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Simulation Analysis for Evaluation of Flood Control Measures on Urbanization Process

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Abstract

In general, the enhancement of land use is promoted by the projects for infrastructure in order to increase the regional stability. Flood control is one of the historical and large-scale measures. But it is difficult to indicate the degree of its contribution to the stabilization of the regional environment. In this study, Regional Dynamic Model with the backward integration on System Dynamics Modeling is proposed in order to evaluate the effect of the flood control to the land enhancement. The empirical results show that regional population depends on the flood control by application of the long-term simulations.

Key Words: Regional Dynamic Model with Backward Integration, System Dynamics, Land Development, Effectiveness of Flood Prevention, Scenario Analysis, Regional Stability.

1. Introduction

In some cities land use has been advanced in the areas which have the worse physical conditions, for instance, low lying area, weak-conditional land and flood-prone areas. In such cities it has become important to build regional planning model which has interrelation between the countermeasures against the disaster and land use policies. However it has become difficult to evaluate the degree of contribution forward the stability of regional living environment by the enhancement the infrastructure or, for instance, flood control measures and it is because of the following viewpoints :

(1) It is difficult to identify the complicated structure relevant to several factors not only of safety but also convenience, accessibility and amenities. The comprehensive structure on regional activities must be considered as the first step to build the model.

(2) Considering regional stabilization which is defined as the satisfactory basic condition of living environment. It is difficult to extract the identified factors as only the attributes of safety, because there exists not only the direct countermeasures but also the indirect influences like foundation problems, underground water, storage capacity of park area and so on.[1]

(3) It is hard to establish the standards and indices in order to indicate the effectiveness of flood control.

(4) It is difficult to decide the analytical method corresponding to the regional dynamic activities.[2]

From these viewpoints, the objective of this study is to establish the analytical method and procedure to be able to reproduce the long-term regional development, in particular, having interrelationship with flood control project and advanced land use, in terms of the dynamic simulation model.

In the analytical method, the backward integration technique of System Dynamics is introduced by combination of several support systems.

The conditions of model building are as follows:

(1) The more the regional stability, for instance, given by inhabitability, employment opportunity and safety together is raised, the more the living space is advanced.

(2) The causal factors which have influences on the regional development and under go change with respect to time in terms of their structure basically but only by their quantitative variation.

(3) The other factors except for the introduced factors of the model are considered to keep the relationship between each other and they remain potential, even if they undergo selfchange.

(4) The model can reproduce the long-term regional activities and provide at least the minimum data and informations necessary for analysis.

2. Method and Procedure

(1) *Analytical Procedure*

The procedure of analysis is shown in Figure 1.

The analysis is carried out using regional dynamic model in order to solve such problems as mentioned above.

The regional dynamic model is composed of; land use sector, flood-hazard and flood control sector and population sector broadly in order to identify the interrelationship between the change of land use and flood control measures.[3] The basic regional dynamic model is simulated based on the data from 1960 to 1980 using the System Dynamics technique. The support system is also considered as the control sector of simulation.[4,5] In this analysis the KSIM is introduced to

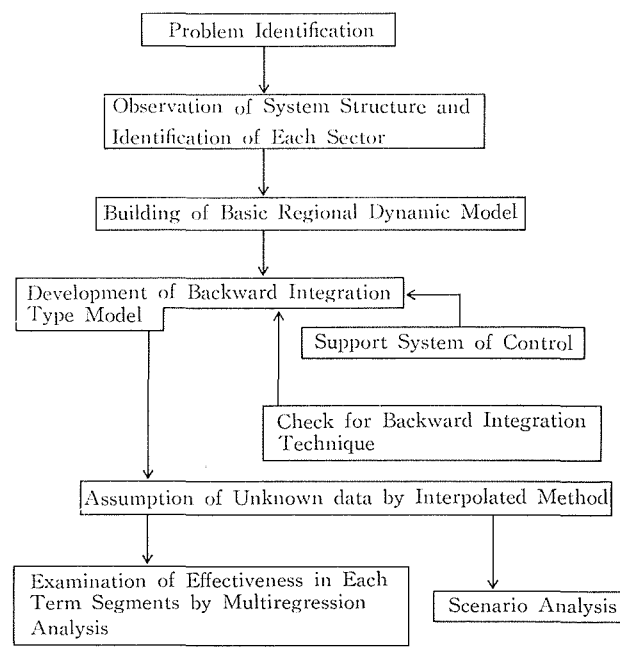

Figure 1. Procedure of Analysis.

decide interrelating multiplies given exogenously.[6] The backward integration of regional model is enforced based on those basic interrelated structure. In the case of the backward integration of System Dynamics, as the state variables of System Dynamics includes in the feedback systems, the problem of error should be solved.[7,8] Finally, the effectiveness of flood control stock is examined using several scenarios.[9,10]

The effects on regional development is indicated by means of the multiregression analysis using data which are assumed by SD simulation interpolatively.

(2) *Problem Identification*

The urbanization is interrelated to the developments reflected by socio-economic activities at that time and, in particular, interconnected with the increase of regional population even if the time lag exists. In such municipalities it is important to examine the long-term effect of flood control measures as typical living environmental measures by model structuring of the urban functions and simulating the dynamic change of the urban system.

The necessity of the analysis in urbanized and inundated area is arranged as follows :

(1) It is difficult to evaluate the contribution to the stability of regional living environment independently, because this exists among many other factors latently.

(2) It is important to consider the history of advanced land use in the developed area, as the worse geological and geographical conditions in developing area must be overcome.

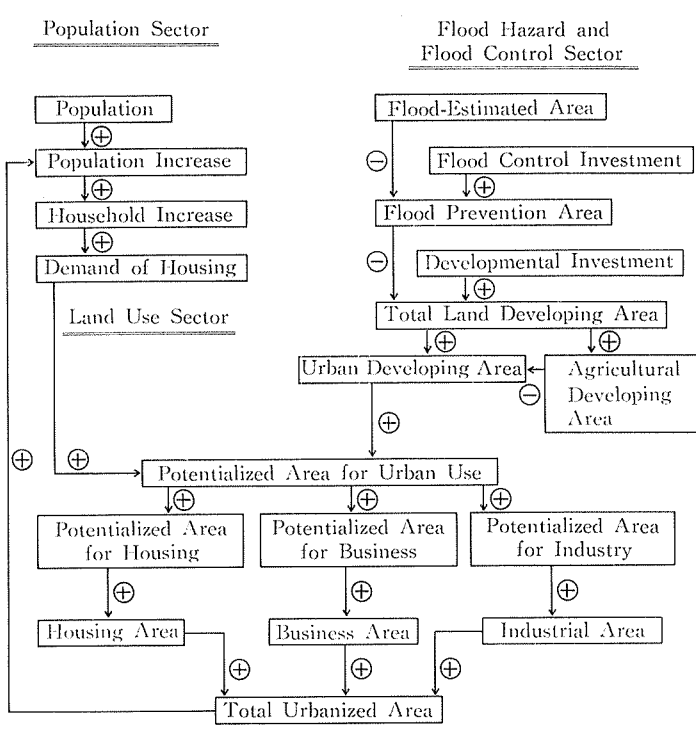

Figure 2. Cause-Efiect Loop of Basic Regional Dynamic Model.

(3) It is easy to get the information and data following the dynamic change of land use because of the recent advancing land use.

(3) *The Building of Basic Regional Model*

The regional dynamic model is composed of three subsectors as follows:

a) Population Sector... This sector gives the variables of population, population change, number of household and demand of housing as the indices which indicate the regional activities.

b) Land Use Sector... In this sector, the agricultural area, the housing area, the commercial area and the industrial area are given and the interrelationship between those variables and land use transfer are considered. The investment of land development required for such infrastructure and the investment of flood control are also introduced.

c) Sector of Flood Damage and Flood Control... The flood projected area is estimated as the land equipped fully with flood control investment assuming the flood prone areas from the regional hydrological informations.

The basic system structure of the model is shown in Figure 2 by the cause-effect loop.

(4) *Support System for the Control*

It is necessary to give the parameters exogenously for verification of the multipliers of the housing area, the commercial area, the industrial area and the agricultural area. These parameters are the variables depending on time and are given by table functions.

Thy are treated by KSIM which is a kind of simulation techniques for policy-making.

The states of those parameters are defined as $m(t)$:

$$m_i(t+\Delta t) = m_i(t)^{p_i(t)}, \qquad i = 1, 2, \cdots, n, \tag{1}$$

$$P_i(t) = \frac{1+\Delta t \ |\text{sum of negative impacts on } m_i|}{1+\Delta t \ |\text{sum of positive impacts on } m_i|}. \tag{2}$$

Equation (2) is calculated by the interrelationship matrix which is obtained from positive and negative impacts on the state variables. When the negative impacts are greater than the positive ones, $P_i > 1$ and x_i decreases; while if the negative impacts are less than the positive ones, $P_i < 1$ and x_i increases. Finally, when the negative and positive impacts are equal, $P_i = 1$ and x_i remains constant.

Equations (1) and (2) describe the solution of the following differential equation:

$$\frac{dx_i}{dt} = -\sum_{j=1}^{N} a_{ij} x_i x_j \ln x_i. \tag{3}$$

(5) *Model Transfer to the Backward Integration Type*

System Dynamics Technique is the model-building to aim the cause-effect relationship of the system components. Therefore, excellent insight is required in the

case of many events, because the model reliability is dependent on the ability to observe system behavior by human subject. The method to confirm this reliability is to verify the model adequacy comparing with the behavior of real system. In particular, the modeling type depended on the system structure has priority over the information available for the determination of cause-effect from the data obtained rather than the determination of parameters. That is, this model has lack of data essentially. It is necessary to verify system behavior of level variables which reflect the state of system in the past in order to increase the model reliability.

In this analysis, firstly, the effectiveness of forward integration model is examined with the existing data in the confirmable simulation term.

This model is the basic regional dynamic model as mentioned above.

Second, the backward integration having time returns inversely is obtained by transferring the basic regional dynamic model inversely. This new model has the simulation technique of the inverse-time integration without changing the system structure of basic regional dynamic model. It has also a role to interpolate historical data.

This analytical method is used in order to corroborate the System Dynamics model and to examine the discussion of model adequacy. Moreover, it has the advantages to make reappear the historical facts.

The meaning of the backward integration is considered as follows:

The general dynamic models may be defined as sets of first order differential equations:

$$\frac{dx_i(t)}{dt} = f\left(x_i(t) + u_i(t)\right),$$
$$x_i(t_0) = x_{i0}. \qquad (3)$$

where x_i represents system state variables of component i, u_i is the exogenous elements and x_{i0} is the initial conditions.

In all cases of practical interest, system equation (3) has a unique solution through initial conditions. If a dynamic system is observable, then its starting point can be recovered. A sufficient condition for observability is that all the elements of the system state vector should be accessible. Since, for computer simulation models, internal states are accessible, these models can be, in principle integrated backwards. But the dynamic models of social systems are usually complex enough so that closed-form analytic solutions do not exist or cannot be found. In this case, numerical integration is used to recover approximate system trajectories. Numerical integrations are corrupted by two sources of error- round-off error due to the finite capacity of digital computers, and truncation error arising from the particular integration scheme used. The importance of these error for solution accuracy depends on the stability properties of the model being integrated. Stability of dynamic models is very different in forward than in backward integration. These models are not only dynamic but feedback dynamic consisting of clusters of positive and negative feedback loops. By asymmetry of feedback loop structure in backward vs. forward integration stability, these models have stable paths for forward evolu-

tion despite persistent, small perturbations of the scale of round-off and truncation errors, but have unstable paths for backward motion.

The element of structure that allows dynamic systems to tolerate small disturbances is the negative feedback loop. Negative loops are deviation compensating. In forward integration a negative loop is asymptotically stable because of reduction of the discrepancy between a desired and an actual value for a state variable. With the direction of time inverted, however, stable negative loops become unstable positive loops, loops that reinforce deviation.

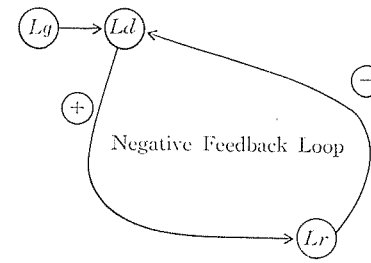

Figure 3. Backward Integration Including Feedback.

Simplified equations for the negative feedback loop in Figure 3 are

$$dLd(t)/dt = Lg(t) - Lr(t) + \xi(t)\,,$$

$$Ld(0) = L0 + \eta\,,$$

$$Lg(t) = \alpha \exp(\beta t)\,,$$

$$Lr(t) = Ld(t)/\gamma\,.$$

Here, $\xi(t)$ and η represent the errors introduced respectively by imperfections in numerical integration and in specification of initial values. α, β, γ are constants.

Equation (5) have an analytic solution :

$$Ld(t) = \exp(-t/\gamma)\Big[Ld(0)+\eta\Big] + \exp(-t/\gamma)\int_0^t \exp(s/\gamma) \Big[Lg(s)+\xi(s)\Big]\,ds\,. \tag{6}$$

The terms $\exp(-t/\gamma)$ show that during numerical integration small errrors corrupting the initial value and the variable $Lr(t)$ and the variable $Lg(t)$ are rapidly forgotten. In order to accomplish a backward integration, the sign of a model's differential equations are inverted.

For the equation (5), in backward motion is increased by the variable $Lr(t)$ and decreased by the variab'e $Ld(t)$.

$$dLd(t)/dt_{\text{Backwards}} = -Lg(t) + Lr(t) + \xi(t)\,. \tag{7}$$

The solution to the backwards system is

$$Ld(t) = \exp(t/\gamma)\Big[Ld(0)+\eta\Big] + \exp(t/\gamma) \int_0^t \exp(-s/\gamma)\Big[Lg(s)+\xi(s)\Big]\,ds\,. \tag{8}$$

Equation (8) includes $\exp(+t/\gamma)$ terms. Now small errors in initial condition specification and in the calculation of the rates of flow will be augmented over time. For example, after ten years, the exponential term has a magnitude of e.

This implies the main source of instability in backward projection of dynamic

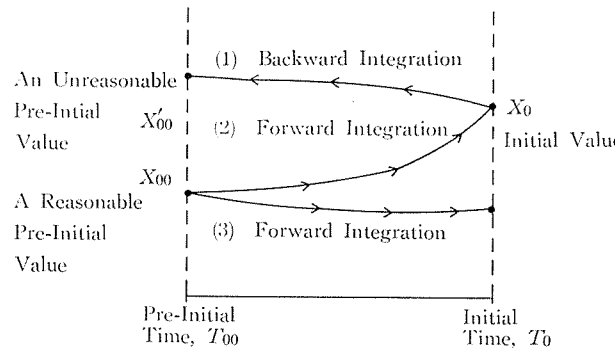

Figure 4. Possible Results from Retrospective Validation Tests.

models. That is, negative loops played backward act as positive loops and compound integration error. The solutions of the state variables which have negative feedback loops must be paid attention to reduction of error accompanied by time inverted.

It is necessary to carry out backward integration considering both structural stability and integration stability as stated above. The structural stability depends on the reliability of the model of forward integration type, whereas the accuracy must be raised by the following technique as for the integrating stability.

Three cases of backward integration are considered as shown in Figure 4.

a) Backwards integration... a backward integration from initial value x_0 indicates an unreasonable trajectory for the pre-initial period. Path 1 may point to the legitimate predecessor state of the model, or it may be a spurious result.

b) Forward integration... Path 2 and 3 are possible outcomes of forward integration from the sought for pre-initial state x_{00}. Since forward integration is stable, a result like path 2 or 3 is nonspurious. A result like path 2 shows the model to behave reasonably for the pre-initial behavior. A result like path 3 shows unreasonable pre-initial behavior. In this last case, the model fails a retrospective test.

In this analysis the general case is based on the Path-1 which is unknown the unreasonable pre-initial value.

The problem in the case of Path 1 is the instability of simulation mentioned above. There is not an complete method to remove the instability but can be represented the range of error by the interrelationship between time interval of simulation and change of state. As a example, The DYNAMO level equations of population in the regional dynamic model with basic type and backward integration type are defined as follows:

Basic regional dynamic model:

$$PO.K = PO.J + (DT)(IPN.JK - DPN.JK + SMP.JK)\,, \qquad (9)$$

where $PO.K$ is the system state of population at time K; $PO.J$ is the system state at the preceding time step, J; DT is the integration time step.

Regional dynamic model with backward integration:

$$PO.K = PO.J + (DT)\left\{-(IPN.JK - DPN.JK + SMP.JK)\right\}, \qquad (10)$$

when the Rate equations are

$$IPN.KL = PO.K/\tau 1\,,$$

$$DPN.KL = PO.K/\tau 2\,, \tag{11}$$

and $$SMP.KL = PO.K/\tau 3\,, \tag{12}$$

where τi is the system time constant of the component i. Equation (9) and (10) are transferred as

$$PO.K = PO.J + (DT)\left\{\pm PO.J(1/\tau 1 - 1/\tau 2 + 1/\tau 3)\right\}. \tag{13}$$

The part of term in (13) is

$$(1/\tau 1 - 1/\tau 2 + 1/\tau 3) = 1/\tau\,.$$

Equation (13) can be transferred as

$$PO.K = PO.J + (DT)\,(\pm PO.J/\tau)\,. \tag{14}$$

This equation is illustrated by the following continuous system :

$$PO(t) = \pm PO(t)/\tau\,;\ PO(t) = PO_0\,. \tag{15}$$

The plus sign applies for a positive feedback (exponential growth) system with the minus sign indicates a negative feedback (exponential goal-seeking) system. The analytic solution to (15) is given by :

$$PO(t) = PO_0 \exp(\pm t/\tau)\,. \tag{16}$$

If the time t, is divided into n intervals of length DT, $t = n(DT)$, the above exact solution after n time steps become :

$$PO_n = PO_0 \exp\left(\pm n(DT)/\tau\right). \tag{17}$$

The consequences of solving (15) using a rectangular integration scheme can be assessed by applying the definition of the derivative to (15) and rearranging :

$$PO'_{n+1} = (1 \pm DT/\tau)\, PO'_n \tag{18}$$

If the system is initialized at PO, n stage of (18) yields :

$$PO'_n = (1 \pm DT/\tau)^n PO'_0\,. \tag{19}$$

A comparison of (17) with (19) reveals that for all $DT/\tau < 1$, rectangular integration underestimates the solution to both positive and negative first order systems. In effect the numberical solution will appear to lengthen the time constant for positive feedback systems and shorten it for negative feedback systems. This modification of the effective time constant becomes more pronounced as DT/τ approaches unity.

A quantitative grasp of the situation can be obtained if the equivalent time constant τ', associated with the numerical solution as the time at which the solution reaches a value of : $PO'_n = PO_0 \exp(\pm 1)$, is defined. Using (19), it can be shown that the equivalent time constant is related to the actual time constant through the relationship :

$$\tau'/\tau = \pm(DT/\tau)/\ln(1 \pm DT/\tau)\,. \tag{20}$$

By means of (20), it is seen that the variation in the simulated system's time constant can be kept below about 5% if $DT/\tau < 1/10$.

As analysed above, the limitation of integration error through a suitable choice of DT is a very simple matter-one merely reduces DT until there is no significant effect in the computer simulation.

(6) *Evaluation of Project Impact by Multiregression Analysis*

The impact of the past projects are calculated by multiregression analysis using the historical interpolated data obtained by the regional dynamic model.

In this analysis, the interrelationship between regional population and other explanatory variables are verified in each age and divided by simulation term appropriately.

(7) *Scenario Analysis*

The transfiguration of regional stability are made to reappear using several scenarios, while the investments of flood control are changed.

3. Results of Simulation

Simulations are introduced by the technique mentioned above. The study region is the Shiroishi-ku in Sapporo City. The basic regional dynamic model was identified the data during the period from 1960 to 1980.

Next, the simulations were run by transferring the established model into regional dynamic model for backward integration from 1980 to 1874 inversely.

The informations used for identification of long-term backward integration were limited to the data of regional population and regional land use which were represented once in every several years.

The relationship between these two models is illustrated in Figure 5. Table 1 indicates the comparison of real values and estimated values of population and land use areas.

In Table 2 the historical flooded areas were assumed from the current flood-estimated area. This estimation can be considered as the effects of flood control.

These results are summarized as follows:

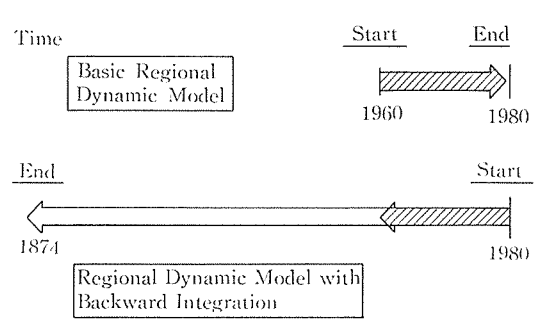

Figure 5. Simulations of Two Models.

Table 1. Simulation Results of Backward Integration

Year	Population		Agricultural Area		Urban area	
	Real	Estimated	Real	Estimated	Real	Estimated
1980	2280	2280	913	913	1477	1477
1970	1575	1612	1845	2080	723	715
1960	730	753	2549	2742	286	290
1950	197	200	2340	2531	91	61
1949	102	117	3362	3239	59	52
1930	84	83	3097	3016	34	29
1920	55	57	2997	2917	22	17
1910	45	44	2897	2818	10	7
1900	34	41	2606	2634	3	3
1890	13	13	1430	1394	2	2
1880	5	4	190	272	1	1
1874	4	3	84	78	1	1

Population (×100); Agricultural area & Urban area (Ha).

Table 2. Estimated Values of Flood Hazard and Flood Control Sector

Year	Flood Estimated Area	Flow of Flood Prevention Area	Stock of Flood Prevention Area
1980	270	54	1425
1970	914	55	780
1960	1310	20	384
1950	1519	0	175
1940	1539	10	156
1930	1629	5	66
1920	1654	5	41
1910	1679	5	16
1900	1694	1	1

1) Every causal factors which decide the level variables on the regional dynamic model with backward integration can be estimated within the errors of more than 5% using variation of the time constant of 1/10. That is, the rapid increase of integrated errors do not appear.

2) The estimations of population and land use areas agreed with those historical data approximately. However, those are not very suitable in terms of the rapid urbanization.

3) The flood estimated area of the Meiji-era is assumed as 28% of total area subject to flooding in the result of the backward integration.

4) The result of assumed population increase is reflected by the influence of historical flood hazard by considering their interrelationship.

4. Impact evaluation of flood control and scenario analysis

As mentioned above, the results of simulation analysis clearly exehibits the several influences on the conditions of living environment, in other words, the regional stability.

In this section the effectiveness of some of the historical projects are considered more distinctly using some time segments divided into simulation years. The multiregression analysis is applied and the standard coefficients of regression are indicated as the indexes of contribution. The data used for the analysis are obtained fromthe simulation of the regional dynamic model with backward integration. The regional population, that is, the objective variable is explained with the other variables in this system. This is because the population change is considered as one of the most appropriate variables reflecting the regional activities.

Table 3 shows in each index in every term segment.

Finally the role of flood control projects are examined using several scenarios. The scenarios introduced in this model can be expressed as follows:

(Scenario-1)... In the case of no historical projects for flood control

(Scenario-2)... In the case of putting forward the start of flood control projects of the Taishou-era in the Meiji-era.

(Scenario-3)... In the case of raising the level of historical projects for flood control to double.

The results in the simulation analysis are shown in Table 4. The numerical values of this table are given by the indices represented the real data as 100s.

The results may be shown as follows:

1) In the first term segment from 1874 to 1912 the population was influenced

Table 3. Influences on Population by the Other Variables

Variables	Standard Coefficient of Regression			
	1st	2nd	3rd	4th
Stock of Flood Prevention Area	—	1.452	0.972	0.827
Agricultural Area	1.695	−0.143	−0.165	0.380
Housing Area	0.498	−0.892	0.252	1.492
Business Area	−0.724	0.475	−0.042	−0.980
Industrial Area	−0.472	0.045	—	—

Term Segments	Coefficients of Multiregression
The 1st Term (1874–1912)	0.965
The 2nd Term (1913–1945)	0.998
The 3rd Term (1946–1959)	0.998
The 4th Term (1960–1980)	0.999

Table 4. Results of Simulation due to Scenarios
(Estimated Value in 1980)

Variables	Number of Scenario		
	1	2	3
Population	95.3	102.7	113.0
Stock of Flood Prevention Area	0.0	118.9	207.6
Agricultural Area	91.7	107.7	108.3
Housing Area	70.0	108.9	140.2
Business Area	71.4	107.1	142.9
Industrial Area	66.4	110.7	147.5
Potentialized Area for Urban use	71.6	105.2	130.2

Real value in 1980=100

by the agricultural area more strongly. This means that the agricultural development contributed to the regional environmental stability. In the second term segment from 1913 to 1945 and the third term from 1946 to 1959 it was effected by flood-prevention area. And then in the last term segment from 1960 to 1980 it was influenced by housing area. These indicate that it has become imperative to rise the factors of urbanization. In other words, the urbanization has advanced rapidly on a continuous curve, but the factors having influences on are different in every term segment.

In such a situation the factors contributing for the regional stability depend the background of regional development activities. In particular, the flood control projects have contributed to the regional stability in this subject area much strongly. 2) The effect of the stock created by the flood control projects influenced the subject area symultaneously. In particular, the scale of projects and the speed to promote the projects have a greater influence.

5. Conclusion

In this study the adequacy of the method was confirmed in order to reproduce the long-term historical facts from the viewpoint of systems analysis. As a result, the backward integration of SD modeling was available to identify the complicated regional stability. Especially, it is necessary to examine the interrelationship among the regional activities and to find out the influences of the regional project such as the flood control measures having long-term effects. This analysis can be fruitful to do such evaluations.

In future, the model must be improved more accurately in order to fit for the real system, because this model is built by the simple frame to explain the regional activities.

The model simulations were calculated by the application program SDS and KHSPSS in Computer Center of Hokkaido University.

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