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Simulating Sustainable Urban Development by Incorporating Social-ecological Risks into a Constrained CA Model

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Abstract: A key solution to urban and global sustainability is effective planning of sustainable urban development, for which geo-techniques especially cellular automata (CA) models can be very informative. However, existing CA models for simulating sustainable urban development, though increasingly refined in modeling urban growth, capture mostly the environmental aspect of sustainability. In this study, an adaptable risk-constrained CA model was developed by incorporating the social-ecological risks of urban development. A three-dimensional risk assessment framework was proposed that explicitly considers the environmental constraints on, system resilience to, and potential impacts of urban development. The risk-constrained model was then applied to a case study of Sheyang County, Jiangsu Province in the eastern China. Comparative simulations of urban development in four contrasting scenarios were conducted, namely, the environmental suitability constrained scenario, the ecological risk constrained scenario, the social risk constrained scenario, and the integrated social-ecological risk constrained scenario. The simulations suggested that considering only environmental suitability in the CA simulation of urban development overestimated the potential of sustainable urban growth, and that the urbanization mode changed from city expansion that was more constrained by social risks to town growth that was more constrained by ecological risks. Our risk-constrained CA model can better simulate sustainable urban development; additionally, we provide suggestions on the sustainable urban development in Sheyang and on future model development.

Keywords: risk assessment; vulnerability framework; social-ecological systems perspective; urban planning; Sheyang County

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1 Introduction

Urbanization is a major theme of the first half of the 21st century (United Nations, 2014). However, it has been a widespread concern that in 2030 where we should put the next billion people (Forman and Wu, 2016). Because urbanization can lead to severe local and global ecological problems, by changing land use and land cover, biodiversity, and hydrosystems, as well as by discharging urban wastes that affect biogeochemical cycles and climate (Grimm et al., 2008). Under this background, studies on sustainable urban development have been raising growing interests (Haughton, 1997; Liu et al., 2014).

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Sustainable urban development is generally recognized as the need to adopt environmentally friendly approaches to urban development (Yigitcanlar and Teriman, 2015), of which effective planning is crucial (Naess, 2001). Regarding the planning of sustainable urban development, decision-making tools from geo-technologies are often needed. Cellular Automata (CA), in particular, can be very useful in its capacity of simulating different urban development scenarios (Santé et al., 2010). Nonetheless, for a CA model to inform the planning of sustainable urban development, it should be able to incorporate sustainability constraints in urban development.

A well-cited framework of constrained-CA models was proposed for modeling sustainable urban development (Li and Yeh, 2000), although difficulties has remained in how to define and specify the constraints on sustainable urban development. While early attempts highlighted mostly environmental suitability for urban growth (Yeh and Li, 2001), recent studies increasingly emphasized the multi-dimensions of sustainable urban development (Liu et al., 2014, Weingaertner and Moberg, 2014). In fact, the potential social-ecological impacts of environmental constraints on urban development, rather than environmental constraints themselves, are the concerns in urban sustainability (Huang et al., 2015). Moreover, the social-ecological impacts of environmental constraints are also dependent on the resilience of social-ecological systems (Wu and Wu, 2013). However, so far, the resilience and impacts dimensions have rarely been incorporated into constrained-CA models for the planning of sustainable urban development.

In this study, a risk-constrained CA model was proposed that incorporates the environmental constraints on, system resilience to, and potential impacts of urban development. The risk-hazard framework (Turner et al., 2003) for vulnerability and sustainability analysis was used to develop the indicator system for assessing the social-ecological risks of urban development. Then, the risk assessment results were added to the basic CA model of urban growth as an extra land use conversion rule. Based on the risk-constrained CA model, a case study of Sheyang County, Jiangsu Province of China, was conducted to demonstrate how the risk-constrained model can be used for better informing the planning of sustainable urban development. Finally, policy implications and model usage were discussed and summarized. This study contributes to fields such as urban sustainability and land use planning by adopting a novel perspective and methodology for the planning of 'more sustainable' urban development.

2 Materials and Methods

2.1 Study area

Sheyang County (33°23′–34°39′N，119°55′–120°34′E) is located on the coastal plain in Jiangsu Province of China (Fig. 1). Sheyang has an area of 2776 km^2 (of which the 2112 km^2 terrestrial areas are studied) and a population of 962 thousand. Sheyang downtown where the county government locates is in Hede Town. The right side of Sheyang is surrounded by Yellow Sea, and most areas of Sheyang are low and flat. Besides, this region has abundant rainfall and dense rivers. With a GDP in 2016 being 6.65 billion US dollars and its urbanization rate being 56%, Sheyang is on a track of fast urban growth. On the one hand, rapid urbanization of Sheyang in the past decade has led to significant environmental problems. For example, area and quality of Sheyang's wetlands, water bodies and farmlands have decreased; discharge of its industrial, agricultural, and domestic pollutants to soils has resulted in severe soil pollution in some areas; expansion of its urban built-up area caused soil sealing and flooding in the downtown. Recently, Sheyang was chosen as one of the few pilot

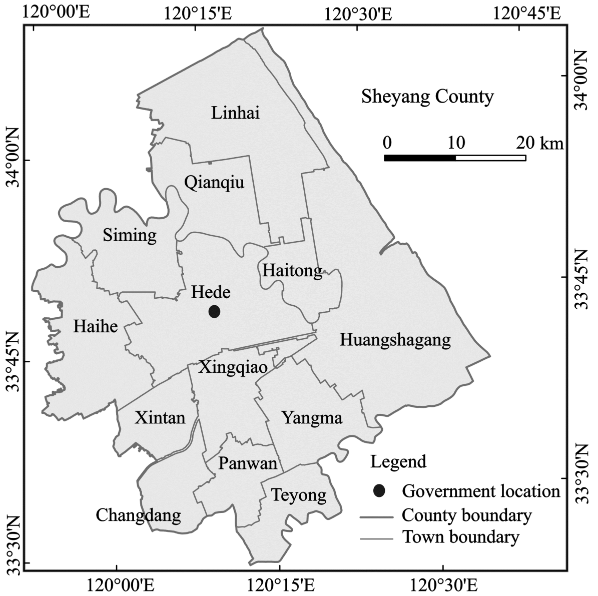


Fig. 1 Location and administrative divisions of the study area

areas for implementing China's New Urbanization policy. Therefore, Sheyang was chosen as our case study area considering its status quo and urgent needs of sustainable urban development.

2.2 Framework for assessing social-ecological risks of urban development

The location of urban development is determined by multiple factors, such as policy interventions, the distance to existing urban centers, land availability, geomorphological conditions, and environmental constraints. In previous studies on the planning of sustainable urban development, it is emphasized that urban development should take place where it is environmentally more favorable. However, environmental constraints may not necessarily be linearly related to their social-ecological impacts and thus sustainability outcomes. Therefore, by following the idea of the hazard-risk framework (Turner et al., 2003), we proposed a three-dimension framework to assess the social-ecological risks that environmental constraints may have on urban development and sustainability (Fig. 2).

As shown in Fig. 2, our sustainability framework for assessing the social-ecological risks of urban development incorporates environmental constraints, system resilience, and potential impacts. Exposure of a social-ecological system to its environmental constraints on urban development (e.g., water pollution, soil contamination) represents the dose of risks. Resilience of the social-ecological system (e.g., various types of natural and human-made infrastructure) determines its dose-response sensitivity to the risks. While the potential impacts of the risks (e.g., population, economy, and ecosystem services) reflect the system's response-impacts sensitivity. The social-ecological risks of urban development are positively related to environmental constraints and potential impacts, but negatively related to system resilience. Mathematically,

$$IR_n = IEC_n \times IPI_n / ISR_n \tag{1}$$

where n denotes the nth land unit of risk assessment; IR_n is the index of the integrated social-ecological risks of urban development of the nth land unit; IEC_n is the index of its environmental constraints; IPI_n is the index of its potential impacts; and ISR_n is the index of its system resilience. Specifically, IEC_n is calculated by the following formula:

$$IEC_n = \sum_{i=1}^{j} EC_{ni}\omega_{1i} \quad \text{and} \quad \sum_{i=1}^{j} \omega_{1i} = 1 \tag{2}$$

where j means the total number of considered environmental constraints on urban development; EC_{ni} is the exposure of the nth land unit to the ith constraint; and ω_{1i} is the corresponding weight of relative importance.

Regarding the calculation of the potential impacts IPI_n and the system resilience ISR_n, the social-ecological systems perspective was taken to explicitly consider both social subsystem and natural subsystem. Specifically, IPI_n can be calculated by the following formula:

$$IPI_n = \alpha_2 \times IPsI_n + \beta_2 \times IPeI_n \quad \text{and} \quad \alpha_2 + \beta_2 = 1 \tag{3}$$

where $IPsI_n$ and $IPeI_n$ are the index of potential social impacts and the index of potential ecological impacts on the nth land unit, respectively; while α_2 and β_2 are their corresponding weights of relative importance. The potential social impacts $IPsI_n$ and the potential ecological

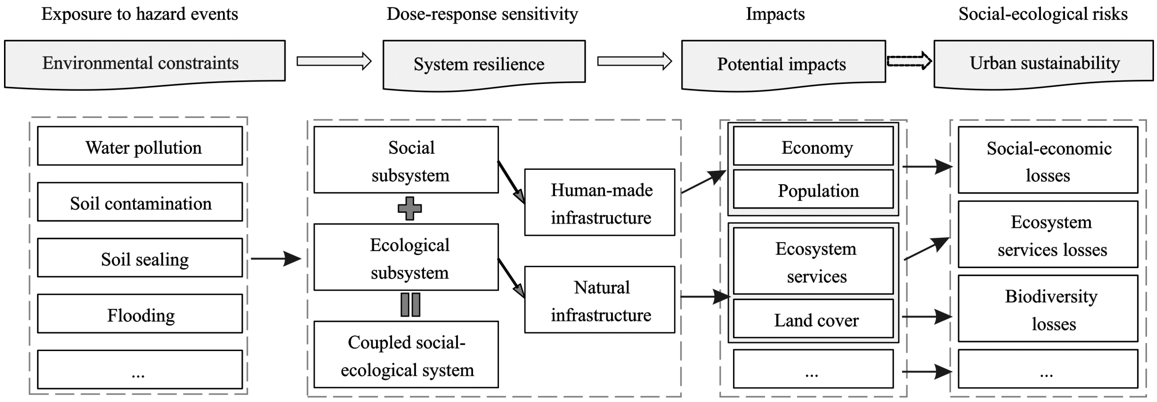


Fig. 2 Framework for assessing social-ecological risks of urban development

impacts $IPeI_n$ are calculated in a similar way as follows:

$$IPsI_n = \sum_{i=1}^{ks} PsI_{ni}\omega_{2si} \quad \text{and} \quad \sum_{i=1}^{ks}\omega_{2si} = 1 \tag{4}$$

$$IPeI_n = \sum_{i=1}^{ke} PeI_{ni}\omega_{2ei} \quad \text{and} \quad \sum_{i=1}^{ke}\omega_{2ei} = 1 \tag{5}$$

where ks and ke mean there are in total ks dimensions of potential social impacts and ke dimensions of potential ecological impacts considered in a specific study; PsI_{ni} and PeI_{ni} are the score of the ith potential social impact dimension and the score of the ith potential ecological impact dimension on the nth land unit, respectively; and again, ω_{2si} (ω_{2ei}) is the weight of each social (ecological) potential impact dimension's relative importance.

Likewise, the system resilience ISR_n can be calculated using formulas (6), (7), and (8):

$$ISR_n = \alpha_3 \times ISsR_n + \beta_3 \times ISeR_n \text{ and } \alpha_3 + \beta_3 = 1 \tag{6}$$

$$ISsR_n = \sum_{i=1}^{ls} SsR_{ni}\omega_{3si} \quad \text{and} \quad \sum_{i=1}^{ls}\omega_{3si} = 1 \tag{7}$$

$$ISeR_n = \sum_{i=1}^{le} SeR_{ni}\omega_{3ei} \quad \text{and} \quad \sum_{i=1}^{le}\omega_{3ei} = 1 \tag{8}$$

where $ISsR_n$ and $ISeR_n$ are the nth land unit's index of system's social resilience and index of system's ecological resilience, while α_3 and β_3 are their corresponding weights of relative importance; ls and le mean that there are in total ls dimensions of system's social resilience and le dimensions of system's ecological resilience considered in a specific study; SsR_{ni} and SeR_{ni} are the score of the ith social resilience dimension and the score of the ith ecological resilience dimension of the nth land unit, respectively; and ω_{3si} (ω_{3ei}) is the weight of each social (ecological) resilience dimension's relative importance.

Therefore, formula (1) for calculating the integrated social-ecological risks of urban development can be further disaggregated in again the two-sided way:

$$IsR_n = IEC_n \times IPsI_n / ISsR_n \tag{9}$$

$$IeR_n = IEC_n \times IPeI_n / ISeR_n \tag{10}$$

$$IR_n = \alpha_1 \times IsR_n + \beta_1 \times IeR_n \text{ and } \alpha_1 + \beta_1 = 1 \tag{11}$$

where IsR_n and IeR_n are the index of social risks and the index of ecological risks of the nth land unit, respectively; while α_1 and β_1 are their corresponding weights of relative importance.

2.3 Risk-constrained CA model for modeling sustainable urban development

A CA is a temporally and spatially discrete dynamic system, first proposed in the 1940s to simulate the complex evolution of spatial structures through a simple local conversion rule. CA models have been widely used for illustrating the spatial evolution of geographical elements such as land use change, in particular urban expansion (Verburg et al., 2004; Geographical Sciences Committee, 2013). There are two basic rules in any CA models, one for the cellular state effect and the other for the proximity effect (Wolfram, 1984). When CA is used to construct specifically urban expansion models, mechanisms that drive conversions between other land use types and urban lands should be incorporated as extra land use transition rules. Based on existing findings on using CA to simulate urban development (Santé et al., 2010), this study considers multiple factors for coding urban development suitability, which includes the attracting effects of existing cities, towns, and transportation lands; the excluding effect of non-developable regions; and especially, the constraining effect of the social-ecological risks of urban development.

In order to demonstrate the constraining effect of the social-ecological risks of urban development, four versions of the CA model were developed, including a base model and three risk-constrained models (i.e., the ecological risk constrained, the social risk constrained, and the social-ecological risk constrained).

Scenario 1: environmental suitability constrained. In this base model, urban development is not constrained by considerations of social-ecological risks, but only environmental suitability. Urbanization expands around downtown areas and town centers, and along traffic lines. Urban development is assumed to avoid those undevelopable areas including rivers, lakes, reservoirs, and natural or cultural reserves. Mathematically the spatial suitability of urban development can be calculated as follows:

$$S_{base} = (W_1 \times D_{city} + W_2 \times D_{town} + W_3 \times D_{road}) \times P_u, \text{ and } \sum_1^3 W_i = 1 \tag{12}$$

where S_{base} is the spatial suitability index in the base scenario; D_{city}, D_{town}, and D_{road} are the standardized values for the minimum distances from the city center, town centers, and roads, respectively; W_1, W_2, and W_3 are the corresponding weights of the three values; and Pu is the developability index defined as follows:

$$Pu = \begin{cases} 0 & Pu' \geq 1 \\ 1 - Pu' & Pu' < 1 \end{cases} \tag{13}$$

$$P'_u = W'_1 \times A_{river} + W'_2 \times A_{lake} + W'_3 \times A_{reserve}, \text{ and } \sum_1^3 W'_i = 1 \tag{14}$$

where P'_u is the unsuitability index of urban development; A_{river}, A_{lake}, and $A_{reserve}$ are the standardized values for the areas of the river, the lake, and the reserve area, respectively; and W'_1, W'_2, and W'_3 are the corresponding weights of A_{river}, A_{lake}, and $A_{reserve}$.

Scenario 2: ecological risk constrained. In this scenario, the spatial suitability index of urban development is revised to incorporate the constraining effect of the ecological risks, as shown in Formula (15):

$$S_{erc} = \gamma_1 \times S_{base} + \delta_1 \times (1 - IeR), \text{ and } \gamma_1 + \delta_1 = 1 \tag{15}$$

where S_{erc} is the suitability index in the ecological risk constrained scenario; IeR is the index of the ecological risks of urban development, as defined in Formula (10); and γ_1 and δ_2 are weights.

Scenario 3: social risk constrained. Similarly, in this scenario, the spatial suitability index of urban development is revised to incorporate the constraining effect of the social risks, as shown in Formula (16):

$$S_{src} = \gamma_2 \times S_{base} + \delta_2 \times (1 - IsR), \text{ and } \gamma_2 + \delta_2 = 1 \tag{16}$$

where S_{src} is the suitability index in the social risk constrained scenario; IsR is the index of the social risks of urban development, as defined in Formula (9); and γ_2 and δ_2 are weights.

Scenario 4: social-ecological risk constrained. Finally, in the fourth scenario, aside from the basic factors, both the ecological risks and social risks of urban development are considered in coding the land use conversion rules. Accordingly, the formula to calculate the spatial suitability index for the composite risk scenario is revised as follows:

$$S_{serc} = \gamma_3 \times S_{base} + \delta_3 \times (1 - IR) \text{ and } \gamma_3 + \delta_3 = 1 \tag{17}$$

where S_{serc} is the suitability index in the composite risk constrained scenario; IR is the index of the social-ecological risks of urban development defined in formula (11); and γ_3 and δ_3 are weights.

2.4 Data sources and processing

2.4.1 Indicators and data sources

To apply our risk-constrained CA model to the case study of Sheyang, we first came up with an indicator system to characterize the environmental constraints on, system resilience to, and potential impacts of Sheyang's urban development. Based on the social-ecological characteristics of Sheyang and correlation analysis of available data, water pollution, soil contamination, soil salinization, soil sealing, and flooding were used to characterize the environmental constraints; regional fiscal revenue, highway density, road density, and density of hydraulic infrastructure were used to characterize the resilience of the social subsystem; vegetation coverage, soil organic matter, precipitation, and percentage of water bodies were used to characterize the resilience of the ecological subsystem; population density and GDP were used to characterize the potential impacts on the social subsystem; and ecosystem services value and ecological land density were used to characterize the potential impacts on the ecological subsystem. Table 1 gives a brief description of the sources and processing of the used data.

2.4.2 Data processing and CA simulations

In consideration of the grain size of the data, the extent of the study area, and calculation efficiency, the GIS-based risk assessment of Sheyang was performed on a 500 m × 500 m grid basis, with 10 308 assessment units in total. Both the socioeconomic data and eco-environmental data were processed, and rasterized/interpolated to the 500 m resolution. Based on the risk assessment results, the constrained CA models were run in four scenarios (i.e., the base scenario, the ecological risk constrained scenario, the social risk constrained scenario, and the social-ecological risk constrained scenario) to simulate the contrasting urbanization patterns of Sheyang in 2016–2022. For objectivity, all the weights in formulas (1)–(17) were given by equal weighting.

3 Results

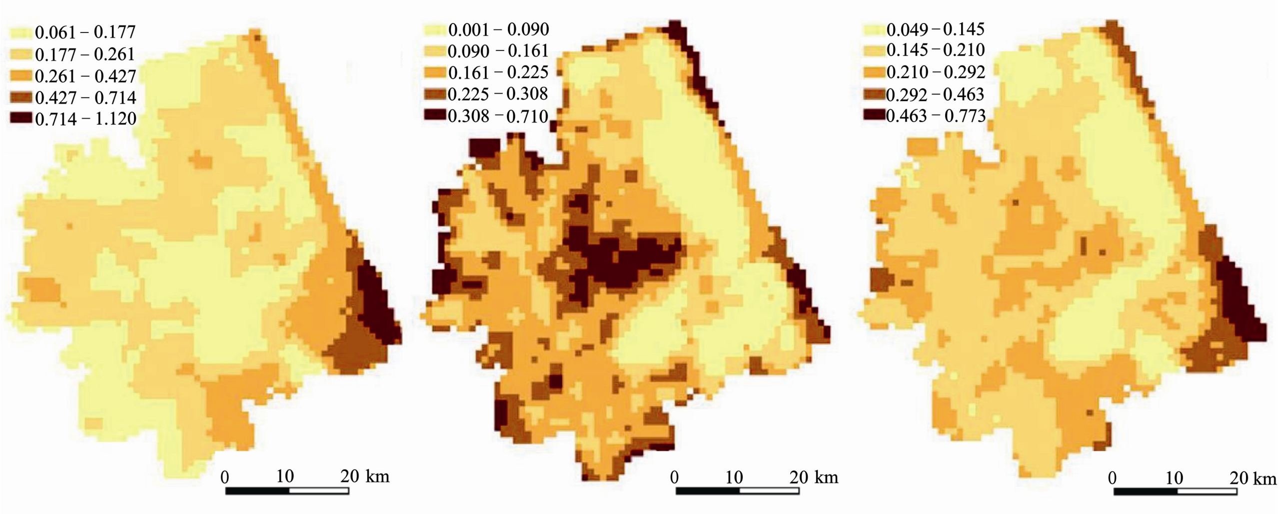
3.1 Social-ecological risks of urban development in Sheyang

As illustrated in Fig. 3(a), there is roughly a core-periphery pattern in the spatial distribution of the eco-

Table 1 List of data sources and processing for the case study of Sheyang

Data	Sources	Processing
Socioeconomic data[a]	Jiangsu Statistical Yearbook 2009–2015	Rasterize town level socioeconomic data
Land use data[b]	Land use cadastral data in 2009–2015, from the Bureau of Land and Resources of Sheyang	Rasterize vector data
Water pollution	Field sampling data in 2012, from the Environmental Protection Agency of Sheyang	Calculate Nemerow Synthetical Pollution Index (Wu et al., 2014) of the monitored river pollutants, and then do Kriging Interpolation
Soil contamination	Field sampling data in 2012, from the Bureau of Land and Resources of Sheyang	Calculate Single Contaminant Index and Nemerow Synthetical Contaminant Index (Gong et al., 2008) of the sampled soil heavy metal contaminants, and then do Kriging Interpolation
Soil salinization	Field sampling data of pH in 2012, from the Agricultural Agency of Sheyang	Do Kriging Interpolation of sampled points
Flooding	National Earth System Science Data Sharing Platform (http://www.geodata.cn/)	Run GIS-based flooding analysis use DEM (30 m) and Landsat TM data (Wang et al., 2002)
Ecosystem services value	Land use cadastral data in 2009–2015, from the Bureau of Land and Resources of Sheyang	Sum up the ecosystem services evaluation of each land use type (Xie et al., 2008)
Vegetation coverage	NDVI product based on 2013 MODIS	$VC = (NDVI - NDVI_{min})/(NDVI_{max} - NDVI_{min})$, where $NDVI = (Band_2 - Band_1)/(Band_2 + Band_1)$[c]
Soil organic matter	Field sampling data in 2012, from the Agricultural Agency of Sheyang	Do Kriging Interpolation of sampled points

Notes: a) including regional fiscal revenue, population density and GDP; b) including soil sealing, highway density, road density, density of hydraulic infrastructure, percentage of water bodies, and ecological land density; c) VC means vegetation coverage, while $Band_1$ and $Band_2$ refer to the two corresponding bands of MODIS



(a) Ecological risk **(b)** Social risk **(c)** Social–ecological risk

Fig. 3 Risk patterns of the urban development in Sheyang. The risk levels were normalized to 0–1

logical risk of urban development in Sheyang. The central areas of Sheyang including the downtown are ecologically less risky; while surrounding the less risky clump is a belt zone of areas with mostly medium ecological risk and the coastal wetlands with relatively high ecological risk. However, there occur again two lumps of less ecologically risky areas in Sheyang's northern and southwestern parts.

Fig. 3(b) shows a west-east pattern in the spatial distribution of the social risk of urban development in Sheyang. The eastern parts of Sheyang, most of which are Huangshagang Town and Yangma Town, are obviously less socially risky. These areas are sparsely populated with relatively high per capita infrastructure, and high social stability. They have great potential in future socioeconomic development. In contrast, the vast western parts of Sheyang, particularly its downtown and the surrounding areas, are of much higher social risk. Those areas have high urbanization level and denser population. Although they have more total infrastructure, their per capita infrastructure is relatively low. Therefore, after the current relatively high urbanization stage, future development will pose increasing pressure on the social subsystem.

The integrated social-ecological risk of urban development in Sheyang, as shown in Fig. 3(c), shows a less spatially variant pattern. The most risky parts are unsurprisingly the coastal zone in Huangshagang Town, resulting from relatively high ecological and also social risk. The majority of Sheyang, including its central, northern, western and southwestern parts, are below the average level of the whole Sheyang's social-ecological risk, resulting from the quite complementary overlap of the ecological risk and social risk at most units. The third clump of areas, including parts of Linhai Town, Huangshagang Town, and Yangma Town, are of least risk.

To get a clearer understanding of how the ecological risk and the social risk overlap, a cross-analysis of the two at each grid was conducted. The result is given in Fig. 4. Apparently, most areas of Sheyang fall into the relatively low ecological risk (below 0.5) and also relatively low social risk (below 0.5) category; followed by the relatively high ecological risk (above 0.5) and relatively low social risk (below 0.5) category; then goes the relatively low ecological risk (below 0.5) and relatively high social risk (above 0.5) category; last is the very rare high ecological risk (above 0.5) and also high social risk (0.5) category. All in all, Fig. 4 says both the ecological risk dimension and the social risk dimension should be considered in the planning of Sheyang's urban development.

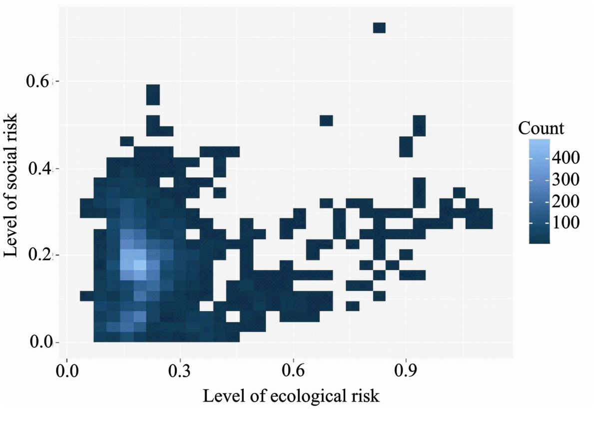


Fig. 4 Cross-analysis of the levels of the ecological risk and the social risk

3.2 Urban development of Sheyang in the four simulated scenarios

The risk assessment results of Fig. 3 were then input in the constrained CA models, for simulating the urban development in Sheyang in Scenarios 2, 3, and 4 correspondingly. The urbanization patterns of Sheyang in 2022 in the three risk-constrained scenarios, together with that in the traditional scenario 1 (i.e., constrained by only environmental suitability conditions), are illustrated in Fig. 5. In general, the urbanization pattern in the environmental suitability constrained scenario (i.e., the baseline pattern) is quite similar to the pattern in the ecological risk constrained scenario. The urbanization pattern in the social risk constrained scenario is unsurprisingly different from the baseline pattern. Likewise, the urbanization pattern in the integrated social-ecological risk constrained scenario is also different from baseline pattern.

In Fig. 5 Scenario 1, the urban lands expand in a monocentric way, growing mainly around Sheyang downtown and filling almost the whole Hede Town. The newly developed urban lands are concentrated in two regions: the Sheyang Development Zone and the Hede Town. However, towns far from the Sheyang downtown have not been well-developed. Obviously, the agglomeration effect of urban development is extremely pronounced in this baseline scenario, for almost only Sheyang downtown is further developed while development of the surrounding areas is limited. In Fig. 5 Scenario 2, although Sheyang's urbanization pattern is similar to that in Scenario 1, the overall urban development rate is slightly slower. This is unsurprising due to the imperfect social-ecological resilience to and the potentially amplifying social-ecological impacts of the constraining environmental disturbances.

In Fig. 5 Scenario 3, the urban lands expand in a polycentric way, growing mainly in the central and eastern parts of Sheyang. Specifically, urban development occurs around Sheyang downtown, the centers of Huangshagang town and Qianqiu Town, and also occurs in the Lingang Industrial Development Zone. While urbanization around the town centers and in the Lingang Industrial Development Zone are surprisingly fast, urban development around Sheyang downtown is significantly slower. In Fig. 5 Scenario 4, the urban lands expand in a bicentric way, growing mainly around Sheyang downtown and the center of Huangshagang Town. Urban development is most significant around Sheyang

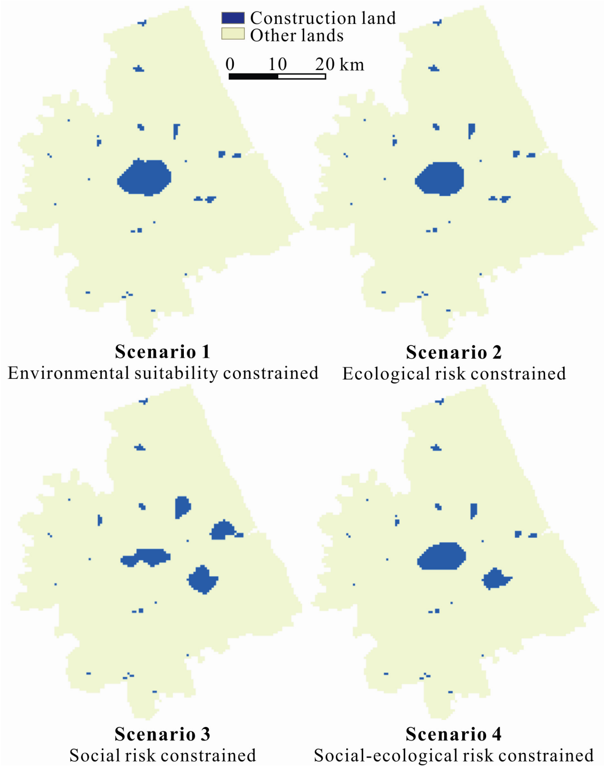


Fig. 5 Urbanization patterns of Sheyang in 2022 in the four simulated scenarios

downtown, followed by areas around the center of Huangshagang Town. The remaining urban growth is relatively insignificant. Compared to the urban developments in Scenarios 2 and 3, the urbanization in Scenario 4 is slower and more agglomerated. This is reasonable because Scenario 4 is more comprehensive than Scenario 2 (Scenario 3) in that it incorporates not only the ecological (social) risk constraints but also the social (ecological) risk constraints.

By simulating the urban growth of Sheyang in 2015–2022 (Table 3), it can be seen that urban development in Scenario 1 is always faster than that in Scenario 4. Considering only environmental suitability underestimates system's constraining effects on urban development, leading to faster yet unsustainable urban development. Besides, urban development in Scenario 2 is faster than that in Scenario 4 before 2018, and becomes slower after 2018; and urban development in Scenario 3 is slower than that in Scenario 4 before 2020, and becomes faster after 2020. It seems that the constraining effect of social risk decreases with time, while inversely, the constraining effect of ecological risk increases with time. This is likely associated with the different modes of urbanization: city expansion in Scenario 1 and Scenario 2, versus, town expansion in Scenarios 3 and 4. To better understand the underlying mechanisms, we further investigated the structures of urban growth in the four scenarios.

In China's land use management and urban planning practices, urban lands are divided into three categories: city urban land, industry urban land, and town urban land. As demonstrated in Table 3, Sheyang in 2015 had in total 60.50 km^2 urban land, and as simulated in 2022, will have 96.50 km^2 total urban land in Scenario 1, have 90.25 km^2 total urban land in Scenario 2, have 100.75 km^2 total urban land in Scenario 3, and have 92.25 km^2 total urban land in Scenario 4. With regard to urban land structure, Sheyang in 2015 had 26.75 km^2 city urban land, 9.75 km^2 industry urban land, and 24.00 km^2 town urban land. Contrastingly, as simulated in 2022, Sheyang will have 72.75 km^2 city urban land, 3.75 km^2 industry urban land, and 20.00 km^2 town urban land in Scenario 1; have 65.75 km^2 city urban land, 3.75 km^2 industry urban land, and 20.75 km^2 town urban land in Scenario 2; have 29.50 km^2 city urban land, 18.50 km^2 industry urban land, and 52.75 km^2 town urban land in Scenario 3; and have 52.00 km^2 city urban land, 3.75 km^2 industry urban land, and 36.50 km^2 town urban land in Scenario 4. All in all, considering only environmental suitability, urban development in Sheyang significantly increases city urban lands and decreases industry urban lands and town urban lands; while by considering the social-ecological risks for urban sustainability, urban development in Sheyang increases less city urban lands but more town urban lands. Tables 2 and 3, together with Fig. 5 suggest that city expansion is more constrained by the social risks while town and industrial land expansion is more constrained by ecological risks.

Table 2 Area of Sheyang's urban construction lands in 2015–2022 in the four scenarios (km^2)

	2015	2016	2017	2018	2019	2020	2021	2022
Scenario 1	60.50	69.50	76.75	83.25	87.50	90.75	94.00	96.50
Scenario 2	60.50	68.50	74.50	78.75	83.25	86.00	86.25	90.25
Scenario 3	60.50	64.50	71.00	77.00	82.50	89.25	94.75	100.75
Scenario 4	60.50	67.25	73.75	79.50	84.25	87.75	90.00	92.25

Table 3 Structures of Sheyang's urban lands in 2015 and in the four scenarios in 2022 (km^2)

	Status quo	Scenario 1	Scenario 2	Scenario 3	Scenario 4
City	26.75	72.75	65.75	29.50	52.00
Industry	9.75	3.75	3.75	18.50	3.75
Town	24.00	20.00	20.75	52.75	36.50
Total	60.50	96.50	90.25	100.75	92.25

4 Discussion

4.1 Policy implications for the sustainable urban development in Sheyang

Based on the findings of the United Nations, urbanization in a region usually follows a S-shape curve: first starts off slowly until about 30%, and then goes into a fast development period, and finally gets to the stabilizing stage at about 70% (Feng et al., 2007). In this case, assuming that Sheyang holds its annual 2% urbanization rate in the past decade, Sheyang will continue to urbanize rapidly until 2022 or beyond. Consequently, cautious planning of urban development and effective land use management are crucial for achieving sustainability.

Our study suggests that the urban development in Sheyang faces relatively high level of ecological risk and also medium level of social risk. The results also indicate that within the coming few years, at around 2019, Sheyang's urban development will likely shift from the current city-expansion dominated mode to town-expansion dominated mode (Fig. 5, Tables 2 and 3). This is reasonable, because along with urbanization come the increasing issues of social risks, such as spatial disparities (Niakara et al., 2007), social disorder (Buhaug and Urdal, 2013), and environmental injustices (Wolch et al., 2014). The constraining effect of social risks of Sheyang downtown expansion will increase to a tipping point to favor instead town expansion, which is more constrained by ecological risks. If the urban planners of Sheyang take only environmental suitability into account, then as simulated in our constrained CA-model in Scenario 1, the urban development of Sheyang will become unsustainable due to increasing social risks. This unsustainable urban development will most likely take a monocentric pattern, expanding around current Sheyang downtown in Hede Town (Fig. 5 Scenario 1). By taking a risk-based sustainability perspective and considering comprehensively the social-ecological risks of urban development, our risk-constrained CA simulations suggest Sheyang to take a bicentric urban growth pattern (Fig. 5 Scenario 4). Specifically, urban development around Sheyang downtown should be the first priority, and development around the center of Huanshagang town should be the second priority. This could mean that in 2022 there will be an increase of up to 25.25 km^2 city urban land surrounding Sheyang downtown, and an increase of up to 12.50 km^2 town urban land surrounding the Huangshagang town center (Table 3).

In Sheyang's Urban Master Planning (2008–2030), Linhai Town in the northeastern Sheyang and Panwan Town in the southwestern Sheyang are determined as the two prior towns for increasing town urban land (Bureau of Housing and Urban-Rural Construction of Sheyang, 2009). However, urban development in Linhai town and Panwan town will face both relatively high ecological and social risks (Fig. 3), and consequently, is not identified as the priority in our simulations (Fig. 5). Recently, Linhai Town and Huangshagang Town were selected as two of the key small towns in China's national urbanization plan (Sheyang Government, 2017). On the one hand, this indicates the necessity of keeping an extra eye on the urban development in Linhai Town for potential social risks; on the other hand, it also demonstrates the disorganization in the planning of Sheyang's urban development, for its urban master planning is clearly inconsistent with a national policy. After all, a solid plan of sustainable urban development needs an organized authority to implement.

4.2 Risk-constrained CA model for the planning of sustainable urban development

In this study, we proposed a risk-constrained CA model to better inform the planning of sustainable urban development. To assess the social-ecological risks of urban development on regional sustainability, we followed the philosophy of the hazard-risk framework (Turner et al., 2003) for vulnerability and sustainability analysis, and came up with a three-dimensional framework that incorporates environmental suitability, system resilience, and potential impacts. Based on the proposed risk-constrained CA model, our comparative simulations of urban development in Sheyang (Fig. 5) indicate that it will underestimate the constraining effect if only environmental suitability is incorporated in the constrained-CA models of urban development. This is unsurprising because the proposed social-ecological risk-constrained CA model is, compared with the traditional ones, more relevant to sustainability in at least two ways. One is that sustainability is not just the opposite to environmental constraints. Rather, the dose of environmental disturbances, together with the social-ecological resilience to the disturbances and the potential impacts of the disturbances on the social-ecological system, determines the sustainability of urban development. For example, the same amount of extreme rainfall and consequent urban flooding can lead to different sustainability outcomes. It will be more risky for cities with larger population or GDP (i.e., indicators of the potential impacts in section 2.4) and less developed hydraulic infrastructure or buffering water bodies (i.e., indicators of the system resilience in section 2.4). The other is that sustainability is more than the environment, but about the whole social-ecological system. Our new CA model adds the social resilience factors and the potential social impacts factors.

The planning of sustainable urban development as a key solution to urban and global sustainability has attracted growing interests. Existing studies on sustainable urban development often offer a quite environment-biased perspective (Berke and Conroy, 2000), highlighting issues like ecological sustainability and equity (Naess, 2001), economy-environment conflicts (Ng, 2002), ecological city (Jepson and Edwards, 2010), but it is increasingly recognized that sustainable urban development depends also on social subsystem and also the interplay between social and ecological subsystem (Kennedy et al., 2012). Actually, in sustainability science (Kates et al., 2001), the concept of sustainability is often conceived as composed of three pillars: environment, economy, and society (i.e., planet, profit, and people). Also, to achieve sustainability, a social-ecological systems (i.e., human-environment systems) perspective would often be adopted (Levin and Clark, 2010). Existing studies on using geo-techniques especially CA related models to inform planning of sustainable urban development have made much progress in the technical aspects of refining CA models for simulating urban growth (Wu, 1996, Yeh and Li, 2001). Instead, our study contributes by developing a theoretic framework that adopts social-ecological systems perspective for understanding and modeling sustainable urban development.

Admittedly, the policy implication for Sheyang's urban development is essentially heuristic. Because the indicator system constructed for the case study is limited by data accessibility and data quality. The selection of the indicators could also be quite subjective. Nonetheless, this can potentially be a merit of our proposed framework. The risk-constrained CA model we developed for informing the planning of sustainable urban development is highly flexible to incorporate finer model elements, and is also easily adaptable to other case studies. The flexibility of our model means that other land use change and urban growth mechanisms like participation of stakeholders (Varol et al., 2011) can be readily incorporated. The adaptability of our model means that the indicators and their corresponding weights for risk assessment can be revised based on data availability, policy orientation, and practical needs in other case studies, following sustainability science's philosophy of being place-based, problem-driven, and transdisciplinary (Kates et al., 2001). How to take better advantage of the model's flexibility and adaptability is an interesting step forward in future research.

5 Conclusions

A risk-constrained CA model has been developed to better inform the planning of sustainable urban development. Instead of considering only the constraining effect of environmental suitability conditions, the risk-constrained CA model incorporates explicitly the social-ecological risks of urban development. To assess the risks, a three-dimensional framework was proposed that integrates environmental constraints, system resilience, and potential impacts. This framework was further developed into a quantitative indicator system specifically for demonstration in a case study of Sheyang County, Jiangsu Province of China.

Our comparative simulations of Sheyang's urban development from 2015–2022 indicate that considering only environmental suitability conditions in the constrained CA model is inadequate. It fails to take into account system resilience and potential impacts, and also neglects the social aspect of sustainability. Consequently, traditional environmental suitability constrained CA models tend to overestimate urban development potential. Our case study further suggests that, along with urbanization, regional urbanization mode is likely to shift from expansion of larger cities to development of smaller cities and towns. Besides, our study illustrates that for sustainable urban development, Sheyang should better follow a bicentric urbanization pattern, prioritizing urban development around Sheyang downtown and the Huashagang town center. It is also urged that authorities of urban planning and land use management develop a coherent and consistent strategy for implementing the plans for sustainable urban development.

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