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# Should big cities grow? Scenario-based Cellular Automata urban growth modeling and policy application

ChengHe Guan* and Peter G. Rowe

*Department of Urban Planning and Design, Graduate School of Design, Harvard University, 48 Quincy Street, Cambridge, MA 02138, USA*

*** Corresponding author email: cguan@gsd.harvard.edu**

**Abstract**

The formation of 'Urban networks' has become a wide-spread phenomenon around the world. In the study of metropolitan regions, there are competing or diverging views about management and control of environmental and land-use factors as well as about scales and arrangements of settlements. Especially in China, these matters alongside of regulatory aspects, infrastructure applications, and resource allocations, are important due to population concentrations and the overlapping of urban areas with other land resources. On the other hand, the increasing sophistication of models operating on iterative computational power and widely-available spatial information and analytical techniques make it possible to simulate and investigate the spatial distribution of urban territories at a regional scale.

This research applies a scenario-based Cellular Automata model to a case study of the Changjiang Delta Region, which produces useful and predictive scenario-based projections within the region, using quantitative methods and baseline conditions that address issues of regional urban development. The contribution of the research includes the improvement of computer simulation of urban growth, the application of urban form and other indices to evaluate complex urban conditions, and a heightened understanding of the performance of an urban network in the Changjiang Delta Region composed of big, medium, and small-sized cities and towns.

Keywords: Scenario-based Cellular Automata; Urban growth modeling; Environmental suitability; Big cities; the Changjiang Delta Region

## 1. Metropolitan regional management and controls

In both the study and management of metropolitan regions there are competing and different views about the influence of environmental, economic and cultural factors, particularly with regard to urban settlement and land use. Among these, at least three broad categories emerge and stand out. The first involves regulation, typically of the spread and composition of urbanization within a host environment (Munizzo & Musial, 2010; Spool, 2014). Sometimes this is done with regard to perceptions of rightness of scale, i.e., the encouragement of smaller-scale settlements at the expense of larger ones, for instance. At other times it is pursued with regard to limits on the extent of urban or land-use characteristics, such as buildable area ratios and the like. The second category involves the use of infrastructure as a guiding hand in development. It is well known, for instance, that a doctrine of highest and best use often follows or correlates highly with spatial proximities and accessibilities (Turner et al., 2014; Fischel, 2015). The presence or absence of vital resources, such as water and energy, not to mention flood control and other aspects of natural disaster mitigation, are strongly influential with regard to urban development and such dependencies can be used to guide urban growth and change. A third category concerns balancing resource allocations and scales of development into virtuous arrangements with respect to production, environmental consumption, and socially equitable outcomes (Mills, 1967; Goulias, 2007). This may well involve both regulation and infrastructural guidance, but also fundamentally uses economic and social incentives to achieve results. Here, lending practices and different levels of investment have formed stimulants favoring certain outcomes over others.

## 2. China's regional urban networks with their own exceptional qualities

China's regional urban networks have their own exceptional qualities. The first characteristic is a strong bi-polar distribution of cities and towns. There are over 600 sizable designated cities plus over 20,000 designated towns, roughly split among the population of China. The second quality is city-clusters that are made up of multiple centers, with large and medium-sized cities interacting with and surrounded by smaller communities. For the Changjiang Delta Region, there are two additional qualities: one involves core and peripheral models of development. For example, Hangzhou, the provincial capital city of Zhejiang Province, is a core and Guali, among other smaller towns, is located on the periphery of the broader metropolitan area. The other describes a peri-urban condition, or a Desakota region as observed by McGee et al. (McGee et al., 2007). (**Figure 1**). Within this region several questions emerge regarding regulatory control, infrastructure development, and resource allocation. For instance, should big cities grow bigger/smaller? Should medium-sized cities growth bigger/smaller? And should small cities grow bigger/smaller? To address these questions, the Changjiang Delta Region, one of the most developed urban networks in China, was selected as a case study.

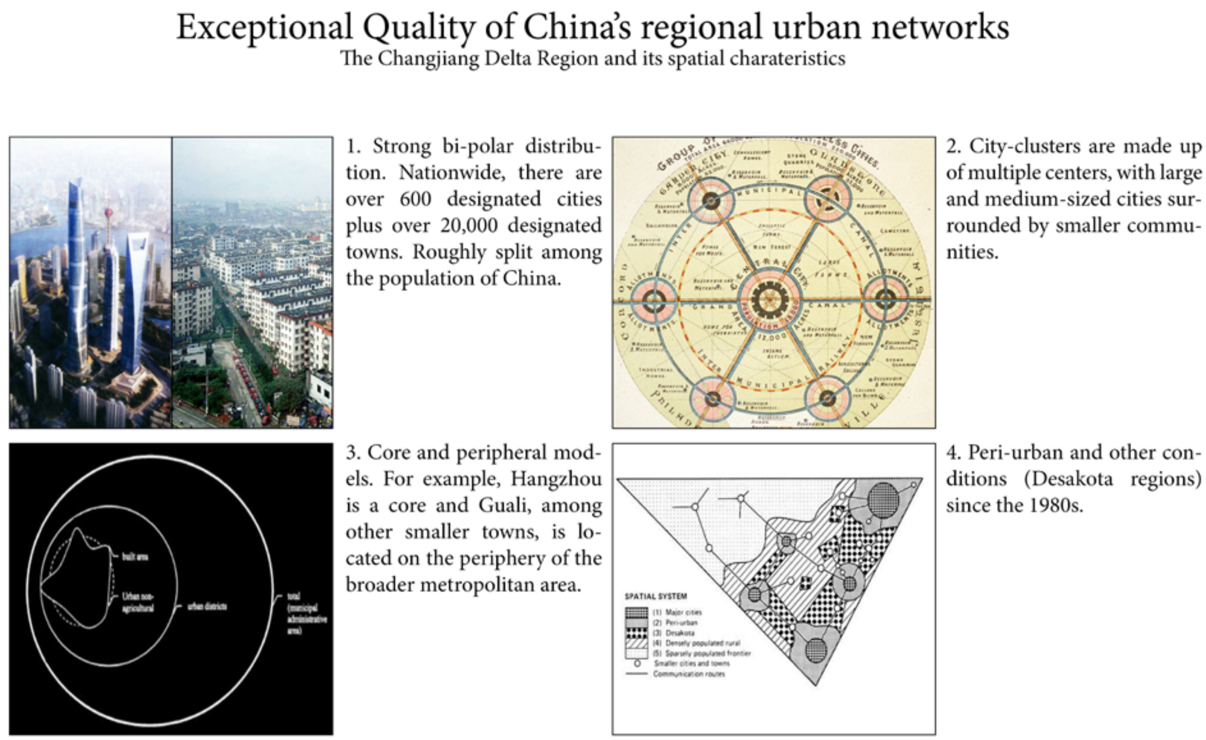


**Figure 1**. Exceptional quality of China's regional urban networks

## 3. The study area

The study area of the Changjiang Delta Region covers an area of 75,900 km2 of territorial land area and 10,200 km2 of water bodies. It includes 16 regional-level cities, 28 county-level cities, and some 1,700 towns. The total population was about 65 million in 2010. The average annual precipitation is between 1,000 and 1,500 mm, and the average annual temperature is between 14 to 17 degrees Celsius. The region is composed of an alluvial flat land located in a transitional zone between the Changjiang and the East China Sea. The study boundary was drawn to include 62 regional level cities and counties from three provinces, Jiangsu, Zhejiang, and Anhui, and one municipality, Shanghai. Additionally, there were no large cities within a buffer zone of 100 km beyond the study area. This helps to rule out the possibility of other significant influences on the internal structure of the urban network.

**Figure 2** shows the administrative boundary of the entire study area with 62 cities and towns[1]. The rectangular outline is the boundary of the study area for urban growth modeling. If partial territory of the cities and towns was situated outside of the boundary outline, then the growth model was adjusted to take account the prorated portion of growth. Population and other measures were counted as if whole cities and towns were located within the outline. The outline was also established to take into consideration economic and environmental conditions of the region.

[1] Zhoushan was removed from the study area because of its island condition, separating the city from the rest of the region with only ferry connections. Shexian and Tonglu were also removed from the study area because their whole administrative boundaries are located outside of the outline boundary. Thus the 65 cities and towns showing in Figure 2 became 62 after removal of Zhoushan.

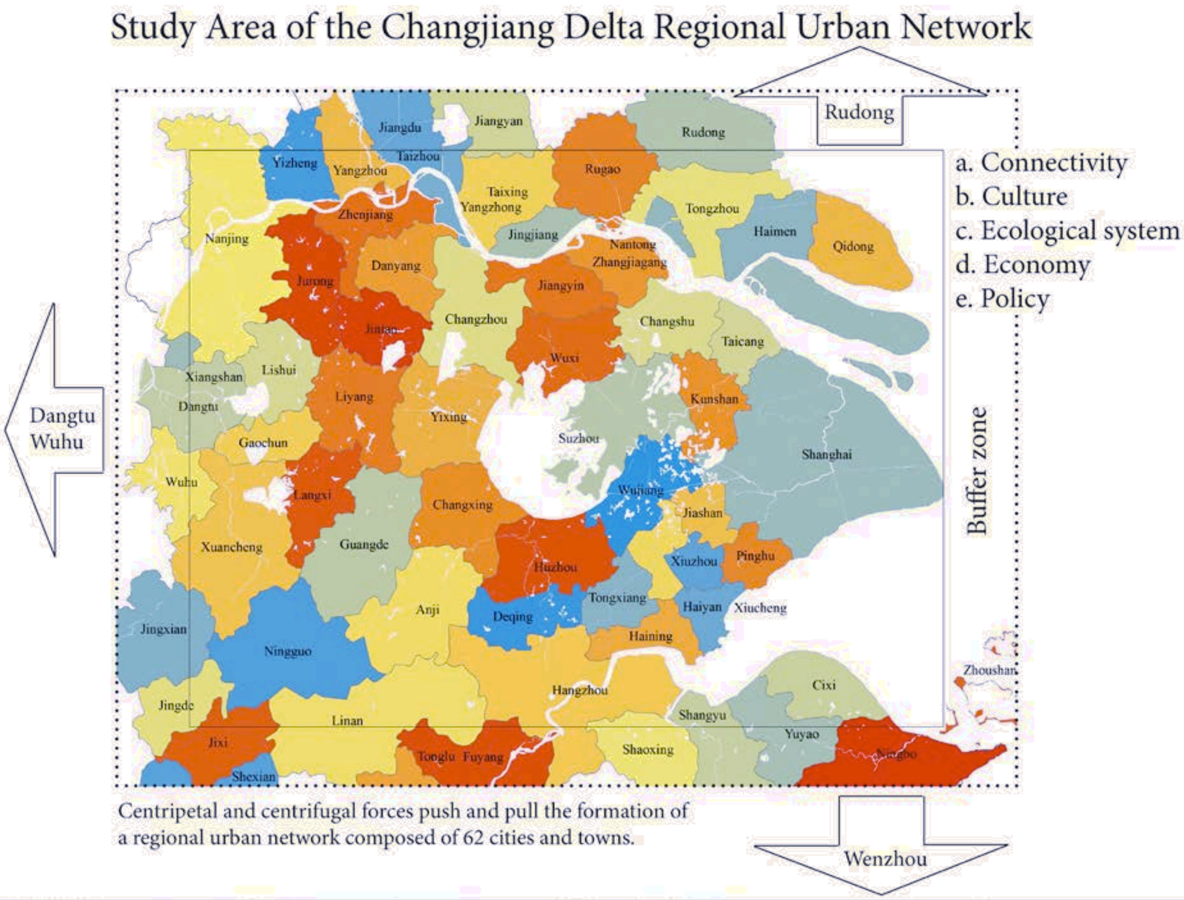


**Figure 2**. The study area of the Changjiang Delta Region including 62 regional level cities and towns.

## 4. Methodology

### *4.1. Cellular Automata*

Cellular Automata (CA) were first devised by John von Neumann and Stanislaw Ulam. The former was an originator of game theory, and pioneer in set theory, quantum mechanics, and the specification of electronic computers (von Neumann, 1966). The latter worked on Monte Carlo simulation and as a part of the Manhattan Project with Edward Teller, and was influential in set theory and number theory in the 1940s as a framework for investigating the logical underpinnings of life. One can say that the 'cellular' comes from Ulam and the 'automata' comes from von Neumann (Rucker, 2003). Simply put, von Neumann and Ulam were interested in exploring whether the self-reproducing features of biological automata could be reduced to purely mathematical formulations, whether the forces governing reproduction could be reduced to logical rules (Sipper 1997).

Even though the principles behind it are not directly related to the social economic factors, CA models can rather accurately reflect the growth patterns that are caused by those factors. In a nutshell, CA mimics the result of an urbanization process through a scientific algorithm. It doesn’t explain the causality of urban growth that is observed but rather simulates it. The association is observable in the calibration process. CA provide a way of examining the forward projection of alternatives. Further, sensitivity studies of policies using ‘difference in difference’ methodologies provide CA models broader application in the field of urban planning and design (Liu, 2009). In short, of the alternative approaches, including Lowry and agent-based models, the use of CA appears to be the most appropriate for this investigation. It requires relatively few assumptions, generates results in an incremental measure allowing concentrated localized analysis and is responsive to baseline conditions of both large- and small-scaled settlement (Clarke et al., 1997; Guan and Rowe, 2016; Li and Yeh, 2002; Wu and Webster, 1998 and 2000).

*4.2. Scenarios of potential developments*

Modeling of potential future urban settlement patterns in the Changjiang Delta Region was taken up under specific scenarios. Four scenarios were proposed and each of these scenarios prescribed a basic trajectory of development with unique features. Also, all represented plausible development trends towards favorable outcomes of development with regard to land cover, scale variety, and association with particular places and settings. They were: ‘development corridors’, ‘development corridors, plus big city growth’, ‘environmental system concerns, plus development corridors’, and ‘disaster prevention, plus development corridors’. The reason why ‘development corridors’ were selected for all four scenarios was that they are already in place via the high-speed rail and highway network and will continue to be one of the most influential factors of urban and regional growth of Changjiang Delta region for the foreseeable future, see **Figure 3.**

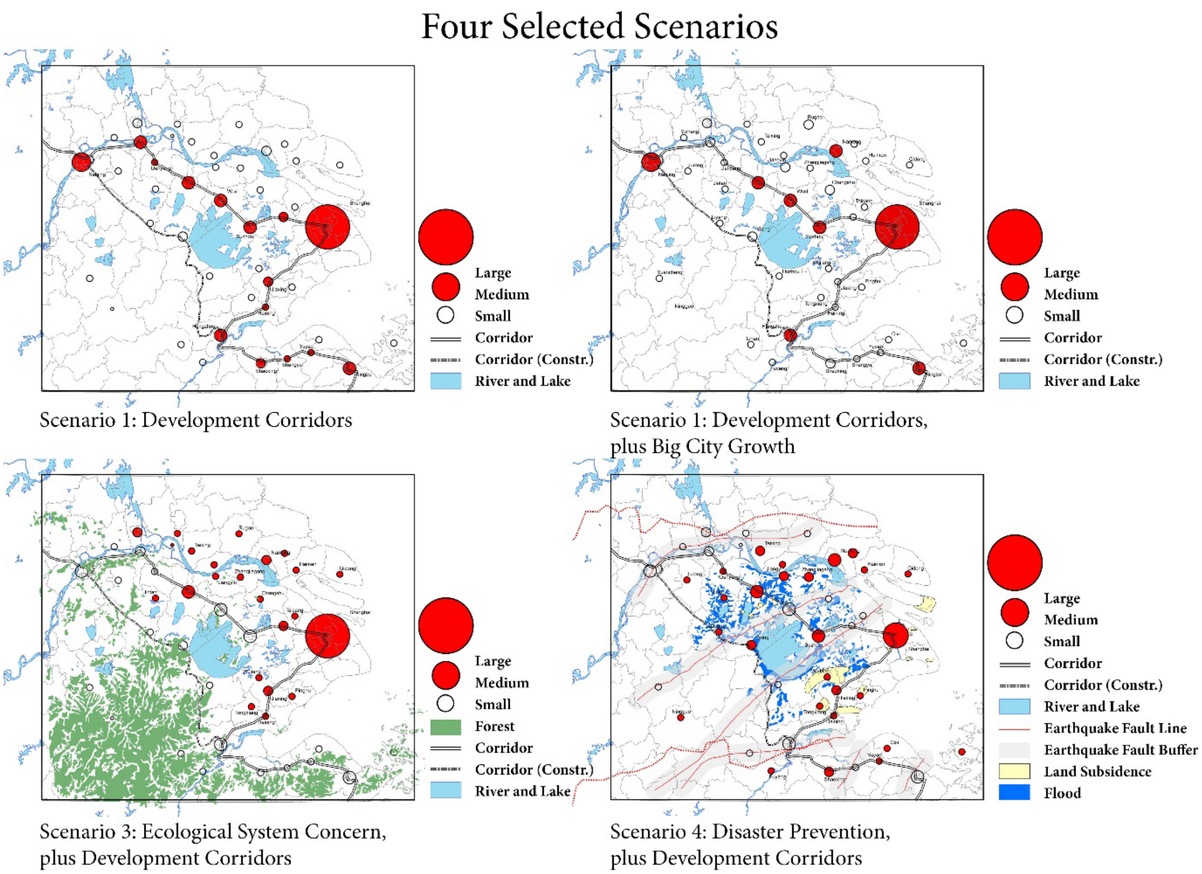


**Figure 3**. Scenario 1: development corridors. Scenario 2: development corridors, plus big city growth. Scenario 3: ecological system concerns, plus development corridors. Scenario 4: disaster prevention, plus development corridors.

*4.3. Scenario-based CA modeling algorithm*

Scenario-based modeling was developed based on the algorithm of a CA model called SLEUTH model and using scripts from the model with additional variables that guide and control the growth pattern[2]. The modification of parameters did not change how the principles of the CA model operated. However, they did provide opportunities to reflect the influences of certain urban policies on the outcome of the urban land growth patterns predictions. In each of the four scenarios, a new variable was added to the existing application of the SLEUTH model. The added applications are written in C programming language. The original SLEUTH scripts were modified using Sublime Text version 3.0, a source code editor. Under the directory SCA_code\SLEUTH3.0beta_p01_linux, the C file *main.c* that sets the rules of five iterations was expanded. For example, the *city* coefficient was added with a start, a stop, and a step, **Appendix 1**. The next step is to modify a series of sub-categorical C files that are linked to the *main.c*. For

[2] The Sleuth model was developed by Dr. Keith C. Clarke at UC-Santa Barbara and integrates two sub-models, the Urban Growth Model and the Land Cover Model (Clarke et al, 1997).

example, in the *coeff_obj.c* file, under the set functions, get functions, and logging functions, modifications were made to reflect the updated coefficients. Other files including *input.c*, *output.c*, and *growth.c*. Then the m*akefile* was updated to link and compile all the source files. A single application file *growth* was then made ready to run the model. In the *scenario_obj.c* file, string match *strcmp* function was applied to read/load parameters from the configuration files. The *configuration* file was prepared for users of the model to adjust coefficients without modifying the original scripts. **Table 1** shows how scenario variables are incorporated into the existing rules in the 'coefficients' section. In the scenario file, the 'Log File Preference', the 'Modes and Coefficient Settings', and the 'Input images' sections were modified. The four variables were not participating the Monte Carlo Iterations predictions at their respective scenarios, since the policy tests are focusing on future scenarios. The formulas are shown in **Table 2**.

*a. Development corridor*

As mentioned in the previous sections, development corridors shape the basic spatial economic structure of the Changjiang Delta region. The scenario-based CA model was modified to reflect the impact of the existence of these development corridors. A new variable, ***G-corridor***, was added to the formula.

*b. Development corridors, plus big city growth*

In this model, the big cities enjoy a similar growth opportunity as the development corridors. The growth priority was given to the development corridors if conflicts were to occur between gird cells of the development corridors and the big cities. The scenario-based CA model was modified to reflect the continuing growth of big cities. A new variable, ***G-city***, was created. The big cities category coefficient was used to define the rate of growth of each individual city or city category. This applied to situations when big cities grow with different rates.

*c. Ecological system concerns (e.g. forest protection), plus development corridors*

In this model, representation of ecological systems, i.e., forest protection, obtained priority over development corridors. If conflicts were to occur between the two, the development corridors were reduced to zero, meaning no future growth was allowed. For this variable, forest protection can be replaced by other research concerns, flooding, and arable land, for example, to address other ecological issues. The scenario-based CA model was modified to reflect the ecological system concerns. ***Geco***l, was formed to reflect these concerns.

*d. Disaster prevention, plus development corridors*

In this model, disaster prevention, obtained priority over development corridors. If conflicts were to occur between the two coefficients, the coefficient for the development corridors were reduced to zero, meaning no future growth allowed. The scenario-based CA model was modified to reflect conditions of disaster prevention. A new variable, ***Gdisa***, was added to the formula, thus, the urban growth prediction model became:

The scenario-based CA model expanded the range of variables under consideration in the SLEUTH model. The enriched model can effectively address issues and policy concerns of regional urban development. It also provided a platform to incorporate further policy-specific parameters and rules of urban growth in computer simulation.

**Table 1**. Four selected variables for the scenario-based CA model.

```
# VIII. COEFFICIENTS
#  A. COEFFICIENTS AND GROWTH TYPES
#     GCORRIDOR: affects number of ROAD INFLUENCED GROWTH attempts and
#                search distance along the road network.
#     GCITY: affects the probability of ORGANIC GROWTH from established
#            urban pixels occurring.
#     GECOL: affects SPONTANEOUS GROWTH and NEW SPREADING CENTER
#            probability and number of ROAD INFLUENCED GROWTH attempts and
#            the probability of ORGANIC GROWTH from existing
#            ecological system pixels occurring.
#     GDISA: affects SPONTANEOUS GROWTH and NEW SPREADING CENTER
#            probability and number of ROAD INFLUENCED GROWTH attempts and
#            the probability of ORGANIC GROWTH from existing disaster
#            prevention system pixels occurring.
```

**Table 2**. Urban growth prediction model.

$$(\boldsymbol{a})\ \boldsymbol{G}_{\boldsymbol{total}}^{\boldsymbol{t+1}} = \sum \boldsymbol{G}_{\boldsymbol{spontaneous}(i,j)}^{\boldsymbol{t+1}} + \boldsymbol{G}_{\boldsymbol{spread}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}} + \boldsymbol{G}_{\boldsymbol{edge}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}} + \boldsymbol{G}_{\boldsymbol{road}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}} + \boldsymbol{G}_{\boldsymbol{corridor}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}}$$

$$(\boldsymbol{b})\ \boldsymbol{G}_{\boldsymbol{total}}^{\boldsymbol{t+1}} = \sum \boldsymbol{G}_{\boldsymbol{spontaneous}(i,j)}^{\boldsymbol{t+1}} + \boldsymbol{G}_{\boldsymbol{spread}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}} + \boldsymbol{G}_{\boldsymbol{edge}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}} + \boldsymbol{G}_{\boldsymbol{road}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}} + \boldsymbol{G}_{\boldsymbol{corridor}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}} + \boldsymbol{G}_{\boldsymbol{city}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}}$$

$$(\boldsymbol{c})\ \boldsymbol{G}_{\boldsymbol{total}}^{\boldsymbol{t+1}} = \sum \boldsymbol{G}_{\boldsymbol{spontaneous}(i,j)}^{\boldsymbol{t+1}} + \boldsymbol{G}_{\boldsymbol{spread}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}} + \boldsymbol{G}_{\boldsymbol{edge}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}} + \boldsymbol{G}_{\boldsymbol{road}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}} + \boldsymbol{G}_{\boldsymbol{corridor}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}} + \boldsymbol{G}_{\boldsymbol{ecological}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}}$$

$$(\boldsymbol{d})\ \boldsymbol{G}_{\boldsymbol{total}}^{\boldsymbol{t+1}} = \sum \boldsymbol{G}_{\boldsymbol{spontaneous}(i,j)}^{\boldsymbol{t+1}} + \boldsymbol{G}_{\boldsymbol{spread}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}} + \boldsymbol{G}_{\boldsymbol{edge}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}} + \boldsymbol{G}_{\boldsymbol{road}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}} + \boldsymbol{G}_{\boldsymbol{corridor}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}} + \boldsymbol{G}_{\boldsymbol{disaster}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}}$$

Where,

$\boldsymbol{G}_{\boldsymbol{total}}^{\boldsymbol{t+1}}$ =Total urban growth prediction, at year t+1
$\boldsymbol{G}_{\boldsymbol{spontaneous}(i,j)}^{\boldsymbol{t+1}}$ = Spontaneous growth, the occurrence of random urbanization of land, at year t+1
$\boldsymbol{G}_{\boldsymbol{spread}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}}$ = Spread growth, the urban spreading of newly urbanized land cell, at year t+1 (pay attention that this excluded the spread growth of existing urbanized land cell)
$\boldsymbol{G}_{\boldsymbol{edge}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}}$ = Edge growth, the further expansion of newly spread urbanized cell, at year t+1
$\boldsymbol{G}_{\boldsymbol{road}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}}$ = Road influenced growth, at year t+1
$\boldsymbol{G}_{\boldsymbol{corridor}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}}$ = Development corridor growth, at year t+1
$\boldsymbol{G}_{\boldsymbol{city}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}}$ = Big cities growth, at year t+1
$\boldsymbol{G}_{\boldsymbol{ecological}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}}$ = Ecological system concerns, at year t+1
$\boldsymbol{G}_{\boldsymbol{disaster}(\boldsymbol{i},\boldsymbol{j})}^{\boldsymbol{t+1}}$ = Disaster preventions growth, at year t+1

*4.4. Baseline: environmental suitability*

The purpose of this exercise was to find suitable areas for urban development and to identify areas that are most vulnerable due to human interference. It involved identifying criteria that define environmental suitability. Previous studies ranged in degree of computational and analytical sophistication included pass/fail screening, weighted factors, penalty point assignment, and composite rating (Banai-Kashani, 1989). More recent studies, built on earlier methods, included the weighted linear combination (WLC) method and the analytic hierarchy process (AHP) (Moeinaddini et al., 2010; Wang et al., 2009). The former accommodated more parameters and the latter dealt with both intangible and tangible factors, however, it required a limited number of factors.

In this research, a combined approach of WLC and AHP was employed. It was a multi-criteria evaluation and decision making process. First, the criteria were selected for this research, including landslides, earthquake, floods, sea-level rise, slope of land, land cover and resources, land subsidence, proximity to drinking water resources, and view shed. Using the WLC method, the criteria were mapped and georeferenced to ArcGIS and converted to raster files. The trade-off among criteria considered the level of correlation that existed in a set of selections. If two variables were highly correlated with each other, for example, sea-level rise and distance to the ocean, one of them was dropped, or both were given a reduced weight. The AHP method was deployed here to specifying the hierarchical structure, identifying the sub-criteria, and assigning weights of each variables. During this process, it was critical to recognize what were more important than others. Assuming criteria were equally important then the weighting should all be 1.0. However, such an outcome depends on the influence of each criterion. Some were always given more weight than others. The weighting was realized by 'weighted overlay' in ArcGIS. The next step was to combine the weighted datasets, for both quantitative and qualitative criteria. A normalization process was applied to summarize all criteria to one single index. The equation was listed as follow.

$$ES = \sum_{i=1}^{n} f(xi * wi)$$

Where,
*ES* is the environmental suitability index
*f* is a normalization function
*Xi* is the criterion selected
*Wi* is the weighting for each criterion
*n* is the total number of criteria

## 5. Results

### *5.1. Baseline - Environmental suitability*

What mattered most, in this research, was to identify the areas that were most unsuitable, or even hazardous, for urban development. The result of the environmental suitability study is shown in **Figure 4**. It included an overlay of urban development in the region as of 2010. Basically, the least suitable areas are colored in red. The more encroachment of urban development in those areas, the less sensibly the scenario concerned environmental issues. A quick visual inspection revealed that the coastal lines, areas around Lai Tai, and the southwestern mountainous region were clustered as environmentally sensitive areas deemed not suitable for urban development. The image was modeled after data acquired from the Ministry of Housing and Urban-Rural Development with adjustment on regional boundary and variable selections (Ministry of Housing and Urban-Rural Development, 2010, 2011 and 2012). Other method of suitability study was based on per capita (Kim, 2012), whereas in this research, the unit was per land parcel. The advantage of using land-based method is to provide compatible baseline results to benchmark and evaluate the simulation results of the scenario-based CA model.

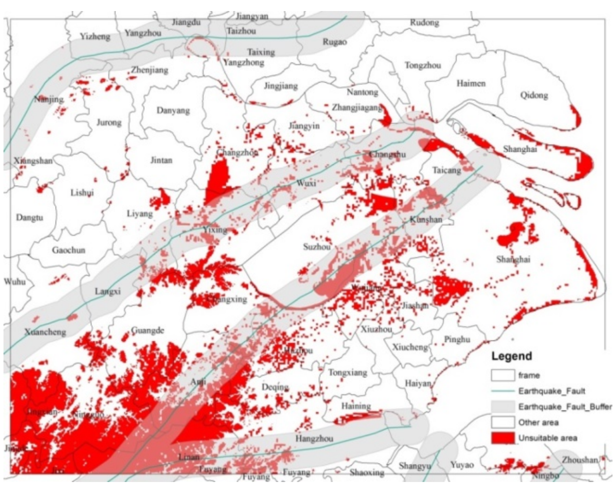


**Figure 4**. Environmentally unsuitable area for urban development in the Changjiang Delta Region, 2010.

### *5.2. Baseline - Environmental suitability vs. Scenario 2: development corridors, plus big city growth.*

The results from the scenario-based CA model predictions of annual growth and environmentally unsuitable development maps are shown in **Figure 5**. The black cells are the urbanized land, the red cells are where unsuitable growth occurred, the green cells are the protected forest and the blue cells are water.

The results were summarized in **Table 3**. The number of grid cells in urbanized area was first counted by year from 2011 to 2030. Then the number of grid cells in suitable areas was deducted from the urbanized area for each year. The results were the number of cells in unsuitable areas for the model prediction duration, listed in column ‘Number of cells in unsuitable area’. These numbers were then divided by the total number of grid cells of the entire study region, again as before. The results are shown in column ‘Urbanization rate based on land area’.

One of the outcomes is the ‘percentage of urban development in unsuitable area’, which revealed a decreasing trend of urban development in unsuitable areas. Basically, if urban growth were constrained to the development corridors and to big cities, the rate of urbanization in environmentally sensitive areas would drop from 10.42% in 2011 to 10.02% in 2030. By emphasizing urban growth in the development corridors and big cities, again the outcome of urbanization patterns also started to evolve in a more environmentally sensitive direction. By way of explanation, first, the rate of growth in environmentally suitable areas was higher than in unsuitable areas. Second, the current development corridors and big cities were in areas distant from the major environmental protection zones. Third, the big cities provided higher urban intensity and grew in a more efficient or confined urban form that reduced infringement on environmentally sensitive areas. However, from 2011 to 2016, there is a gradual increase in the annual growth rate of unsuitable urban development, although from 2016 the rate slowed down until 2030 (**Figure 6**). A relatively environmentally-sensitive policy, despite the long term positive impact, could still yield some short term advantages. This can be explained by the momentum of current development trends which take some time to readapt to new development policies.

Local policies which protect environmentally-sensitive areas within the development corridors and big cities areas are critical to create an environmentally responsible urban form in the region. An area, the east shore of Lake Tai area, was used to provide further detailed comparison between 2011 and 2030 (**Figure 7**). Again, the black cells represent urbanized areas and the red cells represent where environmentally unsuitable development occurred. In these images, there are two major urban settlements: Wuxi to the upper left and Suzhou to the lower right. Visual inspection reveals two clusters of red grid cells appearing both to the north and south of Suzhou. Around Wuxi, there was some sporadic growth of red cells as well. These detailed outcomes also provide spatial evidence as to where unsuitable growth occurred.

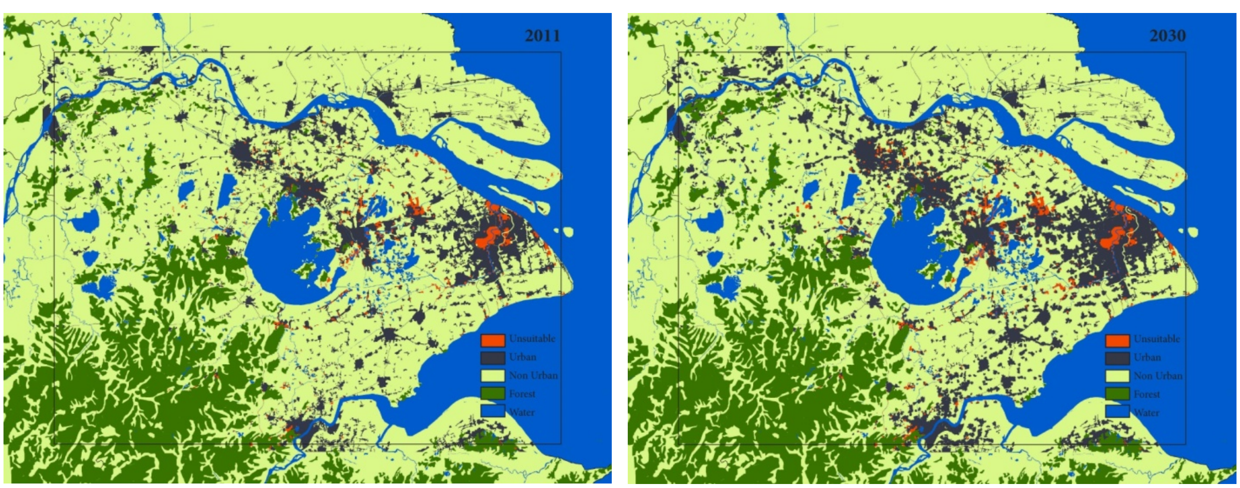


**Figure 5**. Scenario-based CA model predicted urban growth map with buffer zone around study area, 2010 (upper) and 2030 (lower), baseline1: ‘environmental suitability’ vs. scenario 2: ‘development corridors, plus big city growth’.

**Table 3**. Environmental suitability and development corridors, plus big city growth.

| | Scenario 2: Big Cities Grow Bigger + Development Corridors | | | | | |
|---|---|---|---|---|---|---|
| Year | Number of Cells in Unsuitable Urban Area | Number of Cells in Suitable Urban Area | Number of Cells in Urbanized Area | Urbanization Rate based on Land Area | Percentage of Growth in Unsuitable Urban Area | Year to Year Growth Rate of Unsuitable Urban Area |
| 2011 | 103,918 | 893,629 | 997,547 | 15.341% | 10.417% | - |
| 2012 | 106,986 | 924,154 | 1,031,140 | 15.857% | 10.376% | 2.952% |
| 2013 | 110,260 | 956,655 | 1,066,915 | 16.408% | 10.334% | 3.060% |
| 2014 | 113,677 | 990,337 | 1,104,014 | 16.978% | 10.297% | 3.099% |
| 2015 | 117,190 | 1,024,512 | 1,141,702 | 17.558% | 10.264% | 3.090% |
| 2016 | 120,892 | 1,059,288 | 1,180,180 | 18.149% | 10.244% | 3.159% |
| 2017 | 124,577 | 1,093,890 | 1,218,467 | 18.738% | 10.224% | 3.048% |
| 2018 | 128,322 | 1,128,776 | 1,257,098 | 19.332% | 10.208% | 3.006% |
| 2019 | 131,863 | 1,163,494 | 1,295,357 | 19.921% | 10.180% | 2.759% |
| 2020 | 135,487 | 1,197,872 | 1,333,359 | 20.505% | 10.161% | 2.748% |
| 2021 | 139,129 | 1,232,131 | 1,371,260 | 21.088% | 10.146% | 2.688% |
| 2022 | 142,731 | 1,266,193 | 1,408,924 | 21.667% | 10.130% | 2.589% |
| 2023 | 146,217 | 1,299,981 | 1,446,198 | 22.240% | 10.110% | 2.442% |
| 2024 | 149,748 | 1,333,346 | 1,483,094 | 22.808% | 10.097% | 2.415% |
| 2025 | 153,243 | 1,366,830 | 1,520,073 | 23.377% | 10.081% | 2.334% |
| 2026 | 156,705 | 1,399,747 | 1,556,452 | 23.936% | 10.068% | 2.259% |
| 2027 | 160,071 | 1,432,513 | 1,592,584 | 24.492% | 10.051% | 2.148% |
| 2028 | 163,454 | 1,465,086 | 1,628,540 | 25.045% | 10.037% | 2.113% |
| 2029 | 166,848 | 1,497,176 | 1,664,024 | 25.590% | 10.027% | 2.076% |
| 2030 | 170,184 | 1,528,877 | 1,699,061 | 26.129% | 10.016% | 1.999% |

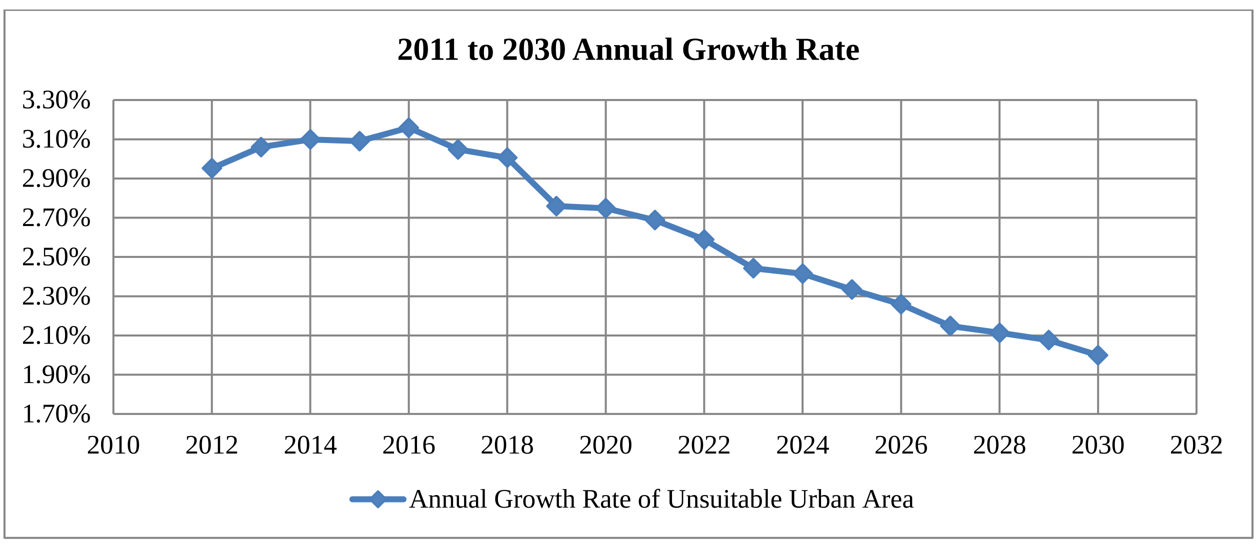


**Figure 6**. Annual growth rate of unsuitable urban development, 2011 to 2030, baseline1: 'environmental suitability' vs. scenario 2: 'development corridors, plus big city growth'.

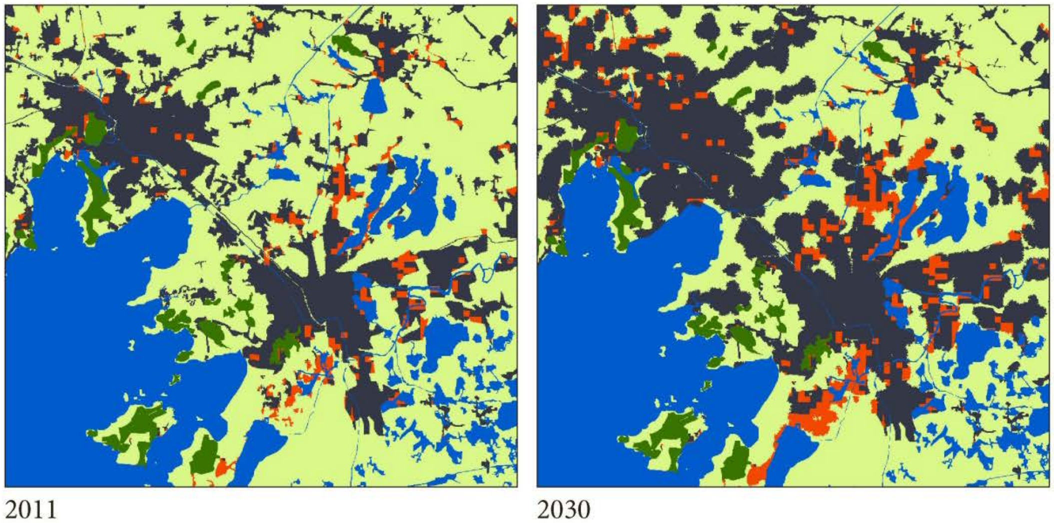


**Figure 7**. Environmental unsuitable area urban development, partial area comparison between 2011 and 2030, baseline1: 'environmental suitability' vs. scenario 2: 'development corridors, plus big city growth'.

## 6. Discussions

### *6.1. Should big cities grow bigger?*

It is important to interpret each individual scenario by comparing them together. The annual growth rate figures are reproduced here for all four scenarios. Notice that the y-axis of each figure is now set to the same numbers with a minimum of 0.8% and a maximum of 3.3%. In **Figure 8** baseline 1: 'environmental suitability' vs. scenario 1: 'development corridors', the peak in 2022 disappeared and the graph exhibited a relatively smooth tendency throughout the study years until 2030. The bumps in baseline 1: 'environmental suitability' vs. scenario 3: 'ecological system concerns, plus development corridors' and baseline 1: 'environmental suitability' vs. scenario 4: 'disaster prevention, plus development corridors' were also alleviated to a degree that no significant cycles of ups and downs existed. It's worth mentioning that in baseline 1 'environmental suitability' vs. scenario 2 'development corridors, plus big city growth', the high rate of annual growth rate of urbanization in unsuitable urban areas became more evident compared with the other three scenarios. From the starting year of 2012 on 2011, the growth rate was always the highest among the four scenarios. Even though the declining trend after 2016, the lowest number of 2030 on 2029 is still larger than any other years of all other scenarios.

Based on the above analysis, a conclusion can be made: Further growth of big cities in the Changjiang Delta Region is not an environmentally responsive policy. Even though big cities have been of some service in terms of environmental resource consumption per capita so far, further expansion could bring more harmful consequences than before. It reinforced the results and advocacies by other scholars who found that while environmental resource consumption per capita was less in big cities than smaller settlements, the reverse held in sheer area of consumption (Rowe, 2011; Kim & Rowe, 2012). However, how much bigger should big cities grow in areas and enjoy the favorable policies they have enjoyed so far since China's opening up in the early 1980s? To answer the question, we need to consider the density of urban growth. The scenario-based CA model, not unlike Lowry and other models, assumes the same density for all newly urbanized land parcels. For example, one urbanized parcel in Shanghai functions equally as one parcel in Suzhou in terms of population increase absorption. In reality, the parcel in Shanghai could take in more people with higher density. The assumption of equal density could undermine the ability of the parcel in Shanghai to accommodate more people per square kilometer. On the other hand, the land use policy in large cities of the Changjiang Delta region restricts the residential land development to an average Floor Area Ratio of two or less, while in many mid- to small-sized cities in the same region, the average Floor Area Ratio was set to three (Interview with local government officials in Fengxian District and Tianfu New District, 2016). If this discrepancy of different Floor Area Ratio between different-sized cities continues to exist, then the large cities may lose their advantage of being much denser in the newly urbanized area. To sum up, the urban growth, the local land-use policy, and the actual population increase, all play a role in deciding how much bigger big cities should grow. To make an argument, for scenario 4, 'disaster prevention, plus development corridors', Suzhou grew 21.59 percent bigger in 2030 than in 2010. Parenthetically, the total allocations of hypothetical population among the four scenarios at a rate of 9,000 people per square kilometer, an average for city-wide density, is on the order of 15 to 45 million more inhabitants and a median of around 23 million more inhabitants, or about 90 million total for the study area.

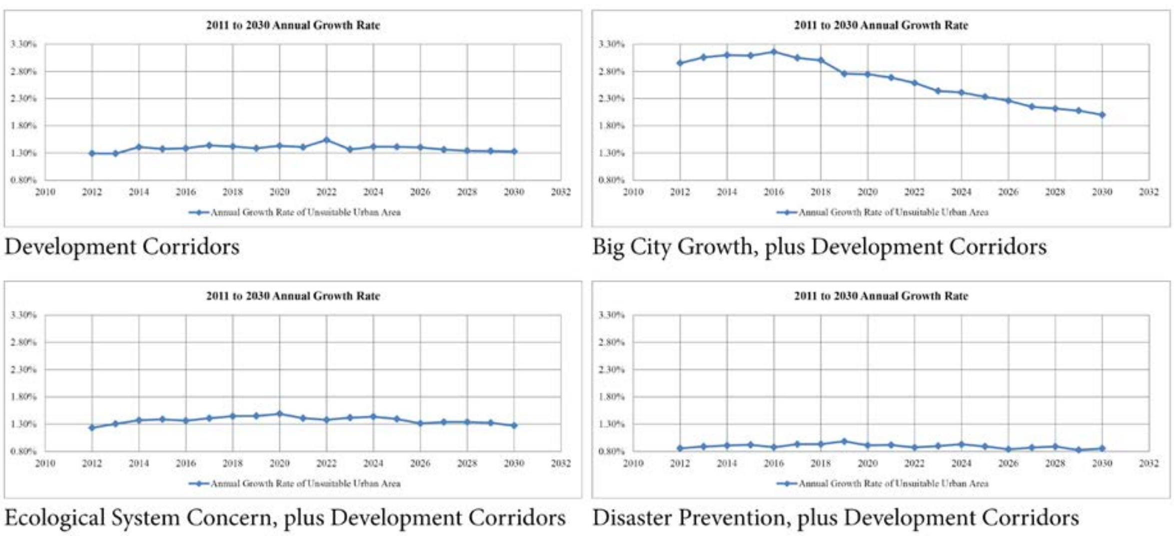


**Figure 8**. Annual growth rate of unsuitable urban area, baseline 1: 'environmental suitability' vs. four selected scenarios.

*6.2. What's the merit of disaster prevention?*

Among the four selected scenarios, scenario 4 'disaster prevention, plus development corridors' came out with the lowest growth rate, lower than one percent consistently throughout the years. One of the explanations is the disaster prevention restricting growth areas cover a large portion of the Changjiang Delta Region. Thus, the scenario provided less urban growth opportunity than the other three scenarios. The result of future urban growth prediction was also the slowest and had the least newly urbanized land parcels among four selected scenarios. To take a closer look at the disaster prevention restricted areas, many of them overlapped with environmental sensitive regions along the coastlines, scenic areas around Lake Tai, and other environmentally unsuitable areas. This further explained the low rate of annual growth rate of unsuitable urban area.

In general, human settlements in close proximity to disaster prone areas often lead to tragedy and even catastrophic events with severe consequences, as stated earlier. The rescue, restoration, and relocation consume disproportionally high socioeconomic resources. The aftermath can also bring long term disabilities and diseases to the affected population. If simply following the disaster prevention, plus development corridors urban growth policy can produce an urban form that optimizes the environmental resource conservation and prevents urban development from encroaching into environmentally unsuitable areas, then it seems to be a reasonable plan to be pursued in regional urban growth policy making. Given the severe repercussions of not following such a policy, it may also be the easiest scenario to implement under simple application of public health and safety principles.

## 7. Contributions and Applications

### *7.1. Scenario-based CA model and its applications*

Compared with the Lowry model, the scenario-based CA model didn't project rapid growth along the Nanjing-Hangzhou corridor. The Lowry model singled out areas along this corridor by prohibiting urban growth in the rest of the region. However, the scenario-based CA model took into consideration of urban growth in all development corridors simultaneously without discriminating one over the others. Thus, the result of the scenario-based CA model seems to more closely simulate realities. First, the creation of large cities along development corridors is very unlikely to happen, nowadays. The high-speed rail from Nanjing to Hangzhou was put in place for better connections not for stops in between. Second, yearly consecutive prediction allows profiles of performance to be assessed over time. Third, the scenario-based CA can also be used among reasonably wide applications to test urban policy on future growth patterns at regional, as well as urban scales with close monitoring of single or multiple variables.

Where the efficiency of the scenario-based CA model is concerned, a validation process is necessary. Previous studies have applied real data to validate proposed CA modeling system (Tsiftsis et al., 2016). In this research, an *a posteriori* approach was applied to the model validation. Basically, empirical evidences from 1980 to 2010 were collected to compare with the calibration outcomes of the scenario-based CA model. Then a thorough comparison was carried out using the real conditions of 1980, 1990, 2000, and 2010 as benchmarks. For either under-prediction and over-prediction, the calibration processes was set to re-adjust the forecast of coefficients and to repeat the procedure until the criterion of less than five percentage errors/mismatch was satisfied. The validation process was divided into coarse calibration, fine calibration, and final calibration, each with an increasing number of Monte Carlo Iterations. The Lee-Sallee Metric was used to evaluate the fit of the model, sorting out the results of Monte Carlo Iterations. The calibrated model enhanced the validity of the growth modeling prediction.

### *7.2. The urbanization rate of land consumption is relevant*

Conventionally, urbanization rates of population are used to describe the urban conditions of nations. It has become an international standard to make comparison among regions and countries. The United Nations World Urbanization Prospects, for example, is one of the commonly referred sources of rankings for urbanization of population. The advantages of such a measure include: first, population, by treating people as commodities, is universal. It is unlike 'household' or any other unit, which may vary by culture and ethnicity. Second, through census collection that occurs regularly in many country and sub-country level entities, the available data are relatively reliable. However, the limitation of using population to evaluate urbanization discounts the urbanized land itself, which provides most of the resources supporting urbanization. The advantages of evaluating urbanization rate using land resources include: first, flexibility. The size of land parcels can be large or small, depending on the research goal and methodology applied. Second is consistency. The administrative boundaries may vary by size, but the land parcel can be divided to equal sized rectangular shapes for accounting purposes. Third, and maybe the most important, is 'spatiality'. Unlike the urbanization rate of population, which is largely constrained to the administrative boundaries, the urbanization rate of land consumption can be measured to the size of specific land parcels and reveal the spatial distribution at a much finer scale. Parameters that could relate to urbanization rate of land resources include but are not limited to Gross Domestic Product, road length, and other infrastructure.

### *7.3. Data became widely available and analytical techniques improved*

As the computer calculating capacity increases astronomically and the development of remote-sensing technique evolves, accompanied by enhanced satellite image resolutions, the study on land-use change and spatial distribution can and will become more sophisticated. Yamaguchi, Chen, Seto, among other scholars, have taken these opportunities to advance the research in the relevant field (Chen, et al., 2012; Srinivasan, et al, 2012). 'Big data', as the growth of and digitalization of global information storage capacity increases exponentially, the volume, velocity, and variety of information assets enable enhanced decision making (Beyer, 2011). The application of big data in regional urban study and urban growth prediction allow the study of entire sets of data, i.e. a collection of people, items, or events about which to make inferences, instead of sampling a subset. In this research, the 350 kilometer, east to west, by 250 kilometer, north to south, study area of the Changjiang Delta Region was divided into 8,750,000 100 meter by 100 meter land parcels. The factors behind environmental suitability were then distributed to these over eight million data points, covering the entirety of the study area, without sampling.

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**Appendix** 1: Scenario-based CA modeling algorithm using the SLEUTH scripts.

```
proc_SetStopYear (igrid_GetUrbanYear (igrid_GetUrbanCount () - 1));

for (diffusion_coeff = coeff_GetStartDiffusion ();
        diffusion_coeff <= coeff_GetStopDiffusion ();
        diffusion_coeff += coeff_GetStepDiffusion ())
    {
     for (breed_coeff = coeff_GetStartBreed ();
          breed_coeff <= coeff_GetStopBreed ();
          breed_coeff += coeff_GetStepBreed ())
      {
       for (spread_coeff = coeff_GetStartSpread ();
            spread_coeff <= coeff_GetStopSpread ();
            spread_coeff += coeff_GetStepSpread ())
        {
         for (slope_resistance = coeff_GetStartSlopeResist ();
              slope_resistance <= coeff_GetStopSlopeResist ();
              slope_resistance += coeff_GetStepSlopeResist ())
          {
           for (road_gravity = coeff_GetStartRoadGravity ();
                road_gravity <= coeff_GetStopRoadGravity ();
                road_gravity += coeff_GetStepRoadGravity ())
            {
             for (city_coeff = coeff_GetStartCity ();
                  city_coeff <= coeff_GetStopCity ();
                  city_coeff +> coeff_GetStepCity ())

             sprintf (fname, "%s%s%u", scen_GetOutputDir (),
                      RESTART_FILE, glb_mype);
             out_write_restart_data (fname,
                                     diffusion_coeff,
                                     breed_coeff,
                                     spread_coeff,
                                     slope_resistance,
                                     road_gravity,
                                     scen_GetRandomSeed (),
                                     restart_run);

             InitRandom (scen_GetRandomSeed ());

             restart_run++;

             coeff_SetCurrentDiffusion ((double) diffusion_coeff);
             coeff_SetCurrentSpread ((double) spread_coeff);
             coeff_SetCurrentBreed ((double) breed_coeff);
             coeff_SetCurrentSlopeResist ((double) slope_resistance);
             coeff_SetCurrentRoadGravity ((double) road_gravity);
```