *d*.

integrated assessment can be made. The orthogonal formula can be derived from a potential function and bifurcation equation.

Take Cusp Catastrophe for example. The factorized equation of the bifurcation set of the potential function in Table 1 can be expressed as:

$$a = -6x^2 \quad b = 8x^3 \tag{1}$$

Equation (1) can be changed into:

$$x_a = a^{1/2} \quad x_b = b^{1/3} \tag{2}$$

In a similar manner, for Swallowtail Catastrophe we can have:

$$x_a = a^{1/2} \quad x_b = b^{1/3} \quad x_c = c^{1/4} \tag{3}$$

and for Butterfly Catastrophe:

$$x_a = c^{1/4} \quad x_b = d^{1/5} \quad x_c = a^{1/2} \quad x_d = b^{1/3} \tag{4}$$

After the calculation, the value-range of both state parameters and control parameters is within 0–1, which is called a fuzzy membership function based on the Catastrophe Theory. In each Catastrophe model, the effect value of each control parameter on state parameters is determined by each model in accordance with the calculation relationship inherent to each model. The arrangement of these values obtained depends on their significance, with the major control parameters being put first, followed by minor parameters. Figure 1 shows a schematic of Catastrophe models.

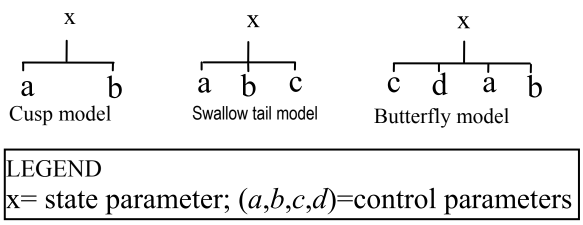


Fig. 1 Schematic of common catastrophe model.

Principles for assessment

Three principles may be used in conducting fuzzy integrated assessment based on Catastrophe Theory: (a) Non-complementary principle: in a system when control parameters can not replace each other in its function, then the smallest value is taken of all values; (b) complementary principle: control parameters can complement each other for their defects, then the mean value can be used; and (c) over-threshold-value complementary principle: control parameters can complement each other when all control parameters reach a certain threshold value (or an acceptable risk level). It can be theoretically proven that by following the preceding principles, the requirements of the bifurcation equation can be met.

METHOD FOR SOCIAL ASSESSMENT OF INTEGRATED FLOOD RISKS BASED ON Catastrophe Theory

In the application of the method for social assessment of integrated flood risks based on the Catastrophe Theory, the weight of each parameter need not be considered, but the primary and secondary sides of a contradiction between parameters should be well identified. The social assessment of integrated flood risks can be performed in the following steps.

Organization of assessment index system

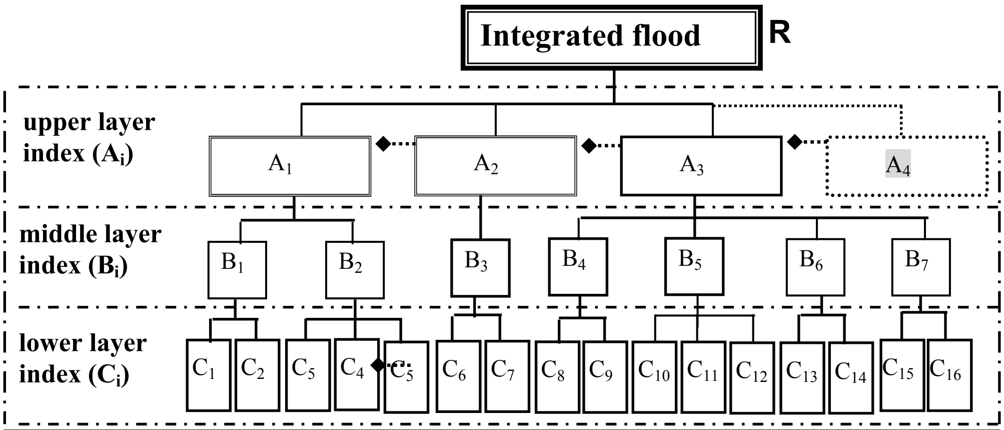
According to the aim of social assessment of integrated flood risks, the overall indices are broken into a multi-layer of sub-indices. Normally, the indices on the upper layers are comparatively abstract and difficult to quantify. The breakdown of abstract indices is designed to obtain concrete targets for quantification of the indices. The breakdown stops when quantifiable indices are obtained. Quantifiable indices can be arranged in an inverse tree structure. As required by the assessment method, the flood risk of the greatest severity is placed in first place, followed by the less severe ones. In addition, those indices that are not significant can be eliminated. Figure 2 shows the social assessment index system of integrated flood risk for the Yangtze River.

Determination of catastrophe type on each layer of the assessment index system

In the breakdown of social assessment indices of integrated flood risks, when one index is broken down into 2, 3, or 4 components, then the system is deemed as Cusp, Swallowtail or Butterfly Catastrophe, respectively. Figure 2 shows the different catastrophe patterns in three layers.

Calculation with orthogonal formula

For the index of flood risks, first r_i, the fuzzy membership of the original data of each index on the lowest layer is first to be determined. Then with the orthogonal equations



LEGEND ♦ potential effect from A_4 to A_1, A_2 and A_3.

A_1= casualty risk; A_2= economic risk; A_3=environmental risk; A_4=potential risk. B_1= personal risk; B_2=social risk; B_3=flood loss; B_4=eco-environmental damage; B_5=farmland damage; B_6=water environment impact; B_7=impact on living conditions; C_1=death toll; C_2=injured persons; C_3=total flood victims; C_4= flooded area; C_5=collapsed houses; $C_{6,}$= direct economic loss; C_7=indirect economic loss; C_8=soil erosion; C_9=years for soil fertility restoration; C_{10}=the added saline area after flood; C_{11}=liable water-logging area after flood; C_{12}=flood-ruined-&-sand-covered farmland; C_{13}=the degradation of water quality after flood(ratio of river sections with water quality inferior to grade III to all river sections); C_{14}=total number of epidemics; C_{15}=the area where snails of blood fluke have to be wiped out; C_{16}=occurrence rate of epidemics (ratio of infected persons to the whole population).

Fig. 2 Schematic of social assessment index system of integrated flood risk.

(1)–(4), the calculation is carried out from the lowest layer to the top layer where the social assessment index for integrated flood risk can be derived.

CASE STUDY

A case study is made of the application of the Catastrophe assessment method in the social assessment of integrated flood risks occurring in the Yangtze River basin during 1995–2000. The data of social assessment indices are listed in Table 2.

Calculation with orthogonal formula

By using the fuzzy membership function method, the original values of all indices are transformed into catastrophe series of 0–1. Then, with the orthogonal equations (1)–(4), the calculation is carried out from the lowest layer upwards, until the assessment indices are obtained at the top layer. The assessment results are shown in Table 3.

RESULTS AND ANALYSIS

With reference to classification of flood severity (Feng, 1997), the integrated risks can be divided into five ranks (Table 4): slight, low, moderate, significant, and extreme.

Table 2 Index values of social assessment of integrated risk of flood disasters in the Yangtze River basin during 1995–2000.

Index (code)		1995	1996	1997	1998	1999	2000
Personal risks (B1)	Death toll (C_1)	1085	1500	1494	2292	334	1509
	Injury(C2)	3900	5630	4360	9890	1020	4780
social risks (B2)	Flood victims total (10^4 person) (C3)	9200	9700	6942	231.6	105	340.9
	Flooded area (10^4 km^2) (C4)	812.4	1238.7	1841.6	14765	15.1	156.1
	Collapse of houses (10^4) (C5)	78.5	264.9	57.8	328.9	69.4	82.8
Flood loss (B3)	Direct (100 million RMB yuan) (C6)	566	800	279	1345	453	468
	Indirect (100 million RMB yuan) (C7)	141.5	200.0	69.9	336.3	113.3	117.0
Destruction of ecoscape (B4)	Soil erosion (10^4 km^2) (C8)	5787	6129	6005	5419	6031	6032
	Soil fertility restoration years (C9)	3	6	4	8	3	5
Ruin of farmland 10^4(km^2) (B_5)	Salinity (C10)	26.73	9.98	27.89	27.58	10.94	10.82
	Waterlogging (C11)	467.1	464.8	464.7	465.5	465.1	464.9
	Sand-covered farmland (C_{12})	124.8	178.4	135.8	130.5	129.5	151.5
Impact on waterscape (B_6)	Water body pollution (%)(C13)	6.9	17.2	32.7	14.3	23.1	26.2
	Epidemic diseases (C14)	3	5	3	6	4	5
Deterioration of living condition (B_7)	Area of wiping out snails (Helicadae) of blood fluke ($10^5$$km^2$) (C15)	1.84	1.19	3.12	1.71	1.84	1.03
	Occurrence rate of epidemics (%) (C16)	53.2	76.5	55.9	83.6	72.3	64.7

Notes: (a) Data sources: Yangtze River Almanacs 1996–2001, reference only. (b) Statistical data of 1997 from 9 provinces and municipal cities of Shanghai, Jiangsu, Anhui, Jiangxi, Hubei, Hunan, etc. (c) Flood loss is the yearly one, and indirect loss is taken at 25%. (d) Epidemics and their occurrence rate are that of flood-stricken regions, not that of the whole basin.

Table 3 Catastrophe series values and assessment result of each risk index.

Index (code)	1995	1996	1997	1998	1999	2000
Personal risk (B_1)	0.7709	0.8573	0.8294	0.9731	0.3502	0.8539
Social risk (B_2)	0.8489	0.9134	0.8205	0.8815	0.5727	0.6745
Flood loss (B_3)	0.5063	0.6685	0.1507	0.9437	0.4054	0.4202
Ruin of ecoscape (B_4)	0.7780	0.9501	0.8791	0.8569	0.7780	0.9219
Ruin of farmland (B_5)	0.9503	0.9168	0.9601	0.9563	0.8990	0.9132
Water environment (B_6) impact	0.3902	0.7795	0.6521	0.7221	0.8327	0.9053
Deterioration (B_7) livingcp	0.8452	0.6868	0.9779	0.8238	0.8452	0.5875
Casualty risk (A_1)	0.8999	0.9409	0.9083	0.9630	0.6793	0.8742
Economic risk (A_2)	0.7970	0.8744	0.5322	0.9809	0.7401	0.7490
Environment risk (A_3)	0.9278	0.9554	0.9650	0.9573	0.9570	0.9551
Integrated risk (R)	0.8749	0.9236	0.8018	0.9670	0.7921	0.8594
Sequencing	3	2	5	1	6	4

Table 4 Hierarchical rank of integrated flood risk.

Risk rank	extreme	significant	moderate	low	slight
Risk index value r	(0.95, 1.0)	(0.85, 0.95)	(0.50, 0.85)	(0.30, 0.50)	(0.0, 0.30)

Based on the above standard, one can obtain the results of social assessment of integrated flood risk. Of the integrated flood risks in the Yangtze River basin during 1995–2000, the risk in 1998 is the largest, falling into the rank of extreme risk; the risks in 1995, 1996, and 2000 are in the rank of significant risk; and the risk in 1997 and 1999 are of moderate risk. The sequencing of the integrated risks during the five years is 1998→1996→1995→2000→1997→1999, which is basically in agreement with the assessment made by the Yangtze River Water Resources Commission in the book *Floods and Droughts in the Yangtze River Basin*.

CONCLUSION

Social assessment of integrated flood risk based on Catastrophe Theory makes use of the advantages of hierarchical analysis, utility functions, and fuzzy assessment. The treatment of bifurcation sets with the orthogonal formula will result in a fuzzy membership function based on Catastrophe Theory. Because the assessment model determines and quantifies each index on the basis of the inherent function mechanism of the orthogonal formula, the subjectivity in judgment decreases relatively, making decision-making or assessment closer to reality. Compared with other assessment methods, the approach presented here is quick in calculation and accurate in result. Finally, the notion of risk evaluation involving societal issues will enrich risk theory and advance the development of risk management.

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