SELF-ORGANIZING CRITICALITY AMONG CHINESE CITIES

A Dissertation

by

SHUJUAN LI

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2009

Major Subject: Geography

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Approved by:

Chair of Committee,	Daniel Sui
Committee Members,	Hongxing Liu
	Robert Bednarz
	Michael Lindell
Head of Department,	Douglas Sherman

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ABSTRACT

Self-organizing Criticality among Chinese Cities. (May 2009)

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This dissertation employs the theory of self-organizing criticality (SOC) into the study of Chinese cities. SOC was proposed at the end of the 1980s to explain system complexity by combining both self-organizing and critical behaviors. SOC has been broadly used in explaining phenomena in physical and social sciences. However, few attempts have been made to connect urban studies with SOC because of the extreme complexity of urban phenomena. This study develops a generalized SOC to study Chinese cities at both the inter-urban and the intra-urban levels.

At the inter-urban level, this study finds that the rank size distribution of Chinese cities has followed Zipf's law since 1984. In addition, the rank size dynamics of Chinese cities experienced a spatiotemporal shift. Before 1996, city rank increases in a few small- and middle-sized cities because of favorable economic policies offered by the central government. After 1996, a majority of the Chinese cities began to be involved in this rank size shuffling. Cities with increasing ranks present clustered distribution, mainly along the south and east coastal areas. Part of the reason is that the market economy mechanism has transcended policy factors in determining the city competitiveness.

At the intra-urban level, the study shows that Shenzhen’s urban physical development is currently facing physical environmental thresholds, shifting the development strategies spatiotemporally from fringe and isolated growth to fringe and infill growth. The resulted urban patches show power law relationship both in the area-perimeter distributions and the magnitude-frequency distributions.

In summary, this research proves the applicability of the generalized SOC in urban studies. At both the inter-urban and the intra-urban levels, the Chinese cities present the characteristics of SOC. Given a stable condition of power law, shifts occur in the inside dynamics of China’s urban system and Shenzhen city.

This study is one of the few empirical urban studies based on SOC. The study contributes to the literature on SOC theory and provides theoretical breakthroughs in studying Chinese cities. Finally, this study has potential implications on urban policies and urban development strategies.

DEDICATION

To my parents and my husband

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CHAPTER I

INTRODUCTION

1.1 Research Background

Cities, serving as centers of population, commerce, and culture, are imperative to human history. The process of development in many developing countries is largely the process of urbanization - with increasing numbers of people migrating to cities. The first predominantly urban century at the global level is coming, and it is projected over half of the world population will be in cities by 2010 (Department of Economic and Social Affairs 2004). The accelerating urbanization trend at the global level has renewed interdisciplinary research interests on the economic, social, and environmental impacts of rapid urbanization (Johnson 2001; Squires 2002; Carruthers and Ulfarsson 2003). Despite the voluminous research on urbanization and cities, the underlying processes and their consequences of rapid urbanization and urban development are far from being fully understood.

Cities, like many other systems of the world, are complex systems (Portugali 2000). The

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This dissertation follows the style and the format of the *Annals of the Association of American Geographers*.

emergent phenomena of cities result from nonlinear interactions among their sub-systems (Batty 2003). These interactions are self-organizing behaviors of urban systems, that are triggered by, but independent of, external causes (Batty 2003). Self-organization is a fundamental property universally found in open and complex systems. To date, self-organization has been established as a formal theory and has provided a new paradigm to all domains of science that study open and complex systems (Portugali 1997). Furthermore, self-organization has become a general umbrella concept that includes several theoretical approaches, such as chaos, fractal, and dissipative structures (Portugali 1997). These theoretical approaches share common principles, but differ in treatment of systems and emphasis on processes and properties (Portugali 1997). Several kinds of self-organizing cities have been identified in the current literature, namely, dissipative cities, synergetic cities, chaotic cities, fractal cities, cellular automata cities, free agents on a cellular space (FACS), and inter-representation networks (IRN) cities (Portugali 1997).

The theory of self-organizing criticality (SOC) was proposed by Per Bak and his colleagues at the end of the 1980s (Bak et al. 1987). This theory has become a new paradigm for studying a variety of phenomena in both physical and social sciences (Portugali 1997). Compared to the general theory of self-organization, SOC is more specific. SOC explains system complexity by combining both self-organization and critical behavior (Jensen 1998; Sornette 2004). Criticality refers to the state of a system in which all components of the system start to influence each other at a critical point

(Sornette 2004). According to SOC theory, complex systems function in a similar way; they coordinate a large number of mutually interacting parts; they exchange energy, material and information with the environment they belong to; and they organize their internal structures and dynamics until some may ultimately reach a critical state (Sornette 2004). Once in this state, small perturbations could induce chain reactions, that may affect any number of parts within the system (Sornette 2004). The emergence of the SOC theory aroused great interest in various disciplines. Since the first SOC paper was published, more than 6,000 papers about SOC could be found using Google Scholar by 2007.

Several scholars have speculated the great potential of SOC in explaining various aspects of cities, such as urban landscape pattern, urban development evolution, and urban hierarchical systems (Bolliger et al. 2001; Portugali 2000; Batty and Xie 1999). Batty and Xie (1999) prove the existence of SOC in real urban dynamics. More recently studies, conducted by Chen and Zhou (2004 and 2008), mathematically connect SOC with urban central place networks and their rank-size distributions. However, there are very few empirical studies on the applicability of SOC in urban studies (Clifford and Walter 2003).

The general concept of SOC is not foreign to urban scholars. Long before the theory of SOC was proposed, urban scholars had reported the existence of critical states in urban development and their characteristics. In the 1960s and 1970s, threshold theory was fairly popular in urban studies (Lean 1969; Malisz 1969; Famelis 1970; Hewings 1975). This theory emphasizes the existence of a limitation within which a variable does not change under the influence of a gradually increasing factor (Malisz 1969). Physical, technological, and structural limitations are the three main thresholds in urban systems (Malisz 1969). However, threshold theory ceased to have any followers and consequently disappeared in the urban literature after its short life span in the late 1960s and early 1970s.

In this research, the author proposes to generalize SOC to a broader consideration of self-organization and criticality in urban studies. The self-organization process reflects a high degree to which patterns, processes, forms, and relationships in urban development are (re)structured independently of external factors. The concept of criticality is extended from attractor, as proposed in the original SOC theory, to boundary conditions or evolutionary milestone as system develop. The generalized SOC considers that a complex system self-organizes to a critical stage. At the critical stage, while the complex system presents power law, there are shifts of inside dynamics. The shifts could be boundary conditions, phase changes, or evolutionary milestones. The generalized SOC will be used to study (1) the urban hierarchy of China at the inter-urban level, and (2) the dynamics of the urban landscape pattern of Shenzhen, China, at the intra-urban level.

Perhaps nowhere in the world parallels the urbanization process in contemporary China, either in the pace or the breath of its geographic distribution (Lin and Wei 2002b). Interestingly enough, contemporary mainstream urban theory inquiries are drawn from urban development in Western developed countries and benefit less from Chinese urban studies (Lin and Wei 2002b). For years, empirical research dominated the urban studies in China, but few studies sought to relate directly, let alone effectively, to the theoretical inquiries in human geography and other social sciences (Lin and Wei 2002b). The lack of theoretical research in urban China studies not only weakened the foundations of empirical studies, but also rendered the mainstream theories less potent for developing universal urban development policies (Lin and Wei 2002b). This study seeks to bridge this gap in China urban studies.

1.2 Research Objectives

The overall objective is to determine the characteristics of generalized SOC in the rapid urbanization process in China, both at the inter-urban and intra-urban levels. The urban system of China is studied for the former level, and Shenzhen metropolitan area is studied for the latter level. The research question is to what extent the dynamics of cities at the inter- and intra-urban scales will exhibit the properties of SOC.

Identifying these urban thresholds would not only help us to understand the urban dynamics in China, but also enable planners and policy makers to achieve sustainable development. Specifically, this study aims to address the following three sets of questions:

1. At the inter-urban scale, does the urban system of China show the attributes of SOC? When and how did the urban system evolve to and under SOC stage?
2. At the intra-urban level, at what spatial and temporal scales will a city reach a critical stage during its development? How does the city organize itself to the critical stage?
3. If criticalities do exist in China's urban and city systems, what are the policy implications for orienting Chinese cities toward a more sustainable future?

1.3 Significance

As previously indicated, there is a lack of SOC-based empirical studies on urban systems. In addition, China's urban theories are rarely found and segregated from the mainstream urban theoretical literature. This research employs Chinese cities to examine the generalized SOC theory in order to provide theoretical breakthroughs in studying Chinese cities. It will improve our understanding of China's urbanization process, especially those critical stages. A better understanding of this critical behavior is crucial for developing effective policies in order to satisfy the growing demands of a rapidly increasing urban population. At the same time, the research will advance our knowledge of SOC. To sum up, this study will make its unique contribution to the understanding of urban system in the theoretical, methodological and policy aspects:

- With aspect to theory, this research will be one of the few empirical urban studies based on SOC. Accordingly, this study will review SOC's development up to date, propose a generalized SOC theory, and expand empirical tests of SOC. To urban studies, this study will empirically introduce a new paradigm. It combines self-organization and thresholds into understanding and explaining urban development. And also, this study will link China's urban research with the mainstream theoretical inquiries.
- With aspect to method, this research will revisit the rank-size distribution of cities with an analysis of Zipf's law at the inter-urban level, and employ a Cellular Automata model—SLEUTH to understand the generalized SOC theory in urban development at intra-urban level.
- With aspect to theory, this research will help governments understand their roles in urban development at different scales, not only in the short run but also in the long run. This research will help the governments redefine their urban development strategies, develop reasonable urban policies, and harness the power of local agents for a more sustainable development path towards a new urban century in China.

1.3 Dissertation Structure

This dissertation is organized into seven Chapters. Following a brief introduction of the research background and objectives in Chapter I, Chapter II synthesizes three sets of literature review— studies on Chinese cities, theoretical development in self-organizing criticality, and recent methodological development in Cellular Automata modeling. Chapter III is an overview of the urban development in china and the introduction of Shenzhen including the physical environment, a brief history, the rapid population growth and economic development since 1978. Chapter IV describes detailed methodology for this study. Chapter V reports self-organizing criticality in the urban system of China with Zipf's law analysis. Chapter VI presents the analysis of criticalities in the self-organizing urban development of Shenzhen. Chapter VII summarizes the theoretical, methodological and policy implications of this study.

CHAPTER II

LITERATURE REVIEW

This research is grounded in three sets of literature: (1) studies on Chinese cities, (2) theoretical development of self-organized criticality, and (3) recent methodological development in Cellular Automata modeling.

2.1 Study on Chinese Cities

China's urban development is complex and unique, which has attracted global interest. Extensive literature deals with the Chinese experience of urban development (Fan 1999; Song and Zhang 2002; Anderson and Ge 2005). At the same time, many research groups are studying the unique features of China's urban development. There include the China Data Center at University of Michigan (United States), the Urban China Research Centre at Cardiff University (United Kingdom), and the Chinese Society for Urban Studies (China), to name a few. All these efforts shed light on the understanding of China's urbanization process.

However, studies on urban China do not come quickly and easily. Before 1978, China's urbanization process was slow, and there are few studies in this period. In Communist China, little effort was made in urban studies. The isolation of China from the outside world prevented urban scholars outside of China from doing field work or collecting data in China (Lin 2002). However, this did not pose an insurmountable barrier to studying China's changing urban landscape (Cressey 1930, 1934; Spencer 1939; Murphey 1954; Chang 1961, 1963, 1970; Chang 1970; Lin 2002). Instead, urban scholars have conducted many studies to examine Chinese cities from outside with a historical perspective (Lin 2002). The limited literature elaborated on cities' function as centers of change, and identified economic forces (commercialization and industrialization) as the internal forces of urbanization. Some literature further points out that China's urbanization process is distinct from those found in Anglo-America cities (Lin 2002). All these papers have potential influence on the future urban studies in China.

After decades of socialist urbanization, especially after the opening policy in 1979, geographers were offered ample opportunities to investigate as well as to experience the vibrant urban landscape in China. However, scholars have been bewildered by the peculiar patterns they observed (Lin 2002). The unique approach China takes in its urban growth has enamored Western scholars to understand the atypical Chinese experience (Kirkby 1985; Lo 1987; Pannell 1990; Chang 1981; Chan 1992; Lin 2002). In the early 1980s, there came a remarkable change in China urban studies. At this time, the focus shifted away from the conventional approach on urban transition study to the investigation of a unique model or framework in order to better explain the patterns of Chinese urbanism (Lin 2002). Sit and Cai (1998) summarize five schools of thoughts from these efforts.

(1) The Anti-Urbanism or De-Urbanization view, popular among U.S. scholars. This school of thoughts attributes the slow urbanization process in China from 1949 to 1978 to an anti-urban ideology (Ma 1976; Cell 1979). According to this idea, all studies on China's urbanization since 1949 should consider the impacts of anti-urban and pro-rural polices of Mao.

(2) Industry/Strategy-Oriented Urbanization, proposed by British scholars (Sit and Cai 1998). This school of thoughts considers the slow urbanization process during 1949 to 1978 was mainly affected by the industrialization strategy. When the People's Republic of China was founded in 1949, the industrialization level in China was at such a low level that the China Central Government was eager to develop industry, especially heavy industry. The government had to lower the consumption level and maximize the capital accumulation in order to support industry development. As a result, the development of urban infrastructure and rural economy were neglected, which diminished the base for further development of cities (Kirkby 1985; Cannon 1990).

(3) Dual System of Urban Centers and Rural – Urban Balance Development, proposed by Chang (1976, 1981). According to this school, dual urban center systems exist in China. One is the traditional urban system inherited from the late feudal period. The other is similar to those in Western developed countries. Reasons for the slow urbanization process can be identified from the interchanges between the two systems.

However, the distinction between the systems is vague in China, compared to those found in developing countries.

(4) Industrialization and Urban – Biased Approach, proposed by Chan (1994). Chan argues that urbanization in China remains a classical socialist model – ‘under urbanization’. The purpose of under urbanization is to put emphasize on heavy industries which reduces the multiplier effect, and to adopt the urban – biased policies in order to prevent the danger of over-urbanization.

(5) A more comprehensive view is offered by Sit (2002). According to him, the urbanization process of China is much more complex than what are described by the above schools. To explain its uniqueness, a comprehensive study on the social, political and economic systems, as well as the traditional culture of China is essential.

Since 1985, Chinese cities began to change substantially after years of open policy and economic reforms (Jankowiak 1998). At the same time, China began to annually release statistical data about cities. This leads to better understandings of the general and actual pictures of China’s urban development (Lin 2002). Chan and Xu (1985), Kirkby(1985), and Ma and Cui (1987) attempted to explain the conflicting and probably inflated city statistics through comparing various Chinese sources. The general conclusions are finally reached that the non-agricultural population in China should be used as approximate actual urban population. The other area that intrigues geographers is Chinese unique approach to city planning and urban housing development (Ma 1979; Kwok 1981; Ma and Hanten 1981; Buck 1984; Ma and Nobel 1986; Lo 1987; Lin 2002). In general, urban studies in this period treat urban development as "unique" and cannot be compared with those in other countries. These studies follow scientism or positivism approaches both based on the premise that land and people can be considered as scientific objects for measurement, comparison and correlation (Lin 2002).

Since the early 1990s, a large number of towns emerged as the results of decentralization of decision making when the Chinese economy made its transition from planned to market-oriented (Lin 2002). The remarkable urban development soon captures the interests of China geographers (Lin 1993; Lin and Ma 1994, Ma and Lin 1993). In order to demonstrate the prominent features of the urban growth, Ma and his colleagues introduce a conceptual framework and coin the label 'urbanization from below' (Ma and Fan 1994; Ma and Lin 1993). This framework explain the parallel tracks –'urbanization from above' and 'urbanization from below'— on which China experience the urbanization process since 1949. With the open door policy and the economic reforms promulgate in China, the tide of globalization is sweeping China in the meantime (Lin 2002). Urban studies of China under the forces of globalization revisit the socialist in China.

As summarized by Lin (2002), four periods of discourse formation can be identified: (1) the 1970s' notion of cities as the centers of change, (2) the 1980s' interpretation of unique features of the Chinese urbanism, (3) the 1990s' modeling efforts on town-based urbanization as well as regional development in general, and (4) the 2000s' using concepts such as space, place, and trans-nationalism to compose a geographic system for the Chinese diaspora. In summary, the empirical studies of China's urbanization flourished in the last two decades, and topics and methods increase both in quantity and quality (Yan 1995). Yet it is ironic that scholars grieve for the under-theorization of Chinese urban studies at the same time. There is a lack of a consistent theoretical framework to rationally explain the complex phenomena documented by empirical studies (Zhang 2008).

Compared with urban studies in the West, theoretically-informed studies on China's urban system are few and lagging behind. Urban studies of China missed not only the developing period of the Chicago school and the central city theory, but also missed the booming period of urban theories after the Second World War, after which several important theoretical schools (e.g. behavior school, positivist school, and political economy) formed successively. Current studies on Chinese cities are at a primitive stage. The major efforts are put either on understanding urban problems and phenomena, or introducing Western urban theories. Another issue is that theoretical China's urban studies are separated from the mainstream theories of Western urban development. The limited theoretical inquiries attempt to explain Chinese urbanization from ideology and the social structure, whereas the state-of-art theoretical focus about Western countries are on structure and agency in urban studies (Piao 2005). The separation becomes more and more obvious. Many Chinese scholars emphasize on the importance of developing an urban theory exclusively for the unique urbanization process in China.

Economic reform and the open-door policy debuted in China in 1978, and have turned China into a world economic power. The urbanization process in China today profoundly differs from those in the previous years, and in many ways, similar to that of the West (Lin and Wei 2002a). This allows the theoretical and conceptual frameworks developed from Western countries to be applied to Chinese urban studies (Lin and Wei 2002a; Fan 2005). Furthermore, the strong dynamics of China's urban landscape will provide fertile ground for mining new knowledge and reconstructing theoretical discourses (Lin and Wei 2002a).

2.2 Self-organizing Criticality

Bak and his colleagues (1987) first introduce the concept of SOC with an attempt to explain the widespread appearance of power-law in nature. The Sandpile model was used as a toy SOC theory as the following:

"Consider the scenario of a child at the beach letting sand trickle down to form a pile. In the beginning, the pile is flat, and the individual grains remain close to where they land. Their motion can be understood in terms of their physical properties. As the process continues, the pile becomes steeper, and there will be little sand slides. As time goes on, the sand slides become bigger and bigger. Eventually, some of the sand slides may even span all or most of the pile. At that point, the system is far out of balance, and its behavior can no longer be understood in terms of the behavior of the individual grains. The avalanches form a dynamic of their own, which can be understood only from a holistic description of the properties of the entire pile rather than from a reductionist description of individual grains: the sandpile is a complex system" (Bak 1996, 2).

At this stage, avalanches of sand slides are in many different sizes. Bak and his colleagues argue that there would be a power law distribution in the sandpile (Bak et al. 1987).

The original temptation of SOC theory is to explain the phenomena of spatial fractals and 1/f fluctuations (Jensen 1998). However, many different views have emerged in latter studies. To date, there is neither a consensus definition of SOC, nor a mathematical formula (Jensen 1998; Sornette 2004). Most researchers generally agree with the essence of SOC which combines two fascinating concepts, self-organization and critical behavior (Jensen 1998; Shiner 2000; Sornette 2004). Self-organization generally means the ability to develop structures, patterns, and large-scale organizations spontaneously (Jensen 1998; Sornette 2004). Criticality refers to a critical point at which all members of the system start to influence each other. The critical state is scale-invariant, at which a minor event starts a chain reaction that can lead to a catastrophe (Sornette 2004).

Compared to the theory of self-organization, SOC is more specific. SOC reveals the internal dynamics behind the final statistical size-distribution of self-organized systems (Portugali 2000). The SOC theory, for the first time, explains the processes of qualitative change to quantitative change, as well as the quantitative relationships among local perturbations and the whole system's changes. It demonstrates how complex the internal dynamics of a steady state can be (Portugali 1997). Bak and his colleagues asserted that SOC is the essence of temporal and spatial scales veiled in non-linear systems. It could even be extended to explain many of phenomena in complex systems (Bak et al.1987; Bak et al. 1988; Bak and Chen 1991; Bak 1996).

2.2.1 Tests and Applications of SOC

Shortly after SOC is proposed, a large number of experiments, computer models, and empirical studies have emerged to test SOC behaviors. Laboratory experiments include various sandpile, ricepile, magnetic flux, and water droplets (Bark 1996; Jensen 1998; Turcotte 1999). Many papers claim the appearance of SOC in their experiments (Turcotte 1999). However, there also many experiments do not exhibit power-law distributions of avalanches (Jensen 1998; Turcotte 1999). Many results of sandpile avalanches experiments present mixed findings (Zhang 1997; Manna and Khakhar 1998; Turcotte 1999). In the sandpiles experiments, failure to demonstrate the general results of criticality may be attributed to the inertial and dilatational effects (Turcotte 1999; Sornette 2004).

With the aid of computers, a dazzling multitude of SOC models have been established (Trucotte 1999). Although substantial numbers of computer models are available to testify the existence of SOC, almost all of them evolve from three simple cellular-automata models: the sandpile model, the slider-block model, and the forest-fire model (Trucotte 1999). Most scholars would take the original sandpile model (Bak et al. 1988) as the classic example of self-organized critical behavior. There is, however, much debate on authenticity of the slider-block and forest-fire models as the original model for SOC (Turcotte 2001).

In the real world, scientists have enumerated many evidences to support SOC theory, such as phenomena observed in earthquake, ecosystem, living system, river bank failure, forest fire, stock market, war, and electric power blackout (Carreras et al. 2004). Those evidences endorse part of SOC, if not all, on power-law distribution and scale invariance. The conclusions about SOC are yet to be definite and certain. Conclusions about those studies are usually characterized by vague terms such as “suggest” (Fonstad 2003, Batty and Xie 1999), and “seem” (Carreras 2004, Jorgensen 1998). Below is a brief review of SOC in different studies.

Ecosystem, from time to time, demonstrates phenomena supported by SOC. For example, the power law relationship, a key feature of SOC, exists between the magnitude and frequency of species extinctions (Raup 1986; Keitt and Marquet 1996; Patterson and Fowler 1996; Sole et al. 1997), between body sizes and abundances of species

(Jørgensen et. al. 1998), between habitat patch areas and frequencies of species (Nikora et. al. 1999), between areas and frequencies of forest fires (Song et. al. 2003), and the fractal properties of the spatial distribution of low-canopy gaps in rainforests (Sole and Manrubia 1995). Mass movements of species exhibit power law distributions (Noever 1993; Haigh 2000). In riverine systems, Fonstad and Marcus (2003) found that a precise power-law relationship exists between the numbers and the magnitudes of bank failures. In river meanders and oxbow-cutoffs, researchers revealed the fractal dimensions (Stolum 1996; Hooke 2003).

Unlike ecosystem studies, SOC applications in social sciences present vague and controversial images (Turcotte 1999). The interactions of social systems are complex enough to allow meaningful quantification of these interactions. The easiest realm of study to begin with is perhaps economics amongst other social science disciplines (Turcotte 1999). Economics have assumptions about human behavior, and have developed systematic data collection, which make economic phenomena easier to quantify (Turcotte 1999). Some researchers propose the similarity between SOC's sandpile model and the dynamic stock market. They observe that the fluctuations of stock market show a log-periodic trend before the avalanched stock markets, and propose that these can be explained by SOC. But both the validity and the interpretation of these studies remain uncertain (Turcotte 1999). Another noteworthy application of SOC is in warfare. Due to the vast similarities between the condition before a war and that prior to the forest fire, it arouses remarkable interests in comparing SOC in wars with that in forest fires (Turcotte 1999). Interestingly enough, the comparisons reveal that the war orders behave just like SOC systems do, which are “independent of the efforts made to control and stabilizer interactions between people and countries” (Turcotte 1999, 1420).

2.2.2 Characteristics of SOC

A comprehensive list of necessary and sufficient conditions for SOC to occur is not yet to be possible (Jensen 1998). However, sufficient evidences have revealed the following three characteristics unanimously found in self-organized critical systems:

(1) Power law: a power law of spatial and temporal sizes is a fingerprint of SOC (Ginzburg and Savitskaya 2002; Yang 2004). Although not all systems that show the power law phenomena are SOC systems, all SOC systems are inherently able to produce power law frequency-size statistics (Bowman and Sammis 2003). The appearances of power law distributions are independent of the detailed evolution processes and fluctuations of SOC systems (Yang 2004).

(2) Catastrophe: in SOC systems, catastrophes (big events) are the hallmark (Bak and Paczuske 1995). Catastrophes are inevitable in SOC systems. They never reach equilibrium, but evolve from one metastable state to the next. Changes amongst different states can alter the system configuration dramatically. In contrast, discarding large events as anomalous is a common practice in statistical study (Bak

and Paczuske 1995). This, however, does not hold true in SOC. Large events are often significant enough to destroy the system as a whole (Jensen, 1998). In fact, large events best show the results of the underlying forces within the system, which is unnoticeable in equilibrium (Sornette 2004).

(3) Correlation lengths: change of correlation length is also an important aspect of the behavior of models that are associated with SOC (Turcotte 2001; Bowman and Sammis 2003). The increase of the correlation length is an important indicator of the starting of the critical stage (Turcotte 2001). In the seismic studies, correlation length has been well-defined, and there has observed the increase of correlation length ahead of a major earthquake (Turcotte 2001, 1999; Bowman and Sammis 2003).

2.2.3 Limitations and Contributions of SOC

The intent of SOC is to provide a universal and unified explanation for the mechanism of power laws in nature (Bak 1996). However, diversified and controversial views emerge, especially on the SOC premise. The theoretical understanding of SOC is rather fragmented without a comprehensive perspective (Sornette et al. 1995). There is still no mathematic framework for SOC, and the general conditions under which a system will exhibit SOC are largely unknown (Sornette et al. 1995). The majority favorable empirical evidences are in the form of 1/f noise, log-linear magnitude –frequency and rank-size distributions. These kinds of distributions, however, can also be generated by other processes (Phillips 1999; Sornette 2004). Suspicions loom large about the significance of SOC may be overblown (Jensen 1998).

However, the above disadvantages do not dilute the academic interests in threshold dynamics, which often result strong fluctuation avalanches. SOC forces researchers to recognize the importance of threshold, metastability, and large fluctuations in the spatiotemporal behavior of complex systems (Jensen 1998). It reveals the internal dynamics behind the final statistical size-distribution in the systems' steady periods (Portugali 2000). Bak and his colleagues assert that SOC is the essence of temporal and spatial scales hiding in non-linear systems, and could possibly explain all kinds of phenomena in complex systems (Bak, Tang, and Wiesenfield 1987; Bak 1996; Bak and Chen 1991; Bak et al. 1988). SOC continues to be a powerful theoretical framework for investigating system complexity in a variety of natural and cultural areas (Walther 1999).

2.2.4 SOC in Urban Studies

The potential of applying SOC in urban studies has already been recognized. In 1992, former U.S. Vice President Al Gore claimed that the global environment changes may follow a trajectory as predicted by the SOC theory (Gore 1992). Batty (1996) hints that the theory of SOC could be used to study the evolution of the patterns of urban developed areas. In *Our Common Journey*, a hypothesis is put forwarded that the rapid urbanization may result in an environmental criticality (Jongh 1999). Through studying SOC characteristics in landscape patterns, Bolliger et al. (2001) propose to use SOC in the urban sprawl study. Clifford and Walter (2003) describe the self-organized systems that have generated fractal patterns in Maya city. Although they do not claim to have proven that Maya society is a SOC system, they suggest it as a hypothesis to be tested in future archaeological research (Clifford and Walter 2003).

However, true urban studies on SOC are sparse and limited. The work of Batty and Xie (1999) is the first genuine SOC study in real urban dynamics. They successfully apply fractal dimensions of urban density into constructing the growth path of built-up areas (Batty and Xie 1999). The phase portraits revealed that there are several criticalities during the growth of Buffalo city, and the city has been at a critical period since the 1920s (Batty and Xie 1999). More recently studies, conducted by Chen and Zhou (2004, 2008), mathematically connect SOC with urban central place networks and their rank-size distributions. There are also two other SOC studies related to urban systems: urban environmental noise and regional power generators (installed capacity) system development. Coensel and Muer (2002) use 1/f-noise to examine the loudness and pitch variation of urban environment. They demonstrate that there is a 1/f noise in the loudness and pitch fluctuation in natural sounds just as there is in music (Coensel and Muer 2002). More than expected, these specific dynamics are also found in loudness and pitch fluctuations in urban soundscapes (Coensel and Muer 2002), which put forward the hypothesis that this is resulted from SOC in the complex urban community.

Šiugždaite and Norvaišas (2002) propose a methodological framework for employing the SOC in the decision-making process on the development of regional power system in long term.

2.2.5 The Theory of Threshold

The general concept of SOC is not foreign to urban scholars. Before the theory of SOC is proposed, urban scholars have reported characteristics of critical states in urban development. Urban scholars observed the constraints of physical environment for further urban development in lots of towns and cities. These limitations are not insurmountable. They could be overcome by additional investments (Kozlowski and Hughes 1967, 1972; United Nations 1977). When confronting a threshold, the physical development usually slow down, be it a city or town. This situation will, confine the urban development inside the physical limit for quite a while (i.e. within the range of relatively normal costs for accommodating new inhabitants). However, the pressure for continuing urban growth will accrue, which leads to much higher costs added to overcome the threshold. As a result, the physical growth of towns and cities does not follow a linear process, but rather carry on a series of jumps. Jumps proceed consecutively after limitations, which is called *thresholds* of urban development (Kozlowski and Hughes 1972).

Malisz (1963), for the first time exerted the groundbreaking impact on the threshold theory. It explains the existence of a confinement within which certain variable ceases to change given the influence of a gradually increased factor (Malisz 1969). A threshold take place once a unit of new development cannot be completed with the same cost of previous unit development, and a much higher additional cost needed. In general, the presence of a threshold is marked by the marginal cost of urban development with either a sharp increase or a discontinuity. Changes of the marginal cost are subject to a number of physical factors, ranging from topography to public manufacture (Lichfield et al. 1975). The threshold analysis applies the threshold concept to compare various scenarios of urban expansion early in the planning process. It thus helps to determine the choice of the most desirable directions for urban physical growth.

The threshold analysis deals with three thresholds for urban development—physical, technological, and structural limitations (Malisz 1969). Physical threshold generally means those limitations caused by topography, such as steep slopes, large water bodies, and wetlands. Technological threshold is determined by limited capacities of infrastructures, such as those of roads, gas, electricity, and other services (Simpson 1977). Structural constraint becomes noticeable when the existing urban structure starts to prevent further development, for example, a new public transport system becomes essential with increased population (Simpson 1977).

The theory and analysis on threshold originates in Poland, largely attributes to Malisz (1969), and has been broadly used in urban planning since the 1960s (Lean1969; Malisz 1969; Famelis 1970; Hewings 1975). Further efforts come from Kozlowski (1972) and the United Nations (1977), and the theory starts to be employed in Scotland (Kozlowski and Hughes 1967, 1972; Scottish Development Department 1973). With all these efforts, the threshold theory and analysis has been flushed in urban planning and literature in the 1960s and 1970s.

Other quantitative methods by all means contribute to the full contribution of threshold analysis. This by and large covers and rationalizes the entire planning process. . However, the threshold theory and analysis also has many deficiencies, such as how to define the threshold (ambiguity both in definition and practice), and whether the costs calculated for long-term period are valid.

Unfortunately, there are few followers of the threshold theory after its climax in the late 1960s and early 1970s. The theory finally disappeared in the urban literature. Entering the 21st century, the threshold theory and analysis can be identified with many hints for the theory of SOC. The concept of threshold and the critical state in urban development have already been emphasized in the threshold theory and analysis.

2.3 Cellular Automata Modeling

Cellular Automata (CA) model is a dynamic system with discrete space and time. The earliest CA modeling can be traced back to Von Neumann’s Self-replicating Turing Machine, done by Stanislas Ulam in the 1940s (Clarke 2006). Later on, CA modeling approach has been broadly applied to other fields outside of computing such as geography (Parker et. al. 2003).

The original CA model is quite simple. The basic elements of a CA model include grid space, states, neighborhoods, and transition rules. The continued space is divided into regular cells (grids), and each state is in one of defined states. During a CA modeling process, the state of a cell is determined by the previous states of its neighboring cells with one or more certain transition rules. The change of the space is treated as the overall consequences of the state conversions of individual cells. The most important step for the development of a CA model is to build the suitable transition rule(s) according the neighborhood interacting relationships.

After decades of development and broadly application, many basic aspects of the original CA model changed and became more sophisticated. The states of cells can change synchronously or asynchronously. Neighborhoods are no longer limited to the local cells, and irregular and directional weighted neighborhoods emerge in many studies. Recent studies have been using graph networks to replace the traditional neighborhoods. Many contemporary CA models are in fact cellular models. In addition, there is also a new trend to develop vector-CA models which break the generic grid space. The original CA models have been evolving and modified, almost changed thoroughly (Parker et al. 2003).

CA modeling presents the potential capability of simulating spatial phenomena due to its intrinsic characteristics. CA models are spatial and dynamic in nature, this enable them to directly represent spatial processes (White and Engelen 2000). In addition, CA models are highly adaptable. Simply adjusting the transition rules allows the models to be applicable for a wide rang of spatial behaviors, situations and processes. What's more, CA models boast enormous computation efficiency (White and Engelen 2000). Up to date, the applications of CA models in representing processes with spatial characteristics are encouraging. They are universally found in areas such as natural resources management, urbanization processes, transportation, and medical application (White and Engelen 1993; Torrens and O'Sullivan 2001; Pinto and Antunes 2007).

Cellular automata apply well to the modeling of urban phenomena (Pinto and Antunes 2007). The evolution of urban systems is in line with the transition mechanics of cellular automata. Urban systems are typically complex systems marked by self-organizing behaviors. The process of urban growth is in essence a local self-organization and aggregate effects (Wolfram 1984; Clarke and Gaydos 1998; Benenson and Torrens 2004). Cellular automata are self-organizing modeling which repeatedly apply the transition rules in the local neighborhood. The models are instrumental in understanding important information of urban theories, for example, the emergence and evolution of forms and structures (Webster and Wu 1999a, 1999b; Wu and Webster, 1998). In addition, the concept of raster data format derived from GIS and Remote Sensing matches precisely with the idea of grid space in the CA models. The development of GIS and remote sensing provide potential data sources and technical support for CA modeling in urban land use and land cover study.

Urban scholars have long noticed the capability of CA modeling, and the application of CA in urban studies can be traced back to the 1980s. After Tobler (1979) first proposes to employ a cellular approach in geographic modeling, his idea is followed by Couclelis (1985, 1988, 1989, and 1995) and later Takeyama (1996). Batty and Xie develop one of the first CA models for urban modeling (1994). Couclelis (1997) and Takeyama and Couclelis (1997) demonstrate cellular automata to be a potential strong input to urban process modeling (Clark and Gaydos 1998). CA modeling has became a dominant simulation technique widely used in studies of urban sprawl, regional growth, residential growth, population dynamics, economic activities, to name a few (Batty and Xie 1994; Cecchini 1996; Batty and Xie 1997). At the mean time, many CA programming environments and platforms are established, such as DUEM, Kenge, JCASim, and SLEUTH (Benenson and Torrens 2004).

Generally speaking, three main categories of urban CA model develop parallel, and each focuses on one aspect of modeling purposes. They are, however, not mutually exclusive to each other:

(1) Many scholars (e.g. Couclelis 1985; White and Engelen 1993; Batty 2005) have been working on the theoretical issues of urban dynamics

with CA modeling. Liu and Andersson (2004) place these models in the context of physical theory in general, and pay attention to the other possible fields these models may imply. They further connect the models development to fractal theory, and correlate the models to power laws' generation (Batty 2005).

(2) There are also many effloets put into simulation urban dynamics in the real world with CA models. Batty and Xie (1997), Clarke, Hoppen and Gaydos (1997) have been investigating on the applicability of using evolutions of CA models to simulate and solve urban problems in many cities in world.

(3) Models on operational tools for planning (Torrens, 2000; Pinto and Antunes 2007; Li and Yeh 2000; Yeh and Li 2006).

Although CA models have many advantages and have been extensively used for decades, they are still in infancy in urban studies (Benenson and Torrens 2004), many critical challenges confronting CA modeling include: calibration and validation, errors and uncertainties, limits of top-down processes, meanings of transition rules, and finally, the match with urban theories (Benenson and Torrens 2004; Pinto and Antunes 2007). A major criticism on urban CA models is the meaning of transition rules. Most of the urban CA models are exclusively developed for physical interpretation, rather for social and economic processes. The transition rules of current urban CA models are valid only in physical changes. Although there are some urban CA models have social and economic mechanisms incorporated, there exists obvious arbitrariness (Webster and Wu 1999a, 1999b). On the contrary, more pragmatic development of urban CA (Papini and Rabino 1997) fits transition rules iteratively using genetic algorithms and other learning strategies. Thus, fit between two patterns at different points is optimized (Batty 2005).

When applied to real city studies, CA models are subject to many inherent errors and uncertainties due to data sources, GIS operations, and limited human knowledge (Yeh and Li 2003). The data source errors of urban CA range from every possible steps in building GIS database, including investigation, mapping, and digitization errors. Manipulation of the GIS program can also cause uncertainties to the CA model. The errors and uncertainties are further aggravated by model uncertainties due to inadequate human knowledge, complexity of nature, and limitation of technology. CA models serve only an approximation to reality, just like the other models behave.

The limitations of CA models also lead to inadequate model evaluation. Many researches use the highly general measure— fractal dimension, to compare the overall shapes of simulated cities with those in reality. Monserud and Leemans (1992) introduce the Kappa Index—a cell-by-cell comparison to evaluate CA modeling. However, the Kappa Index cannot capture the general similarity or pattern in a global picture. Later, a map comparison theory based on local configuration is developed by

Power (1998), using fuzzy set theory. Overall, the ability to model reality surpasses the ability to evaluate the results (White and Engelen 1997).

CHAPTER III

STUDY AREA AND DATA

This study tests the generalized SOC in Chinese cities at both inter- and intra-urban scales. At the inter-urban scale, the urban system of the Mainland China is used for analysis. At the intra-urban scale, the city of Shenzhen is selected as the case study.

3.1 Urbanization and Urban System of China

3.1.1 Definitions and Data

Before discussing the urban system of China, it is necessary to clarify the definitions of 'city'. In China, there is yet no precise definition of city (Fan 1999). A city is an administrative unit designated by the central government. Generally speaking, the designation criterion is "a function of political-administrative status, economic development, total population and nonagricultural population of the settlement, or a combination of the above" (Fan 1999, 496).

The designation criterion of cities is neither spatially nor temporally uniform. The definition of city in China has been updated three times since 1949. The first time is in 1955 when the People's Republic of China gave the definition. A place was legible to be a city when it occupied 100,000 or more permanent residents. At that time, 166 cities were designated. The second definition is designated in 1963. The central government carried out more stringent criteria on how to define a city in order to reduce the numbers of city. Smaller-sized cities with a population of less than 100,000, except provincial capitals and other special cities, were degraded into towns. The latest update happens in 1984. And the definition for cities is eased and quite a few small cities were designated (Kojima 1995).

There are several types of urban population data available in China. One is to count the total population living within the city boundaries. This type of urban population will potentially overestimate the urban population, as many cities include considerable amount of agricultural land and population (Chan 1992). The nonagricultural population locating in the city proper (shiqu feinongye renkou) is typically regarded as the urban population for China's urban studies (Chan 1992). This type of population only includes residents with households officially registered in the city district. This terminology is considered to be the official and only reliable estimation of urban population for the entire array of cities in China (Fan 1999).

The availability of data is also a serious problem for studies of contemporary urban China. Some quantitative data on Chinese cities are available for the period 1950-1957. . However, neither the coverage nor the quality of the data could lead to meaningful analyses. Since 1977, China began to release some statistical data on urban development. But these data are far from being systematic and they turned out to be less useful either.

The Urban Statistical Year Book has been published each year since 1985 to systematically summarize the urban development of the previous year. The Urban Statistical Year Books have proved to be informative and valid for studying Chinese cities. In this study, non-agricultural population in urban areas in year 1984, 1988, 1992, 1996, 2000 and 2003 are used to measure the city sizes. In addition, the metropolitan population in 1938 and 1953 from the report "Cities of Mainland China: 1953 and 1958" by U.S. Department of Commerce, Bureau of the Census are employed for comparison.

3.1.2 Premodern Urbanization History of China

China has a long history of urbanization which can be traced back to the second and third millennia BC. Urbanization in the premodern China enjoyed its rapid growth and dissemination during the Tang (618-907 A.D.) and the Song (960-1279) dynasties (Lin 2007). According to Chao (1986), the percentage of population living in cities has already exceeded over 17 percents in the Han Dynasty (206 B.C. –A.D. 220), and surpassed 21 percent in the Southern Song Dynasty (1127-1279). These numbers might be somewhat extravagant. Hoverer, even a far more conservative estimation by Mark Elvin (1973) concludes the percentage of population living in large cities (more than population of 100,000) is around 6-7.5 in the Song Dynasty. China had a quite high percentage of population living in cities thousands years ago. Following this trend, urban development maintained to grow and flourish spatially well into the late Ming (1368-1644) and later Qing (1644-1911) Dynasties (Lin 2007). At the turn of the 19th century, China's metropolises are perhaps the world largest cities. Before the industrial revolution took place in Europe, China had the largest population living in large cities than anywhere in the world where still belongs to the premodern conditions (Wheatley 1971; Rozman 1973).

In the pre-modern era, cities are primarily used for ceremonial functions. They also served administrative and military foundations for the Kingdom (Chang 1961; Wheatley 1971; Wright 1977; Lin 2007). Physically, these early Chinese cities are primarily walled for better security and defense considerations.

During the premodern history, the growth of cities and urban population were based on the development of agriculture. The immediate rural hinterlands were the sources of food for cities. There maintained free and extensive interchanges between cities and rural areas. The development of transportation system was also imperative to move food to consuming populations in cities. The transportation system facilitated the significant expansion of cities and the urban boundaries they occupy.

3.1.3 Modern Urbanization History of China

3.1.3.1 Treaty Port Cities

The year 1840 witness the new era of urban development of China came when the foreign powers invaded China. Failing in wars, China were forced to open five port cities where foreigners from invading countries were granted special privileges. They were permitted to live and do business without subjecting to Chinese laws and regulations. Western firms began to seek trading opportunities in China through those port cities. These activities not only introduced western ways of doing business but also new administration systems, both of which influenced profoundly on the urbanization processes and the Chinese urban lives.

The number of treat port cities increased exponentially, and altogether around 100 cities were designated as treat port cities. These port cities soon came to play an important role in forming the city hierarchy in China (Murphey 1974). A number of these port cities turned out to be China's large and important cities, such as Shanghai and Dalian. In 1910, with a population of above one million, Shanghai became China's largest city. What's more, these port cities have substantial long-term impacts on China's urban system. The majority of the large contemporary Chinese cities were at times, the treaty port cities.

The development of treat port cities also spatially shifts the distribution of China's urban system. Around two centuries of pre-modern era, China focuses largely on the development of its interior. In the late 19th and early 20th centuries, this focus gradually shifts to the eastern coast and northeast where the treaty ports cities conglomerate. These treaty port cities became more and more in economy connected to the world shipping routes and joined in the international market networks.

3.1.3.2 Socialism Cities of China

After the long period of foreign intrusion and years of the civil war, the foundation of the People's Republic of China in 1949 brought the urban development in China to the Socialism period. Unlike the western capitalism whose urban development is intrinsically driven by economic forces, the socialism urban development in China is externally managed by the Central Government with planned economy. The Chinese Communist Part mimicked the way of the former Soviet Union to develop the socialist system, mainly through revolutionary activities (Zhang 2008). Under the Marxian critiques on capitalism, the communist leadership strove to diminish the differences between the city and countryside, and between industry and agriculture (Jankowiak 1998). This process of socialism urbanization in China can be divided into two phases—the early revolutionary period and the later transitional period.

In the early revolutionary period, production was the main function of cities. From 1949 to 1957, China experienced a successful economic recovery after the long period of foreign intrusion as well as the civil war. With substantial assistance from the Soviet Union, China experienced intensive growth on heavy industries, mainly centered in large cities. A large number of labors were attracted from the countryside to the cities. Urban population grew rapidly in this period, averaging 7.2% a year. From 1958, an explosive urban population growth was triggered by the Great Leap Forward which motivated the great enthusiasm to accelerate industrialization in China. Thousands and millions of peasants abandoned their agricultural businesses and came to work for industries in cities. The percentage of urban population quickly increased from 16.2% in 1958 to 19.7% in 1960, the all-time high in the pre-1980 period. However, in the rural countryside, the shortage of labor for food-producing soon loomed large. To make things worse, the three year consecutive natural calamities hit the whole country at the same time. The combined result was a national wide famine which took away 20 million lives. The Great Leap Forward stopped in 1961 with 20 million people as the new city residents.

Lessons learned from the Great Leap Forward and its aftermaths have had profound impacts on subsequent urbanization policies in China. The urbanization process was geared to a 180 degree reversed direction. Contrary to increase the urban population, the government sought to send the new urban residents back to their home villages and limited migration from rural to urban areas. Since 1961, the urban population experienced a downsizing process for three years in a row, with urban population in 1963 decreased to 17%, a level below that prior to the Great Leap Forward. From 1966, the ten-year Cultural Revolution was initiated, and the Shang Shan Xia Xiang (“up to the mountains and down to the villages”) movement was launched. Urban youths were sent to rural area “to be reeducated by the peasants” (Chan 1992). About 30 to 50 million urban youths were migrated out of cities (Xu 1986; Chan 1992). Many urban studies on China refer this period as an anti-urbanization process (Ma 1976; Cell 1979; Sit and Cai 1998). During the ten-year Cultural Revolution, the urbanization process worked backward and decreased to a very low level.

The low level of urbanization and slow urbanization process in the early revolution period were mainly due to the controls of government. Tremendous efforts were made to limit the city growth and adjust the spatial distribution of cities. Spatially, great efforts were put into shifting urban development from the coast to the less developed interior (Yeh and Xu 1990). The national security is a consideration at this time. Investments concentrated on the interior cities, such as Xi'an, Lanzhou, Wuhan, and Chongqing, because they are less vulnerable to be attacked compared to coastal cities.

The central planned economy is the especial import tool for the control under the central government to control urban development(Ebanks and Cheng 1990). With the plan economic system, the Chinese government took control of population migration and resource allocation. In 1954, the household registration (*hukou*) system was established to limit unauthorized migration from countryside to cities. This system continues to be active till present, and has exerted profound impacts on Chinese urban development. After its initiation four years later, the household system was further tightened under a migration law in order to prohibit the peasants from entering into cities.

China came to the post-Mao period after he passed away in 1976. From 1978, some of the stringent urban policies were eased. The rusticated urban youth and intellectuals began to return back to their urban residences. Soon after 1978, China also debuted its open door policy and a series of economic reforms were launched. In addition, a program to relax the control of rural-to-urban migration was implemented in 1983 together with a large number of other reform programs (Ma and Noble 1986). Overall, China entered the transitional development period since 1978.

The open policy initiated in 1978 set the target of attracting foreign investments for economic development. In 1979, the first four Spatial Economic Zones (SEZs)—Shenzhen, Zhuhai, Xiamen, and Shantou were established with a suite of favorable conditions provided for foreign investors. The success of SEZs encouraged the opening of another 14 coastal cities to be SEZ. In 1988, three “open economic regions” were set up – the Yangtze River Delta Economic Region, the Pearl River Delta Economic Region, and the Minnan Delta Economic Region. The favorable economic policy was extended from the SEZs to larger areas in China.

At the same time, economic reforms were launched to replace the central planned economy with the market economy. One of the most important economic reforms is the transformation of the State Owned Enterprises (SOEs) into independent enterprises or privatized entities. This reform offered autonomy to enterprises and enriched the previously homogenous state-owned economy (Yeh and Xu 1996). Another important reform is to release the stringent migration policies. Many of the benefits exclusively enjoyed by urban residents have been reduced or re-structured through various reforms.

Benefited from both the open policy and economic reform, rural areas are also urbanizing by themselves. Other terms are also coined to embrace the phenomenon such as “invisible urbanization”, “urbanization from below” and “deagriculturization” (Shen et al. 2002). Agricultural restructuring and rural industrialization have led numerous towns to flourish and thrive. Rural development has tremendous impetus for upgrading towns into cities and expanding small cities. In response to the growing demand for urban development, the Chinese government has relaxed its control over the designation of cities since 1984 (Lin 2002).

Overall, the year 1978 is a turning point in China’s urban development. During the past three decades, economic reforms towards a more market-oriented economy have revibrated urban development in China at all levels. The political economy in China has undergone profound transformations, moving away from central planning to more market-oriented planning with increasing levels of decentralized local controls (Lin 1999; Guthrie 2000), and from isolation to active participation in global capital accumulation. As a result, Chinese cities experienced major economic and spatial shifts away from the socialist patterns (Ma 2002), and the entire society witnessed rapid urbanization processes. The number of cities increased from 194 in 1978, to 450 in 1989, and to 661 in 2004. The urbanization level reached 26.7% in 2000 and 37% in 2003. It is predicted that the Chinese urbanization level will be over 75% in fifty years.

China’s urban system is a distinct and valuable case for urban study for many reasons. Firstly, from socialism planned economy to market economy, China provides a natural experiment in the consequences of following top-down, administrative methods versus bottom-up, market methods in directing urban growth (Yeh and Xu 1996). Secondly, even though the Chinese cities began to capture some good aspects from the capitalist since 1978, the inherited socio-spatial framework from the pre-reform socialism system continues to be dominating and shape the current urban development. Thus, China's idiosyncratic post-reform urbanization promises to be a testing field for theoretical reevaluation of the post-socialist city transitions (Zhang 2008). Lastly, both the remarkably fast pace and the wide breath of geographic distribution make the urbanization process in China unparallel in the world (Lin and Wei 2002a). The strong dynamics of China's landscape may provide fertile ground for mining new knowledge and reconstructing theoretical discourses (Lin and Wei 2002a).

3.3 Shenzhen City

Among the booming coastal cities, Shenzhen is one of the most significant cities. Shenzhen is one of the first four special economic zones in China. It continues to serve as a window of China to show off to the world about its commitment to economic reform and overall open-door policy (Ng 2003). The geographic advantage of next to Hong Kong made Shenzhen to be selected as one of the SEZs to develop an export-oriented economy. They are granted the responsibility and opportunity of running the local economy instead of having to follow investment decisions from central ministries (Ng 2003). This is the first time in the history of the People's Republic of China to devolve central authorities to the local level (Ng 2003). Politically, Shenzhen is directly under the lead of the central government as a sub-provincial city of Guangdong Province. Shenzhen enjoys highly autonomous economic development and favorite policies.

Since Shenzhen was established in 1979, it experienced a rapid urbanization process from a small border town with a population of several tens of thousand to a metropolitan area with several million population during the past three decades. Shenzhen is often teased as ‘a city of overnight growth’. Accompanying the growth of population is the spatial expansion of developed area. In 1983, only 20 km^2 of land were developed, but in 1997 this number increased to 299.47 km^2 (Ng 2003). The direct consequence of rapid urban development is the extreme changes of land use and land cover in Shenzhen. From Shenzhen, one can mirrors the rapid urbanization process of China.

Shenzhen, locates in southern China between longitude $113^o46^,$ to $114^o37^,$ and latitude $22^o27^,$ to $22^o52^,$. The Pearl River Delta where Shenzhen is located is one of the most developed areas in China (Figure 3-1). Shenzhen lies right to the north of Hong Kong with the east flanking on the Daya Bay and the west flanking on the Peal River Estuary. DongGuang and Huizhou lie to its north.

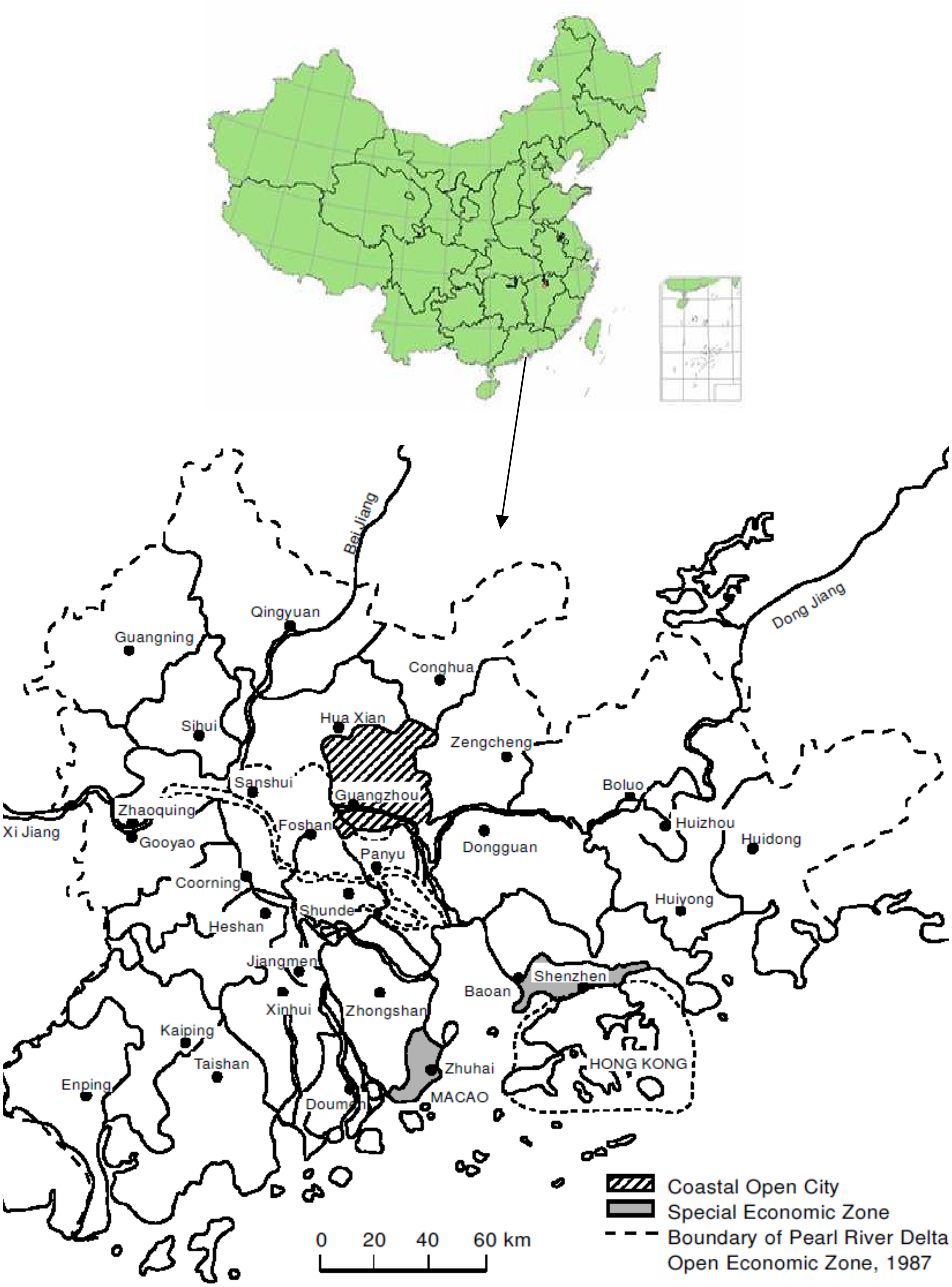

Figure 3-1 Pearl River Delta Region, China. Source: Sit and Yang, 1997.

Currently, Shenzhen City consists of Shenzhen Special Economic Zone (SSEZ), Bao’an District, and Longgang District. SSEZ comprises another four districts (Figure 3-2): (1) Luohu, the financial and trading center, (2) Futian, the administrative center where the Municipal Government is located, (3) Nanshan, the center for high-tech industries, and (4) Yantian, the second largest deepwater container port in China and the 4th largest in the world. Bao’an District, is home of Shenzhen Bao’an International Airport. Bao’an District contains ten sub-districts—Xin’an, Xixiang, Longhua, Guanlan, Gungming, Songgang, Guangming, Shanjing, Fuyong, and Shiyan. The third district, Longgang District, also has jurisdictions over ten sub-districts—Buji, Dapeng, Henggang, Kengzi, Kuichong, Longgang, Nan’ao, Peingdi, Pinghu, and Pingshan.

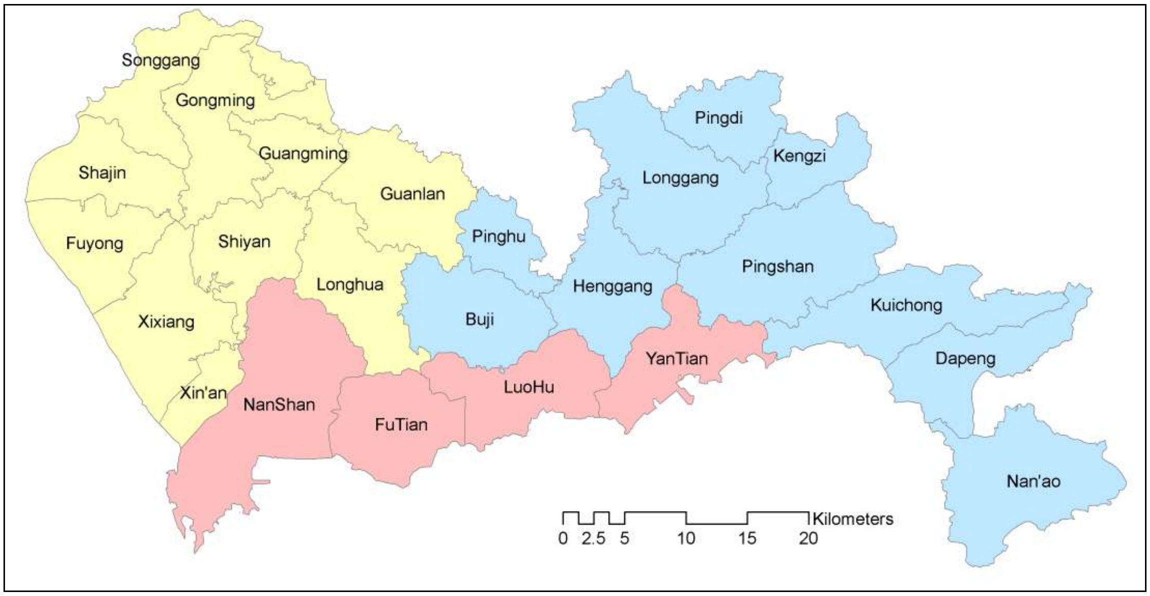

Figure 3-2 Shenzhen City, China.

3.3.1 Physical Environment

The terrain of Shenzhen is moderately hilly (Table 3-1). Over 50 percent of the land has an elevation over 50 m, amongst which over 31 percent is 80 m above the mean sea level. Near 40 percent of land has a slope over 15 percent, and 24 percent of land has a slope over 30 percent. There are several mountains with altitude above 500 m, such as Yangtai, Qiliang, and Meishajian Mountains. Wutong Mountain is the peak of Shenzhen City with a height of 943.7 m.

Table 3-1. Physical conditions of Shenzhen City.

	Elevation (m)				**Slope(%)**			
	less than 20	21~50	51~80	> 80	0~5	6~15	16~30	> 30
ShenZhen	24.15	24.96	19.83	31.05	45.26	16.19	15.73	22.81
SSEZ	53.26	12.90	6.77	27.07	48.70	12.33	13.28	25.69
Bao’an	54.43	22.41	12.14	11.02	58.06	17.59	12.02	12.33
LongGang	5.29	26.44	25.53	42.73	32.80	16.80	20.02	30.38

Spatially, the topography of Shenzhen is high in southeast and low in northwest (Figure 3-3). The southeast area is primarily small mountains. The northwest and central parts of Shenzhen are covered by hilly land and small mountains, and there are a range of alluvial plains between them. The northwest part of Shenzhen is a large area of alluvial plain.

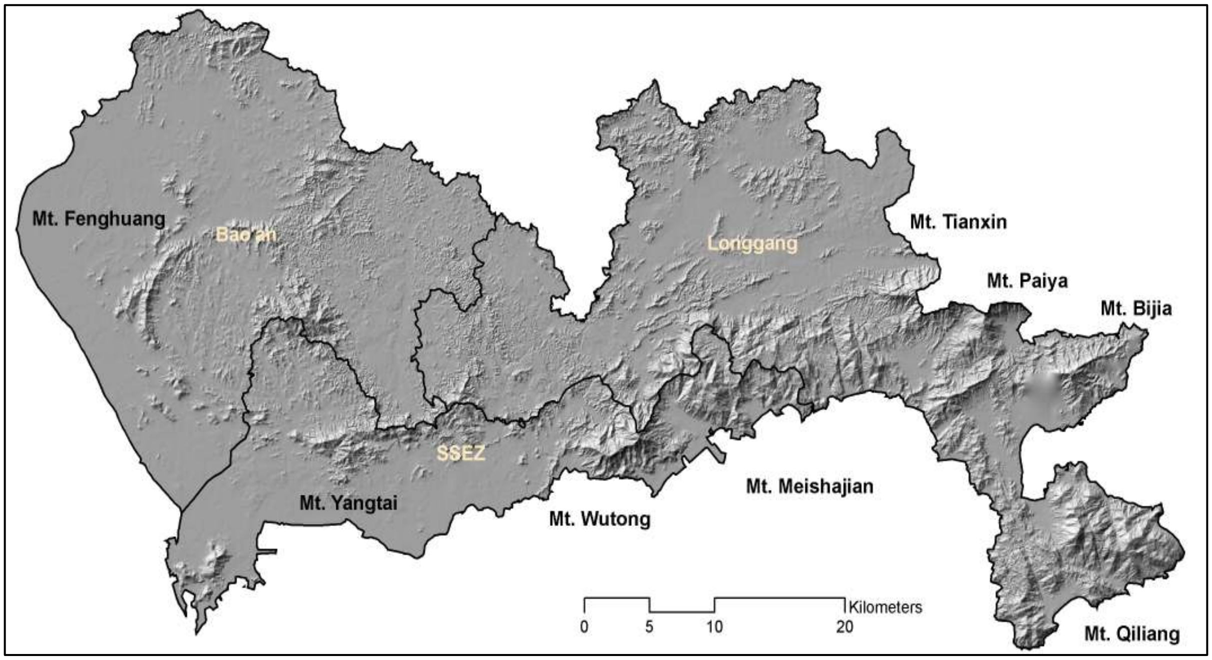

Figure 3-3 Topography of Shenzhen, China.

The climate in Shenzhen is mild subtropical maritime weather. Summer is very long, and generally lasts to six months each year while winter is really short. The annual average temperature is around 24 centigrade. The highest temperature in history reached 36.6 centigrade, and the lowest temperature reached 1.4 centigrade. Sunshine is plenty in Shenzhen, and could be as along as 1975 hours per year. Rainfall is also plenty in Shenzhen with around 1608mm precipitation annually. There are also existing the possibility of typhoons during summer and fall.

3.3.2 History of Shenzhen

Shenzhen's history can be traced back to six thousands years ago. In the Xia and Shang dynasties, Shenzhen was the habitats of ancient Baiyue tribes. In 1573, Xinan County was established on the territory of today’s Shenzhen and Hong Kong. During the period of 1842 to 1898, Britain forced China to separate 1,055.61 km^2 land, including Hong Kong Island and Kowloon Peninsula from Xinan County. In 1913, Xinan County was named as Bao’an County. The detailed history of Shenzhen is beyond the scope of this study. The main focus will be on the development of Shenzhen since the People’s Republic of China was founded in 1949.

In 1949, Shenzhen belonged to Bao’an County and was inhabited mainly by Hakka people. Due to its proximity to HongKang, Bao’an county residents traditionally went to Hong Kong to make their livings. During the 1960s and 1970s, Hong Kong’s economy began to take off and labors were largely needed. The sharp contrast between Hong Kong’s prosperity and China’s poverty further attracted residents in Bao’an County to flee to Hong Kong illegally. Statistics show that between 1957 and 1977, 119,274 residents in Bao’an attempted to flee to Hong Kong, and 60,156 succeeded. In some villages, the males were almost totally depleted due to the illegal border-crossing.

Chronic illegal border-crossing results in a severe shortage of capable labor force in the Bao’an County to serve the local economy. Moreover, under the planned economy, the commodity economy was suppressed; agricultural production was overemphasized; and political campaigns overshadowed economic development. In 1978, Bao’an County’s total industrial output was as shabby as RMB 31.42 million while its agricultural output was over tripled, RMB 95.75 million.

In 1978, China central government set up the open and reform policy. Shenzhen was designated as one of the first four Special Economic Zones (SEZs) because of its spatially neighboring Hong Kong and emotionally close to many Chinese oversea residents. In 1981, an area of 327.5 km^2 in Shenzhen was set aside as the Shenzhen Special Economic Zone. Shenzhen City was divided into SSEZ and Baoao County. These SEZs were granted with high local autonomy rather than following top-down decisions from the central ministries, as typical Chinese cities do (Ng 2003). Since the foundation of SSEZ, Shenzhen enjoyed exponential growth. Shenzhen played an important test field for China's economic development. A series of administrative, enterprise, trade, land and housing reforms took place in Shenzhen first. By the mid-1990s, economic enterprises were separated from administrative units, land market was introduced, and the major housing source switched from state to market in Shenzhen.

With the expanding of the Open Door Policy and the close competition from other cities, SSEZ's status as China's window to the world has been threatened (Ng 2003). To contend for its position as a modern mega city, Bao'an County was devided into two districts—Bao'an District and Longgang District, and the two districts were incorporated into SSEZ as two new districts of the Shenzhen Municipality in 1993 (Ng 2003). Since then, Shenzhen stepped forward to develop a world class city.

3.3.3 Shenzhen's Urban Planning and Self-organizing Development

Shenzhen's urban development needs to be discussed separately, one on SSEZ and the other on area outside of SSEZ, which are Bao'an and Longgang districts. SSEZ's urban development was well planned while urban development in Bao'an and Longgang districts followed a bottom-up, spontaneous, and "out-of-order" growth.

Even before SSEZ was founded, its urban development plans had already been delineated by the central government. The first draft master plan of the SSEZ was produced under the joint efforts of the central government and the Shenzhen government (Ng and Tang 2004). The first master plan lists not only all the development targets but also designates a linear spatial layout of the SSEZ. To match the startling rapid urban development of SSEZ in the early 1980s, the second draft master plan is provided shortly after the first one in 1985. The second master plan also only covers the SSEZ in the second master plan, a clustered linear spatial structure layout was proposed for the SSEZ's urban spatial development. It was until the third master plan in 1996, the area outside of SSEZ in Shenzhen was first covered into the plan. A clustered network spatial structure was proposed in the third master plan. In addition to these three master plans, many other urban development plans and environment protection plans jointly directed urban development in the SSEZ.

The urban planning is SSEZ is usually regarded as a typical and successful case of urban planning in China. There are many stories about how the Shenzhen government successfully followed the original plans and reserved hot land for long time benefits. Many urban scholars and planners sang high praise for urban planning, especially the second master plan in Shenzhen. In the past 20 years, Shenzhen grasped almost every development opportunity such as trade, low-valued added industries, high-tech industries, entertainment industries, and education. The clustered linear plan provided potential flexibility for urban development and gave lots of alternatives which are crucial during the rapid urbanization process. Some scholars recommended giving the second master plan of Shenzhen a milestone status in China's urban planning history.

However, urban development outside of the SSEZ in Shenzhen is another story (Figure 3-4). Towns and villages outside of the SSEZ operated under a different planning system. These surrounding areas were competing with the SSEZ through establishing their own mini-economic zones. Arable land was converted into factory land. These towns and villages, like the SSEZ, also enjoyed rapid development but in a self-organizing and disordered manner. Town governments, village committees, and villagers were the dominant agencies in urban land use development outside of SSEZ.

Figure 3-4 Towns and villages outside of the SSEZ. Source: Shenzhen News, 2006.

The different stories of urban development between the inside and the outside of SSEZ have to be attributed to the land ownership in essence. In China, landownership has two types— owned by the state and owned by rural collectives. Land inside SSEZ is owned by the state while the majority of the land outside of the SSEZ was owned by rural collectives. For state-owned land, city governments have the authorities to grant or lease the land, and specify the land uses. For collective land, village collectives own the land, and grant the right of land use to the peasants, mainly for agricultural activities. In addition, each household legally owns a parcel of land for residential purpose, where the parcel size is subject to the family size. However, village collective or committee is not an official administrative unit in China. The committee representatives are selected by villagers. Thus village committee stands for the villages' interests and directs the development in a way favorable to that particular village.

Although there are fairly stringent rules on how to convert rural land into urban land, rural collectives in Shenzhen accelerated this process without following the rules due to the high profits. In the early period, town governments and village committees literally sold the land to manufactures or enterprises wishing to set up factories in their villages. And then using the revenues generated from land sales, town governments and village committees develop buildings, and rent them to enterprises. With large amount of investments and enterprises rushing into these areas outside of the SSEZ, the floating population increased dramatically. The tremendous need for residential areas promptly encourages the villagers using their residential areas to join in the housing market. In addition to building residential buildings higher than what is prohibited, villagers also built residences in areas where not originally assigned to them. These types of illegal development overwhelmed areas outside of the SSEZ. It turned out to be a huge regret for urban planners and the Shenzhen Government for failing to cover these areas in the second master plan.

In 1993, the previous Bao’an County was separated into two districts—Bao’an and Longgang, and both were incorporated into the SSEZ. The third master plan began to cover Bao’an and Longgang districts. However, areas outside of the SSEZ were still under the self-organizing development controlled by local village collectives. In 2003, the Shenzhen government implemented a city wide activity to convert all the rural collective land into state owned land. There is a long way to go to carry out this action, since villagers are reluctant and will inevitably resist giving up the huge benefits associated with land

In summary, Shenzhen experienced rapid urbanization process during the past three decades under the combination of urban planning and self-organizing development in both SSEZ and area outside of SSEZ. With the rapid urbanization process, the urban landscape changed potentially.

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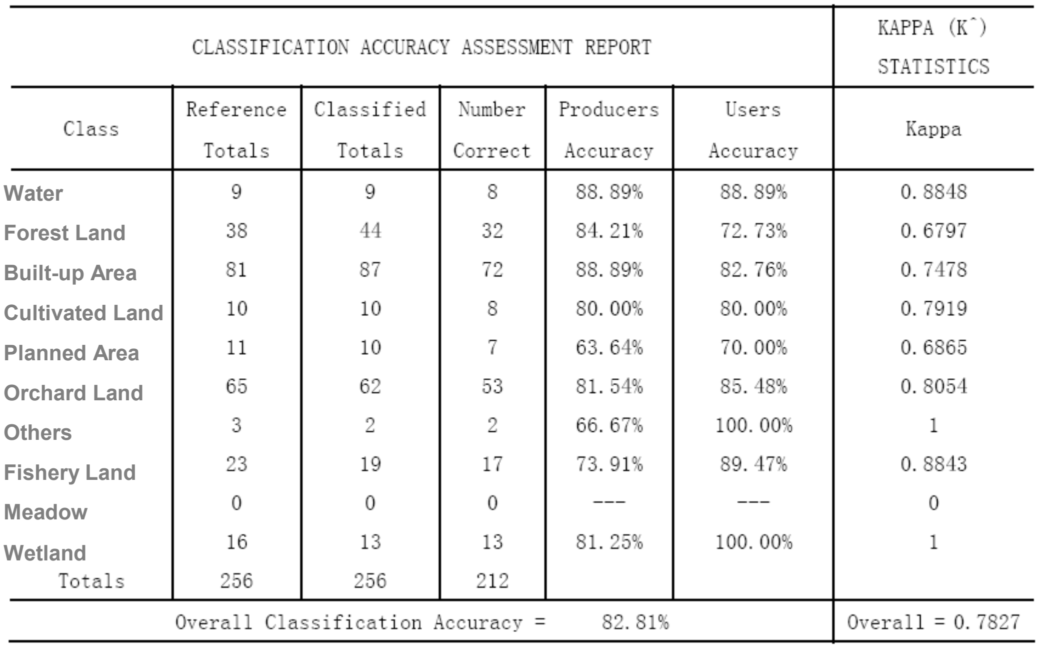
3.3.4 Data for the Study of Shenzhen

To study the urban landscape change of Shenzhen, the Landsat remote sensing data, Master Planning data, and transportation planning data are used. The remote sensing data include TM images in 1988, 1992, 1995, 1999, and ETM images in 2002. The Master Plan of Shenzhen 1996-2010, the Regional Transportation Plan 2010 of Shenzhen and Shenzhen's Subways Plan 2020 are also employed for analysis and modeling.

The classification of the remote sensing images was conducted by my colleagues at the Shenzhen Graduate School of Peking University. The classification accuracy assessment report is shown in Table 3-2. The user accuracy is a map-based accuracy, calculated by dividing the number of pixels correctly classified as one type of land use or land cover with the total number of pixels classified as the type of land use of land cover. The user accuracy measures the classification accuracy of one type of land use or land cover. The user accuracy of built-up area which is very important to the dissertation research is over 80%. The overall accuracy represents the classification accuracy of all types of land use or land cover, and it is calculated by dividing the number of pixels correctly classified with the total number of pixels. The overall classification accuracy is also over 80%. The classification results are valid for this dissertation study

Table 3-2 Classification accuracy assessment report.



CLASSIFICATION ACCURACY ASSESSMENT REPORT						KAPPA (K^) STATISTICS
Class	Reference Totals	Classified Totals	Number Correct	Producers Accuracy	Users Accuracy	Kappa
Water	9	9	8	88.89%	88.89%	0.8848
Forest Land	38	44	32	84.21%	72.73%	0.6797
Built-up Area	81	87	72	88.89%	82.76%	0.7478
Cultivated Land	10	10	8	80.00%	80.00%	0.7919
Planned Area	11	10	7	63.64%	70.00%	0.6865
Orchard Land	65	62	53	81.54%	85.48%	0.8054
Others	3	2	2	66.67%	100.00%	1
Fishery Land	23	19	17	73.91%	89.47%	0.8843
Meadow	0	0	0	---	---	0
Wetland	16	13	13	81.25%	100.00%	1
Totals	256	256	212			
Overall Classification Accuracy = 82.81%						Overall = 0.7827

CHAPTER IV

RESEARCH METHODOLOGY

4.1 Inter-urban Analysis

4.1.1 Rank-size Distribution and Zipf's Law

Zipf's law describes the negative linear relationship between the logarithm of population size and the logarithm of city rank. It is closely related to the rank size rule and the Pareto law (Batty 2003). Urban systems which conform to Zipf's law also present the Pareto distribution and the rank-size rule (Batten 2001; Chlebus and Ohri 2005). The following equation is often used to examine Zipf's law empirically (Brakman et al. 1999):

$$\mathbf{Ln(M_j)=a - bln(R_j)} \qquad (1)$$

where R_j is the rank of city j, and M_j is the size of city j, usually measured by population. Parameters a and b are the intercept and slope of the rank-size curve respectively. Nowadays, the term Zipf's law is generally referred exclusively to cases when b equals 1, whereas for more general slopes, the term rank-size distribution is used (Reed 2002). When $0<b<1$, it means a more even distribution of rank sizes than predicted by Zipf's law. If $b>1$, the rank-size distribution is much more uneven than it is predicted by Zipf's law (Reed 2002). However, it is almost impossible to get an exact 1 for the regression coefficient b in real world studies (Nitsch 2005). In fact, Nitsch (2005) found that the combined estimate of the Zipf's coefficient was significantly larger than 1 in his review of the empirical literature of Zipf's law on cities. In this study, the rank-size distribution is a substitute for Zipf's law.

The meaning of Zipf's law is important. There are ample evidences that Zipf's distributions of population and other socio-economic activities are related to mature or steady systems (Shiode and Batty 2000). Shiode and Batty (2000), in their study of the growth of web pages in different countries, showed that most developed countries with mature domains followed Zipf's law. However, in developing countries which fall behind in the web development and Internet technologies, city size relations fail to show a Zipf's law distribution.

For urban system, an ideal Zipf's distribution accompanies a well-balanced urban hierarchy in which resources, wealth, and activities tend to be spatially dispersed and well-balanced among regions. On one hand, rank-size distribution of cities may suggest, but by no means to prove, that an urban system is spatially integrated and a variety of forces have affected the development of the system. On the other hand, an urban system characterized by high urban primacy may suggest that the system has been shaped by only a few strong and easily identifiable forces. It is possible that a nation's urbanization history may show a gradual trend of city-size evolution from high primacy to a matured hierarchy of cities having a variety of sizes.

There have been many attempts to explain this observed regularity of Zipf's law. These studies can generally be divided into two categories – economic models and stochastic models. The economic models were built on delicately-balanced transport costs, positive externalities, negative externalities and productivity differences (Gabaix 1999a). However, it is doubted that different economic structures would produce the same delicate balance of forces (Gabaix 1999a). Stochastic models seek to explain Zipf's law based on some simple probabilistic assumptions on the formation and growth of cities. Stochastic models indeed generate the shape of the Zipf's distribution, but only when an unrealistic dynamics of individual city is given, and these models may be uninformative about the underlying mechanism (Overman and Ioannides 2001). Neither the economic models nor the stochastic models turned out to be thoroughly successful (Overman and Ioannides 2001). A convincing theoretical microeconomic foundation for the existence of Zipf's law is still lacking (Brakman et al. 1999).

However, Zipf's law does not hold true everywhere (Li 2002). Many studies have been conducted to check the existence of Zipf's law in different countries (Rosen and Resnick 1980; Soo 2005). As to what kind of urban system conforms to Zipf's law, the current literature presents confusing and controversial evidences. Batten (2001) stated that Zipf's law works best in large countries with almost self-sufficient economies such as the United States and the former Soviet Union. It also works well in "large countries with long urban traditions – like China and India" (Batten 2001, 97). In contrast, Marsili and Zhang (1998, 2741) contended that "countries which have a unique social structure, such as the former Union of Soviet Socialist Republics or China, do not follow Zipf's law" . Whereas for other developed countries, Zipf's law can still be considered as a reasonable explanation of the city rank size distribution (Marsili and Zhang 1998). In the above studies, China and the former Soviet Union were presented as contradictory examples. This study will examine whether or not China's urban system conforms to Zipf's law.

Although many studies have been conducted to test and explain Zipf's law in city size distribution, intra-distribution dynamics have received relatively little attention. Empirical studies tend to focus more on the overall shape of the city size distribution. In fact, different urban systems will show different intra-distribution dynamics (Overman and Ioannides 2001). For example, French and Japanese urban systems are characterized by parallel growth. Cities in both countries have a tendency to grow at the same rate, maintaining their relative rankings in the overall city size distribution and consequently showing little intra-distribution mobility. In contrast, American urban system is characterized by the entry of new cities and a high degree of intro-distribution mobility (Overman and Ioannides 2001).

In this study, Zipf's law is applied to both the entire national and cities of different sizes. In addition, intra-distribution dynamics of city sizes and ranks are analyzed in order to better understand Zipf's law in China's urban system.

4.2 Intra-urban Analysis

In the intra-urban study, CA modeling turns out to be an ideal choice because the ability to simulate self-organizing activities is the most important concern. CA models and related techniques have been extensively used to investigate complex systems and self-organization behaviors theoretically by Langton (1990), Kauffman (1988, 1990, and 1993) and many others (e.g., Forrest 1991). CA modeling method has provided deep insights into the behavior of the whole classes of complex systems. Cellular techniques dramatically shortened the distance between highly specific models (on actual cities) and models developed to investigate fundamental theoretical issues. They may enable richer and more useful applied models, co-evolving with a deeper understanding of city systems (White 1997).

SLEUTH model is chosen for this study amongst the family of well-developed urban CA models. SLEUTH, a self-modifying CA program, is originally developed by Clarke in 1992, and perhaps has become the most broadly used CA program in urban studies (Clarke et al. 1997, 2007; Pinto and Antunes 2007). There is a list of reasons to use SLEUTH model in this study.

First, the variables used to simulate urban growth by SLEUTH model are also important factors which shape urban development of the study area. The SLEUTH model takes the physical environment into consideration by incorporating physical thresholds for urban development in the model. Transportation and existing urban spatial extent are also incorporated into transition rules in the model. The exclusion layer of the SLEUTH model provides the platform to include the urban and environmental planning processes, which Shenzhen government has been putting great efforts into. The exclusion layer thus allows the top-down impacts on urban and environment planning to be included in simulation.

A critical improvement of the SLEUTH model is the incorporation of self-modification function. This function can modify the model's behavior over time, and update transition rules at different stages of urban growth (Clarke et al. 2007; Pinto and Antunes 2007). As the result, the self-modification function enables the SLEUTH model to make urban simulation in a manner of linear normal growth. This improves the model realistic and makes the growth prediction more reasonable (Yang and Lo 2003).

In addition, the SLEUTH model has many improvements on model calibration and validation. For model calibration, the model incorporates some rigid statistical measures including the overall population, location and clusters' shape to characterize the historical fit. Using historical land use and land cover data, it is possible to verify the model fitness thorough past to present calibration. With these improvements, the SLEUTH model surpassed many game-type of models which are seldom associated with rigid validity (Yang 2000).

Lastly, SLEUTH model has higher flexibility and can be applied to different regions with different datasets, compared with large amount of existing urban CA models,. If only concentrating on model calibration, validation and scenario design, researchers can save tremendous amount of time and efforts on model design and programming (Yang 2000). By far, the model has been extensively used to simulate urban dynamics in the United States and other countries (Candau 2002; Silva and Clarke 2002; Jantz et al. 2004; Yang and Lo 2003; Oguz 2003). This allows the simulation of urban growth in different places more comparable, which is especially imperative for knowledge production. Clarke and his colleagues are currently searching for the “DNA” of urban growth using the SLEUTH model in different cities (Silva 2001; Clarke 2007).

For the intra-urban study, SLEUTH model will be employed to simulate the self-organizing urban landscape dynamics. And then, thresholds of physical environment, phase shifts in urban growth process and the power laws of urban landscape will be explored using statistical analysis of classified data and simulated urban growth.

4.2.1 SLEUTH Model Introduction

SLEUTH is a Cellular Automaton-based urban growth model originally developed by Keith Clarke. It is a C program module running in the UNIX environment. The program uses the standard Gnu C Complier (GCC) and may be executed in parallel. The SLEUTH model and associated patches can be downloaded from the SLEUTH website (http://www.ncgia.ucsb.edu/projects/gig/) for free. This model aims to create a high resolution simulation tool to model urban growth (Benenson and torrns 2004). Besides simulating future urban dynamics, SLEUTH is capable of ‘backcasting’ urban extent (Clarke et al. 2007).

The SLEUTH model comprises two tightly coupled models – the urban growth model and the Deltatron land use model. The urban growth model is the major component of SLEUTH and is used to simulate urban/non-urban dynamics. The Deltatron land use model is an optional add-in. It simulates land use dynamics driven by the simulated urban dynamics according to the results provided by the urban growth model. In the following text, a working definition for SLEUTH is the *urban growth model of SLEUTH*.

Figure 4-1 shows the general simulation process of the SLEUTH model. After model calibration, a set of coefficient values are generated. With these coefficient values, the Urban Growth Model and/or the Deltron model are initiated to simulate urban and land use/land cover dynamics. After the first round of growth rules are applied, urban growth rate is calculated. If the urban growth rate falls out of the range of certain thresholds, the self-modification rule is activated to modify the coefficient values. Then, a new set of coefficient values is applied to the second round urban growth and land use/land cover dynamics. If the urban growth rate is within certain thresholds, the set of coefficient values will be fixed and used for the rest simulations. The following text will describe in details about the input data, the coefficients, the simulated urban growth types, the self-modification mechanism and the calibration and fit statistics.

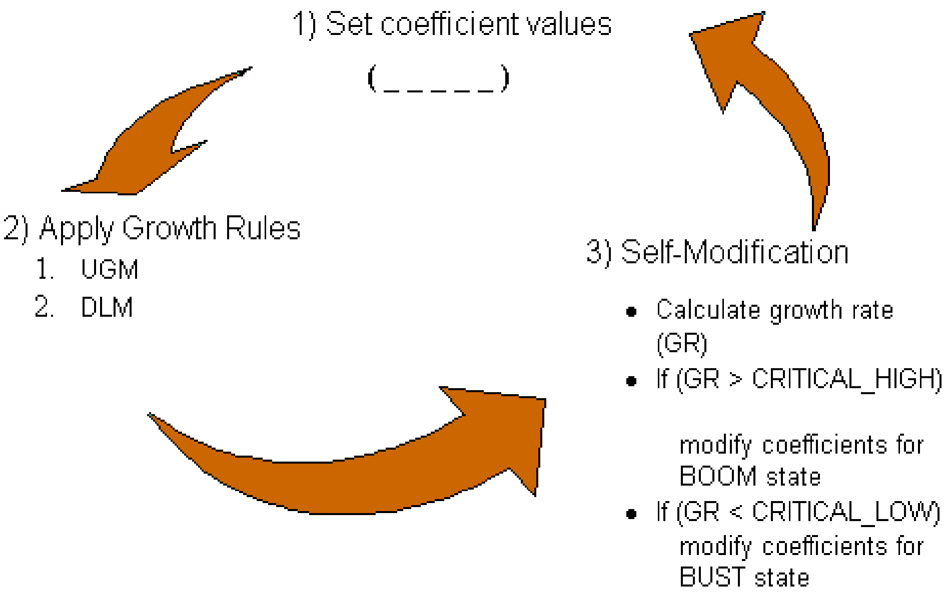


Figure 4-1 The general simulation process of SLEUTH model. Source: Candau, 2002.

Each character in “SLEUTH” represents a type of data required by the SLEUTH model – Slope, Land Use, Exclusion, Urban, Transportation and Hillshade. All the input data must be in an 8-bits Grayscale GIF image format with the same projection, the same spatial extent and resolution.

- *Slope layer* represents the slope distribution in percent slope. Each pixel has a value in the range from 0 to 100. If the percent slope is larger than 100, it will be given the value of 100.
- *Land use layers* are optional input for the Urban Growth Model. Each pixel value falling in the range of 0 to 255 which stands for a unique land use class.
- *Exclusion layer* is originally designed to represent constraints on urban growth. It includes areas which are impossible for urban development, such as water bodies

and national parks. In the exclusion layer, areas excluded are given a value of 100 or greater. However, in the SLEUTH model values larger than 100 will be read as 100. Locations suitable for urban development are given a value of zero. The exclusion layer has been proved to be a very useful layer to in simulating urban growth under different scenarios (Yang and Lo 2003; Clarke 2007).

- *Urban layers* are the binary dataset (urban/nonurban) of previous urban development. They are used to initialize and calibrate the SLEUTH model. At least four layers (i.e. urban distribution in four different times) are needed.
- *Transportation layers*, also called road layers, could be binary data to show road/non-road or relative values. Relative values represent a weighted importance of roads on urban development. One road layer is used to initialize SLEUTH model and at least one more road layer is needed.
- *Hillshade layer* is an optional but highly recommended layer. It provides a background for urban growth presentation. For example, in the outputs the simulated urban growth will be shown in the hillshade background.

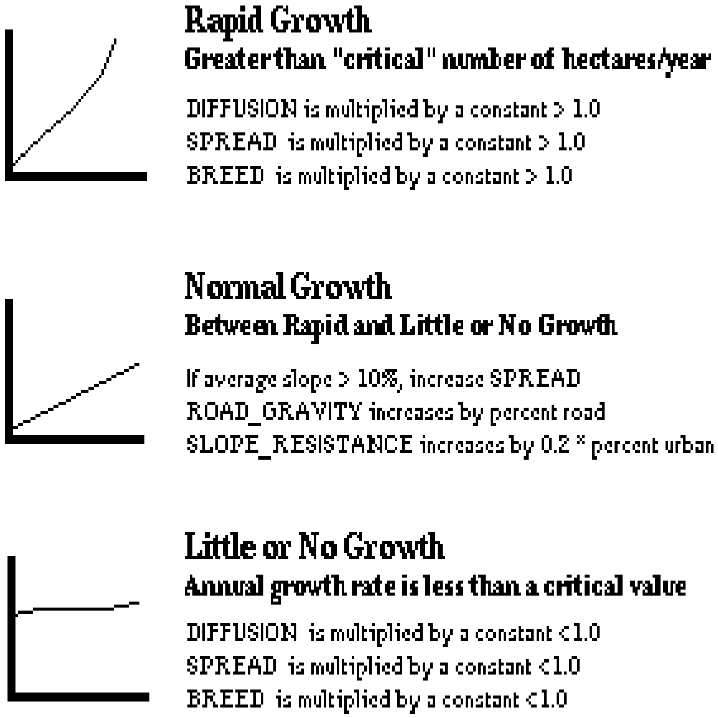
Overall, the most flexible data layer is the exclusion layer. Many studies used this layer to represent different scenarios for urban development. Similarly, the transportation layer can also be used to simulate future urban growth in different future transportation systems.

This study will take advantage of both flexible data layers for urban development simulation. Master plans will be used to generate exclusion data. Different types of planned areas will be given different weighting factors. In addition, three scenarios will be built according to different degrees at which the master plans are put into force. Planned transportation system will also be added into the transportation data layer to simulate urban growth. Therefore, by adding a "planned" system, government's impacts on urban development could be simulated.

SLEUTH can simulate four types of urban land-use change: spontaneous growth, new spreading center growth, edge growth and road-influenced growth. The urban physical development is the sum of the four types of growth. These four growth types are applied sequentially during each growth cycle, or year. "S*pontaneous growth* simulates the occurrence of a new urban settlement on the landscape without necessary relation to preexisting infrastructure. *New spreading center growth* controls the likelihood that one of the newly established *spontaneous growth* settlements will become a center for continued growth. *Edge growth* models outward growth from the city edge as well as urban in filling growth. *Road-influenced growth* generates spreading centers next to routes of transportation and simulates the tendency for new growth to follow lines of transportation" (Jantz et al. 2004, 254).

Five growth coefficients, falling in the range of 0 to 100, control the above four types of urban growth. They are derived from a linear regression goodness-of-fit scores (r^2) of the simulated and the actual land cover changes. “The **dispersion coefficient** controls the number of times a pixel will be randomly selected for possible urbanization during *spontaneous growth*. The **breed coefficient** determines the probability of a pixel urbanized by *spontaneous growth* becoming a *new spreading center*. The **spread coefficient** determines the probability that any pixel that is part of a spreading center (a cluster of pixels of three or more in a nine cell neighborhood) will generate an additional urban pixel in its neighborhood. The **slope coefficient** affects all growth rules in the same way. When a location is being tested for suitability of urbanization, the slope at that location is considered. Instead of enforcing a simple linear relationship between the percent of slope and urban development, the slope coefficient acts as a multiplier. If the slope coefficient is high, increasingly steeper slopes are more likely to fail the slope test. As the slope coefficient gets closer to zero, an increase in local slope has less affect on the likelihood of urbanization. During *road-influenced growth* the maximum search distance from a road pixel is proportionally to the image dimensions which are determined by the **road gravity coefficient”** (Candau 2002, 30).

During the urban growth computation, self-modification is invoked if the model’s growth rate is different from the critical number (Figure 4-2). The self-modifying rules are important to ensure reasonable urban growth results. Three constants, *CRITICAL_HIGH, CRITICAL_LOW, and CRITICAL_SLOPE* are used to control the self-modification process. After a growth cycle which starts with setting up the coefficients and the complement of each growth type, the urban growth rate is calculated and compared with *CRITICAL_HIGH and CRITICAL_LOW*. If the urban growth rate is higher than the value of *CRITICAL_HIGH*, the coefficients will be increased for the next growth cycle. In this way, a 'boom' state is initiated, and a period of accelerating urban growth is launched. If the urban growth rate is lower than the value of *CRITICAL_HIGH*, the coefficients will be decreased. As a result, a 'bust' state is initiated, and a period of decreasing urban growth is launched (Candau 2002). Currently, there is no criterion on the establishment of the *CRITICAL_HIGH and CRITICAL_LOW* values.



Rapid Growth

Greater than "critical" number of hectares/year

DIFFUSION is multiplied by a constant > 1.0
SPREAD is multiplied by a constant > 1.0
BREED is multiplied by a constant > 1.0

Normal Growth

Between Rapid and Little or No Growth

If average slope > 10%, increase SPREAD
ROAD_GRAVITY increases by percent road
SLOPE_RESISTANCE increases by 0.2 * percent urban

Little or No Growth

Annual growth rate is less than a critical value

DIFFUSION is multiplied by a constant <1.0
SPREAD is multiplied by a constant <1.0
BREED is multiplied by a constant <1.0

Figure 4-2 The self-modifying rules of SLEUTH. Source: Clarke et al., 1997.

Self-modifying rules are important to present a reasonable simulation. Without the self-modification growth rules, a linear or exponential urban growth will be produced. The self-modification is essentially simulating the typical S-curved urban growth (Candau 2002). Under self-modifying rules, the coefficients increase quickly and result in a rapid urban growth during the beginning of urban growth simulation. In the early period of urban development, undeveloped cells available for urbanization are abundant, and the growth rate has the high possibility to exceed the *CRITICAL_HIGH* value. In later urbanization process, the cells available for urbanization become limited. Then the coefficients begin to decrease and fall below the C*RITICAL_LOW* value. Urban development begins to slow down (Candau 2002).

Calibration is the most important part of the SLEUTH model. It derives the above five urban growth coefficients that can effectively simulate urban dynamics for the data time period. The SLEUTH model employs a brute-force Monte Carlo method to achieve the goals of calibration. With a range of values for each coefficient set up by the user, the SLEUTH model will iterate with every possible combination of coefficients. For each combination, a set of least square regression measures will be calculated based on comparing the simulated growth with the actual growth. The number of Monte Carlo iterations to be specified is a very important parameter determining the computation time and the simulation error level at large.

Table 4-1 Fit statistics calculated by SLEUTH. Source: Jantz et al., 2005. [a]

Fit statistic	Definition
Compare	Ratio of modelled population (P_M) of urban pixels to the observed population of urban pixels (P_O) for the final control year: Compare$=P_{M(\text{final year})}/P_{O(\text{final year})}$ If $P_M>P_O$, then Compare$=1-(P_{M(\text{final year})}/P_{O(\text{final year})})$
Lee and Sallee	Ratio of the intersection to the union of the simulated (S_{Mi}) and the actual urban areas (S_{Oi}) for each control year (i) averaged over all control years (N_i): Lee and Sallee$=\frac{\sum(S_{Mi}\cap S_{Oi}/S_{Mi}\cup S_{Oi})}{N_i}$
Population	OLS regression score for modelled urban pixels compared with actual urban pixels for each control year
Edges	OLS regression score for modelled urban edge pixels compared with actual urban edge pixels for each control year
Clusters	OLS regression score for modelled number of urban clusters compared with actual urban clusters for each control year; urban clusters are areas of contiguous urban land; in cell space, clusters can consist of a single pixel or multiple, contiguous urban pixels; contiguity is determined using the eight-neighbour rule
Cluster size	OLS regression score for modelled average cluster size compared with actual average urban cluster size for each control year
Slope	OLS regression score of the average slope for modelled urban pixels compared with actual urban pixels for each control year
% Urban	OLS regression score for the percentage of available pixels urbanized during simulation compared with the actual urbanized pixels for each control year
X-mean	OLS regression score of average x-axis values for modelled urban pixels compared with actual average x-axis values for each control year
Y-mean	OLS regression score of average y-axis values for modelled urban pixels compared with actual average y-axis values for each control year
Radius	OLS regression score of the average radius of the circle that encloses the simulated urban pixels compared with the actual urban pixels for each control year
Product	All scores multiplied together; unweighted composite score

[a] Measurements derived from the modelled data are averaged over the set of Monte Carlo iterations. Ordinary least-squares (OLS) regression scores are calculated by fitting a linear model, $y=mx+b$, where modelled values for each control year are represented by the dependent variable y, observed values for each control year are represented by the independent variable x, slope (m) describes the increase in y as x increases over each time step, and b is the y-intercept.

The current version of the model computes a dozen or so statistical scores for characterizing the historical fit in the phase of model calibration such as the number of urban pixels, Lee and Sallee metric, urban cluster edge pixels and the number and size of urban clusters. Table 4-1 presents part of the meanings of these statistical measures. Each fit statistics measures some aspects of the SLEUTH's performance. These statistics are calculated internally by the model. The results are exported to a log file and can be manipulated by the user to evaluate the performance of different coefficients sets. The coefficient combinations with the best overall statistical scores are selected and the final values for these coefficients are determined accordingly.

Because of the large computational requirements for this approach, calibration was recommended to be executed in three phases—coarse, medium and fine—according to different purposes. For the coarse calibration, the input images are resampled to 4*4 times of the original resolution, and "the maximum parameter value range (1 ~ 100) is used, and the increment used by SLEUTH to step through the range is set to 25" (Jantz et al. 2004, 258). For each coefficient, 0, 25, 50,75 and 100 will be tested and four Monte Carlo iterations are used. After a coarse calibration, all the possible combinations with the 13 statistical measures are produced in the *control_stats.log* file. Based on these statistical measures, the user can narrow down the parameters' value range, and the increment size can generally be reduced to 5 to 10 after the fine calibration. Also in this process a lager number of Monte Carlo iterations will be used. For final calibration, the range of possible coefficient values is further narrowed down based on the statistical measures produced by the fine calibration. "Ideally, the ranges will be narrowed so that increments of 1-3 may be used while still only using about 5-6 values per coefficient and a large number of Monte Carlo iterations are used" (Jantz et al. 2004, 258).

Another important issue about calibration is how to select the best-fit values for those coefficients at each calibration step. Previously, there was no agreement on which performance measure or set of performance measures is the best. Clarke et al. (1997) primarily employed four statistical measures: population, edges, clusters and Lee and Sallee. Three statistical measures (compare, population and Lee and Sallee) were selected by Jantz et al. (2004) in their application of SLEUTH to the Washington-Baltimore metropolitan area. While in another study of Atlanta, a weighted sum of all the metrics were employed (Yang and Lo 2003). In simulating urban development in Porto and Lisbon, Silva and Clarke (2002) only used the Lee and Sallee metrics to measure of model performance. Recently, Dietzel and Clarke recommended an Optimal Calibration method to combine seven current measures based on a study of the complete set of possible coefficients.

The model generates both numeric and graphic outputs. Numeric statistical data such as the total number of new urban pixels generated from different types of urban growths, the average urban pixel column and row values, and the average slope of urbanized cells are exported in the avg.log file. The coefficient values applied to the simulation in each year and each run are listed in the coeff.log file. The graphic outputs include annual urban growth probability maps, a map of urban probabilities for the stop date, annual urban growth type maps for certain Monte Carlo run, annual urban and land use change map for the final Monte Carlo iteration.

4.2.2 Simulation of Urban Development in Shenzhen

Because the SLEUTH is a C program running under UNIX, the Cygwin, a Linux-like environment software for Windows were download from the website of Cygwin and used for this study. The complete SLEUTH 3.0 code with p01 patch, libraries for Linux or Cygwin were download from the Gigaloplis website. The model calibration and execution were performed under the Cygwin environment.

4.2.2.1 Input Historical Data

Using ArcGIS, all the input data were georeferenced and classified. All the input data were clipped to the same map extent for Bao'an, Longgang and SSEZ respectively. Using ACDSee, all the data were converted into an 8-bits grayscale GIF format with a 30-meter resolution. Table 4-2 shows detailed information of input data.

Since this study only focuses on urban growth model, land use data are not included. Hillshade data are used to provide the spatial context of urban extent, and they will be incorporated into the output images. Because the output images will be used for further analysis, the hillshade data set up a background for this study.

Table 4-2 The input historic data of SLEUTH model.

Layers	Year	Description
Urban Area Map	1988,1992,1995,1999	0, non-urban area; 1, urban area.
Road Data	1988,1992,1995,1999	100, major roads; 0, non-road.
Slope Layer	N/A	0-100 percent slope; Area with slop larger than 100 percent; degree is coded into 100.
Excluded Layer	N/A	0, available for building; 90, excluded major water bodies 100, background.
HillShade	N/A	0, background
Land use data	N/A	N/A

4.2.2.2 Calibration

As described above, the calibration process consists of three steps – coarse calibration, fine calibration, and final calibration. The best-fit values of the coefficients might be excluded during the coarse and fine calibration steps. To avoid this possibility, the author maintains the input data in a 30-meter resolution instead of resampling data into different resolutions for the three different calibration steps. This decision increases the validity of results. However, it potentially increases the time of calibration.

The *CRITICAL_HIGH* and *CRITICAL_LOW* are set up as the default values. The *CRITICAL_SLOPE* is at 15 percent degree for SSEZ, and 30 percent degree for area outside of SSEZ based on the Urban Planning Standards and Guidelines of Shenzhen (Shenzhen Government 1997).

During the calibration process, the SLEUTH model generates eleven best-fit values for each set of coefficients' combinations. The Optimal SLEUTH Metric (OSM) is used as goodness-of-fit measure and calculated for each set of coefficients' combinations. OSM is built up using the following formula:

$$OSM = COMPARE * POPULATION * EDGES * CLUSTERS * SLOPE * X\text{-}mean * Y\text{-}mean$$

The top ten coefficients combinations with highest OSM value are used to narrow down the range of coefficients for calibration in the next step.

In the coarse calibration, the MONTE_CARLO_ITERATION was set as 4 (Table 4-3). For all the five coefficients, the _START value was set as 0, the _STOP value was set as 100, and the _STEP value was set as 20. As a result, there are 7776 sets of coefficients combinations.

Table 4-3 The parameter settings of coarse calibration.

Coarse Calibration	Diffusion	Breed	Spread	Slope Resist	Road Gravity
Start	0	0	0	0	0
Step	20	20	20	20	20
Stop	100	100	100	100	100
Possible units	6	6	6	6	6
Possible Combinations	7776				
Monte Carlo Iterations	4				

From the ten sets of parameters with highest OSM values (see the Appendix), the ranges of the five coefficients are narrowed down for the fine calibration for Bao'an, LongGang and SSEZ respectively (Table 4-4). With the narrowed coefficients ranges, the _step value is reduced for each coefficient, and the number of Monte Carlo iterations increased to 7.

Table 4-4 The parameter settings of fine calibration.

Fine Calibration		Diffusion	Breed	Spread	Slope Resist	Road Gravity
Bao'an	**Start**	80	60	80	80	60
	Step	4	10	4	4	10
	Stop	100	100	100	100	100
	Possible units	6	5	6	6	5
	Possible Combinations	5400				
	Monte Carlo Iterations	7				
Longgang	**Start**	20	20	90	60	0
	Step	10	10	5	5	10
	Stop	100	100	100	80	100
	Possible units	9	9	3	5	11
	Possible Combinations	13365				
	Monte Carlo Iterations	7				
SSEZ	**Start**	0	0	90	90	0
	Step	10	10	5	5	10
	Stop	80	80	100	100	60
	Possible units	9	9	3	3	7
	Possible Combinations	5103				
	Monte Carlo Iterations	7				

In the fine calibration process, the top ten OSM values improved slightly for Bao'an, Longgang and SSEZ (see the Appendix). As the result, data ranges of the five coefficients narrowed down, and the _step values are reduced to 1~5. The number of Monte Carlo iterations is increased to 9 for the final calibration (Table 4-5).

Table 4-5 The parameter settings of final calibration.

Final Calibration		**Diffusion**	**Breed**	**Spread**	**Slope Resist**	**Road Gravity**
Bao'an	**Start**	92	90	96	92	60
	Step	2	2	1	1	5
	Stop	100	100	100	96	100
	Possible units	5	5	5	5	9
	Possible Combinations	5625				
	Monte Carlo Iterations	9				
Longgang	**Start**	20	60	95	60	40
	Step	2	5	1	1	5
	Stop	30	100	100	65	100
	Possible units	6	9	6	6	13
	Possible Combinations	25272				
	Monte Carlo Iterations	9				
SSEZ	**Start**	50	0	90	95	20
	Step	5	5	2	1	5
	Stop	80	40	100	100	60
	Possible units	7	9	6	6	9
	Possible Combinations	20412				
	Monte Carlo Iterations	9				

4.2.2.3 Derive Forecasting Coefficients

Table 4-6 presents the deriving forecasting coefficients. To calculate these coefficients, the set of coefficients with the highest OSM value from final the calibration is used for Bao'an, Longgang and SSEZ (see the Appendix). The derived foresting coefficients (Table 4-7) are initializing coefficient values that best simulate historical growth for the three areas. For Bao'an District, all the five coefficients are high, which implies a rapid urban growth rate and indicates that the urban growth is highly influenced by road construction and limited by slopes. In Longgang District, Slope Resistance is relatively low but Road Gravity reaches 100. This means road, but not slope, is an important factor in shaping urban growth. In SSEZ, the Road Gravity is much lower compared with Longgang District. In SSEZ, urban planning has played very important role in urban development. As a result, urban growth does not spontaneously follow the road development. In contract, Bao'an and LongGang are often teased as road cities without enforced regulations and lack of urban planning.

Table 4-6 The parameter settings for deriving forecasting coefficients.

Derive Forecasting Coefficients		**Diffusion**	**Breed**	**Spread**	**Slope Resist**	**Road Gravity**
Bao'an	**Start**	100	100	100	95	100
	Step	1	1	1	1	1
	Stop	100	100	100	95	100
	Possible units	1	1	1	1	1
	Possible Combinations	1				
	Monte Carlo Iterations	100				
Longgang	**Start**	20	80	98	60	100
	Step	1	1	1	1	1
	Stop	20	80	98	60	100
	Possible units	1	1	1	1	1
	Possible Combinations	1				
	Monte Carlo Iterations	100				
SSEZ	**Start**	80	10	90	100	35
	Step	1	1	1	1	1
	Stop	80	10	90	100	35
	Possible units	1	1	1	1	1
	Possible Combinations	1				
	Monte Carlo Iterations	100				

Table 4-7 The derived forecasting coefficients.

	Diffusion	Breed	Spread	Slope Resist	Road Gravity
SSEZ	88.37	11.05	99.42	78.7327	37.1271
Bao'an	100	100	100	85.4485	100
Longgang	22.09	88.37	100	53.6785	100

4.2.2.4 Model Prediction

Roads layers of year 2010 and 2020 are produced by overlaying the 1999 roads with the improved roadways and new roadways, according to the Regional Transportation Plan 2010 of Shenzhen and Shenzhen's Subways Plan 2020.

Three scenarios are developed in the model prediction. For all the scenarios, Urban Area Map 1999, Road Data 1999, 2010, and 2020 and Slope Data are used. Because city railways exert an important impact on urban development and are more efficient in transportation than other roads. City railways are given a value of 2 while other roads are given a value of 1 in Road data 2010 and 2020. The only difference between the three scenarios is the excluded layer, presented in Table 4-8. The available area for development is set as 0, excluded major water bodies as 90, and background as 100. The value for protected environment area is quite different in three scenarios. In scenarios 1, it is assumed that there is no effective environment protection, and the protected environment area is set up as 0. In scenario 2, environment protection is assumed to be moderately managed, and the protected environment area is given a value of 50. In scenario 3, environment protection plans are considered to be strictly put into force, and the protected environment area is given a value of 90.

Table 4-8 The input layers for model prediction.

Layers	Year	Description
Urban Area Map	1999	0, non-urban area; 1, urban area.
Road Data	1999, 2010,2020	2, city railways 1, major roads; 0, non-road.
Slope Layer	N/A	0-100 percent slope; Area with slop larger than 100 percent; degree is coded into 100.
Scenario 1 Excluded Layer	N/A	0, available for building; 0, protected environment area 90, excluded major water bodies 100, background.
Scenario 2 Excluded Layer	N/A	0, available for building; 50, protected environment area 90, excluded major water bodies 100, background.
Scenario 2 Excluded Layer	N/A	0, available for building; 90, protected environment area 90, excluded major water bodies 100, background.

After the five parameters are derived from the calibration process, 100 Monte Carlo iterations are applied for each scenario in SSEZ, Bao’an District, and Longgang District with the prediction stat year in 2000. The predicted results will be used for criticality analysis.

4.2.3 Criticalities Measurement

In the analysis of the physical thresholds in urban development, the physical environment characters including slope, elevation, water body, and protected environmental area will be overlaid with the simulated urban growth to identify the thresholds for future urban development, and urban development under different physical thresholds.

To analyze the urban development process, this study will detect the phase change of urban growth. The urban growth types are divided into three types—fringe growth, isolated growth and infill growth (Figure 4-3). Isolated growth means the newly developed area locates away from the existing urban area, which is often referred as ‘frog-leap’ growth. The new development skips surrounding available land and leaps far away in isolated land with low price. Fringe growth is an outward growth of the existing urban area. It often borders the existing development and takes advantage of the existing infrastructure. Infill growth occurs in undeveloped area surrounded by developed area. The three urban growth types will be analyzed at both the temporal and spatial dimensions.

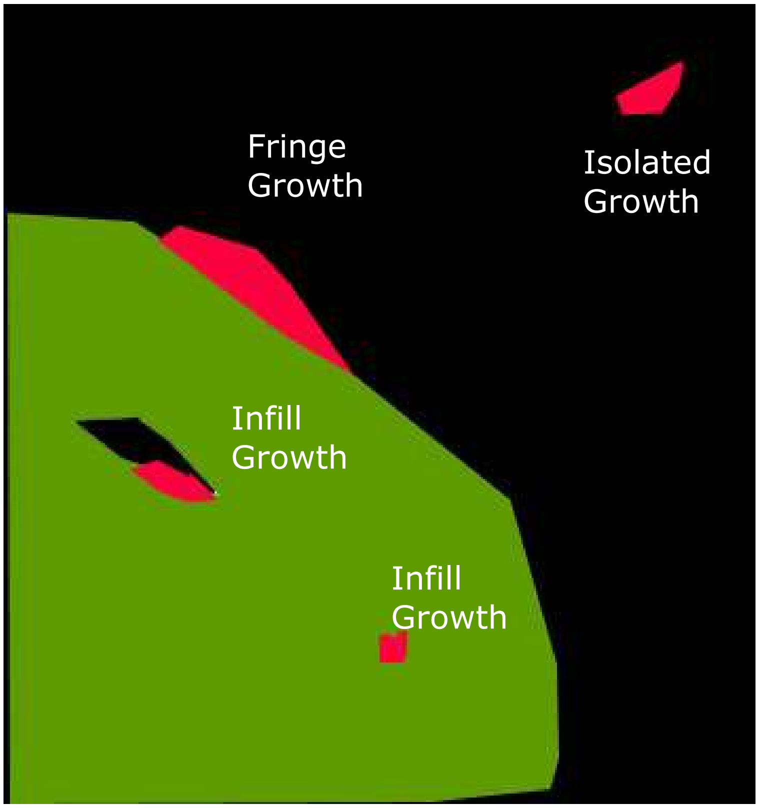


Figure 4-3 Urban growth types.

Under the thresholds of physical environment and different urban growth types, the formed urban landscape is analyzed with power law. In analyzing the formed urban landscape, patch, a basic and important concept of landscape ecology, will be employed. Patch is defined as a relatively homogeneous area which differs from its surroundings (Forman 1995). The power law of urban landscape is detected from both the magnitude-frequency and area-perimeter relationships of urban patches.

The magnitude-frequency distribution of urban patches can be quantified by the following equation:

$$\mathrm{LogM}(A) = \alpha \log A + S$$

where M (A) is the number of urban patches with a size A, and α is the slope of the line defining the relationship.

The area-perimeter distribution of urban patches can be quantified by the following equation:

$$\mathrm{Log}A = \alpha \log P(A) + S$$

where P (A) is the perimeter of the patch with a size A, and α is the slope of the line defining the relationship. If a linear α trend fits the perimeter data well over a large range of event size, then the system is considered to be composed by different size of urban patches with similar shape.

Perimeter-Area Fractal Dimension (PAFRAC) is measure by dividing 2 with the log-log regression coefficient of patch area against patch perimeter. The PAFRAC equation can be described by the following equation (Leitao 2006):

$$\mathrm{PAFRAC} = \frac{2}{\dfrac{\left[n_i \sum_{j=1}^{n} (\ln p_{ij} \cdot \ln a_{ij})\right] - \left[\left(\sum_{j=1}^{n} \ln p_{ij}\right)\left(\sum_{j=1}^{n} \ln a_{ij}\right)\right]}{\left(n_i \sum_{j=1}^{n} \ln p_{ij}^{2}\right) - \left(\sum_{j=1}^{n} \ln p_{ij}\right)^{2}}}$$

a_{ij} = area of patch ij.

p_{ij} = perimeter of patch ij.

n_i = number of patches in the landscape of patch type i.

$1 \leq \text{PAFRAC} \leq 2$

According to FRAGSTAT, a PAFARC value greater than 1 means the two dimensional landscape mosaic is away from a Euclidean geometry, and the patch shapes of the landscape are more complex. Generally, a landscape with the PAFRAC value approaching 1 are in simple shapes, while a landscape with the PAFRAC value approaching 2 is in highly complex shapes. It is important to note that a meaningful PAFRAC is based on an acceptable linear log-log relationship between perimeter and area of patches. Overall, the PAFARC index is favorable as it can measure the complexity of patches across different patch sizes (Leitao 2006).

CHAPTER V

INTER-URBAN SELF-ORGANIZING CRITICALITY

China's urbanization process can be divided into three periods (Figure 5-1). The first period is from 1949 when the People's Republic of China was founded to the early 1960s. During this period urbanization rate (the percentage of urban population over total population of China) increased quickly from 10.64 in 1949 to 19.29 in 1961. During the second period from the early 1960s to the end of 1970s, the urbanization process almost stopped, and there was no increase but a slight decrease of urbanization rate from 19.29 in 1961 to 17.91 in 1978. From 1978, China entered into the rapid urbanization period. The urbanization rate reached 29.04 in 1995 and 41.76 in 2006.

At the same time, the number of cities in China increased potentially (Figure 5-1). In 1949, there were 132 cities, and this number had been quite stable in the 1960s and 1970s. By 1978, the total number of cities only increased to 193. However, the total number of cities in China increased quickly during the 1980s and the 1990s, and there were 668 cities in China by 1997. The rapid increase of the total number of cities has to be contributed by the open door policy and economic reforms since 1978 in China. From Figure 5-1, we can see that the rapid increase of the number of cities come to stop from 1996. In fact, there was a little decrease of the total number of cities from 1998, and there were only 656 cities in 2006.

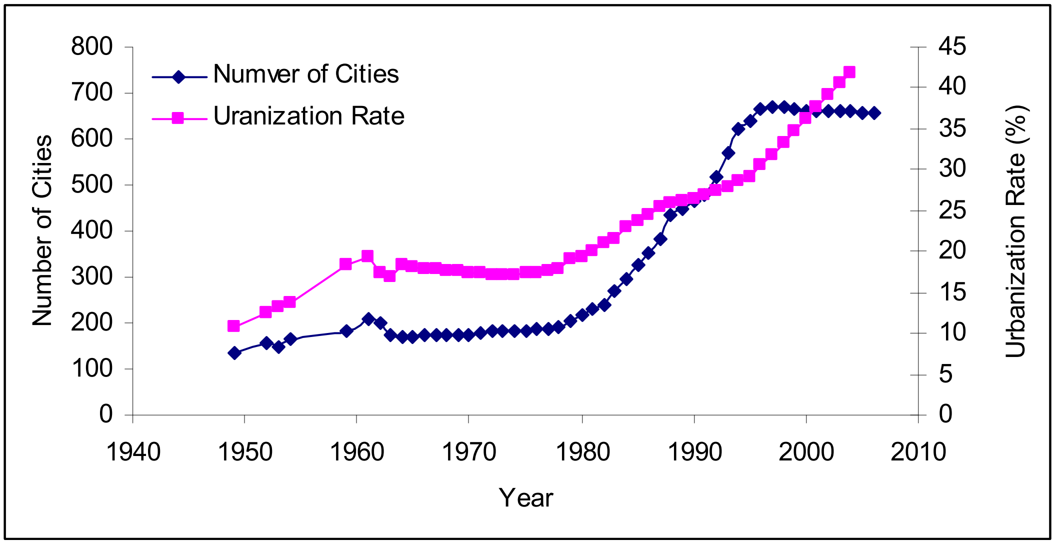


Figure 5-1 The urbanization rate and the number of cities during the past six decades.

However, the increases of urban population and the number of cities were not at the same step (Figure 5-2). During the period from 1960 to the 1970s, the increase rate of urban population was slightly higher than that of the number of cities. However, from the early 1980s, the increase rate of the number of cities exceeded that of urban population substantially. From the end of 1990s, the increase rate of urban population began to surpass that of the number of cities again. The possible reason could be that lots of towns were promoted into cities at the start of rapid urbanization process. However, after a large number of towns were promoted into towns, they could attract much more urban population without the need of more new cities. It is kind of the phase change from quantitative increase of urban population to qualitative change from town to city. After the qualitative change, the state will be kept for a while. The period from the early 1980s to 1996 could be the phase change period.

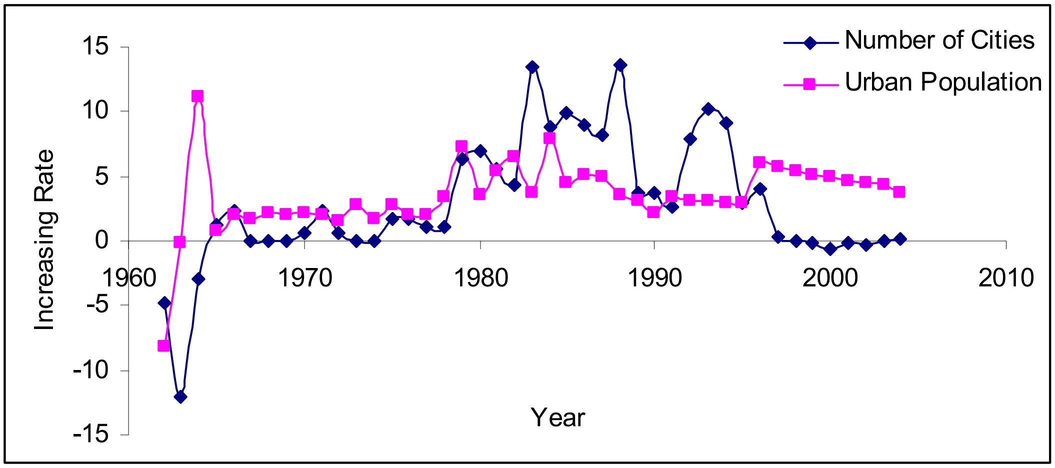


Figure 5-2 The increasing rates of the urban population and the number of cities.

5.1 City Rank-size Distribution

In 1938, there were 108 cities with reasonably reliable data available. Among the 108 cites, 62 cities had a population grater than 0.1 million. The rank-size scatter plot of Chinese cities shows three curve sections in 1938 (Figure 5-3). If a linear log-log rank size relationship is considered as a smooth profile, the rank size distribution of the few relative large cities in 1938 shows no smooth profile. In contrast, the relative medium and small cities above certain size developed a relatively smooth profile.

In 1953, a population census was conducted, and data on city population became available. By 1953, there were 149 cities. Out of there 1949 cities, 26 cities were with a population over half million, 27 cities were in a population size between 0.2 and 0.5 million, 45 cities were in a population size between 0.1 and 0.2 million, and 51 cities were smaller than 0.1 million.

The graph for 1953 shows similar distribution to the 1938 pattern (Figure 5-3). Although there exists a trend toward a relatively more normal or rank-sized distribution of cities, the 1953 graph still indicates the lack of integrated spatial urban system. Compared with the few large cities in 1938, the rank size distribution of those large cities in 1953 is relatively smooth. But, a smooth profile of relative large cities has not been formed yet by 1953. Cities with population size between 0.1 million and 0.6 million developed a smooth profile.

In both 1938 and 1953, relative large cities are few and smaller than Zip'f law predicted while relative small cities are bigger than Zipf's law predicted. After thousands of years of feudalism urbanization, cities in China were developed under an extremely unstable social environment with both domestic wars and foreign invasion during the first half centenary of the 20th. The instability of social environment might be the direct cause of the lagging development of large cities. As argued by Chen, Chinese citizens ran away from large cities and looked for safety in the countryside during the national instability and wartime.

The few large cities are relative similar in size in 1938 and 1953. It appears to indicate the presence of several sets of regional urban systems. This conforms to some extent with Skinner's depiction of the 1843 network and Pannell's depiction of the 1937, 1949, and 1953 network (Skinner 1978; Pannell 1981).

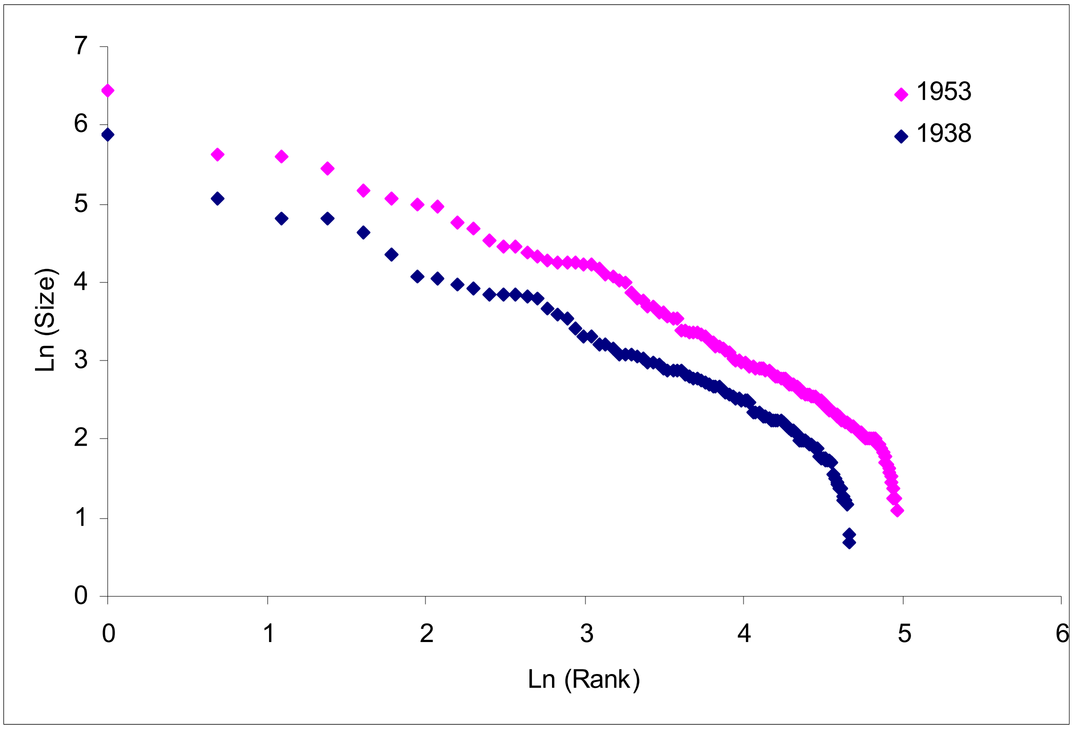


Figure 5-3 Rank-size distribution of Chinese cities in 1938 and 1953.

Over all, the rank size distributions of Chinese cities in 1938 and 1953 are still away from Zipf's law distribution and indicate the lack of a well integrated national network. The relatively large cities are the major reasons. A well integrated urban network has not been formed by 1953 in China. This is in tune with previous studies. Studies by Skinner (1978) and Pannell (1981) indicated the complete national network of China's urban system was formed in late 1950s or1960s.

While the city data is lack for the late 1950s, 1960s, and 1970s, it is almost impossible to study the rank size distribution of Chinese cities during these periods. This study continues to check the urban hierarchy of China from 1980s with Zipf's formula and quantitative methods.

Figure 5-4 shows the rank-size natural log-log plots of Chinese cities in 1984, 1988, 1992, 1996, 2000 and 2003. From this figure we can see that the development of relatively large cities and relatively small cities was quite uneven during the period from 1984 to 2003, and the growth of relatively small cities was faster than the remaining cities. The phenomenon is in consistent with China's urban development strategy. The urban development strategy in China has long been controlling the size of large cities and developing small cities (Zhao and Zhang 1995). During the 1950s, the central government put great efforts into building industrial cities. By the end of the 1950s, Mao proposed to 'limit the growth of big cities and promote small cities' several times (Zhao and Zhang 1995). In 1980, the central government adjusted this policy and sought to 'limit the growth of big cities, moderately develop middle cities, and promote the development of small cities'. Although there were some wording changes, the general urban strategy of the central government has maintained a more or less similar policy since the 1950s.

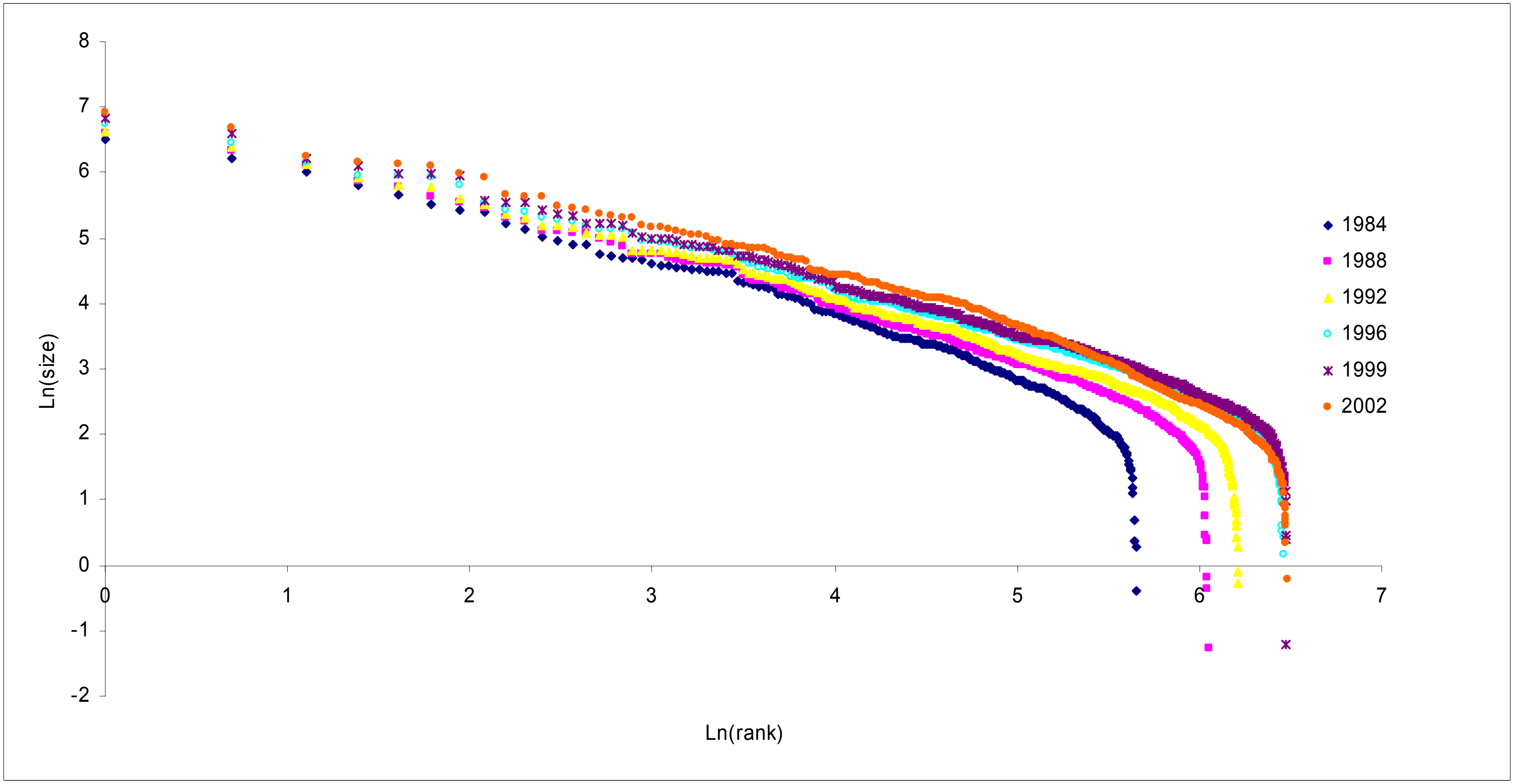


Figure 5-4 Rank-size distribution of Chinese cities between 1984 and 2002.

In addition, Figure 5-4 also indicates that there are good linear relationships with city sizes above certain sizes in each year. This result is not surprising and in consistent with previous studies. Early studies of China's urban hierarchy have demonstrated that the city size distribution of Chinese cities could be described with Zipf's law.

As mentioned before, this linear relationship may suggest that the urban system is spatially integrated and that a variety of forces have affected the development of the system. In 1984, an integrated urban system has already been formed in China. The urban development was not just concentrated in some certain regions. However, as the limitation of the available data, it is impossible to judge when and how the urban system experienced from regional development to integrated growth.

Under the certain thresholds, there is a tail for each rank-size distribution. This is in consistent with previous findings (Reed 2001). In fact, many distributions follow power law only in certain range in urban systems (Newman 2005). A distribution pattern as predicted by the Zipf's law is often found only when very small cities are excluded from the sample (Newman 2005). If the size of the city drops below a certain level, there is hardly any negative correlation between size and rank for this group of small cities (Brakman et al. 1999). And this certain level is neither constant through time nor the same for every country (Newman 2005). A possible rationale for the existing of the thresholds is that very small cities are indistinguishable from rural areas and can be omitted from the data (Brakman et al. 1999). For the Chinese urban system, the existence of these tails to some extent is the result of administrative adjustment. As cities are designated by the central government basically based on population size, many small settlements were administratively set up as cities for regional balance and local economic development. For instance, in 1993, the central government lowered the bar of qualifications for a town to be classified as a city in Western China to promote the development of China’s West. As the results, quite a few new cities were designated in Western China. No matter in term of urban population or the basic infrastructure, these new cities were much more underdeveloped compared with other cities in China.

5.2 Zipf’s Law in the Urban System of China

To model the upper tails of city rank-size distributions, we need to determine the threshold for city size. Many studies have been done to determine the city size thresholds for rank size distribution of urban systems (Newman 2005). Cheshire (1999) proposed three possible solutions – a fixed number of cities, a fixed size threshold, or a given proportion of a country’s cities. In this study, the author chooses a fixed size threshold—100,000. The numbers of cities included to model city size distribution are shown in Table 5-1.

The linear regression results are presented in Figure 5-5. Several interesting findings can be identified. First, in all the six graphs, the largest 10 cities are obviously below the regression lines. That means the sizes of largest 10 cities are smaller than the predicted sizes by the general linear trend of rank size distribution. Secondly, given the fact that the R^2 values are higher than 0.96 for all the regression results, it appears that the linear model describes the Chinese city size distribution very well. Last, all the estimated coefficients locate within the range from 0.8 to 1.0. So, city size distribution in China conforms to Zipf's law in general. This result is in line with the findings of previous urban hierarchy studies of China.

Table 5-1 Regression results on Zipf's distribution of Chinese cities.

Year	Slope Coefficient	R^2	Number of cities
1984	0.8803	0.9797	221
1988	0.841	0.9903	307
1992	0.8163	0.9909	367
1996	0.7942	0.9901	496
2000	0.8092	0.987	519
2003	0.9001	0.9701	457

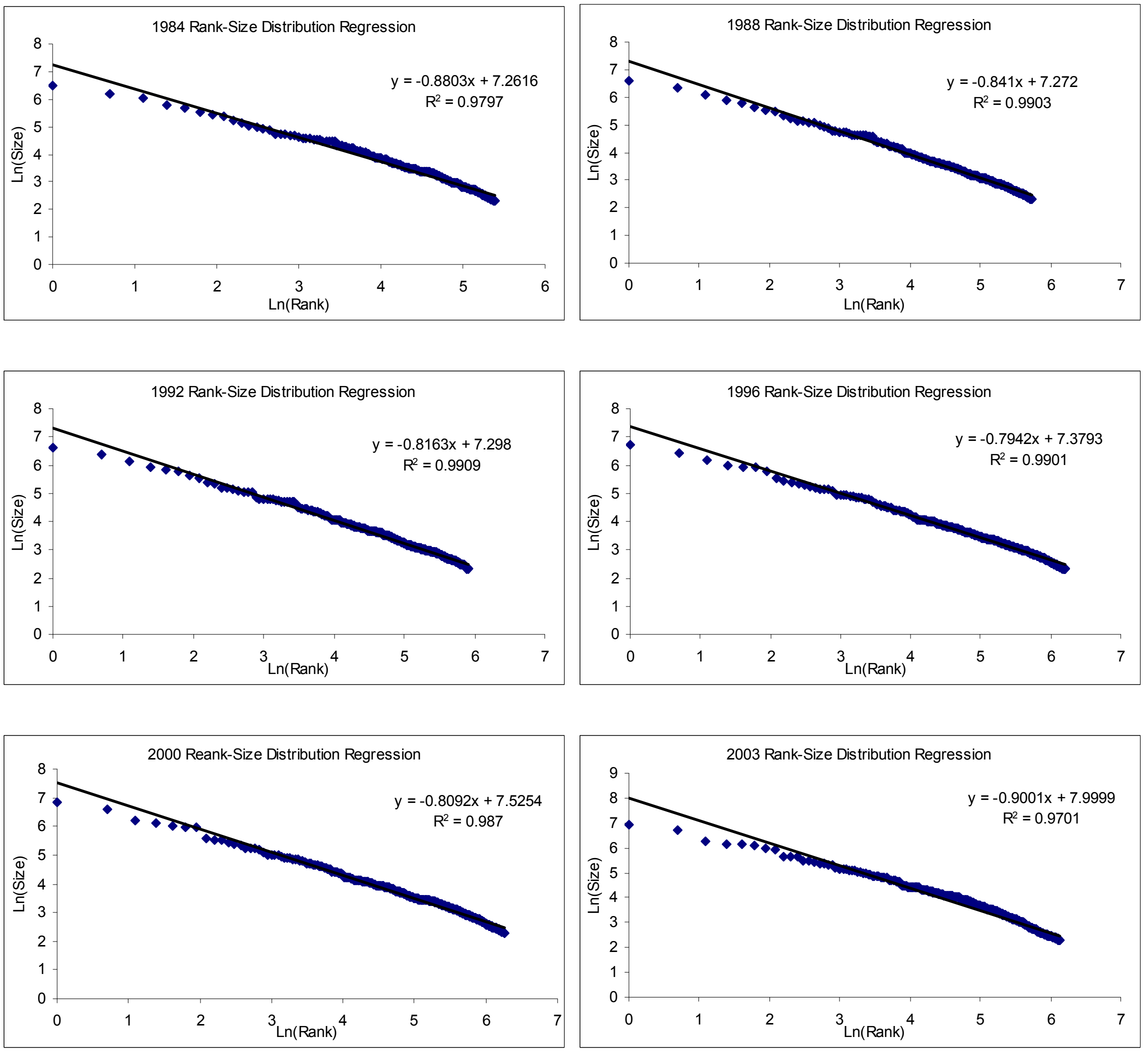


Figure 5-5 Rank-size distribution regression of cities.

Zipf's law is an important indicator of SOC in urban system (Bak 1996). Studies by Chen and Zhou (2004, 2008) have mathematically proved the connection between Zipf's law and SOC. Chen and Zhou (2004, 2008) consider hierarchy as a parallel concept to 'space' and 'time' in geography, and propose that Zipf's law, like fractal and 1/f noise as the 'snap' and the 'fingerprint' of SOC in space and time (Bak 1996), should be considered as a signature of SOC in the self-organized process of urban hierarchies. In their word, “if we think of the urbanization process as a phase transition from a rural to an urban settlement system, rank-size distribution (Zipf’s law) is actually the ‘fingerprint’ of spatial complexity in the self-organized critical state of urban systems” (Chen and Zhou 2008, 357).

In fact, previous urban hierarchy studies have already hinted the connection of Zipf’s law with SOC. Urban researchers have already long been attempting to explain this observed regularity of Zipf’s law with economic models and stochastic models. Although neither economic models nor stochastic models have been wholly successful (Overman and Ioannides 2001), there are a general agreement that rank-size distribution appears in an urban system with huge area, large population, long history of city development. Large area and huge population means the urban system as complex system with large number of interacted sub-urban systems. The long history of city development is the process of urban network development form local to regional, to the whole network connection. The early established complete urban system indicates the state of SOC of the urban system with all cities related to each other. At the state of SOC, Zipf’s distribution will be formulated in urban system.

In China’s case, the urban system was composed by several regional systems before the1950s, and evolved to a national network later. Historically, the large and rugged terrain with little transportation development made the regional urban systems spatially discrete (Skinner 1977). With the increasing investment in transportation system, especially in road, rail and air transport, there developed strong spatial linkages among the regional urban systems, and a well-connected national urban network system formed. The studies by Pannell (1981) and Skinner (1978) indicated the complete national network of China's urban system was formed in the late 1950s and 1960s. This dissertation study also concludes the formation of Zipf's law distribution formed after 1953 and before 1984 in China's urban system. If Zipf's law is considered as a signature of SOC in the self-organized process of urban hierarchies, China's urban system has reached the stage of SOC in the 1980s. The urban rank-size distribution has followed the Zipf's law during the study period from 1984 to 2003.

There are also some fluctuations of Zipf's coefficient. During the period between 1984 and 1996, the estimated coefficient decreased, which means Chinese cities became more evenly distributed. From 1996, there shows a relatively quick increase of estimated coefficient. Chinese cities become more unevenly distributed. But, all the estimated coefficients are located within the range from 0.8 to 1.0.

In fact, previous studies have already noted that the slope coefficient of Zipf's law changes with time in many countries (Fonseca 1989). According to Brakman et al. (1999), the temporal distribution of the Zipf's coefficient will be in n–shape with a peak value of 1 or more, which is supported by American cities (Figure 5-6). Parr (1985) considered that the position occupied by an individual nation in the sequence of the n-shaped coefficients is related to its overall level of development, and perhaps to its age. For China's case, it is impossible to locate the short 20 years' curve in the sequence of the n-shaped curve.

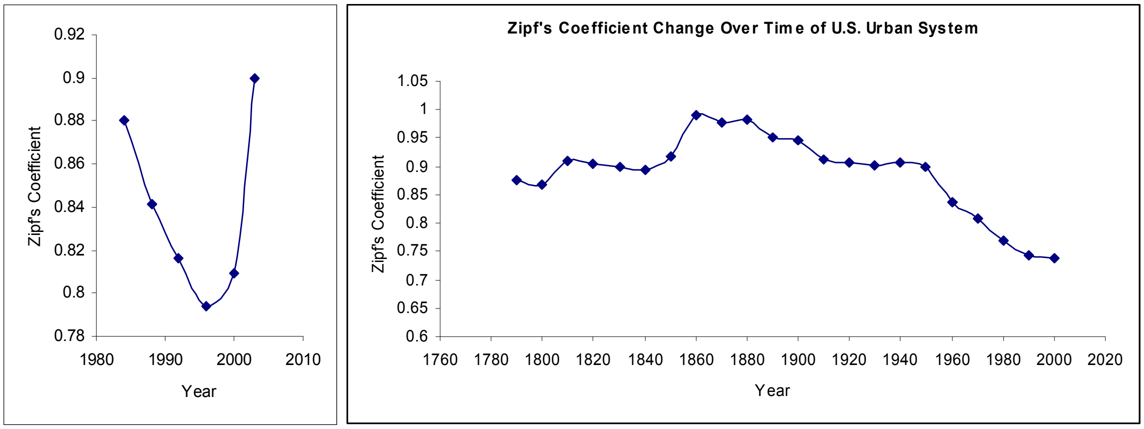


Figure 5-6 Zipf's coefficient change over time of Chinese and U.S. urban systems.

As for the decrease of Zipf's coefficient of the US urban system from the 1880s, Gabaix (1999b) suggests that one possible explanation is that more small cities flourished, and that the small cities have a lower local Zipf's coefficient (Ioannides and Overman 2003). The Zipf's coefficient of US cities decreased from 0.983 to 0.737 in 120 years (Batty 2003). This explanation seems could also be applied to China's case. The period with decreasing Zipf's coefficient from 1984 to 1996 is also the time when large number of towns was promoted into cities in China. These small new cities with relatively short history of urban development are definitely not well connected to the existing complete national urban network. To some extent, these new small cities bias the state of SOC of the urban system which explains the existing of the long tail in the city rank-size distribution and the need of a threshold for Zipf's law in urban system.

The important contribution of SOC is that it reveals the internal dynamics behind the final statistical size-distribution of self-organizing systems in their steady periods (Portugali 2000). While the above part has analyzed Zipf's law in China's urban system as the final statistical size-distribution of SOC, the following explores the internal dynamics of China's urban system.

5.3 Zipf's Law in Different Sized-tiers of Cities

According to urban population size, China divides its cities into four tiers – extra-large cities with urban population over 1 million, large cities with population between 0.5 and 1 million, medium cities with population between 0.2 and 0.5 million, and small cities with population below 0.2 million (China State Statistical Bureau 1985). In this study, cities with population below 0.1 million are grouped as extra-small cities. From Table 5-2, we can see that the numbers of large and extra-large cities have been kept increasing, while the number of small cities has been increased rapidly during the period from 1984 to 1996, and then began to decrease a little from 1996. The number of medium-sized cities increased potentially from 1984 to 2000, but began to decrease since 2000.

Table 5-2. The size distribution of Chinese cities.

Number of cities	1984	1988	1992	1996	2000	2003
Total	295	434	517	666	663	660
Extra-large cities (> 1 Million)	20	28	32	35	39	47
Large cities (0.5~1.0 Million)	30	30	32	45	56	71
Medium cities (0.2~0.5 Million)	78	108	132	185	194	151
Small cities (0.1~0.2 Million)	93	141	171	231	229	188
Extra-small cities (< 0.1 Million)	74	127	150	170	145	203

The rank-size analysis indicates that Zipf's law also presents in different size-tiers of cities. The Ln-Ln regression of each size-tier of cities gets the value of R^2 above 0.95 (Table 5-3). There exists significant relationship between sizes and ranks of cities. The Zipf's coefficient varies from 0.62 to 1.3. Since the Zipf's law analysis of the national urban system of China doesn't have extra-small cities included, the Zipf's law analysis of different sized-tiers of cities doesn't include extra-small cities either.

Table 5-3 Zipf's coefficient and R^2 values of each sized-tier of cities in China.

		1984	1988	1992	1996	2000	2003
Extra-large Cities	**Zipf's coefficient**	0.6838	0.6542	0.6336	0.6211	0.6433	0.631
	R^2	0.9839	0.9908	0.9881	0.9895	0.9896	0.9912
Large Cities	**Zipf's coefficient**	0.8051	1.0086	0.8956	0.8382	0.7943	0.6617
	R^2	0.9573	0.9811	0.9825	0.9766	0.9785	0.991
Medium Cities	**Zipf's coefficient**	0.9013	0.8562	0.8878	0.7807	0.7788	1.1121
	R^2	0.9872	0.9948	0.9902	0.9981	0.9904	0.9974
Small Cities	**Zipf's coefficient**	1.3035	1.1088	1.1008	1.154	1.1768	1.2439
	R^2	0.9907	0.9912	0.988	0.9944	0.9962	0.9925

Small Cities have higher Zipf's coefficients while the extra-large cities have the lowest Zipf's coefficients (Figure 5-7). In each respective year, the Zipf's coefficient of small cities is larger than 1 while that of extra-large cities has always been between 0.6 and 0.7, and the Zipf's coefficients of large cities and medium cities are between the zipf's coefficients of extra-large cities and those of the small cities. The Zipf's coefficients' difference reveals the different distribution of cities in terms of size. The low Zipf's coefficients of extra-large cities mean that the extra-large cities are relatively similar in size while small cities are more unevenly distributed in size as their Zipf's coefficients are higher.

The Zipf's coefficient's dynamics of China's urban system seem more rely on small and medium-sized cities. The overall Zipf's coefficient trends of small and medium-sized cities are both decreasing first and then increasing, which is similar to the dynamics of the Zipf's coefficients' of China's urban system. The reason is because there are large numbers of small and medium sized cities but few extra-large and large cities. The Zipf's coefficient of large cities decreases overtime. The Zipf's coefficient of extra-large cities is relatively stable overtime.

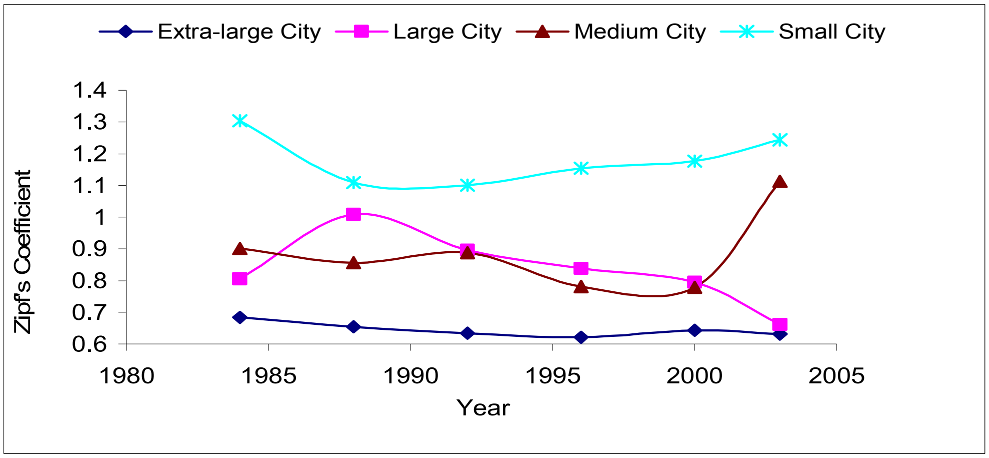


Figure 5-7 The dynamics of Zipf's coefficients of different size tiers of cities.

While many urban scholars suggests that small cities have a lower local Zipf's coefficient in their Western urban systems studies (Gabaix 1999b; Ioannides and Overman 2003), this study of China's urban system finds that small cities have a higher Zipf's coefficient. There are differences on the definition of small cities. But, China's case prove that the smaller the cities, the higher the Zipf's coefficient in general. Do there exist fundamental differences between China's urban system structure and the structure of Western urban systems? It will be interesting research for the future.

The break-down of Zipf's coefficients among different sized-tiers of cities may indicate the relative maturity of different sized-tiers of cities. In fact, there is widespread evidence that Zipf's distributions of population and other socio-economic activities are in related with mature or steady systems (Shiode and Batty 2000). However, there is still no common accepted explanation on the relation between the maturity of a system and the Zipf's distribution.

It is quite imaginable that those extra-large and large cities are generally with long history of urban development and well connected while small cities are mainly composed by new cities recently promoted from towns. Among the 47 extra-large cities in 2003, 44 cities can be traced back to at least 1938. Thirty three out of the 71 large cities in 2003 can also be traced back to at least 1938. During early years' development, these long-history cities were the local urban centers attracting around population. With urban development, these cities became bigger and attracted population from larger surrounding areas. With this positive feedback, these long-history cities turned out to be current extra-large and large cities.

The small city data proved that the small cities of China were mainly composed by new cities. Among the 391 small cities in 2003, 340 cities were set up in 20 years. The promotion of new cities mainly took place during the period from 1984 to 1996 (Figure 5-8). The newly promoted cities were dominated by small cities and a few medium cities. The large amount of new small cities were set up based on towns, and these small cities are mainly served as regional centers and might not be well connected to the urban system network.

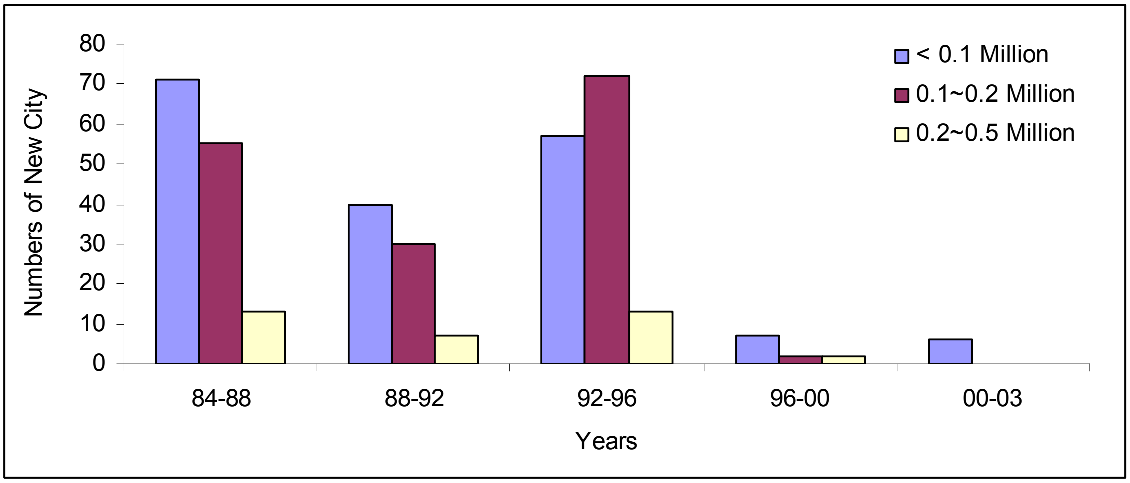


Figure 5-8 The numbers of newly promoted cities during each period.

After being promoted into cities, those small new cities still need a period to really merge into the well-collected urban system network (Table 5-4). This can be judged from the evolution of population sizes of these cities. For Example, of the 71 new promoted cities with population size smaller than 0.1 million in 1988, 40 percent were still tiny cities with population smaller than 0.1 million, 54 percent made slight growth with population bigger than 0.1 million and smaller than 0.2 million, and only seven percent grew into medium cities in 2003. Of the 54 new promoted cities with population size smaller than 0.2 million but bigger than 0.1 million, two cities even experienced population loss, 54 percent were still in a population size smaller than 0.2 million, 44 percent grew into medium cities, and only one city became a large city in 2003. From these data, we can see that these new promoted cities still need long time to grow and merge into the existing well connected urban system network. The reality is that only part of the new cities which really get connected to the urban system network.

Table 5-4 The development of cities promoted during 1984-1988 by 2003.

	< 0.1 Million	**0.1~0.2 Million**	**0.2~0.5 Million**	**0.5~1.0 Million**
< 0.1 Million	39.44	53.52	7.04	0.00
0.1~0.2 Million	3.70	50.00	44.44	1.85
0.2~0.5 Million	0.00	7.69	76.92	15.38

While it is difficult to tell the direct relationship between the city maturity and Zipf's coefficient, the study here indicates that large cities with long history, supposed to be relative mature, have a rank-size distribution with smaller Zipf's coefficient. While small cities, relatively newly promoted, have a rank-size distribution with larger Zipf's coefficient.

At the same time, the results also justify the necessary to set up a threshold and exclude certain amount of small cities for Zipf's law analysis. While using Zipf's law in urban system, a very important precondition is what a city is. While governments can designate a place as a city, weather and when the designated city can be connected to the urban system are still uncertain.

5.3.1 City Size Dynamics in Different Sized-tiers

After the quality change from towns to cities, the new promoted cities will be able to accommodate more urban populations, and there will quantitative urban population increase in the future.

While the numbers are relatively small and the contribution to the dynamics of Zipf's coefficients is limited, the attractiveness to new urban population of extra-large and large cities are as competitive as the small and medium cities as the whole. During the period 1984 to 1996, small and medium cities experienced relatively larger population growth (Figure 5-9). However, from 1996, population increase only happened in the tiers of extra-large and large cities while the tiers of small and medium cities experience potential population loss.

However, Figure 5-9 may not reflect the true growth of cities. The population increase of extra-large and large cities as a group is contributed by the population growth of existing extra-large and large cities and also the upgrade of medium and small cities into large and extra-large cities. The population increase of small cities as a group is contributed by the population growth of existing small cities and also the promotion of towns to small cities.

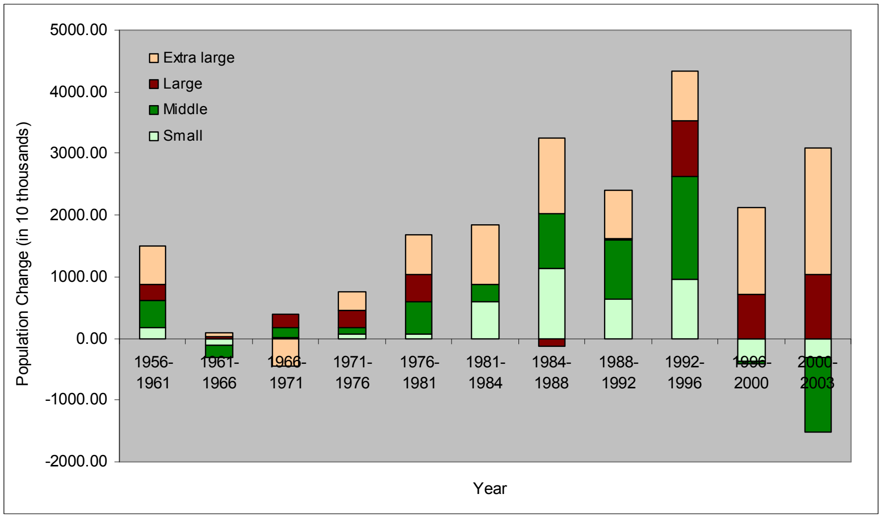


Figure 5-9 Population growth of cities in different sized-tiers during each period.

From Figure 5-10, we can see that the new promoted cities were the major sources of urban population growth during the period from 1984 to 1996. As discussed before, these new promoted cities were dominant by small cities. Once included in small cities, the contribution of extra-small and small cities, in terms of attracting urban population, is much lesser than that of large and extra-large cities. During the period from 2000 to 2003, those extra-small and small cities even experienced potential urban population loss.

In contrast, large and extra-large cities have continually been the major sources of urban population growth. Especially during the period from 2000 to 2003, almost all the urban population growth happened in large and extra-large cities. One important thing need to be mentioned here is the floating population. With the economic reforms and relief of previous stringent migration policies, large amount of previous agricultural labors were released from agricultural activities, and turned into floating population in urban areas, especially large cities. The major floating population works in cities, but is still registered as residents and develops homes in their home towns. The floating population was not counted as urban population at all. The actual urban population in large cities in China is underestimated in, which is agreed by most urban scholars.

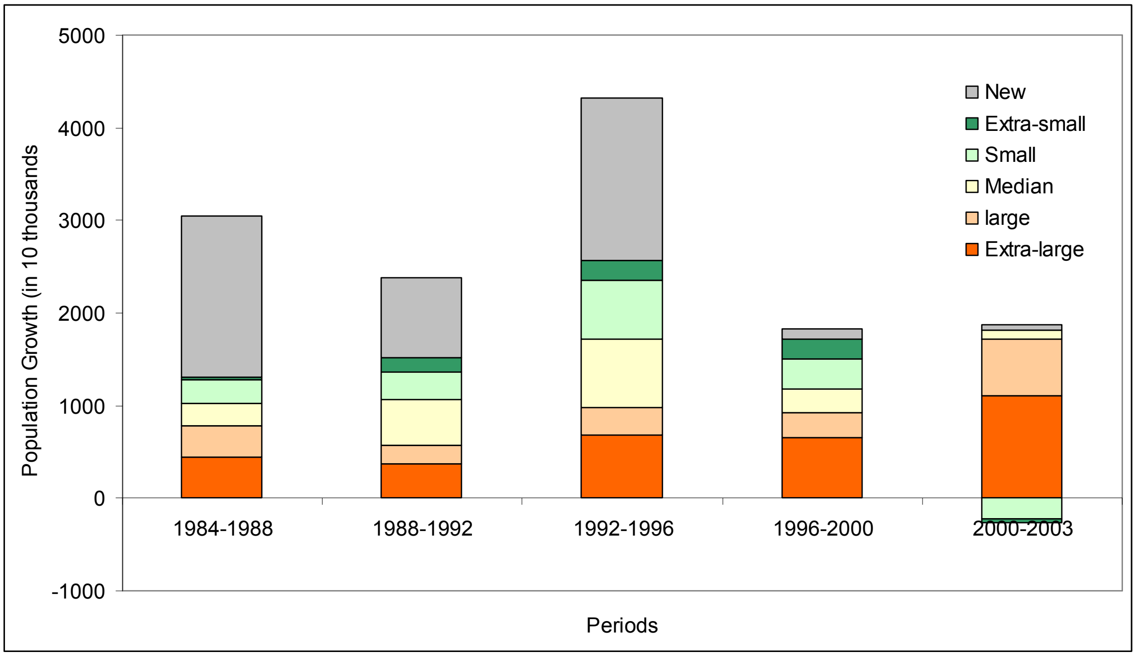


Figure 5-10 The distribution of new urban population in different sized-tiers of cities during each period.

5.3.2 City Rank Dynamics in Different Sized-tiers

To analyze and explain city rank dynamics, understanding of the relationship between city rank and population size is necessary. During the rapid urbanization process, almost all Chinese cities experienced the increase of urban population. While urban population increased more rapidly in some cities and relatively less rapidly in other cities, the rank dynamics show the relative urban population growth more directly. However, one thing needs to be remembered is that the same urban population increase will cause larger rank increase of small cities while less rank increase of large cities.

Extra-small and small cities are much more dynamic than extra-large and large cities on rank (Figure 5-11). During the periods from 1984 to 2003, the average absolute rank change is around 40 to 100 for extra-small cities, and 25 to 80 for small cities in each period. In contrast, the average absolute rank change is only 0 to 3 for extra-large cities, and 2 to 12 for large cities. At the same time, we can also see the medium-sized cities are becoming more dynamic.

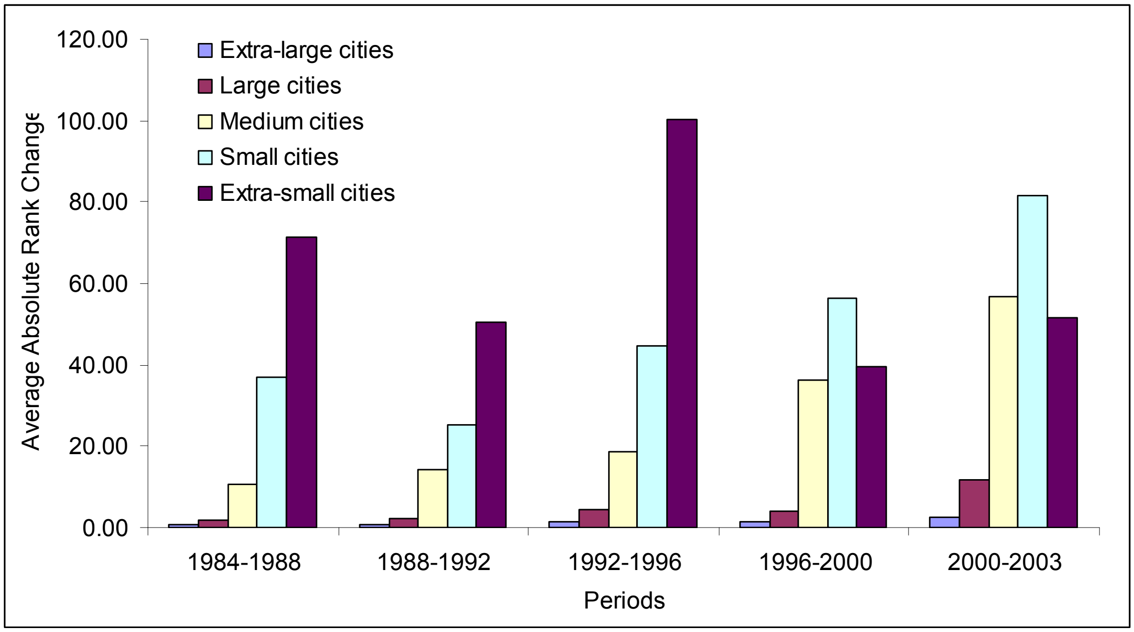


Figure 5-11 Average absolute rank change of cities in different sized-tiers during each period.

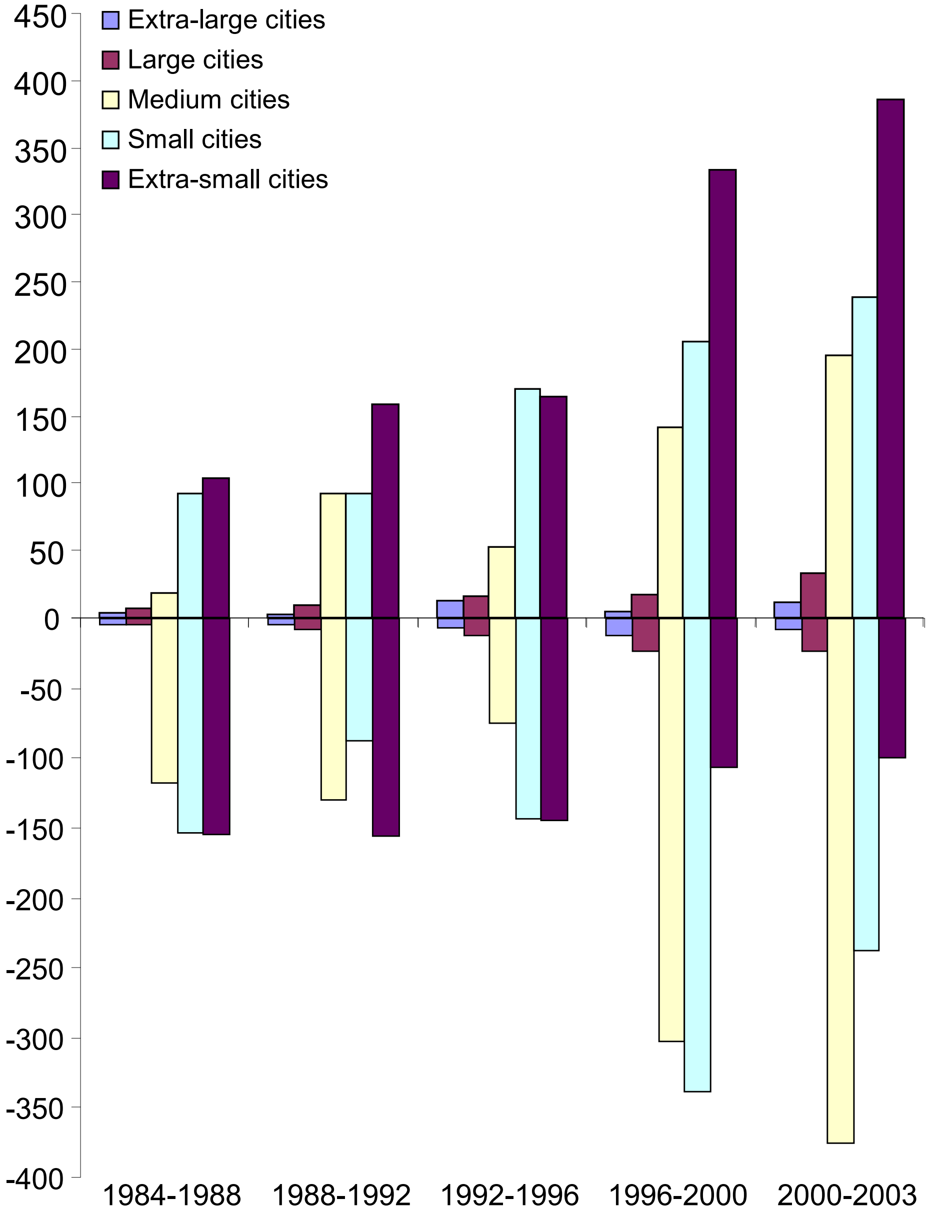


Figure 5-12 Maximum rank change of cities in different sized-tiers during each period.

In terms of maximum rank increase and rank decrease, the possible rank increase or decrease of small cities are much higher than that of large cities (Figure 5-12). The extra-large and large cities are all very stable with the maximum rank increase less than

11 and 33 respectively, and maximum rank decrease less than 8 and 23 respectively. In contrast, the maximum rank increase of extra-small and small cities reaches as high as 386 and 239 respectively. The maximum rank decrease of extra-small and small is as large as 156 and 338 respectively.

The stability of extra-large and large cities in rank might be contributed by institutional factors. Overall, those extra-large and large cities are generally with high administrative levels while those small cities are generally with low administrative levels.

Cities in China are designated by the central government. The central government has long been considered as the major factor shaping the urban system of China. The impact of the central government on China's urban system is in various aspects, but the administrative level is definitely one of the most constant and has long-term effect ones. In China, cities are divided into multiple administrative units with different economic decision-making power, which in turn affects the outcome of their speed and level of development. In general, cities can be classified into five administrative tiers in China. The first tier is municipalities reporting directly to the central government, which include Beijing, Shanghai, Tianjin, and Chongqing. These four cities, known as "Zhi Xia Shi" in Chinese, are at the top of the administrative hierarchy among Chinese cities. The second tier includes 15 semi-provincial level cities and 9 of them are capitals of provinces. They are cities with independent planning authorities, often possessing provincial level power in economic administration. The third tier is the remaining 18 provincial capital cities. The fourth tier is prefectural level (regional) cities. Their development is directly subordinate to the provincial government. Compared with prefectural cities, capitals of provinces are the locations of the provincial governments, so they have a relatively higher administrative power. The last group is county-level cities. Over all, the 37 cities at first three tires are with relatively high administrative powers.

By the end of 2003, there are 47 extra-large cities (cities with population over 1 million). Among those 47 extra-large cities, 31 of them are with relatively high administrative levels. From the rank changes of cities with high administrative levels, we can tell that their ranks were quite stable, except Shenzhen, Haikou, Xiameng, Yinchuan and Ningbo with obvious rank increase (Figure 5-13). Shenzhen and Xiameng are the first four Special Economic Zones designated in 1979. Haikou and Ningbo are relatively newly upgraded cities. The administrative upgrading of cities seems activate the further growth of these cities. Compared with the dynamics of those medium and small cities with low administrative levels, rank changes among those large cities are rather minor.

While some cities were upgraded after the urban population growing into certain level, some cities were upgraded and then experience rapid population growth. It is difficult to tell which the cause is and which the result is between the administrative upgrade and the urban growth. One thing for sure is the institutional factors have positive impact on the urban development of large and extra-large cities in China. In contrast, the rapid urban development of small cities has been termed as "bottom-up" growth with common agreement by many scholars.

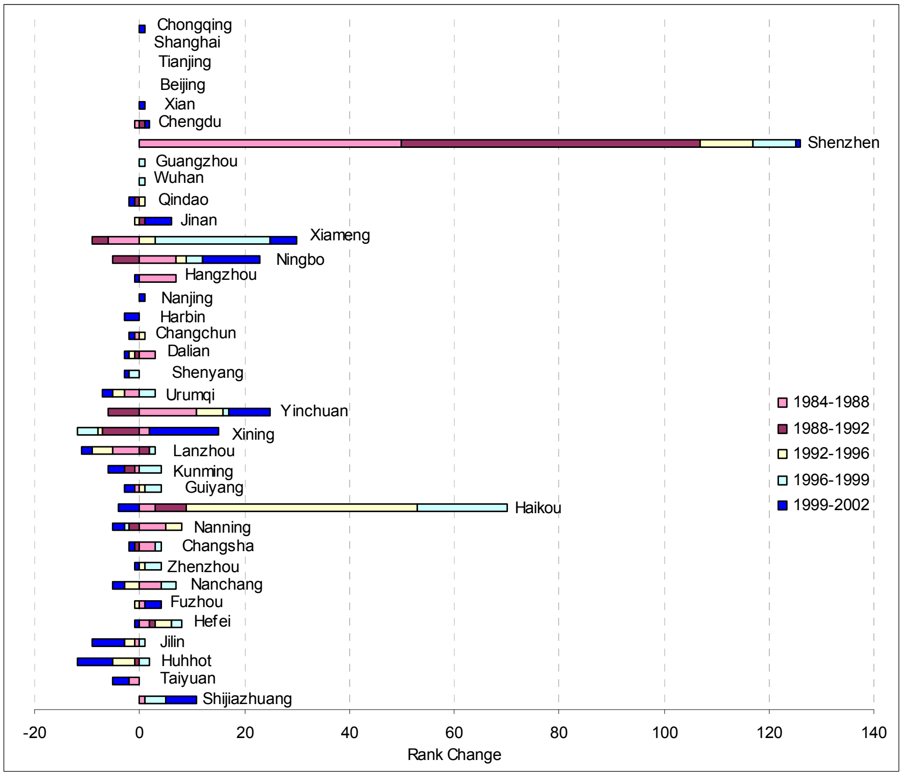


Figure 5-13 Rank change of cities in high administrative levels from 1984 to 2003.

In summary, small Cities have relatively higher Zipf's coefficients while large cities have the lower Zipf's coefficient. In China, small cities are generally new cities and large cities are relatively mature. The result further provides positive support for the conclusion that the Zipf's coefficient may indicate the relative maturity of cities to some extent. Overall, small cities have more impact on the Zipf's coefficient of the urban systems than large cities because of the large number of small cities. However, large cities accommodate more new urban population than small cities do, especially in the past decade. Large cities are stable, and generally with higher administrative level.

The relation between Zipf's coefficients of different sized-tiers of cities with those of the urban system will lead to the discussion of developing large or small cities. In fact, to develop large or small cities has long been a debate in China's urban development. While previous studies have mainly concerned on economic efficiency and environment protect, SOC theory here may provide a different vision. SOC is a balance between order and disorder. While China has long been emphasized the development of small cities, the direct results are the long tail of city rank size distribution and under development of large cities. This will influence the energy and entropy interaction among cities in urban system. In the long run, larger catastrophe may happen to the urban system. In fact, the burst of floating population to large cities since 1990s have already caused large number of serious problems.

5.4 City Rank Dynamics

The city rank dynamics show quite interesting pattern from 1984. First, large cities were still quite stable in rank sequences. Almost all the top 100 large cities showed little rank dynamics. Second, the rank dynamics patterns before 1996 (Figure 5-14) are quite different from those after 1996 (Figure 5-15). During the periods from 1984 to 1988, 1988 to 1992, and 1992 to 1996, there were a few relatively medium-sized cities with rank increase but large number of relatively small cities with rank decrease. The overall pattern is with rank increasing, a city's rank decreasing more. For the periods from 1996 to 2000 and 2000 to 2003, there were lots of small cities with rank increasing while there were quite a lot of middle-sized cities with rank decrease. The plots of rank dynamics of cities reveal quite different urban growth pattern before and after 1996.

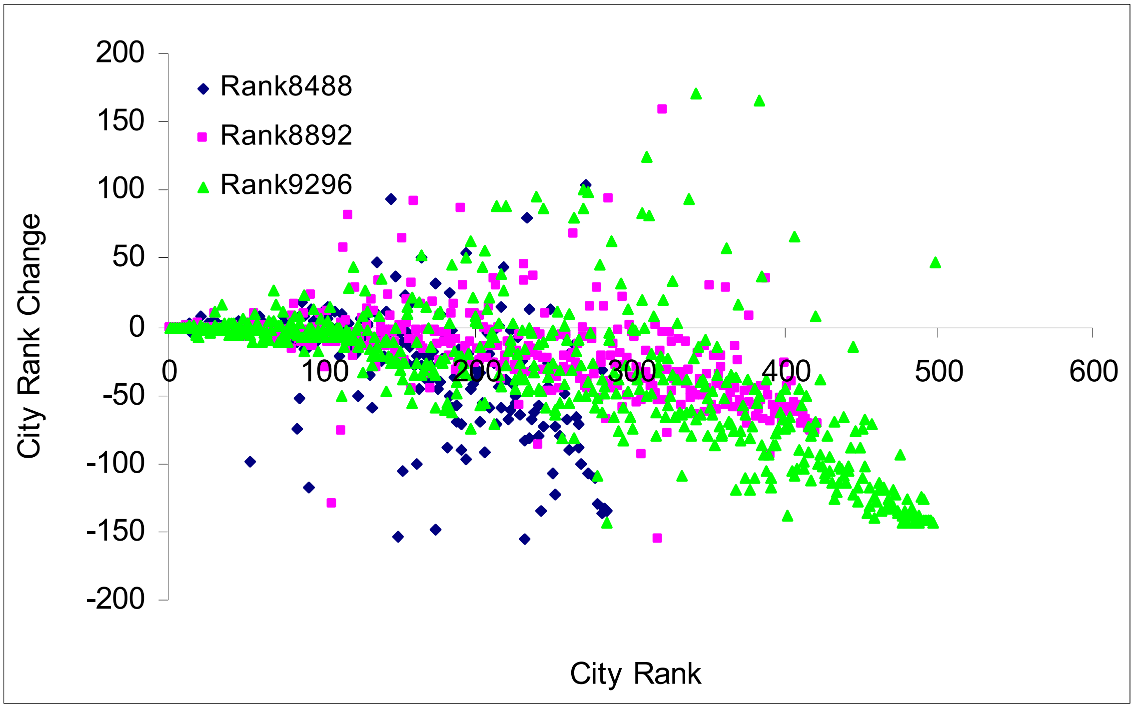


Figure 5-14 City rank dynamics during the periods from 1984 to 1996.

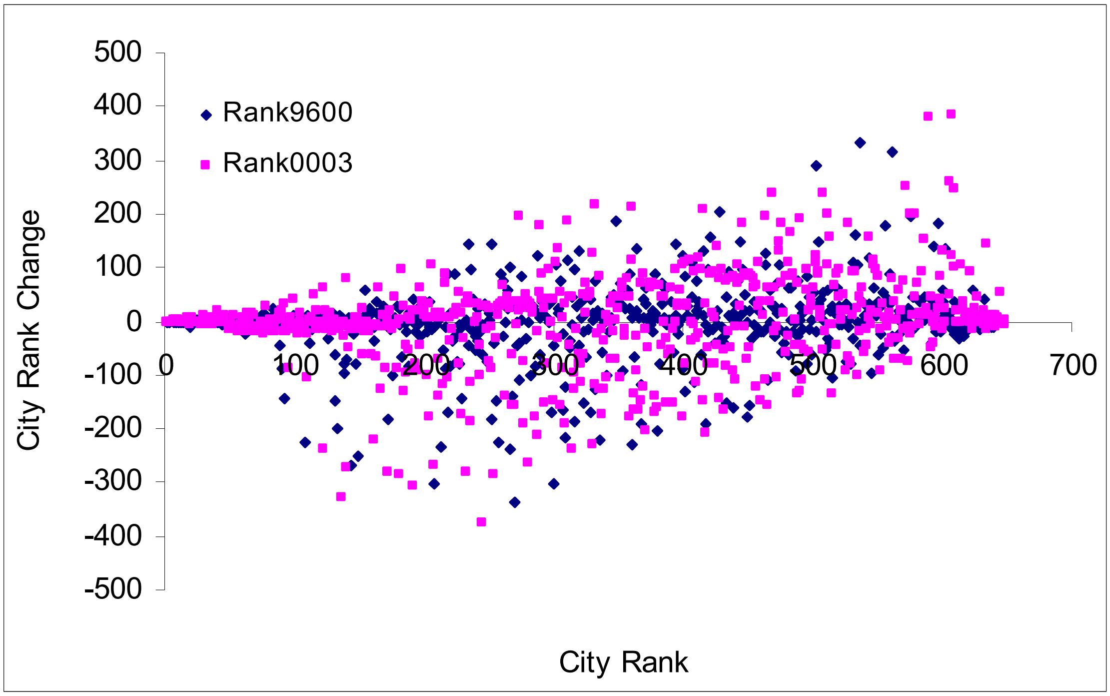


Figure 5-15 City rank dynamics during the periods from 1996 to 2003.

As there are a large number of cities, the author mapped the distribution of cities with rank decline and distribution of cities with rank increase separately to show the spatial distribution of rank dynamics (Figures 5-16 & 5-17).

Before 1996, cities with rank decline are spatially distributed all over the country and the distribution of cities with rank increase is relatively random. During the period between 1984 and 1988, there are 51 cities with rank increase, and broadly distributed in east area. During the period between 1988 and 1992, the 65 cities with rank increase show relatively clustered distribution mainly in Guangdong and Shandong provinces. Guangdong Province has been the earliest area with economic reform and open policies.

Three out of the first four special economic zones designated in 1980 locate in Guangdong. In 1984, Qingdao and Yantai in Shandong Province along with other 12 costal cities were opened to overseas investment. During the period between 1992 and 1996, Guangdong and Shandong provinces are still the major areas with city rank increase, but we also can tell that many cities along Yangtze River also experienced rapid rank increase. Yangtze River Delta was set up as an open economic zone as early as in 1985. In 1990, more cities in the Yangtze River valley were opened to overseas investment. A chain of open cities along the Yangtze River was formed.

From 1996, a large number of cities were involved in rank increase and rank decrease. Both the cities with rank decrease and cities with rank increase show clustered distribution. During the period between 1996 and 2000, cities with rank increases clustered in the provinces of Jiangsu, Zhejiang, and Hubei while Shandong and Guangdong witnessed major decrease of city ranks. During the period between 2000 and 2003, increase of city rank mainly took place at southeastern costal area while cities in the Northeast China, Hubei and Jiangsu provinces experienced quite rank decrease. Since 1992, a large number of border cities and all the capital cities of inland provinces have been opened by the central government of China. In fact, the open policies have been broadened throughout the country and are not special anymore. Overall, the favorate economic policies affected the spatial distribution of city development before 1996.

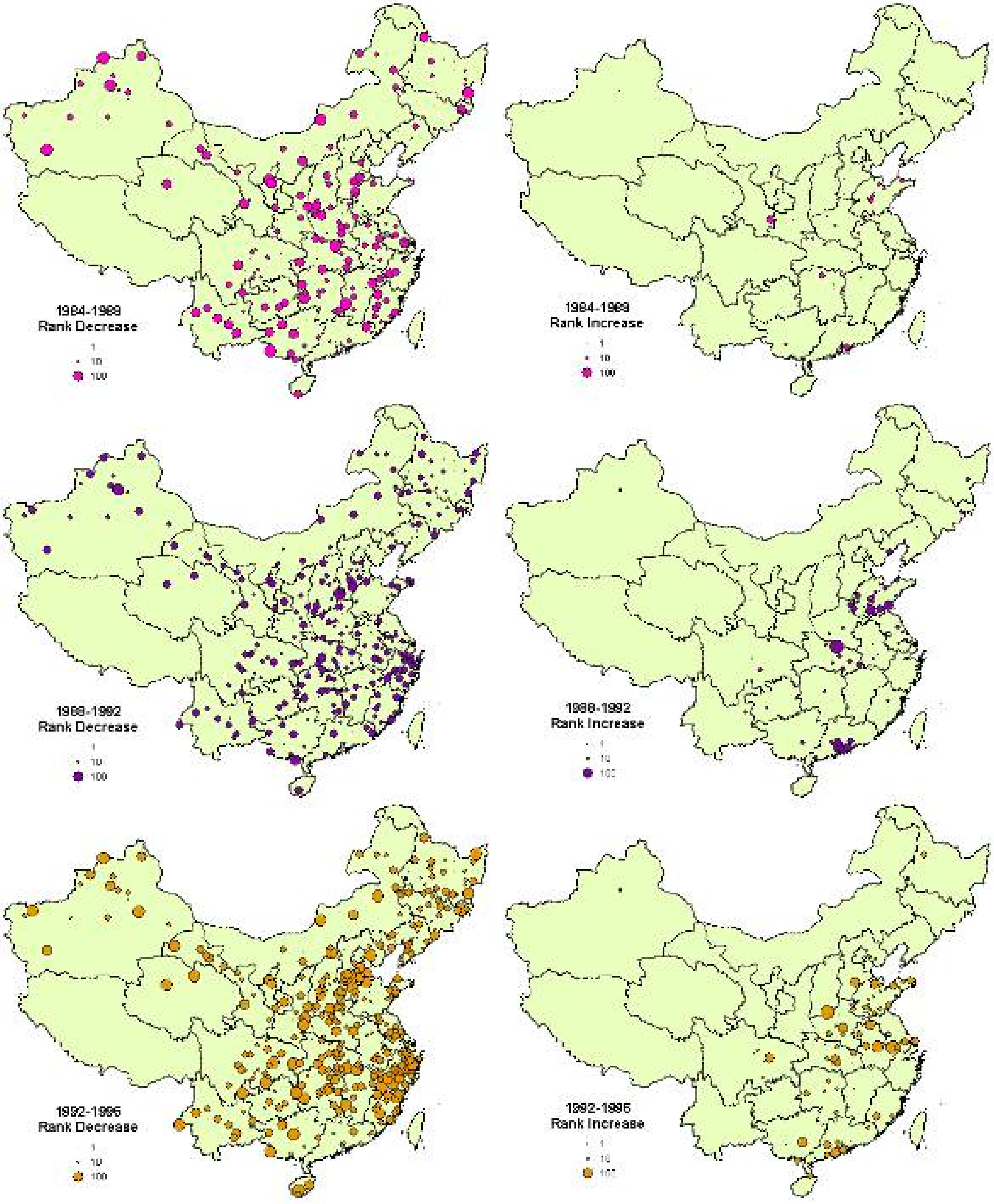


Figure 5-16 Spatial distribution of cities with rank decrease and increase in during the periods of 1984-1988, 1988-1992 and 1992-1996.

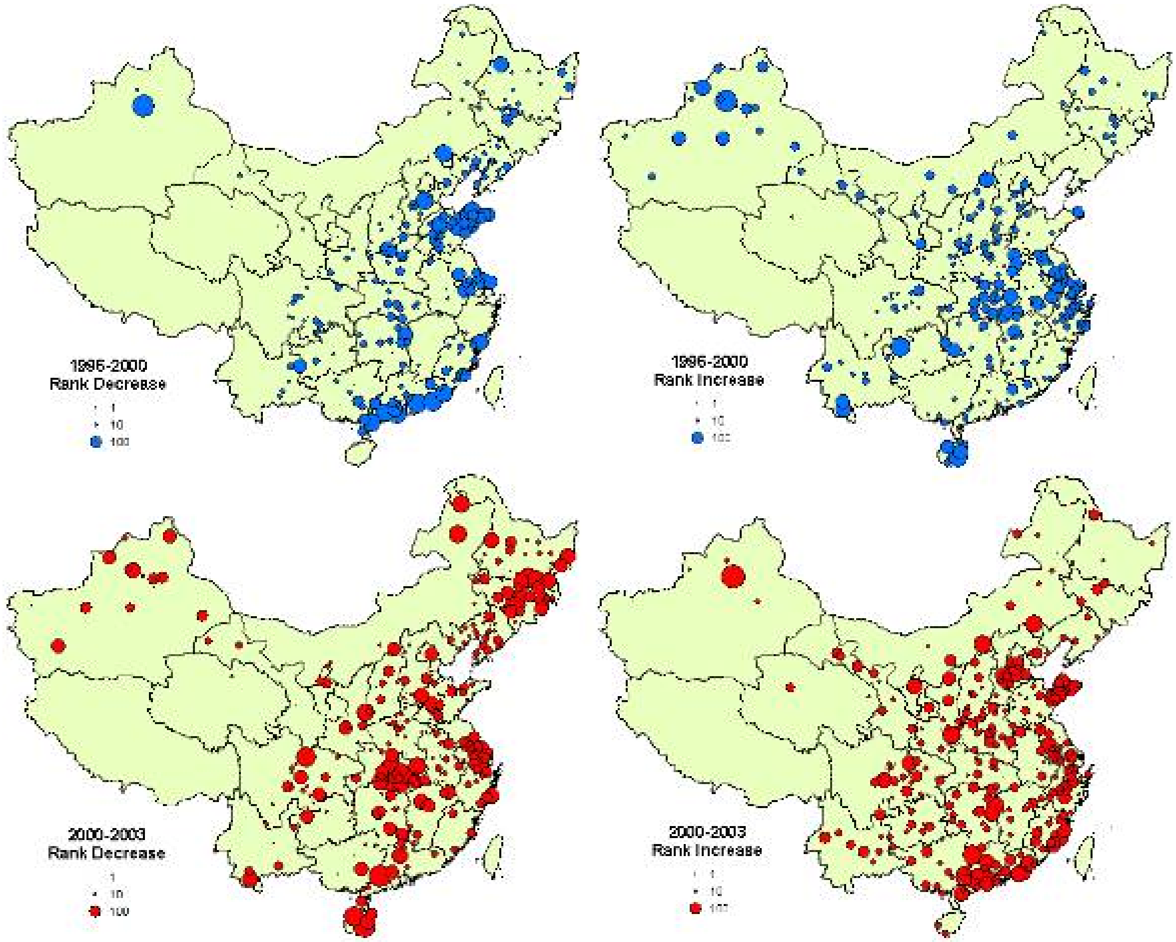


Figure 5-17 Spatial distribution of cities with rank decrease and increase in during the periods of 1996-2000 and 2000-2003.

From above analysis, we can see that the central government played an important role in spatial dynamic of city ranks during the period between 1984 and 1992. Although not all open cities showed rapid rank increase, the limited number of cities with rank increase mainly located in areas with favorite economic policies by the central government. With the economic reforms broadened through the country, those economic policies are not special anymore. From 1996, large number of cities experienced rank increase. Both cities with rank increase and rand decrease show clustered distribution. For the dynamic of the urban system during the period between 1996 and 2003, the agglomeration of economies might be the major factor.

5.5 Results and Discussion

Zipf's law, as an important indicator of SOC in urban system, depicts the urban hierarchy of China very well since 1984, but not in 1938 and 1953. Although Zipf's law only can not prove the existence of SOC, it indicates the possibility of SOC in the urban system. In China's case, the well connected urban network has been developed since the late 1950s and 1960s.

The fail of Zipf's law in China's urban system in 1938 and 1953 seems mainly be caused by large cities. While the rank size distributions of relatively small cities were in a linear profile in 1938 and 1953, those of large cities were not. Cities during this period were in regional networks. The lack of large cities serve as the national economic centers resulted in the missing of a well connected urban network before 1953.

Since 1984, not only all the cities with a population over 100,000 but also cities in different size groups follow Zipf's law. Small cities have relatively higher Zipf's coefficients while large cities have lower Zipf's coefficients. As small cities are generally newly promoted from towns and large cities are relatively mature, the Zipf's coefficient may indicate the relative maturity of cities to some extent. The maturity of cities also indicates the development of urban system. If an urban system is dominated by large number of small new cities which generally serve as the regional economic centers, a well connected urban system has not been set up. This is the case of China's urban system in 1938 and 1953. From 1984, a well-connected urban system has been formed in China, but this is based on the exclusion of those extra-small new cities.

Overall, small cities have more impact on the Zipf's coefficient of the aggregate urban systems than large cities because the number of small cities is large. Since Zipf's law is based on the best fit regression of rank and size of cities in the urban system, the number is an important factor. The few large cities have relatively less impact on the overall regression direction. As the results, the small cities have larger impact on the dynamics of Zipf's law.

However, large cities as a group accommodate more new urban population than small cities do, especially in the past decade. Large cities are stable, and generally with higher administrative level. Although the number of large cities is few, they are the critical factors of a national well-connected urban system.

Under the stable Zipf's law, the cities in China show quite different rank dynamics. Overall, big cities and cities with high administrative power (usually large cities) are relatively stable in rank dynamics. The rank dynamics are mainly caused by small and medium-sized cities. Before 1996, cities were relatively stable in rank, fewer cities were involved into rank dynamics, and there were a few small and medium-sized cities with rank increase while relatively large numbers of small cities with rank decrease. Spatially, cities with rank decline are distributed all over the country and the distribution of cities with rank increase is relatively random which can be explained by favorite policies by the central government. From 1996, large numbers of cities were involved into rank dynamics, and there were lots of small cities with rank increasing while there were quite amounts of medium-sized cities with rank decrease. Spatially, both the cities with rank decrease and cities with rank increase show clustered distribution. The agglomeration of economies might be the reason.

CHAPTER VI

INTRA-URBAN SELF-ORGANIZING CRITICALITY

6.1 Rapid Urban Development in Shenzhen

During the past three decades, Shenzhen experienced rapid urban development. In this part of study, the urban development is defined as the development of built-up area. Urban development in Shenzhen started almost from scratch with built-up area less than 1 km^2 in 1978, and reached 474.73 km^2 in 2002 (Figure 6-1). During the first ten years from 1978 to 1988, the development of built-up area was relatively slow, and mainly took place in SSEZ. From 1988, the urban development began to accelerate, which was mainly contributed by the rapid urbanization in Bao'an and Longgang. The built-up area in Bao'an increased from 24.58 km^2 in 1988 to 221.14 km^2 in 2002, and the built-up area in Longgang in creased from 22.23 km^2 in 1988 to 139.95 km^2 in 2002. By Contrast, the development of Built-up area in SSEZ slowed down, and there was only 15.45 km^2 new built-up area during the period from 1995 to 2002 in SSEZ.

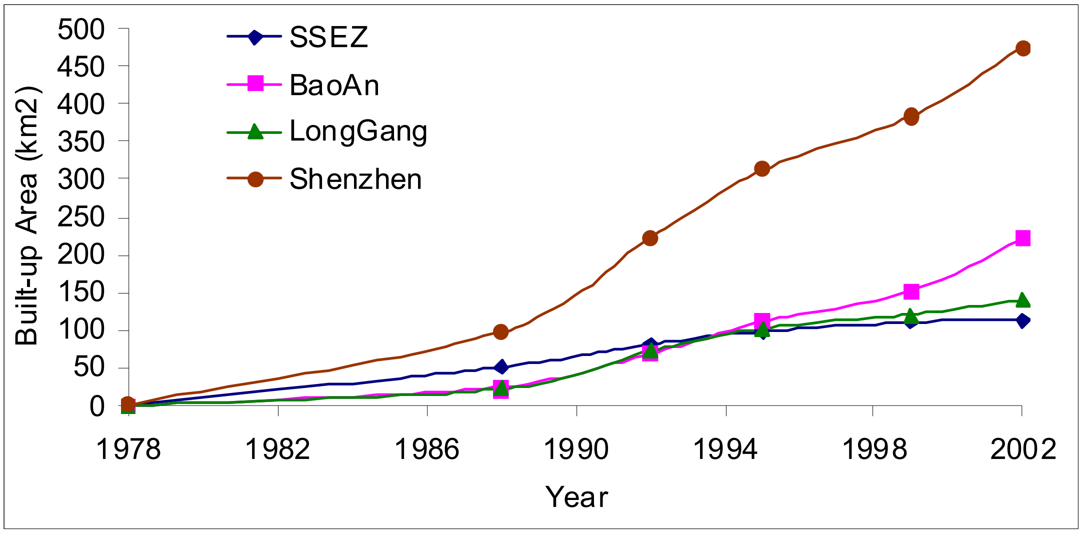


Figure 6-1 Rapid urban growth in Shenzhen.

The prediction results show different urban growth trends in Bao'an and Longgang districts and SSEZ while they will continue rapid urban development in the future (Figure 6-2). Bao'an and Longgang districts are going to be the centers of rapid urban development. Bao'an area will undergo a rapid urbanization process with an almost linear growth speed. Urban development in Longgang area will slow down from 2010. The developed area will reach over two times of the developed urban area in both Bao'an and Longgang districts no matter in which scenario. Relatively, the urban development in SSEZ will slow down. And, there will be almost no new urban development by 2020.

There presents quite similar urban growth in different scenarios in SSEZ, Bao'an and Longgang (Figure 6-2). In Bao'an and Longgang, the total numbers of urban cells in Scenario 1 are a little larger than those in Scenario 2. In contrast, the total number of urban cells does not show obvious difference in different scenarios in SSEZ. The major reason is that there is much less protected environmental area in SSEZ than in Bao'an and Longgang districts. As the results, the differences of scenarios on the management of the protected environmental area show less effect in SSEZ than in Bao'an and Longgang distics. Overall, the difference of protected environmental area management can affect the urban development in magnitude greatly.

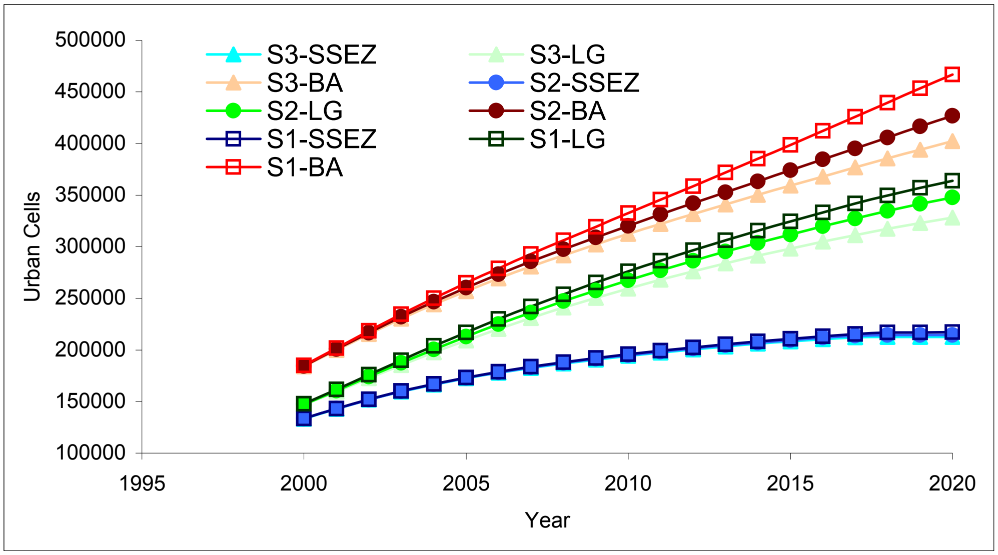


Figure 6-2 Urban growth under different scenarios.

Spatially, rapid urban sprawl will shift to area outside of SSEZ. New urban development in the future will concentrate on west seashore area and north area in Bao'an District, the north central area of Shenzhen, and northeast area of Longgang District in all the three scenarios. Urban development in the east area of Shenzhen will still be separated, and relatively slow. There will be relatively little urban development in SSEZ in the future.

There is no obvious spatial difference of urban development among the results of the different scenarios (Figures 6-3, 6-4, and 6-5). The current urban development has already set up the urban skeleton of Shenzhen. Generally, new urban development in the future will be conducted around the current developed urban area in Shenzhen.

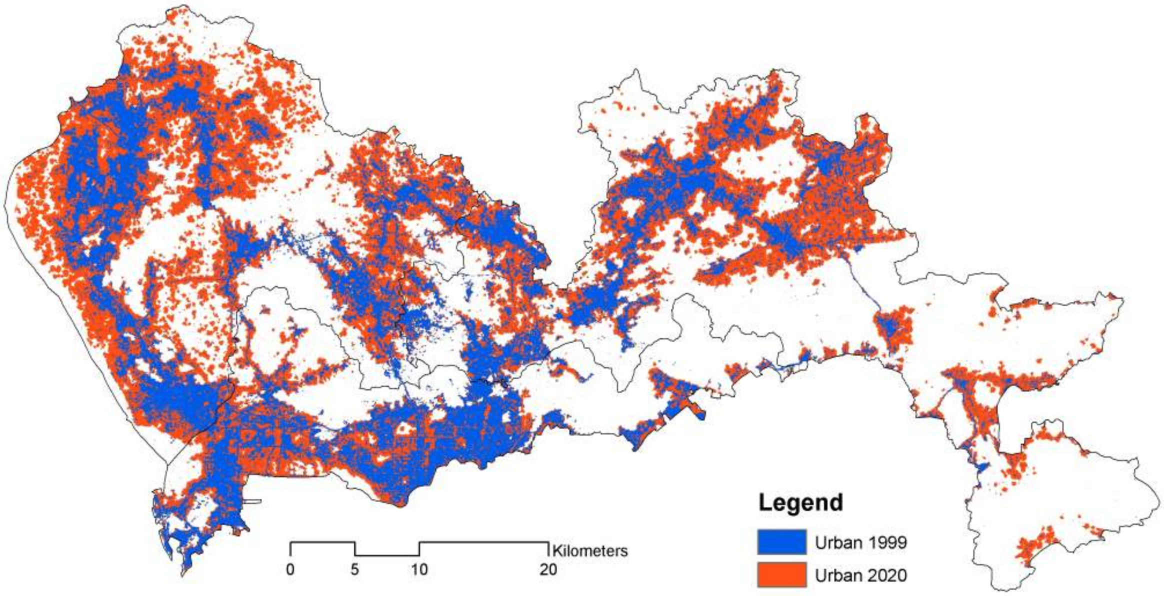


Figure 6-3 Urban development by 2020 in Shenzhen with Scenario 1.

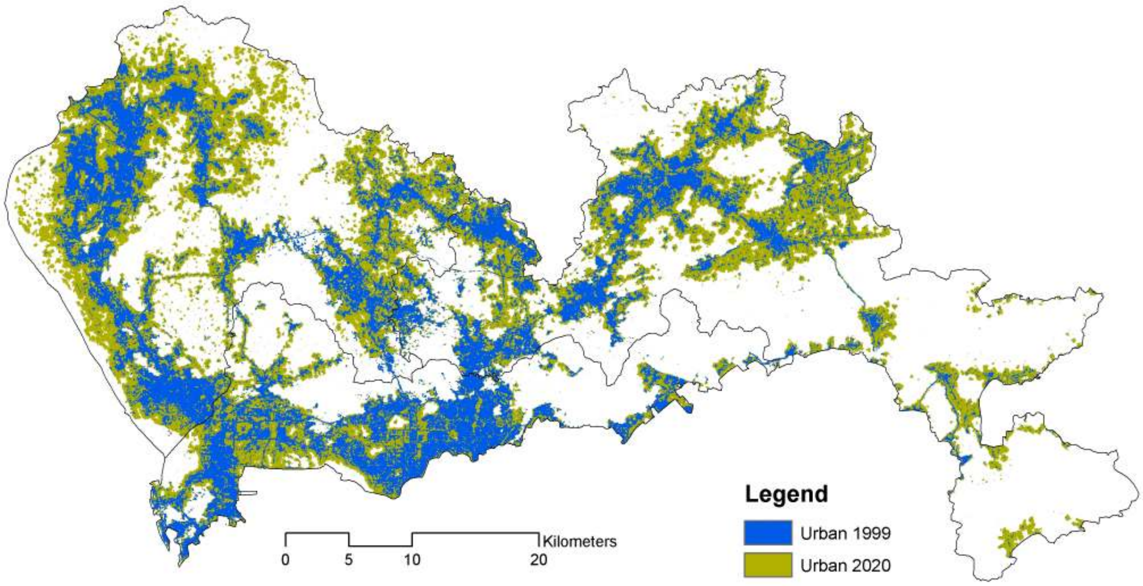


Figure 6-4 Urban development by 2020 in Shenzhen with Scenario 2.

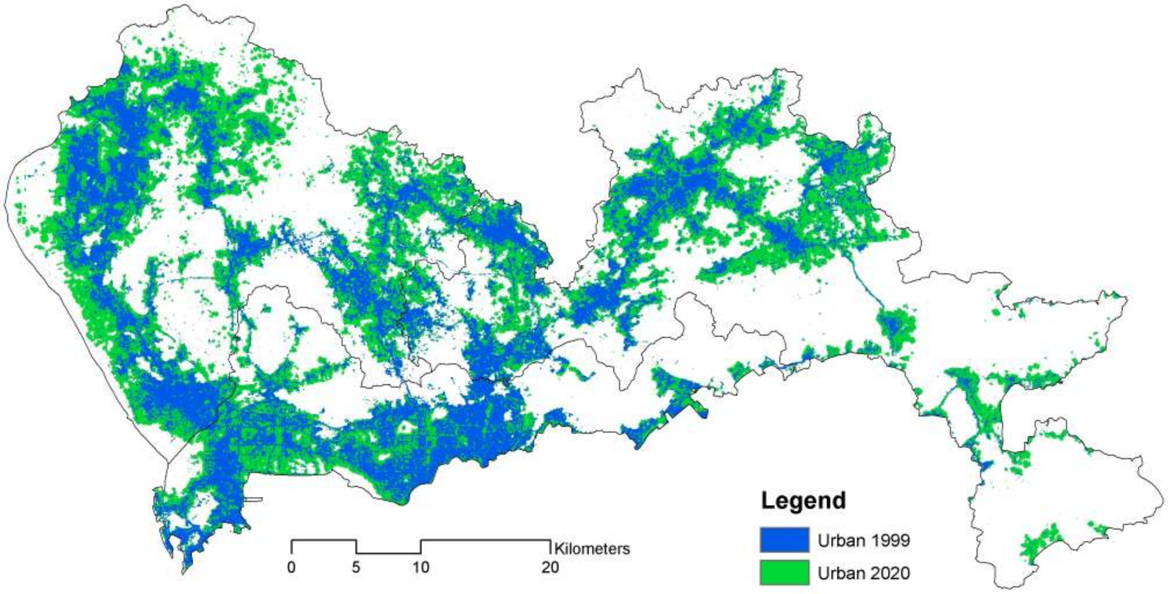


Figure 6-5 Urban development by 2020 in Shenzhen with Scenario 3.

In summary, Shenzhen will still be undergoing rapid urban development in the future. The rapid urban development will be spatially shifted outside of SSEZ. There is little urban development difference among the results of three different environmental plans, no matter in terms of the total area or the spatial distribution. The different environmental protection plans can play little roles in future urban development in Shenzhen.

Since there is little difference among the urban development results of the three scenarios, the simulated urban development in the future from Scenario 1 is used for the left analysis.

6.2 Physical Threshold in Urban Development

6.2.1 Physical Environment

Land physically feasible for urban development is limited in Shenzhen. According to the Urban Planning Standards and Guidelines of Shenzhen (Shenzhen Government 1997), area for building activities should be lower than 50m in SSEZ and 80m outside of SSEZ in terms of elevation, and the slope should not surpass 30 percent degree. These criteria might be changed in future urban development under the pressure of land source need or the development of technology. In this study, these criteria are treated as the physical environmental thresholds. And in fact, these physical environmental thresholds limited and are limiting the urban development spatially in Shenzhen. So, areas satisfying the criteria are considered to be suitable for urban physical development in this study. As a result, there is only 63.60% of land suitable for urban development in Shenzhen. Bao’an has a relatively higher percentage of land suitable for urban development, near 80, while near half of the land in Longgang is not suitable for urban development. Over 40% of the land in SSEZ is not feasible for urban development either (Figure 6-6).

In addition, there are also many large water bodies existing in the study area, and those are definitely not suitable for urban development. To extract those large water bodies, the author had the water areas in 1988, 1992, 1995, 1999, and 2002 overlaid together, and those water bodies existing in all the five years were extracted and a 3*3 majority filter was applied to the extracted water bodies to smooth those results. As a result, those water bodies as a whole comprise of another 2.85% of land that is physically not suitable for urban development. Most of the blocked areas by water bodies distribute in SSEZ and Bao’an District (Table 6-1).

Table 6-1 The distribution of land on physical environment.

	DEM Blocked (%)	Water Blocked (%)	Left (%)
SSEZ	40.49093	4.317851	55.19122
Bao’an	20.60483	4.71682	74.67836
Longgang	47.9211	0.582482	51.49642
Shenzhen	36.4021	2.849631	60.74827

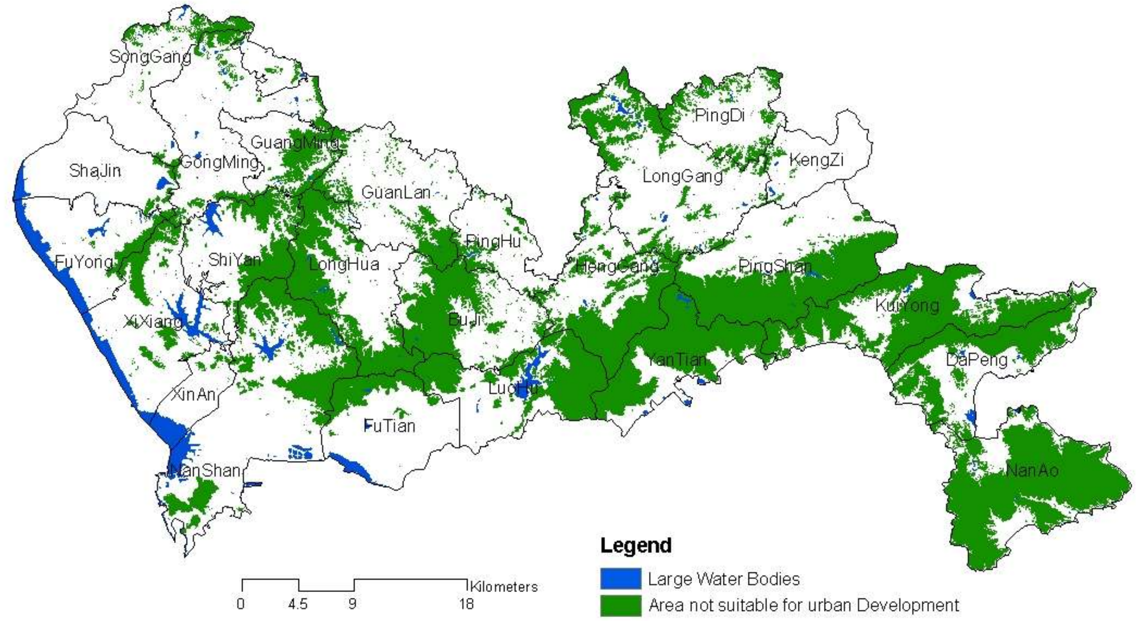


Figure 6-6 The distribution of areas physically not feasible for urban development.

The existing urban development demonstrates that the physical environment shaped the evolvement of urban development in Shenzhen. During each of the five study years, over 90 percent of developed area located on those areas physically feasible for development in SSEZ, Bao'an and Longgang. After over 20 years of rapid urban development and the recent large pressure of land shortage, those physical thresholds haven't been overcome yet.

However, one phenomena need to be noticed is that the percentage of developed area distributed on the land feasible for urban development decreases in each area during the period from 1988 to 2002 (Table 6-2). The decreasing trend indicates that more and more newly developed areas located in area physically not suitable for urban development. Although the amount of developed area on the land physically not feasible for urban development is small, the decreasing trend indicates the existing of the physical thresholds, and the possibility to be overcome in future urban development in Shenzhen.

Table 6-2. The percentages of developed area distributed on the land feasible for urban development.

	1988	1992	1995	1999	2002
SSEZ	98.17	96.83	95.71	95.53	94.65
BaoAn	99.03	97.65	96.70	96.45	95.10
LongGang	96.55	93.95	93.50	93.75	90.36

6.2.2 Environment Protection

In addition to the thresholds of the physical environment for urban development, many areas are set up for environment protection from the urban development by the city government. First Class Protected Water Source Area and Protected Agricultural Land (Figure 6-7) were the only two types of protected environmental area with laws and regulations by 2003. In this study, only these two types of protected environmental areas are included for analysis.

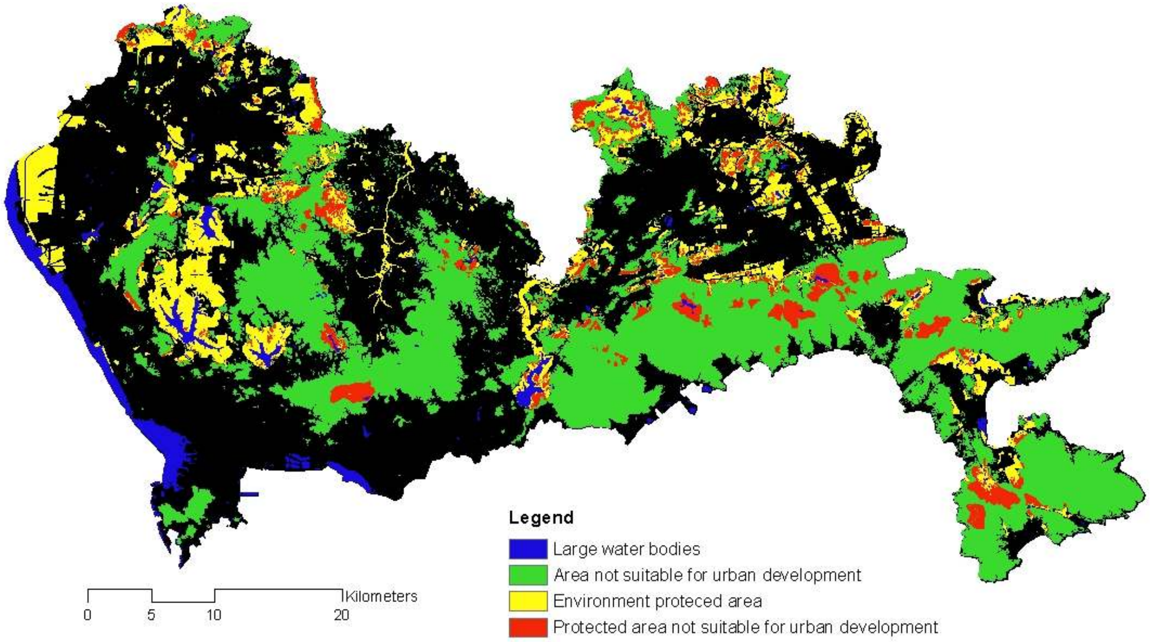


Figure 6-7 The distribution of areas physically not feasible for urban development and protected environmental areas.

The total area of the First Class Protected Water Source Area and Protected Agricultural Land is 305.40 km^2. Some parts of First Class Protected Water Source Area and Protected Agricultural Land have overlaps with area not suitable for urban development. The new added area protected from urban development is 196.76 km^2, 10.26% of the area of Shenzhen. The added protected area primarily distributes in Bao'an and LongGang districts (Table 6-3). As a result, there is only 52.6 percent of land left for urban development in SSEZ, 59.50 percent left in Bao'an, and 41.86% percent in Longgang. Overall, Shenzhen has only 50.49% land feasible for urban development.

Table 6-3 The distribution of land under physical prevention and environment protection.

	Total Area (km^2)	Physically Blocked Area (km^2)	Protected Environmental Area (km^2)	Environment Protection Added Area (km^2)	Left (%)
SSEZ	384.84	172.44	26.74	9.93	52.61
BaoAn	704.29	178.34	136.72	106.93	59.50
LongGang	829.26	402.22	141.95	79.94	41.86
Shenzhen	1918.39	753.00	305.40	196.79	50.49

During the rapid urbanization process, the physical environment and environment protection have resulted in the shortage of land resource in Shenzhen. The simulation results reveal that the shortage of land resource for urban development will become more serious in the future urban development. With the area physically infeasible for urban development excluded, there is limited land feasible for urban development. By 2020, there will be only 7.92 % of land feasible for urban development left in SSEZ, 19.89% in Bao'an and 22.87% in Longgang (Figure 6-8).

Unlike Bao'an and Longgang districts which will continue the high-speed urban growth, urban development in SSEZ will slow down. In SSEZ, there will be almost no new urban development from 2015 since no more land left physically feasible for urban development. The physical threshold in urban development is expected to come in SSEZ. Alarmingly, Bao'an and Longgang are also approaching the physical threshold given the limited land available.

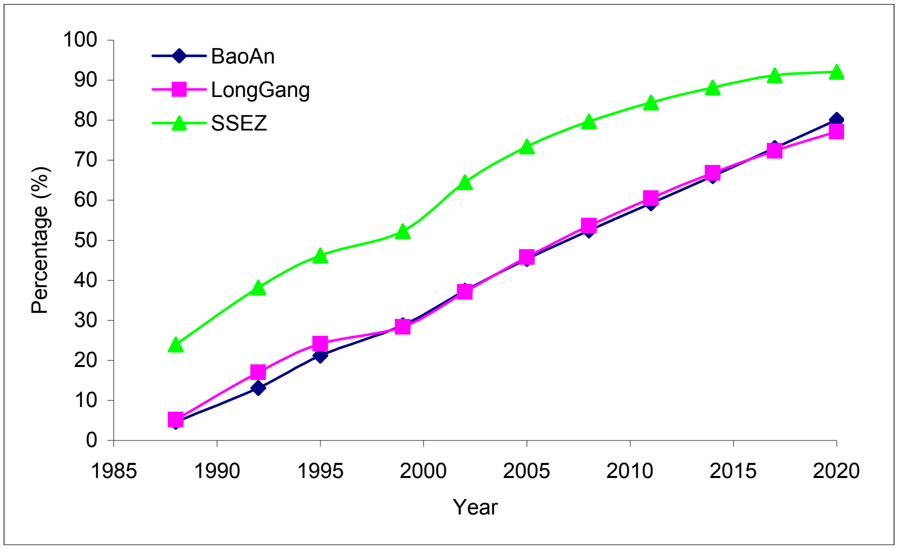


Figure 6-8 The percentages of developed feasible area in different years.

6.3 Phase Change of Urban Growth

While physical environment limits the amount of areas for urban development, urban development adjusts the growth types over time. The phase transitions of urban growth types hold true no matter in the self-organizing 'disordered' urban development of Bao'an and Longgang or in the relatively highly managed urban development in SSEZ.

6.3.1 Temporal Dynamics of Urban Growth Types

Urban growth is divided into three types—fringe growth, isolated growth and infill growth. Isolated growth is the new developed area located away from existing urban area, which often referred as 'frog-leap' growth. Fringe growth is the outward growth of existing urban area. It often borders the existing development and takes advantage of the infrastructure established. Infill growth happens in the undeveloped area surrounded by urban area.

The dynamics of urban growth and ever shifting development types over time in SSEZ, Bao'an, and Longgang are not surprising (Figure 6-9). Overall, fringe growth is the major type of urban growth in these three areas. In the early years of development, isolated growth is the second major type. It is reasonable since there is ample land available and there are not many developed areas to begin with. However, with the rapid urbanization, the shortage of land resource looms large. Developers begin to consider developing in the vacant spaces in urban areas. As a result, infill growth gradually takes over to be the major type of growth in later phase of urban development.

The dynamics of urban growth types, however, are quite different between SSEZ and Baoan and Longgang districts. Both in Bao'an and Longgang districts, fringe growth peaks around 80%, and are quite stable overtime. The minor types of urban growth are isolated growth and infill growth. The relative dominance of isolated growth is replaced by infill growth around 2000 both in Bao'an and Longgang districts. In contrast, the percentage of fringe growth shows a decreasing trend before 2005 while increases later. While fringe growth is the major urban growth type in SSEZ, it is not as dominant as it is in Baoan and Longgang districts. Infill growth also plays a very important role in urban development in SSEZ. Figure 6-9 shows that infill growth replaced isolated growth and becomes the second major urban growth in SSEZ from the period of 1992 to

1995, and the percentage of infill growth keeps increasing gradually. During the period of 2000 to 2005, infill growth reaches its peak, and it contributes almost the same percentage of urban growth as fringe growth does. However, the percentage of infill growth decreases while the percentage of fringe growth increases since 2005. By 2020, infill growth still contributes over 30 percent of urban growth in SSEZ.

Overall, in terms of urban growth types, urban growth dynamics in SSEZ and outside of SSEZ are quite different. The major difference is caused by infill growth. However, it is not surprising but quite reasonable. In SSEZ, urban development since the beginning is highly planned. While urban growth in SSEZ was pushed outwards, Shenzhen government put great efforts on the management of urban growth. Extravagant land use was prohibited and land developers were forced to develop land efficiently with lots of infill development. At the same time, many areas were reserved by Shenzhen government for later development. A good example is the development of Shenzhen Axis—the administrative center with large area of recreational areas in the CBD of Shenzhen in the 21st century. In other words, the high percentage of infill growth in SSEZ also confirmed the urban growth in SSEZ is highly planned and managed.

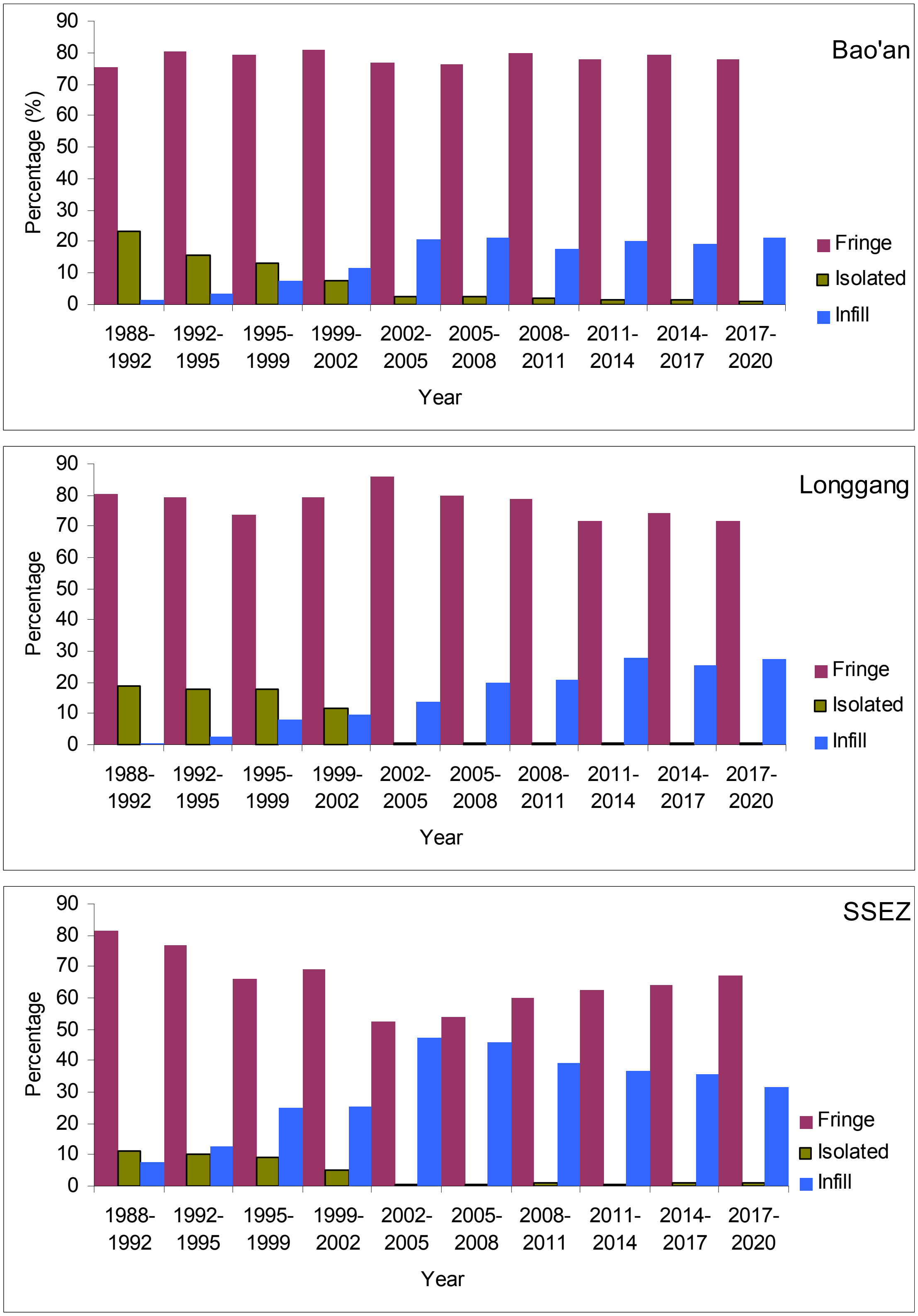


Figure 6-9 Dynamics of urban growth types in different areas.

6.3.2 Urbanization Rate and Urban Growth Types

In essence, the temporal changes of urban growth forms are directly caused by the increasing urbanization rate (the percentage of developed area). In another aspect, the above temporal dynamics of urban growth types can be interpreted as the dynamics of urban growth types over urbanization rate.

With more and more land is developed, the urbanization rate increases in every corner in Shenzhen. During the early years of urban development, the urbanization rate was very low, and there was plenty of land for urban development. When sprawl continues, there are quite a bit of frog leap growth of urban areas. However, with increasing of urbanization rate, large area of open space for frog leap growth is decreasing, but infill growth takes place in area with high urbanization rate. In both Bao'an and Longgang districts, the shift from isolated growth to infill growth occurred when the urbanization rate reach near 30%. In SSEZ, shifting of urban growth types is triggered by urbanization rate as well. As shown in Figure 6-10, the percentage of fringe growth decreases first and then begins to increase when the urbanization rate reaches around 70%. Contrary to this trend, the percentage of infill growth increases first and then decreases when the same urbanization rate is reached.

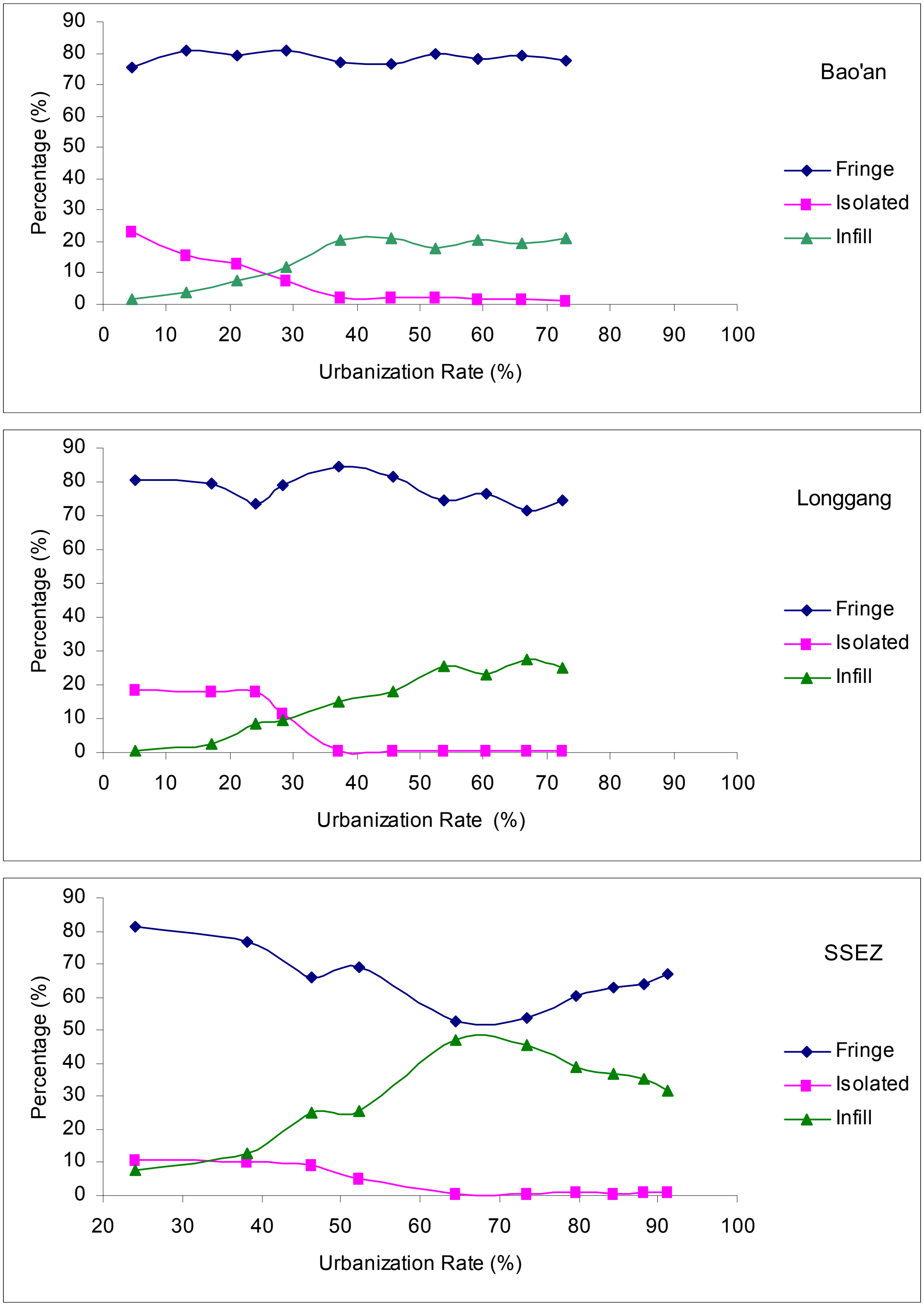


Figure 6-10 The temporal distributions of the percentages of different urban growth types over urbanization rate.

The phase transitions of urban growth types could also be identified spatially. Spatially, urbanization rate is the percentage of pixels in a 500m neighborhood that are developed. For each study period, the urbanization rate map is generated for the beginning year. The urban growth type data of each period is then overlaid with the urbanization rate map of the beginning year of each period. And then, the spatial dynamics of urban growth types over urbanization rate are analyzed.

Spatially, the dynamics of urban growth types in SSEZ, Bao’an and Longgang are surprisingly similar. Here, the spatial dynamics of urban growth types of Longgang during the period from 1988 to 1992 is used as an example for Bao’an and Longgang (Figure 6-11). Generally, area with low urbanization rate is denominated with fringe growth. There is some part of isolated growth in areas with low urbanization rate. With the increase of urbanization rate, the percentage of fringe urban growth decreases while the percentage of infill growth increases quickly. In area with high urbanization rate, infill growth becomes the dominant urban growth type.

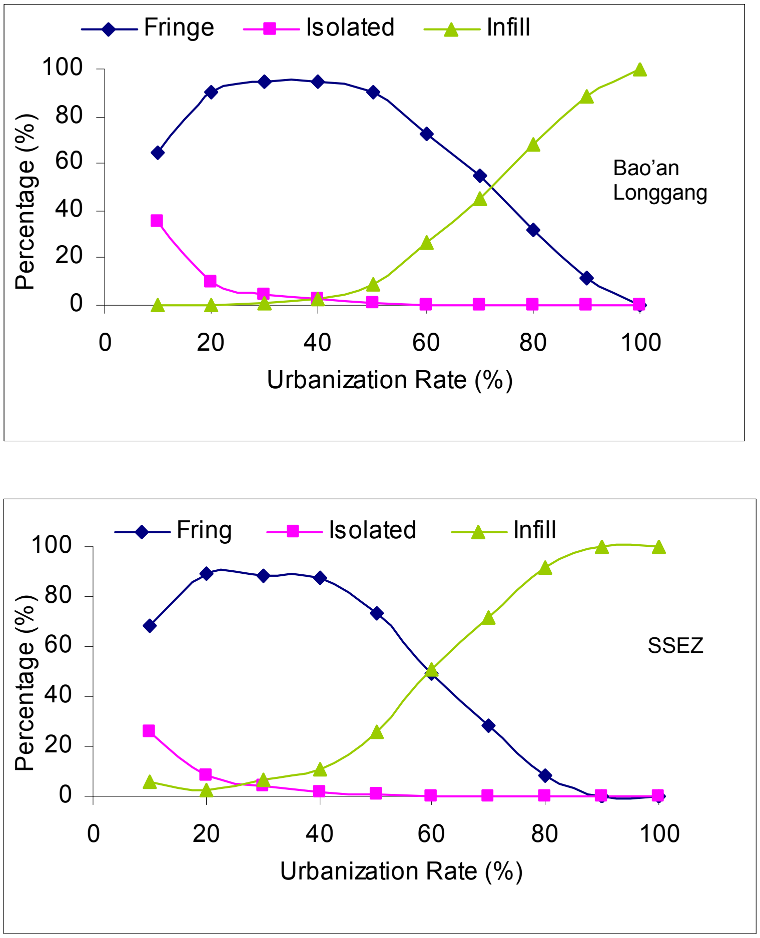


Figure 6-11 The spatial distribution of the percentages of different urban growth types over urbanization rate.

Comparing these figures of urban growth types in details, we can also find there are many noticeable differences. First, the urbanization rate at which the dominant urban growth type changing from fringe growth to infill growth is different in Bao'an and Longgang districts from in SSEZ. In Bao'an and Longgang districts, when the urbanization rate reaches around 70% to 80%, the dominant place of fringe growth in new urban development will be replaced by infill growth gradually. In contrast, this shift will happen in SSEZ when the urbanization rate reaches 60% to 70%. The slight reduce of urbanization rate where major urban growth type changes resulted in quite large increase of the percentage of infill growth in SSEZ throughout the study period.

In summary, throughout the urban growth stages, there are transitions of urban growth types. During the early years of urban development in Shenzhen, isolated urban growth is an important urban growth type. With the evolution of urban development, the part of urban growth contributed by isolated urban growth is replaced by infill urban growth gradually.

Urban development management could modify the pattern of urban growth types over time. In Bao'an and Longgang districts, urban development is highly self-organizing and disordered. Urban development in both areas is mainly in form of fringe growth although there are also certain amount of isolated growth and infill growth. In SSEZ, urban development is relatively highly managed and planned. Urban development in SSEZ is dominantly under the joint efforts of fringe growth and infill growth.

Spatially, urban development strategies are similar in SSEZ, Bao'an, and Longgang. In area with low urbanization rate, fringe growth is the dominant urban growth type, but there is also certain amount of isolated urban growth. With the increasing of urbanization rate, infill growth contributes more percentage of new urban growth and becomes the dominant urban growth type gradually. The point where infill urban growth replaces fringe urban growth and become the dominant urban growth type is similar in Bao’an and Longgang, at around 70-80%, and a little different from SSEZ around 60-70%.

Based on above analysis, we can see that slight spatial difference of local development strategies could result in quite different urban growth type pattern over time between Bao’an, Longgagn and SSEZ. For urban management and planning, more localized strategies might be more able to achieve large scale objectives.

6.4 Criticalities of Urban Landscape

6.4.1 Power Law in Urban Landscape

The urban landscape of Shenzhen is studied based on the comparison of the real urban development, the simulated urban development and the planned urban development. The real urban development data are the classified remote sensing images before 2002. The simulated urban development data are the simulated urban development results from the SLEUTH model from 2003. The combination of the real and simulated urban development mosaics the evolution of urban development in Shenzhen from the past to the future. Based on the combination, the developed urban patches are defined as the clusters of real or simulated urban area. The planned urban patches are the clusters of planned urban area by 2010 extracted from the 1996-2010 Shenzhen Master Plan.

In terms of area-perimeter distribution, the planned urban patches in all the three areas (SSEZ, Bao’an and Longgang) are more compacted than the developed urban patches. As the limit of space, Figure 6-12 lists the area-perimeter distributions of the planned urban patches and the developed urban patches in 2011 in each area. On the three area-perimeter scatter plots, the points of the planned urban patched are distributed above the points of the developed urban patches. The planned urban patches have smaller perimeters than those similar sized developed urban patches.

Compared with those developed urban patches in 2011, the planned urban patches are less in number and more even in area and perimeter. There are few extremely large or small planned urban patches. The developed urban patches are more dispersed in term of shape. There are lots of small developed patches and also some extremely large patches.

The Ln-Ln area-perimeter distribution of developed urban patches is linear in all the three areas in each study year. All the linear regressions of developed urban patches have a R^2 larger than 0.9. The Ln-Ln area-perimeter distribution of planned urban patches also to some extent shows linear relationship respectively in SSEZ, Bao’an and Longgang. However, the linear regressions of planned urban patches have the R^2 values less than 0.9.

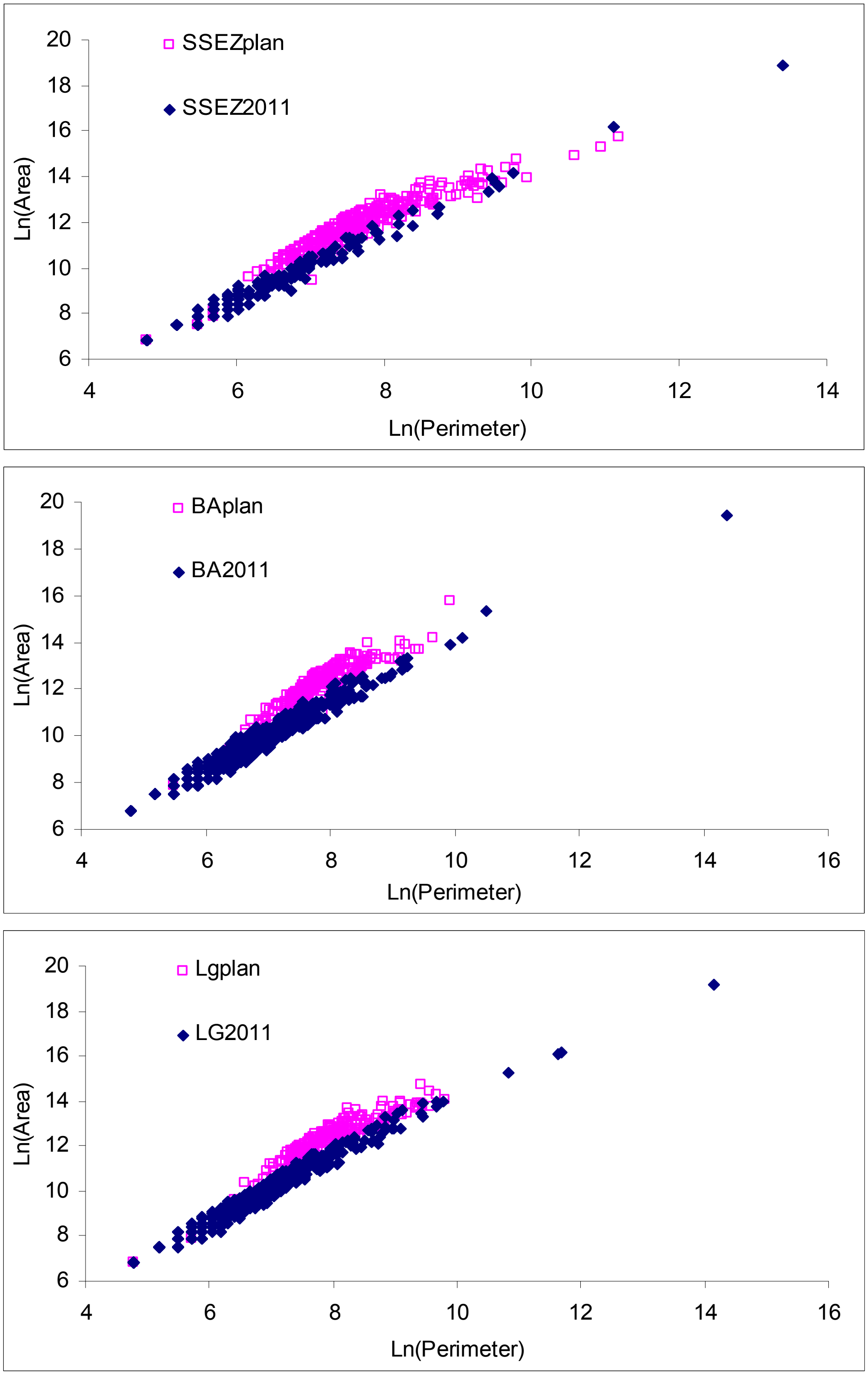


Figure 6-12 The area-perimeter distributions of urban patches and planned urban patches.

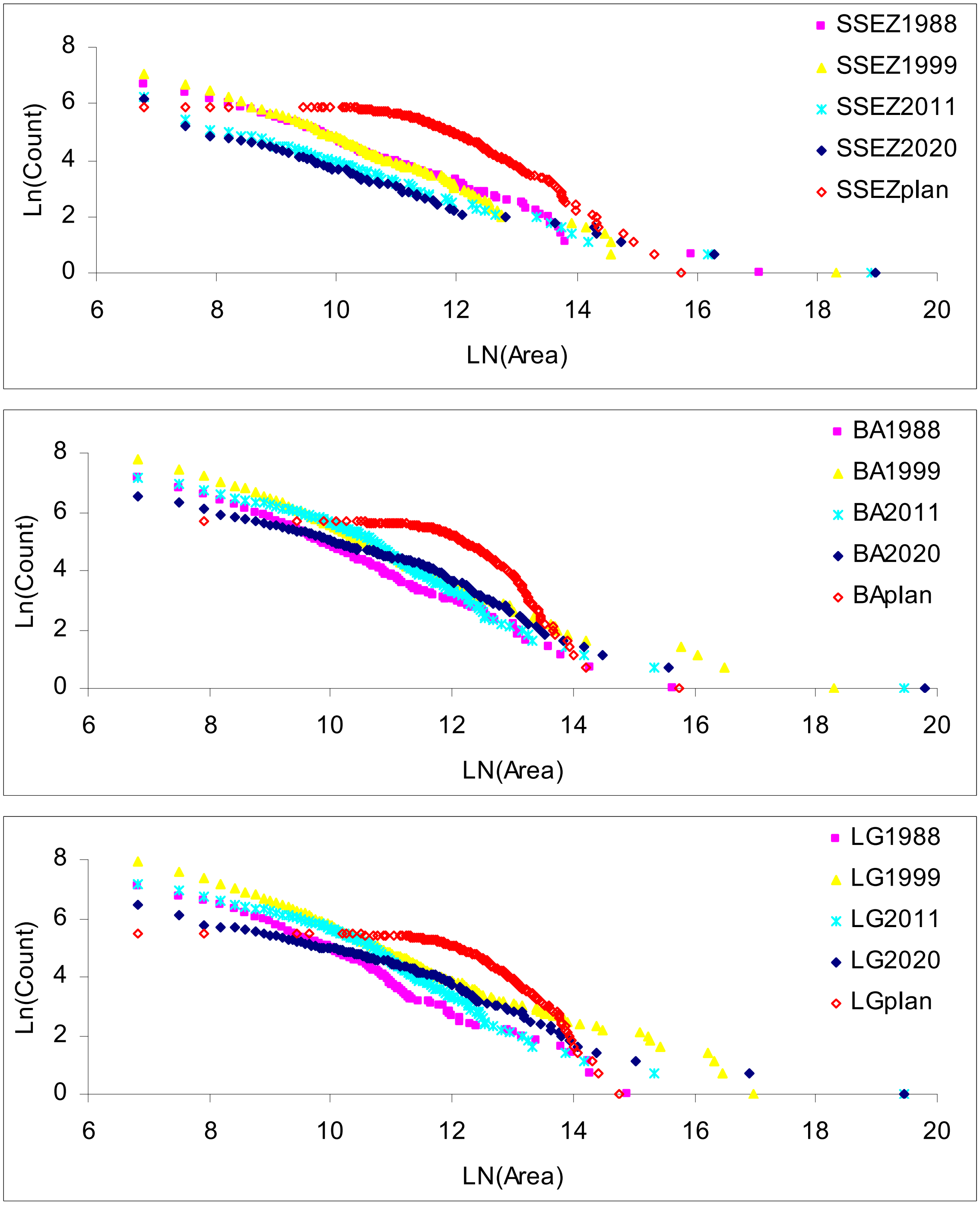


Figure 6-13 The magnitude- frequency distributions of urban patches and planned urban patches.

The magnitude-frequency distributions of developed urban patches are quite different from those of the planned urban patches. In Figure 6-13, the Ln-Ln magnitude-frequency distributions of the developed urban patches in 1988, 1999, 2011, and 2020 and the planned urban patches are shown together for SSEZ, Bao'an and Longgang respectively. The Ln-Ln magnitude-frequency distributions of the developed urban patches show linear relationships while those of planned urban patches are in curved lines and far away from linear relationships.

The power law is one of the major characteristics of self-organizing systems. It is also one of the criteria for judging the traditional self-organizing criticality in many landscape ecology studies. Here, both the area-perimeter and magnitude-frequency distributions of the developed urban patches show power law both in highly self-organizing disordered urban development areas – Bao'an and Longgang districts and the relatively highly planned urban development area—SSEZ. At the micro level, urban development is dominantly conducted by self-organizing behavior. The institutional factors, for example urban planning exerts limited impact but not ultimate controls over the self-organizing behaviors. This might explain the power law distributions at the landscape component level in SSEZ.

6.4.2 Landscape Pattern

Perimeter-Area Fractal Dimension (PAFRAC) measures landscape complexity on different scales. The PAFRAC is based on the assumption of linear log-log perimeter-area relationship of different sized patches. In the above analysis, the area-perimeter distributions of developed urban patches show log-log linear relationship in all the three areas. So, PAFRAC can be applied into measuring landscape complexity in Shenzhen.

In all the three areas—SSEZ, Bao'an, and Longgang, the PAFRAC value increases first and decreases with the increasing urbanization rate (Figure 6-14) which means urban landscapes in these area become complex first and then simpler later. The PAFEAC value reaches the peak when the urbanization rate increases to around 40% in Bao'an and Longgan districts, and around 65% in SSEZ. The peak values of PADEAC in both Bao'an and Longgang districts are similar, but higher than that in SSEZ.

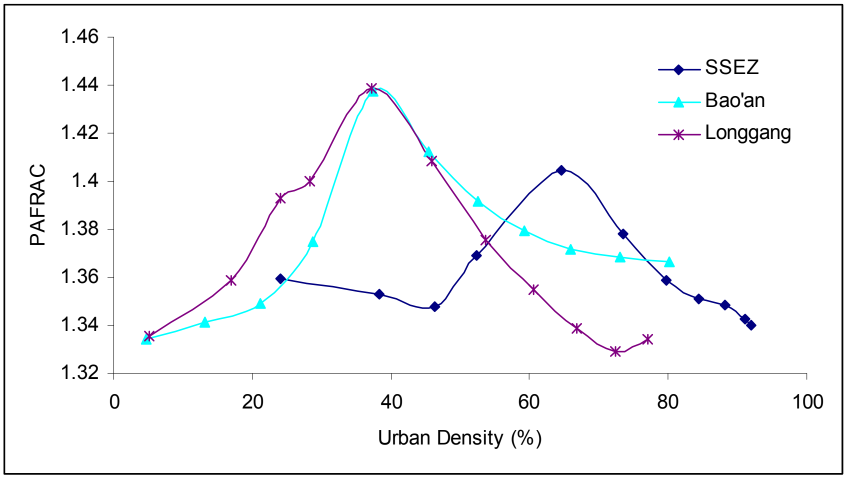


Figure 6-14 The distribution of PAFRAC over urbanization rate.

6.5 Conclusions and Discussion

With the help of SLEUTH model, this study is able to check the urban land development from the beginning to the stage of almost fully developed. The general conclusions are as the following.

1. Physical environment is the threshold for the physical urban development in Shenzhen. With the rapid urbanization process, the shortage of land resource is foreseeable. The urban development in SSEZ has already slowed down and the new urban development center has shifted to the outside of SSEZ. In fact, in the newly announced Urban Development Strategy of Shenzhen 2020, the shore area of Baoan District is set up as the new CBD of Shenzhen in the future. The purpose of shifting urban center is to release the land needs pressure for urban development in SSEZ. However, the hilly terrain determines the feasible land resource for urban development is also limited outside of SSEZ. With current urban development speed, Baoa'an and Longgang will be out of feasible land resource soon.
2. While the shortage of land resource is foreseeable, the urban development adjusts the growth types during the process of rapid urbanization. There are phase changes of growth types during the urban development process both in Bao'an and Longgang districts SSEZ. In SSEZ with relatively high level of urban planning and management, while fringe growth is still the major urban growth type during early years of urban development, the percentage of new urban area developed in the type of infill growth increases gradually and becomes the

second major urban growth type. During later period of urban development, there is little amount of new urban development, and this little amount of urban development is mainly in the type of fringe growth. For Bao'an and Longgang districts with little effective urban planning and management, fringe growth has been the dominant urban growth type throughout the complete urbanization process. But there is a shift of the second major urban growth type from isolated growth to infill growth in both Bao'an District and Longgang District. The phase changes of urban growth types are different in SSEZ from those in Bao'an and Longgang districts.

3. As the results of limited land resource and the adjustment of urban growth types, the urban landscape presents critical pattern in both SSEZ and the two districts outside of SSEZ. Both the distribution of area-perimeter and that of magnitude-frequency of the developed urban patches show power law relationships. And, the critical patterns of the developed urban patches are quite different from those of planned, which furthermore proves that urban development in Shenzhen is highly self-organized in both Bao'an and Longgang districts and SSEZ.
4. Under the backdrop of critical patterns of urban patches is the shift of urban landscape complexity. The power law distribution of area-perimeter of urban patches guarantees the application of PAFRAC which actually is a fractal dimension index. The PAFRAC index indicates that the complexity of urban landscape increases first and then decreases in both SSEZ and Bao'an and

Longgang districts. Overall, the urban landscape of Bao’an and Longgang districts is more complex than that of SSEZ.

From this case study at intra-urban level, the evolution of urban landscape pattern in Shenzhen presents characteristics of self-organizing criticality. The physical environment is the vital threshold for the continuing rapid urbanization in Shenzhen. Shenzhen’s urban development will inevitably enter into the redevelopment of urban area from the current spatial sprawl with the threshold of the physical environment. Under the pressure of the physical environmental threshold, the urban development adjusts the growing strategy. Consequently, there present the phase changes of urban growth types in SSEZ and Bao’an and Longgang districts. As a result, the formed urban landscape pattern shows power law distribution.

Urban development is self-organizing in both SSEZ and the area outside of SSEZ. The urban development in SSEZ started with well enforced urban planning and management by the city and up level governments. The governments’ planning and management did influence the local urban development. The phase changes of urban growth types and the complexity of urban landscape in SSEZ are different from those in Bao’an and Longgang districts where urban development is dominated by self-organizing behaviors with little effective urban planning and management. However, the urban development is eventually executed by multi agencies and local residents with their judgment under the direction of city and up level governments’ planning and management. At the end, the urban development in SSEZ like those in Bao'an and Longgang districts inevitably faces the physical environmental threshold, and shows the phase changes of urban growth. Finally, the resulted urban landscape in SSEZ comes to the same end of SOC like those of Bao'an and Longgang do.

CHAPTER VII

SUMMARY AND CONCLUSION

7.1 Summary

SOC theory proposed by Bak and his colleagues (1987) provides a new paradigm for studying a variety of phenomena in both physical and social sciences (Portugali 1997). By combining both self-organization and critical behavior, SOC explains system complexity and the widespread appearance of power-law in nature (Portugali 1997). The advantages of SOC theory are obvious. SOC theory, for the first time, explains the processes of qualitative change to quantitative change, as well as the quantitative relationships among local perturbations and system changes as a whole. It reveals the internal dynamics behind the final statistical size-distribution in the systems' steady periods. It demonstrates how complex the internal dynamics of a steady state can be (Portugali 1997). As the result, it forces researchers to recognize the importance of threshold, metastability, and large fluctuations in the spatiotemporal behavior of complex systems.

However, to apply SOC in real world studies is difficult. A system's self-organization activity currently is almost impossible to be measured except in some limited physical phenomena. The original concept of criticality as attractor is too abstract to be applied in real physical and social systems. Although a large number of studies have proved the theory of SOC based on 1/f noise, log-linear magnitude–frequency and rank-size distributions, suspicions remain on the significance of SOC. The general conditions under which a system will exhibit SOC are largely unknown (Sornette et al. 1995). The lack of a mathematic framework turns out to be the ‘criticality’ in the application of SOC.

In urban studies, it is even difficult to link urban system with SOC.. The evolution of an urban system could not be analogous to a simple sandpile formation. The development of any urban system is under the joint efforts of governments, local agencies and even global economy. It is by no means possible to find a completely self-organizing urban system or city system.

This dissertation combines SOC with threshold theory and generalizes SOC to a broader consideration of self-organization and criticality in urban studies. The self-organization process reflects a high degree to which patterns, processes, forms, and relationships in urban development are (re)structured independently of external factors. The concept of criticality is extended from attractor, as proposed in the original SOC theory, to boundary conditions or evolutionary milestone as the system develops. The generalized SOC considers that a complex system self-organizes to a critical stage. At the critical stage, while the complex system presents power law, the internal dynamics are evolving to a boundary condition or a phase change. There is an evolutionary milestone in the subsystems. The generalized SOC is applied into exploring urban development which is largely absent in current SOC studies. In this dissertation, the generalized SOC provides a theoretical frame to study (1) the urban hierarchy of China at the inter-urban level, and (2) the dynamics of the urban landscape pattern of Shenzhen, China, at the intra-urban level.

At the inter-urban level, Zipf's law, one of the four typical power laws, is applied to check the evolution of China's urban system from 1984 to 2002. The results show that Zipf's law is applicable not only at the national level, but also at different size tiers of Chinese cities. To better understand Zipf's law in urban system as the fingerprint of SOC, intra-distribution dynamics of Chinese city rank size are also analyzed. Under the stable Zipf's law, the cities in China show quite different rank dynamics. Overall, big cities and cities with high administrative power (usually large cities) are relatively stable in rank dynamics. The rank dynamics are mainly influenced by small and medium-sized cities. Before 1996, cities were relatively stable in rank. There were a few small- and median-sized cities increased their ranks while a large number of small cities decreased in ranking. Spatially, cities, not matter declining or increasing in ranks, were distributed all randomly over the country. From 1996, a large number of cities were involved in rank dynamics. Since this year, there were a lot of small cities have their ranks increased and meanwhile a large amount of middle-sized cities have their ranks decreased. Spatially, both increasing and decreasing city groups show clustered distribution. The year 1996 is a turning point for cities' rank-size development.

At the intra-urban level, SLEUTH model is employed to simulate the self-organizing urban landscape dynamics of Shenzhen. Then thresholds of physical environment, phase shifts of urban growth process, the power laws of urban landscape composition and spatial shape are explored with statistical analysis using both the classified data and the simulated urban growth. The results show that physical environment is the threshold for the physical urban development in Shenzhen. With the rapid urbanization process, the shortage of land resource is foreseeable. Therefore, urban growth types changed from fringe and isolated growth to fringe and infill growth spatiotemporally in SSEZ, Bao'an and Longgang districts. As a result of limited land resource and the adjustment of urban growth types, the urban land use presents power law in SSEZ and the two districts outside of SSEZ. Both the distribution of area-perimeter and the distribution of magnitude-frequency of urban patches show power law relationship. The PAFRAC index, which is inversely related with the slope coefficient of the area-perimeter distribution, indicates that the complexity of urban landscape shapes increases first and then decreases in SSEZ and outside of SSEZ.

7.2 Conclusion

This dissertation research approves the applicability of the generalized SOC in urban studies. At both the inter-urban and the intra-urban levels, there are shifts in the internal dynamics of cities under the stable stage of power law distributions. The shift could be a turning point, or a phase change process. The urban system of China presents Zipf's law (power law) in city rank-size distributions since 1984. The internal dynamics of China's urban system revealed that year 1996 is a turning point. This case study of Shenzhen shows the power law distributions of urban patches in term of area-perimeter and magnitude-frequency relationships. The urban patch growth spatiotemporally shifts from fringe and isolated growth to fringe and infill growth.

Compared with the abstract attractor which is considered as 'criticality' in the traditional SOC theory, the turning point and the phase transitions are more meaningful and rational 'criticalities' in social science, especially in urban studies.

Three points need to be emphasized. Firstly, a complete self-organizing urban development is difficult to find, especially in China. The concept of self-organization in this dissertation research reflects a high degree to which patterns, processes, forms, and relationships in urban development are (re)structured independently of external factors. External factors influence the urban development in a relatively indirect manner instead of direct manipulation.

Secondly, the analysis of China's urban system development is based on the assumption that the population data could rationally measure the city sizes. Although the non-agricultural urban population index is commonly used in China's urban studies, there are many potential problems of the non-agricultural urban population in China. The huge floating population in cities, especially large cities, is not included in the statistic of non-agricultural urban population. This explains why large cities in China are synthetically over predicted by Zipf's law.

Lastly, there is a basic assumption on the underline that the SLEUTH model can be used to simulate the urban landscape dynamics in Shenzhen. To predict the exact urban development in the future is impossible. Many unpredictable factors many change urban development dramatically. Urban models include the SLEUTH model, can only simulate urban development, and provide an abstract description of future urban development.

This dissertation research advances the knowledge on the SOC theory. It also has potential contributions to urban studies. In summary, this study makes its unique contribution to the understanding of urban complexity in the theoretical, methodological and policy aspects and the urbanization of China. The three aspects are addressed specifically as follows:

- On the theoretical aspect, this research turns out to be one of the few empirical urban studies based on the theory of SOC. This study proposes a generalized SOC theory based on up-to-date literature review. The generalized SOC theory enhances the applicability of SOC in social science and urban studies. The generalized 'criticality' is rational and easy to understand in urban studies. In addition, this study empirically introduces a new paradigm to identify criticalities of internal dynamics of complex system. Using Chinese cities as the study subject potentially expands the domain of urban theoretical inquires. Finally, this study bridges China's urban research with the mainstream theoretical inquiries.

- On the mythological aspect, this research employs a Cellular Automata model—SLEUTH to understand the generalized SOC theory in urban development at intra-urban level. As mentioned in the literature review, an important limitation of CA modeling in urban studies is lack of matching with urban theories. This research takes the advantage of the intrinsic self-organizing ability of CA into simulation self-organizing urban development on landscape; therefore it connects the model with the theory.

- On the policy aspect, this research helps governments to understand their roles in urban development at different scales, not only temporarily but also in the long term. While China has been trying to control urban development for a long time, the urban system analysis indicates the limitations of previous urban development strategies. Shenzhen also proves the importance of planning at the local level. This research will help the governments to redefine their urban development strategies, to establish reasonable urban policies and to harness the power of the local agents in order to place China on a more sustainable development path towards the new century.

- This research improves the understanding of China’s urbanization, especially the understanding of various criticalities in the urban development. With the rapid urbanization process, China is facing many serious problems including shortage of land resource, large amount of migrants and environmental pollution. While substantial efforts have been made to manage urban growth at a macro-level, the efficiency remains limited. The low efficiency is caused by our limited understanding of China’s current urbanization process. Although institutional factors used to be and still are important factors influencing urban development in China, urbanization in contemporary China follows more of a bottom-up process than subject to the traditional top-down institutional direction. To direct urban development, the top-down instruction needs to be planned and executed from the bottom local level. To better understand the urban development criticalities, it is crucial to develop effective policies to meet the challenges of rapid increasing urban population.

7.3 Remaining Issues and Future Research

This research is not perfect. Due to the objectives of this research, the limited efforts in Ph.D. study, and the availability of data, many aspects can be improved. Future research will first address the following two issues.

The first issue is the lack of clarity in the mechanism of city rank-size dynamics. While Zipf's law as a power law is used to examine SOC, the mechanism generating the Zipf's law in urban system is still a mystery. The current research only spatially and temporally analyzes the individual city's rank-size dynamics. Future research will explore the possibility to simulate the Zipf's law from individual city's dynamics. Batty et al. have already used a CA model to simulate rank-size dynamics of an ideal urban system. One of the logical methods for future research will use a CA-based agent model. Each city will be regarded as an agent with fixed location, but they can exchange population with one another. Using a CA-based agent model, social economic factors can be included into simulating individual city's population growth. In addition, the aggregated results of individual city's dynamics will help explain Zipf's law and enhance the understanding of SOC in urban system.

The other issue is the limitation of the CA model at the intra-urban scale. Although CA modeling is relatively well developed for simulating self-organizing bottom-up activities, the rationale of modeling is abstract and lacks the base of reality behaviors. The next step is to use agent-based modeling to study the urban land-use dynamics of Shenzhen. The study will be based on the perspectives of local agencies' developing behaviors. With agent-based modeling, the developing behaviors and the interactions of agencies can be represented, simulated, and analyzed. With the simulated results of individual agency's developing activities, the aggregated spatial allocation of Shenzhen urban development will be analyzed. To that end, the local agencies' behaviors can be directly related to the urban development results. Therefore, critical relationship between local agencies’ behaviors and urban development will present more “reality” and become easy to understand. Policy guidelines and implications for urban development generated based on this research will be more on target and effective.

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APPENDIX

The parameters of the top ten OSM values during each stage of SLEUTH model calibration of each area.

1 Coarse Calibration

Table 1 The parameters of the top ten OSM values with coarse calibration in Bao'an District.

BA1	Compare	Pop	Edges	Cluster	Slope	Xmean	Ymean	Diff	Brd	Sprd	Slp	RG	OSM
1	0.77628	0.96947	0.99453	0.99537	0.90377	0.92238	0.94953	100	100	100	100	100	0.589701
2	0.7743	0.96912	0.99574	0.9963	0.876	0.93336	0.94106	100	100	100	100	80	0.572787
3	0.68488	0.96723	0.99282	0.99984	0.99697	0.90993	0.95433	80	100	80	80	100	0.56929
4	0.72313	0.97334	0.9959	0.99998	0.92513	0.90755	0.95319	100	60	100	80	60	0.560972
5	0.77731	0.96836	0.99434	0.99737	0.85258	0.93084	0.94613	100	100	100	100	60	0.56051
6	0.73595	0.97143	0.99544	0.99915	0.90136	0.90826	0.95221	100	80	100	100	60	0.554302
7	0.67092	0.97652	0.99751	0.99943	0.97413	0.90503	0.95742	60	60	100	80	40	0.55132
8	0.69528	0.97471	0.99735	0.99807	0.92249	0.91209	0.95539	60	80	100	80	80	0.54228
9	0.69447	0.97454	0.99524	0.99997	0.93127	0.90694	0.95017	60	80	100	80	40	0.540535
10	0.65098	0.96847	0.99296	0.99977	0.99141	0.90641	0.9597	80	80	80	80	80	0.539758

Table 2 The parameters of the top ten OSM values with coarse calibration in Longgang District.

LG1	Compare	Pop	Edges	Cluster	Slope	Xmean	Ymean	Diff	Brd	Sprd	Slp	RG	OSM
1	0.63206	0.92992	0.99746	0.99978	0.99914	0.99416	0.98816	20	60	100	60	40	0.575326
2	0.63288	0.93229	0.99796	0.99518	0.998	0.99511	0.98495	20	60	100	60	60	0.573196
3	0.62968	0.93261	0.99916	0.9999	0.9971	0.99479	0.98387	20	60	100	60	1	0.572558
4	0.61869	0.93396	0.99999	0.99217	0.99905	0.99641	0.99005	20	20	100	60	100	0.565022
5	0.61598	0.9344	0.99998	0.99929	0.99861	0.9972	0.98124	20	20	100	60	40	0.561999
6	0.7659	0.91129	0.98496	0.82646	0.99939	0.9934	0.97754	100	100	100	60	1	0.551395
7	0.62478	0.92912	0.99762	0.99943	0.96449	0.9941	0.98355	20	100	100	80	80	0.545809
8	0.62136	0.92984	0.99743	0.99555	0.96437	0.99501	0.98692	20	100	100	80	40	0.543313
9	0.61914	0.93066	0.99715	0.9931	0.9669	0.99496	0.98602	20	80	100	80	80	0.54126
10	0.62855	0.93382	0.99987	0.93759	0.99793	0.99596	0.98714	20	40	100	60	100	0.539859

Table 3 The parameters of the top ten OSM values with coarse calibration in SSEZ.

SSEZ1	Compare	Pop	Edges	Cluster	Slope	Xmean	Ymean	Diff	Brd	Sprd	Slp	RG	OSM
1	0.93987	0.98171	0.99953	0.99678	0.94707	0.70348	0.96042	60	40	100	100	40	0.588222
2	0.90724	0.98555	0.99892	0.9741	0.95784	0.72431	0.96923	1	1	100	100	60	0.585032
3	0.95021	0.9802	0.99637	0.98662	0.9575	0.68868	0.95877	40	80	100	100	40	0.578863
4	0.93916	0.98131	0.99884	0.9709	0.95381	0.70494	0.96208	60	40	100	100	60	0.578151
5	0.94516	0.98072	0.99621	0.98048	0.95372	0.6988	0.95592	80	40	100	100	1	0.576813
6	0.95242	0.97916	0.99107	0.97633	0.9593	0.69231	0.9607	40	100	100	100	1	0.575739
7	0.90766	0.98523	0.99752	0.96689	0.92933	0.736	0.97403	20	1	100	100	40	0.574619
8	0.92546	0.98228	0.99765	0.99972	0.93397	0.70434	0.96332	40	40	100	100	1	0.57456
9	0.90696	0.9849	0.99601	0.97791	0.95468	0.72312	0.95621	1	1	100	100	1	0.574334
10	0.86336	0.9821	0.97909	0.99558	0.99909	0.70664	0.98006	60	1	80	100	80	0.571876

2 Fine Calibration

Table 4 The parameters of the top ten OSM values with fine calibration in Bao'an District.

BA2	Compare	Pop	Edges	Cluster	Slope	Xmean	Ymean	Diff	Brd	Sprd	Slp	RG	OSM
1	0.77867	0.96909	0.99476	0.9974	0.99844	0.9242	0.94735	100	100	100	96	70	0.654491
2	0.78223	0.96893	0.99542	0.99638	0.99996	0.92121	0.9448	100	100	100	96	100	0.654243
3	0.78229	0.96848	0.99506	0.99411	0.99947	0.92098	0.94738	100	100	100	96	90	0.653561
4	0.77733	0.96852	0.99521	0.99249	0.99989	0.92347	0.94959	100	100	100	96	60	0.652028
5	0.77098	0.96876	0.99459	0.9978	0.99951	0.92463	0.95179	92	100	96	92	90	0.651993
6	0.7634	0.96968	0.99459	0.99443	0.99951	0.93811	0.94847	96	90	100	96	100	0.651124
7	0.78253	0.96853	0.99491	0.99432	0.98461	0.92806	0.9484	100	100	100	92	60	0.649764
8	0.76856	0.96926	0.99507	0.99617	0.99999	0.92528	0.94932	92	100	100	96	80	0.648614
9	0.78295	0.96899	0.99479	0.99502	0.98401	0.92723	0.94637	96	100	96	92	100	0.648432
10	0.76935	0.96901	0.9946	0.99952	0.99992	0.92011	0.95068	92	100	100	96	90	0.648234

Table 5 The parameters of the top ten OSM values with fine calibration in Longgang District.

LG2	Compare	Pop	Edges	Cluster	Slope	Xmean	Ymean	Diff	Brd	Sprd	Slp	RG	OSM
1	0.64082	0.92883	0.99794	0.99058	0.99804	0.99449	0.98496	20	80	95	60	80	0.575219
2	0.64048	0.92766	0.99652	0.99123	0.99763	0.99574	0.98289	20	100	95	60	50	0.573027
3	0.62922	0.93192	0.99938	0.99527	0.99669	0.99583	0.98433	20	60	100	60	1	0.569821
4	0.62922	0.93192	0.99938	0.99527	0.99669	0.99583	0.98433	20	60	100	60	10	0.569821
5	0.63867	0.93082	0.99927	0.98044	0.99584	0.99497	0.98641	20	70	100	60	80	0.56925
6	0.61875	0.93472	0.99999	0.99997	0.99842	0.99585	0.98805	20	20	100	60	100	0.568153
7	0.62093	0.93203	0.99915	0.99885	0.99659	0.99674	0.98836	20	50	95	60	20	0.567044
8	0.62634	0.93131	0.99909	0.99782	0.99273	0.99359	0.98773	20	60	100	65	60	0.566549
9	0.62818	0.93225	0.99869	0.99122	0.9936	0.99685	0.98602	20	50	100	60	40	0.566167
10	0.63062	0.93023	0.99897	0.99107	0.99614	0.994	0.98316	20	70	95	60	40	0.565387

Table 6 The parameters of the top ten OSM values with fine calibration in SSEZ.

SSEZ2	Compare	Pop	Edges	Cluster	Slope	Xmean	Ymean	Diff	Brd	Sprd	Slp	RG	OSM
1	0.93919	0.98096	0.99879	0.99522	0.96648	0.69836	0.96278	60	40	100	100	60	0.59511
2	0.93943	0.98109	0.99978	1	0.96034	0.69391	0.95745	60	40	100	100	40	0.587925
3	0.89748	0.98268	0.99305	0.98039	0.97369	0.7205	0.97523	50	1	90	100	40	0.587447
4	0.90573	0.98104	0.99827	0.9836	0.97093	0.70864	0.9761	80	10	90	100	60	0.585949
5	0.92306	0.97856	0.99858	0.98457	0.99094	0.68911	0.96558	50	50	90	100	20	0.585559
6	0.92508	0.98284	0.99957	0.97561	0.97438	0.70128	0.965	70	20	95	100	60	0.584654
7	0.90922	0.98072	0.99642	0.9856	0.97964	0.70005	0.97348	40	30	90	100	20	0.584628
8	0.91216	0.98054	0.99552	0.99381	0.97294	0.69635	0.97221	70	20	90	100	1	0.582859
9	0.91216	0.98054	0.99552	0.99381	0.97294	0.69635	0.97221	70	20	90	100	10	0.582859
10	0.91914	0.9841	0.99701	0.99119	0.93792	0.71771	0.9676	70	10	100	100	1	0.582221

3 Final Calibration

Table 7 The parameters of the top ten OSM values with final calibration in Bao'an District.

BA3	Compare	Pop	Edges	Cluster	Slope	Xmean	Ymean	Diff	Brd	Sprd	Slp	RG	OSM
1	0.78324	0.96903	0.99551	0.99628	0.99917	0.92694	0.95137	100	100	100	95	100	0.663284
2	0.78508	0.96844	0.99523	0.99428	0.99995	0.92596	0.94901	100	100	100	94	90	0.661089
3	0.77981	0.96857	0.99515	0.99668	0.99879	0.92976	0.95007	98	100	97	94	75	0.660944
4	0.77723	0.96904	0.99548	0.9973	0.9982	0.93438	0.94721	94	98	97	93	100	0.660598
5	0.78001	0.96899	0.99541	0.99765	0.99993	0.92867	0.94747	98	100	98	96	85	0.660383
6	0.77728	0.96843	0.99402	0.9985	0.99999	0.93133	0.9489	98	100	98	95	80	0.66025
7	0.78394	0.9685	0.99469	0.99504	0.99952	0.92796	0.94712	98	100	99	94	95	0.660141
8	0.78007	0.96845	0.9941	0.99736	0.99879	0.93334	0.94542	98	98	99	95	100	0.660133
9	0.78511	0.96838	0.99473	0.99741	0.99536	0.92759	0.94769	98	100	98	93	100	0.660021
10	0.77789	0.9686	0.99463	0.99623	0.99717	0.93291	0.95016	96	100	98	93	80	0.659917

Table 8 The parameters of the top ten OSM values with final calibration in Longgang District.

LG3	Compare	Pop	Edges	Cluster	Slope	Xmean	Ymean	Diff	Brd	Sprd	Slp	RG	OSM
1	0.6427	0.92954	0.99843	0.99973	0.99897	0.99344	0.98483	20	80	98	60	100	0.582817
2	0.64832	0.92867	0.99738	0.99678	0.99372	0.99483	0.98393	20	100	100	62	85	0.582221
3	0.64276	0.92925	0.9969	0.99995	0.99865	0.99451	0.98443	20	85	100	61	85	0.582128
4	0.64203	0.92875	0.99765	0.99791	0.99726	0.99351	0.98835	20	90	95	60	70	0.58132
5	0.64593	0.92858	0.9976	0.99903	0.9922	0.99488	0.98492	20	100	99	63	75	0.58118
6	0.64209	0.93002	0.99699	0.99832	0.99479	0.99598	0.98542	22	75	99	62	100	0.580299
7	0.64397	0.929	0.99807	0.99966	0.99203	0.99434	0.98434	20	95	96	62	80	0.579561
8	0.64575	0.9294	0.9983	0.99175	0.99571	0.99403	0.98469	24	80	97	61	100	0.579112
9	0.63613	0.93141	0.99825	0.99975	0.99679	0.99566	0.98579	20	70	98	61	60	0.578518
10	0.637	0.93113	0.99859	0.99897	0.99573	0.99372	0.98727	22	65	98	60	65	0.578004

Table 9 The parameters of the top ten OSM values with final calibration in SSEZ.

SSEZ3	Compare	Pop	Edges	Cluster	Slope	Xmean	Ymean	Diff	Brd	Sprd	Slp	RG	OSM
1	0.90639	0.98164	0.99771	0.99262	0.98496	0.71189	0.97305	80	10	90	100	35	0.601203
2	0.8983	0.98287	0.99733	0.99944	0.96401	0.71841	0.98079	75	1	90	100	30	0.597782
3	0.92424	0.9789	0.99928	0.99889	0.98516	0.68867	0.96856	75	30	90	99	30	0.593434
4	0.92098	0.98236	0.99875	0.99998	0.96257	0.70386	0.96896	80	15	94	100	30	0.593189
5	0.91471	0.98464	0.99874	0.99826	0.94447	0.72188	0.96856	75	5	96	100	60	0.592975
6	0.91965	0.9838	0.99925	0.99773	0.9604	0.7106	0.9624	80	10	96	100	30	0.592447
7	0.93249	0.98201	0.99964	0.99988	0.95479	0.70212	0.96442	80	25	96	100	35	0.591748
8	0.91556	0.98328	0.99726	0.9862	0.97139	0.712	0.96603	80	10	94	100	45	0.591564
9	0.91502	0.98446	0.99991	0.99924	0.94345	0.71569	0.9732	75	5	96	100	50	0.591433
10	0.91004	0.98445	0.99762	0.99801	0.95276	0.72072	0.96438	80	1	94	100	60	0.59068

4 Derive Forecasting Coefficients

Table 10 The parameters of the top ten OSM values with the step of deriving forecasting coefficients in Bao'an District.

BA Year	**Diffusion**	**Breed**	**Spread**	**Slope Resist**	**Road Gravity**
1989	100	100	100	94.5603	100
1990	100	100	100	94.0495	100
1991	100	100	100	93.4451	100
1992	100	100	100	92.7106	100
1993	100	100	100	91.8682	100
1994	100	100	100	90.9053	100
1995	100	100	100	89.7691	100
1996	100	100	100	88.4887	100
1997	100	100	100	87.0527	100
1998	100	100	100	85.4485	100
1999	100	100	100	83.6273	100

Table 11 The parameters of the top ten OSM values with the step of deriving forecasting coefficients in Longgang District.

LGYear	**Diffusion**	**Breed**	**Spread**	**Slope Resist**	**Road Gravity**
1989	20.2	80.8	98.98	59.6696	100
1990	20.4	81.61	99.97	59.2824	100
1991	20.61	82.42	100	58.8504	100
1992	20.81	83.25	100	58.3366	100
1993	21.02	84.08	100	57.7623	100
1994	21.23	84.92	100	57.125	100
1995	21.44	85.77	100	56.3688	100
1996	21.66	86.63	100	55.5436	100
1997	21.87	87.49	100	54.6478	100
1998	22.09	88.37	100	53.6785	100
1999	22.31	89.25	100	52.6123	100

Table 12 The parameters of the top ten OSM values with the step of deriving forecasting coefficients in SSEZ.

SSEZ Year	**Diffusion**	**Breed**	**Spread**	**Slope Resist**	**Road Gravity**
1989	80.8	10.1	90.9	98.4701	35.15
1990	81.61	10.2	91.81	96.8208	35.32
1991	82.42	10.3	92.73	95.0438	35.4989
1992	83.25	10.41	93.65	93.0901	35.69
1993	84.08	10.51	94.59	91.0116	35.9
1994	84.92	10.62	95.54	88.8114	36.12
1995	85.77	10.72	96.49	86.4633	36.3519
1996	86.63	10.83	97.46	83.9993	36.6001
1997	87.49	10.94	98.43	81.4209	36.8588
1998	88.37	11.05	99.42	78.7327	37.1271
1999	89.25	11.16	100	75.9049	37.4098

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