Dynamic model for earthquake disaster prevention system: a case study of Taichung City, Taiwan

Yufeng Ho[1] Chienhao Lu[2] Hsiao-Lin Wang[3]
Graduate School of Architecture and Urban Design,
Chaoyang University of Technology, Taichung, Taiwan
[1] Email:hyfarch@ms32.hinet.net
[2] Email:timonlu@hotmail.com
[3] Email:whl1435@ms11.hinet.net

Abstract

On 21 September 1999 at 1:47 am, an earthquake measuring 7.3 on the Richter scale struck central Taiwan, causing serious damage and loss of lives. As of February 2006, only 70% of the reestablishment work has been completed. With rapid advances in urban development, the destruction incurred by earthquake disasters increases both in extent and severity. With the aim to minimize loss in human lives and properties caused by natural disasters, this study probes into the urban disaster prevention mechanism, examines the problems encountered in disaster prevention and strategies for prevention. A system dynamics model is established to simulate changes in the disaster prevention system on the basis of related statistics and survey data of September 21 Earthquake. Strategies for urban planning, development and management are suggested from the perspective of disaster prevention. The simulation analysis can offer valuable insight to policy-makers for assessing and deciding on the most feasible and effective strategies to be implemented.

Keywords: earthquake, disaster prevention, dynamic model, strategy simulations

Introduction

Being a small island with a high population density, 617 persons/km^2 (UHDD, 2005), Taiwan's industrial and economic growth has resulted in over-concentration of people in the cities. Not only does this create burden on public facilities, local resources and the natural environment, overcrowded urban development also complicates the management of open space. In face of disasters, the safety of heavily populated cities is in jeopardy owing to the lack of suitable area for refuge and shelter.

On 21 September 1999 at 1:47 am, an earthquake of magnitude 7.3 on the Richter scale hit central Taiwan. The rippled shaking of this near-field earthquake with its epicenter only 1.1 km underground extended over 100 km along the Chelungpu Fault, causing massive damage to the four neighboring prefectures, which include 13 towns and villages in central Taiwan(Figure 1). According to the survey report of the Architecture and Building Research Institute, (ABRI, 1999), Taiwan suffered 2455 fatalities with over 10,000 injured. In addition, 51,378 dwellings collapsed and 53,822 were severely damaged, making 380,000 homeless.

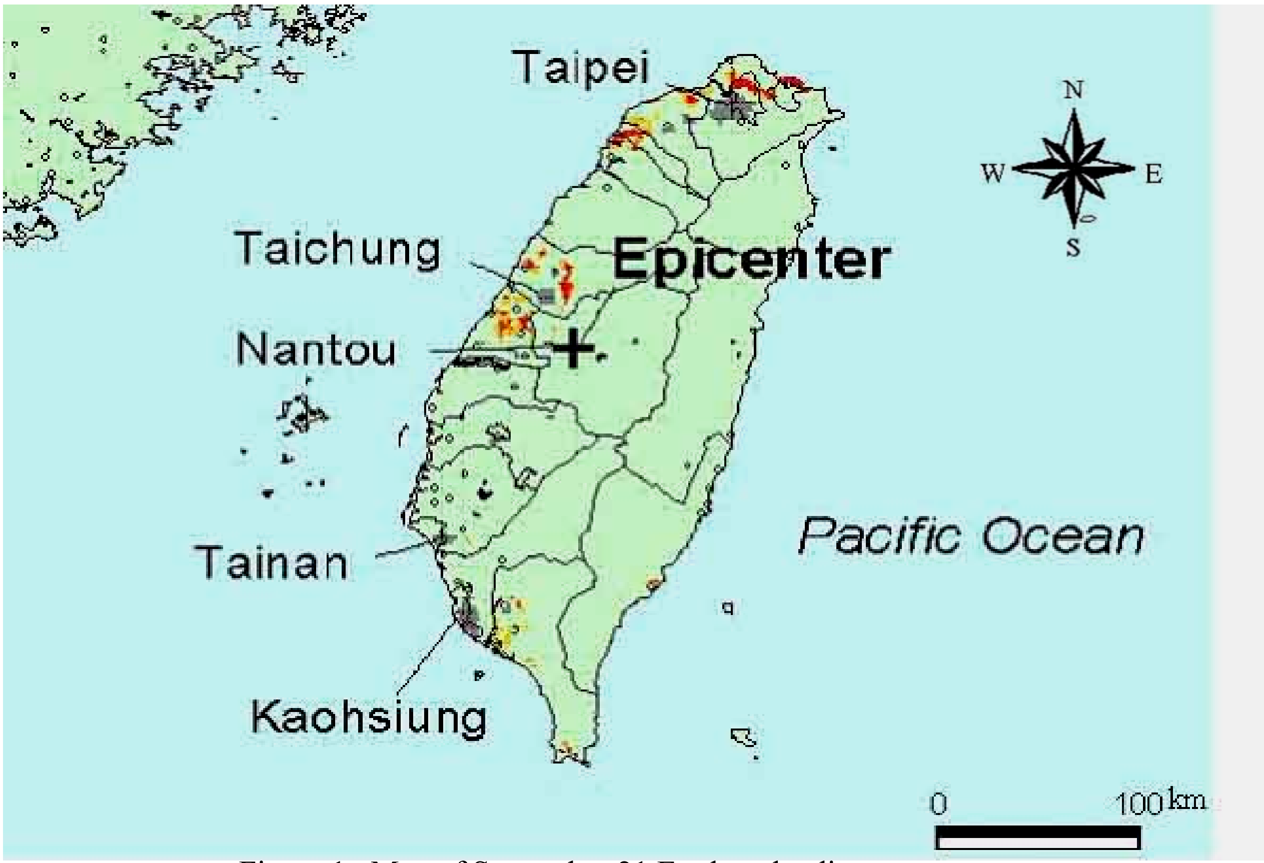

Figure 1. Map of September 21 Earthquake disaster area

In face of natural hazards and urban disasters, the government has devoted much effort to developing different assessment methods that assist urban planning, development and management. The National Center for Research on Earthquake (NCRE) adopted the Hazard Loss Estimation Methodology (HAZUS), jointly developed by the Federal Emergency Management Agency (FEMA), to establish HAZ-TAIWAN for local assessment of loss incurred by earthquakes in 1997 (NCRE, 1997).

Prevention is better than cure. While the occurrence of earthquakes can hardly be predicted with high accuracy or prevented entirely, attention should be made to planning for minimizing the possible damage. The September 21 Earthquake exposed the inadequacies of current disaster prevention measures and paved the way for a new urban disaster prevention system to be developed. Greater effort is needed to equip the people with knowledge of disaster prevention and mitigation, and there is much room improvement with respect to urban management and policy-making concerning relief operations. To ensure sufficient open space available for offering refuge and adequate resources for providing relief would be an important issue for metropolitan areas. For any urban disaster prevention system to be effective and efficient would require an overall assessment of the city. This research simulates the dynamic behavior of Taichung City and attempts to establish an earthquake disaster prevention system that would ensure a safe and comfortable urban living environment. From the perspective of sustainable development, strategies for disaster prevention are also proposed for references by those involved in urban management and policy-making.

Theory and Research Method

Theory: Urban disaster prevention system

In the aftermath of a disaster, most functions of the urban system are either damaged or destroyed. This results in reduction or suspension of production, as well as interruption or delay in the flow of people, materials and information, thus incurring economic losses or inefficiencies. The longer the recovery takes, the heavier the damage will be and the greater the loss it entails. Hence, to sustain post-disaster development in the economic system requires inputs of materials, energy and information from outside, which help improve system structure, enhance system stability and boost its natural organization ability. In order for an earthquake disaster prevention system to be effective, knowledge of the effect of earthquake on urban ecology is of paramount importance(Fig 2) (Chiang and Jin, 1992). Urban disaster prevention system can be viewed as artifact, this artifact is the interface of the inner environment of the community or the substance and organization of the inner environment, and the rest of the elements on the surroundings in which the artifact will be operated is the outer environment. If the inner and outer environment are appropriate to each other, the artifact will serve its intended purpose. Therefore, earthquake disaster prevention is affected by its environment, imports labour, material, finance, medical care, construction, gas, road, railway, electricity, communication, sewage, industry and so on (Table 1).

Table 1. Urban flow vs Urban System

Urban flow	Urban System
Population flow	Population System (such as population density 、population quality)
Cash flow	Industry System (Such as industry value employment opportunity)
Material flow	Transportation, Public facility, Housing System (Such as Vehicle, communication, shelter, precaution point)
Energy flow	Life-supporting (Such as water supply, electricity supply)
Information flow	Environment protection system (Such as environment health)

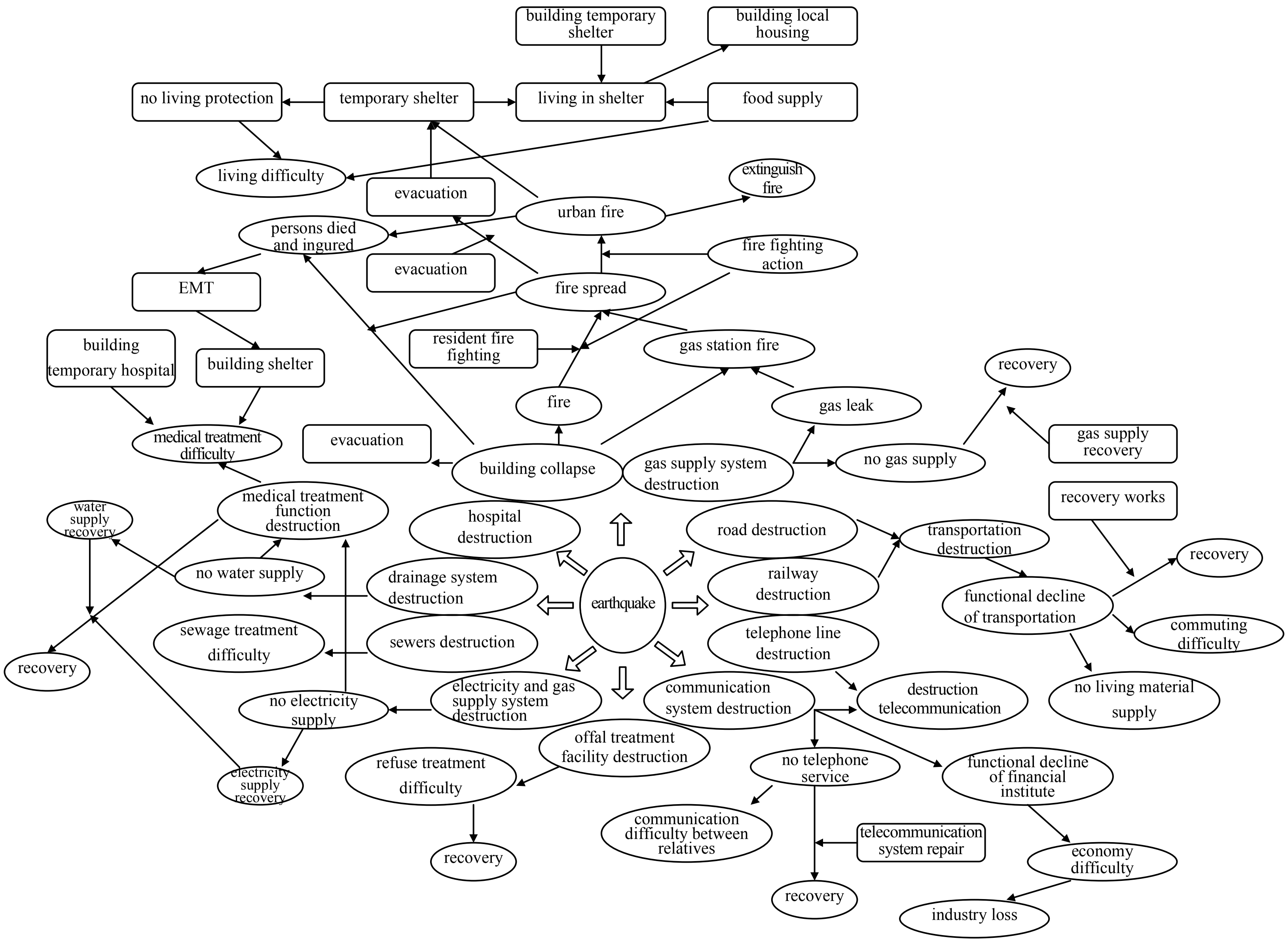

Figure 2. Impact of earthquake on various aspects after

Source: Chiang and Jin (1992)

An urban disaster prevention system can be divided into seven subsystems concerning (1) population, (2) industry, (3) transportation, (4) public facilities, (5) housing, (6) life-supporting, and (7) environmental protection. Among these subsystems, the population and industry subsystems denote the state variables of the city scale, the transportation and public facilities subsystems represent the state variables of urban functions, the housing and lifeline subsystems are resources that fuel urban construction and development, and the environmental protection subsystem reflects the pollution level and city quality. In face of disasters, human lives and properties are most affected, while damage to the life-sustaining functions of a city, such as transportation and communications, as well as power and water supply, will further aggravate the harmful impact of disasters, subjecting quake survivors to life-threatening conditions.

Research method

In the past, considerable interest has been generated in the study of planning method for earthquake disaster prevention. A member of researchers have been involved in research into this field (Kaji, 1988；FEMA, 1990；Smith, 1993；Spudich et al, 1998；Mayes, 1999；Setiana, 2000；Gu, 2000；Takanashi, 2000；Kobuna, 2000；Chen et al 2004；Wang et al, 2004), Unfortunately it is found that no work has been done in the formulation earthquake disaster prevention method with a systems approach. It is the purpose of this study to discuss the need for a systematic approach to achieve a better result of this study. Earthquake disaster prevention system is a very complex system, which usually invole multivariable, non-linear and time series. It is best suited for dealing with the complexity of a disaster prevention system with all its variable factors, and for devising future and long-term policy on disaster prevention. The research method of this study can be described briefly as follow:

1.System analysis

System analysis takes into consideration all variable factors of a real or planned system, searches and evaluates all feasible means of a achieving the pre-set goal, thus helping the policy-makers to evaluate and choose the strategies to be adopted. Hence, systems analysis employs both quantitative and qualitative analytical tools to search and confirm the target through assessing all feasible alternatives. It emphasis comprehensiveness and allows intuition a role to play when making judgment (Ossenbruggen, 1984). This research uses the principles and approaches of the systems theory, which focuses on complexity and interdependence of relationships, to analyze the indicators of the different subsystems and how they relate to and affect each other. With the knowledge concerning the nature of the whole system and the rules governing it, we can establish a comprehensive system model that takes into account all the variables of the different subsystems.

2.Fuzzy Delphi

To ensure the objectivity of our approach, we employ the Fuzzy Delphi method to screen the indicators. The Fuzzy Delphi method has the advantages of (1) less investigations required, (2) complete expression of the experts' opinion, and (3) due consideration given to the inevitable ambiguity encountered during interviews (Wang, 2005). The experts' opinion is evaluated by the similarity function to obtain an integrated fuzzy screening value. All indicators are then screened with reference to the threshold value calculated. Finally, the screened indicators are employed to establish the causal loops between all the variables of the subsystems for constructing the dynamic model for an urban disaster prevention system.

3.System Dynamics

System dynamics can assist in strategy assessment and provides insights into possible changes in the system during policy implementation (Sterman, 2000). A simulation model, combining urban system analysis with system dynamics techniques is suggested. Through model simulation, the proposed strategies are taken as changes in parameters and structure. The objectives of earthquake disaster prevention system can be pursued to achieve a better safety of life for every citizen.

Generally speaking, the use of system dynamics in planning has a number of advantages:

(1) The emphasis is placed on the mathematical ideas of planning. Data processing facilities could be used to help in reducing the work load on the planner;

(2) The use of models to understand and predict the behaviour of urban earthquake disaster under different conditions provides the planner with a clear picture of activities taking place in adapted space and the flows between those activities taking place on channels;

(3) By a combination of (1) and (2) above, the planner is able to change behaviour through policy making to archive earthquake disaster prevention.

Model Formulation

Indicators and Feedback Loop Diagram

According to the theories and research findings of urban earthquake disaster, the 103 indicators formulated with respect to the seven subsystems of an urban disaster prevention system, as shown in Table 2. Thirty academic experts and scholars from various disciplines were invited to assess these indicators. The Fuzzy Delphi method is then employed to screen the indicators. Indicators with experts' assessment value above the threshold (25%) will be selected while those below it will be discarded. In the end, 35 indicators are obtained as marked with * in Table 2.

Table 2. Indicators of urban disaster prevention system and their assessment value

Sub-system	Indicator	Value	Sub-system	Indicator	Value	Sub-system	Indicator	Value
Population subsystem	Natural increase rate	0.54		Industry value per unit of energy consumption	0.65		Ratio of real estate income	0.70*
	Social increase rate	0.64*		Total industrial energy consumption	0.66		Different landuse to total area ratio	0.68*
	Total birth rate	0.51		Total industrial water consumption	0.69*	Lifeline subsystem	Water supply rate	0.85*
	Average life expectancy	0.55	Transportation subsystem	Road area ratio	0.77*		Electricity supply rate	0.85*
	Total population	0.78*		Road density（km/km²）	0.76*		Gas supply rate	0.77*
	Population increase rate	0.76*		Transportation index (road area/person)	0.72*		Water consumption per capita	0.73
	Population density	0.83*		Transportation expenditure ratio	0.62		Electricity consumption per capita	0.73
	Population distribution	0.80*		Population served by public transportation	0.65		Gas consumption per capita	0.68#
	Dependency rate	0.52		No. of passenger cars per 1,000 persons	0.65		Water supply	0.81*
	Aging index	0.60		No. of motorcycles per 1,000 persons	0.62		Electricity supply	0.80*
	Percentage of homeless population	0.46#		Passenger car growth rate	0.60		Gas supply	0.76
	Average no. of persons per household	0.55		Motorcycle growth rate	0.57#		Total electricity consumption	0.74
	Age structure of population	0.60		Automobile density	0.65		Total water consumption	0.74
	Marital status of population	0.40#		Automobile ownership rate	0.61		Total gas consumption	0.70
	Sex ratio of population	0.42#		No. of parking lots per car	0.65		Ratio of expenditure on water resource development	0.66#
	Education index	0.60		No. of telephones per capita	0.65		Ratio of expenditure on electricity development	0.67#
	Illiteracy rate	0.48		No. of letters per capita	0.57#		Average water consumption	0.80*
	Labor force ratio	0.56	Public facilities subsystem	Area ratio of public facilities	0.83*	Environmental protection subsystem	Length of sewers	0.73*
	Employed population by occupation	0.55		Green belt area	0.78*		Daily refuse production per capita	0.66
	Unemployment rate	0.53		Green space per capita	0.79*		Ratio of general refuse produced	0.65#
	Average income per capita	0.62*		Green coverage	0.69		Ratio of solid refuse recycled	0.69
	Income distribution	0.58		Average water pervious	0.60#		Daily refuse production per capita	0.72*
	Average consumption per capita	0.59		Leisure facilities per 10,000 persons	0.53#		No. of refuse collection employee per 1,000 persons	0.69*
	Consumption index	0.59		No. of hospital beds per 10,000 persons	0.85*		Rate of refuse disposal	0.72*
Industry subsystem	Average industry value	0.73*		Area ratio of education facilities	0.74		Daily sewage disposal per capital	0.70*
	Industry capital ownership rate	0.61		Cultural facilities per km	0.61#		% of sewage treated	0.72*
	Rate of industry investment cost	0.62		No. of fire hydrants per 1,000 persons	0.81*		% of sewage recycled	0.67
	Industry growth rate	0.71*		No. of fire engines per 10,000 persons	0.84*		Ratio of rivers exceeding pollution limit	0.67
	Industry structure	0.81*		Ratio of public health expenditure	0.68		Noise pollution index	0.64#
	Labor supply and employment rate	0.65	Housing subsystem	Floor area per capita	0.72*		Environmental pollution load	0.68
	Industry population	0.60		No. of room per capita	0.58#		Ratio of environmental pollution expenditure	0.68
	Ratio of foreign labor force	0.56#		Housing ownership rate	0.64			
	Average labor productivity	0.67*		Unoccupied house rate	0.60			
	No. of working hours for maintaining basic living	0.58#		Housing expenditure as % of family expenditure	0.61			
	Industry land area	0.63		Housing investment as % of GDP	0.60			
	Industry land price index	0.63		Regional land price (land price index)	0.64			

Note:1.＃: discarded indicators with assessed value below screening value
2.＊: selected indicators with assessed value above screening value
3.Screening value: population subsystem (0.474), industry subsystem (0.590), transportation subsystem (0.587), public facilities subsystem (0.623), housing subsystem (0.592), lifeline subsystem (0.692), environmental protection subsystem (0.659).
4.Threshold value: population subsystem (0.609), industry subsystem (0.666), transportation subsystem (0.663), public facilities subsystem (0.779), housing architecture subsystem (0.649), lifeline subsystem (0.773), environmental protection subsystem (0.694).

Figure 3 shows the interrelationships between the seven subsystems of an urban disaster prevention system. Evidenced by its complexity, this closed system involves intricate causal feedback loops between the different variables, revealing the impact each subsystem has on the others. As can be seen, there are 11 causal loops, 8 input and 3 information feedback ones.

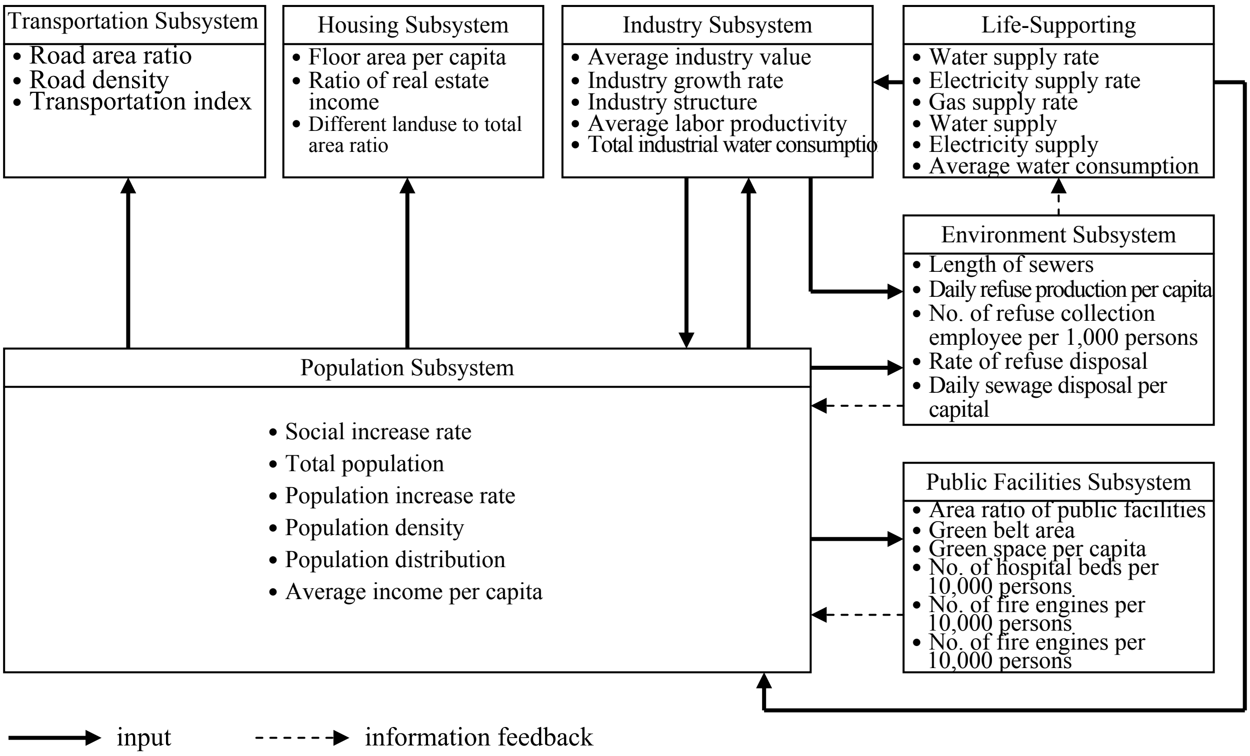

Figure 3. Interrelationships between subsystems

Model Formulation

In view of the many parameters of an urban disaster prevention system and their complex relationships, we assume in this study that the behavior in such system is in a continuous state in order to facilitate model formulation and simulation analysis. Therefore, changes in system behavior are not a matter of probability; rather they are the results of some causal loops of the variables. Dynamic models of the seven subsystems of urban disaster prevention are each formulated using STELLA (HPS, 2000) programming language, shown in Figures 4-10. As can be seen, the dynamic model for an urban disaster prevention system comprises 173 variables and 184 equations. Among these equations, 11 are level equations, 11 are initial value equations, 20 are rate equations, 132 ancillary equations and 10 constant equations. With the system dynamic model formulated, we conducted computer simulation and analysis of the feasible disaster prevention strategies for Taichung City.

(1)Population subsystem

Urban disasters cause death, injury and migration of the population. In the case of earthquakes, the city infrastructure is damaged jeopardizing the safety and life quality of the dwellers. Naturally, people will move to safer place to meet their psychological need for security and protection, as well as to a better living environment that meets their physical need for relief and comfort. Apart from the impact of human flow, death incurred by the disaster also affects the population of the city. Hence, the model is formulated taking into consideration the level variable of total city population and the rate of three influencing factors, namely birth, death and floating population.

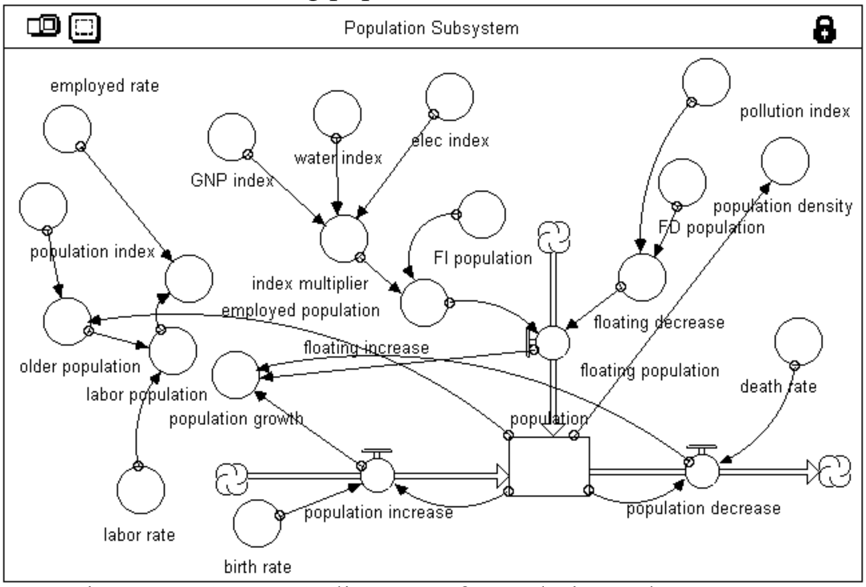

Figure 4. STELLA diagram of population subsystem

(2)Industry subsystem

Industry forms the basis and provides the impetus for the development and expansion of a city. The most obvious damage incurred by urban disasters is the loss of human lives and properties, both public and private. This upsets the equilibrium and results in wealth redistribution in society. Not only the disaster itself causes destruction, post-disaster relief and reestablishment also leads to adjustment in land resources development and regional industrial growth, incurring changes in resource investment and distribution. All these will affect the economy, industrial development, employment opportunities and competitiveness of the city. The model thus formulated takes industrial output as the level variable. The changes in the gap between outputs from the industry and service sectors also reflect the industrial profile and city nature. In addition, the labor population indicator from the population subsystem should also take into account in the industry subsystem because an adequate quality labor supply can enhance production and foster accumulation of industry value.

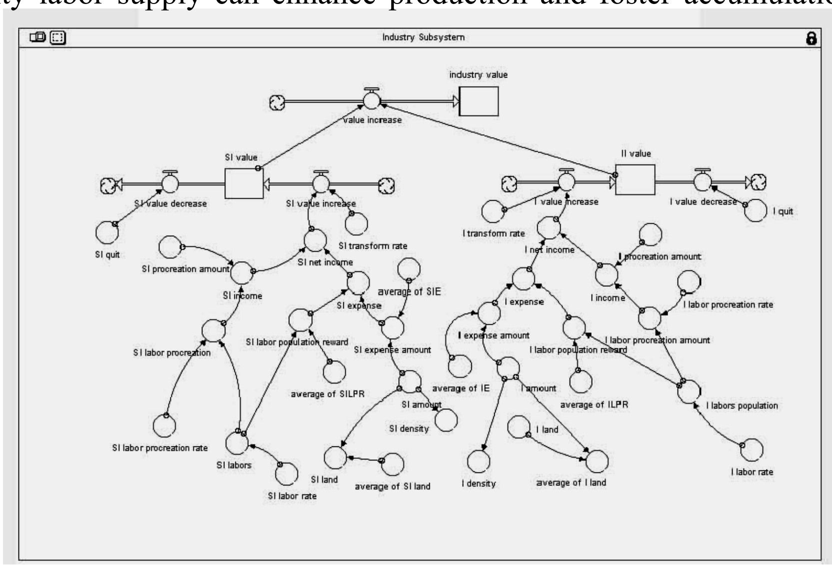

Figure 5. STELLA diagram of industry subsystem

(3)Transportation subsystem

Transportation networks make up an important part of the city infrastructure. They are responsible for transporting materials and power needed for urban living. Connected by transportation networks, different regions can share resources to recreate greater diversity of city life. In addition, roads and freeways constitute ribbon-like open space. During disaster outbreak, the roads and railways become critical for delivering emergency relief and supplies, and the open space can serve as temporary refuge or shelter for victims. The main level variable of the transportation subsystem is roadway area, which is affected by the rate of roadway development. Other ancillary variables include the length and width of roadway, which is used for calculating the area of roadway developed; as well as roadway area ratio, roadway density and transportation index, which are estimated using urban land area and total city population.

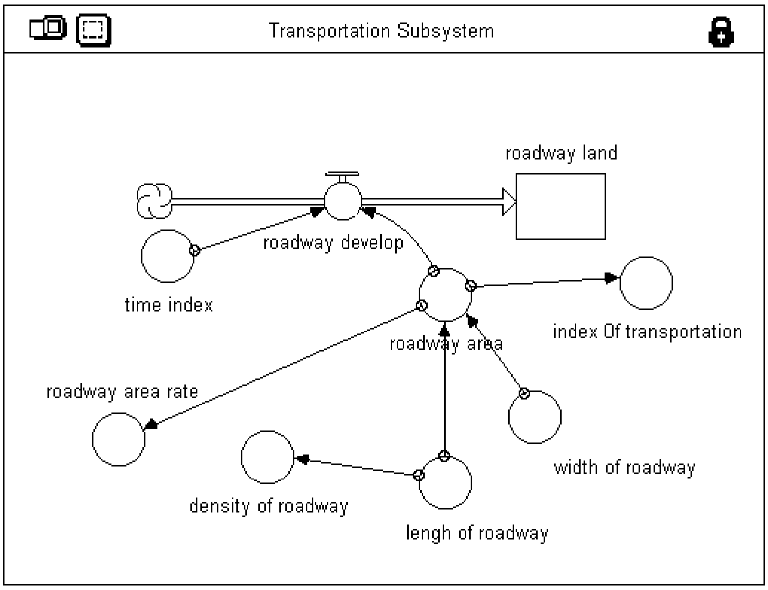

Figure 6. STELLA diagram of transportation subsystem

(4)Public facilities subsystem

The six selected indicators are area ratio of pubic facilities, green belt area, green space per capita, as well as number of hospital beds, fire hydrants and fire engines. The area considered in this subsystem includes land devoted to public institutions (such as police stations, fire stations and hospitals) and public facilities (such as parking lot, playground and stadium) that are related to disaster prevention and refuge provision. Changes in such area in proportion to the total land area of the city reflect the trend in urban land use and planning. Calculating the number of hospital beds, fire hydrants and fire engines per capita can shed light on the service availability. With the information of total population provided by the population subsystem, we can calculate the per capita area of public facilities, green belt and educational facilities to reflect the adequacy of different types of public facilities.

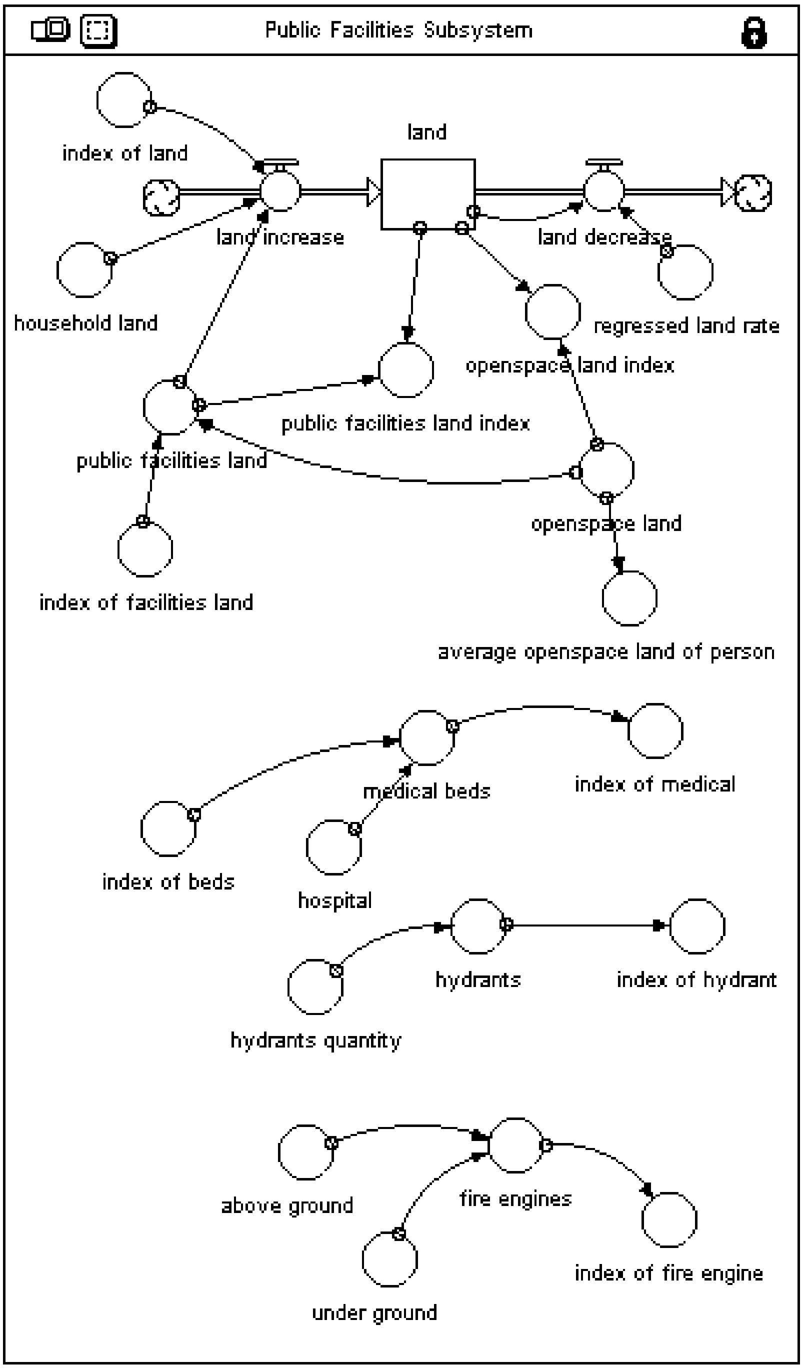

Figure 7. STELLA diagram of public facilities subsystem

(5)Housing subsystem

Damage to housing makes victims of disaster homeless. This subsystem probes into the changes in living behavior and land utilization due to destruction of living abode as a result of disaster. These changes include number of persons per household, number of households, floor area of each household, price and income of housing. Natural disasters can impact the number of households, which then affects the demand of housing. Observing changes in the subsystem can help in the planning of housing distribution so as to maintain a steady supply of living abode for the citizens.

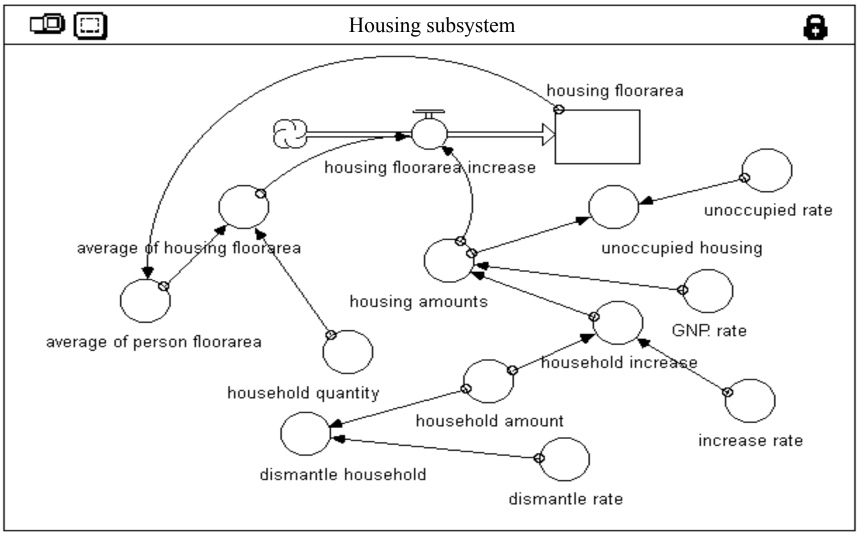

Figure 8. STELLA diagram of housing subsystem

(6)Life-supporting subsystem

Water, electricity and gas all have different units and can hardly be integrated. However, they share some characteristics. First, damage to the pipes and power lines will cause suspension to service supply and affect the daily living of the people. Second, the supply of different types of utilities are independent, all using different pipes and lines for transmission. Third, their service is affected by the source of resource or energy supply. The life-supporting system simplifies the overall causal relationships and probes into the inflow and outflow of different types of resources. Changes in supply due to the impact of disaster and disaster relief and variation in demand due to population changes are observed. The three main levels of the life-supporting system are water, electricity and gas, all with different inflow and outflow rate. The inflow rate is the product of the regional supply and supply rate, while the outflow rate comprises the total population and the average amount of use per person.

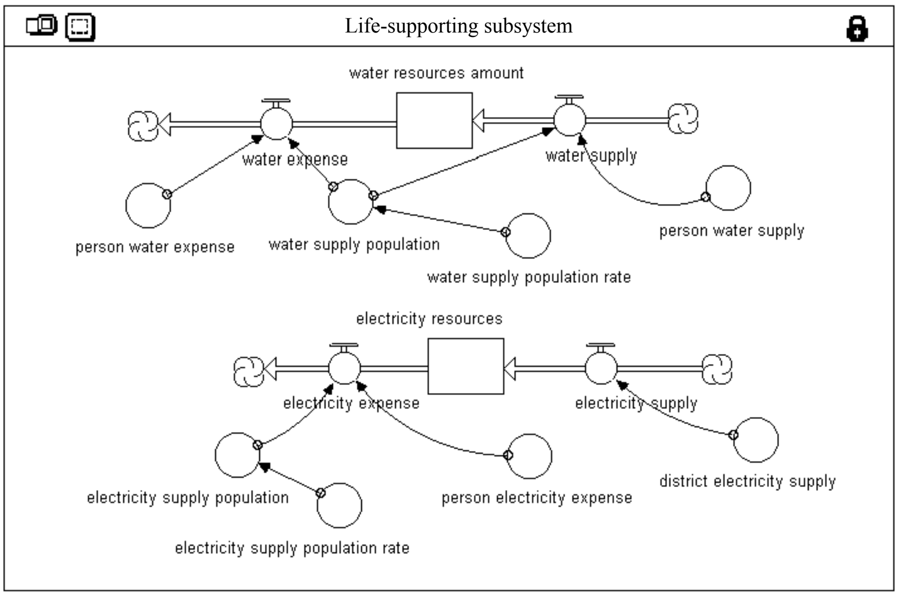

Figure 9. STELLA diagram of life-supporting subsystem

(7)Environmental protection subsystem

Water pollution is caused by the disposal of sewage with high concentration of organic matters. Decomposition of these organic matters increases the oxygen consumption in the water, thus worsening the water quality. In the aftermath of disaster, apart from general refuse, debris from damaged architecture also constitute the source of pollution. This model simulates the changes in total amount of refuse produced taking into consideration the changes in total population and average amount of refuse produced. Finally, whether the production of refuse will result in pollution will depend on the capacity of incinerators and landfills. Hence, our simulated results on refuse production will shed light on the demand for refuse treatment facilities and the possible severity of pollution.

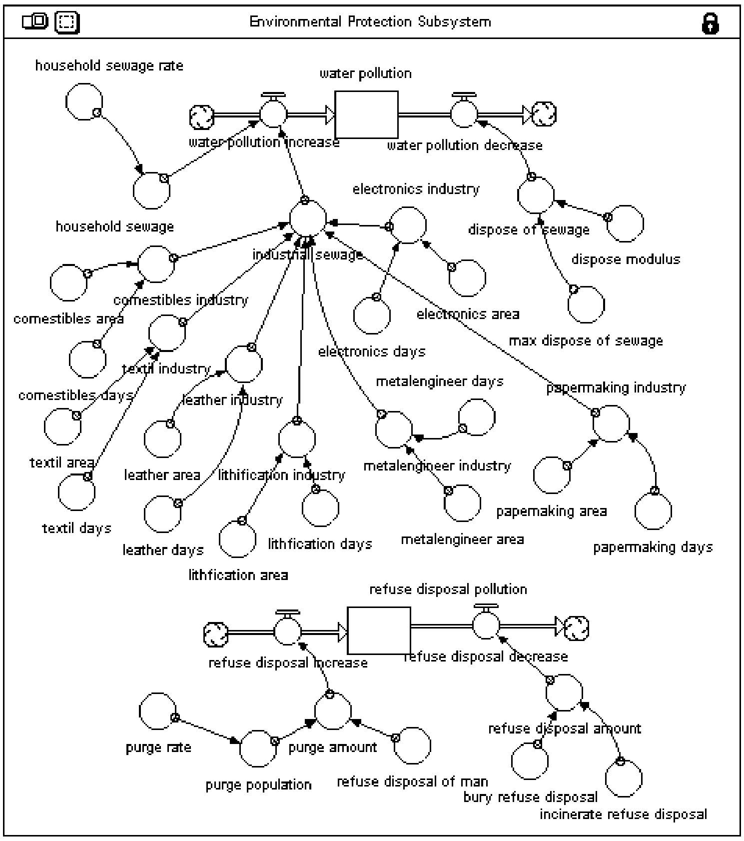

Figure 10. STELLA diagram of environmental protection subsystem

Simulation Analysis of Earthquake Disaster Prevention Strategies for Taichung City

The September 21 Earthquake measuring 7.3 on the Richter scale occurred near central Taiwan. Its epicenter lies 12.5 km west to Sun Moon Lake (23.85N, 120.78E). It was a shallow (approximately 7 km) thrust earthquake, caused by collision between the Philippine Sea and Eurasian plates. Followed by a series of strong aftershocks, the earthquake caused significant damage not only along the ruptured faults but also in the nearby urbanized areas, notably the Taichung metropolitan area (Fig 11). Taichung City suffered 113 deaths, 23 citizens were seriously injured, 1112 required medical assistance and 20,000 became victims. A total of 2803 buildings collapsed and 3743 were severely damaged.

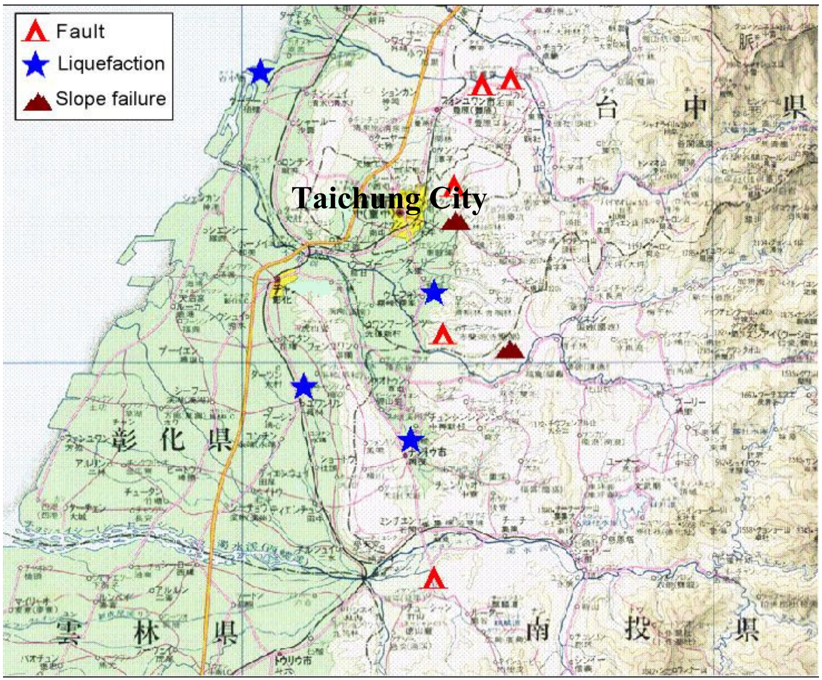

Figure 11. 921 earthquake Disaster area of Taichung City

Model Justification

The model thus developed was justified with the historical data of Taichung city from 1986 to 1996. As seen in Figure 12, the simulation results were very close to the actual ones. Hence, the data estimated by the model for 2003 to 2011 should be accurate in reflecting the future trend of development in Taichung City.

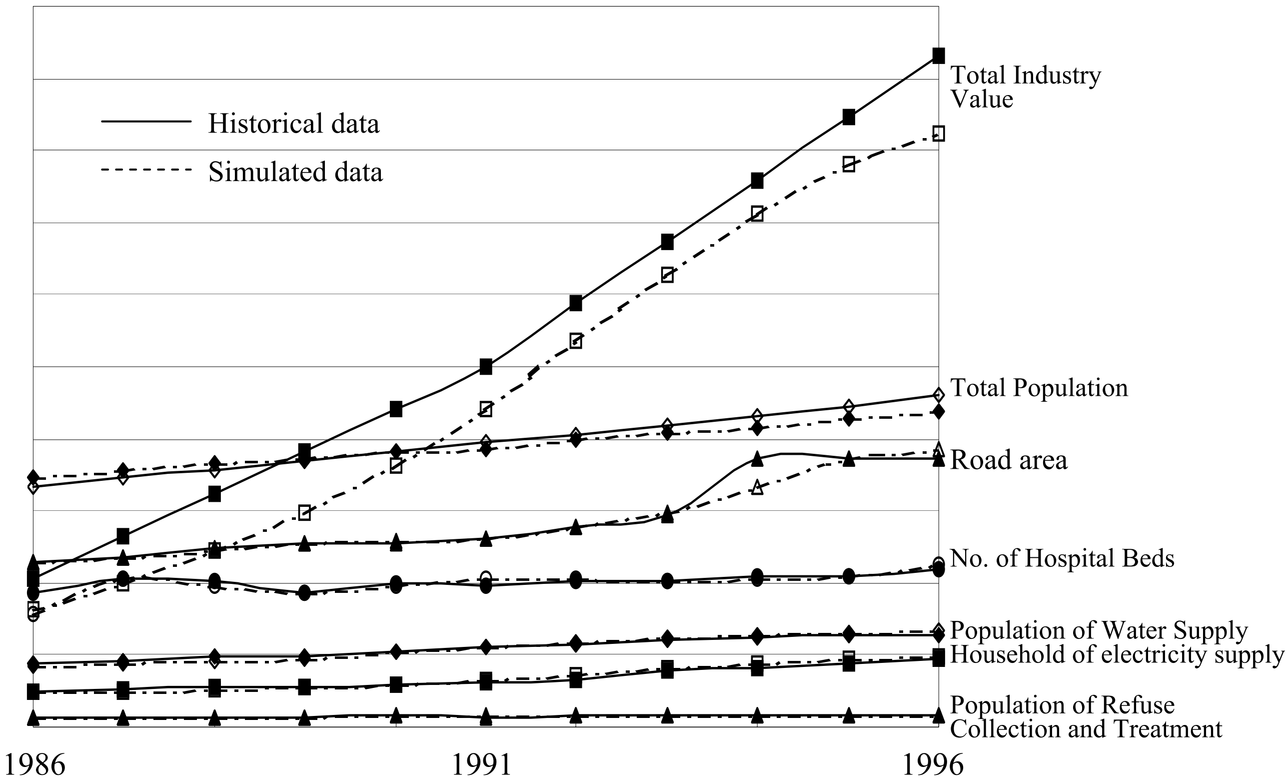

Figure 12. Simulated data with respective to historical data of Taichung City.

This study used the ‘Effect-Efficiency Matrix’ to select the sensitive variables in the Model (Kano, 2003), The results indicate the most sensitive ones are total population, population density, open space and water supply. (Ho & Lu, 2004)

Strategy Simulation

The aims of disaster prevention lie not only in decreasing the outbreak of disasters and minimizing the losses incurred, but also in creating a safe and comfortable urban living environment balancing both economic growth and sustainable development. Using urban management approach, this study simulates three disaster prevention strategies for Taichung City. These strategies can serve as useful references for policy-makers when designing disaster prevention measures that can meet the future development of Taichung City as estimated from the simulation analysis. Detailed simulated results of these strategies are discussed in the following.

(1)Strategy 1: Strengthen training for emergency relief and rescue operation to reduce casualty

While outbreak of disaster can hardly be forecasted or avoided, the loss of lives and properties directly or indirectly caused by the disaster can be minimized. Apart from establishing an efficient and effective disaster prevention system, people should be equipped with the necessary information on how to prevent disasters, seek refuge, save themselves and offer rescue for others. Survey reports done in the aftermath of the September 21 Earthquake reveal that the fatalities suffered by Taichung City were partly due to the lack of knowledge, experience and ability in seeking refuge and rescue in face of earthquakes. Hence, it is of great need and paramount importance to strengthen the training for emergency relief and rescue operation to reduce casualty.

High casualty leads to increase in death rate, which impacts the development of a city. Statistics show that Taichung City has all along a rather low death rate, below 4000 per year. Even the 113 deaths of the September 21 Earthquake caused no significant increase in death rate or posed no serious problem to urban development. Using 2001 as the baseline, this study simulates three scenarios of death rate at 5000, 8000 and 10000 per year and examines how such rise in fatalities will affect the future population growth of Taichung City and how great the damage in loss of lives Taichung City can tolerate with the least impact on its development.

Figs 13, 14 Shows the simulated population and population density between 2003 and 2011 with increase in death rate. As can be seen, the total population forecasted by the original model reaches 1.08 million with a population density of 202.55 persons / hectare. However, increase in death rate will lead to decrease in future population. The figures in figs reveal that the higher the death rate, the less the total future population and the lower the population density. Despite this, the growth of Taichung city remains steady with potential for development, implying that its tolerance to a great damage in loss of lives is relatively high.

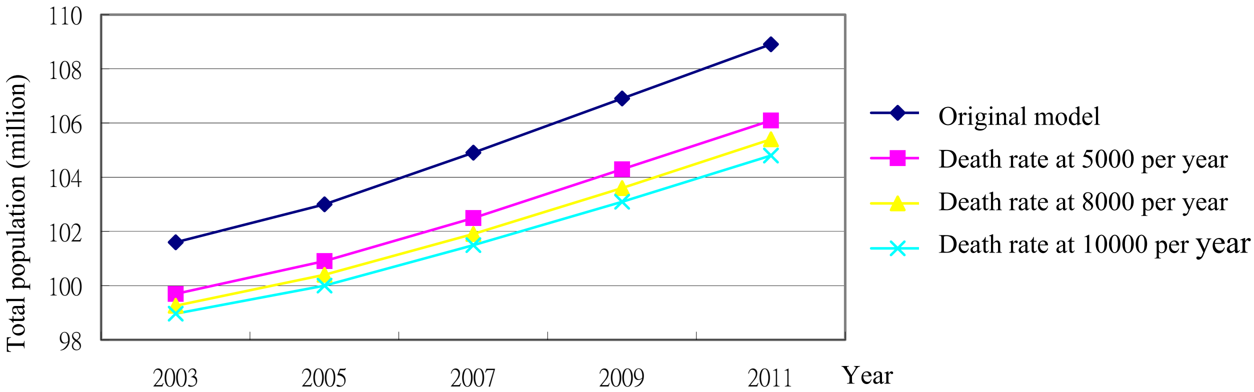

Figure 13. Total population simulation

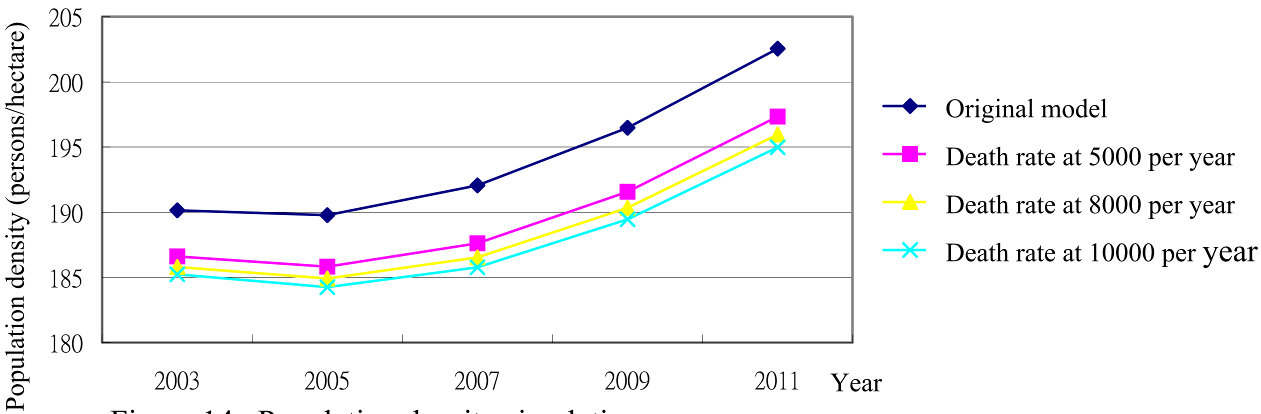

Figure 14. Population density simulation

Nevertheless, human lives are precious and human resources are invaluable for growth and development. Thus, loss of human lives should be avoided at all cost. To enable people to self-help and help others in face of earthquakes, more training should be provided to equip them with the skills and knowledge while disaster drills should be conducted at regular intervals to let them apply the know-how, acquire the experience and build confidence in dealing with disasters. In addition, the communication systems should also be upgraded to ensure prompt delivery of information between various agencies involved in disaster relief and operation. Hospitals should also be well prepared and fully equipped to provide relief support and medical care so as to minimize fatalities.

(2)Strategy 2: Establish a comprehensive system to utilize open space for refuge and shelter

At ordinary times, open space of a city provides venue for activities organized by and for the citizens; while during disaster outbreak, it will be utilized as refuge and shelter for those affected. Effective and efficient management of open space can help improve urban environment and proper utilization of open space is an important strategy for disaster prevention and mitigation. Current planning concerning open space utilization of Taichung City has not taken disaster prevention and refuge provision into consideration. Hence, not only are the open space and peripheral roadways not meant for disaster prevention, the related facilities are not equipped for serving as refuge shelter. As a result, during earthquakes or floods and with no refuge shelter pre-specified by the government, citizens have no idea where to seek refuge and can only take temporary shelter in neighboring schools, parks, temple plazas, markets and parking lots. Thus, open space, large ones in particular, plays a vital and indispensable role in urban disaster response. However, how to reserve sufficient large open space in a densely populated living environment has always been a challenge to urban planning in Taiwan, and Taichung City is no exception.

Statistics of 1996 show that the open space area per capita in Taichung City is 1.5 m^2, which is lower than 2 m^2, the refuge density of disaster prevention specified by the Japanese government. Compared with other metropolitans around the world, Taichung City offers a much smaller green area for its citizens.

In view of the frequent occurrence of earthquakes, Taichung City should ensure that there is sufficient open space both for recreation activities of its citizens at ordinary times and for disaster mitigation during disaster outbreak. This not only can increase the comfort of the living environment, but also offer safety and support for the city dwellers. Urban planning should aim at ensuring sufficient total open space in a community to accommodate a refuge ratio of 40% of the population planned and that there should be 4 m^2 (double that specified by Japan) of shelter space made available to each refuge.

This study simulates the trend of increase in open space area per capita using the original model and three scenarios with target increase in open space area of 5%, 9% and 10%. The results are shown in Figs 15,16,17. As can be seen, even with rising total population and population density, increase in percentage of open space area can result in a higher open space area per capita. An increase of 10% open space area can reach the open space area per capita of 4.07 m^2 in 2011, exceeding the target of 4 m^2.

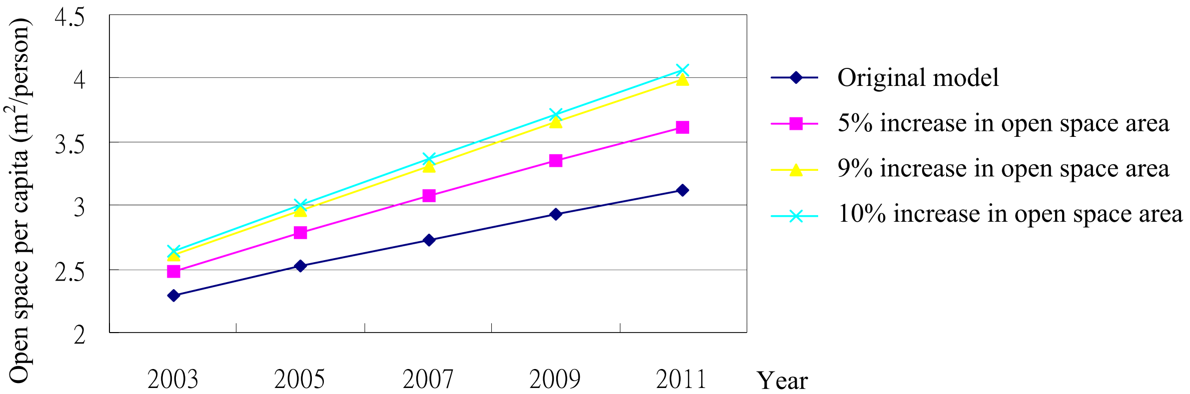

Figure 15. Open space per capita simulation

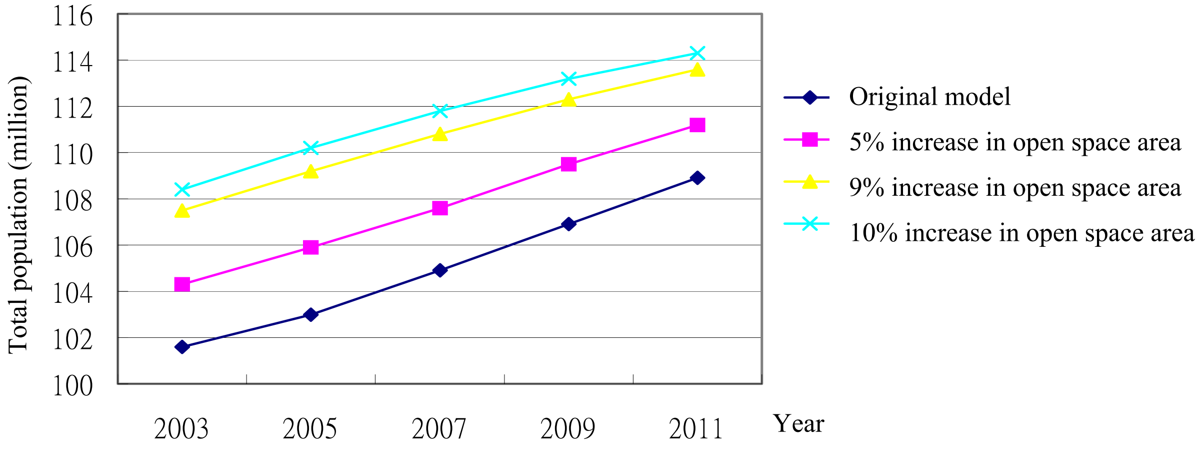

Figure 16. Total population simulation

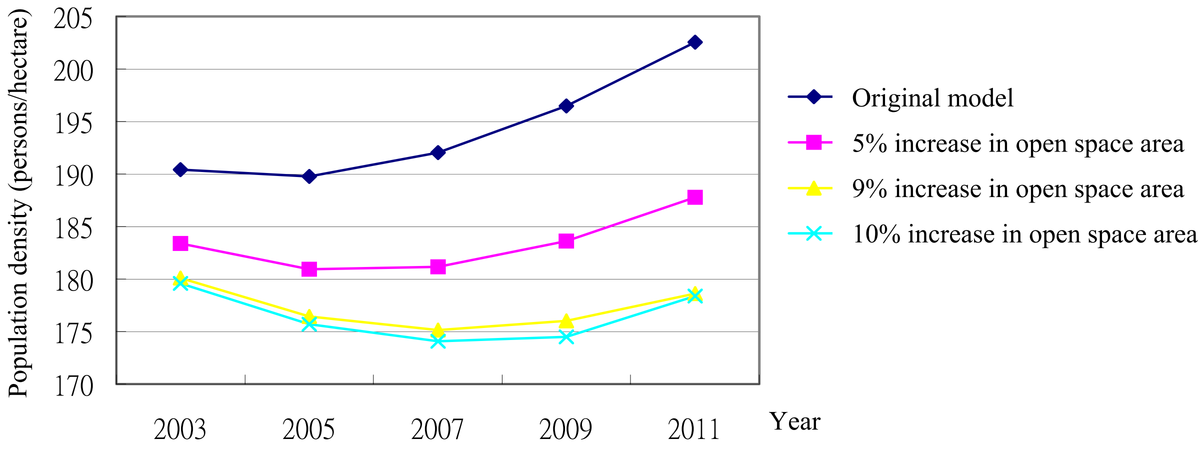

Figure 17. Population density simulation

In order that people can benefit from the increase in open space area, Taichung City should make better utilization of open space through creating parks, green lawns, plazas and squares. The farmlands 30-50 m on both sides of roadways threading through Taichung County can be acquired for establishing a landscape green belt. The techniques of ecological afforestation can also be employed to establish quality urban forests. Efforts for linking the transportation networks with leisure travel can be made to encourage investment in leisure parks. Urban renewal can increase green area in commercial districts. In launching the above measures, care must be taken to integrate disaster refuge provision with existing and future public facilities so as to ensure sufficient quake-resistance and effective disaster mitigation. Areas specified for refuge shelter during disaster outbreak should be planned and citizens should be fully aware of their locations.

(3)Strategy 3: Enhance the life-supporting subsystem and maintain the supply for basic needs of urban living

In the aftermath of the September 21 Earthquake, the damage to the water supply facilities, including reservoirs and pipes, resulted in suspension of water supply and serious water ration in the Taichung metropolitan area. Total water supply by reservoirs and various sources can only meet around 60% of the daily water need of the Taichung area, causing 280,000 households to suffer from water shortage. Ensuring adequate water supply is an important issue worthy of concern.

According to the statistics, the daily water consumption per capita is 307 L and it is forecasted that such will increase to 395 L in 2021, which would exceed the capacity for sewage treatment, resulting in pollution to the environment. Excessive use of water not only depletes regional resources and create burden, but also poses threat to the environment. At the Conference of National Land and Water Resources, the target was set to reduce daily water consumption per capita to 250 L so as to achieve water saving and long-term management of water resources. Continuous growth and sustainable development of a city relies heavily on a constant and abundant supply of natural resources. To avoid over dependence and reduce the threat of shortage, cutting down on consumption would be the key to achieve economy of use and long-term sustainability.

This study simulates the changes in daily water consumption per capita with an annual reduction in water supply of 1%, 2% and 5%. The results are shown in Figs 18,19,20,21. As can be seen, reduction in water supply can help decrease the daily water consumption per capita. The higher the reduction, the greater the decrease will be. The simulated results show that a 3% reduction in water supply can bring down the daily water consumption per capita to 214.4 L, thus achieving the pre-set target of 250 L.

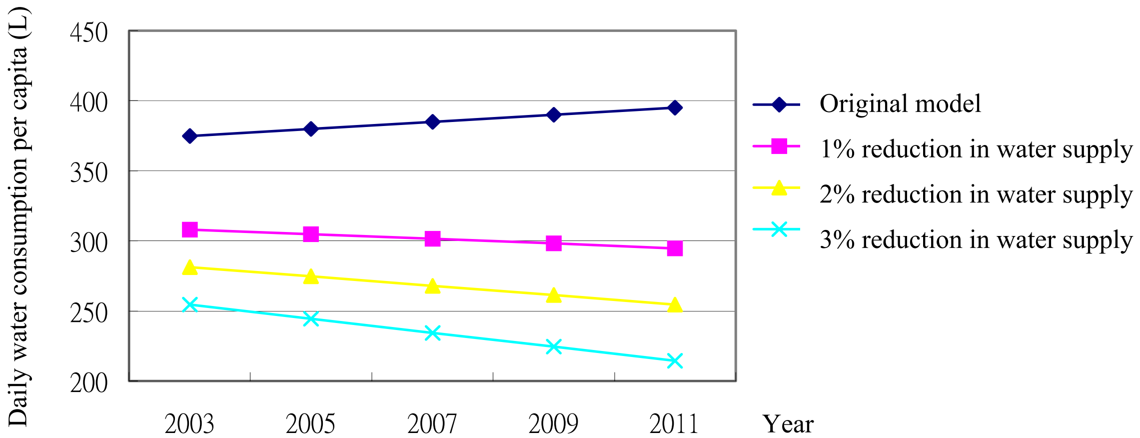

Figure 18. Daily water demand simulation

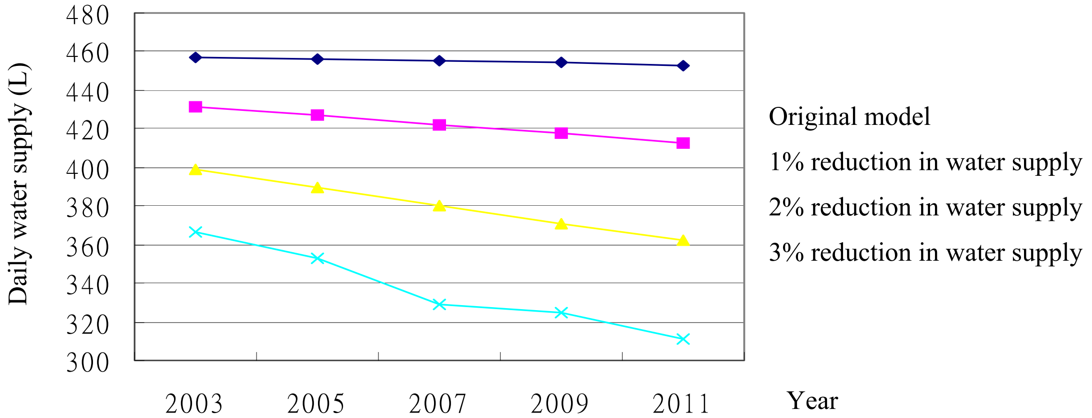

Figure 19. Daily water supply simulation

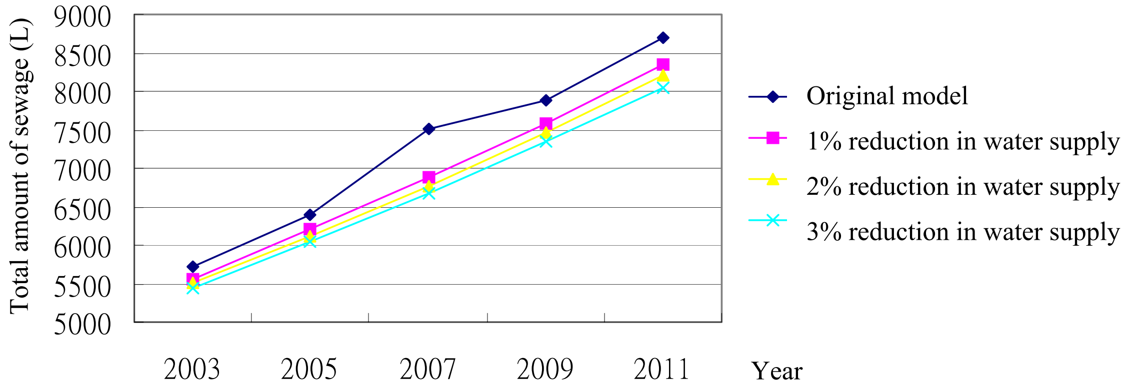

Figure 20. Total amount of sewage simulaton

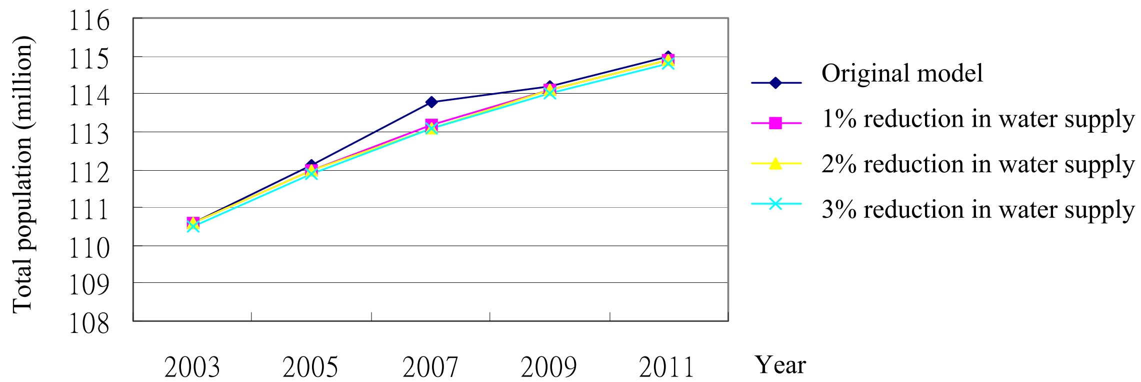

Figure 21. Total population simulation

Apart from the changes in daily water consumption per capita, decrease in water supply seems to have contrasting effects on total population and total amount of sewage. That is, lower water supply has a slight negative impact on total population but significant enhancement in sewage treatment. Thus, simulation analysis of different strategies can help policy-makers to decide on an optimal management that would create a win-win situation for all.

To maintain constant sufficient water resources for sustainable development requires not only increase in water storage capacity of reservoirs and protection of water sources, but also demands more thrifty water consumption habit. The 3R approach – reduce, recycle and reuse should be adopted. Reduction in water use can be achieved by installing facilities that saves water. Rainwater can be collected, stored and filtered for use in everyday life. Similarly, wastewater can be treated and recycled as non-drinking water. Efforts should be made to protect and maintain both the quality and quantity of water resources in order to meet the basic daily needs of the population.

Life-supporting facilities such as electricity, gas, water, drainage, waste disposal and telecommunications are key elements for advances in modern society. The government should support developers in providing these facilities in pursuit of a comfortable urban living environment. At the same time, there should be efficient management of these public utilities and social services for the benefit of the population. Supporting systems for monitoring, replacement, reporting, as well as repair and maintenance should also established to achieve the best economic value of the life-supporting system.

Conclusions and Suggestions

Conclusions

Strategies for enhancing the disaster prevention system of Taichung City should include the following.

1. Provide better training for people in disaster prevention and mitigation through courses and drills to enhance their confidence and ability in responding to disasters:
   This not only can help reduce casualty, but also keep population growth within control, thus achieving effective management of population distribution, balancing regional development, and preventing overexploitation of resources.
2. Increase green area and open space as well as enhance their proper utilization as specified refuge locations to ensure adequate supply of shelter during disaster outbreak:
   This adds not only comfort but also security to the urban living environment both at ordinary times and in times of disasters.
3. Strengthen the life-supporting system to meet the basic needs of urban living:
   It is also important to educate the public on more efficient use and management of natural resources, in particular water, through reduce, recycle and reuse. Proper monitoring, replacement, report as well as repair and maintenance systems should be established to minimize possible interruption or suspension of supply.
4. Promote the development of precision and information industries that involves advanced technology and causes little environmental pollution:
   Efforts should also be made to increase facilities for waste disposal and sewage treatment so as to reduce environmental pollution.

Suggestions

Suggestions for future research are as follows.

1. Enhance the completeness of the model:
   One of the problems in model formulation is that the characteristics of the harmful effects of disaster cannot be qualitatively or quantitatively measured. This undermines the complete formulation of the causal loops in the system. The completeness of the model should be improved to meet the diverse and multi-dimensional nature of the study on disaster prevention.
2. Conduct comparative studies from different perspectives:

This study focuses on the effects of disaster on the future development of the city as a whole from a macro perspective. It would be interesting to conduct similar studies on disaster prevention from a microscopic point of view and perform simulations on a shorter time scale.

3. Promote and apply system dynamics:

A system for managing the database of the urban spatial structure of an urban disaster prevention can be established using the GIS and remote sensing technology. This system can offer insight into a reasonable urban spatial structure and a safe living environment, thus providing a scientific basis for strengthening and improving the urban management strategy.

References

1.Architecture and Building Research Institute (ABRI), 1999, Survey Report of 921 Earthquake Disaster, Ministry of the Interior, Taipei.

2.Chiang, W. and Jin, L., 1992，The Counter Measures for Urbanization Integrated Disaster in China, Chinese Construction Industry Publisher, p.94.

3.Chen, C., Zheng, X., & Chang, W. 2004, The Study of Crustal Shear Wave Anisotropy Associate with 1999 Chi-Chi, Taiwan, Earthquake, Institute of Seismology, National Chung Cheng University.

4.Forrester, J. W., 1969, Urban Dynamics, The M.I.T. Press, Cambridge, Massachusetts.

5.FEMA, 1990, Multi-hazard Loss Estimation Methodology (HAZUS-MH), NIBS, Washington D.C.

6.HPS, 2000, STEILA and STELLA Research: An Introduction to Systems Thinking, High Performance Systems, USA.

7.Ho, Y.F. & Lu, C.H., 2004, Dynamic Simulation Model for Urban earthquake Disaster Prevention System, Working Paper No.11, pp.89-90, GSAU Chaoyang University of Technology.

8.Kaji, H., 1988, A Conceptual Model for Predicting Long-Range Effects of the Forthcoming Kanto Earthquake, Proceeding of International Seminar on Regional Development Planning for Disaster Prevention and UN Centre for Regional Development, pp.157-161.

9.Kobuna, K., 2000, Enhancing the Public’s Awareness towards Disaster Mitigation and Education for Disaster Prevention.

10.NCRE, 1997, HAZ-Taiwan, National Science Council, Taiwan.

11.Ossenbrugen, P.J., 1984, System Analysis for Civil Engineers, John Wiley and Son, USA.

12.Smith, K. 1993, Environmental Hazards: Assessing Risk & Reducing Disaster, London, Routledge.

13.Spudich, P., Guatteri, M., Otsuki, K., & Minagawa, J., 1998, Use of Fault Striations and Dislocation Models to Infer Tectonic Shear Stress During the 1995 Hyogo-Ken Nanbu

(Kobe) Earthquake. Bulletin of the Seismological Society of American, Vol. 88(2), pp.413-427.
14.Sterman, J., 2000, Business Dynamic: Systems Thinking and Modelling for a Complex World, McGraw-Hill, pp.41-81.
15.Setiana, A., 2000, Earthquake Disaster Preparedness and Reduction in Indonesia.
16.Urban and Housing Development Department (UHDD), 2005, Urban and Regional Development Statistics, Council for Economic planning and Development, Executive Yuan.
17.Wang, W. & Chen, Y., 2004, Evidence of a Fault Value at the Rupture of the Chelungpu Fault (Chi-Chi Earthquake) in Taiwan 1999, IAG, National Chung Cheng University.
18.Wang, H.F., 2004, Multicriteria Decision Arralysis, Tinglung Book Co., Taichung, pp.303-304.
19.Yeh, J. S., 2000, Simulation of earthquake scenarios and loss assessment, Science Development, Vol. 27, No.3, pp.260-268.