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Integrated Risk Management of Flood Disasters in Metropolitan Areas of China

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ABSTRACT *A review of flood disasters in China during the past five decades has shown a steady increase in the disaster toll due to rapid urbanization, especially through landscape urbanization in metropolitan areas. This paper illustrates the relationship and the interactions between urbanization in the metropolis and the process of flood disaster changes. Furthermore, a solution is proposed to alleviate fluctuations in flood disasters through the adjustment of the land use structure and pattern in metropolitan areas. Based on the solution, the authors conclude that the proportion of 'ecological land' in metropolitan areas should not be lower than 40%. The proportion of water and wetlands in ecological land should not be lower than their area in the years of average precipitation and water level. This means that in the Pearl River Metropolitan Area and the Yangtze River Delta Metropolitan Area, the proportion of water and wetlands in ecological land should be more than 25%. Moreover, the authors propose constituting a regional management mode which combines government, society, and insurance companies for controlling flood risk in metropolitan areas.*

Introduction

Large-scale human activities have significantly changed the hydrological cycle in natural conditions and, to some extent, have made a great change in the stability of this process, and also aggravated the problems of regional water shortage, flood disaster, and water pollution. In land use and land cover change research, scientists have paid more attention to how land use and land cover changes affect water circulation, water supply, and water quality (Lambin *et al.*, 1999). The urbanization process, especially landscape urbanization in metropolitan areas, has directly changed regional landscape structures on a large scale and caused a sharp decrease in the ratio of wetlands and water bodies. As a result, the natural water level is overlapped by the 'social water level',[1] and useful precipitation cannot be conserved. It turns into a flood disaster and further heightens the flood vulnerability of the metropolis (Shi *et al.*, 2002a). There are many relevant research studies on floods and urbanization. The report of the United Nations Educational, Scientific, and Cultural Organization (1974) systematically explained the hydrological effects in the process of urbanization, among which the most crucial effects are seepage

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reduction and peak-flow increase. Hall's (1984) research pointed out that the main hydrological responses to the urbanization process are the problems of the river head, flood control, and sewage management. Brun & Band (2000) also discussed the impact of urbanization on run-off yield and concentration. They particularly emphasized that the increased run-off coefficient accelerates the flow concentration process, heightens flood peak, and shortens concentration time. All of these show that urbanization has changed local run-off and directly affected the formation of urban floods. In metropolitan areas, the urbanization process as landscape change actually affects the hydrological process and precipitation change (Shi *et al.*, 2000; Fu, 2001).

Drawing on the discussion of how to balance flood disaster magnitude and vulnerability in metropolitan areas (Shi *et al.*, 2002a), this paper attempts to determine the relationship between landscape urbanization and flood disaster changes using two case studies: run-off yield and concentration in Shenzhen; and water-level changes in urban water bodies (including wetlands and low-lying lands) in Shanghai. Then, the paper puts forward a solution to alleviate the increase in fluctuating flood disaster in metropolitan areas, through adjustments in land use structure and pattern. Finally, the authors propose an optimal approach for integrated risk management of flood disaster in Chinese metropolitan areas.

Urbanization Process and Water Problems in China

The Relationship between Water Resource Shortage and Flood Disasters

Water is a crucial resource for sustainable development. In recent years it has become one of the scarce resources limiting local development in China. The gross amount of water in China is large, but the per capita share is small. Thus, there is a distinct conflict between supply and demand (Liu & He, 1996). In particular, in the urbanization process, the amount of water supplied by water conservancy facilities cannot meet the growing demand for agriculture, industry, and residential use (Shi, 1997). Since the 1990s, more than 300 cities in China have become short of water, of which 144 cities are in an extremely serious situation. For example, in the northern metropolitan areas, the water shortage in the central Liaoning area is 1.5 billion m^3; in the Beijing–Tianjin–Tangshan area in a normal year it is 2.0 billion m^3, and in a dry year it is 4.0 billion m^3; and in the Shandong Peninsula it is 2.2 billion m^3 in a normal year, while in a dry year it reaches 2.6 billion m^3 (Shi, 1997).

Lack of water resources has increased the risk of local flood disaster greatly. Overexploitation of groundwater triggered by water shortage has resulted in serious land subsidence. Now, there are different funnel areas of groundwater in the North China plain, the Huang-Huai-Hai plain, and the Yangtze delta area. They have extended to almost 90 000 km^2, accounting for 70% of the total plain areas. Among these, a water-bearing layer of 10 000 km^2 has been exhausted and has formed a deep groundwater funnel area with a separate centre of Tianjin, Hengshui, Cangzhou, and Langfang and with a total area of 56 000 km^2 (Liu, 2004). Surface elevation loss caused by subsidence has surpassed the impact of sea-level change 10-fold (Zhang & Shi, 1994). Thus, the problem of the so-called 'little flood, serious consequence' appears and the risk of local flood disaster increases greatly. On the other hand, in metropolitan areas, floods are not often caused by absolute surplus water alone, but are also due to the irrational land use structure and pattern, which turn useful precipitation into flood. Hence, if we can adjust the land use structure and pattern, relieving water shortage and flood disasters, a win–win situation will result.

The Intensification of Flood Disaster in China

With the development of urbanization, flood disaster in metropolitan areas has been intensifying and further threatening regional sustainable development.

The Increase in the Incidence of Floods

Flood frequency has obviously increased with rapid urbanization since 1978. From 1949 to 1966, the flood frequency of each county was less than 50 times/100 years, and only 25 counties reached 20–50 times/100 years; however, from 1976 to 1998, the flood frequency of one county has exceeded 50 times/100 years, and 125 counties have reached 20–50 times/100 years (Figure 1).

As shown in Figure 1, the 10 metropolitan areas are mainly located in the middle or lower reaches of major rivers and are thus more vulnerable to flood disaster. Since reforming and opening up in 1978, except in the Jing–Jin–Tang area and the central China area, flood incidences in the remaining eight metropolitan areas have increased markedly (Figure 2). Comparing this result with annual precipitation in the same areas (Figure 3), it is found that precipitation did not affect the incidence of floods.

The Increase in Flood Losses

Since 1978, though the capacity of flood control in China has been strengthened considerably, flood disaster losses have not decreased correspondingly. There was no large flood in the drainage basins, but flood-affected areas and flood damage percentages have continued to increase (Table 1). Moreover, the annual direct economic losses from floods in 1991 reached almost US$10 billion, while the one in 1998 resulted in US$30 billion more, a dramatic increase.

Cases of Flood Disaster Intensification in Metropolises

The Case of Shenzhen

In the Shenzhen Region there are 160 rivers, of which 13 have drainage basin areas larger than 10 km^2 and five larger than 100 km^2. The authors selected the Buji River basin as their study area. The Buji River flows through the town of Buji to the downtown area of Shenzhen City. The length of the Buji River is 17.7 km and the total area of its drainage basin is 57 km^2. In recent years, with economic development, the urbanization level in the Buji River basin has been rising rapidly.

Data and Methods

Relevant land use/cover data (Table 2) were acquired from Landsat images in 1980 (Landsat's Multi Spectral Scanner), 1988 (Landsat's Thematic Mapper (TM)), 1994 (TM), and 2000 (TM). Meteorological data including annual and monthly precipitation

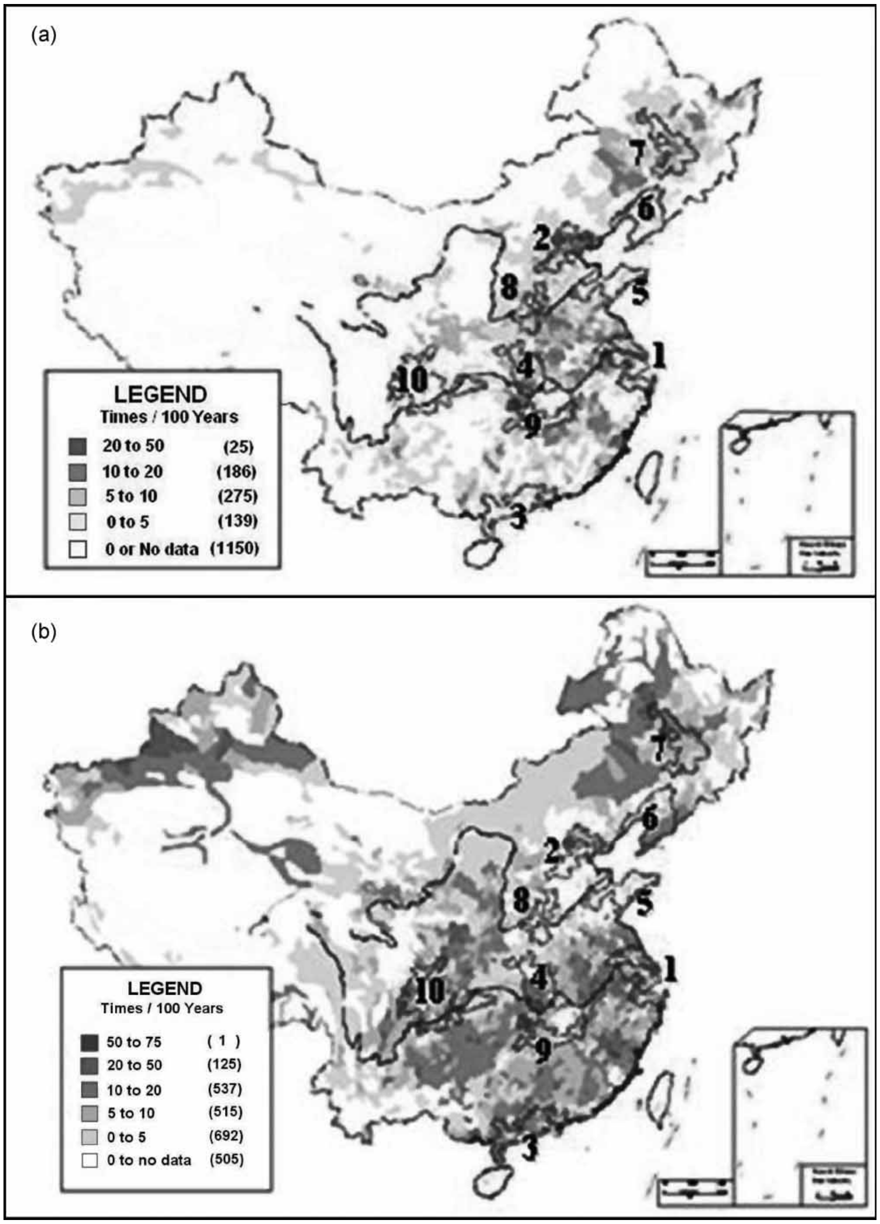


Figure 1. Incidence of county floods in China: a, 1949–66; b, 1976–98.

(1953–2000), average precipitation and run-off, annual maximum rainfall in 24 h (1954–93), and precipitation data for some typical rainstorms were obtained from the local meteorological stations. Moreover, social data from Shenzhen statistical yearbooks and landscape urbanization data collected by Global Position System (GPS) were also used.

As the hydrological and meteorological data are not extensive enough in our research, it is unsuitable to simulate the process of run-off yield and concentration through common

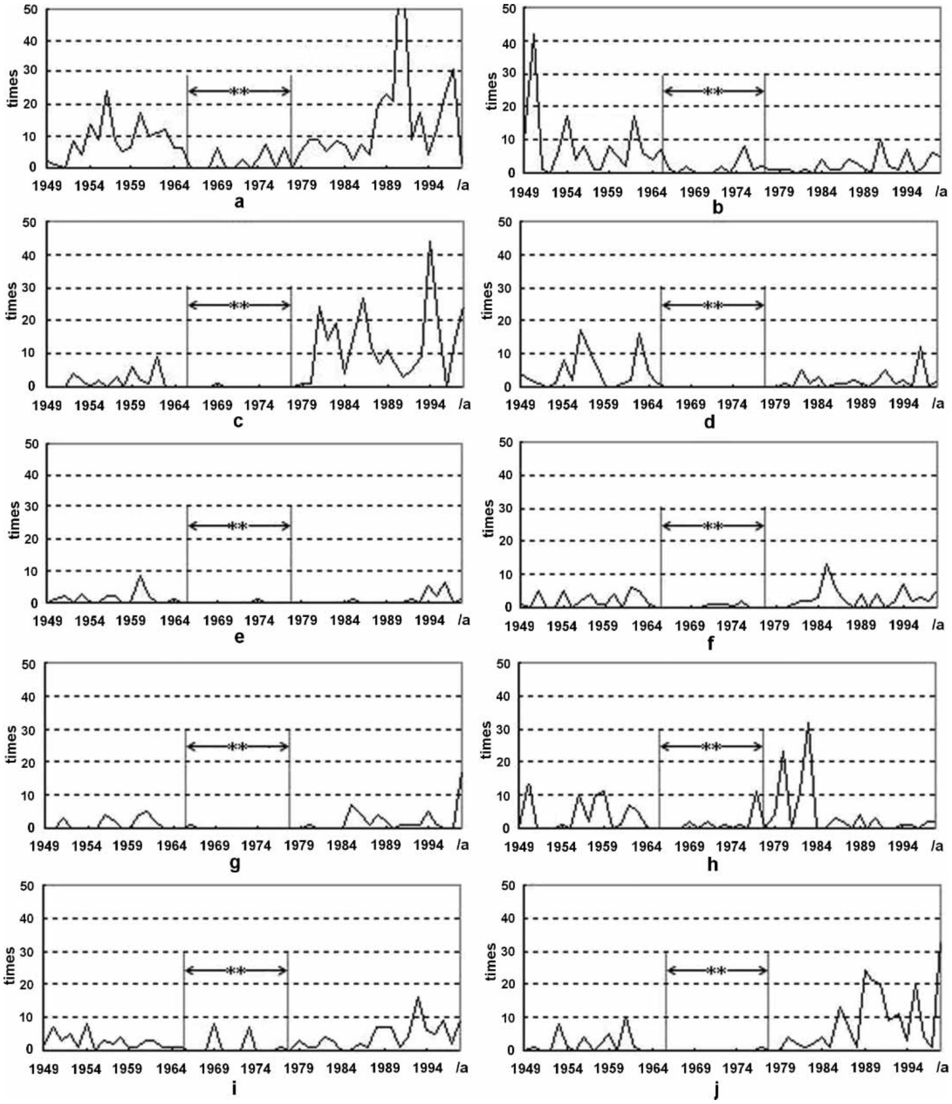
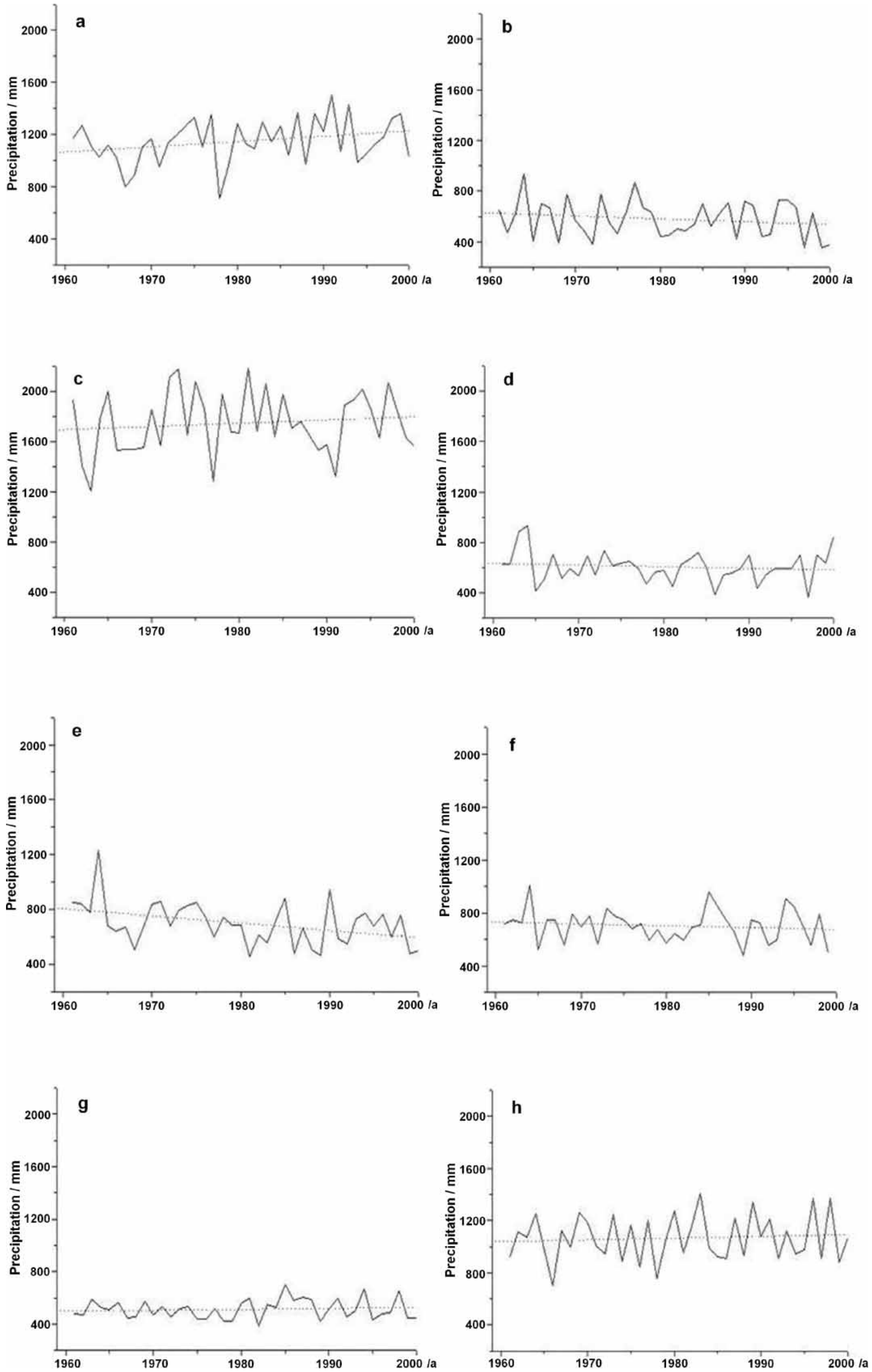


Figure 2. Incidence of floods in each metropolitan area in China: a, Yangtze delta; b, Beijing–Tianjin–Tangshan; c, Pearl River delta; d, central China; e, Shandong Peninsula; f, central Liaoning; g, Harbin–Daqing–Qiqihar; h, Wuhan; i, central Hunan; j, Sichuan basin. **Unreliable data during Cultural Revolution. *Source:* Natural Disaster Database of China, established by Key Laboratory of Environment Change and Natural Disaster, Ministry of Education, Beijing Normal University.

hydrological methods. Furthermore, the parameters and structure of traditional hydrological models are not adaptable to data from remote sensing (Wang, 1989; Lu, 1990) because few of them take land use condition as an influencing factor directly or indirectly. Therefore, it is advisable to use a hydrological model based on remote sensing to simulate the run-off process in the Buji River basin. The US Department of Agriculture Soil Conservation Service (SCS) model (SCS, 1972) has been widely used for water


a
b
c
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Precipitation / mm
400
800
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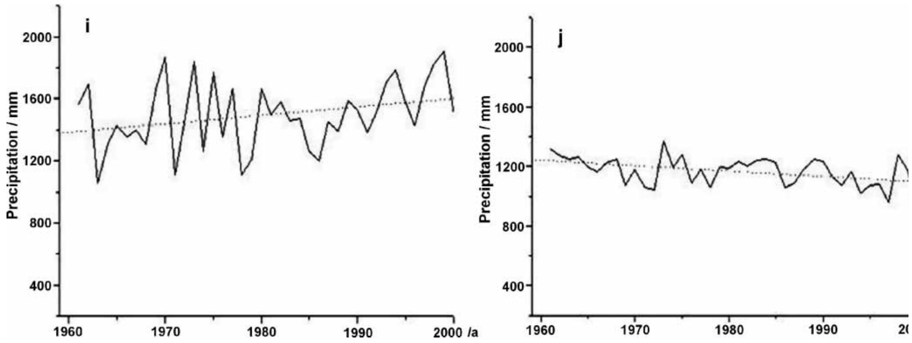

Figure 3. Precipitation in each metropolitan area in China: a, Yangtze delta; b, Beijing–Tianjin–Tangshan; c, Pearl River delta; d, central China; e, Shandong Peninsula; f, central Liaoning; g, Harbin–Daqing–Qiqihar; h, Wuhan; i, central Hunan; j, Sichuan basin. *Source:* Natural Disaster Database of China, established by Key Laboratory of Environment Change and Natural Disaster, Ministry of Education, Beijing Normal University.

resources management and planning. It has also been introduced and applied in China. Since the major input parameters for the SCS model are land use and soil type, the SCS model is potentially compatible with remote-sensing input (Lewis *et al.*, 2000). The SCS model can be expressed as:

$$\left.\begin{array}{ll} Q = \frac{(P-0.2S)^2}{P+0.8S}, & P \geq 0.2S \\ Q = 0, & P < 0.2S \end{array}\right\} \tag{1}$$

where Q is direct run-off, P is storm rainfall, and S is potential maximum retention or infiltration. For convenience and standardization, S is expressed in the form of a dimensionless run-off curve number (CN):

$$S = \frac{25400}{CN} - 254 \tag{2}$$

where CN represents the run-off potential of the land cover–soil complex, governed by soil property, cover type, and the hydrological condition of the land surface. Hence, it can reflect the impact of human activities on run-off indirectly, and link the hydrological model with remote-sensing applications. CN also depends on the antecedent wetness of the drainage basin. Three antecedent moisture conditions (AMCs) were defined as dry, moderate, and wet, and denoted as AMCI, AMCII, and AMCIII, respectively. The soil

Table 1. Flood disaster damage in China (1950–89)

	Flood-affected		Flood-damaged		
Period	Area (km^2)	Percentage increase	Area (km^2)	Damage ratio (%)	Percentage increase
1950–66	80 000	0	50 000	62.5	0
1970–78	52 000	− 35	22 000	42.3	− 20.2
1979–89	100 000	92.3	52 600	52.6	10.3

Note: In 1954, a large flood of the entire Yangtze River drainage occurred.
Source: Liu & He (1996).

Table 2. Land use types in the Buji River basin: 1980, 1988, 1994, and 2000

Year	Index[a]	Urban land with high density	Urban land with middle and low density	Farmland	Orchard	Forest	Grassland	Water	Wetland	Unused land
1980	A (km^2)	0.00	2.02	18.50	0.00	24.80	7.64	1.15	0.31	2.77
	P (%)	0.00	3.53	32.35	0.00	43.37	13.36	2.01	0.54	4.84
1988	A (km^2)	1.28	20.99	4.45	8.77	17.89	0.74	0.56	0.01	2.48
	P (%)	2.23	36.71	7.79	15.33	31.29	1.30	0.99	0.02	4.34
1994	A (km^2)	2.85	25.04	2.27	6.59	13.73	0.00	0.70	0.02	5.98
	P (%)	4.98	43.80	3.97	11.53	24.01	0.00	1.22	0.04	10.46
2000	A (km^2)	6.08	27.50	1.52	4.45	13.51	0.00	0.87	0.02	3.24
	P (%)	10.63	48.09	2.65	7.77	23.63	0.00	1.52	0.04	5.66

[a] *A* represents the area of land; *P* represents the proportion of the total area of the area of a specific land use.

data were compiled from Guangzhou Institute of Geography Science (1983), according to soil classification categories in the SCS model. Based on this information, CN values in the Buji River basin were estimated and are shown in Table 3.

Results and Analyses

Impact of Landscape Urbanization on Run-off Yield in the Buji River Basin

The run-off coefficient is an index reflecting hydrological characteristics on different land surfaces. In this study, the run-off coefficient in each pixel was calculated using the SCS model. Run-off coefficients for designed storm probabilities of 90%, 50%, and 10%, respectively, were obtained (Table 4). From 1980 to 2000, under the dry antecedent soil condition, the run-off coefficient increased by 33.49%, 20.65%, and 12.57% for the 90%,

Table 3. Estimated CN values in the Buji River basin

	Soil and hydrology classification of CN											
	A			B			C			D		
Land use type	I	II	III	I	II	III	I	II	III	I	II	III
Urban land of high density	79	90	97	84	93	98	86	94	98	88	95	99
Urban land of middle or low density	39	60	80	56	74	90	68	83	94	74	87	96
Farmland	47	67	85	61	78	92	71	85	95	78	89	97
Garden plot	22	40	61	42	62	81	58	76	91	67	82	94
Forest	13	25	44	35	55	76	51	70	87	59	77	91
Bush and grass	20	36	57	39	60	80	56	74	90	64	80	93
Wetland	17	32	52	38	58	78	53	72	88	62	79	92
Unoccupied land	53	72	88	67	82	94	76	88	96	79	90	97
Water	94	98	100	94	98	100	94	98	100	94	98	100

Note: 1.In this Table, I, II, III respectively represent three early humid phases of soil: AMCI (relatively dry), AMC II (moderate) and AMC III (relatively wet). 2. Land surface infiltration categories: A, high infiltration rate; B, moderate infiltration rate; C, low infiltration rate; D, no infiltration.

Table 4. Integrated run-off coefficients of designed storm run-offs in the Buji River basin

		Antecedent soil moisture conditions			
Rainfall frequency	Year	AMCI	AMCII	AMCIII	AMCI → AMCIII
90%	1980	0.215	0.457	0.742	71.02%
	1988	0.227	0.477	0.76	70.13%
	1994	0.267	0.517	0.786	66.03%
	2000	0.287	0.533	0.793	63.81%
	1980 → 2000	33.49%	16.63%	6.87%	—
50%	1980	0.368	0.609	0.832	55.77%
	1988	0.387	0.628	0.845	54.20%
	1994	0.427	0.66	0.863	50.52%
	2000	0.444	0.672	0.868	48.85%
	1980 → 2000	20.65%	10.34%	4.33%	—
10%	1980	0.541	0.743	0.899	39.82%
	1988	0.56	0.759	0.907	38.26%
	1994	0.596	0.782	0.918	35.08%
	2000	0.609	0.789	0.921	33.88%
	1980 → 2000	12.57%	6.19%	2.45%	—
90% → 10%	1980	151.63%	62.58%	21.16%	—
	1988	146.70%	59.12%	19.34%	—
	1994	123.22%	51.26%	16.79%	—
	2000	112.20%	48.03%	16.14%	—

Note: 1980 → 2000 represents the comparative change of runoff coefficient when the condition of land use in 1980 changed into that in 2000; AMCI: low soil moisture; AMCII: moderate soil moisture; AMCIII: high soil moisture.

50%, and 10% storm probabilities, respectively; under the wet antecedent soil condition, it increased by 6.87%, 4.33%, and 2.45%, respectively. Therefore, urbanization could lead to higher run-off coefficients and thus to a greater risk of flooding.

Impact of Landscape Urbanization on Water Concentration in the Buji River Basin

First, rainfall intensities of 1%, 2%, and 5% were simulated and the results validated according to the designed floods reported in Shenzhen Water Resources Bureau (1994). Then, according to the SCS model, 24 h flood peak discharge in outlet sections for 36 situations under different rainfall probabilities and antecedent soil moisture conditions was simulated (Table 5).

From an analysis of the data, the conclusion was drawn that the impact of landscape urbanization on water concentration is also determined by rainfall intensity and antecedent soil condition. Figure 4 shows the flood peak discharges at three different rainfall probabilities at AMCI, AMCII, and AMCIII. The flood peaks in 2000 took place generally 1–2 h earlier than in 1980. This indicates that urbanization could lead to a quicker run-off confluence and higher flood discharge. These will bring more difficulties to flood emergency management.

The Case of Shanghai

Shanghai is the centre of the Yangtze River delta metropolis, and its urbanization level is the highest of the provinces in China. In 2000 it reached 88.31% (the ratio of urban population to total population) and landscape urbanization (not including county or borough data) stood at 86.56%.

Table 5. 24 h flood peak discharge of designed storms with different landscape urbanization scenarios in the Buji River basin ($\times 10^4$ m^3)

		Antecedent soil moisture conditions			
Rainstorm frequency	Year	AMCI	AMCII	AMCIII	AMCI → AMCIII
1%	1980	1058.8	1491.7	1756.3	39.7%
	1988	1167.6	1561.3	1802.0	35.2%
	1994	1254.5	1606.6	1821.8	31.1%
	2000	1270.2	1618.1	1828.4	30.5%
	1980 → 2000	16.6%	7.8%	3.9%	—
2%	1980	887.5	1302.9	1562.9	43.2%
	1988	986.7	1370.1	1607.7	38.6%
	1994	1069.5	1415.3	1626.5	34.2%
	2000	1085.5	1425.1	1633.0	33.5%
	1980 → 2000	18.2%	8.6%	4.3%	—
5%	1980	648.0	1041.3	1296.4	50.0%
	1988	739.0	1103.1	1335.3	44.7%
	1994	816.1	1147.0	1354.6	39.8%
	2000	830.3	1155.6	1358.9	38.9%
	1980 → 2000	22.0%	9.9%	4.6%	—
5% → 1%	1980	38.8%	30.2%	26.2%	—
	1988	36.7%	29.3%	25.9%	—
	1994	34.9%	28.6%	25.6%	—
	2000	34.6%	28.6%	25.7%	—

Note: In the table, 1%, 2% and 5% are rainfall frequency; 1980 → 2000 represents the comparative change of peak discharge when the condition of land use in 1980 changed into that in 2000; AMCI: low soil moisture; AMCII: moderate soil moisture; AMCIII: high soil moisture; 5%?1% refers to the comparative change when the rainstorm frequency changes from 5% to 1%.

Data and Methods

Surface data, hydrological data, and meteorological data were used to study the process of run-off yield and concentration triggered by landscape urbanization in Shanghai. The district of Shanghai has been adjusted several times after 1949, which adds difficulty to the study. Ten urban zones (Yangpu, Hongkou, Zhabei, Putuo, Changning, Nanshi, Jingan, Luwan, Xuhui, and Huangpu: 280 km^2 in total) were selected as the study area. Based on local land use data for 7 years, the change of land use structure from 1950 to 2001 was simulated. The meteorological data used in this paper consisted of precipitation from May to September in 1991 and maximum 24 h storm precipitation in 1962. As the hydrological data were inadequate to directly explore the change of run-off yield in urban areas of Shanghai using the run-off yield formula, the authors had to simulate the situation in other ways. First, based on the water yield from different land cover types of the Taihu Lake basin with each rainfall from May to September 1991 (Gao & Wen, 2002), the water yield per unit area for different land use types was calculated using the following formula:

$$R = R_{\text{total}}/(A^{*}P) \tag{3}$$

where R stands for water yield from different land use types per unit area, R_{total} refers to the gross water yield in the Taihu Lake basin, P refers to the precipitation from May to September 1991, and A refers to the area of each land use type. Considering Shanghai as a part of the Taihu Lake basin, the water yield of various land use types in Shanghai was estimated with the data gained using equation (2). In addition, the run-off depth of

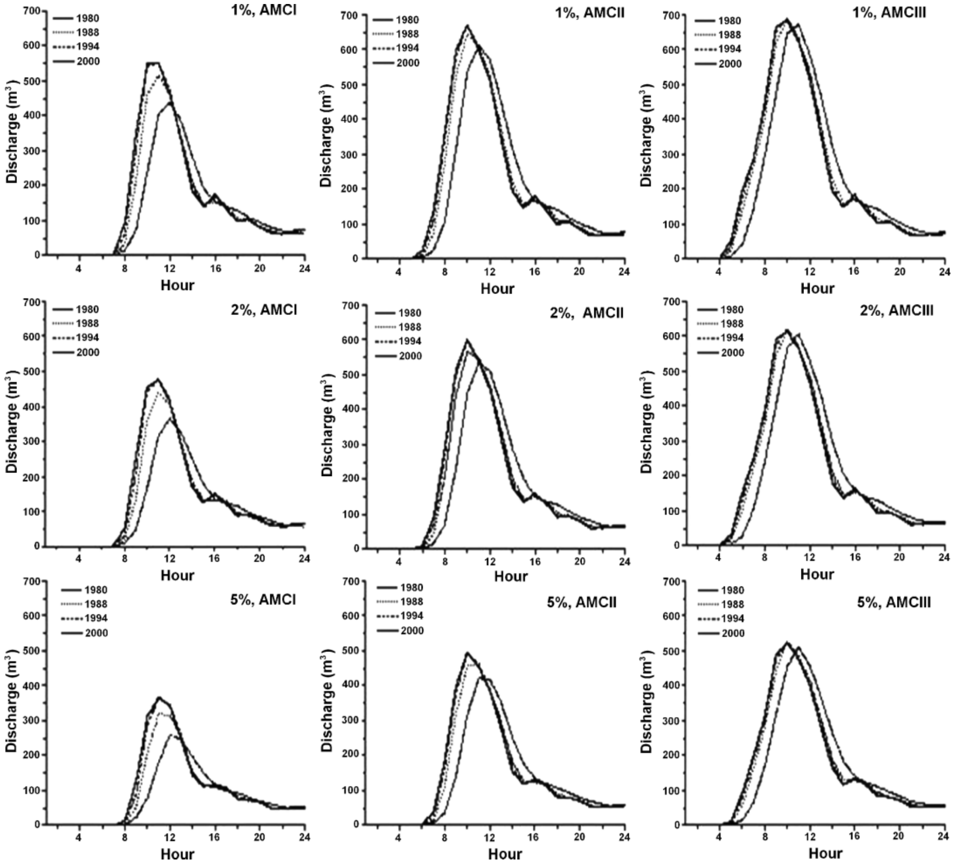

Figure 4. 24 h flood peak discharge under the designed storms (1%, 2%, 5%) and different landscape urbanization scenarios (1980, 1988, 1994, 2000).

different land uses in Shanghai was estimated (Table 6). Although there is an error of absolute measurement with this estimation method, the emphasis of this paper is on the trends in water yield in time series caused by land use changes, and therefore the impact of this error can be ignored.

Results and Analyses

The land use structure change simulated above (1950–2001) shows that the area of construction land (namely, urban land) rose to 79.97% in 2001 from 59.93% in 1950, and the area of water decreased to 0.41% in 2001 from 1.71% in 1950. As a result, the water storage capacity decreased substantially.

The urban area of Shanghai began to experience a surface subsidence from 1921 and a ‘disk-like depression’ at the bottom of the urban centre was formed (Yan *et al.*, 2002). Without taking drainage into account, the water level measured in August 1962 in Huangpu Park, Shanghai, was taken as the benchmark water level for this research. The benchmark water level (4.76 m) should be considered as a synthesized water level resulting from the

Table 6. Estimated run-off depth (in mm) for different types of land use in the Shanghai urban area

	Land Use			
Year	Construction land	Farmland	Water	Paddy-field
1986	711.4	657.2	468.2	387.6
1996	784.8	683.2	468.2	347.5
Average	748.1	670.2	468.2	367.6

natural water level and the social water level. The influence of sea-level change and some other factors was ignored here. To assess the influence of land use on water level using a quantifying method, it was assumed that the surface subsidence from 1950 to 2001 was the same as in 1962, because there are relatively complete data for this year. First, with the maximum 24 h storm precipitation in 1962, the difference between water yield in 1962 and in any other year was calculated; second, the annual area of urban water bodies was divided by the difference in water yield; and third, the difference in water level was added to the original level of 1962, so that the approximate water-level change from 1950 to 2001 was estimated (Figure 5) (here, the shore gradient change is ignored). This result shows that landscape urbanization results in the rise of the social water level. When the natural water level is overlapped by the social water level and the problem of the so-called ‘little flood, serious consequence’ appears, it turns into an accelerative process of heightening the flood risk in metropolitan areas.

Integrated Management Strategies to Alleviate Flood Risk

Based on the above study, the conclusion can be drawn that water resource protection and flood prevention have the same importance and they are mutually dependent. In regions of water shortage, especially coastal regions, overusing groundwater has led to sea water

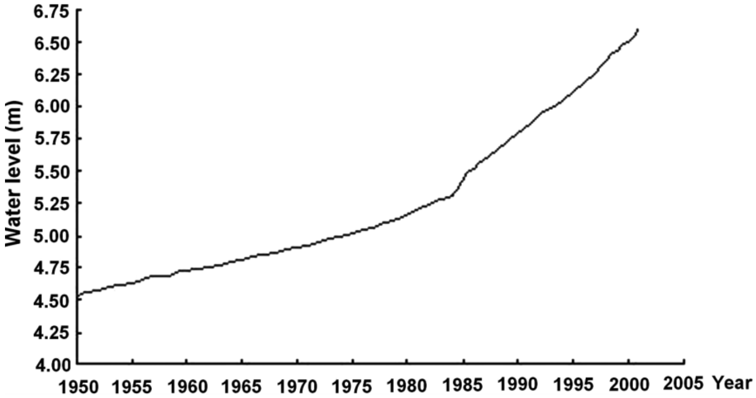

Figure 5. The estimate of water level affected by land use in the ‘disk-like depression’ of the Shanghai urban area.

intrusion and elevation loss, which further adds to the relative flood level and aggravation of flood disaster. In regions with abundant water resources, wetland is decreasing on account of land use/cover change caused by accelerating landscape urbanization. This weakens the regional flood control ability, raises the social water level, and increases flood risk. Therefore, in metropolitan areas, flood risk control should be strengthened and disaster mitigation should be combined with water conservancy development, so that a regional integrated risk management pattern can be formed.

Adjusting Land Use Structure and Pattern, Balancing the Natural Water Level and the Social Water Level

Floodwater in a metropolis is a product of the natural flood level and the social flood level. One of the important strategies is to balance these levels (Shi *et al.*, 2002b, 2003). However, implementing this strategy is still a difficult problem. According to the two cases above, which illustrate the role of landscape urbanization in increasing surface water yield and concentration comparatively, it is obvious that we should adjust improper land use structures and patterns. Then, the balance between the natural flood level and the social flood level can be retained, the surface seepage rate can be increased, and the run-off coefficient can be reduced. With reference to the authors' successful experience in Dongting Lake and testing in the Buji River basin of Shenzhen and Shanghai, it is found necessary to keep the percentage of various types of 'ecological land' above 40% in the urbanizing basin,[2] in which vegetation should not be lower than 50% in the regions with a slope over 10°, and urban vegetation should not be lower than 30% in the regions with a slope under 10°. These measures can decrease the run-off coefficient by 30–40%. In metropolitan regions, especially on downstream deltas, such as the Yangtze River delta and the Pearl River delta, in which the relative gradient is lower than 1/1000, urban wetlands and water areas should not be lower than 10% and the water area should reach about 2%. For those metropolises with higher population density, it is a wise policy to develop satellite towns.

Constructing a Flood Risk Transferring and Sharing Mode

Flood disaster management in metropolises is an integrated effort involving insurance, water conservancy, and the development of agricultural, economic, and civil affairs. Therefore it calls for co-operation among them in transforming an original mode of government and society into a new one of government, society, and insurance companies (Zhou & Shi, 1999).

Government. Government is responsible for decision making and macro-level risk management, and hence its participation is very important in flood risk management. However, the decision making of government in flood risk management is limited by economic and political conditions. It is urgent for government to clearly delineate the responsibility and obligation of each management sector in order to avoid overlap, conflict, and discontinuity. Government should also develop flood prevention policies and water resources insurance. Meanwhile, it must establish policies and regulations for flood risk management to confirm the rights and obligations of victims and beneficiaries, and set up risk-sharing mechanisms among different groups.

Society. The function of society is mainly performed by non-governmental organizations and communities, whose work generally involves propaganda, education, assisting government to carry out policies, and organizing social donations. Providing social relief is extremely important in coping with flood disaster and is indispensable for flood risk management. In China, there is obvious advancement in social relief, although problems still exist.

Insurance companies. According to certain flood prevention standards developed by government, insurance companies should actively expand flood risk insurance and enrol more community members. Technical support for flood prevention should also be strengthened to reduce losses caused by floods to the minimum level and further reduce the loss ratio of insurance companies.

Conclusions

Although the authors have determined the optimal mix of ecological land, wetlands, and water bodies for urbanizing areas, especially in the delta plains, it is necessary to consider how to plan the spatial pattern of ecological land. The study points to two critical considerations in this context.

(1) Adjust the land use structure and pattern in order to control and prevent urban floods. Conserving ecological land over 40% of the urbanizing region and maintaining wetlands and water bodies over 10% could limit the increase in flood disaster in China.
(2) Establish an integrated risk management plan to cope with flood disaster in the future. Flood risk insurance as an effective measure will enhance flood prevention and mitigation, and improve the efficiency and benefit of disaster mitigation. Integrated risk management should shift from the government–society paradigm to the government–society–insurance paradigm, which will help facilitate regional sustainable development.

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Notes

1. Social water level: an additional water level caused by irrational and unsafe human activities such as human occupation of wetlands and water areas, deforestation, etc.
2. Ecological land: the land has clear ecological value and includes farmland, garden plots, forest, bush, grass, wetlands, and water.

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