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*(Article begins on next page)*

## **Are Master Plans Effective in Limiting Development in China's Disaster-Prone Areas?**

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## Highlights

- The effectiveness of adopting urban master plans to limit development in disaster-prone areas was empirically tested for China's Yangtze River Delta region over the past thirty years.
- Environmental risk modeling was conducted to estimate the cumulative scope of urban built-up land located in highly hazardous areas.
- Master plans, especially when the pattern of urban development shows high compliance with master plans' preservation zoning, have a significant effect on limiting development in high-risk areas.
- The effect of master plans was not significant in a region vulnerable to high risks from multiple environmental hazards.
- Locational adjustment through municipal planning may avoid large-scale property losses from unexpected environmental hazards during the rapid development phase of a city.

1 **1. Introduction**

2

3 Multi-billion-dollar disasters—a flood in Bangkok, a tsunami in Sendai, a hurricane in New  
4 Orleans—have devastated cities worldwide in the last ten years. Large-scale risks associated with  
5 environmental hazards may test a government’s preparedness across a wide spectrum of planning  
6 issues, including land-use, transportation, and the provision of power supply, medical services,  
7 food and shelter. Among these, the locational adjustment of housing, industries, and roads  
8 through planning control is probably the most cost-effective governmental intervention,  
9 especially under favorable socio-political circumstances. However, it is unclear how different  
10 components of master planning counteract urban spread over areas with multiple environmental  
11 hazards during periods of rapid urban development. Do master planning exercises, even without  
12 adopting articulated measures of disaster-prevention or compulsory insurance systems, benefit a  
13 community that would otherwise expand into disaster-prone areas?

14

15 This paper intends to broaden the findings of previous research on the relationship between  
16 master planning and environmental hazards by examining examples in a Chinese context. A  
17 regression-based study of 176 local governments in the United States by Burby and Dalton  
18 (1994) indicated that a local government, under state-planning mandates, is more likely to adopt  
19 land-use planning measures for disaster mitigation. In China, local governments were  
20 empowered with strong control over land-use conversions under the central quota-allocation  
21 system in the 1980s, although explicit measures of localized disaster prevention were adopted  
22 later. Also, more recently, local governments’ capitalistic engagement with land conversion has  
23 demonstrated a strong supply-side influence on urban development. Thus, this paper focuses on

24 the compliance of Chinese cities' actual land-cover patterns with their master plans, rather than  
25 describing whether or not state mandates for zoning were adopted by local governments. From a  
26 methodological perspective, multiple spatial databases, such as high-resolution aerial  
27 photographs, remote-sensed images, and master plans from 1980s' China, were georeferenced  
28 using map-overlay techniques to create a normalized environmental risk map across the Yangtze  
29 River Delta region. The objective was to illuminate the urban-planning factors associated with  
30 cumulative urban development in disaster-prone areas.

31  
32 In China and elsewhere, master plans often become victims of their own merits, such as  
33 “comprehensiveness” in approach and so-called “rationality” in interpreting public interests. The  
34 stated role of master plans is to coordinate the collective wishes of the community and different  
35 development proposals made by specialized planners in light of the overall goals of a society. Yet,  
36 master plans are often regarded as window-dressing exercises, being too general to be supported  
37 by serious political commitments and having fragile links to actual development outcomes  
38 (Altshuler, 1965). Friedmann (1971) referred to comprehensive planning as a “colossal failure,”  
39 criticizing it for pursuing an abstract common good while ignoring the fine-grained needs of  
40 localities. Even from an empirical perspective, master planning was viewed as a necessary, but  
41 hardly sufficient tool for guiding urban development. An investigation of 30 U.S. comprehensive  
42 plans by Berke and Conroy (2000), for instance, found no significant difference in how selected  
43 sustainability principles are supported between plans with stipulated environmental principles  
44 and plans without them. Nonetheless, master plans are still, and will continue to be, a critical  
45 expression of long-term public intentions for urban places. Governments worldwide make or  
46 advocate for master plans under different titles, such as *chengshi zongti guihua* in China (urban

47 master plan) and *tosi kibon kyehoek* (city basic planning) in South Korea. Innes (1996) contends  
48 that recent progress in consensus-building among stakeholders and planners has provided new  
49 foundations for comprehensive planning. In other words, master planning *per se* is not  
50 fundamentally flawed, as long as planners' substantive judgments can steer patterns of urban  
51 development toward socially and environmentally favorable directions.

52

53 The so-called "second spring" of China's urban planning period in the 1980s, referred to by Leaf  
54 and Hou (2006), provides a window for investigating the effects of master plans on land  
55 development. By the end of 1984, 241 municipalities, or approximately 80% of China's cities,  
56 had completed their master plans. These plans—aimed at making socialist modern cities—  
57 incorporated planning measures such as coordinating future development between the city and its  
58 countryside, designating special economic zones, defining city population size and overall  
59 layouts of housing, industry, and road networks. The majority of the plans were codified in the  
60 1984 City Planning Ordinance and approved by the State Council, which became influential in  
61 shaping the physical layout of rapidly growing cities, along with other macro-level plans (**Table**  
62 **1**). Although a master plan was not a legally binding document, development control measures,  
63 e.g., site-selection notes, land-use and building permits, and penalties for illegal land occupations,  
64 were adopted by city- and district-level planners in accordance with the approved master plans  
65 (Yeh and Wu, 1998).

66

67 **[Table 1 near here]**

68

69 What remains unclear is what master plans have actually achieved without explicit measures for

70 preventing large-scale, negative environmental hazards. In China, the annual costs of  
71 environmental disasters amounted to approximately 3-6% of the national GDP between 1977 and  
72 1994 (Yang, 2007). Although several government departments concerning disasters were  
73 established in the 1950s, coordinated efforts between the central government and local  
74 municipalities started much later (Li *et al.*, 2010). The lack of disaster-prevention measures in  
75 the plans, however, does not mean that urban planners paid no attention to tragic consequences.  
76 Unlike the plans of the 1950s, the plans of the 80s were more responsive to a wide spectrum of  
77 public demands for a better quality of life. In the same period, investment in urban housing  
78 development rose rapidly and industries were relocated from densely populated urban districts.  
79 In a country where some 49.8% of total population lives in disaster-prone areas (World Bank,  
80 2006), protecting people and lands from large-scale disasters remains a high priority, along with  
81 national concerns about people's livelihoods, food self-sufficiency, and promoting further  
82 economic growth. "Serving the people (*wei renmin fuwu*)" is not only a political slogan, but is  
83 often the *modus operandi* of Chinese leaders standing with the masses in need of immediate  
84 assistance.

85

86 Against this backdrop of China's urban planning, two specific questions were addressed in this  
87 article: Is compliance with master plans a significant factor that has limited urban developments  
88 in disaster-prone areas of the Yangtze River Delta region? How does the importance of master  
89 planning change as the definitions of a high-risk zone change? In accordance with the definitions  
90 established by Smith (1996, 5), this study employed three synonymous, but slightly different,  
91 terms such as "hazard," "risk," and "disaster." *Hazard* is a general and potential source of threat  
92 to humans, associated with natural or human-induced environmental events. *Risk* is the actual

93 probability of a specific type of hazard. *Disaster* is defined as a manifest hazard that leads to the  
94 death and injury of a large number of people and the damage of properties.

95

## 96 **2. Research methods: mapping master plans and environmental hazards**

97

### 98 2.1. Study area

99

100 The Yangtze River Delta region is located at 29°69′–32°30′N and 118°39′–122°36′E in a  
101 transitional zone between the Yangtze River (Changjiang) and the East China Sea. The region's  
102 alluvial land includes 44 cities and 1,730 towns, with a total of about 63 million household-  
103 registered inhabitants. Urbanization in the Yangtze River Delta region has involved highly  
104 dispersed spatial patterns of land-cover change, along with a susceptibility to large-scale  
105 environmental hazards, in addition to a loss of valuable environmental resources due to outward  
106 expansion of cities and towns (Kim and Rowe, 2012). The region has shown great geomorphic  
107 dynamics, such as changes in the coast line and water bodies, as well as the occurrence of land  
108 subsidence dating back to the 1920s in Shanghai. These geological and hydrological features  
109 have been involved with the occurrence of earthquakes, landslides, and floods. Climatic change  
110 in the near future also poses a challenge, as some 55.3% of the inland Taihu watershed is made  
111 up of lowlands less than 3 meters above sea level (Sun and Mao, 2008). Population growth has  
112 been fairly incremental: the annual growth rate of total population in Shanghai was 2.32%  
113 between 1978-2010, whereas other provinces in the region showed a lower rate, e.g., 0.94% of  
114 Jiangsu, 0.74% of Zhejiang and 1.16% of Anhui (Anhui Sheng tongjijubian, 2012; Jiangsu Sheng  
115 tongjijubian, 2012; Shanghai Shi tongjijubian, 2012; Zhejiang Sheng tongjijubian, 2012). Yet,



116 the growth in the number of total households was much faster than population growth, due to the  
117 decrease in average household size with simultaneous increases in population. In Jiangsu and  
118 Zhejiang provinces, the number of households grew twice as fast as the overall population, at  
119 1.82% and 1.84%, respectively.

120

## 121 2.2. Data collection and analysis

122

123 In this study, five methodological steps were adopted to identify the components of master plans  
124 that contribute to the limitation of development in disaster-prone areas. They were: (i) collection  
125 of spatial data about major hazards, land-cover patterns, and master plans, (ii) quantification of  
126 the degree of compliance between master plans and actual development patterns, (iii) generation  
127 of an environmental risk map using appropriately scaled data, (iv) calculation of the size of urban  
128 lands in high-risk zones using a stratified sampling approach, and (v) analysis of planning factors  
129 associated with variations in areas of urban development at risk by way of the multiple  
130 regression method.

131

132 Multiple databases were collected, including scanned 1980s master plans, multispectral remote-  
133 sensed images from the late 1970s and 2000, aerial photographs, and other environmental  
134 variables across the Yangtze River Delta region. Master plans were selected from an initial  
135 sample of 96 cities in the four Chinese provinces of Shanghai, Jiangsu, Zhejiang, and Anhui, all  
136 collected from *Zhongguo chengshi ditu ji bianji weiyuanhui* published in 1994 (**Fig. 1**). Shortages  
137 of available master plans limited the number of cities from which data was collected, finally  
138 leading to 24 cities and 23 towns near regional-level cities. Land cover in the study areas was

139 extracted from Landsat images, such as Multispectral Scanner (MSS; 57 m resolution) and  
140 Enhanced Thematic Mapper Plus (ETM+; 30 m resolution), downloaded from the U.S.  
141 Geological Survey (USGS) Earth Resources Observation and Science Center. All images were  
142 geometrically rectified and re-projected with a 100 meter resolution. Supervised classification  
143 was then conducted to extract seven standardized land-cover classes, such as urban land,  
144 agricultural land, rangeland, forest, water bodies, wetland, and barren land. The outcome was  
145 compared with other spatial data, such as 1 km<sup>2</sup> population-grid data acquired from the  
146 University of Michigan China Data Center. All layers were then georeferenced and digitized in  
147 ArcGIS to the Xian 1980 GK Zone 19 coordinate system. Although some original data have  
148 lower resolutions, it was assumed that the coarser value would be evenly assigned across all 100  
149 m<sup>2</sup> cells.

150

151 **[Fig. 1 near here]**

152

153 How each city's actual urban pattern complies with its master plan was estimated based on five  
154 urban-form giving factors: road patterns, average block size, the area of urban built-up lands, the  
155 locations of the three largest industrial sites, as well as the three largest preservation zones. The  
156 above-mentioned measures of compliance were selected based on each plan's prominent spatial  
157 features that were readily identifiable from the classified remote-sensed images. The road pattern  
158 and block size are indicators of a city's urban structure and street network connectivity, which  
159 are widely used variables in the urban planning and transportation literature (e.g., Moudon *et al.*,  
160 2005; Brownson *et al.*, 2009). The area of urban lands is a factor in the size of cities. Locations  
161 of industrial sites and preservation zones measure the degree of locational compliance between

162 the planned and actual land uses. Further detailed criteria for the variables were as follows:

163

164 • The road pattern (0 or 1): If a ring road was present in compliance with a master plan, its  
165 value was coded as 1. Throughout the 1980s and 90s, for instance, multiple ring roads  
166 were built in Chinese cities, such as Beijing and Shanghai’s inner ring roads.

167 • The difference in average block size (km<sup>2</sup>): The mean size of ten randomly selected  
168 urban blocks in the periphery of urban districts from master plans was compared with  
169 actual block sizes shown in remote-sensed images. The differences between the average  
170 size of planned and realized blocks were then recorded.

171 • The difference in the area of total built-up land (%): The percentage of changes in the  
172 areas of urban built-up land between master plans and remote-sensed images were  
173 measured. From this a surplus of land that was actually developed, compared to what  
174 had been planned across all cities, was identified.

175 • The locations of major industries and preservation zones (0 or 1): The location of the  
176 three largest industrial and preservation zones was represented respectively as a binary  
177 variable. The value of 1 was given to each industry and preservation zone if all three  
178 planned zones were actually visible from remote-sensed images. Merging scattered  
179 industries into larger clusters, relocating them to satellite cities, and preserving large-  
180 sized greenspaces were adopted in the master plans to shape the physical structure of  
181 Chinese cities. Throughout this paper, “preservation zones” refer to the sites that are  
182 protected for environmental or ecological conservation purposes through master  
183 planning guidelines.

184

185 In order to create an environmental risk map, a multi-criteria suitability analysis was conducted.  
186 This involved compiling data about five types of hazards: earthquakes, floods, landslides, land  
187 subsidence, and sea-level rise (**Fig. 2**). These hazards were chosen based on the availability of  
188 geospatial databases (**Table 2**). Moreover, China's Agenda 21, which was adopted at the 1994  
189 Executive Meeting of the State Council after the United Nations Rio Conference on Environment  
190 and Development in 1992, described those hazards among the "major types of disasters" in  
191 China (China's Agenda 21, 1994).

192

193 **[Fig. 2 near here]**

194 **[Table 2 near here]**

195

196 Areas prone to earthquakes were mapped based on the distribution of fault lines digitized from  
197 *Guojia dizhenju dizhiyanjiusuo* (1979). China is located between the Pan-Pacific and the  
198 Eurasian seismic belts, and is potentially vulnerable to recurring earthquakes (**Table 3**). In the  
199 study area, a M-5.0 earthquake occurred in Changshu in 1990, for instance, on one of the  
200 mapped fault lines. Areas prone to flooding were drawn based on a map of a 1991 flood event  
201 during the East Asian summer monsoon followed by heavy precipitation. Potential sites  
202 vulnerable to landslides were mapped based on a combination of geo-environmental factors such  
203 as lithology, the slope of lands, and land use (Gupta and Joshi, 1990). Areas afflicted by land  
204 subsidence were mapped according to the study of Wu *et al.* (2008). They illustrated the  
205 distribution of cumulative land subsidence in the Yangtze River Delta region between 1960-2000,  
206 which was associated with intensive groundwater extraction from the second and third confined  
207 aquifers. Lastly, areas potentially vulnerable to sea-level rise were mapped based on two

208 different studies: a simulation study of areas directly impacted by sea-level rise conducted by  
209 Weiss *et al.* (2010), who assumed that by the year of 2100 at least 4-6m of sea-level rise will take  
210 place; and Gu *et al.* (2010), who mapped potentially inundated areas based on the assumption  
211 that the sea-level rise will be even more rapid—about 4m by 2030. The latter assumed that most  
212 regions in Shanghai, the Taihu watershed, Nantong, and Jiaying will be flooded, if sea walls with  
213 a height of 1-1.5m are not constructed. Both sets of spatial data were digitized with an equal  
214 weight, reflecting more or less equal importance to each mapped set of measurements.

215

216 **[Table 3 near here]**

217

218 Cumulative scores for disaster hazards were calculated by adding re-scaled values in location  $i$ .  
219 The risk score for each hazard variable ( $D_i$ ) was transformed between 0 (= no impact) and 1 (=   
220 the strongest impact) using a linear fuzzy operator in ArcGIS. This operator rescaled each raster  
221 value between 0 and 1 based on a distance threshold  $d$  for input layers, enabling the addition of  
222 their standardized scores. The distance threshold for each hazard was defined as the average  
223 distance at which the intensity of the impact of certain hazards is reduced to being negligible (i.e.,  
224 very weak or no impact). Although there is a fairly large variation in this threshold distance  
225 within the literature, recent findings by environmental scientists provide key insights for  
226 establishing working estimates. For instance, Bakun *et al.* (2005) calculated that the mean  
227 intensity of ground shaking during an earthquake dropped by one-third of the highest intensity  
228 when the distance from the fault line increased by 30 km or more. At this point, the peak  
229 horizontal acceleration (PHA) value of an earthquake fell below 0.1 g—a threshold of weak to  
230 moderate land shaking that only lightly damages buildings—although the damage may also

231 depend on the magnitude of earthquake *per se*. Based on this finding, a site located on a fault line  
232 was given the maximum impact score ( $D_I = 1$ ) for earthquake hazard. As the location of a site  
233 moved away from the fault line, the value of  $D_I$  decreases, leading to  $D_I = 0$  if  $d > 30$  km. For  
234 estimating the threshold distance of floods, there is, unfortunately, no comparable research. A  
235 distance of 10 km from major water bodies located in lowlands less than 3 meters above sea  
236 level was used as a proxy for 100-year floodplains. This estimation was based on the average  
237 distance between impacted areas from a 1991 flood in relationship to major water bodies in the  
238 region. For other types of hazards, 1 km was applied as a threshold distance by default.

239  
240 However, simply aggregating rescaled risk values may, in fact, underestimate the significance of  
241 certain land cover in mitigating the magnitude of environmental events. For instance, mature  
242 woody vegetation near roads absorbs excessive water flow during rainfall, which greatly reduces  
243 flood hazards in downstream water bodies (Forman and McDonald, 2007). This environmental  
244 benefit is more valuable if the function is *rarely* provided within the region. Thus, in this study, a  
245 rarity-weighted index, or  $w_{i,k}$ , was proposed and applied to weigh the loss of specific land cover  
246  $L_k$  at a location  $i$ , so that more valuable land cover could be weighted more heavily. A logistic  
247 function was then used to scale the rarity index between 1 (not rare) and 3 (rare):

248

$$249 \quad w_{i,k} = \frac{2}{1 + e^{\left(t - \frac{T}{2}\right)}} + 1 \quad (1)$$

250  
251 where  $t$  is the number of specific land-cover cells within the boundary of a city or a town and  $T$  is  
252 the total number of cells within the same area. There are two assumptions associated with this

253 premise: forests mitigate risks associated with floods and landslides; and wetlands and water  
254 bodies decrease the probability of floods by enhancing the hydrological capacity of a flood-prone  
255 area. Other hazards like earthquakes, land subsidence, and sea-level rise were assumed to be  
256 relatively independent of terrestrial land-cover types, thus a baseline weight of 1 was applied.  
257 Cumulative environmental risk scores were calculated using the following conventional formula:

258

$$259 \quad C_i = \sum_{k=1}^q \sum_{i=1}^p D_i \times L_k \times w_{i,k} \quad (2)$$

260

261 where  $D_i$  is a normalized intensity of a hazard;  $L_k$  is the presence (= 1) or absence (= 0) of land  
262 cover at location  $i$ ;  $p$  is the number of total hazards investigated (= 5); and  $q$  is the number of  
263 land-cover classes distinguished (= 6). The results were mapped across the study area (**Fig. 3**).

264

265 **[Fig. 3 near here]**

266

267 Using the created map, areas of urban lands exposed to high-risk zones were calculated based on  
268 the sampling boundary of 1,000 people per km<sup>2</sup>, or higher, around the center of selected cities  
269 and towns. In this study, a high-risk zone was defined by sites with the top 25% scores within the  
270 region. For sensitivity analysis, different percentage definitions of the score, such as 15% and  
271 50%, were also tested. After calculating the magnitude of urban lands in high-risk zones, the  
272 values were divided by the total amount of urban land within each sample boundary, in order to  
273 normalize the underlying differences in sizes between cities.

274

275 The effects of master plans associated with urban areas in disaster-prone sites were assessed

276 using the multiple regression method. Because master plans are likely to influence developments  
277 in the long run, it seemed more reasonable to use averages over a longer period than focusing on  
278 a single-year outcome. Accordingly, the average value of the normalized risk scores for the years  
279 of 2000 and 2010 was used as a dependent variable. Then, three different high-risk criteria were  
280 analyzed using the regression method with backward elimination, as the significance of variables  
281 could be sensitive to the definition of risk.

282

283 Also, besides the five key variables related to compliance with master plans, multiple historic  
284 and socio-economic factors were included. These covered: (1) municipal services and  
285 institutional capacity, e.g., density of sewers ( $\text{km}/\text{km}^2$ ), per-capita road areas maintained by  
286 governments ( $\times 10 \text{ m}^2$  per person), and garbage treatment capacity (tons per day per 1,000  
287 people). These variables were selected as a proxy for planning staff capacity and institutional  
288 commitments with regard to the prevention and mitigation of environmental disasters. (2)  
289 Demand for hazard mitigation, such as previous disastrous floods in 1951 and degrees of air  
290 pollution measured by the level of  $\text{PM}_{10}$ . These variables were selected based on the notion that  
291 local governments in an area with recurring environmental threats would be more aware of the  
292 planning measures associated with other types of hazards. (3) Economic resources, such as per-  
293 capita GDP in yuans in 2005 and the administrative hierarchy of cities (= 1 if regional-level  
294 cities). The exploitation of land and water resources for economic purposes may cause conflicts  
295 with environmental planning goals. (4) Barriers for controlling developments, e.g., population  
296 growth rate (%) between 1997 and 2005, slope of lands, and the presence of mining sites (= 1 if  
297 present). These variables were selected as a proxy for human-created or geographical  
298 impediments to planning controls on urban development in disaster-prone areas.



299

### 300 **3. Results**

301

#### 302 *3.1. Compliance of master plans with urban development patterns*

303

304 Adopting master plans has a moderately significant impact on limiting urban developments in  
305 disaster-prone areas. A city showing high compliance with its master plan generally has a lower  
306 proportion of urban lands exposed to risks from environmental hazards, although no causal  
307 relationship can be inferred from the result (**Table 4**). Among the five measures of master plans,  
308 preservation zoning may have a particularly significant influence on limiting developments. For  
309 instance, cities that have protected their planned preservation areas have, on average, 14 km<sup>2</sup> less  
310 urban land exposed to high risks according to the regression model (4). Preserved areas are  
311 largely located in vegetated patches on steep hills or lowlands near water bodies—often having  
312 high environmental value and amenity as well as being exposed to potential disaster risks.

313

314 Sensitivity analysis was conducted to test whether the significance of preservation zoning is a  
315 result of the definition of a high-risk zone. Three different definitions—the top 15%, 25%, and  
316 50% risk scores within the region—were applied to estimate the areas of urban development in a  
317 high-risk zone, and multiple regression analysis with backward elimination was conducted. The  
318 results show that preservation zoning remain significant when relatively greater risks at the top  
319 15% and 25% are accounted for (**Table 5**). Yet, when the definition was relaxed to include the  
320 50% scores, master planning did not seem to be a significant factor. These outcomes suggested  
321 that complying with master plans, especially with preservation zoning, may be associated with

322 mitigated vulnerability of urban lands related to fairly high risks. But if the vulnerability is  
323 defined with a lower level of risks, there seems to be little room for master planning measures to  
324 be effective.

325

326 **[Table 4, 5 near here]**

327

328 The total area of urban land is a second influential factor of master plans associated with  
329 developments, when municipal services and institutional capacity are controlled for in the  
330 regression model (2). But in other models, this variable was not significantly related to hazard  
331 risks. Also, not all dimensions of master plans were equally important. Compliance with ring  
332 roads, block sizes, or locations of major industries were not significantly associated with  
333 development outcomes of disaster risk. A joint hypothesis test using all five variables of master  
334 plans supports this outcome. Their combined effect is not significant (P-value = 0.399) at the 5%  
335 significance level. The results indicate that complying with every aspect of a master plan does  
336 not necessarily lead to substantial planning gains *vis-à-vis* hazard protection, but adopting certain  
337 elements of master plans such as preservation zoning and limiting total urban built-up areas may  
338 benefit a city during its rapid expansion phase.

339

340 *3.2. Barriers to urban master plans and limiting development in a disaster-prone area*

341

342 The significance of master plans becomes diminished when major historical flood events are  
343 included. It is likely that compliance with plans plays a less important role in a region with  
344 fundamentally high risks from multiple environmental disasters. In the sensitivity analysis, a

345 historical flood event was the only variable found to be significant across all risk scores at the  
346 1% significance level (**Table 5**). Some lowlands below sea level near Taihu Lake and the eastern  
347 coastal area of Shanghai and Chongming Island are potentially vulnerable to a multitude of  
348 environmental hazards. The normalized risk score of a town like Huinanzhen in Shanghai or  
349 Fuqiaozhen in Taicang, for instance, is about twice as high as a relatively safe site near Nanjing.  
350 Areas to the eastern side of Gehu Lake in Changzhou have risk scores that are more than three  
351 times higher than Nantong. Localized planning efforts in these areas may not eliminate all major  
352 hazards. Regions widely differ in their basic vulnerability to disasters for reasons of geography,  
353 climate, historic land uses, and cumulative investment in engineering projects. These  
354 fundamental differences can hardly be neutralized through master planning.

355  
356 This geographical impediment to successful land-use management is consistent with the outcome  
357 of a recent country-level study by Kellenberg and Mobarak (2008). According to the study, the  
358 inherent locations of countries, such as their proximity to coasts or fault lines, strongly affect the  
359 impacts they suffer from environmental disasters. But an interaction between environmental  
360 hazards and human responses can reverse this negative cycle. Indeed, some types of disasters  
361 with adverse short-term impacts might eventually make way for a society's positive economic  
362 growth, as long as the impacts can be withstood with capital re-investment, increases in total  
363 factor productivity, and technological innovations (Noy, 2009; Skidmore and Toya, 2002). For  
364 instance, Horwich (2000) analyzed how the Japanese port city of Kobe could quickly recover  
365 from the 1995 earthquake damage. The city's large-scale loss of physical capital could be quickly  
366 rebuilt through various combinations of intensive capital reinvestment, as long as the majority of  
367 human capital could be saved from losses. Therefore, geographical features are fairly influential,

368 but not necessarily decisive factors in the success and/or failure of land-use management with  
369 regard to environmental consequences.

370

### 371 *3.3. Spatial distribution of environmental hazards in the Yangtze River Delta region*

372

373 Predicted susceptibility of urban lands to disasters showed a fairly dispersed pattern in the  
374 Yangtze River Delta region (**Fig. 4**). About 6.2% of total urban land, or approximately 377 km<sup>2</sup>,  
375 is located in highly disaster-prone zones with a cumulative impact score > 0.553 (= 25%  
376 definition). Shanghai, Jiaxing, Changshu and Wuxi are cities that are exposed to  
377 disproportionately high risks from environmental hazards in absolute terms. In proportional  
378 terms, however, eight out of the top ten cities in high-risk areas are actually towns (**Fig. 5**). Only  
379 two cities—Huzhou and Kunshan—have 20% or more of their lands exposed to high risks  
380 according to these proportional terms. The overall susceptibility of these ten places increases  
381 rapidly as sites with the upper 50% risk scores are defined as high risk: more than 80% of these  
382 cities' and towns' urban lands are classified into high-risk areas.

383

384 **[Fig. 4, 5 near here]**

385

386 If individual cities are investigated, the wide variation in the spatial distribution of urban lands  
387 exposed to environmental hazards is clearly illustrated. For instance, sites approximately 45-50  
388 km away from the center of Shanghai show the highest agglomeration of high-risk zones (**Fig. 6**).  
389 These lands include the eastern part of Pudong, Dianshan Lake to the west of Shanghai, and the  
390 G1501 suburban ring road. By contrast, Hangzhou and Wuxi demonstrate increasing

391 vulnerability of urban lands to environmental disasters as the distance from their city centers  
392 increase. Nanjing presents a rather even shape in the distribution of vulnerable lands across all  
393 distances. The results indicate that urban plans for mitigating hazard impacts should be carefully  
394 made according to the distribution of sites potentially vulnerable to different risks.

395

396 **[Fig. 6 near here]**

397

398 Large-scale infrastructural development projects, such as the Pudong International Airport, the  
399 Shanghai-Nanjing high-speed railway, and Kunshan New Hi-tech Industrial Development Zone  
400 seem to be highly vulnerable to environmental hazards. Although there is no evidence that these  
401 projects actually increased the amount of property loss due to environmental disasters, intensive  
402 capital investment by the State was one of the major drivers behind placing large-scale  
403 infrastructure in hazardous areas. These perverse incentives took different forms, such as  
404 government-friendly policies in Jiangsu province for hosting more than 10% of the nation's total  
405 industrial land use in locations that are spatially correlated with areas impacted by land  
406 subsidence; or the more recent \$586 billion stimulus package injected into transportation  
407 infrastructure and housing development, some of which will be constructed in hazardous areas.  
408 This national policy further escalated the growth curve of built infrastructure in China, as  
409 exemplified by more than ten-fold increase in the length of the national road network between  
410 1978 and 2009 (Houjiezhubian jianshebu bangongting, 1997; Jianshebu zonghe caiwusibian,  
411 2010). Undoubtedly, well-connected infrastructure does not fundamentally present a problem, i.e.,  
412 transport corridors can be used for swift evacuation during a crisis. Yet, excessive investment in  
413 fixed assets may induce a negative cycle between a location's dramatically improved

414 accessibility and large-scale urban development in a highly disaster-prone area. In the regression  
415 models, the positive correlation between the construction of ring roads and increases in  
416 hazardous developments tends to support this argument, though this relationship is not  
417 statistically significant.

418

#### 419 4. Discussion

420

421 The risks from environmental disasters in China are extensive, various, and increasingly frequent.  
422 Among the different regions of China, densely populated delta regions such as Yangtze, Huanghe,  
423 and Zhujiang deltas are most vulnerable to the risks associated with flooding and land subsidence  
424 (Syvitski *et al.*, 2009). In the delta regions, vertical change in the level of land surface relative to  
425 mean sea level has been striking for several reasons: sedimentation along the major rivers has  
426 decreased rapidly; sea levels are rising; and human-induced subsidence associated with  
427 groundwater pumping has taken a toll over the last 100 years. These causes of land subsidence,  
428 along with coastal inundation from storm surges or flooding from rivers and lakes, may  
429 aggravate potential environmental threats. At the same time, droughts and flooding have directly  
430 affected more than 3% of China's total surface area in 2000 (**Table 3**). Droughts are believed to  
431 be caused by both global climatic change and human-induced landscape transformation. The  
432 removal of stream corridor vegetation and riparian forests disturbs the water cycle by interfering  
433 with groundwater recharge. Also, excessive soil erosion and the resultant sedimentation in the  
434 lower reach of rivers and lakes leads to the reduction of a region's water-holding capacity,  
435 potentially making it vulnerable to both flooding and droughts. The Shanghai Key Laboratory for  
436 Urban Ecology and Sustainability, for instance, recently initiated intensive research focusing on

437 public safety, health, and social equity issues in recognition of the challenges on the path to  
438 urban sustainability and environmental change (Xiang *et al.*, 2011).

439

440 The results of the research present important findings from urban policy and planning  
441 perspectives. Master planning, despite its often-criticized generality, may provide spatially  
442 explicit guidelines for limiting or leveraging urban development away from unsuitable areas.  
443 This planning intervention seems to be more important to limiting urban development in a high-  
444 risk zone than in a low-impact zone. Locational adjustment through plans can also potentially  
445 reduce negative consequences from environmental disasters if backed up by institutional support,  
446 economic resources, and communities' self-protective actions, as reflected in the positive  
447 influence of regional-level city variables in the regression models (4) and (5) in **Table 4**. Cities  
448 like Nanjing, Yangzhou, Nantong, and Ningbo, for instance, are all regional-level cities with  
449 fairly strong planning capacities and financial resources, interactively limiting land  
450 developments in hazardous areas below the regional average level. From an urban design  
451 perspective, design components such as road pattern and block size do not seem to affect cities'  
452 macro-scale vulnerability to disasters.

453

454 In the face of those environmental hazards, the misplaced agglomeration of buildings and  
455 infrastructure in a disaster-prone area can lead to tragedy. In this regard, structural prevention—  
456 reinforcing building codes and maintaining the capacity of infrastructure—has been a  
457 conventional approach for hazard mitigation. This preventive measure against property loss is  
458 often accompanied by large engineering works, such as building reservoirs for flood mitigation  
459 or making canals for reliable water supply. Yet, these policies are also subject to *perverse*

460 *incentives*: subsidies that are adverse in the long run due to the development in disaster-prone  
461 areas through public investment. If coupled with systemic underestimation of unpredictable  
462 events, environmental disasters beyond salient design codes may ravage a large number of  
463 properties and cause loss of human lives. Facing the limitations of structural prevention, multiple  
464 methods have been proposed to deter further development in unsuitable areas through state  
465 mandates and land-use zoning (Burby and Dalton, 1994), as well as through multiple socio-  
466 political responses to unexpected events (Adger *et al.*, 2005).

467  
468 Despite the significance of diversifying a menu of choices for pre- and post-disaster responses,  
469 the effectiveness of mitigating hazardous impacts through land-use controls should not be  
470 underestimated. Avoiding intensive developments in disaster-prone areas is probably the most  
471 cost-effective measure in downsizing the cumulative cost of recurring disasters. Relocating  
472 people to a safer place after development is often prohibitively expensive. Furthermore, once a  
473 community or urban district constitutes an economic base for surrounding neighborhoods,  
474 reshaping its physical, social, and institutional circumstances requires a considerable amount of  
475 time and political will. In China and elsewhere, making master plans usually involves public  
476 hearings, expert consultation, municipal reviews, and approvals from the central government.  
477 Priorities in the locations of near-future development are shared among land owners, developers,  
478 bureaus, and households who all may have a limited capacity for differentiating among troubled  
479 and untroubled sites. Furthermore, fine-scaled neighborhood planning or “detailed control  
480 plans,” as they are labeled in China, can be integrated into master plans, allowing them to  
481 become more refined at the local level. Also, master plans may serve as guidelines for disaster  
482 mitigation by coordinating the extraction of resources. For instance, under the *Regulations of*



483 *Shanghai Municipality on the Administration of Water Supply*, groundwater exploitation in  
484 Shanghai is not allowed if any surface water source is available for use, or if an area has already  
485 been affected by intensive groundwater extraction, or if the proposed site is located near  
486 protected building structures (Shanghai Water Authority, 2006). These measures, if stipulated in  
487 master plans, can mitigate land subsidence and protect groundwater sources by guiding  
488 developers and land owners to adopt rainwater-harvesting and water-storage technology in the  
489 early phases of land development.

490

491 In the Yangtze River Delta region, cities like Jiaxing, Changshu, Wuxi, and the coastal area of  
492 Shanghai are exposed to disproportionately higher risks than other cities. Nonetheless, small-  
493 sized towns like Dongshanzhen and Chengqiaozen may be more vulnerable to potential hazards  
494 like earthquakes, flooding, and sea-level rise due to their intrinsic diseconomies of scale and  
495 geographical insularity. Small towns may also have high external transportation costs and time  
496 delays in the provision of relief during disasters. Internal hazard-forecasting systems and relief-  
497 fund programs are relatively weak compared to large cities. Additionally, productive assets,  
498 infrastructure, and emergency shelters are often spatially concentrated in a few places. Therefore,  
499 extending the resilience capacity of a metropolitan city to smaller towns and villages is very  
500 important. Also, combining market-oriented incentives and regulatory frameworks for disaster  
501 mitigation can bring mutual benefits to urban and rural areas. For instance, setting appropriate  
502 prices for water resources, controlling the amount of groundwater exploitation, and ecological  
503 planning such as reforestation and wetland protection can reduce environmental costs in the  
504 urban regions.

505

506 The majority of low-impact areas in the Yangtze River Delta region are located outside the  
507 jurisdiction of Shanghai and the Suzhou-Wuxi-Changzhou corridor, in cities such as Nanjing,  
508 Nantong, and Ningbo. These cities are not part of the Taihu watershed, and are less affected by  
509 recurring floods and land subsidence. On the other hand, master planning efforts have had a  
510 fairly strong influence on the patterns of urban spread of these cities. For example, Nanjing was  
511 one of the earliest cities where a Municipal Planning Bureau was re-established in November  
512 1978, after the long demise of planning in China during the Cultural Revolution. There is a  
513 report on the Nanjing Master Plan, which was approved by the State Council in 1983, showing  
514 that, “Construction and redevelopment must be strictly in accordance with master  
515 planning...preserving the characteristics of ancient capital Nanjing as a socialist modern city  
516 (Nanjing Shi difangzhi bianzuanweiyuanhui, 2008).” Moreover, the plan-making process of the  
517 1983 Master Plan of Nanjing involved a multitude of institutional agencies. Experts from the  
518 Nanjing Institutes of Technology and Geography, as well as other institutions such as Tongji and  
519 Tsinghua Universities, and a provincial-level planning commission convened by the chairman  
520 Yang Tingbao worked on the draft. The scope of planning was more inclusive of residential and  
521 social components than the earlier versions. Unlike the 1950s plan’s narrow focus on Soviet-style  
522 industrialization, for example, the large scale of housing construction in the 1980s unfolded  
523 under the principles of residential districts (*juzhuqu*)—a template of large housing blocks and  
524 coarse-grained street patterns—described in the master plans.

525

526 The late 1980s was a period of economic, social and political turmoil in China. Economic  
527 fluctuations were followed by the central government’s macro-economic adjustments through  
528 which housing properties and enterprises became incrementally privatized; the supply of basic

529 resources like water and energy to urban sectors remained below municipal standards; and the  
530 remediation of negative socio-environmental damage was a daunting task. Therefore, strict  
531 compliance with master plans may be less attributable to a plan's theoretical legitimacy, and  
532 more to the pragmatic choices made by local municipalities in need of reasonably tested tools for  
533 coordinating large-scale urbanization. Between 1986-1990, the total floor area of newly  
534 constructed urban housing in China, for instance, was about 1,055 million m<sup>2</sup>. This volume, in  
535 turn, was equivalent to ample residential areas for a third of total urban residents in China,  
536 considering that there were some 301.9 million urban inhabitants in 1990 (NBS, 2011c). Under  
537 conditions of necessary housing development, conforming with a master plan appears to be a  
538 reasonable option *vis-à-vis* avoidance of environmental disasters.

539

540 One of the policy prescriptions for preventing losses from environmental disasters is to  
541 encourage households to relocate to safer places. In Beijing, for instance, a new countryside  
542 planning program was initiated in 2005 in conjunction with the Beijing Master Plan 2004-2020.  
543 Under this program, the central government provided financial subsidies to local municipalities  
544 to improve the living standards of the population, which initiated a comprehensive investigation  
545 of Beijing's some 4,000 villages. The preliminary results indicated that about 2 million people in  
546 2,395 rural settlements are exposed to geological hazards such as earthquakes and landslides, and  
547 another 1.6 million people are located in unsuitable lands near water-quality protection zones or  
548 flood-prone areas. As a planning response, village settlements were classified into three zones:  
549 relocation (*quan jian anzhi*), rearrangement (*chengzhen hua zhengli*), and maintenance (*baoliu*  
550 *fazhan*) zones. Although this program is in process, considerable diversity in rural settlements,  
551 villagers' preferences, and the high costs of relocation have posed a great challenge to these

552 efforts. Yet, on the other hand, diversity in villages can be exploited for selective resettlement.  
553 According to Smith *et al.* (2006), different social groups respond to hazards in different ways,  
554 i.e., wealthy households, who have the greatest self-protective capacity, are not likely to readily  
555 relocate when faced with a probable hazard, whereas those in the middle class rather quickly  
556 move out to avoid perceived disaster. Therefore, municipal planning action will be more  
557 effective if it is flexible enough to adjust according to the individuals' differing perceptions of  
558 their property and risks.

559  
560 In 2010, more than 35% of China's large-sized industrial enterprises were located in the Yangtze  
561 River Delta's four provinces (NBS, 2011b). Certainly the region's industrial specialization has  
562 led to increased environmental degradation. Nonetheless, the other side of this also needs to be  
563 highlighted. The locational choices of large firms became dramatically widened through  
564 clustered development. Scattered supply chains, production units, and transportation  
565 infrastructure are increasingly clustered under the local governments' orchestration into big  
566 industrial quarters like the Zhangjiang High-tech Park in Shanghai. Within the scope of this  
567 analysis, the benefits of clustering industries seem to outweigh its costs, as long as their locations  
568 are carefully chosen away from disaster-prone areas and other types of perverse incentives.

569

## 570 **5. Conclusion**

571

572 In this paper, a rarity-based environmental risk map was constructed to empirically test the  
573 effects of master plans in limiting developments in disaster-prone areas. The results indicate that  
574 cities showing high compliance with their master plans generally have smaller areas of urban

575 land exposed to environmental hazards. Among the different planning elements, preservation  
576 zoning is a significant factor associated with limiting developments. Other properties of urban  
577 patterns such as the presence of a ring road, block size, and the locations of major industries have  
578 no significant relationship to limiting developments with regard to disaster-prone areas. It seems  
579 that physical planning plays an important role in limiting urban development in or near fairly  
580 high-risk sites. However, in a region with very high risks from multiple environmental hazards,  
581 planning compliance seems to play a less important role during the rapid development phase of a  
582 city.

583  
584 Although this paper presents the status quo estimates of the distribution of environmental  
585 hazards, these estimates are incomplete for the following reasons. First, only a limited number of  
586 hazards were included in this analysis, due to the constraints of data availability. Nonetheless,  
587 this limitation in conceivable numbers does not necessarily negate the legitimacy of a suitability  
588 model, since incorporating many variables with a high spatial correlation may lead to an  
589 unjustifiable emphasis on a few hazard effects on the region. In this study, five variables were  
590 relatively independent, which suggests that such inflation has a minimal impact on the model.  
591 Second, aggregating different environmental risk scores may lead to a unitless value that is not  
592 subject to any intuitive interpretation using conventional units of intensity. Yet, the purpose of  
593 the model was to spatially differentiate locations with high environmental risks from sites with  
594 relatively low risks, not calculating a singular index that standardizes all types of disasters. Third,  
595 a full-scale environmental assessment can be made by not only calculating risk scores, but also  
596 by addressing the vulnerability of buildings and the exposure of different social groups to risks.  
597 If parcel-level data bases of Chinese cities become available in the near future, this approach

598 may reveal more useful information about the interactions amongst government planning,  
599 environmental conditions, and community responses. Fourth, this research assessed master plans  
600 based on a set of standardized land-cover classes. Applying more fine-grained land-cover  
601 classification systems may reveal some variations in the compliance of a city's urban pattern  
602 with its plan, such as differences in the degree of compliance between road patterns and housing  
603 developments.

604

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726

## List of Tables

### Table 1. History of master plans in Shanghai, 1950-present.

*Note:* In this paper, *Shanghai chengshi zongti guihua fangan*, approved in 1986, was adopted for analysis. This plan represents a major breakthrough in the second spring period of China's urban planning due to its comprehensive contents.

*Source:* *Shanghai Shi difangzhi bangongshi* (1997), *Shanghai Shi chengshi guihua guanliju* (2006).

### Table 2. Data sources on environmental hazards and land cover.

<sup>a</sup> Estimated based on Bakun *et al.* (2005).

<sup>b</sup> Estimated based on Taihu Basin Authority (2000).

<sup>c</sup> Original data sources are as follows: Landsat Orthorectified Multispectral Scanner (MSS; 57 m resolution, recorded in August 1979) and Enhanced Thematic Mapper Plus (ETM+; 30 m resolution, recorded in July 2001) acquired from the US Geological Survey (USGS) Earth Resources Observation and Science Center. Before performing analysis, these remote-sensed images were geometrically rectified, re-projected, and re-sampled using ERDAS Imagine (Hexagon Group, Stockholm, Sweden) with a 100 meter resolution.

### Table 3. Environmental disasters in China, 2000-2010.

*Note:* Percentage of affected areas by flood and drought was calculated based on China's total land area of 9.6 million km<sup>2</sup>.

*Source:* NBS (2010a, 2011b, 2011c).

### Table 4. Multiple regression estimates of urban lands in high-risk areas in the Yangtze River Delta region.

*Note:* The correlation coefficients of listed variables were calculated using multiple regression analysis. The dependent variable is the variance in the urban built-up land areas located in high-risk sites divided by the total urban lands of cities (unit: km<sup>2</sup> per 100 km<sup>2</sup> of urban lands). High-risk areas were defined by the top 25% of pixels with the highest value of cumulative environmental risk scores in the region. In the table, the correlation coefficients of listed variables are shown without parentheses and heteroskedastic consistent standard errors are shown in parentheses. The significance level is as follows: \* $p < 0.10$ , \*\* $p < 0.05$ .

*Source:* *Zhongguo chengshi dituji bianji weiyuanhui* (1994), *Jianshebu zonghe caiwusibian* (2006), NBS (2010a, 2011b, 2011c).

### Table 5. Multiple regression estimates with backward elimination using different definitions of a high-risk area.

Note: The correlation coefficients of listed variables were calculated using multiple regression analysis with backward elimination. The variables were retained at the 10% significance level. High-risk areas were defined by three different definitions for sensitivity analysis: the top 15%, 25%, and 50% of pixels with the highest value of cumulative risk scores in the region.

**Table 1**

History of master plans in Shanghai, 1950-present.

Period	Year of approval	Title of master plan
1950s-1970s	1953	<i>Chengshi zongtu guihua</i> (Schematic map of city)
	1955	<i>Shanghai 1956-1967 nian jinqi guihua caoan</i> (Draft proposal for 1956-1967 short-term urban planning of Shanghai)
	1959	<i>Guanyu Shanghai chengshi zongti guihua de chubu yijian</i> (Preliminary views on the master planning of Shanghai)
	1978	<i>Guanyu jiaqiang chengshi jianshe gongzuo de yijian</i> (Views on strengthening urban construction)
1980s	1986	<i>Shanghai chengshi zongti guihua fangan</i> (Scheme of urban master plan for Shanghai)
	1991	<i>Shanghai chengshi wenhua mingcheng baohu guihua</i> (Shanghai urban conservation plan)
	1993	<i>Pudong xinqu zongti guihua</i> (Pudong New Town master plan)
	1993	<i>Shanghai hongqiao guoji hangkong zongti guihua</i> (Master plan of Shanghai Hongqiao International Airport)
1990s-present	2001	<i>Shanghai shi chengshi zongti guihua 1999-2020</i> (Shanghai urban master plan 1999-2020)
	2009	<i>Shanghai shi jinqi jianshe guihua</i> (Shanghai contemporary construction plan)

*Note:* In this paper, *Shanghai chengshi zongti guihua fangan*, approved in 1986, was adopted for analysis. This plan represents a major breakthrough in the second spring period of China's urban planning due to its comprehensive contents.

*Source:* *Shanghai Shi difangzhi bangongshi* (1997), *Shanghai Shi chengshi guihua guanliju* (2006).

**Table 2**

Data sources on environmental hazards and land cover.

Data		Original data resolution	Threshold distance	Years	Data sources
Environmental hazards $D_i$	Earthquake ( $D_1$ )	1 : 4,000,000	30 km <sup>a</sup>	1979	<i>Guojia dizhenju dizhiyanjiusuo</i> (1979); Earthquake events were collected from USGS Earthquake Hazards Program 1973-Present.
	Flood-prone area ( $D_2$ )	1 km <sup>2</sup>	10 km <sup>b</sup>	2000	Taihu Basin Authority (2000)
	Landslide ( $D_3$ )	100 m	1 km	2010	Estimated based on NASA Shuttle Radar Topography Mission (SRTM) DEM data 2000; Gupta and Joshi (1990)
	Land subsidence ( $D_4$ )	1 : 2,000,000	1 km	2008	Wu <i>et al.</i> (2008)
	Sea-level rise ( $D_5$ )	1 km <sup>2</sup>	1 km	2010	Gu <i>et al.</i> (2010); Weiss <i>et al.</i> (2010)
Land covers $L_k$	Forest ( $L_1$ )	30 m (rescaled to 100 m)	1979, 2000	USGS 1979, 2000 <sup>c</sup> ; Google Earth	
	Cultivated land ( $L_2$ )			USGS 1979, 2000 <sup>c</sup> ; Google Earth	
	Cash-crop field ( $L_3$ )			<i>Guojia dituji bianzuan weiyuanhui</i> (1993); USGS 1979, 2000 <sup>c</sup>	
	Wetland ( $L_4$ )			USGS 1979, 2000 <sup>c</sup> ; Gong <i>et al.</i> (2010)	
	Water body ( $L_5$ )			USGS 1979, 2000 <sup>c</sup> ; Changjiang Water Resources Commission (1999)	
	All other lands ( $L_6$ )			USGS 1979, 2000 <sup>c</sup> ; Google Earth	

<sup>a</sup> Estimated based on Bakun *et al.* (2005).

<sup>b</sup> Estimated based on Taihu Basin Authority (2000).

<sup>c</sup> Original data sources are as follows: Landsat Orthorectified Multispectral Scanner (MSS; 57 m resolution, recorded in August 1979) and Enhanced Thematic Mapper Plus (ETM+; 30 m resolution, recorded in July 2001) acquired from the US Geological Survey (USGS) Earth Resources Observation and Science Center. Before performing analysis, these remote-sensed images were geometrically rectified, re-projected, and re-sampled using ERDAS Imagine (Hexagon Group, Stockholm, Sweden) with a 100 m resolution.

**Table 3**  
Environmental disasters in China, 2000-2010.

Year	Geological Disaster (number of events)			Earthquake (number of events)		Flood		Drought	
	Landslide and collapse	Mud- rock flow	Land subsidence	M 5.0-6.0 Richter scale	M > 6.0 Richter scale	Affected areas (1,000 ha)	% of China	Affected areas (1,000 ha)	% of China
2000	16,376	1,958	347	7	2	4,321	0.45	26,784	2.78
2001	3,617	1,539	554	8	3	3,614	0.37	23,698	2.46
2002	34,344	4,976	521	4	0	7,388	0.77	13,174	1.37
2003	12,844	1,549	574	10	7	12,289	1.27	14,470	1.50
2004	11,723	1,157	445	8	1	3,747	0.39	8,482	0.88
2005	17,021	566	137	9	2	6,047	0.63	8,479	0.88
2006	101,683	417	398	9	0	4,569	0.47	13,411	1.39
2007	23,200	1,215	578	1	1	5,105	0.53	16,170	1.68
2008	21,530	843	454	6	6	3,656	0.38	6,798	0.71
2009	8,688	1,442	326	5	2	3,162	0.33	13,197	1.37
2010	27,938	1,981	478	4	1	7,024	0.73	8,987	0.93

*Note:* Percentage of affected areas by flood and drought was calculated based on China's total land area of 9.6 million km<sup>2</sup>.

*Source:* NBS (2010a, 2011b, 2011c).

**Table 4**

Multiple regression estimates of urban lands in high-risk areas in the Yangtze River Delta region.

Regression models		Planning	Planning, municipal services, demand for hazard mitigation, and barrier for controlling development		All factors considered	
		(1)	(2)	(3)	(4)	(5)
Compliance with master plan	Ring road (1 = compliance)	-1.677 (9.683)				7.584 (6.362)
	Block size	-6.634 (8.383)	-7.918 (7.544)		-6.253 (7.689)	
	Total area of urban land	0.124 (0.152)	0.247* (0.146)	0.163 (0.163)	0.0995 (0.188)	0.00345 (0.197)
	Location of industry (1 = compliance)	10.88 (6.774)		-5.292 (7.185)	-8.874 (7.910)	
	Preservation zoning (1 = compliance)	-12.33** (5.683)	-16.01** (6.194)	-11.02 (6.919)	-14.03** (5.723)	-10.59* (5.522)
Municipal services	Sewer density		-0.531 (0.404)	-0.898* (0.493)	-0.523 (0.538)	-0.681 (0.465)
	Road maintenance		9.414* (5.344)	9.334 (8.355)	10.17* (5.943)	11.48* (6.187)
	Garbage treatment			-5.593 (232.9)		-141.2 (196.2)
Demand for hazard mitigation	Historic flood event (1 = yes)			19.04** (5.210)	13.58** (5.352)	16.64** (5.856)
	Air pollution			-178.5 (265.6)		
Economic resources	GDP per capita				0.000161 (0.000146)	0.000182 (0.000164)
	City status (1 = regional-level city)				-11.57* (6.281)	-4.535 (7.307)
Barriers to controlling developments	Presence of mining site (1 = yes)					-18.33 (13.14)
	Population growth rate (%)					-0.280 (0.653)
	Average slope of lands (degree)					1.445 (3.864)
Intercept		10.97* (5.997)	7.558 (8.903)	24.43 (25.84)	5.651 (8.799)	-1.089 (10.99)
Adj. R-Square		0.083	0.193	0.280	0.314	0.286
Sample size		47	47	47	47	47

*Note:* The correlation coefficients of listed variables were calculated using multiple regression analysis. The dependent variable is the variance in the urban built-up land areas located in high-risk sites divided by the total urban lands of cities (unit: km<sup>2</sup> per 100 km<sup>2</sup> of urban lands). High-risk areas were defined by the top 25% of pixels with the highest value of cumulative environmental risk scores in the region. In the table, the correlation coefficients of listed variables are shown without parentheses and heteroskedastic consistent standard errors are shown in parentheses. The significance level is as follows: \* $p < 0.10$ , \*\* $p < 0.05$ .

*Source:* Zhongguo chengshi dituji bianji weiyuanhui (1994), Jianshebu zonghe caiwusibian (2006), NBS (2010a, 2011b, 2011c).

**Table 5**

Multiple regression estimates with backward elimination using different definitions of a high-risk area.

Definitions	Significant variables	Regression coefficients	$p >  t $
Top 15% risk scores	Preservation zoning	-6.130	0.024
	Historic flood event	7.843	0.004
	Road maintenance	6.617	0.048
Top 25% risk scores	Preservation zoning	-10.624	0.046
	Historic flood event	19.611	0.000
	City status	-9.240	0.035
Top 50% risk scores	Ring road	14.792	0.074
	Historic flood event	33.480	0.000
	Presence of mining site	-18.610	0.012

Note: The correlation coefficients of listed variables were calculated using multiple regression analysis with backward elimination. The variables were retained at the 10% significance level. High-risk areas were defined by three different definitions for sensitivity analysis: the top 15%, 25%, and 50% of pixels with the highest value of cumulative risk scores in the region.



## List of Figures

**Fig. 1.** Selected master plans of the cities in the Yangtze River Delta region in the 1980s. A: Nanjing, B: Hangzhou, C: Changshu.

*Note:* The scale of the master plans varies between 1:28,000 and 1:140,000. Each plan was labeled with land-use classifications such as residential (yellow), central (red), service (orange), industry (brown), storage (purple), transport (grey pattern), rotary, government (dark green), preservation (light green), and water-body (light blue) zones. For land-cover layers, Landsat remote-sensed images were used for supervised classification by utilizing a maximum likelihood classifier in Multispec with a 100 m<sup>2</sup> resolution. Urban land, agricultural land, rangeland, forest, water bodies, wetland, and barren land were extracted from the original images. Finally, land in the study area was subdivided into 1 km<sup>2</sup> grid cells so that a dominant land-cover type within each cell can be recorded in ArcGIS. Each black dot in the figure represents 1 km<sup>2</sup> of urban built-up land that had been converted from non-urban land since 1980.

*Source:* *Zhongguo chengshi ditu ji bianji weiyuanhui* (1994).

**Fig. 2.** The theoretical process of environmental risk modeling.

*Note:* Five raster-type hazard layers were digitized and georeferenced to the original map's coordinate system using five control points per image. Original raster data was chosen based on its spatial resolution (< 1km<sup>2</sup>), regional coverage (equal or larger than the Yangtze River Delta region), and data availability.

**Fig. 3.** Environmental risk map of the Yangtze River Delta region.

*Note:* Each dot represents the location of 47 cities and towns. Their names are as follows. 1: Shanghai, 2: Chengqiaozhen, 3: Huinanzhen, 4: Jiangchuanjiedao, 5: Songjiangzhen, 6: Zhujingzhen, 7: Jinshanweizhen, 8: Qingpuzhen, 9: Kunshan, 10: Yongzhizhen, 11: Suzhou, 12: Dongshanzhen, 13: Mochengzhen, 14: Changshu, 15: Gangxiazhen, 16: Zhangjiagang, 17: Wuxi, 18: Changzhou, 19: Jiangyin, 20: Danyang, 21: Guanlinzhen, 22: Heqiaozhen, 23: Yichengzhen, 24: Yixing, 25: Zhenjiang, 26: Nanjing, 27: Yizheng, 28: Yangzhou, 29: Xiongzhouzhen, 30: Lukouzhen, 31: Yongyangzhen, 32: Chunxizhen, 33: Huzhou, 34: Tangxizhen, 35: Linpingzhen, 36: Jiaxing, 37: Haining, 38: Hangzhou, 39: Dangshanzhen, 40: Shaoxing, 41: Cixi, 42: Ningbo, 43: Zhoushan, 44: Pingchaozhen, 45: Luqiaozhen, 46: Nantong, 47: Qidong.

**Fig. 4.** Histogram of environmental risk scores describing land areas in different risk groups in the Yangtze River Delta region.

*Note:* Histogram bars (x-axis) are displayed by 1% of area ratio in the order of environmental risk scores calculated based on formula (2) in the article.

**Fig. 5.** Ranks of cities and towns in the Yangtze River Delta region by their percentage of urban

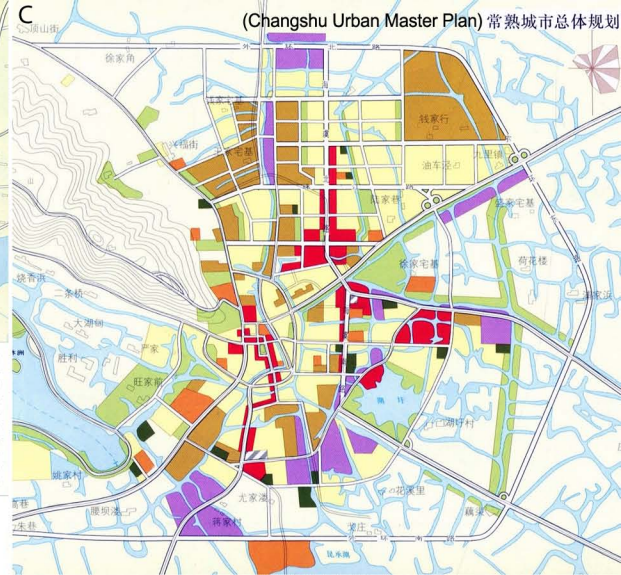
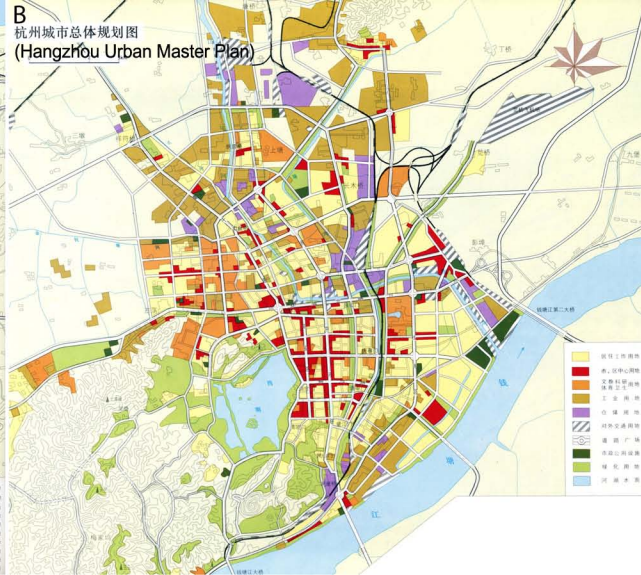
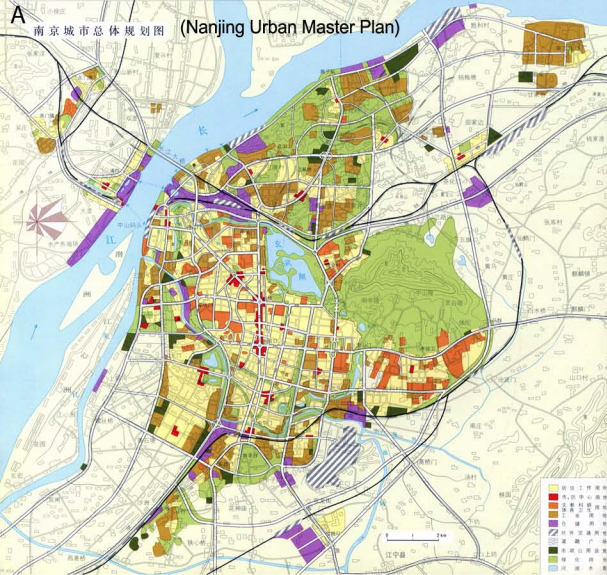
lands in high-risk areas.

*Note:* Three different definitions of high-risk zones—50%, 25%, and 15% of the region’s total lands—were used in the analysis. The Y-axis is the percentage of urban lands located in high-risk zones as specified by all three definitions. The X-axis represents the ranks of 47 cities and towns arranged in descending order based on the 25% definition. The top ten ranked cities and towns are as follows: Dongshanzhen (1), Chengqiaozen (2), Mochengzhen (3), Tangxizhen (4), Zhujingzhen (5), Huinanzhen (6), Kunshan (7), Huzhou (8), Yongzhitown (9), Jinshanweizhen (10).

**Fig. 6.** Histogram of the distribution of urban lands in high-risk areas. The distribution is represented by the distance (km) of 1 km<sup>2</sup> urban land pixels from the city centers of Hangzhou, Nanjing, Shanghai, and Wuxi.

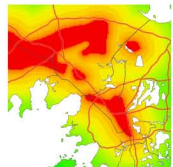
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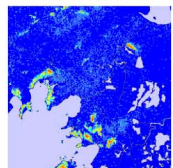


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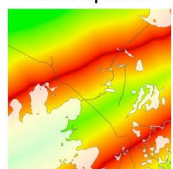
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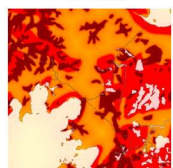
Landslides



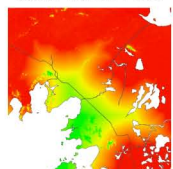
Earthquake



Floods



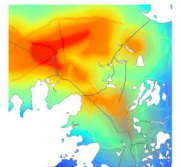
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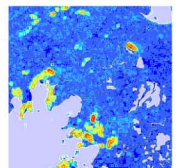
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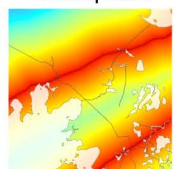
Land subsidence



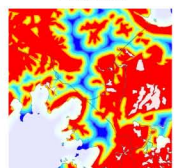
Landslides



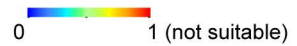
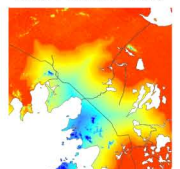
Earthquake



Floods



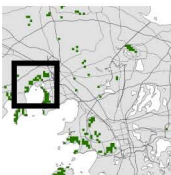
Sea-level rise



linked with land-cover

# Land-cover layer

Forest



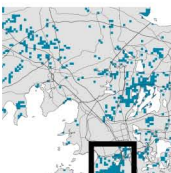
Paddy fields



Cash-crop fields

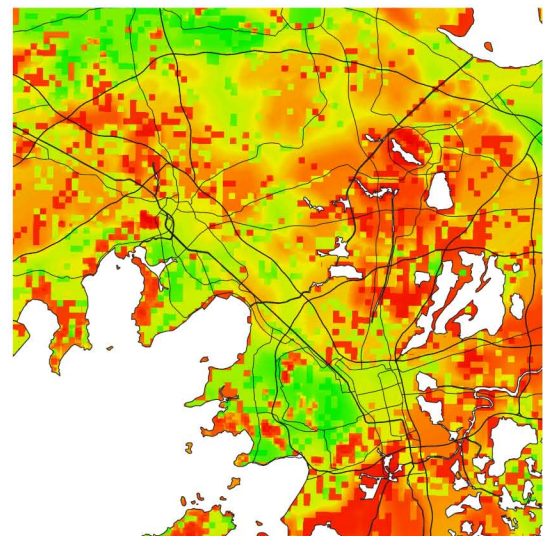


Wetlands



weighted sum

# Environmental hazards with risk scores



Logistic transformation of rarity-based Index

