Residential Area Modelling Using Cellular Automata with Estimated Water Resources - A Case Study in Darkhan, Mongolia -

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モンゴル国ダルハン市における事例研究ー)

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CHAPTER 1. INTRODUCTION

1.1 Problem statement

Water is a vital resource for human activities. Its natural distribution is governed by climate and the physical character of the land surface. Urbanization, however, has altered this natural distribution as water has been utilized to supply man's needs and to carry away his wastes. Water is, in a sense, both artery and vein to urban life (William J. Schneider et al., 1973). When urban growth is based on the migration from rural areas to city, population growth, especially that which will occur in third world cities, would be responsible for a substantial part of this increase.

The urban population in 2014 accounted for 54% of the total global population, up from 34% in 1960, and continues to grow. The urban population growth, in absolute numbers, is concentrated in the less developed regions of the world. It is estimated that by 2017, even in less developed countries, a majority of people will be living in urban areas (World Health Organization 2017). Thus, the cities of the developing countries faced with unplanned population growth and other issues which were related to natural resources.

The main determinant of increases in water demand is population growth. Population of urban increased and the concentration of water demand have become constraints of resources. The cities are critical areas from the viewpoint of water supply. The issue of water as a general constraint on development, so far has been approached through indices describing no more than the "density" of population relative to water resources.

The trends of global urban population is expected to grow approximately 1.84% per year between 2015 and 2020, 1.63% per year between 2020 and 2025, and 1.44% per year between 2025 and 2030 (World Health Organization, 2017). It is vivid that urban population is not stopped. But in cities of developing countries could not accept with that of intensive growth population particularly related to water consumption, public water supply facility and water purification. As it is mentioned at the starting point, the basic condition of the population growth of city is water consumption.

As a developing country Mongolia, has a lot of problems related to urbanization process which leads to shortages of water resource and urban land use change. These problems need to be studied scientifically towards the solutions. Our goal of research is focused on these aspects.

Growing demand for water, uncertainties in natural water supply and new requirements imposed by environmental legislation are posing serious challenges at maintaining water quality and meeting demand for water resources.

Our case study area - Darkhan city is third large city of Mongolia which is located at Kharaa river basin, in the northern side of Mongolia and is an influencing area of the new industrial zone. This includes water from the main rivers, their tributaries, groundwater and overland flows. Natural climate condition is within semi-arid area and annual precipitation is 300-400 mm year. It proves that water resource of the area is limited.

Darkhan was first established on October 17th, 1961 with the technical and economic support of socialist brother states, the Soviet Union in particular. After its foundation Darkhan had developed quickly as one of the main centers of Mongolian industry, specialized on the production of construction materials. The feasibility studies and project works to establish Darkhan city started since 1960s and the first general plan was developed in 13 institutions of the Gorstroy project Institute of Soviet Union in 1963, so that the construction works were launched.

The second general plan was developed at the “Central Science and Research Institute Project Urban Planning” in Moscow, Soviet Union in 1983, approved by the government of Mongolia, the planning period was defined up to 2000 when the population reaches 100,000 people. It was planned to become the main industrial junction as well.

Urban modelling for the Darkhan city has not made before and there have been several urban planning activities which were studied by Russian planners and Mongolian researchers. Previous studies were concentrated on natural condition and industrial resource. Nowadays, the modelling of urban landscape mainly divided in four types of models. The first type defines that urban structure and morphology, most models of this type were studied before the 1940s. The second type is based on Newton’s theory of gravity, and focuses on delineate the spatial interactions between different entities of city land use type. The most common examples were the gravity model (Foot, 1981) and the Lowry model (Harris, 1985). The third type is to represent the spatial process. The models were firstly proposed in the 1970s.

The fourth type cellular automata model which is a rule-based algorithm that has been long employed in computer science to explore social and physical phenomena (Wolfram, 2002). Also one of the leading researcher Batty (1971) pointed out that main roles for cellular automata model of cities can be divided into 3 types.

First, models have been developed to help in finding and attempting with hypotheses of the structure of cities. They form an essential part of theory development in urban research. Second, models have been used to provide methods for educating planners in urban theory. Third, and might be the most important, the models can be used in practical planning studies to help predict the likely consequences of planning or not planning the future of cities. These possibilities of cellular automata modelling is appropriate for research on Darkhan city.

1.2 Aims of the study

The planned objective of this study aims to achieve to improve the methodology of urban modeling by investigating a number of questions:

1. Modelling of the residential area of Darkhan city and future trends of the urbanization process. This urbanization activity affection for water resource.
2. Creating scenarios which are based on population growth and ground water resource. To analyze each scenarios and forecast water resource utilization of the research area.
3. To define socio-economic and natural linkages using system dynamics method.

   This research attempt is to obtain systematic explanation of linkage between socio-economic factors such as population growth and environmental factors like water resource. In the next year urban growth of Darkhan city depends on sufficient water resource and its sufficiency for residents that are rapidly increasing. This research mostly considered that obtain results about urban growth in the next years. To reach the study goals, several case studies such as urban growth scenarios and redictions were used. A number of methods, historical data and urban modelling techniques were used further.

Also following aspects will be tackled in the study:

- To study good water management, their causes, consequences and impacts on society and economy and the livelihoods of the herders and farmers in particular.
- To determine most influential factors affecting water demand and use
- To forecast the water demand and use of research area.
- To determine, compare and classify water utilization types.

1.3 Structure of the research

This dissertation is divided into 6 chapters. The research flowchart, which outlines the flow of the study, is illustrated in Figure 1.1.

Chapter 1 is a general introduction of the research. This includes problem statement, generic objectives and short outline of the structure of the study.

Chapter two includes the literature review of the research methodology. In this chapter that we discussed is mainly on cellular automata technique which used for research work. Also main parameters and their functions are explained. Another method namely system dynamics is also briefly discussed in this chapter. This chapter is published in the online journal named Reviews in Agricultural Sciences.

Chapter three included definition of research area and their characteristics. It is divided into two main sections according to the factors influencing urban development as Hydro-environmental factors and socio-economic factors. These two main factors and their sub categorized sections were included in modelling parameters.

Chapter four is mainly written about method using for Darkhan city modelling. Also, some theoretical explanations of urban expansion is included.

Chapter five shows some results of the simulation. This chapter consists of three scenario based simulations and their result shown by maps and graphs. It is published in the Journal of Rainwater Catchment Systems. Chapter six shows the summarized results of the study and analyzed city expansion. City expansion trend and its intense prediction is important achievements of the research. In that conclusion mainly considered is that the city expansion and its relation with water resource.

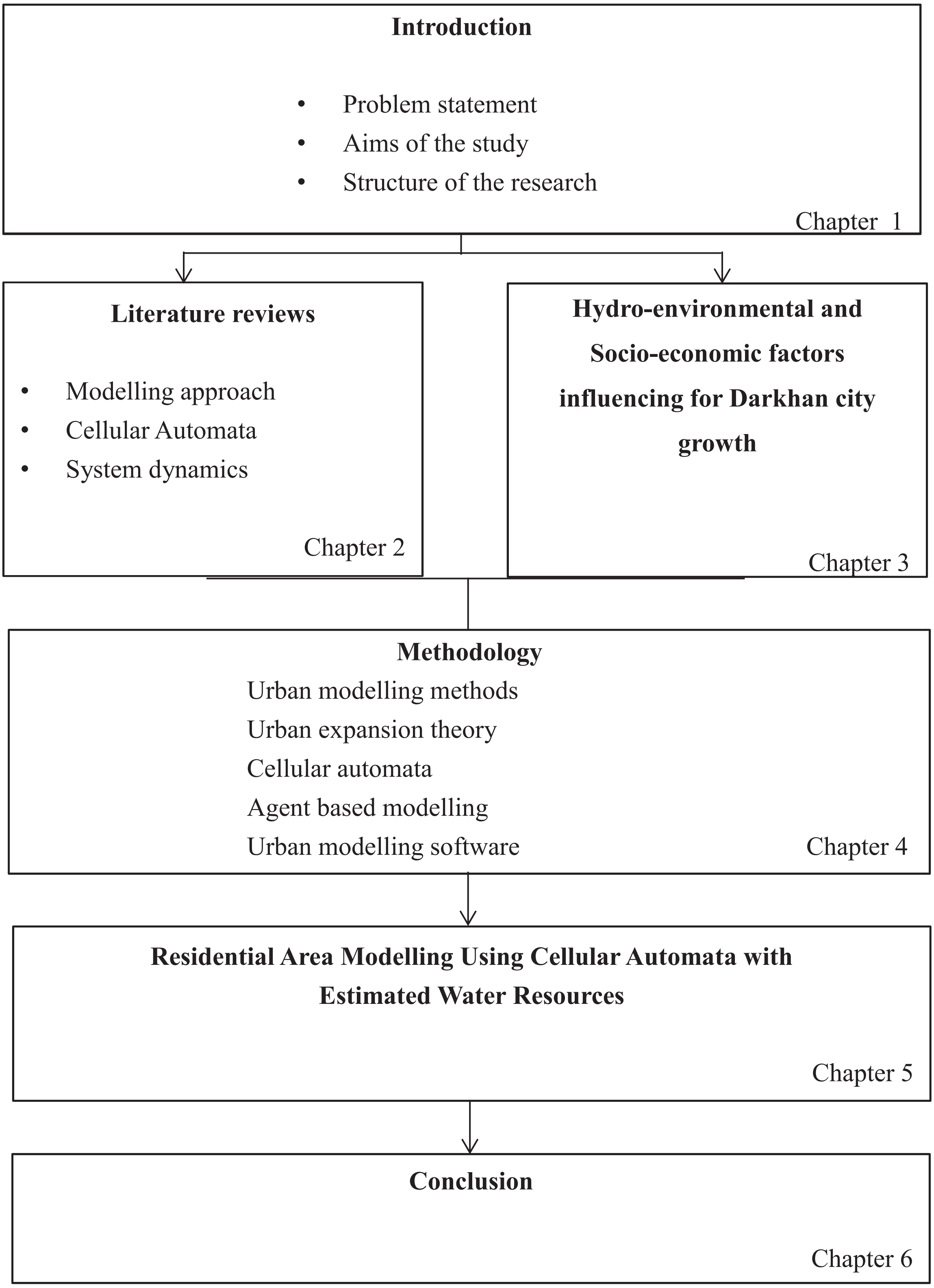


Figure 1. 1 Structure of the research

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

The urban expansion is always an inevitable issue in our human history and has become more intensive during a past several decades with explosive population growth of the world. The urban expansion is sometimes praised as a result of economic development, but at the same time, it might induce serious problems such as traffic jams, soaring price of real estate, trash problems, and shortage of natural resources. Thus, it is one of serious concerns many countries are facing. Therefore, a lot of modeling techniques have been introduced, discussed and developed for this problem (Batty, 1971; Forrester, 1969, Makse et al., 1995). Among them, cellular automaton (CA) is one of most dominant techniques, because both of the urban expansion and the CA inherently and similarly include complexity in their behavior.

CA was initially introduced by John von Neumann and Stanislaw Ulam as a simple model for biological process such as self-production (Burks, 1971). CA may express any non-linear system with identical discrete elements undergoing deterministic local interaction (Wolfram, 1982, 1983, 1984). Aggregation phenomena such as snowflake growth, shell patterns, wildfire, turbulence in fluid, as well as neurons obey repetitive application of simple local rules akin to CA. The urban growth is neither strictly biological nor physical phenomenon, but human-induced phenomenon. However, it is also a kind of aggregation of residents' actions, showing unexpected complexity, and it resembles to CA behavior.

CA is an aggregate of cells interacting in a simple way but displaying complex behavior (Wolfram, 1982, 1983, 1984). Conway's game of "life" is a famous and typical two-dimensional cellular automaton which was invented in 1970 by the British mathematician John Horton Conway, who have made CA applicable to various research fields (Gardner, 1970). It can mimic some group of living things interacting each other. It has only 4 simple rules, i.e., 1) Any live cell with only one live neighbors dies, as if caused by underpopulation, 2) Any live cell with two or three live neighbors lives on to the next generation, 3) Any live cell with more than three live neighbors dies, as if by overpopulation, and 4) Any dead cell with exactly three live neighbors becomes a live cell, as if by reproduction. In spite of the simple rules, it shows the surprising evolving patterns of cells, especially in its self-similarity and self-organizing. The complexity of the pattern shed light on the various academic problems and gave inspirations to science of complex systems. Urban growth is one of them.

Before the game of "life" appeared (Table 1), the first application of cellular automata to urban land use was done by Chapin and Weiss in the early1960s (Batty, 1997). In their framework, the patterns of human actions form urban growth. Cell-space modules were used to express states as a function of various behavioral factors including neighborhood effects, which is corresponding to the early stage of CA.

Tobler (1970, 1979), who is the first person brought a cellular approach into the geographic research. He assumed the land use at any location is dependent on the land use at other locations. Dependency is random, functional, historical, and sometimes multivariate. "Everything is related by everything else, but near things are more related than distant things" is the first law of geography he imposed. He, however, concluded the cellular geographical model actually does not give realistic results, while fruitful insight can be easily obtained through modeling processes. Actually, he admitted his main purpose in his formulation was pedagogical. Following to Tobler (1979), Couclelis (1984) pointed out the constraints of the geographic application, and generalized the cell-space principal based on the discrete model theory. The model was applied to a complex but hypothetical problems such as individual decision and large-scale urban change.

The first realistic application might begin from Batty and Xie (1994a,1994b) and Batty (1997). Since they proposed versatile and flexible algorithm, various urban expansion models based on the algorithm have been developed so far (e.g. Santé et al., 2010; Uesugi, 2009; Mendbayar et al., 2018). Many of them are modified to include particular relaxation rules such as "distant-decay effect", "zoning", "constraints", etc., which enables to reproduce more complex and realistic phenomena, while initial CA model adopts a simple transition rule in which the state of a cell depends on the previous state of neighboring cells and itself only.

This paper aims to categorize CA models with their motivation. Accordingly, characteristics of relaxations and techniques introduced in the CA urban growth model are examined. Also the scale problems that is frequently discussed in the validation of the CA model is reviewed in this paper.

Table 2. 1 Brief history of Cellular Approaches

Motivation	Leading researchers (references)
Robotics, Biology (cybernetics), Chemical, Engineering, Mathematics, Fluid mechanics	John von Neumann and Stanislaw Ulam (Neumann, 1966; Burks, 1971; Ulam, 1991)
The Game of "life"	John Horton Conway (Gardner, 1970)
Self-replicating machine (Codd's CA)	Edgar Frank Codd (1968)
Mathematics, Space physics	Konrad Zuse (1970, 1982)
Non-linear dynamic mathematical systems	Stephan Wolfram (1982, 1983, 1984)
Artificial life	Christopher G. Langton (1984)
Application of simple local rules to geographic problems	Waldo R. Tobler (1970, 1979)
	Helen Couclelis (1985, 1997, 2003)
	Robert M. Itami (1994)
	Michael Batty and Yichun Xie (1994)

2.2 Outline of cellular automata for urban growth

Figure 2.1 shows the number of articles on urban studies using CA from 18 countries (Australia, Brazil, Canada, China, Germany, Italy, Iran, Israel, Japan, Malaysia, Mongolia, Morocco, Netherland, Russia, Spain, UK, USA, and Venezuela) referred in this review. The articles are arbitrarily chosen by the authors according to the context. Therefore, it might not indicate the current research trend exactly, but it shows the development of this kind of researches. As shown in Figure 2. 1, the CA in urban growth models have rapidly increased during the past two decades. Though the number of articles seems to decrease after 2010, it is due to our method of selection of articles and actually the number of the urban researches with CA, especially in application to real regions, is still increasing. CA urban growth models are presently used for verification of urban growth, scenario based predictions, population dynamics and so on (Figure 2.2). Thus, it can be concluded that CA would be a major technique in planning and verification of the city.

The wide variety of CA methods applied for urban studies might require a brief definition of CA in urban studies. The simple definition of the CA is that cells on a grid in a scaled area expand through a number of distinct time steps following to a set of rules defined by states of neighboring cells. The rules are then applied iteratively for as many time steps as desired (Wolfram,1982,1983,1984). As numerous authors (e.g., Tobler, 1979; Couclelis, 1985, 1997, 2003; O'Sullivan and Torrens, 2000) described the CA elements and main concepts, an elementary CA is comprised of 1) Space and Cell states, 2) Neighborhood, and 3) Transition rules.

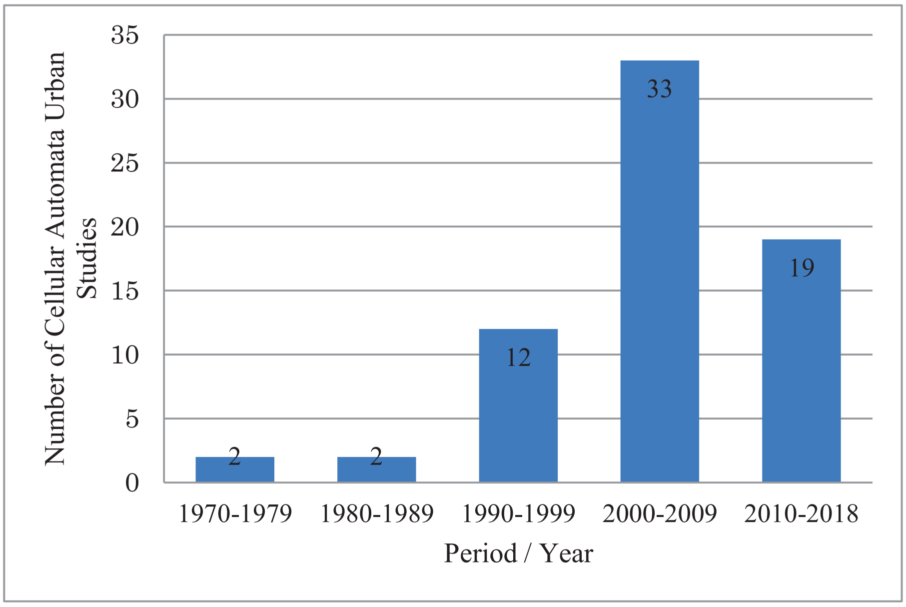


Figure 2. 1 Number of articles which applied CA to the field of urban studies.
(68 articles are selected among 87 articles listed in References.)

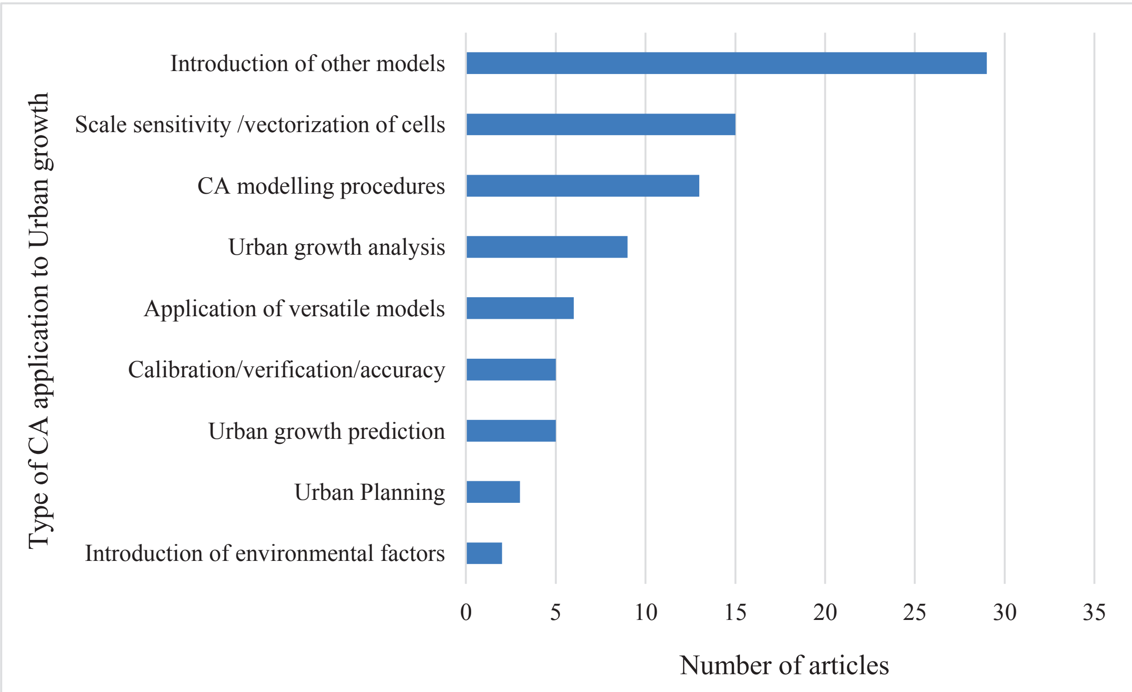


Figure 2. 2 Different types of urban cellular automata application (68 articles are selected among 87 articles)

2.2.1 Space and Cell state

Though the dimensions of CA can be either 1, 2 or 3, 2-dimension is frequently used in the urban growth modeling. Lattice is applied to divide the space into uniform square cells. Each cell is numbered by the row and column. The cell size is arbitrarily chosen so as to fit the observed geographical data, such as a pixel size of satellite image. Even if a same CA model is applied, different cell sizes make results different. The effect of cell size and shape is described later. Each cell divided by the lattice has its own state. The cell state in a primary CA is given by binary bits, e.g. live or dead in the game of "life". On the other hand, in case of urban growth, cell state is relaxed to have various states, such as land use, degree of development, and population.

2.2.2 Neighborhood

In a simple square lattice used in the conventional CA, neighborhood can have two definitions. One is von Neumann's neighborhood, composed of a center cell and its four adjacent cells in upside, downside, right hand side, and left hand side. The other is Moore neighborhood, composed of a center cell and all of surrounding cells. If we write the center cell as Cij, the Moore neighboring cells can be written as Ci±1,j±1, where subscripts indicate the row and column, respectively. In the conventional CA, the neighbor is just defined as adjacent nodes, but in the urban growth the neighbor sometimes indicates the relation of land use, human activity, and other geographic conditions. Therefore, it often extends to express the reality. But the basic concept of neighborhood is universally given by the first law of geography.

2.2.3 Transition rule

In a CA model, the cell state changes according to the transient rules related with neighbor states. When Moore neighborhood is simply used, the number of the cell states is just 2^9=512. Thus, the cell state in the next time step is given by one of 512 patterns. Even if the patterns are 512 and all of behavior can be made out, possible behavior of cell patterns are highly complex. In other words, CA can simply simulate spatiotemporal complex patterns without difficulties. On the other hand, its inherent simplicity cannot reproduce reality and it often lacks driving forces of urban growth (Al-Sharif and Pradhan, 2013). This may be resolved by introducing relaxation and integration of other quantitative, qualitative and stochastic models at the sacrifice of inherent simplicity of CA. In addition, it can include not only deterministic processes, but also stochastic processes and environmental conditions, which is the core of the relaxation of CA described later (Couclelis, 1997).

2.3 Types of relaxation in the transition rules of CA and external techniques/models

Actual urban growth does not only depend on the state of the cell and its interaction with surrounding cells, but also on external factors such as government policy, socioeconomic factor, natural resources, infrastructures and so on. Thus, the conventional CA has some limitations to reproduce realistic city due to its simplicity. Then, many kinds of relaxation of the rules are proposed and also some additional techniques/models such as geographic information system (GIS) and system dynamics are introduced. However, relaxation of rules might weaken the conventional CA, because simplicity and locality of CA might be lost. Moreover, CA component might be no longer the core of the model (Santé et al., 2010).On the other hand relaxations are inevitable for giving a reality to CA of urban growth. Followings are typical relaxations rules of CA and additional models.

2.3.1 Accessibility

According to a number of censuses, urban area tends to expand under the influence of the distance from traffic infrastructures, i.e., roads, railways, airport, and entrance of highway. For example, Mendbayar et al. (2018) shows the urbanization is clearly expressed by the logarithmic function of the distances from a highway or a station, which apparently obeys a distance-decay effect 3). In addition, a city center attracts the residents and similarly factories, hospitals and shopping centers are of interest of the residents. The distances from such facilities have strong influence on the urban growth. Then, a quite number of CA models include the concept of distance in their rules. Clarke et al. (1996) includes the road effect that encourages urbanized cells to develop along the transportation network replicating increased accessibility. Park and Wagner (1997) gave higher probability to become an urban cell for a non-urban cell which locates near the road network. Samat (2006) considered the employment centers, major roads, school and health clinic and hospitals as the regional factors accounting for the spatial location of the cells. Similar modification of the rule has been frequently adopted by various models (White and Engelen, 1993; Clarke et al., 1996).

2.3.2 Cell state

The conventional CA has binary state in its cell, like “Life” and “No-Life” in a game of “life” and the primitive urban growth model also used binary bit of “urban” or “non-urban” like Batty and Xie (1994a, 1994b), Xie (1996) and the framework in Couclelis (1985). Even if contemporary models with a variety of extensions, quite a number of models still use such binary state (Samat, 2006; Lin and Li, 2016). For example, He et al. (2008) uses “urban” and “non-urban” for the cell state, but incorporate the concept of potential to expand the model. In the development of CA for urban growth, it was natural that the cell state becomes more specific and more complicated than the conventional state. White and Engelen (1993) introduced four types of land use, i.e., “vacant”, “housing”,” industrial” and “commercial” as a cell state. White and Engelen (1997) subdivided the states into two categories, i.e., functions and features. Functions indicate active state such as housing, forestry, or commerce that can be converted to any other, while features are a kind of fixed land use such as water, parks, and airport that affects transitions but remains stable. Barredo et al. (2003) introduces 22 cell states to precisely model urban land uses. Among these states, road, airports, water bodies and etc. are categorized as features similar to White and Engelen (1997) and the function is additionally divided into passive functions and active functions. Arable land, forest, and wetland are passive cells, which participate in the land use dynamics, but are not driven by an exogenous demand for land. Other nine urban land uses are active cells which are forced by exogenous demands to the CA in response to the growth of the urban area. Combined with GIS, introducing various states for each land use seems to be straightforward. Then, a number of models can obtain their own originality in the cell state. As of localized extension of the model, Mendbayar et al. (2018) introduces the state of “*ger*” that is a typical temporal residence of nomads .

2.3.3 Zoning and geographical information

In order to establish the reality of the model, GIS and remote sensing (RS) may remarkably contribute to the CA model, especially in the data collection, calibration and verification. Satellite images are helpful to consider the model applicability and offer the measure to find reality in land use and land cover. Park and Wagner (1997) pointed out the poor ability of GIS to handle dynamic and temporal dimension and proposed to couple GIS with CA as spatial diffusion operators. Herold et al. (2003) described that

RS can provide synoptic view which is detail in space and time, while social data are often restricted to limited stakeholders and they are poor in temporal accuracy and consistency. Both RS and GIS are introduced in some models due to their compatibility (e.g., Fan et al., 2008; Moghadam et al., 2017). Amongst them, iCity (Stevens et al., 2007; Stevens and Dragićević, 2007) is one of the most major GIS-CA collaborated modelling tools. It extends the traditional formalization of CA to include an irregular spatial structure, asynchronous urban growth, and a highly spatiotemporal resolution to aid in spatial decision making for urban planning. SLEUTH (a cellular urban growth model and land use change model, Dietzel and Clarke, 2007; Clarke et al., 2007; Clarke, 2014) is also one of the major models of CA. Herold et al. (2003) analyzed past 72-year data set complied from interpreted historical aerial photography and satellite imagery of Santa Barbara and also forecast the urban growth using SLEUTH model. They concluded that the combination approach using RS, spatial metrics and urban modeling is powerful and may prove a productive direction for better understanding of spatiotemporal urban growth.

2.3.4 Markov Chain

Markov Chain is a stochastic concept that a probability of the coming event depends only on the state in the previous event. Coupling with urban growth model, Markov Chain is utilized in the transition probability of land use and land cover change (LULCC). Originally, both CA and Markov Chain models were utilized for prediction of the spatial distribution of the specific land use and land cover by using the knowledge gained in the previous years. Markov Chain, however, failed to incorporate external socio-ecological factors and spatial information. CA, on the other hand, failed to include stochastic transition through time. Pontius and Malanson (2005) applied Cellular Automata Markov (CA_Markov) model to predict land change in central Massachusetts and concluded that the added complexity of CA_Markov is of no benefit. The accuracy of CA_Markov is inferior to those model that does not use spatial contiguity explicitly, which is due to the efficient combination of the two models (CA and Markov model) into a single holistic model. Myint and Wang (2006) overcome the shortage of CA_Markov model by using a multi-criteria decision-making technique in predicting the future land cover land use information and then demonstrated the usefulness for landscape change. Currently CA Markov is considered to be one of successful tools to forecast land use changes and trends (Guan et al., 2011). Fan et al. (2008) also utilized Markov chain with TM image. They applied post-classification method and produced a change matrix to show a “from-to” information for land class. The change matrix give a quantity and rate of land use change through time.

2.3.5 Fuzzy Logic and Fuzzy Reasoning

Zadeh (1965, 1968) proposed fuzzy logic to allow real number between 0 and 1 in the logic, while Boolean logic uses only 0 and 1 often called crisp by contrast to the work ‘fuzzy’. It is often said that fuzzy is quite similar to probability. Therefore, it is also introduced into CA model, especially in the transition rule of land use. Wu (1998) employed fuzzy logic to capture the feature of land conversion behavior, while CA was used to simulate global pattern from local rules and implemented in GIS. Dragićević, (2004) claimed the fact that some descriptive or uncertain knowledge of the system behavior is not actually in crisp rules and then a single variable function in transition rules are used for each type of transition. Liu and Phinn (2001) delimited the urban areas using a fuzzy membership function and transition rules are applied using linguistic variables to represent the non-deterministic nature of urban development. It enables “partly urban” in the land use. Similarly, Mantelas et al. (2008) divided the study area into fuzzy sets as “static non-urban”, “dynamic non-urban” and “urban” and then uses fuzzy system to calculate the next status of each area.

2.3.6 Logistic regression (LR), Artificial Neural Networks (ANN) and Support Vector Machines (SVM)

The logistic model is a kind of generalized linear model and usually applied to a binary dependent variable. It guesses that whether the result is 0 or 1 from explanatory variables. In urban growth, it is useful to understand the cell transition with explanatory variables such as environmental factors and driving force. LR is used to find the parameters of the logistic model. Hu and Lo (2007) applied LR to associate the urban growth with demographic, econometric and biophysical driving forces and generated an urban growth probability map. The number of the explanatory variables excluding geographical coordinates.is 18. LR is considered to be equivalent to a simple perceptron and it is proved to be inapplicable to non-linearly separable problems.

ANN mimic neural networks of animal brains in computers. It consists of layered nodes or artificial neurons and synapses that connect nodes. It is equivalent to the combination of simple perceptrons, thus, usually called a multilayer perceptron applicable to non-linear problems. Each synapse transmits a signal from connected node to another connected node. Transmitting signal is often expressed by non-linear function such as a sigmoid function. The strength of connection is given by weight and is usually adjusted through learning process. Thus, ANN is a kind of interpolation method of input-output relationship by learning a priori knowledge. In tuning of the ANN, backpropagation is the most frequently used algorithm to modify the weight of connections by minimizing the error of the output layer.

SVM is another learning machine. It projects the supervised data on another map so that data of different categories is divided with maximum clear margin. SVM, a kind of clustering algorithm, enhances the ability to categorize unlabeled data and clear the relationship between input and output, the usage of which is very close to ANN.

In urban growth model, ANN is often utilized in the transition rule and its calibration is similar to other external models. Using the past land use pattern and transition, it learns the relationship underlying the land use change. Instead of conventional transition rules, Li and Yeh (2001) and Yeh and Li (2003) applied ANN to CA model to estimate development probability based on the inputs of site attributes. Pijanowki et al. (2002) developed a spatial allocation and forecasting module that can automatically extract the basic rules of spatially dominant factors of land use conversion by machine learning and neural network training method. Wenhui (2011) adopted this module to develop the dynamic urban growth model. As ANN has the advantage in practical use for the various observed data, ANN-CA models are often discussed such as Yang et al. (2016) that used ANN to mine the transition rules of the land use change from the observed data. On the other hand, abundant data sets are required for accurate reasoning by ANN, which is sometime disadvantage in the practical application. Yang et al. (2008) tested SVM as a method for constructing nonlinear transition rules for CA and concluded that SVM achieves high accuracy in simulating complex urban systems. Rienow and Goetzke (2014) introduced SVM into SLEUTH to overcome the uncertainty of driving force of urban growth. In the model a SVM-based probability map of urban growth was introduced.

2.3.7 Genetic Algorithm (GA) and optimization

Genetic Algorithm is a kind of metaheuristic optimizer inspired by the process of natural selection. Using repetition of crossover, mutation and selection, GA produces a new generation of the solution to make the objective function maximum. Similar to Monte Carlo Method, it does not require the derivative of objective function, but it converge much faster than the Monte Carlo Method.

Several parameters obtained through calibration are keys which enable the CA based urban growth model to generate urban pattern close enough to reality. For example, it is known that the SLEUTH model has its own calibration method through visual and statistical assessment to discover the best parameters, but its computational burden is exhausting. Next, multiple methods to improve the calibration of CA, including the SLEUTH model have been discussed and GA is one of them. Shan et al. (2008) describes the number of parameters will exponentially increase the computational burden if GA is introduced in the calibration. They concluded that GA significantly benefit urban modeling problems with larger set of input data and bigger solution spaces. Jafarnezhad et al. (2015) also introduced GA to the SLEUTH model for calibration and found the excellent performance of GA in computational time and the accuracy. Compared with other models and methods, GA seems to be often used rather in calibration than in transition rules.

2.4 System Dynamics (SD)

External factors often expressed by scenarios is essential to establish the reality in urban growth. Natural conditions such as water supply and climate can be included in the external factors. Barbier and Chaudhry (2014) examined the problem of water provision in an urban economy and found that, ceteris paribus, higher water use and population growth are associated with greater per capita economic growth in urban areas, but urban areas with higher total water availability are not experiencing lower per capita economic growth. McDonald et al. (2011) discussed the relationship among urban growth, climate change and freshwater availability by 2050 and described some cities in certain regions would struggle to find enough water because of demographic growth and climate change, in other words, urban growth relies on climate and water supply. Xu et al. (2014) integrated SD into CA model and land use demand was simulated under constraints of population, economic growth, and also those of water resources and climate change at the macro level. SD that is famous for "The limit to Growth (Meadows et al. 1972)" is a method to understand a complicated system with feedback. It consists of stocks, flows, and feedback loops to expresses non-linear behavior of the system (e.g., Walter et al., 2016). Mendbayar et al. (2018) also introduced simple SD of water supply system in the CA model as a constraint on urban growth. When water resources are sufficient, the urban growth is not restricted, but insufficient water resources due to demographic growth suppresses the urban growth in that model, which is expressed as a kind of feedback loop.

2.5 Characterizing the scale sensitivity

2.5.1 Scale Effect

Amongst reviewed articles, a several articles are addressing scale selection. Most of them were macro-scale model, and development of the regional models were of their main interest. A few also focused in relatively micro-scale model, i.e., urban areas of a city. Editorial of Computers, Environment and Urban Systems (Benenson, 2007) warned similarity of the result by different scale of the model and discussed the available scale of the model. The CA model possesses sufficient degrees of freedom with respect to the model's spatiotemporal resolution. In numerical computation of fluid dynamics, such as advection and dispersion, the expression of physical phenomena is restricted by the discretization of time and space. To obtain the stability of computation, e.g. time increment must be small enough for the wave not to travel to adjacent grids in the duration, which is called Courant-Friedrichs-Lewy condition. The urban growth is not definitely a physical phenomenon but must have some similarity like as Park and Wagner (1997) considered CA as spatial diffusion operators. Even when the computation by CA is not dynamically executed, the results must be influenced by the resolution of time and space. In the game of "life", the simple two-dimensional cellular automaton, shows the different resolution of space results in obviously different features (Benenson, 2007). So, discussion of scale effect is essential in versatility of the CA models in the urban growth problems.

Scale is an important concept in representing space since the result obtained at specific scale cannot be valid at another scale (Samat, 2006; Dietzel and Clarke, 2004). Jenerette and Wu (2001) compared coarse and fine scales using Markov CA with parameters produced by Monte-Carlo optimization. The result showed the accuracy in the coarse scale was superior to that in the fine scale. Jantz and Goetz (2005) tested the performance of SLEUTH (Clarke et al., 1996) in response to varying cell resolutions and suggested that the sensitivity of scale extends beyond issues of calibration. They concluded the consideration of appropriate scale is necessary in land use change modeling. Dietzel and Clarke (2004) also examined the impact of spatial resolution using SLEUTH urban growth model (Clarke et al., 1996) and found that the parameter sets and forecasting results of urban growth in fine and coarse scaled data did not coincide through the calibration routines. In addition, several other literatures (Pan et al., 2010; Zhao, 2013; Moreno et al., 2008, Yeh and Li, 2006) reported the spatial scale has significant impact on the outcome of CA, especially raster CA and only if the model is used for its appropriate scale, the outcome has reality.

2.5.2 New Cellular Space

White (1998) mentioned that cells represent cadastral unit and so they are not necessarily lattice, but any shapes. Each cell has its state of land use or land cover and also its intrinsic quality representing e.g., soil quality, slope or land use regulation, which is useful for a heterogeneous cell space. Graph CA was proposed by O'Sullivan (2001a, 2001b) in order to overcome the scale sensitivity in a conventional raster-based CA. It allows cell neighborhoods to be nonstationary, but it is stored in a graph of adjacency relations. Any lattice can be regarded as a graph. It indicated some probability to specify model structures concisely, but it seemed to be inadequate in the urban growth, as it need to be matched with reality to the time.

Following them, a vector-based CA (VCA) (Shiyan and Daren, 2004; Moreno and Marceau, 2006) and an object-based CA (OCA) (Moreno et al., 2008) has been advocated. In the VCA and OCA the cell is no longer regular lattice, but expressed by a vector/polygon space corresponding with a geographical entity such as land, school and commercial center. Each cell indicates one of geographic features and has its proper behavior. This kind of irregular shaped cell is often generated from the geographical feature, but on relative early stage the irregular shape was based on Voronoi diagram and Delaunay triangles (Moreno et al., 2008). Adamatzky (1995) introduced the theoretical method to construct Voronoi-like lattice structure in CA and showed the possibility of alternative cellular space. Voronoi diagram is a method to divide the space so as to make the distance minimum from the points scattered on the space. The resulted shape becomes a polygon and the nearest point from any position in each polygon should be included in each polygon. The method is known as Thiessen Method in meteorology to divide the catchment area. Shi and Pang (2000) implemented a Voronoi diagram based irregular shaped cell, but some misfit with the real geographical entity was still observed. Recently Ouardouz et al. (2014) applied Voronoi diagram in CA for assigning (some company's) technicians in the domain, which seems another way of usage. The cell space using Voronoi diagram seems not to be flexible enough to fit the geographically corresponding polygons yet.

Moreno et al. (2008) introduced more flexible VCA, the space in which was defined as a collection of geographic objects of irregular shape showing the real entity, georeferenced, and whose spatial representation can be associated to a geometric feature. The neighborhood is considered as a region of influence of each geographic object. It means the neighbor needs not be an adjacent cell. The status of cell is clearly given such as urban, forest, and agriculture and the cell can easily correspond to GIS polygons. It is, however, noted that the implementation of VCP requires intensive computational loads due to the reconstruction of the topology after each geometric transformation of the polygons. A vector CA combined with graph theory to get a better operability was proposed by Barreira-González et al. (2015). It showed the superiority of VCA to raster based CA within GIS tools and succeeded in the reduction of embarrassing computational loads using graph theory after O'Sullivan (2001a, 2001b). Stevens and Dragićević (2006) developed the iCity prototype integrated within GIS with polygon cells. Each cell corresponds to a cadastral land parcel and the iCity succeeded to represent asynchronous urban growth with reality. Though Stevens and Dragićević (2006) might not resolve the complexity and accompanying computational load of CA model embedded in GIS, this kind of consistency between CA and GIS would induce new paradigm of urban growth model.

2.6 Conclusion

CA is one of the most useful techniques to assess and simulate the urban growth that is a kind of complex problems. As aforementioned, it is relaxed in various ways to make the result realistic. One of the major relaxations is creating meaning to the cell state, the neighbor, and the transition rules. Originally, they are just defined as the topographic relations, but they are relaxed to link the real characteristics of land use, geography and urban growth. Another relaxation is introduction of stochastic process to CA. The original CA also uses random number and hence it is not completely deterministic, but the relaxation introduces the concept of probability, which make CA more realistic and the result of CA more complex. Another relaxation is the application of arbitrary cell shape. It is somewhat reasonable for geographers and regional planner to make the cell fit to the land use or some meaningful shape, but it is a big perceptional change. The irregular cell might abandon the original characteristics of CA that is based on lattice, while the models with irregular cell certainly show praiseworthy results. For the urban growth the relaxation of CA is inevitable, but it loses the simplicity that is a superiority of the original CA on the other hand. Further, the characteristics or the essential points of CA can be concluded as follows; that the rule is simple, but the result is complex to represent the inherently complex natural phenomena. This tradeoff must be a big issue for the further researches.

CHAPTER 3. HYDRO-ENVIRONMENTAL AND SOCIO-ECONOMIC FACTORS INFLUENCING DARKHAN CITY

3.1. Study area

In 1994, under the 32nd decree of the State Ikh Khural, within the law of the administrative and territorial units of Mongolia and their governance, today's Darkhan Sum was established on the territory of Darkhan City with 16 bags. Darkhan Sum now occupies a territory of 10,315 hectares along the Kharaa River in the basin of Orkhon and Selenge Rivers. Darkhan city borders with Khongor Sum in the eastern and southern part, with Orkhon Sum in the northern part, and with Saikhan Sum of Selenge Aimag in the western part. Sharyn Gol Sum is situated at a larger distance south east of Darkhan City. The city center is located around 220 km north of Ulaanbaatar.

The total population of Darkhan city comprises of 79,938 people, who live in 23,349 households. Thus, the size of average household is around 3.3 persons. According to the census of 2014, only 107,690 heads of livestock were kept in the sub-urban area. The major factories producing construction materials are in Darkhan city. Their location is very favorable due to the well-established traffic infrastructure at the junction of the international railway lines and the main asphalt auto roads, connecting with Russia, Ulaanbaatar City, Bulgan and Orkhon-Uul Aimags.

Due to these location advantages, the major economic facilities of Darkhan-Uul, Selenge and Orkhon Aimags are concentrated in Darkhan city, such as bank services, electricity power supply, fuel distribution, wholesalers, trading and communication centers as well as intercity and inter sum transportation. There are more than 1000 economic entities operating in the Darkhan city, although there is a considerable number of big companies where the majority of the entities are small and medium enterprises.

3.2. Field research for data collection

The research was conducted based on two main steps as following; using human geographical research methods, and then the preparation and evaluation of fieldwork by analyzing the results. In the frame of preparation of fieldwork, necessary data on the present economic status of Darkhan City from the Aimag and sum administrations as well as from other agencies, development organizations and research institutes were collected.

Fieldwork was conducted from August 1 to August 15, 2015. The fieldtrips and the related activities were mainly focused on meetings with responsible representatives of the Darkhan City administration, delegates for foreign trade and the economic sector, and representatives of NGOs and research institutes such as Kharaa-Yuruu river basin authority.

Also the collected data was analyzed and mapped by using GIS software. The whole research is based on a combination of qualitative and quantitative research methods. The qualitative research approach is the overriding paradigm in the study. Different methods forecasting water demand and usage are described in practice of countries.

In order to reach the goals of the study the following methodological steps have to be undertaken:

a.) *Forecasting demographic development*

The crucial point in all forecasting models for water demand is to have the best possible knowledge about the future development of population since most of the operational goals of water management are directly or indirectly linked to population.

b.) *Regional Science Methods-Examines models of regional growth and development*, including export base, input-output and econometric, cohort component and spatial interaction; emphasizes socio-economic impact analysis and forecasting sub-national economic and demographic change.

3.3. Hydro-environmental factors

3.3.1. Climate and natural condition

Darkhan city is located in the Kharaa river basin area. Its average altitude is 850 meters above sea level. Many small rivers such as Sharyin Gol and Khuitnii Gol flow into the Kharaa River. Mountain black soil and brown soils dominate. The fauna and flora is characterized by 400 species of birds, 4 different lizards and 5 kinds of hoofed animals.

The major plants are feather grass, bushes and shrubs. Forest is concentrated in the south eastern part of the territory, dominated by birch and annual evaporation is 250 mm per year. Climate is defined by long and cold winter, dry hot summer, and low high temperature amplitude. Average annual precipitation reaches 300-400 mm (Figure.3.1).

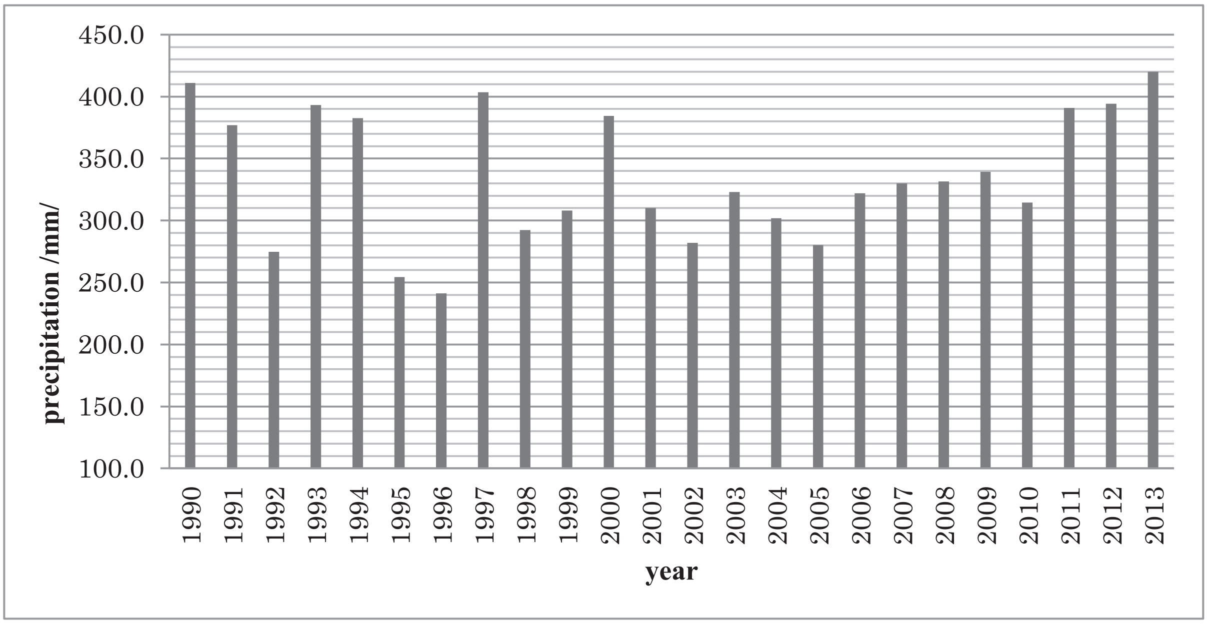


Figure 3.1 Annual precipitation

The maximum and minimum air temperature amplitude is high, where maximum temperature occurs in July. Minimum temperature is occurred in January. Annual average temperature is about -3 C^0 (Figure 3.2)

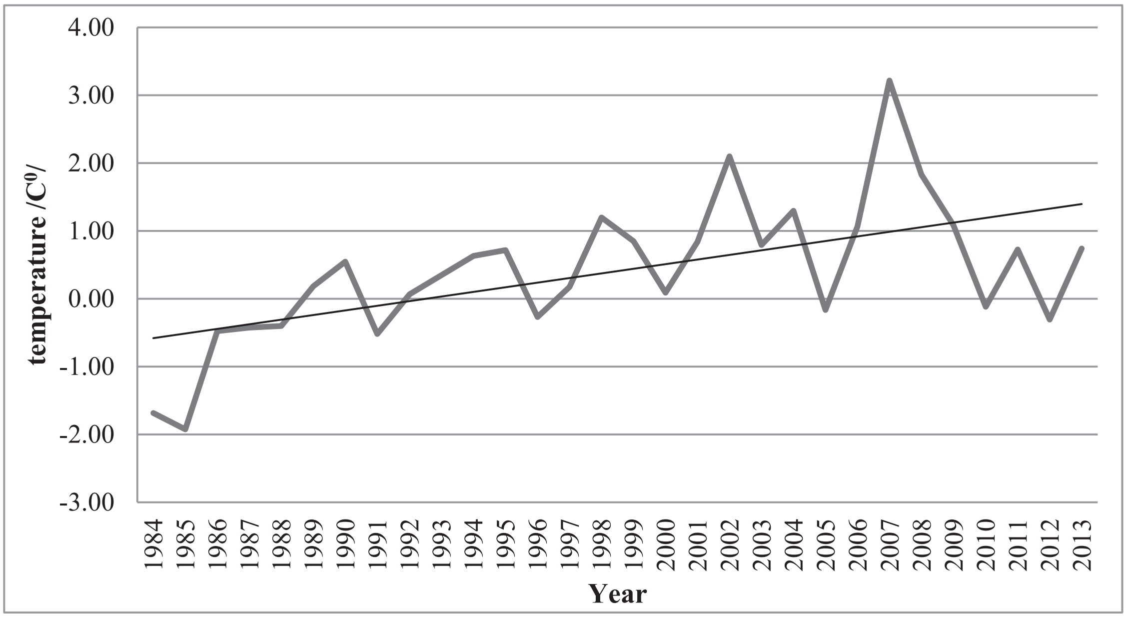


Figure 3.2 Annual temperature

3.3.2. Surface water resource

Kharaa River is studied first time between 1949 and 1952 by Russian hydrologist Kuznetsova. N.T, he had obtained that river network, hydrology, water regime of the Kharaa river basin. Also Kharaa River is the one of tributary of Orkhon River which flows to Baikal Lake. Kharaa river basin area is interesting area for researchers and international organizations. For example, in this basin area, several projects such as MoMo project are implemented. The Kharaa river basin where Darkhan city is located, forms part of the Arctic Ocean basin and can be divided into ten sub-basins. The river originates at an altitude approximately 2500 meters and has length of about 290 km until it flows into the Orkhon stream. There are two main run-off peaks in the flow regime of the Kharaa River including spring snow melting and summer rainfall floods. In general, spring flood starts from mid-April to end of May due to accumulated snow and also snow and ice melting. Kharaa river flow composition is as follows; 43% Ground water, 42% rainfall and 15% melting snow and ice.

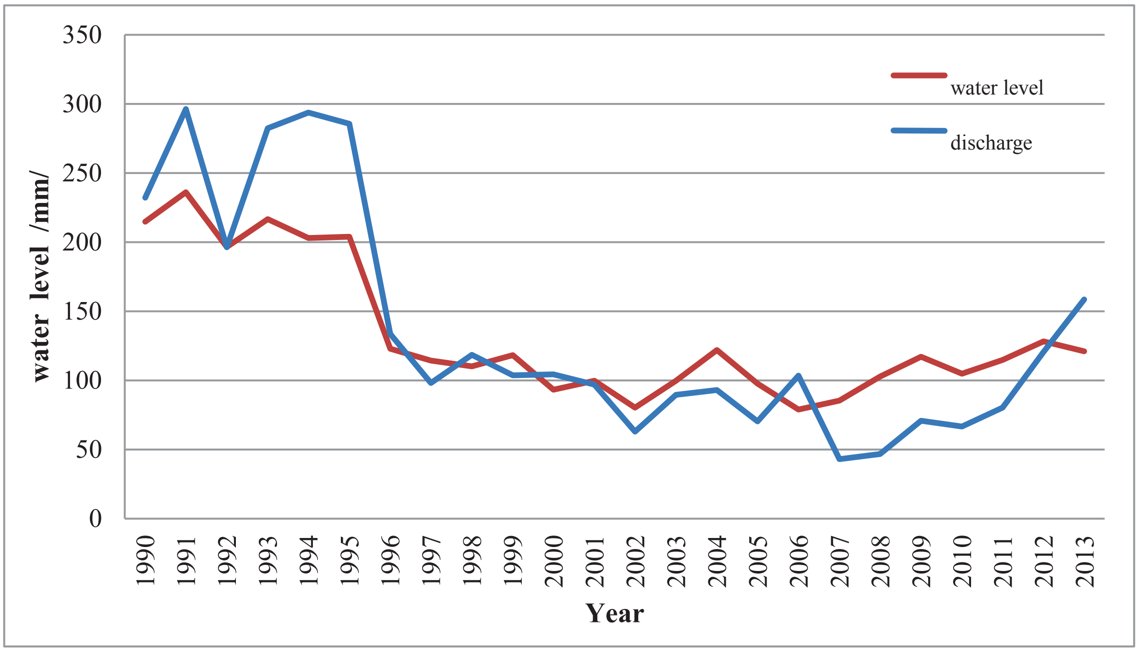


Figure 3.3 Kharaa river water level and water discharge

According to the data obtained from Meteorological station of the Darkhan city, river water level is high between 1950 and 1970, and is low between 1970 - 1980. Again, the water level is high between 1980 -1990 and is been low since 1990 - until today comparatively (Figure 3.3).

3.3.3. Ground water resource

Darkhan is the third big city which consumed public water supply system. There are 18 deep wells used for public water system. The wells' capacity of water sprout out is 726 liters per second. Surrounding area of the Darkhan city's hydro-geological condition is studied by the team from Institute of Construction and Planning of Russia led by E. A. Kojevnikova in 1962. The study finds out the geological structure, lithological composition of alluvial aquifers, water table and chemical composition of ground water.

Figure 3.4 Photo of deep-wells

Based on this research, 11 wells used for public water supply were constructed in 1965. After that, water consumption of the city is increased and additional 7 wells were also constructed (Figure 3.4).

Since 1965 with its construction to the first time, those wells have been working for more than 40 years until today. Within this period some wells were outdated and some of them had gone technical renovations funded by Japanese International Cooperation Agency (JICA) in 2010. Figure 3.5 shows that automated systems which control the

Figure 3.5 Photo of deep-well`s inside

pumps.

Although groundwater resource of Darkhan city is not affected by ecological change, but now utilizing wells are deteriorated. In this reason groundwater exploration work is made by D. Dorj, R. Battumur et al, in order to investigate water well sites (Figure 3.6).

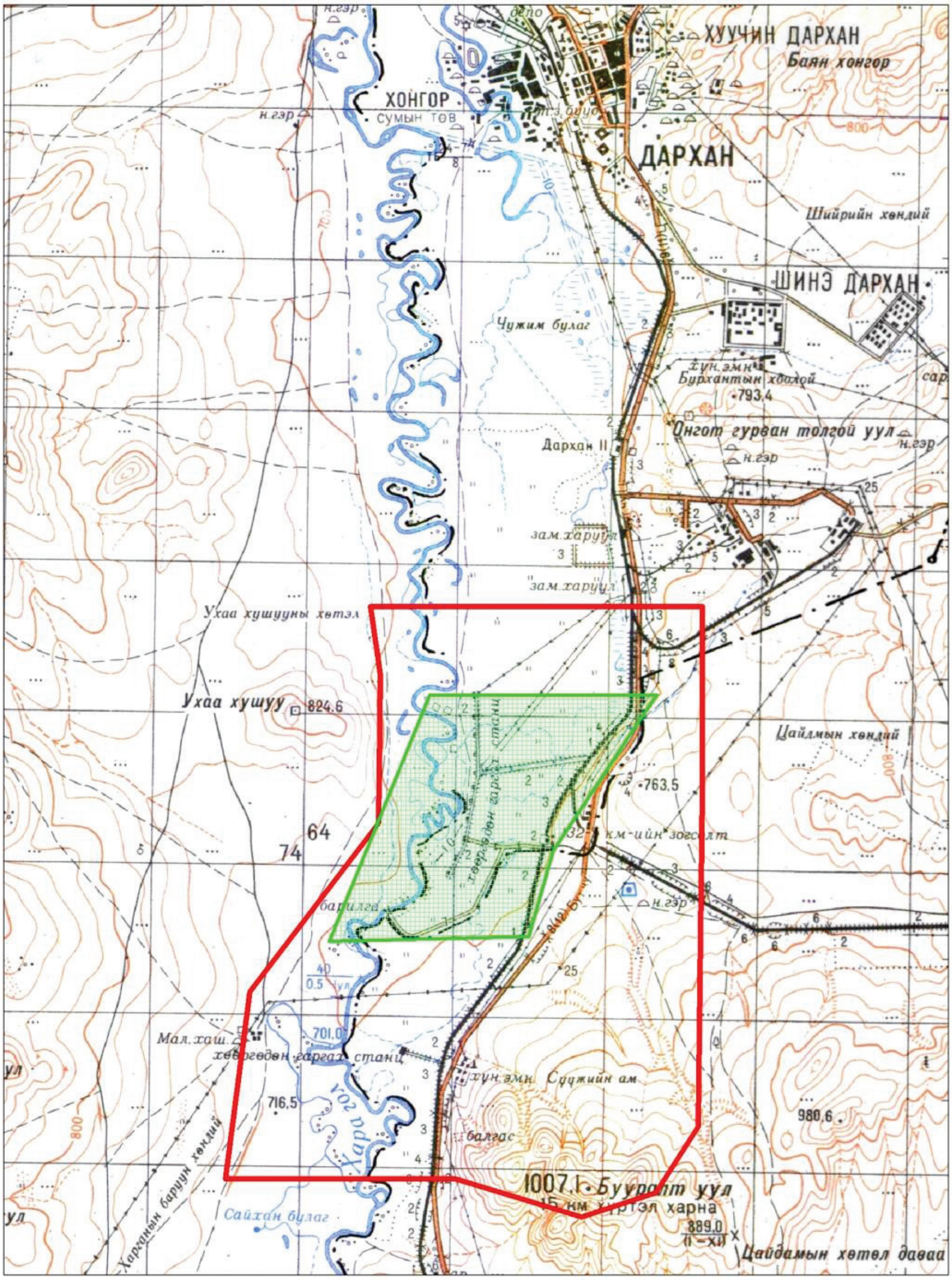


Figure 3.6 Map of groundwater exploration area 1962 (by green) and 2007 (by red)

Kharaa River has become the source of direct and indirect water supply of the Darkhan city. River water direct users are livestock keepers and residents who live nearby river bench. Also, this river has become a water source of deep wells that are supplied for public water consumption. It had been proved by a research organized by Engineering exploration institute of Russia, which had carried out in between 1962 and 1963. Kharaa River is the important environmental area for natural water and city water consumption (Table 3.1).

Table 3. 1 Water usage of Kharaa river

Sectors	**2008**	**2010**	**2015**	**2021**	**Water usage source /year 2010/**	**Explanation**
	Water consumption mil.m^3/year					
Irrigated agriculture	9.29	10.97	18.88	29.00	50% ground water 50% surface water	Wheat, potato, vegetable are cultivated in irrigated land
Domestic water	4.29	4.31	5.04	5.39	95% ground water	Darkhan city water usage,
Electricity, heating system	3.90	3.90	5.22	7.40	100% ground water	Located Darkhan city
Mining	5.90	4.11	3.33	5.43	100% ground water	Boroo Gold mining, Shariin gol coal mining
Livestock	2.94	2.72	3.93	4.91	45% ground 55% surface water	River, spring, ground water become a source
Factory /light, food, construction/	0.94	1.03	1.43	2.09	95% ground water, 5%-surface water	Light, food industries and heavy industries are located in the Darkhan city
Other	0.05	0.06	0.11	0.26	100% ground water	Recreation and green zones
Total	**27.31**	**27.09**	**37.94**	**54.47**		

Table source-Integrated water resource management plan of Mongolia

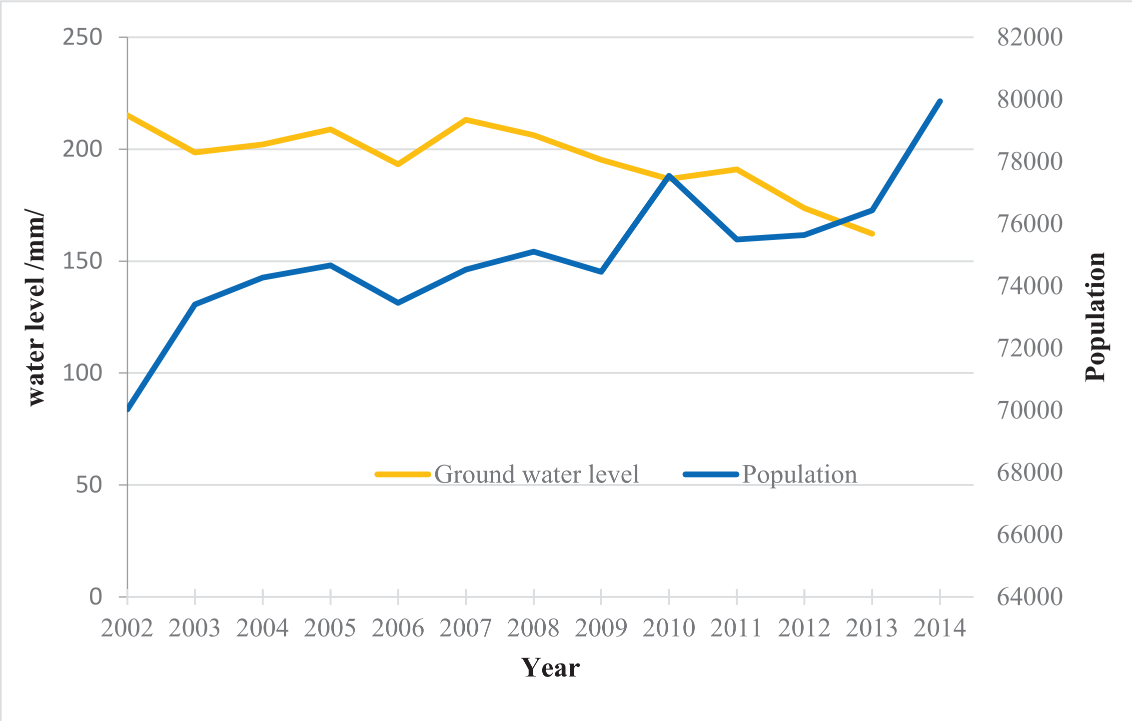


Figure 3.7 Graph of population and groundwater level

In the last years Darkhan city population has increased. It is the one main reason for groundwater decline (Figure 3.7).

3.3.4. Elevation and slope

In many developing countries, natural inconvinence is a constraining factor of urban planning activity. Darkhan city area expansion is one of the examples. The map of elevation proved that city area expansion follows through lower-altitudes (Figure 3.8).

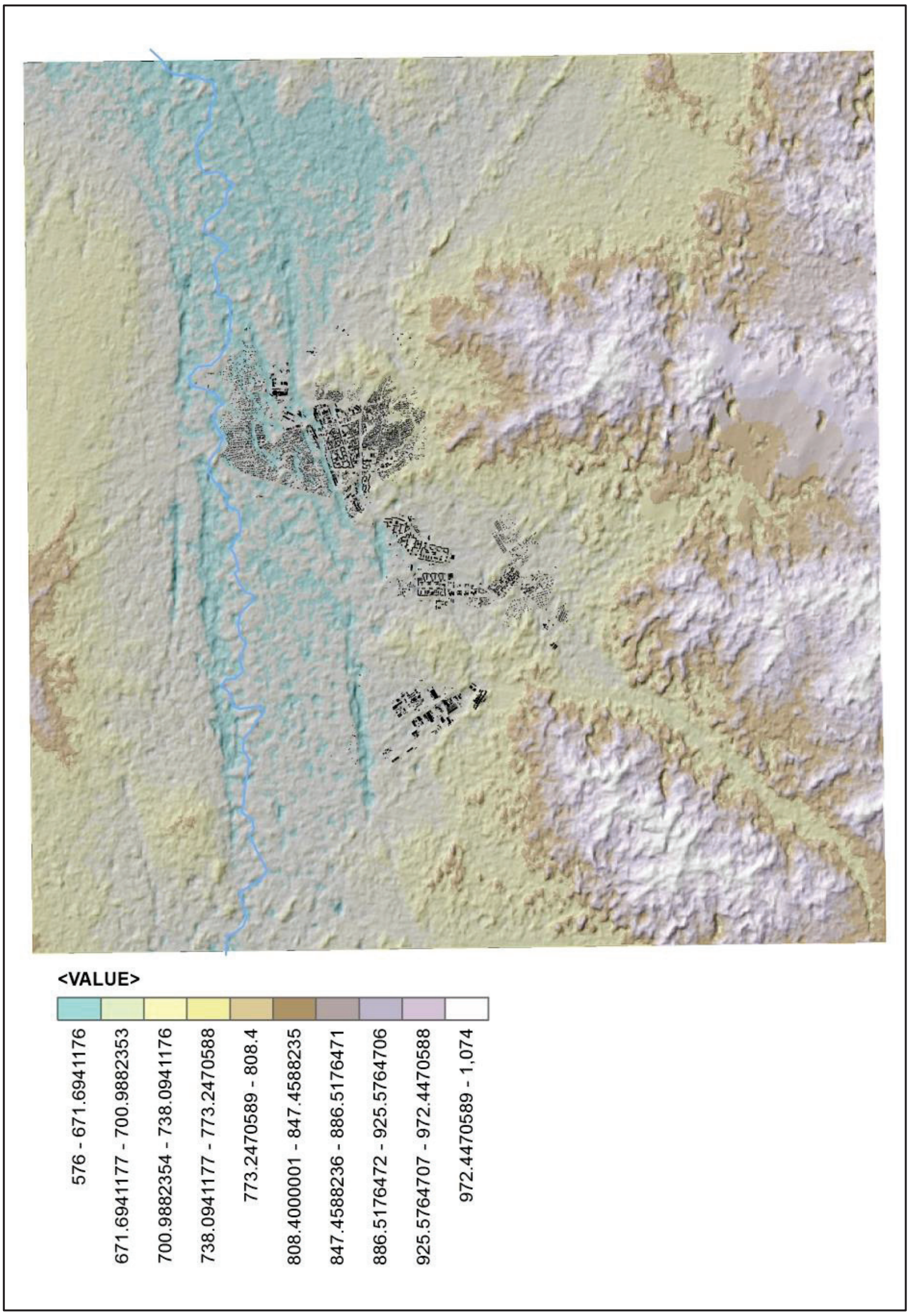


Figure 3.8 Elevation map of basin area

For immigrants who have settled in urban area has to deal with poor financial conditions. Most of them are seeking for jobs in urban area. After that, it is difficult to find construction facilities due to economic conditions with the settling in new area. Alternatively, they choose to settle in the lower steeped area. Accordingly, slope has become another constraint factor for city expansion. As shown in the slope map in Figure 3.9, urban expansion is marked by black color and low-steep area is by green color. We can see that the residential area is expanding through lower-steeped area.

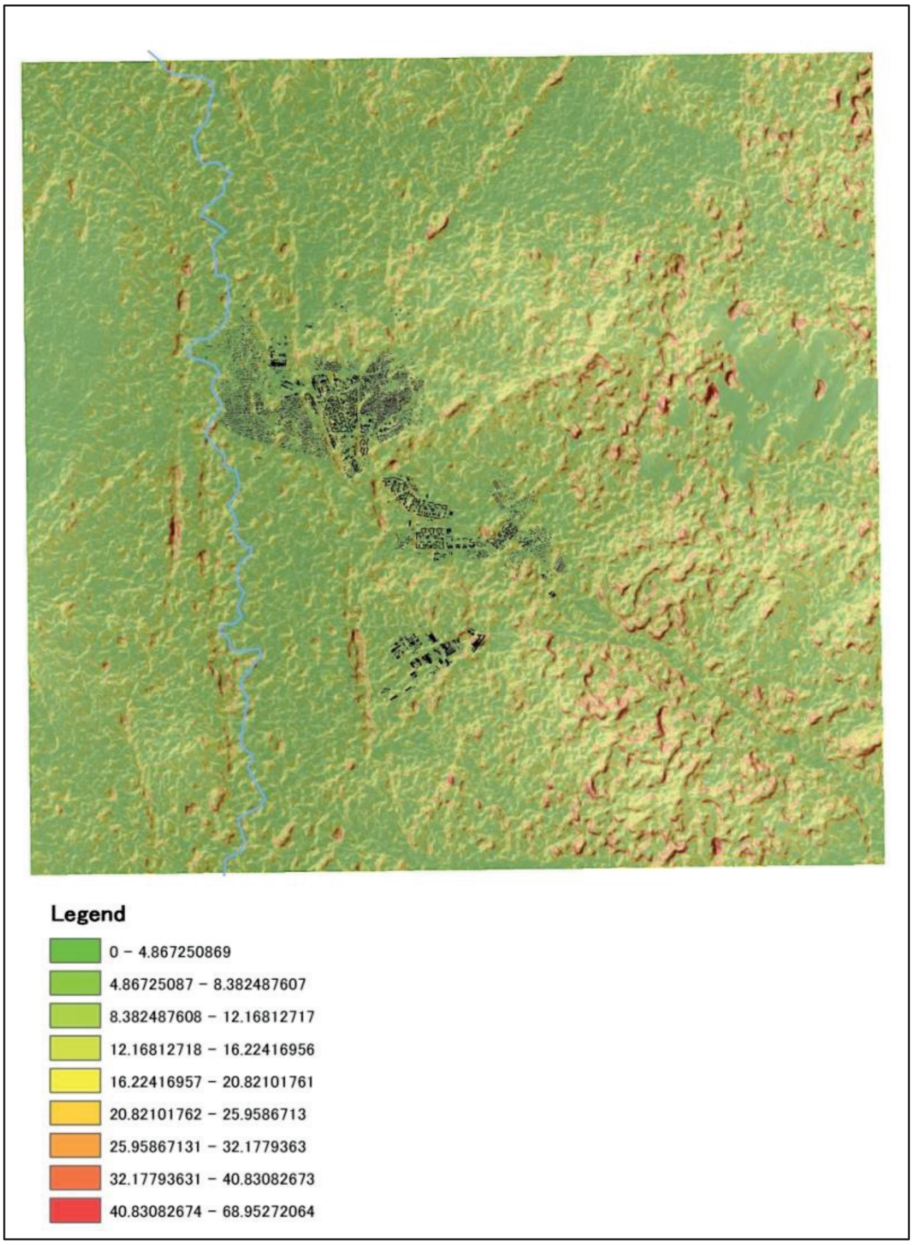


Figure 3.9 Slope map of basin area

3.4. Socio-economic factors

3.4.1. Urban development of Darkhan city

The resolution no. 196/260 of 1961 by the Ministerial Council of the People Republic of Mongolia approved establishment of Darkhan city and the first foundation of Darkhan city was laid on October 17, 1961. Historical photo of the Darkhan city is shown by the Figure 3.10. Up to date, the population of Darkhan city is 79,938 people, and it has the territory of 327,500 hectares. It is the third biggest city of Mongolia (Figure 3.11). In 1994, by the resolution no.32 by the State, Ikh Khural Darkhan city was re-organized to Darkhan-Uul province with administrative unit of 4 soums and 24 bags. The feasibility studies and project works for the establishment of Darkhan city started since 1960s and the first Overall plan was developed in 13 institutions of the Gorstroy project Institute of Soviet Union in 1963. As a consequence, the construction works were launched.

The second Overall plan was developed at the "Central Science and Research Institute Project Urban Planning" in Moscow, Soviet Union in 1983, approved by the government of Mongolia, the planning period was defined up to 2000, when the population reaches 100,000 people. It was planned to become the main industrial junction as well.

"Concepts of regional development of Mongolia" was approved under the resolution no.57 of 2001 by the State Ikh Khural of Mongolia. The objective was to develop Darkhan city as the economic hub of central region. The project and research institute of the capital city renewed the overall plan and it was approved by the resolution no.46 of 2004 by the Citizens Representatives Khural of the province. The overall plan put an objective to develop Darkhan city as the administrative, industrial, cultural, educational and scientific center with the population of 115.0 thousand people and to become the economic hub of central region up to 2020.The current architectural and special planning of Darkhan city is determined by the overall plans, approved in 1983 and 2004, respectively. The Action Plan 2012-2016 of the new Government for Changes of Mongolia included the article "To develop Darkhan city as the first Sample city of Mongolia, which satisfies the world level". In 2013, a counseling work of the overall plan to develop Darkhan as the Smart city was announced and the executive company was selected, however, the work hasn't begun yet.

The issues of urban growth particularly related with urban population growth and water usage has become one of the important questions faced during the past urban planning activities in Mongolia.

Figure 3.10 Historical photo of Darkhan city in 1965

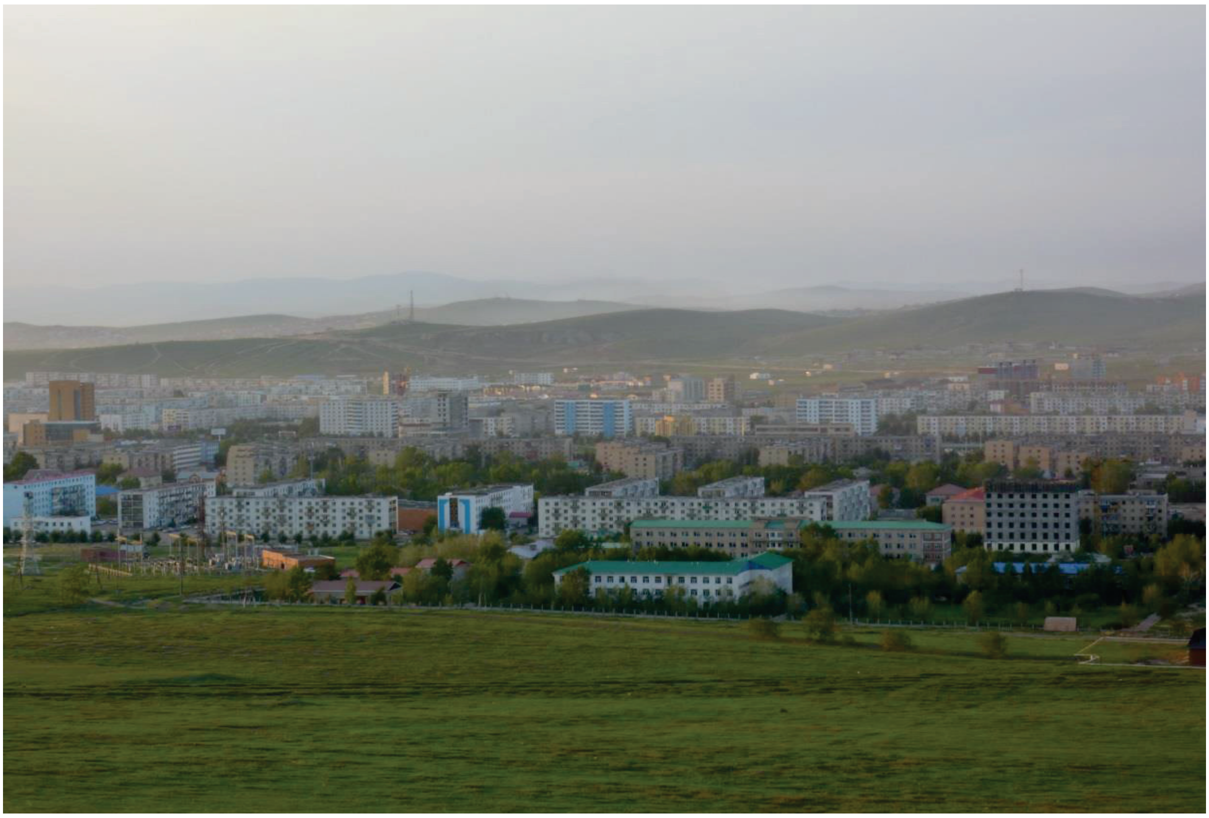


Figure 3.11 Photo of Darkhan city in 2015

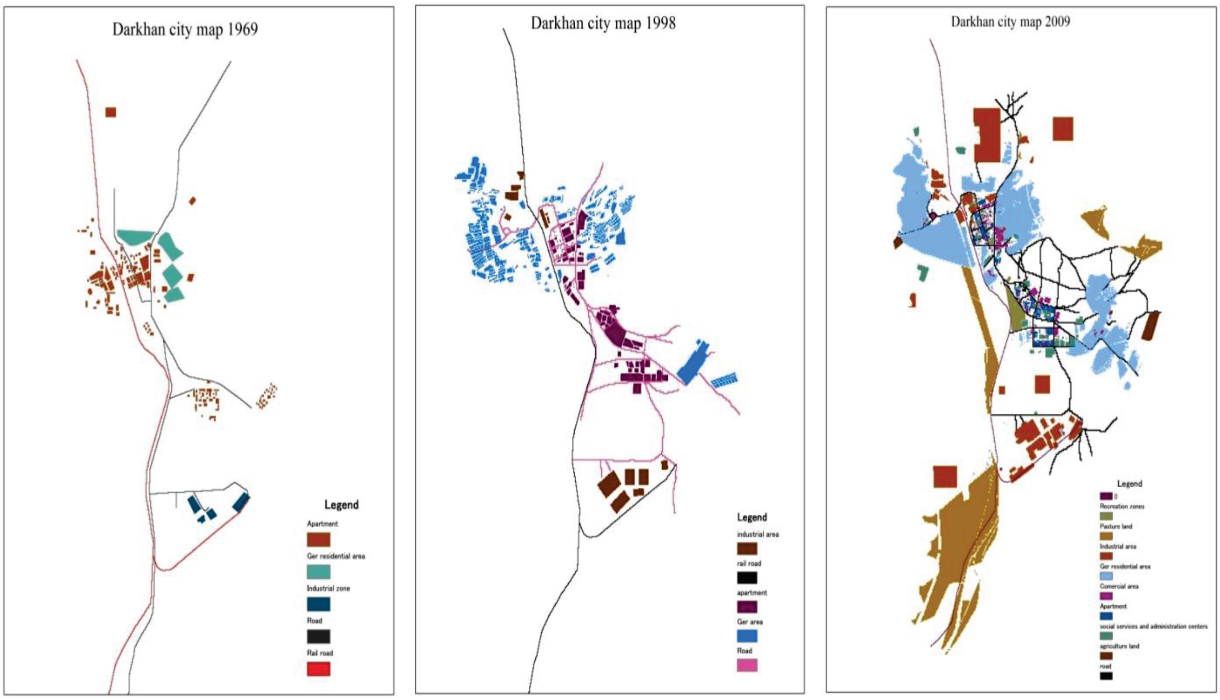


Figure 3.12 Map Darkhan city expansion

Table 3. 2 Urban growth statistics

Year	1969	1998	2009
Buildings /ha/	0.5	156.2	235.5
Ger area /ha/	92.4	306.1	971.8
Road length /km/	30.6	42.7	72.2
Industrial area /ha/	28.12	98.9	464.3
Total urban area /ha/	120.02	561.2	1671.6
Annual growth /ha/	-	15.2	100.8
Annual growth rate		12.6%	17.9%

Figure 3.12 shows that urban expansion by 1969, 1998 and 2009. This mapping is based on topographic map made in 1969 which is the oldest data used in the study. Based on this map urban growth is calculated in three phases of time (Table 3.2).

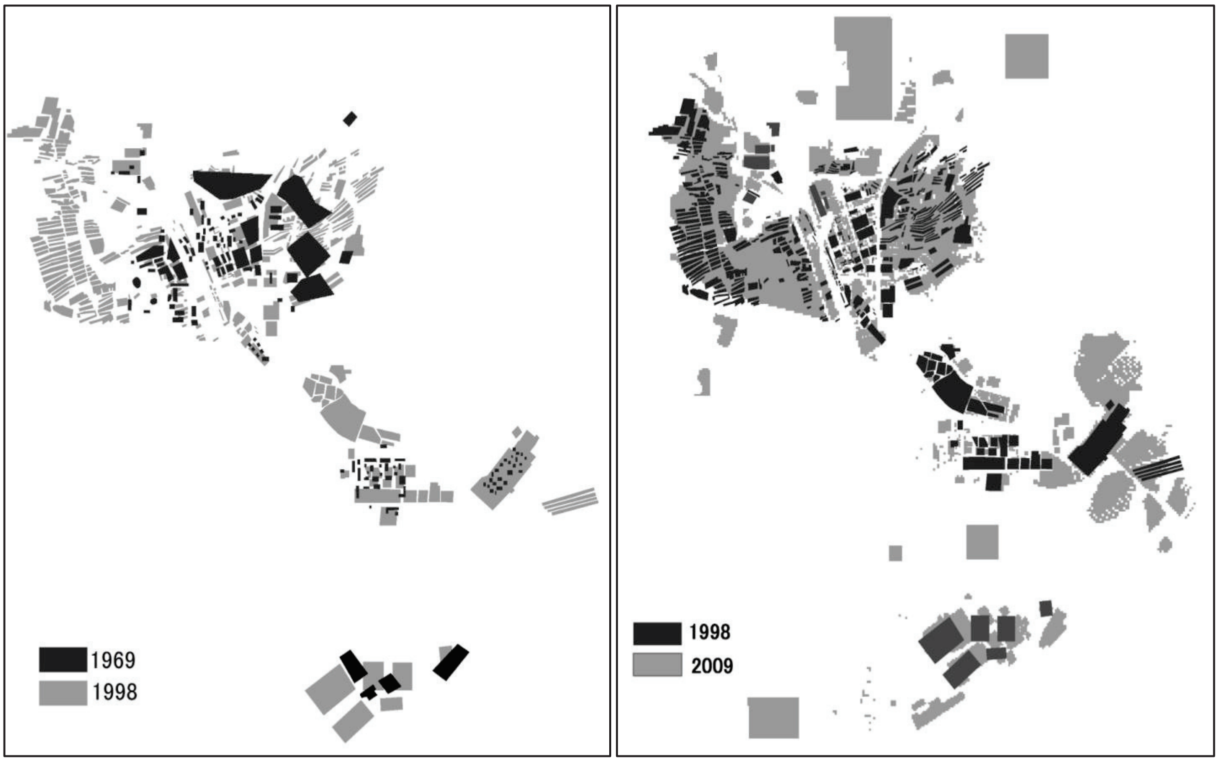


Figure 3.13 Map of urban morphology

Using the topographic and digitized maps urban morphology is defined (Figure 3.13). The direction of newly residential area and urban shape can be seen from that map. City is expanded mostly in southern side which named *ger* district (Figure 3.14), but the expansion through north side is slow. In the western side, Kharaa River is located and it can become one of restricting factor for expansion. In general, old residential area is concentrated along major road accesses. Also urban expansion is required to shift from monocentric to multi-center spatial structure. The reason why it is required a new center in that city is for the provision of social services and infrastructure facilities for the increasing number of residents of continuously expanding *ger* district. Present condition in the new residential area is of poor living standard. For example, some area is not provided by drinking water and elecricity (Figure 3.15).

Figure 3.14 Photo of *ger* residential area

Figure 3.15 Photo of residential area expansion

3.4.2. Population

In 2014, Darkhan city had 79,938 inhabitants from 23,349 households. The population density was 2.7 persons per square km. Even though the natural growth of the population is low, a considerable number of immigrants contribute to the population growth. According to the census of 2014, number of immigrants from the Western Region, Khangai Region, Central Region, Eastern Region and Ulaanbaatar are 925, 611, 1047, 89 and 982 respectively. Employment rate and participation level of working force among the population is relatively low in comparison with the state average which is related to the higher amount of unemployed, students and disabled people who are in working age.

Administration units named bag and their population density is shown in Figure 3.16.

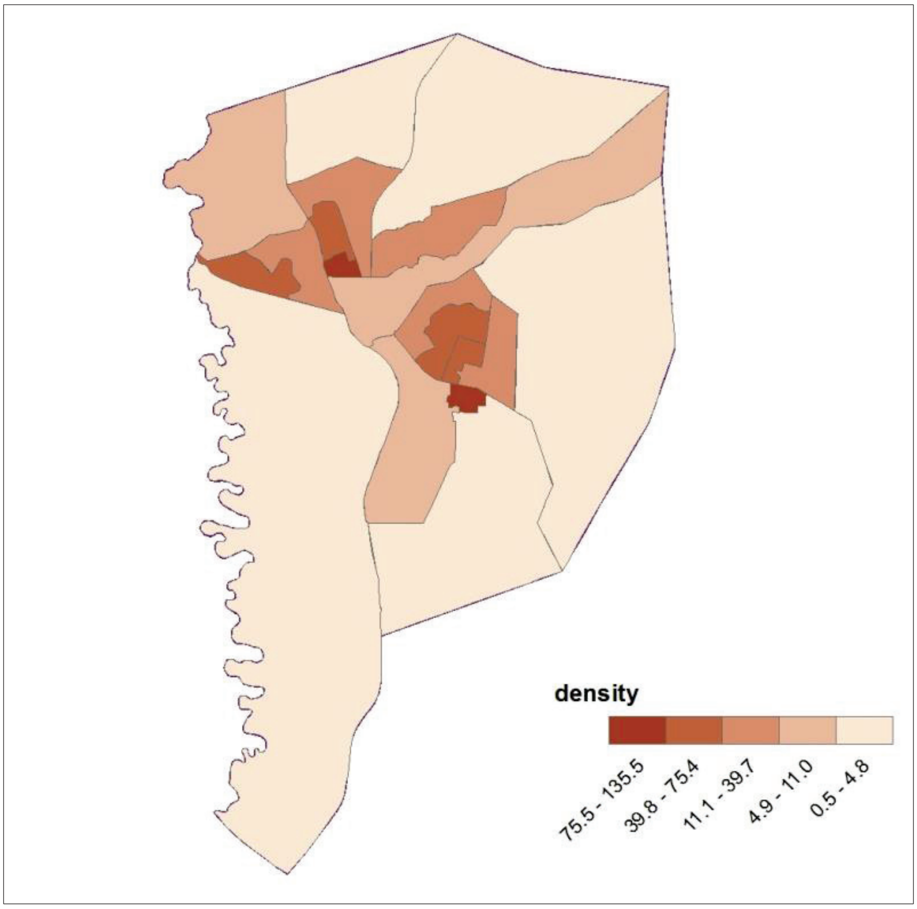


Figure 3.16 Map of population density, 2014

Population concentrated area is city center and residential area including apartment. Low density area is peri-urban area which is also traditional resident area named *ger* area. Figure 3.19 shows that number of population is slightly increased since 1961.

Figure 3.18 shows the population growth by bag and year.

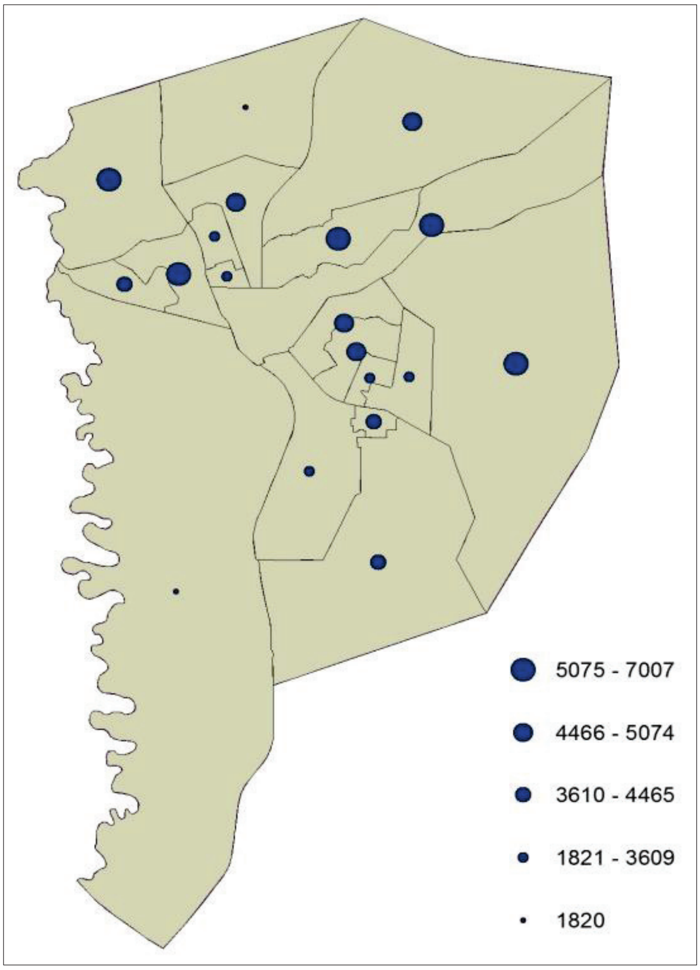


Figure 3.17 Map of population number, 2014

The migration from the other areas to Darkhan city has become intensive in the last years. The main reasons were based on people's basic demands such as to perceive good education, health service and for seeking jobs. Also livestock keepers are mostly immigrated from western area which has a relatively low economic development and thus seeking a livelihood near the city market where they can sell dairy products.

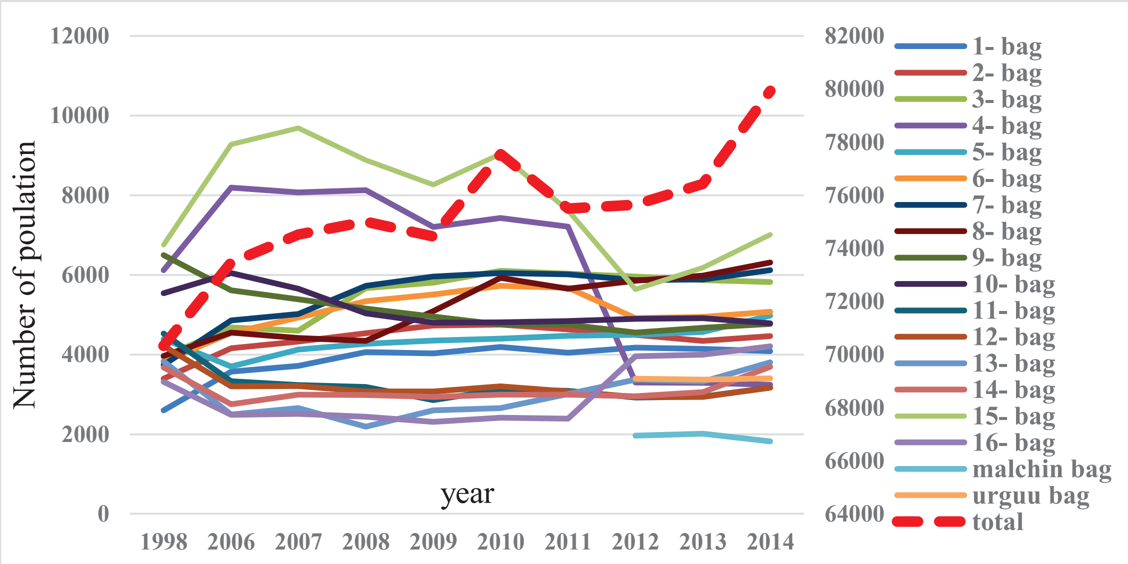


Figure 3.18 Population growth graph by *bag* 1998-2014

Since the time when Darkhan city established, population has been continuously increased and a rapid growth can be seen between 1965 and 1989. In that time industrial development was at the highest level. After 1990, population is decreased. This can be related with economic transfer when Mongolia shifted from command economy to market economy. In this period, all state owned factories stopped and as a result, unemployment rate is increased. For this reason citizens of the Darkhan city immigrated to other area for seeking jobs. Since 1995, economy has been getting better and some factories are revived. After that, population of the city increased continuously.

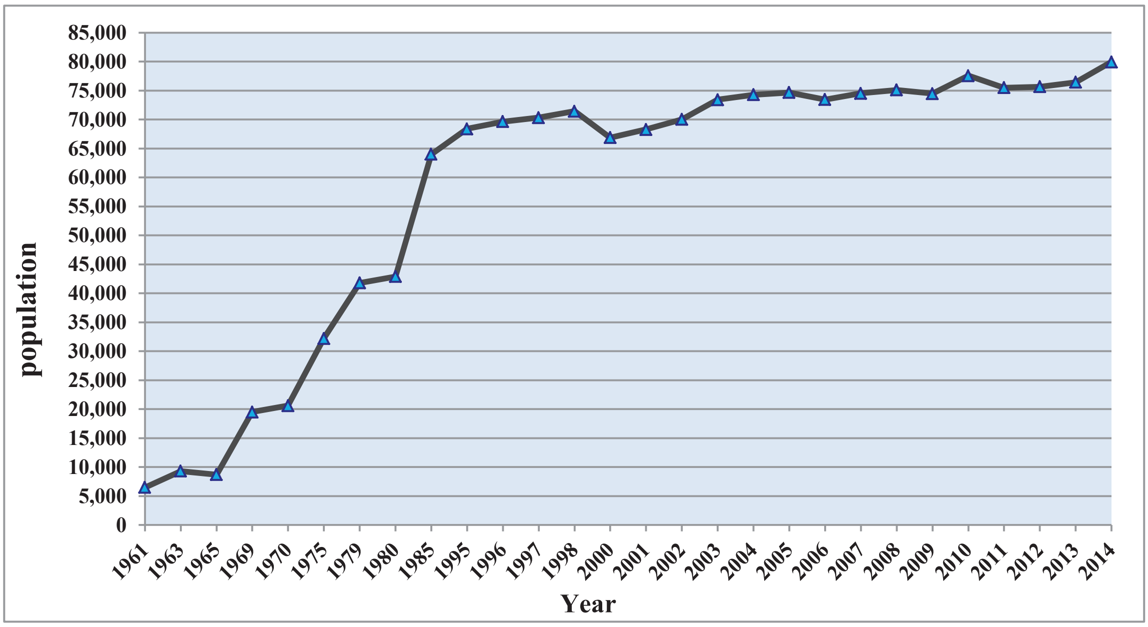


Figure 3.19 Population growth graph 1961-2014

3.4.3. Social service

Education sector - Darkhan City was established according to a decree of Parliament (Ikh Khural) on August 17, 1962. The first complete secondary school, a railway station school, was established in Darkhan City with 730 pupils, over 30 teachers and 10 workers, in the academic year of 1962-1963.

As of 2014, there were 19,813 pupils in 2 Lyceum schools and in 26 secondary schools where 50.6% are female and 10,013 students are studying in many fields at 10 universities and institutes and 2 vocational and technical professional colleges. For instance, the Agricultural University and the University of Science and Technology, the Darkhan Institute, Mandakh Burtgel Institute, New Darkhan College, Medical College, Tsagaan Suld College and Administration Institutes have all opened up branches in Darkhan.

Approximately 7000 students are studying in these universities, mainly in the fields of banking, finance, medical science and social work. Students come from 21 aimags. Over 1500 students are studying in the Professional Training and Industrial Center affiliated to the Ministry of Education, Culture and Science. The staff consists of 15 professors and over 60 teachers and educators. Also over 1200 students are studying in vocational training in Darkhan Urguu Professional Training centre and Industrial Center affiliated to the ministry. The number of students in technical and professional centres has increased year by year depending on available scholarships and free dormitory places. Over 50% of the students in the center originally are from Darkhan-Uul aimag, 40 % from Selenge and Orkhon-Uul aimags, while the rest comes from Ulaanbaatar and other aimags, such as Tuv, Bulgan, Khuvsgul, Uvs, Khovd, and Uvurkhangai. Darkhan-Uul aimag collaborates with many foreign countries in in the fields of educational development and culture because it has recognized as an “International Friendship City”.

Many pupils are studying at international and private schools, such as the Mongolian-German joint secondary school, the Turkish-Mongolian joint school, as well as the “Naran” complex 23rd school, funded by Japan. After finishing school the pupils have good chances to study abroad. The training level in Darkhan-Uul aimag meets the international standards of general academic secondary and higher education. Therefore, Darkhan-Uul aimag has become the educational and cultural centre of the Darkhan and Selenge region where it attracts many young people.

Railway and road transportation - Darkhan City is located at the international railway and main road, which connect the city with Central and Southern Mongolia as well as PR China and the Russian Federation. Consequently these two traffic routes connect East Asia with Europe. Darkhan City is also connected to Erdenet City, by railway and asphalt road (Figure 3.20). The excellent access to the national and international traffic system and the relatively short distance to the national capital Ulaanbaatar is an important prerequisite for the future economic development of Darkhan Uul aimag.

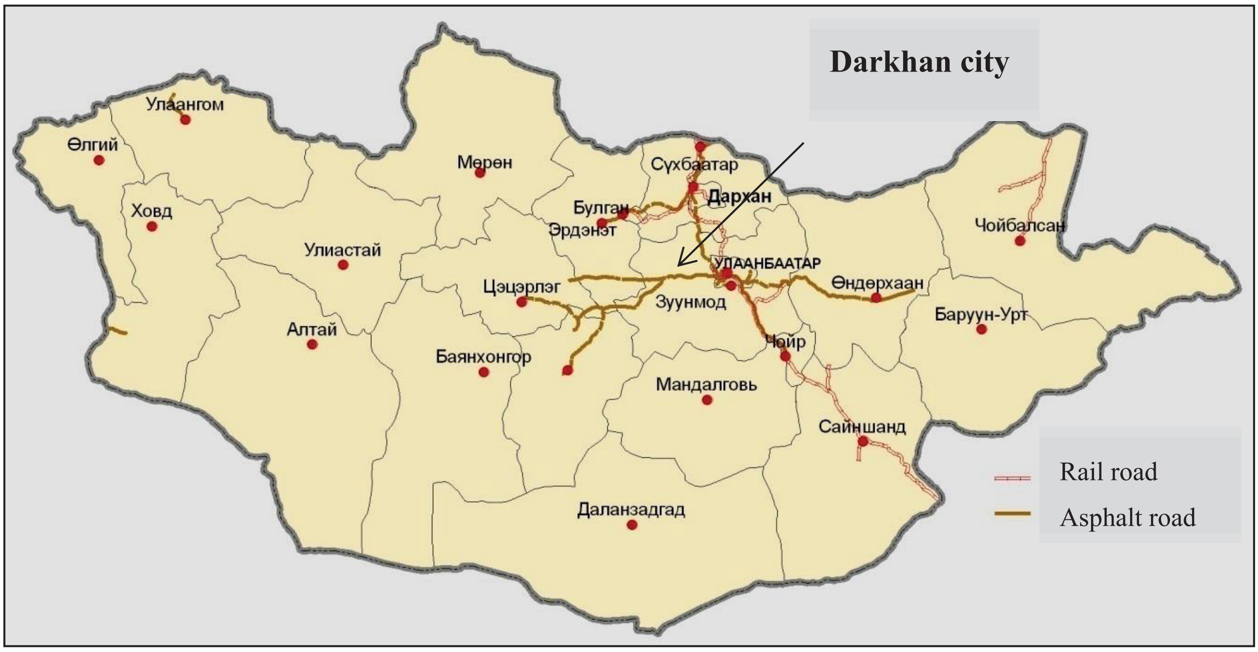


Figure 3.20 Map of road network

Also in the last years new roads were constructed in the city (Figure 3.21).

a) b) c)

Figure 3.21 Map Darkhan city road network (a - 1969, b - 1998, c - 2009)

Public water supply-In Darkhan city area, water supply is divided into two types. One is public water facility where the other type is privately constructed wells. In the report of environmental condition there are around 400 private wells registered by administration units (Figure 3.24) and their water usage (Figure 3.22).

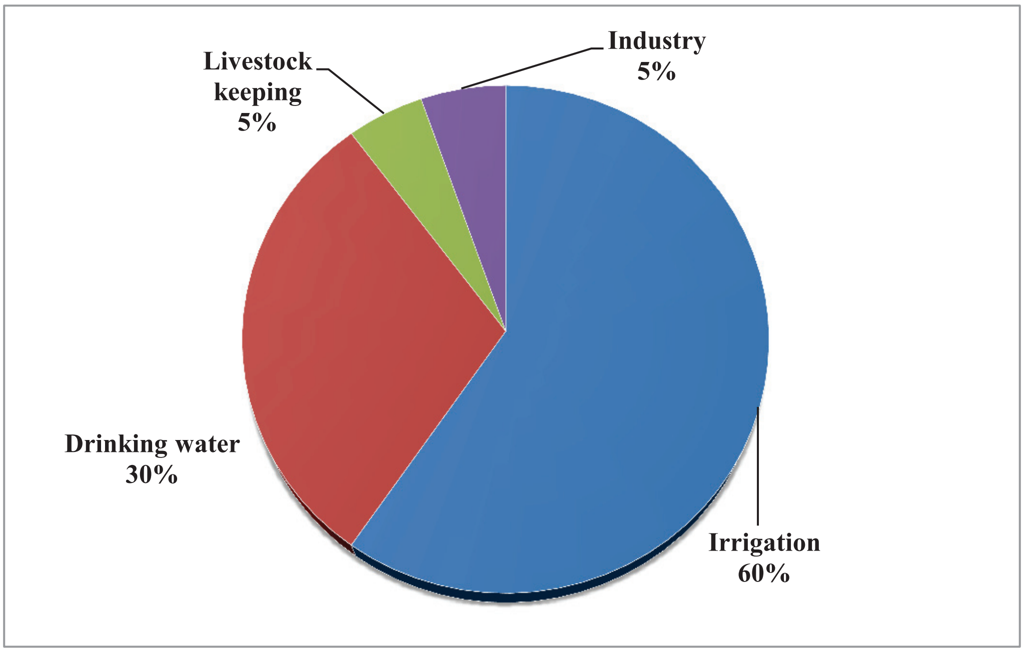
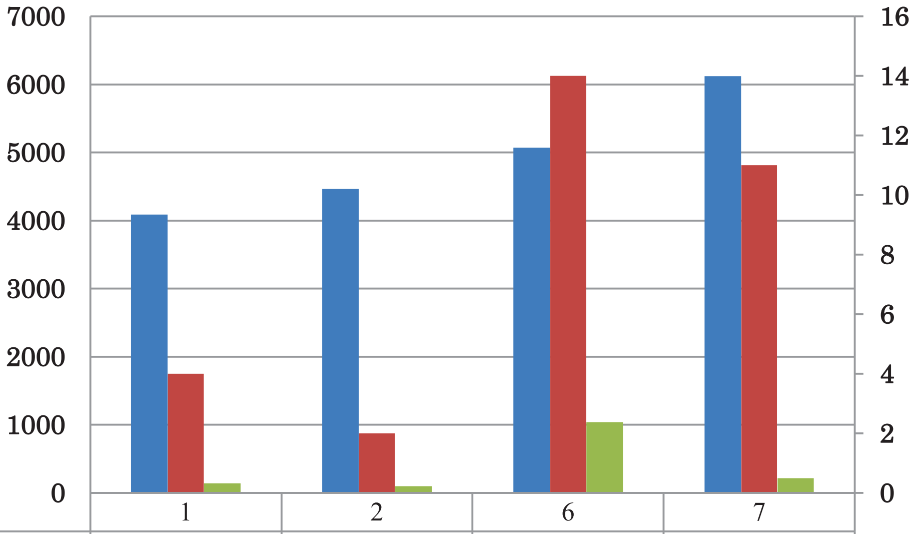


Figure 3.22 Water usage type of private wells

The figure 3.23 shows the number of public wells which are connected to main line of water facility. If we compare the population numbers with the number of wells, it seems that water consumption is inadequate. Also bag territory is quite a big and the number of wells are a few. It means that distance is far between the wells. It also can be one of the clues to mention that people of the city are not provided with enough drinking water. In that case, households want to dig their own well in the yard which is named khashaa.



	1	2	6	7
Population number	4089	4465	5074	6121
Bag territory /ha/	141	96	1037	215
Number of public wells	4	2	14	11

Figure 3.23 Graph of public well number

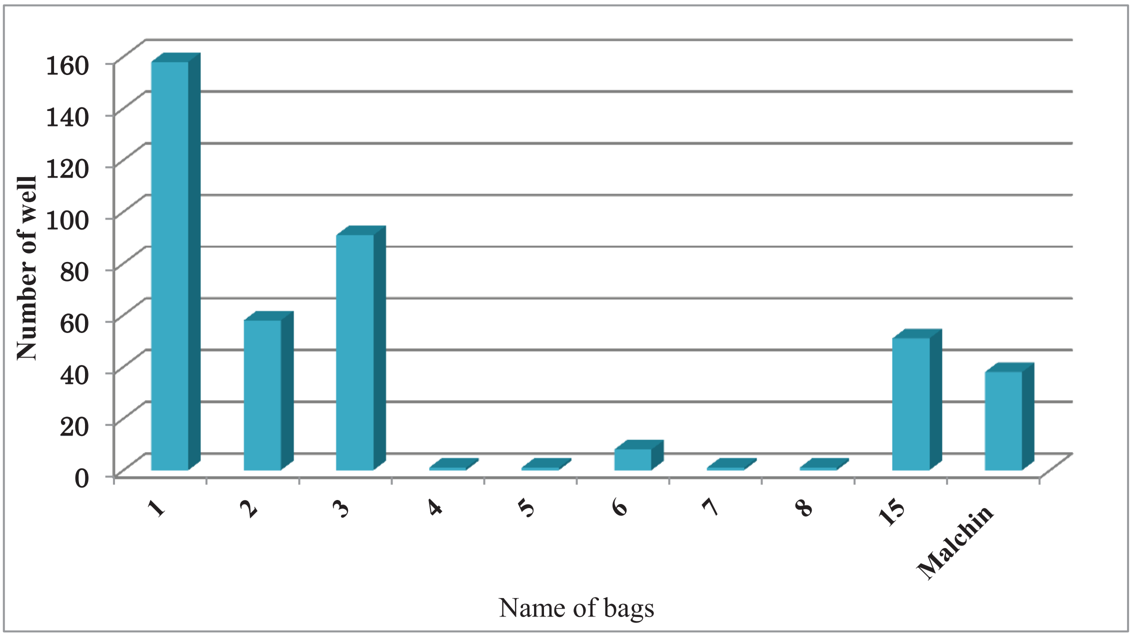


Figure 3.24 Graph of private well number by *bag*

Electricity -Mongolia has separated the power grids for the central and eastern regions. Darkhan-Uul aimag is included in the central united power grid which connects Sukhbaatar, Darkhan, Zuunmod, Nalaikh, Baganuur, Bor, Undur, Mandalgobi, Choir, Sainshand, Zamyn-Ude, Darkhan, Erdenet, Bulgan, Tsetserleg, Murun, Arvaikheer and Bayankhongor (Figure 3.25).

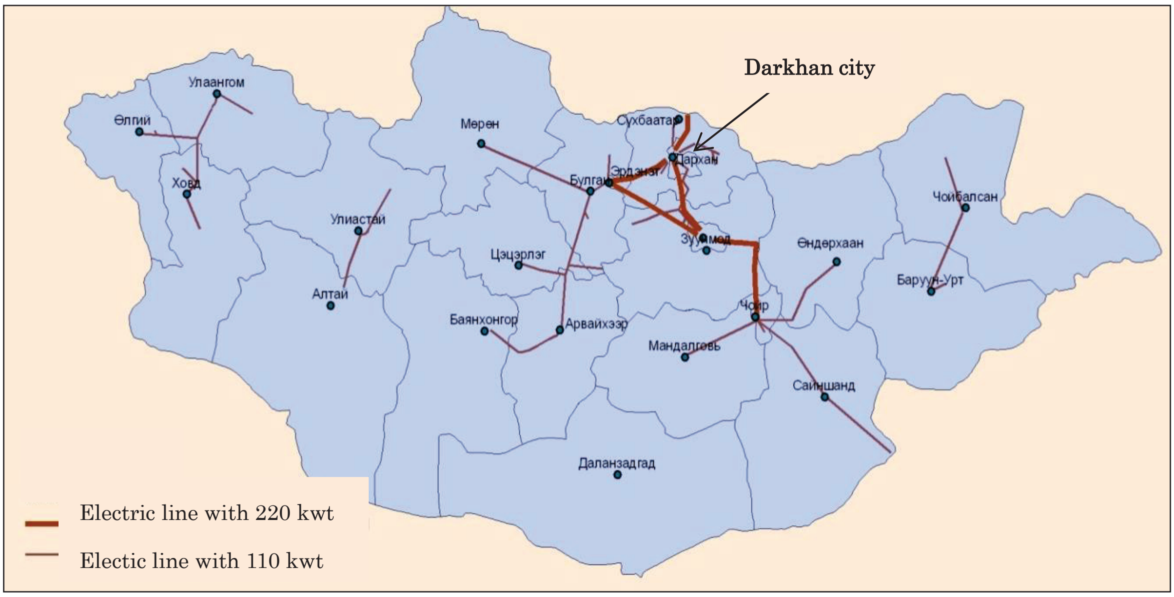


Figure 3.25 Map of electricity network

The total capacity of thermal power stations of the Central power grid is 764mWt. During the peak times, additional power is bought from the Russian Federation. The country's grid consists of lines of over 8000 km. Mongolia annually produces power of over 4 billion kWt hours, and thermal power of approximately 7.8 million gkal.

3.4.3. Industrial sector development

Mining sites - Nowadays, the number of mining and other industries are increasing (Figure 3.26). According to (Battsengel V, 2000) one of the main economic sector would become mining industry in the Mongolian economy in the next years, and also opportunity to attract foreign investment is mineral resources of the country. As can be seen from Figure 3.30, although it is effective for economic development, but the influence for environment cannot be ignored. One example for the above is that mining licenses are been issued for the Kharaa river basin. These mining sites cause land and water degradation as well as destruction. Also, there is no recovery steps or

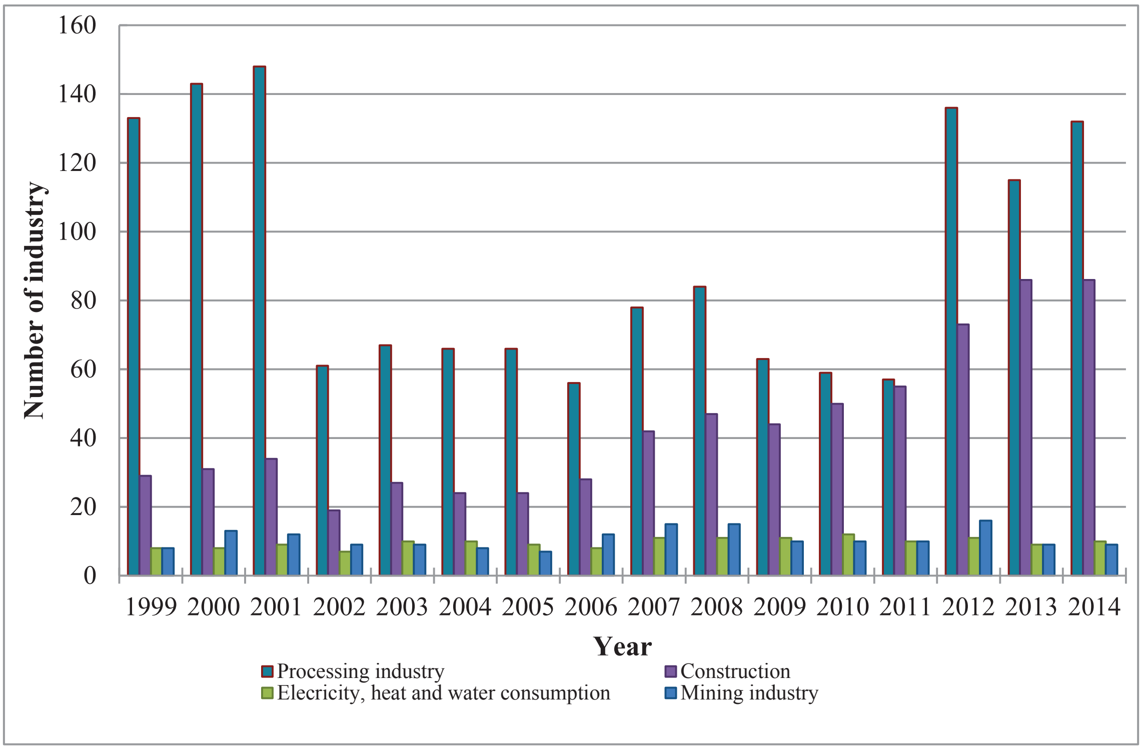


Figure 3.26 Graph of industrial sector growth

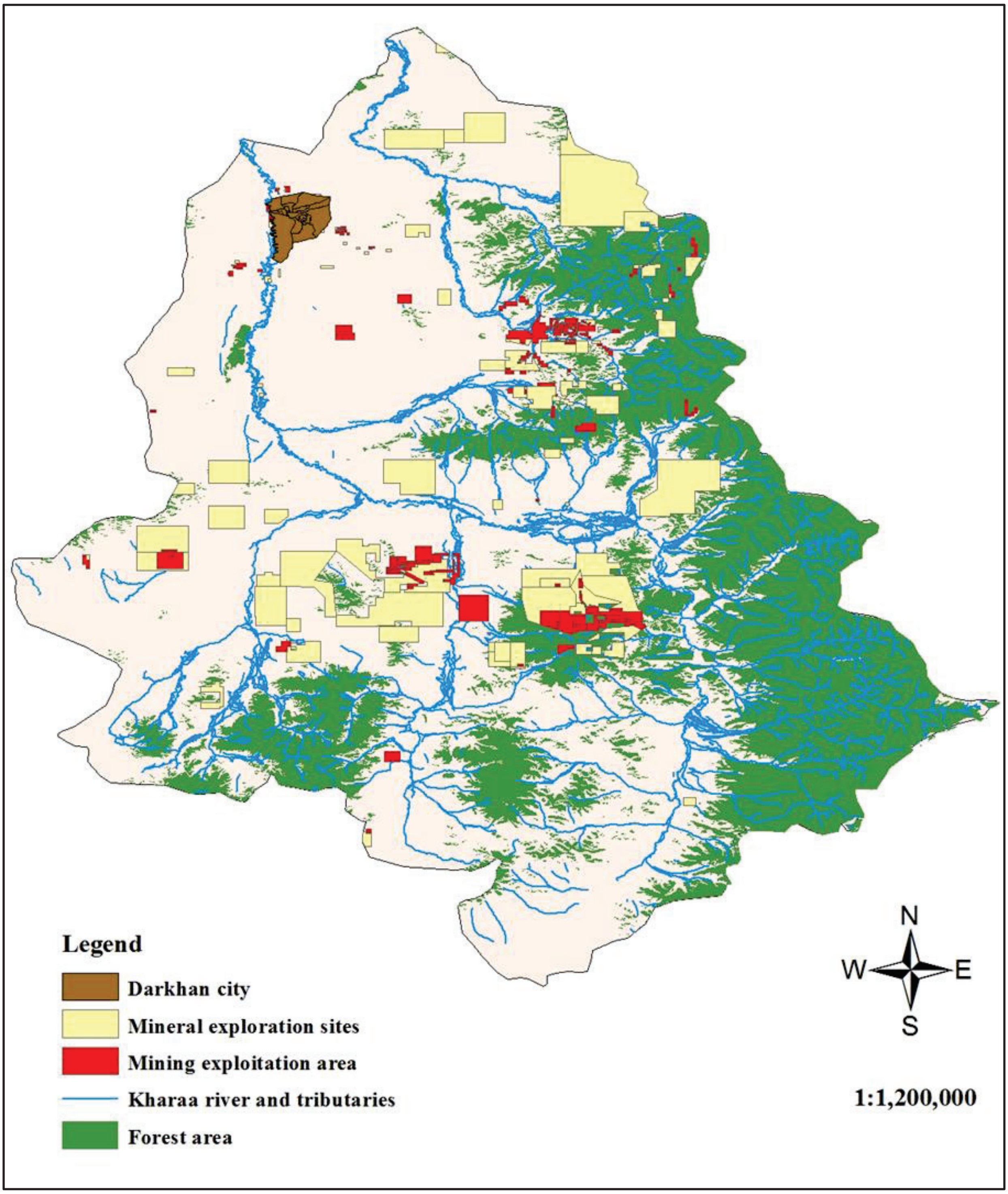


Figure 3.27 Map of mining activity in the Kharaa river basin

environmental rehabilitation activities are taken yet. One of the problems is that licenses for exploitation and exploration are issued in the area where Kharaa River collects the water. Figure 3.27 illustrates that areas of mining activities and their affects for water resource are not assessed and also their water usage is not calculated. The main sector of heavy metal industry is metallurgy. The ferrous metal industry is a relatively young sector which has been developed intensively recent years, and Darkhan has become the leading center. Darkhan is equipped with modern leading equipments and tools. It was built with the purpose of producing construction metal. Productions using metal ore of Tumurtei, Tumurtolgoi of Darkhan region cause the waste metal resources accumulated domestically.

Thermal power station of Darkhan City - A thermal power station with the capacity of 50.000 kWt is currently working in Darkhan City (Figure 3.28). It uses coal from Sharyn Gol and Baganuur. Darkhan City's thermal power station was put into operation in 1965 and has the capacity to produce 1196 gkal of hot water/steam and 48 MWt of power. It was the third station of this capacity within the territory of Mongolia. The power plant employs approximately 430 people. The plant is connected to the power system of the central region. Coal comes from the mines of Sharyn Gol and Baganuur. The present consumption is 380.000 tons per year. With the planned increase of production, it will increase to up to 540.000 tons.

This high coal consumption can only be satisfied with coal extracted from the Ulaan-Ovoo mine in Zelter sum, Selenge aimag. For that reason, it is planned to build a new 90 km - railroad between the relay station at Shaamar and the power plant.

Figure 3.28 Photo of thermal power station of the Darkhan City

Construction material production - Construction material production is the biggest sector of heavy industries. Many of the processed construction materials are assembled to larger commodities, such as prefabricated beton pieces etc. The product's primary costs are relatively low, because the access to the necessary raw materials is relatively easy and due to its good quality as well. Darkhan city's cement industry was the first in Mongolia. Also the other industries are concentrated in the southern area of the city (Figure 3.29).

The raw material for the cement industry is not widespread in Mongolia. A second larger lime and cement complex was built in Khutul, located near the railway from Darkhan to Erdenet. This was necessary as the cement consumption has been increasing continuously. The greater part of the cement industry's production is used for construction works and installations in settled areas, mainly located along the Mongolian railway. Furthermore, there is a quickly increasing demand for cement and iron commodities in the Gobi regions of Mongolia where major mining activities are carried out. Factories in Darkhan City also produce red brick stones which are needed in large quantities in all the economically developing parts of the country.

Construction assembling and repair companies play a main role in construction material manufacture. The construction companies of Darkhan City are mainly located in the Central Region.

Figure 3.29 Photo of industrial zone

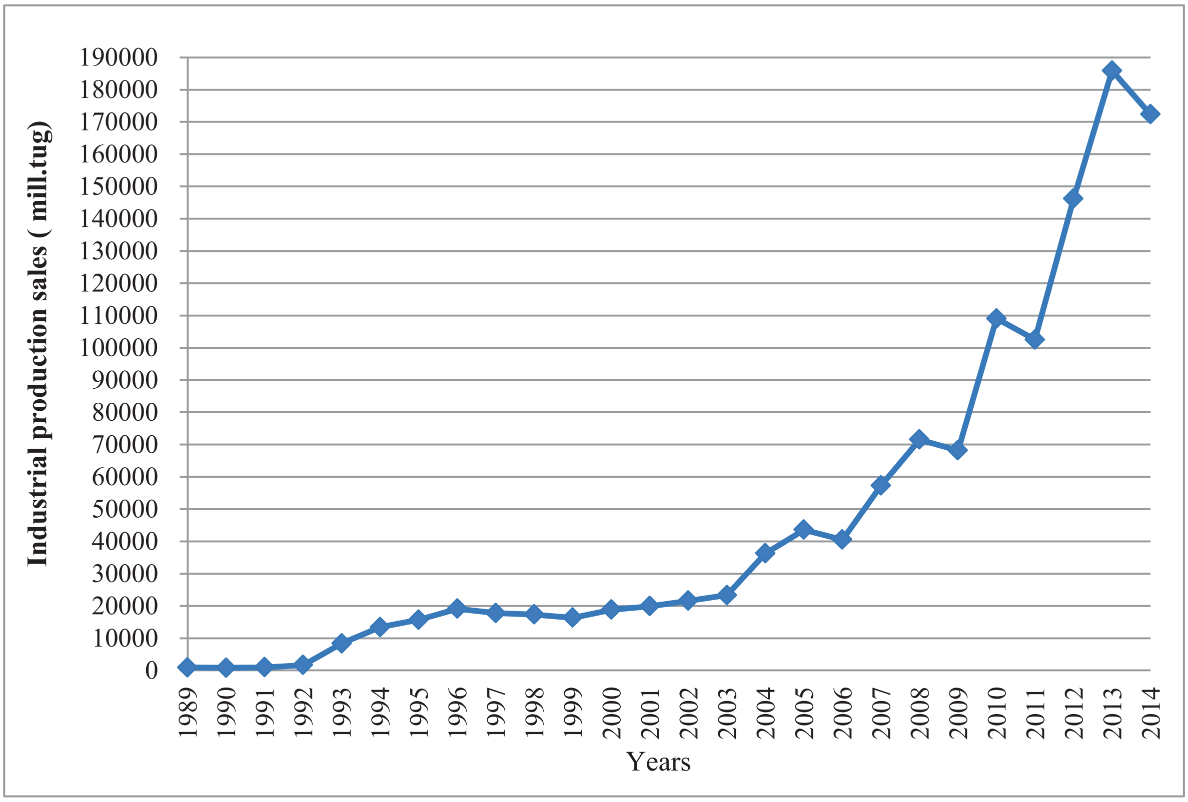


Figure 3.30 Industrial production sales

Darkhan Metallurgical plant - The Darkhan Metallurgical Plant is the first ever of such plants in Mongolia which was built according to the contract between Mongol Impex and Itochu Corporation**.** The plant was established in 1993 and started to fully operate in 1994. The industry is currently producing steel metals with the size of 115*115 mm, steel bars of metal concrete structure with the diameter of 10-35 mm and length of 2-6 m, angles with the length of 3.5-12 m, 30*30*30 mm and 45*45*45. Because products of the metallurgical plant fully meet the requirements of the Mongolian standard, the National Center of Standards issued ISO 9001:2000 certificates, accepting international quality management. The plant also established its own authorized laboratory. A product guarantee of the plant are the matching certificate and the national matching badge of the Center as it fully meets national standard requirements. Semi-processed steel works of the steel mill of Darkhan fully meet the advanced standard requirements of ISO-6935, EN-10080, DIN-488, BS-4449 and JISG-3112.

In 2009, Tumurtei mine was opened and its metal ore concentration is going to be executed this year. It annually produces 120,000 tons of reinforcement steel and metal ropes of 40.0-50.0 thousand tons. It uses the equipment from Japan while the cranes are imported from Germany. It collaborates with the metallurgical plant of Bughat, in the People's Republic of China. Waste metal, the main raw material, is bought from centers along the railway. It is planned to produce metal plates in the future. However, although the company is interested in exporting products abroad, this is impossible because of high customs fees. It recruits its employees from universities, institutes, and the professional training and industrial center of Darkhan-Uul *aimag*, and trains them in their jobs.

Since the steel mill started to operate, it has produced 538.8 thousand tons of semi-products, 376.7 thousand tons of cast products, and exported 171.5 thousand tons of semi-products.

3.4.4. Economic condition

Darkhan Uul *aimag* has an economic relation with its north and south neighboring countries. Before 1990, when its peak Industrial development period Darkhan –Uul *aimag* played a good role having high economic activity with socialist countries. At that times construction materials and sheepskin garments were exported to foreign countries in a bigger quantities.

The seven most important goods have all been imported include wheat and petroleum products, which were mainly imported from the Russian Federation and the PR China. Also agricultural and industrial equipment were imported from Canada, Russian Federation, PR China and Japan. Chemical substances which use in sheepskin producing factory are imported from Spain and Turkey.

Raps seed, metal ore, wooden chopsticks... etc. are directly exported to the P.R. of China. Meat and sheepskin garments in low quantity are exported to the Russian Federation also cashmere and fine wool products are sold to the Norway, Sweden and Germany.

The location where it lies at a junction of main road and railway from China to Russia is a main advantage of foreign economic relation of the *Aimag*. Big companies as well as small and medium sized firms from all economic sectors were included in the survey. Attention was not only given to the present situation but also to the historical background, in order to make better understood the deep reaching changes that have taken place during the transformation phase from a planned Socialist economy to a capitalist market economy. Based on a large number of expert and company interviews, a representative impression about the contemporary situation and necessary measures for a more sustainable future economic development is presented.

Since its foundation in 1961, until 1990 Darkhan City was concentrating itself on the industrial development. Large State owned companies were founded. Darkhan became Mongolia's second important economic agglomeration, the country's center for the construction material industry, and an important location of Mongolia's light industry such as food, animal raw materials and wood processing manufacture. The production was focused on satisfying the domestic demand for many commodities as well as exports to the Soviet Union and other Socialist countries.

The industrial collapse followed by the dissolution of state property strongly hit Darkhan's construction industry, although some enterprises of the construction material sector such as "Cement" and "Silikat" could integrate themselves masterly to the new market situation and recover their production. The establishment of Darkhan's Metallurgical Plant (DMP) Company occurred as an important event for the economy not only at the *aimag*, but also at the national level. It is the first steel melting industry of the country. In the perspective of exploiting iron ore production facilities, the plant could increase and it will be able to produce new steel products of high quality. Thus in the future Darkhan City's economy could reach a higher national and international importance similar to Erdenet City.

As far as the technical infrastructure of Darkhan-Uul *Aimag* is concerned, circumstances for future economic development can be considered as very favorable. It has a prominent location within the national and international traffic and transportation as well as electricity and heating supply network, due to its position in the Mongolian railway and highway system and its access to high voltage power lines as well as the presence of an efficient power plant. The close location to its major market Ulaanbaatar, only 220 km away, is of great relevance for future improvement of the economic situation in Darkhan City. According to the economic ranking within Mongolia, since a few years Darkhan City keeps third place after Ulaanbaatar and Erdenet. Another important factor positively influencing economic development in Darkhan City is the sufficient availability of all kinds of raw materials, minerals, wood as well as animal and farming products.

Last but not least a well-established medical and educational system offers a solid frame for social and economic development. The Mongolian Government and foreign national and international organizations of development cooperation are aware of the favorable development opportunities of Darkhan City and its surrounding sums and therefore run a great number of projects not only supporting large companies but also to an increasing extent small and medium sized enterprises.

CHAPTER 4. MODELLING URBAN GROWTH USING CELLULAR AUTOMATA

4.1. Introduction

In the recent decades, urban study is mostly following the new methods based on technological advancements. Traditional trend is focused on social and economic analyses which is considered on basic theories. But in the recent years, these methods are more practical in which they are connected with the development of information technology. Furthermore the possibilities for these research are being investigated.
One of these methods is Cellular Automata basic concept which is invented in 1960s. At the beginning, it is used in the field of biological sciences for cell related research. After then, this method is being used in the other fields of natural sciences. One of the key areas related to this research concept is on its development through the geographical research as well. A priori researcher namely Tobler, used this method for land usage model. He divided the land usage into 5 categories.

(I) The independent model: $a^{t+\Delta t}_{xy}$ *is a random variable in no way related to* a^{t}_{xy}.

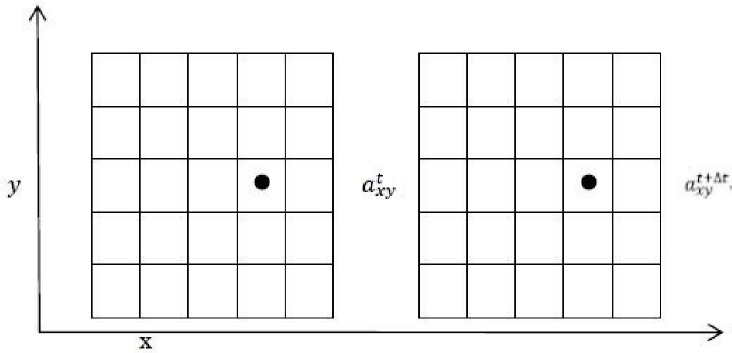


Figure 4.1 The independent model

The functionally dependent model. The land use at location x,y at time t + Δt *depends on the previous land use at that location,* $a^{t+\Delta}{}_{txy} = F(a^{t}_{xy})$.

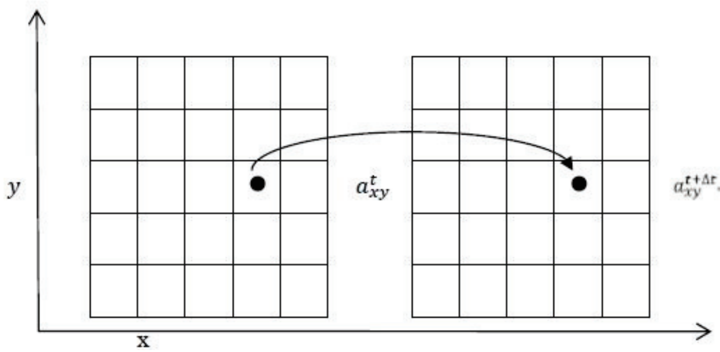


Figure 4.2 The functionally dependent model

(III) The historical model. The land use at position x, y at t + Δt depends on the several previous land uses at that location:
$a^{t+\Delta t}_{xy} = F\,(a^{t}_{xy}, a^{t-1}_{xy}, a^{t-2}_{xy}, \ldots, a^{t-k\Delta t}_{xy}$

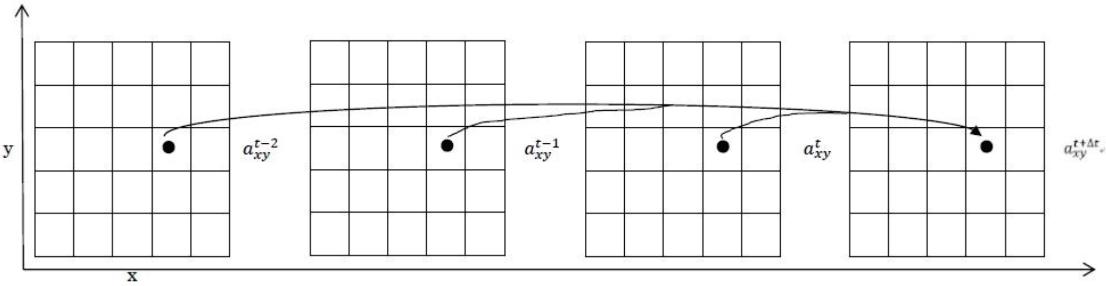


Figure 4.3 The historical model

(IV) The multivariate model. The land use at location x,y is dependent on several other variables at that location: $a^{t+\Delta t}_{xy} = F\,(u^{t}_{xy}, v^{t}_{xy}, w^{t}_{xy}, \ldots z^{t}_{xy})$.

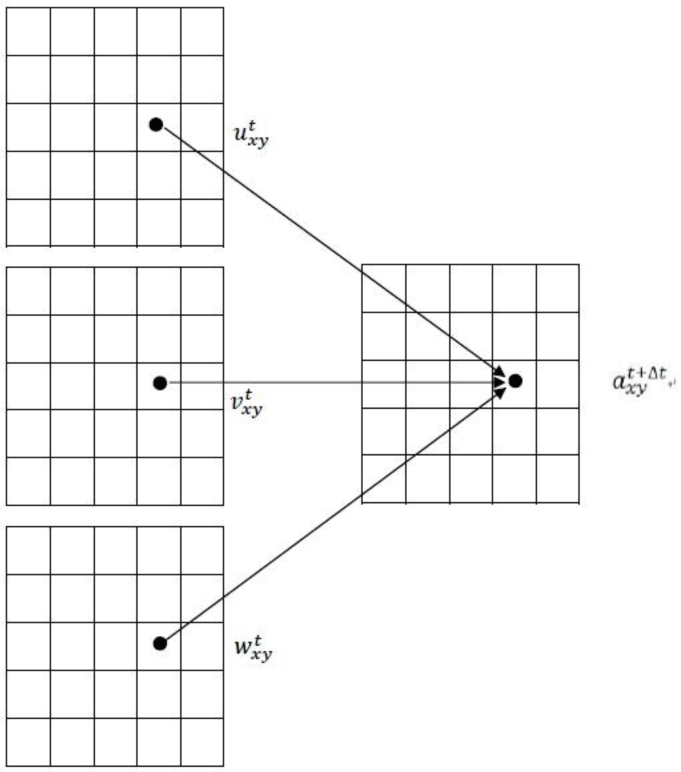


Figure 4.4 The multivariate model

(V) The geographical model. The land use at location i, j is dependent on the land use at other (neighboring) locations: $a^{t+\Delta t}_{xy} = F(a^{t}_{x\pm p,\, y\pm q})$*. /Tobler 1979/*

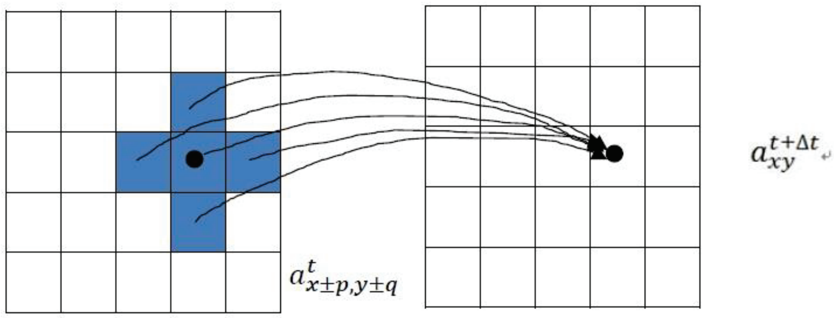


Figure 4.5 The geographical model

4.2. Urban expansion theory

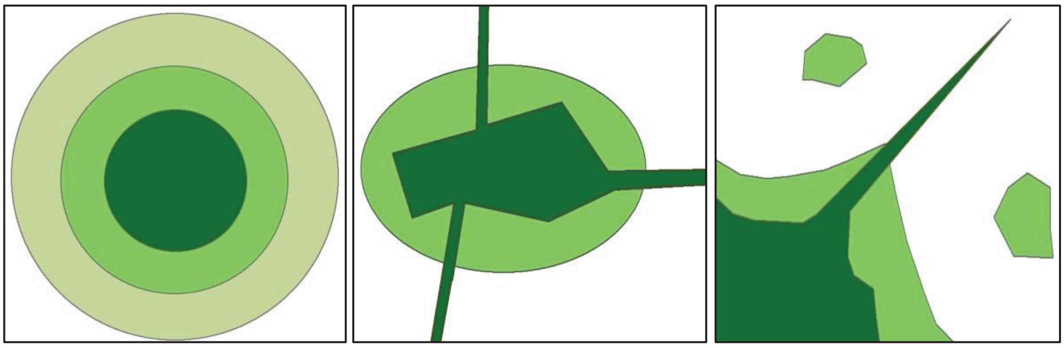
Harvey and Clark (1971) classified the shape of urban expansion. The types are defined as causes of urban expansion eg., population growth, economy, land use and infrastructure development ...etc.

According to Harvey and Clark peri-urban area requires a prior planning that includes water consumption, electricity and sanitation... etc. Our research area also has faced with problems including water consumption and infrastructure development. In particular, peri-urban residential area is getting rapidly expanded, but it is required new planning of the city for recent years. It has become one of the problems which faced in intensive urbanization of Mongolia. It is also shown that new urban planning is not made in the new residential area, but in the peri-urban which is already created. They are not supplied by public facilities such as wells, electricity and road networks and so on. Due to the lack of public needs in the peri-urban residential area, newly migrated people want to reside in an area where they are supplied by public facilities. But this area has already become a human settlement area eventhough the price of the land is higher than peri-urban area. This type of problems are required a study which is needed for city planning decision.

According to Harvey and Clark urban expansion divided there categories which are listed in below. (Figure 4.6 a,b,c) In our research area Darkhan city sprawl is also included these types of urban sprawls. In particularly, Darkhan city sprawl is shown all types of sprawls. (Figure 4.7)

Low-density Sprawl

Low-density continuous sprawl is a phenomenon caused by outward spreading of low-density suburban land use as currently being experienced by many of cities like America as their population becoming bigger and bigger and there is no lack of land supply.



a) b) c)

Figure 4.6 a) Low-density Sprawl b) Ribbon Sprawl c) Leapfrog Development Sprawl

Ribbon Sprawl

Ribbon sprawl is a type of sprawl characterized by concentration of development along major transportation arteries, primarily roads. while development occurs on land adjacent to the major roads, areas without accessibility to the roads tend to remain as green areas, waiting for conversion into urban land uses when land values increase and infrastructure is extended from the major roads.

Leapfrog Development Sprawl

Leapfrog development sprawl is a scattered form of urbanization with disjointed patched of urban land uses, interspersed with green areas. Leapfrog development may be caused by obvious physical limitations such as prohibitive topography, water bodies and wetlands or by more subtle reasons such as differences in development policies between political jurisdictions.

Figure 4.7 Darkhan city sprawl

4.3. Urban modelling methods

4.2.1. Cellular automata based urban modelling

Cellular automata classification-Wolfram categorized cellular automaton rules into four types basically, as we can see that how cell is created and expand to these basic rules. In classes I (Figure 4.8) and II (Figure4.9) automata cells are so strongly interdependent to allow a useful information processing.

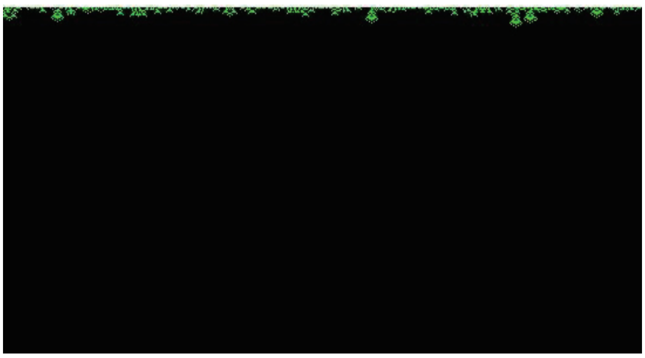


Figure 4.8 Evolution leads to a homogeneous state. (rule 36)

According to Wolfram, CA belonging to class IV (Figure 4.10) generates structures that are strongly reminiscent of the game of life. Then he puts forward the hypothesis that class IV characterizes the automata having universal computation capability. In order to let this capability emerge, the cells must be able to communicate and to transmit information.

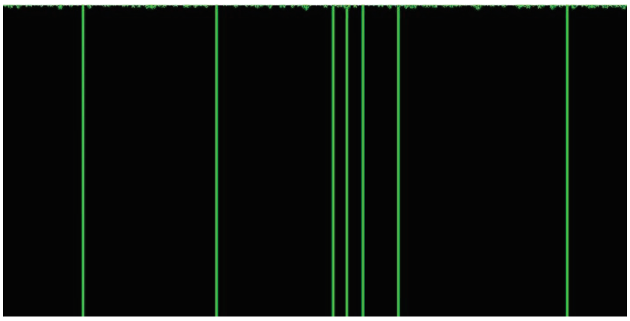


Figure 4.9 Evolution leads to a set of separated simple stable or periodic structures. (rule 40)

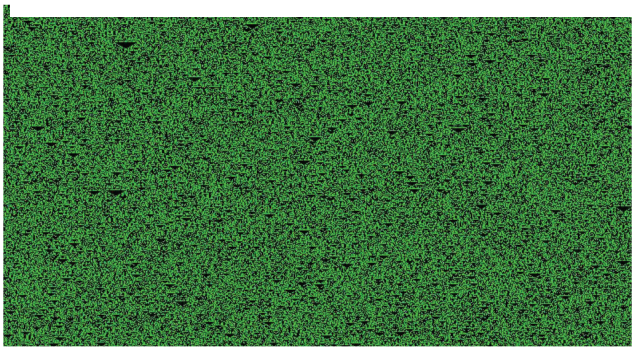


Figure 4.10 Evolution leads to a chaotic pattern. (rule 18)

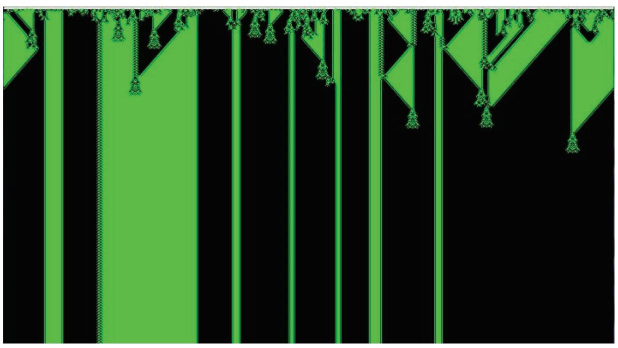


Figure 4.11 Evolution leads to complex localized structures, sometimes long-lived. (rule 20)

Game of Life

In 1970s, life game was invented by Conway and now it is one of the most recognized cellular automata today. In the game of life, considering a plane partitioned by sized cells, each cell can take two states, "live" and "died". Game of life is a two-dimensional cellular automata which cell has two states.

The transition rule(Figure 4.12,4.13,4.14) in the game of life is defined by neighboring cell and their state.

The game of life is designed according to the following simple rules:

1) Any live cell with two or three live neighbors lives into the next generation.

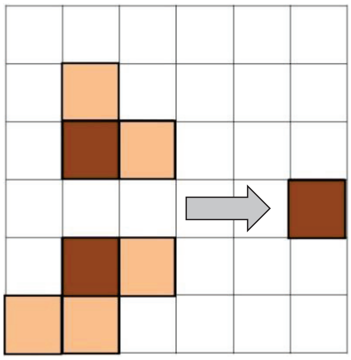


Figure 4.12 Rule 1

2) Any live cell with fewer than two live neighbors cell dies, it is caused by depopulation.

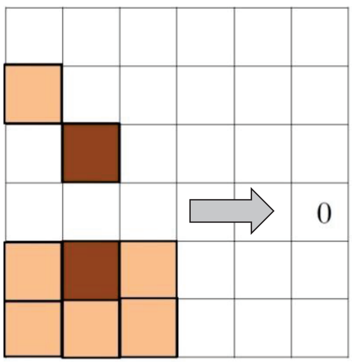


Figure 4.13 Rule 2

3) Any dead cell with exactly three live neighbors becomes a live cell.

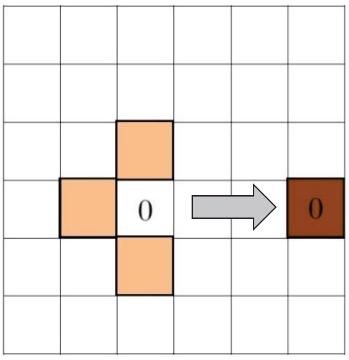


Figure 4.14 Rule 3

It is a very simple rule which consists of three processes of survival and death, birth.
As a Moore's neighborhood considering eight cells around himself is generally adopted, and the process to shift is the next generation which is decided by the state of the neighbor cell.
In this model, CA defines the urban growth in the time period. In that time period, the rate of urban growth is determined by the growth rate (λ), and the main aspect of cellular automata is controlled by this growth rate.
According to this growth rate, population increase and decrease constrained by amount of water resources. The water resource amount at each time step calculations are performed using system dynamics.

Model structure-Darkhan city is in the range of 15 km north to south and 10 km east to west is the drawing area of the model. Also, area is divided into a lattice of 100 m × 100 m basic unit of cell.

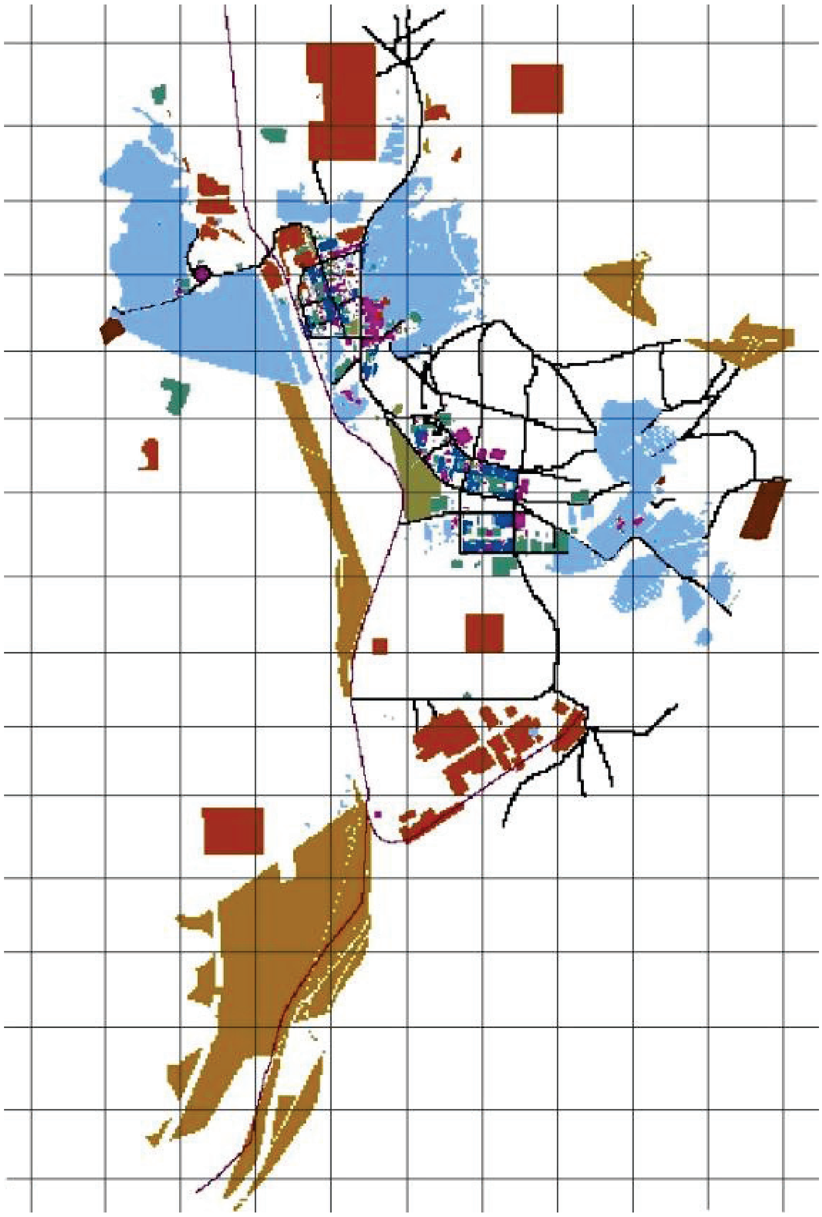


Figure 4.15 Model drawing area

Each cell has two types of main states, urban and non-urban. Here, a cell in an urban state means a cell included in an urban area, and a cell in which a residence or the like is located inside the cell. On the other hand, a non-urban cell represents a cell that has no urban activity in its internal area and can be newly developed. For urban cells, agents are deployed according to the main purpose of use of the area. Besides this, as a representation of the fundamental nature of the cell, we also give the cell as an internal state about the slope of the land and the presence of roads and stations.

Land slope-This literally represents the slope of the land in that cell. It is a unique value for each cell, and it affects the location of the agent.

Roads and stations-In addition to the internal state of a urban or non-urban, each cell also gives the presence or absence of a road or a station in the inner area of the cell as an internal state. Even if it has a road or a station, if the internal state is a non-city, it will not be treated as an urban area.

Interaction between urban growth and water resources

In this model, we consider "population" and "urban area" as the quantitative scale of the city size, and assume that these rising and falling are influenced by the amount of water resources. Regarding population, it considers inflow and outflow from outside. Inflows considered here are immigrants who have moved from the surroundings and outflows are those who move into another city. For urban areas, consider the number of urban agents in the drawing area. Among urban agents, *ger* and Apartment are recipients of residents living in cities, they develop or proliferate as population increases, and decline and disappear when population declines. In this model, it is assumed that the rate of change in population is regarded as the growth rate of the city, and the water resource amount has an influence on this growth rate.

Growth of the city

When water resources are adequately secured, the city will accomplish steady growth. The population that has flown from outside is housed in a residential agent such as *ger* or Apartment, which is a receiver of residents, but this process is divided into the two stages .

First stage, which is starting the growth rate, the influx population into the city at that time step is determined. It is the *ger* agent that becomes the first recipient for the influx population to accommodate the population by existing *ger* agents or by creating new *ger* agents in non-urban areas.

Second stage represents the apartment area in which residents live their lives based on their cities more dependent on their lives.

In this model, it is assumed that the inhabitants will eventually be attracted by the convenience of the city and change into a lifestyle that will settle in the city. Therefore, the apartment agent leaves the *ger* agent and treats it as a receiver for residents seeking a more urban life.
For the *ger*, apartment also accommodates the population due to the creation of new agents or the development of existing apartment agents.

Decline of cities

We assume that there is a certain number of spill population per time step, regardless of the size of the city. If the growth rate is sufficiently high, the population will increase and the city will continue to develop, but as the growth rate goes down, the outflow population will become excessive and the city will gradually decline. In this model, we treat such decline phenomenon as declining or annihilation of agent.
The agent declines due to population leakage, and the agent (agent without residents) whose population leaked completely disappears. After the agent disappears, the internal state of the cell becomes non-city and new development becomes possible.

Water resources and demand

In principle, the supply of water resources is assumed to be constant, and the outflow of water resources is considered as the water demand from the city.

Water demand in residential area-The degree of development in the agent represents the population amount contained in the agent. Therefore, in this model, it is assumed that the water demand amount in each agent depends on the population amount contained in the agent, and the water demand amount is determined from the degree of development of the agent.
Water demand in factory-An industrial agent is generated in a cell used as a factory. Here, in the industrial agent, the population is not accommodated, but since Darkhan is an industrial city, assuming that the size of the factory is synonymous with the size of the city, the developmental degree of the industrial agent is the degree of development of the city to express it.

Variables and Formulas

Growth rate

Under unrestricted conditions, we assume that development of the city is naturally and this growth rate named natural growth rate in the city. The actual growth rate is determined by this natural growth rate and water resource quantity.

$$\lambda = \beta - \delta$$

λ: growth rate β: natural growth rate δ: inhibitory action from water resources

Here, the natural growth rate (β) is calculated from a logistic equation which is known as an expression of the change in the number of individuals in an organism and is also used as a model expression of population variation.

$$\beta = \frac{P_{(t)} + \Delta P_{(t)}}{P_{(t)}}$$

$$\Delta P_{(t)} = \mathrm{r} P_{(t)} \left(1 - \frac{P_{(t)}}{k}\right)$$

$P_{(t)}$: City population at time t $\Delta P_{(t)}$: increasing population at time t

r: internal natural increase rate k: environmental capacity.

In addition, the influence (δ) from the water resource amount is obtained from the initial amount of the water resource amount and the remaining amount at the time t by the following formula.

$$\delta = 1 - \frac{R_{(t)}}{R_0}$$

$R_{(t)}$: water resource amount at time t R_0: initial value of water resource amount

Here, the resource amount $R_{(t)}$ at time t is given by the following equation from the resource amount at time t - 1 and the water demand (consumption at time t - 1).

$$R_{(t)} = R_{(t-1)} - Demand_{(t-1)}$$

4.2.2. Agents used for modelling

***Ger* agent-** It represents the residential area of the people live in expansion area of the city. *Ger* is a name of the traditional house for living nomadic people. But in Mongolia it is still used in peri-urban area, newly migrated people from countryside to the city is still commonly used today. Particularly in urban areas, the "*Ger* district" where the nomadic people and others coming from the surrounding area is often formed, and in the Darkhan city also occupies a some part of the urban area.

In general, infrastructure development is weak in the *ger* district and also other social service condition is poor in the area. The people living in that area wants to improve their living condition. Then if they find better place where provided a infrastructure moves fast to other area. It is the reason of agents that can easily multiply and extinguish .

Apartment-It represents the space in which people living the foundation of the city live. In Mongolia, the people who lived in the *gers* mentioned earlier will eventually migrate to a fixed residence and start settling in many cases. In compared with *gers* apartment is a district where such settlers live permanently, and apartment agents are difficult to multiply and extinguish.

Industrial agent- It represents an industrial area. It is an agent given without transition.

Commercial- It represents a commercial area. It is an agent that has without transition.

The population that can be accommodated in the residential agent is determined by the location conditions of the agent. Generally, the more convenient the area, the more urban development and the higher population density, so the maximum value of the population that can be accommodated in the agent is determined from the location conditions.

Table 4.1 Comparison CA and agent based model

Level	City level	Household
	Regional level	Deals with decisions posed to people more frequently
	Landscapes and transitions	Human actions
	Most suitable in urban simulation context for representing infrastructure	Better to use model population dynamics
Spatial mobility	CA are only capable of exchanging data spatially with their neighborhoods.	Agents can be designed to navigate (virtual) spaces with movement patterns that mimic those of humans.

4.2.3. Calibration

Fractal dimension analysis

In order to confirm the reproducibility of the model against Darkhan, the fractal dimension of the city shape by Darkhan and the model was compared.

The fractal dimension is a statistic that expresses the filling factor of a space by a figure and is used here as an index for examining how much the tendency of change in city shape matches the reality.

Box counting method

There are various definitions of fractal dimensions, but this time we use what is called box dimensions. The method of measuring the box dimension is called the box count method, and it is the most general method for finding the fractal dimension.

The box dimension D - 0 of the figure S is defined as follows.

$$D_0 = \lim_{\epsilon \to 0} \frac{\ln N_{(\epsilon)}}{\ln \frac{1}{\epsilon}}$$

Where $\ln N_{(\epsilon)}$ is the total number of n-dimensional cubes of diameter (ϵ) necessary to cover S.When actually measuring the box dimension, it is obtained as the slope when changing the length of the side of ε and displaying the corresponding $\ln N_{(\epsilon)}$on a logarithmic graph.

It is close to the dimension, which indicates that the tendency of the actual urban shape is also very similar.

4.4. Urban modelling software

4.4.1 Netlogo

When creating the model, we mainly used the NetLogo application (Figure 4.16) which is an open source modeling software that can simulate natural and social phenomena. The functions of Netlogo are applicable for complex system changing by time. Netlogo gives several opportunities for users made their own models and change parameters by yourself. This open source programming software established by Wilensky in 1999. Netlogo is based on Starlogo principle which is multi-agent modelling languages. Start Logo developed as educational languages, it is possible to simulate emergent phenomena in various fields, although it is a simple usage.

The dynamic agent called a turtle (turtle) moves around a static agent called a patch, enabling reproduction of a complex system.

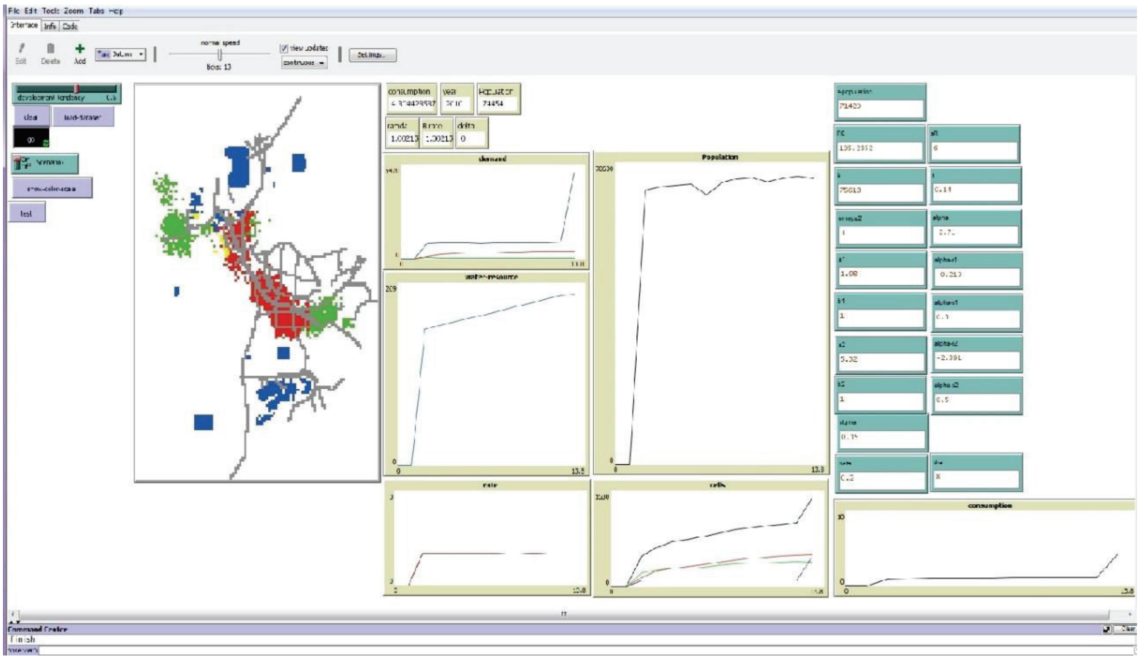


Figure 4. 16 User interface of Netlogo

4.4.2. Stella

The field of system dynamics originated in the end of 1950 with the work of Jay W. Forrester and his colleagues at the Massachusetts Institute of Technology. Forrester expanded the ideas by applying conceptions from feedback control theory of the industrial system. One of the best known appliance of Forrester is Urban Dynamics. Afterwards Urban Dynamics is expanded and became approach which known as system dynamics. System dynamics is a methodology for researching and managing complexity of the systems which change over time. This method uses computer modelling to focus our attention on information feedback loops that give rise to the dynamic behavior.

The theoretical and practical evolution of system dynamics in water research areas over the 50 years. Problems in regional planning and river basin management, urban water management, flooding and irrigation exhibit important short-term and long-term effects. System dynamic application in water research management have branched off in many directions. For example, regional analysis and river basin planning, urban water, flooding and irrigation. In the early 1970s system approach is used in water resource management and 1971- Anderson, Biswas, Grigg, Helmeg, Camara. Participatory modelling-1988- Vennix, Winch, Andersen and Richardson, Van den Belt.

Practical developments of system dynamics transmitted into regional analysis and river basin planning by the leading researchers Hamilton, Camara, Ford, Costanza and Ruth Simonovic , Xu Carthwright and Connor; Den Exter and Specht et al. in 1968.

Urban water resource management study using system approach is started since 1974 pioneering researchers were Wallace, Palmer, Grigg, Cloud, Stave Bagheri and Hjorth.

The flooding and irrigation related studies which were used system dynamics are intensively increased since 2000. Ahmad and Simonovic, Li and Simonovic, Saysel Diaz-Ibarra, Fernandez and Selma, Elmahdi were made a several research work in that field.

As a scales of research area in system dynamics can be divided three levels. First is regional level study is focused on river basin modelling, integrating complex hydrologic data with other information (e.g., policy, regulatory, and management criteria), analyse a factors and constraints in the basin area and which enables them to better understand the system via the simulation of multiple scenarios. (Sehlke G1, Jacobson J. 2005).

Second level is national one of well-known study is made by Simonovic and Rajasekaram in 2004, integrated water resources management model for Canada, CanadaWater, has been developed using the system dynamics simulation approach.

In the global level, study using system dynamics is include number of socio-economic factors, and emphasize improved computer capabilities as well as changing problem such as global water crisis and social impacts. Simonovic and Rajasekaram (2004) note a recent trend in the reduction of spatial scales to basin and watersheds with the aim of identifying regional and local solutions.

Application in regional analysis have often had a strong economic focus examining feedback relationships between industry and available water resources.

River basin and watershed management application is focus more narrowly on water resources and their interaction with population growth, as with regional analysis tools, temporal scales of these models are typically long-term (50-100 years).

Urban water resource management may be seen as a special case of watershed management where concerns are more immediate and more contentious.

One of broadly used software systematic research is Stella. Using Stella software and simple conceptual diagram population growth is calculated in case birth rate is 23.6, 21.1 and 18.9 (Figure 4.17). Also number of population is showed in Table 4.2.

Furthermore, urban growth is calculated in the software using death rate (Figure 4.18). Table 4.3 shows that highest number of population in case which death rate 4.13 in the lowest number. Next step is sensitive analysis (Figure 4.19) which selecting the highest death rate and lowest growth rate. It is one of the attempt to predict the lowest number (Table 4.4) of population of Darkhan city.

Water usage is calculated based on the lowest number of population (Figure 4.20).

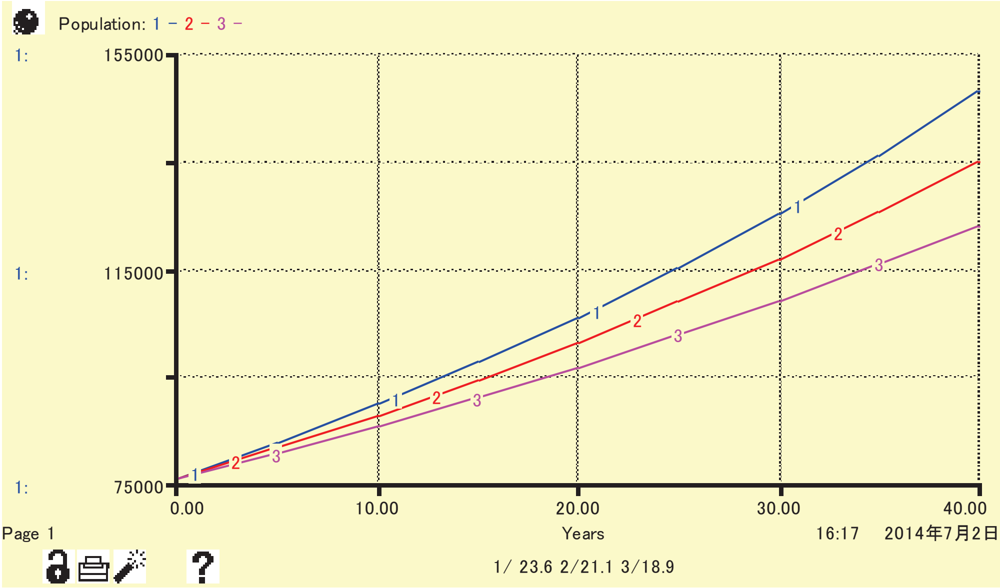


Figure 4. 17 Exponential growth of population, birth rate is (23.6-18.9)

Table 4. 1 Population growth (exponential)

Year	**Number of population**
2013	75644
2020	82251
2025	89436
2030	97248
2035	105743
2040	114979
2045	125023
2050	135943

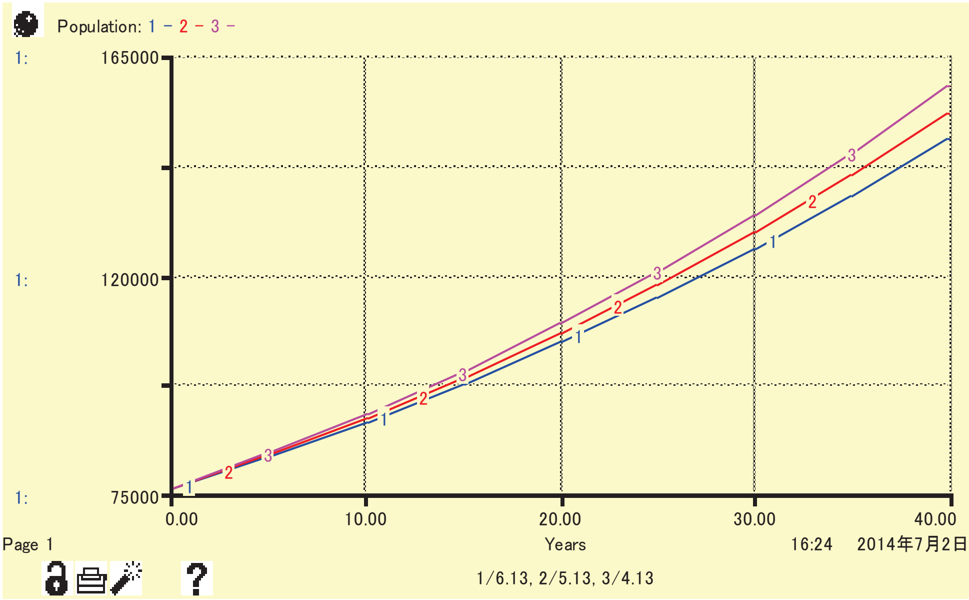


Figure 4. 18 Exponential growth of population, death rate is (6.13-4.13)

Table 4. 2 Growth population (death rate)

Year	Number of population
2013	75644
2020	83007
2025	91088
2030	99956
2035	109687
2040	120365
2045	132082
2050	144940

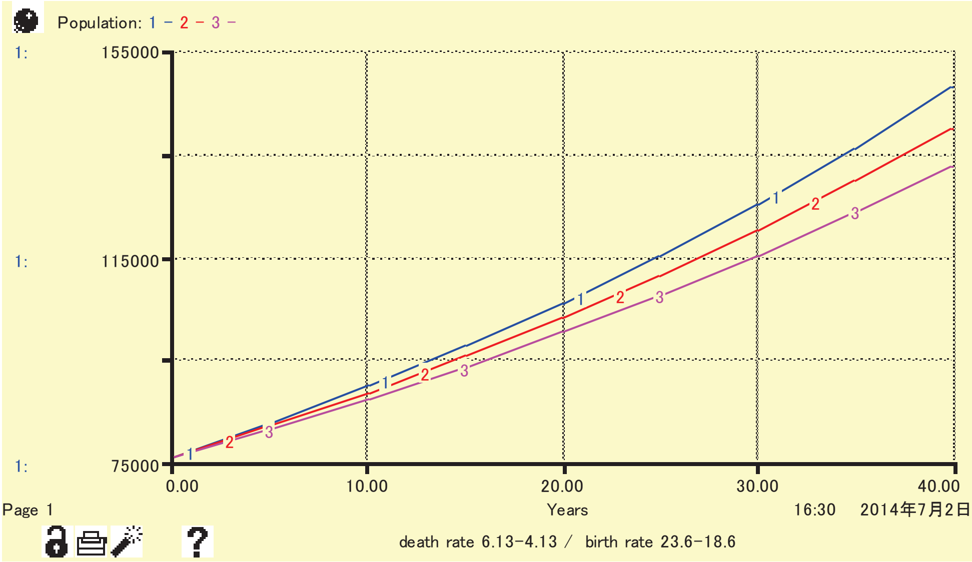


Figure 4.19 Sensitive analyze

Birth rate 23.6-18.6

Death rate 6.13-4.13

Table 4. 3 Growth population (Sensitive analysis)

Year	**Number of population**
2013	75644
2020	81116
2025	86985
2030	93279
2035	100027
2040	107264
2045	115025
2050	123347

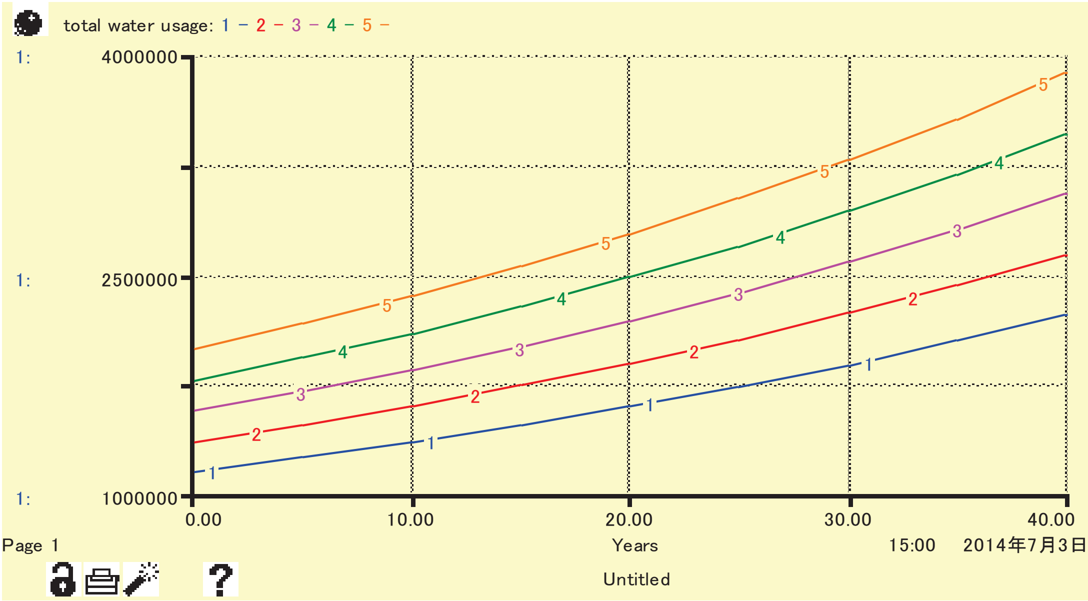


Figure 4. 20 Comparative analyze of domestic water usage

CHAPTER 5. RESIDENTIAL AREA MODELLING

5.1. Modelling parameters

5.1.1. Land use

The land-use of the domain is categorized into seven patterns, i.e., residential area (apartment, *ger*), industrial area, commercial area, road, station, others (unused) and unavailable area. Simulation occurs on a regular lattice of which size is 100m x 100m in this research and the model does not have a concept of vector data, which means roads and stations cannot be expressed by cells properly. Then, the categories of roads and stations can exist simultaneously with other categories in a cell. Residential area consists of apartment and *ger* of which existence is quite unique characteristics of this region. A *ger* is originally a round tent covered with animal's skins or felt for nomads in Mongolia and adjacent regions. Nomads generally immigrate for better grassland with their *gers* and livestock. In these years, however, quite a large number of nomads assemble to suburb of cities and often settle down in such areas unexpectedly within the regional and city planning. There are poor infrastructures for water supply, electricity, sewage and so on in the *ger* area. Therefore, though the *ger* area is certainly a residential area, it can be thought as a kind of temporal resident compound with relatively low population density. In addition, it is often the case that they move to another suburb or apartments in the city without hesitation, when the *ger* area becomes too crowded. Considering this property, *ger* area is discriminated from the apartment and its mobility is included in the transition rule. Compared with *ger* area, apartment has higher capacity for residents and higher consumption rate of municipal water. The location of apartment is much more stable than that of *ger*. The location and magnitude of commercial area, road and station cannot be determined autonomously by the model. They are given exogenously by the local government or scenarios for prediction.

5.1.2. Potential

Potential is defined as an indicator for prosperity and convenience of the cell and around the cell, and it also shows how much the cell affords to develop up to the capacity. It is utilized to decide the allocation of birth, transition and decay of the cells. In this research the potential depends on the ratio of urbanity in the extended Neumann neighborhood (7 cells x 7 cells, Ω_2), distance from the station, that from the road, slope condition and room for new agents as given by Eqn. (1).

$$PT = RU \cdot \{AR + AS + (CP - DL)\} \cdot SL \quad (1)$$

where PT is potential, RU is a ratio of urban cells that consist of *gers* and apartments in the neighborhood, AR is an index of distance from roads, AS is an index of distance from the station, DL is an index of prosperity or conceptual number of agents, CP is a capacity for agents (constant for *ger* and equals to DL for apartment) and SL is an index of slope (classified slope into 5 levels, 1.0 for flat, 0.0 for more than 1/5), respectively. Figure 5.1 shows the cumulative number of *gers* against the distance from roads and that from the station, respectively, in this region, which apparently indicates logarithmic distributions. Hence, AR and AS are expressed by Eqns. (2) and (3), respectively.

$$AR = CR_1 \ln(dr/100) + CR_2 \quad (2)$$

$$AS = CS_1 \ln(ds/100) + CS_2 \quad (3)$$

where dr is a distance from nearest road in (m), and ds is a distance from the station in (m), CR_1, CR_2, CS_1, and CS_2 are coefficients to accommodate to the statistical data, respectively.

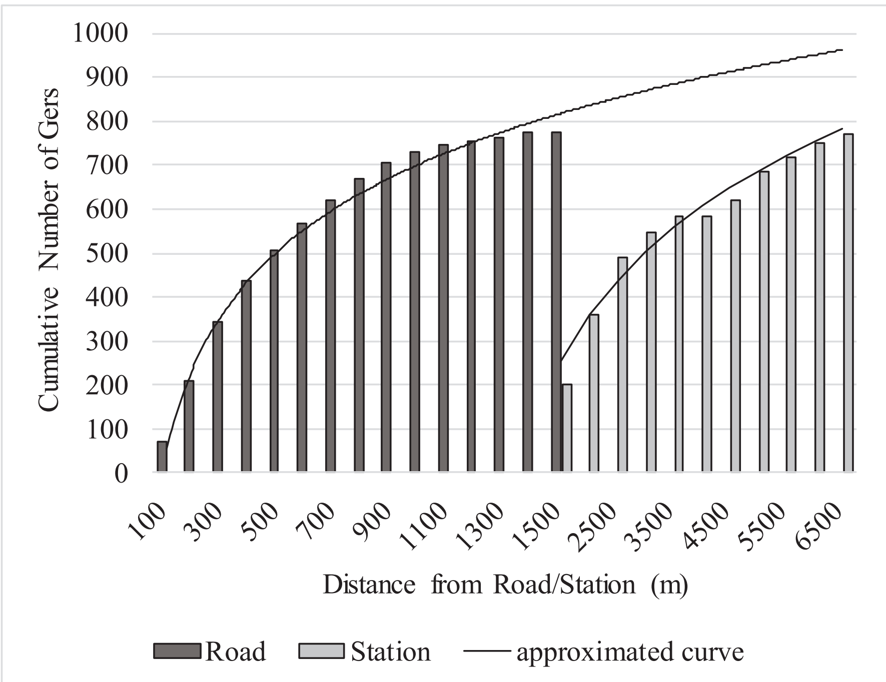


Figure 5.1 Relation between Cumulative number of gers and distance from road/station

5.1.3 Birth and decay

This CA model proceeds by birth and decay of the cell, similar to Conway's famous life game. The birth of this model is, however, controlled by externality, while the life game determines it intrinsically. It is due to immigrants from outside of the domain (Ω_1: objective domain), which is frequently seen in every city and moreover the mobility of nomads is very high. Judging from a statistical data we assume that the population of this city (*PP*) obeys to a logistic function expressed as;

$$\frac{dPP}{dt} = rPP\left(1 - \frac{PP}{k}\right) \qquad (4)$$

where r is the intrinsic growth rate and k is the carrying capacity, respectively. These coefficients are sought by Monte Carlo method for the calibration period and they are assumed to be valid throughout our simulation. Herein, additional assumption that the growth is restricted by water deficiency is introduced and then the growth rate (λ) is modified as;

$$\lambda' = \frac{PP_{t+1}}{PP_t} - \left(1 - \frac{WR_t}{WR_0}\right) = \lambda - \delta \quad (5)$$

where λ' is a modified growth rate, WR_0 and WR_t are amount of water resources of initial and time t, respectively. Subscript t and t+1 means time steps (year).

As is often the case in CA, some ratio of cells decays or dies randomly in the time marching. This model has a system almost similar to other CAs, but cells with lower potential and with more water deficiency are easy to die in this process as;

$$\begin{aligned}&\text{if } n(t) = 1,\ PT < PT_{av}, \text{and rand}(\lambda' + PT) < 1 - \sigma + w_{dif},\\ &\text{then } n(t+1) = 0\end{aligned} \qquad (6)$$

where $n(t)$ is a binary index of urbanity for a cell at time t, rand(x) is a random number between 0 and x, σ is a survival rate defined between 0 and 1, and w_{dif} is an index of water deficiency given by a scenario, respectively. Subscript *av* means average over the domain. Then, the decrease of population (*DC,* non-dimensional value) is computed by;

$$DC = \sum \{DL(t) - DL(t+1)\}, \quad \text{for } n(t) - n(t+1) > 0 \qquad (7)$$

5.1.4 Transition rules and development

Transition of cells is an essential part of CA. Originally CA has simple rules, which is a superiority of the model, but the relaxations are inevitably introduced to simulate realistic urban expansions and such introductions become the originality of the models.

As time proceeds, $(\lambda'-1)NG_{\Omega 1}$ number of *ger* cells are selected randomly as parent cells and divided by a certain rate (β) into two types, i.e., parent cell to produce a new *ger* cell (child cell) and that to enhance the prosperity of an existing *ger* cell. The number of parent cells to produce child cells (= the number of child cells, NG_{new}) is given by;

$$NG_{new} = \beta(\lambda'-1)NG_{\Omega_1} \qquad (8)$$

where $NG_{\Omega 1}$ are number of *gers* in the domain, and β is a fraction coefficient that indicates the ratio of inflowing immigrants in the population growth. Then, each parent cell picks up a candidate unused cells (child cells) in their neighborhood according to the following probability (P_{ij});

$$P_{ij} = \frac{PT_{ij} DS_{ij}^{-\alpha}}{\sum_{k,l \in \Omega_2} PT_{kl} DS_{kl}^{-\alpha}} \qquad (9)$$

where subscript *i*, *j* indicates the location of the candidate cell, *DS* is distance from the parent cell, and α is an empirical coefficient so as to make probability half on the edge of neighborhood (Ω_2).

Subsequently, the rest of the parent cells contribute to develop the prosperity index of the existing *gers*. When a *ger* cell is selected similarly according to Eqn. (9), the index of prosperity increases by one. In addition, when the prosperity of a cell attains to the capacity, agents begin to move to a newly built apartment and then the prosperity of the cell will be mitigated. The location of the new apartment is selected randomly at an

unused cell adjacent to the existing apartment (3 cells x 3 cells, Ω_3). The probability for this case is almost same to Eqn. (9) in which Ω_3 is used in place of Ω_2.
Finally, the population (non-dimensional value) in the model is computed by the sum of *DL* of all the cells.

5.1.5 System dynamics for water resources

System dynamics (SD) was born at MIT in the 1950s and it is frequently used for understanding the nonlinear behavior of complex systems. It solves the problem of simultaneity by using flows, stocks, delay and feedback loops. This concept is applicable to water resources problems (e.g. Nakatsuka, 2007). The growth of the city depends on the water resources as seen in Eqn. (5),
and vice versa. The amount of water resources is expressed by a groundwater level at battery of wells and it is initially set as 200 cm above the impermeable layer. The consumption of municipal water (WD_m) is also expressed by the index in unit of length and computed using *PT*. The consumption for a *ger* cell is set as 1.0*PT*, and that for apartment is 2.0*PT*. The consumption for a factory cell (WD_f) is given by;

$$WD_f = 10.0 \times \frac{\sum_{\Omega_1} DL_t}{\sum_{\Omega_1} DL_0} \qquad (11)$$

where the subscript t and 0 indicates time. The water consumption (*WD*) is given by the sum of WD_f and WD_m. Contrarily, groundwater is recharged and gains or recovers its water level of which amount is derived from the calibration.
In the model, a simple SD model with a single loop is complementarily introduced as in

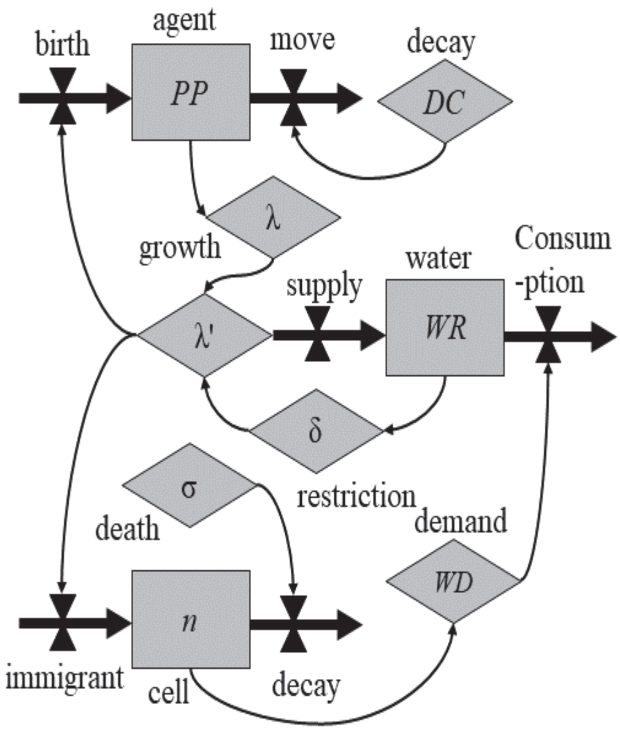


Figure 5.2 Conceptual diagram of the model supported by SD procedure

Figure 5.2. Consequently, the stock of water resources makes the growth of the city either increase or decrease.

Table 5. 1 Coefficients and parameters in the calibrated run

Coefficient/ parameter	**Symbol**	**Value (unit)**	**Note**
Survival rate	σ	0.15	estimated from fractal dimension
Intrinsic growth rate	r	0.1431(-)	sought from calibration data
Carrying capacity	k	75,618(-)	sought from calibration data
Capacity for *ger*	$CP_{for\ ger}$	5(-)	arbitrarily decided
Initial prosperity of *ger*	$DL_{for\ ger}$	3(-)	arbitrarily decided
Initial prosperity of apartment	$DL_{for\ aparment}$	5(-)	arbitrarily decided
Rate of *gers* in transition	β	0.4(-)	estimated from fractal dimension
Damping coefficient for neighborhood (Ω_2)	α_2	-2.71	empirically decided
Damping coefficient for adjacent area (Ω_3)	α_3	-2.71	empirically decided
Coefficient of logarithmic distribution for road	CR_1	2.83	sought from calibration data
Coefficient of logarithmic distribution for road	CR_2	0.527+ln100	sought from calibration data
Coefficient of logarithmic distribution for station	CS_1	3.23	sought from calibration data
Coefficient of logarithmic distribution for station	CS_2	-0.673+ln100	sought from calibration data
Increase of groundwater level without withdrawal	ws	6(cm)	sought from calibration data

5.2 Simulation

5.2.1 Model calibration

In the simulation for 1998-2009 the actual population data is applied to calibrate the model. The domain is a center of Darkhan of 12 km north to south and 10 km east to west. It is divided into 120 by 100 cells of which side lengths are 100 m. The coefficients used in the simulation is shown in Table 5.1.

Figure 5.4 (a) indicates the land-use of Darkhan in 1998 that is the initial stage of the simulation. Figures 5.4 (b) and 5(c) show the observed and simulated land-use maps in 2009, respectively. As seen, they do not differ much to show the calibration successfully executed qualitatively.

In addition to confirmation of the calibration quantitatively, the computed and actual properties of the urbanity are compared with fractal dimensions (*FD*) by Box-Count method (Eqn. (12)).

$$FD = \lim_{\varepsilon \to 0} \frac{\ln NB_\varepsilon}{\ln(1/\varepsilon)} \qquad (12)$$

where ε is a side length of the box, and NB_ε is a number of box requires to cover the urban cells. The calibration is basically carried out by trial and error and *FD* for actual Darkhan and simulated one finally become 1.5488 and 1.5586, respectively (Figure 5.3). *FD* indicates only rough feature of the city, but we guess their similarity is appropriate enough by these parameters.

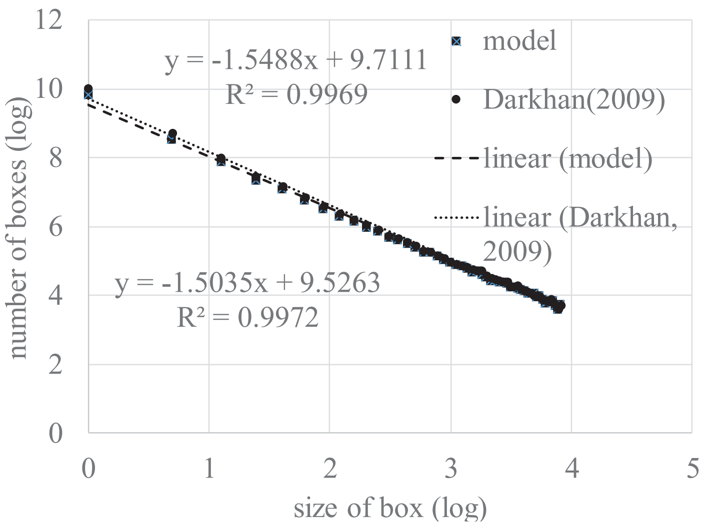
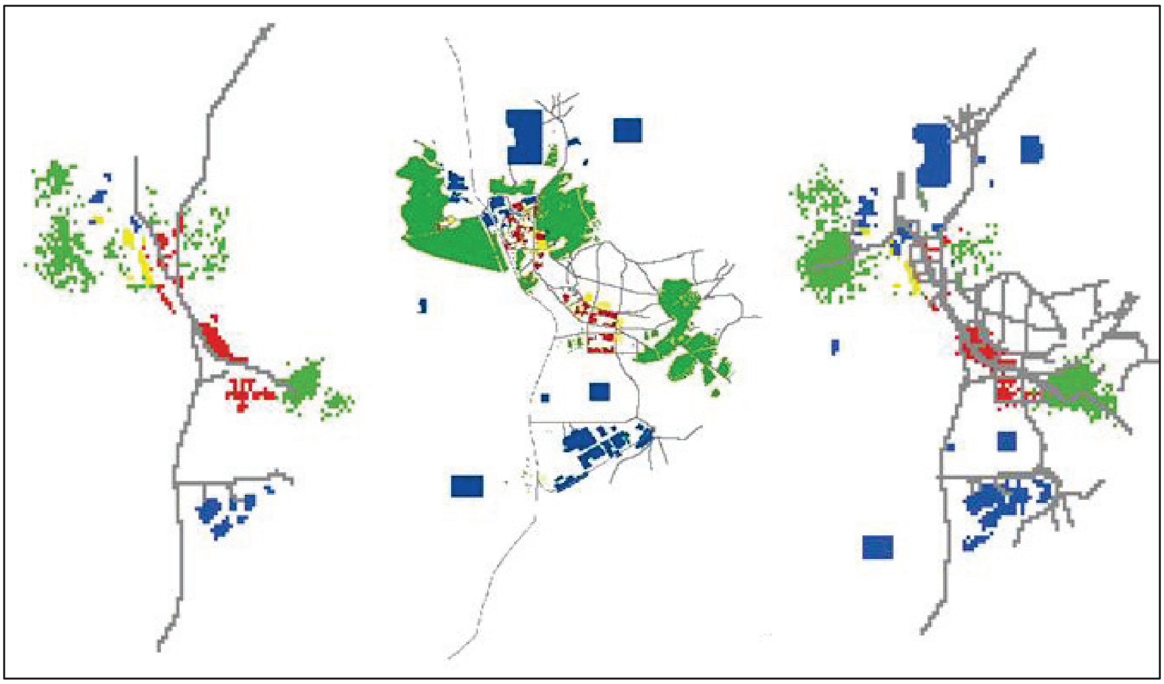


Figure 5.3 Fractal dimension sought by Box-Count method



(a)1998 (b) 2009obs. (c) 2009 sim

Figure 5.4 Land-use of Darkhan in 1998(left), 2009 observed (center), and 2009 simulated (right). Red, green, blue and grey cells indicate apartment, *gers*, factories and roads

5.2.2 Scenario and results

In the simulation urban growth is assumed to depend only on the coefficients (intrinsic growth rate and carrying capacity) of the logistic equation for population and water deficiency, though urban expansion actually includes miscellaneous factors unknown a priori. The coefficients are basically computed from the statistical data of Darkhan, but it might change abruptly due to the local economic growth and the government policy, e.g. a new factory is invited or some enterprise goes bankrupt. Herein, the coefficients are also considered variables suitable for each scenario. Then, the following three scenarios are considered;

Scenario 0: Continuing current condition

All the parameters and coefficients sought by calibration are used to simulate the urban expansion for coming 41 years (2010-2050). Simulated results are illustrated in Figure 5.5. Figure 5.6 shows the simulated and observed groundwater levels and the number of *gers* and apartments.

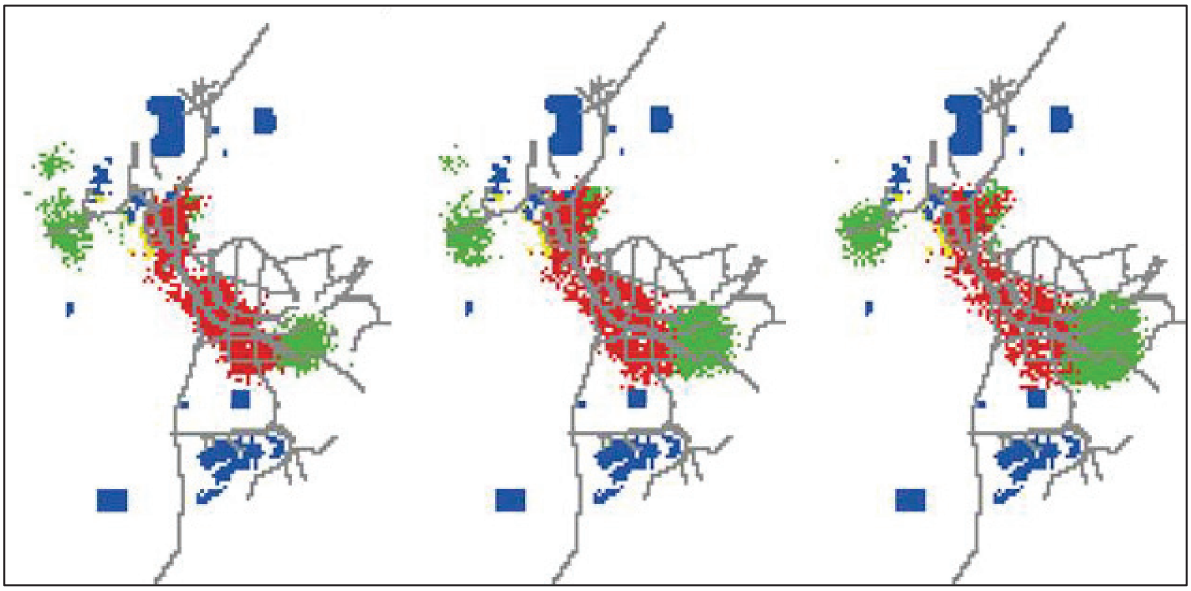


Figure 5.5 Land-use of Darkhan simulated by Scenario 0 in 2010(left), 2030 (center), and 2050 (right). Red, green, blue and gray cells indicate apartments, gers, factories and roads, respectively

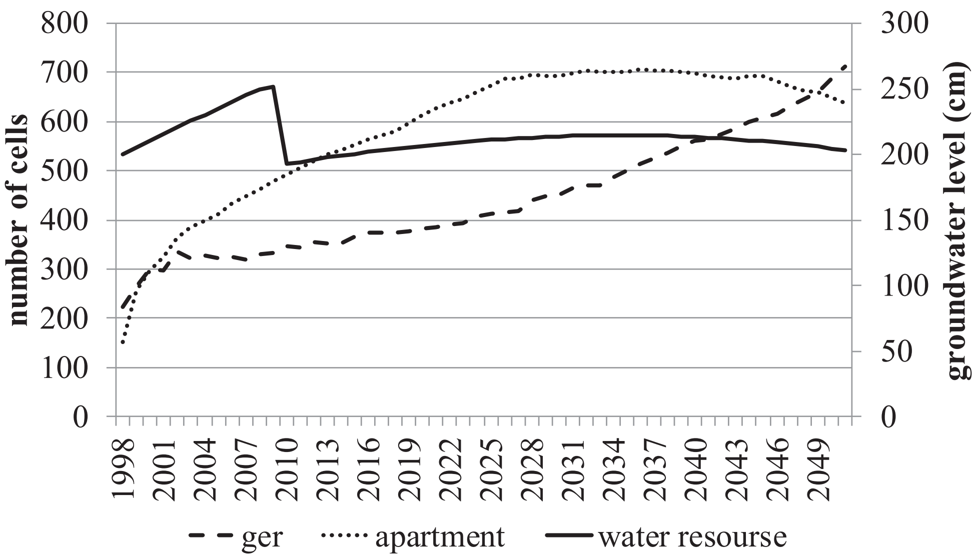


Figure 5. 6 Relationship among apartment, ger and groundwater level in Scenario 0

They indicate that *ger* settlement is gradually increasing and apartment area is growing rapidly between 2010 and 2030. Then expansion of the apartment area is getting slow and almost converges during two decades after 2030 due to relative deficiency of groundwater. In this scenario water deficiency, however, is not critical to maintain the city. In contrast to the apartment , the expansion of *ger* area that consumes less water continues to increase gradually throughout 2010-2050. In addition, sudden drop of the groundwater level in 2009 is due to a newly built factory given in the scenario a priori. Here it should be noted that *Ger* area expansion implies neither population growth nor economic growth of Darkhan city exactly. It is due to several reasons listed below;

1) In comparison with apartment area, *ger* area has much less population density.
2) Installation of *ger* settlement does not require much investment, furthermore the market price of apartment is higher than the income of people living in the *ger* area.
3) Though there are a number of households using small wells in their own properties, the water quality of the well and their demand/consumption are unclear.
4) Massive migration from countryside to suburb area has started since 2000s in Mongolia.

If the development of the city continues after 2050 similarly, the expansion of the *ger* area might induces water deficiency problems. Or even if the water is kept sufficient enough to maintain the city, its quality of life would be worse instead of the growth in the number of *gers*.

Scenario 1: Gradual decay with water deficiency

The supply of water to the city depends on the increase of groundwater level without withdrawal (*ws*). In this scenario water supply is assumed to be restricted by one-third due to some factor, e.g. heavy consumption by factories. Then, the number of the employee might increase, and so the carrying capacity is assumed to 100,000. In addition, we assume the development of the city depends more seriously on the amount of water resources than Scenario 0. Then, we let the index of water deficiency (w_{dif}) 0.1, so as to make the effective survival rate (σ) low, when the amount of water resources reduces by half. Moreover, when the amount of water resources reduces by one-third, w_{dif} increases to 0.3.

The intrinsic growth rate and the carrying capacity of the logistic equation are not unchanged from the value in calibration.

There are two concentrated zones of *ger*, located in northern and southern sides of the city as seen in Figure 5.7. The maps show that northern *ger* settlement area is declined year by year, while the southern area of *ger* settlement expands gradually. Compared with the expansion of the *ger* settlement area in scenario 0, the area in this scenario became much smaller. It means the residents of the *ger* area quickly react against the water deficiency (Figure 5.8). The resistance to the water deficiency of the residents in the *ger* area is actually not known well, but the results might show the possibility of the decay of the *ger* area with severe water deficiency.

Although apartment area is growing between 2010-2030, it decreases and becomes sparse after the period. In the model the mobility of the residents in the *ger* area is considered high, while the residents in the apartment do not move easily after their settlement. This assumption might give the slow response to water deficiency of the apartment area. It demonstrates that the decay of the city and accordingly reduction of economic condition of the city might occur due to severe water deficiency.

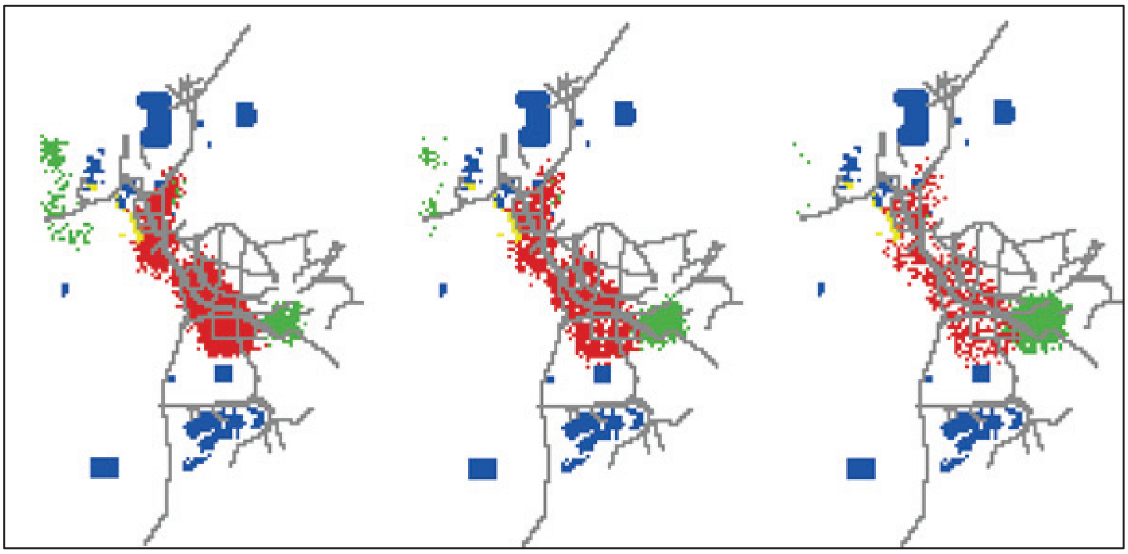


Figure 5.7 Land-use of Darkhan simulated by Scenario 1 in 2010(left), in 2030 (center), in 2050 (right) Red, green, blue and gray cells indicate apartments, gers, factories and roads, respectively

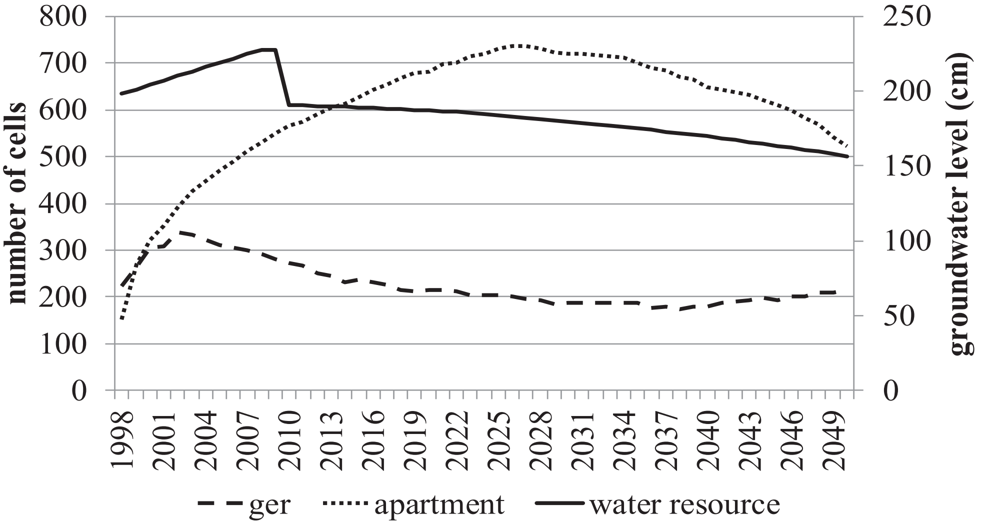
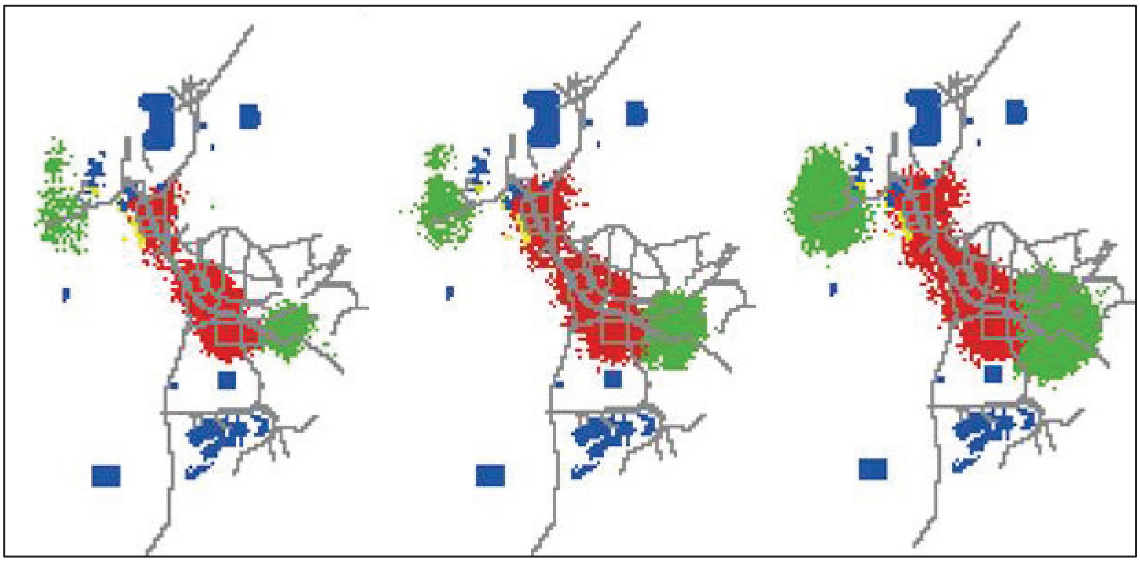


Figure 5.8 Relationship among apartment, ger and groundwater level in Scenario 0

Scenario 2: Development of new water resources

When the amount of water resources reduces by half, new wells are assumed to be installed to supply sufficient municipal water in Scenario 2. Then *ws* increased twice as that of the Scenario 0. It indicates that water deficiency can be avoided by new well installation, even if extensive factory building such as mineral exploitation factory in 2009 happens. In such a case available water resource increases, so that the growths of both the *ger* and apartment areas are kept high. Then, the carrying capacity is assumed 300,000. Figure 5.9 shows that *ger* settlement area is remarkably increasing, much more extensively than other scenarios.

The behavior of the *ger* areas seems quite similar to that of the Scenario 0 (Figure 5.10), though their magnitudes are slightly different. On the other hand, the apartment area shows different tendency, namely, the apartment of Scenario 2 keeps expanding, while that of Scenario 0 shows its peak. They are due to the difference of the response to the water deficiency between *ger* and apartment defined in our model.



a) 2020 (b) 2035 (3) 2050

Figure 5. 9 Figure 11: Land-use of Darkhan simulated by Scenario 2 in 2010(left), 2030 (center), and 2050 (right). Red, green, blue and gray cells indicate apartments, *gers*, factories and roads, respectively

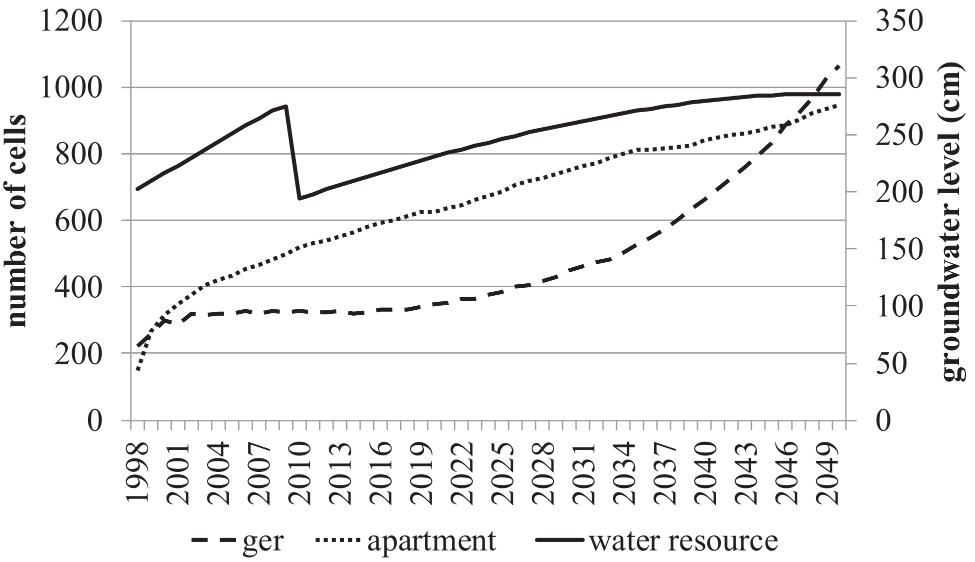


Figure 5. 10 Relationship among apartment, *ger* and groundwater level in Scenario 2

CHAPTER 6. SUMMATION

6.1 Research summary

The chapter 3 described the influencing factors for Darkhan city growth. These factors were divided into two sections as hydro-environmental factors and socio-economic factors.
The former is hydro-environmental factors; e.g., water resource, climate condition and land slope. The climate condition, surface water, ground water and land slope data were analyzed in the chapter. In brief, results of water resource related data analysis is on that of surface water resource which depends on rainfall, but this area has only an annual precipitation of 300-400mm. Hence, it could not be a trustworthy source of public water consumption by quality and quantity. Also the data shows that the level of river water is decreasing as the usage of surface water is increasing. The surface water is used for livestock keeping, agriculture and mining sectors.
The latter is the socio-economic factors, which includ population, industrial sectors and general economic condition. In conclusion, it can be mentioned that development of infrastructure, living condition and social service are quite well developed in Darkhan city. It has become one of the main reasons to settle population in this area, especially for those who are immigrated from other areas of Mongolia. Also this migration can be expected to increase in the next years. Since, it is required to make plans of the city and to assess natural resources in particularly drinking water resource.
In the chapter 4, we introduced the methodology of city growth modelling. Also it described some theories about urban expansion and software which were used in the modelling.
In the chapter 5, residential were modelled and their results were shown. Simulation results might change to some degree according to the given parameters, scenarios and also inherent randomness of the model. They must ,however, show one of the possible results in the development of Darkhan city and can alert the sign of the decay. At least, in our scenarios, water resources are one of the critical factors to maintain the development of the city, especially for *ger* area. The model includes some simple SD model regarding water resources and the survival rate, which must effect significantly to the development of the city. However, the remarkable fluctuations of the water resources, *ger,* and apartments are not seen, indicating that the response of the city to the SD model is not sensitive, compared with other factors.

In the calibration of the model, simulated results are consistent with the observed data to a certain degree, proved by the fractal dimensions. Some scenarios are successfully carried out for the prediction of the city. However, the brushing up of the model is still required, because of its lacks of some information and some subsystems to express the transition of the city, such as well withdrawal in the *ger* area and factories, the relationship between employment and population and so on. In the coming years, Darkhan city is expected to develop as an industrial center of Mongolia, according to the planning and decisions of the Mongolian government. Therefore, the model suggests that water management is essential for its sustainable development.

6.2 Conclusion

World population that was 2.5 billion in 1950 increased to 6.1 billion in 50 years, in 2000. At present, it is estimated more than 8 billion. The majority lives in urban areas and then the urban areas rapidly grow during these few decades. The urban growth is usually considered positively, but many negative problems such as traffic jam, soaring price of real estate, trash problems and shortage of natural resources occur at the same time. Such phenomena are frequently seen in Asian cities where their economic growth is remarkable and Mongolian cities located in Central Asia are included in them. Consequently, discussion on related factors and building up of the appropriate urban plan are essential to make the city develop properly and sustainably. For such a purpose, a number of models as planning tools have been proposed thus far and Cellular Automaton has become a major tool, because the urban growth is essentially a complex system that consists of many extreme small events and the Cellular Automaton has an inherent ability to counter the complexity.

This research aims to develop an urban growth model using Cellular Automata with water resources as a restriction factor for Darhan City, Mongolia of which economics is growing rapidly. The standard Cellular Automata model by Batty and Xie (1994) is used as a base of the model and is developed to adapt the locality of Darhan.

Cellular Automaton is a model in which the cells change their states according to simple repetitive rules with their contiguous and adjacent cells, which often expresses an unexpected complexity. Based on the principle, aggregation phenomena such as snowflake growth, pattern of shells, wildfire, turbulence in fluid and also recently brain consists of neurons obey repetitive application of simple local rules akin to CA. The urban growth that is neither strictly biological nor physical phenomenon, but a human-induced phenomenon, is also aggregation of actions of residents showing unexpected complexity and resembles to CA behavior. On the other hand, it includes external factors such as land use plan, infrastructure, politics, economics, and geography and therefore the original cellular automaton lacks reality. Then, relaxation of rules and introduction of external models are often discussed to make the model realistic.

In this research the cell state is expressed by the development, potential and land use with geographic factors such as slope, and land use plan as fundamental conditions. It is emphasized that *Ger*, nomads' temporary residence is introduced as one of land use pattern in the model. *Ger* is originally a temporary residence that nomads bring with their cattle. Recently, nomads tend to assemble in the suburb of the city and sometimes settle down there. Then, we simply define *Ger* as a temporal residence that is easy to increase and also decrease. When the cell develops enough, which means the population density becomes high, either of the *Ger* moves to another place, the *Ger* split to plural *Gers*, or the residents move to Apartment, is selected. The movement or expansion of the urban/residential area obeys the transition rules in which the first law of geography "Everything is related by everything else, but near things are more related than distant things" is adopted. In addition, the distance decay effect of main roads and railways are examined with actual data and is introduced stochastically into the transition rules.

While the general and conventional urban area in the cellular automaton grows according to the adjacency relations, the population of Darhan depends not only on the internal conditions, but also external conditions, such as immigration of nomads and government policy of industrialization. So, we assume that the population growth obeys to Logistic function given by a calibration procedure. The coefficients of the Logistic function are controlled by water resources as a growth restriction factor through the system dynamics, because of the arid climatic condition of Darhan. Box count method is used to find the Fractal dimension of the urban area in the calibration.

Simulations are based on the Scenarios, i.e., 0) Current condition is maintained, 1) insufficient water resources, 2) insufficient water resources, but new water resources are developed. In Scenario 0 *Ger* area of which water consumption is not large keeps growing throughout the simulation period, while Apartment area with higher water consumption converges into a certain level. In Scenario 1 Apartment area grows for first two decades, but later the urban area shrinks gradually. In Scenario 2 the growth of the *Ger* area is quite similar to the Scenario0, but the growth of the Apartment area is restricted by water resources before the new water resources development. However, the Apartment area grows remarkably rather than the *Ger* area after the development.

Though the simulation results indicate just some of possible feature of the urban area, it proves that there are some certain differences between the growths of the *Ger* area and the Apartment area due to their dependency of water resources, which is useful information for land use planning. On the other hand, the sensitivity of the system dynamics model is too low to contribute the urban growth efficiently. The design of the system dynamics, the extrapolation of population due to the external factors and selection of the cell scale are not resolved yet. The model should be modified to be a realistic tool for the planning.

Overall, we attempted to develop the urban growth cellular automaton model in which the development indicates residents as agents and applied it to Darhan, Mongolia. The model is localized to the target area by introducing *Ger* type into the cell state, introducing the system dynamics showing the relationship between the population and water resources, and introducing the Logistic function for population due to the external factors. Scenario based simulation results show that the water resources have strong influence to the growth of the *Ger* and Apartment areas and consequently the water resources should be well considered in the urban planning of Darhan. This model proves the cellular automata can be applicable to the urban growth of Darhan, and it can be a powerful tool though some further modifications are required.

This type of method is used for the first time in Mongolian case. It might accelerate the simulation research of urban growth and land use in Mongolia. Previously studies about urban growth are mostly based on analysis of topographic maps and digitized maps in some software such as ArcGIS.

6.3 Future works

In the chapter 2, scale problems of cellular automata are mentioned. Thus, research method to model a small town is required and also adopting it to a small town area in Mongolia as a pioneering case is expected.

Also in chapter 5 we selected only 3 scenarios, which also should be expanded in future works for the reality of the model.

In this model we choose two factors and discuss their relations, which is a first step of urban modelling in Mongolia for its sustainable development. The problems of water resource and water usage in arid and semi-arid areas could become much serious in the next years. Previous researches about urban expansion and urban growth in Mongolia were mostly based on topographic maps and their analysis. Using a cellular automata model the research might be developed to the prediction stage and become fruitful to discuss the future of the city and its water resources in Mongolia. Therefore, the model should be brushed up to be applicable to the other cities of Mongolia and also the parameters should be discussed and altered to express reality. Finally the author hopes that this work might be helpful to the sustainable development of Mongolian cities and contribute to the related researches in Mongolia.

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