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World Continental Modeling Considering Water Resources Using System Dynamics

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Synopsis

This research assesses the severity of future water scarcity and its impact on the growth of human civilization through System Dynamics modeling of the world at regional level. Six sectors of activities are modeled in each continent to represent the human society. Continental interactions such as migration and trade are also modeled to express the synergy of activities among the various continents. Results of the model simulations from 1960 to 2100 show that water scarcity, unlike other limitations such as nonrenewable resources and persistent pollution, gives severe, detrimental problems within short delays after its occurrence.

Keywords: Continental Model, System Dynamics, Trade and Migration, GCM

1. Introduction

Currently, many countries in the world experience problems related to water resources. Droughts, water contamination and floods are only one of the most serious problems. One of the reasons is the mal-distribution of water resources even at small region. This problem is even worse in the less developed world, where, as an aggravation, water pollution has been a constant threat for society. It is obvious that problems are aggravated due to rapid population growth, unsustainable economic growth and massive urbanization. In the bulletin report by the Secretary General of the United Nation drafted at the environmental development summit held in Johannesburg, South Africa in August 2002, it was advertised that about half of world's population (3.5 billion people) may experience water shortage by 2025, and water related problems, such as ground water depletion and water pollution are expected to become even more serious. To avoid such world water crisis, it is imperative that concrete counter measures have to be taken in advance.

On the other hand, as available water resources are quite sensitive to climate change, the development of complete stable water resources systems based on sound hydrological cycles is not an easy task. As global warming is believed to affect the whole global hydrological cycle, it is forecasted that the serious global crisis related to water resources crisis might occur in the near future.

Moreover, qualitative aspect of water is also becoming gradually more important. Such as upstream and downstream issues related to waste water disposal from industrial and agriculture activities, which frequently result in the complete degradation of water resources for the downstream communities. Even though water is quantitatively available, water utilization may become impossible due to the pollution.

When considering water related problems, it is important to deal with water supply and water demand independently. These two issues are closely connected and related to each other, so that; they should be treated together, considering how changes of water resources distribution affect social activities (such as food production, economic development and migration). Moreover, it is important to understand how changes of social activities can affect water demand. Furthermore, because water is a finite resource, water related problem can become a crucial constrain for the development and continuation of human activities in the near future. Considering such close relationship between water and social activities, it is important to recognize the metabolic structure of the water resources systems as one of components of the socio-economic system.

System Dynamics (SD) is one of appropriate methods for analyzing hierarchic feedback structures and dynamic characteristics, which are always presented in socio-economic system. SD is a consecutive and dynamic model, which has the ability to handle feedback loop. Moreover, SD can easily handle the nonlinearity, which is frequently not easy to be quantified in other ways. Therefore, SD is an appropriate technique for long-term simulation.

In this research, the relationship between water distribution and socio-economic activities assuming a worldwide scale is analyzed through the development of a system dynamics based model. Works considering the world socio-economic system modeling using SD have been already carried out by Meadows *et al.* (1974, 1992) and Simonovic (2002). Meadows developed the world3 model which included socio-economic sectors without the direct consideration of water as a limiting factor. Simonovic developed the world water model which can be said to be an extension of Meadows' work, by introducing the water quantity and quality factors as important driven-forces of the system. Having the two previous models as basic start, the objective of the present research is to develop a world system dynamics model at the regional scale. Because of data and information availability, the regional scale as modeled unit is chosen to be handled in a continental level, with six main units representing continents, namely: North and South America, Europe, Australia, Africa and Asia. Fig. 1 shows the regional classification of the world.

The aim of research is to grasp the relationship between the socio-economic activities concerning the water demand and the water supply mechanism at the continental scale. Moreover, the model considers the mass transfer and migration between continents. The model consists of seven main sectors of activities, such as: population, capital, agriculture, nonrenewable resources, persistent pollution, water quantity and water quality. The simulation for future scenarios is carried out using GCM (Global Circulation Model) data as the input of water budget calculation for the available water estimation.

2. Water Budget Calculation Using GCM

This research takes into account the effects of possible future climate changes on available water resources through the introduction of simulation results from the Global Circulation Model (GCM) in water budget calculation. Monthly temperature and precipitation results from the HadCM2 climate change model developed at the Hadley Centre, Bracknell UK are used.

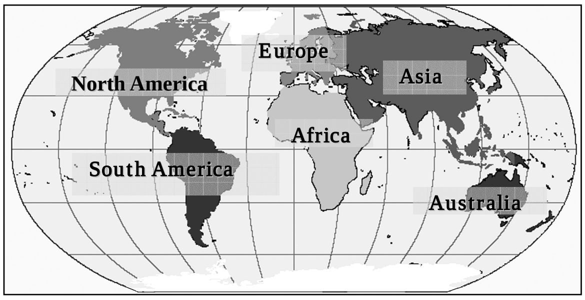


Fig. 1 World Division into six continents

Besides the reference scenario, two other scenarios in which CO^2 concentration is increased 1% annually, and both CO^2 and aerosols concentrations are increased 1% annually are tested. The Hamon method （Hamon, 1963） is chosen for the calculation of potential evapotranspiration. C.J.Vorosmarty (Vorosmarty *et al.*, 1998) compared the characteristics on accuracy or applicability among the 11 commonly employed methods for the calculation of potential evapotranspiration used in the global-scale water balance. They are compared whereby considering observed data of 679 locations in United States of America. From a statistical viewpoint, Vorosmarty found that the Hamon method has relatively small bias for different type of climate and vegetation.

The Water Balance Model (WBM) is used to generate spatially distributed monthly runoffs which are then used for prediction of the future water resources availability. The WBM also includes snow coverage process, which results in snow accumulation under -1.0℃ and snow melting when temperature is above -1.0℃. Observed runoff data from the International Hydrological Programme (IHP) is used for calibration and validation of the WBM.

3. Structures of World Continental Modeling

3.1 Basic Concepts of proposed System Dynamics

In this model, the world is treated as an aggregation of six continents, each having its own social and economical characteristics. Six sectors deemed most significant in representing human development are modeled in each continent. They are population (birth, maturation and death), agriculture (land development, land fertility, food production); capital (industrial and service outputs), nonrenewable resources (resources use and extraction), persistent pollution (pollution emission and assimilation) and water (water quality and water quantity). Exchanges of information and material among the continents are also considered. The interactions modeled are migration, trade of food, nonrenewable resources and industrial outputs, and foreign investments of services. Each sector of each continent is calibrated using data from 1960 to 1995 before integrating the sectors to form the entire model. The model is built and run from 1960 to 2100 at yearly time steps using STELLA, a graphics interface SD simulation software. Since the model is not a replica of the real world, some assumptions have to be made to justify the model structure. One assumption is the exclusion of socio-political issues such as war and religious conflict in the model due to the unpredictable psychological decisions involved. Also, although water is a renewable resource, accessible and usable water supply is assumed to be limited and its impact on development needs examination.

3.2 Trade and Foreign Investment

The trade mechanism of the industrial sector is considering being proportional to the import and export of manufacturing goods among continents. Moreover, foreign investment in service sector is including the exchange of service output across the continents. Both mechanisms which determine the volume of industrial output trade and service output for foreign investment are almost the same. Also the trade mechanism of migration, food and nonrenewable resources are almost the same. This section just focuses on the trade mechanism of the industrial output.

Fig. 2 shows the casual diagram of industrial sector. The governed equations determining the volume of industrial output trade are listed below;

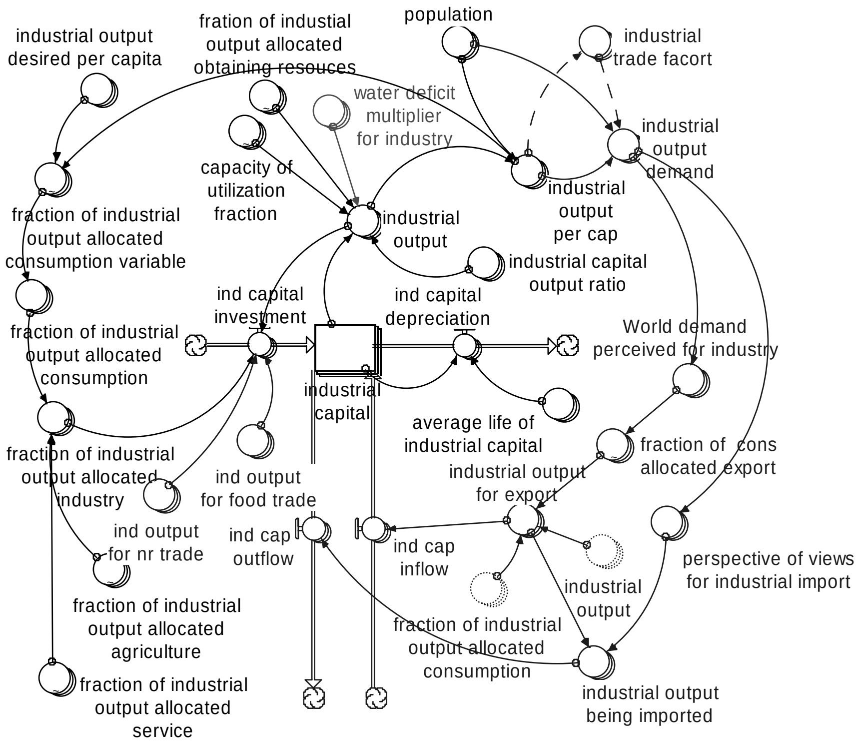


Fig.3 Casual Diagram of Industrial Sector

$$io\_for\_expo = ind\_out \times fioa\_con \times fr\_cons\_al\_expo \cdots (1)$$

$$io\_being\_impo(A,B) = io\_for\_expo(A) * \frac{POVs\_ind\_impo(A,B)}{\sum_i POVs\_ind\_impo(A,i)} \cdots (2)$$

$$W\_demd\_perc\_ind(i) = \sum_j ind\_output\_demd(j) - ind\_output\_demd(i) \cdots (3)$$

$$ind\_out\_demd = pop \times io\_per\_cap \times ind\_trade\_fact / 0.54 \cdots (4)$$

$$ind\_trade\_fact = IF(\frac{6 * io\_per\_cap(i)}{\sum_j io\_per\_cap(j)} > 1) THEN(1) ELSE(\frac{6 * io\_per\_cap(i)}{\sum_j io\_per\_cap(j)}) \cdots (5)$$

The demand of industrial output is defined based on the amount of industrial outputs that one is willing to consume. Fig. 3 shows the high correlation between GDP per capita and consumption per capita (demand per capita).

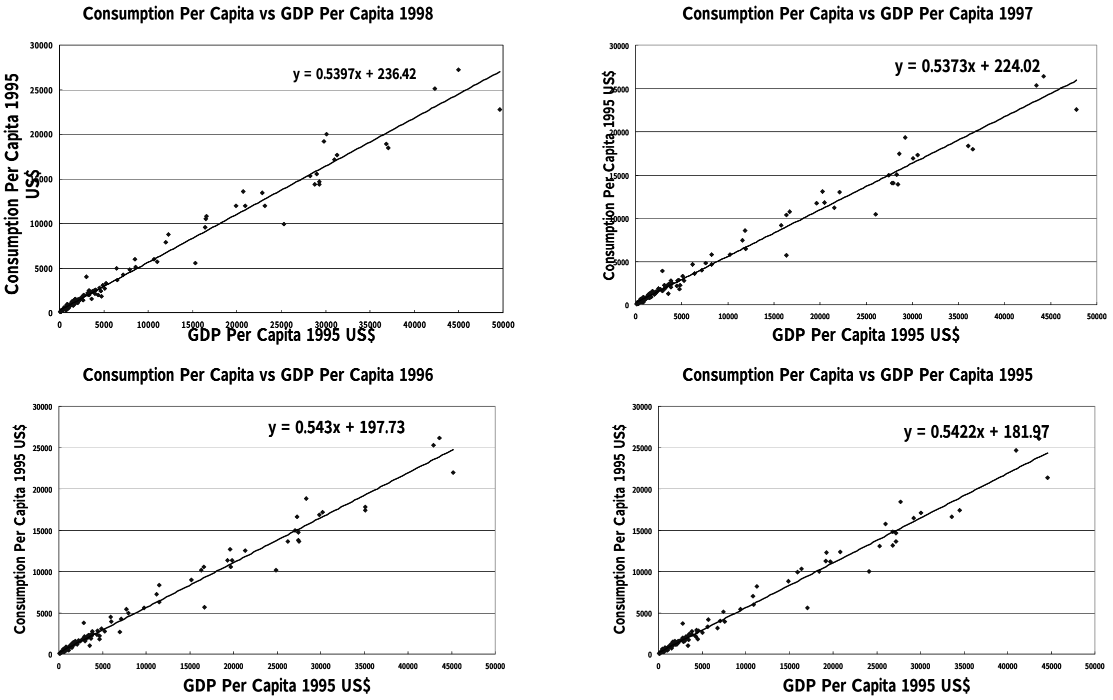


Fig. 3 Relation between GDP per capita and Consumption per capita

The coefficient of correlation for the conversion from GDP per capita (industrial output per capita) into consumption per capita (in eq.(4)) is equal to 0.54. Industrial trade factor are the components which restrict the intensive outflow of industrial capital by reducing apparent local demand of industrial output reflected to foreign exporters shown in eq.(5).

Perceived world demand is the summation of all foreign demands in eq.(3). There are many uncertainties related to how exporters react to the foreign market they perceived. Fig. 4 shows the fraction of local consumption exported by some countries with respect to world consumption. With reference to Fig. 4, the relationship between fractions of consumption output allocated to export (in eq. (1)) and perceived world demand *(W_demd_perc_ind)* is determined roughly as graphical function. The graphical function is calibrated to match the result of whole trade sub-sector and historical trade data. Export from all continents is distributed according to *perspective of industrial import (POV_ind_impo)* which is the bilateral relationship between any two continents shown in Table 1. Parameter (A,B), where B is the importing/invested continent and A is the exporting/investing continent, means how much continent B is willing to import from continent A relative to other exporting continents or to be invested by continent A relative to other investing continents.

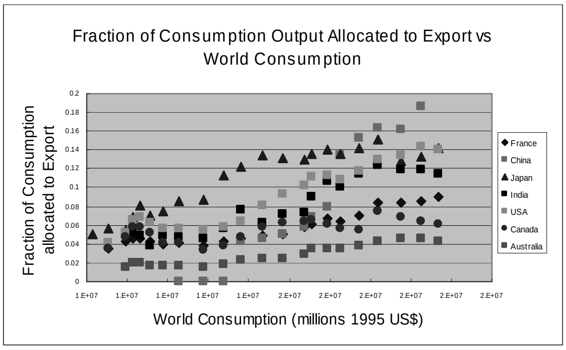


Fig. 4 Relation between World Consumption and Fraction of Consumption Allocated to Export

Table 1 is derived from the analysis of annual average volumes of imports of goods by some countries of the respective continents from known continental goods exporting sources. Parameters for foreign investment of service are set to be the same as that for trade of goods.

3.3 Effects of Water Resources Restriction to Other Sectors

In this model, the effects of water deficiency to population, food and industrial sector are considered. This section just focus on the effect to industrial sector. Water deficit multiplier (*ws_def_mlt_for_ind*) is defined as a restrictive factor for industrial output when industrial water demand exceeds industrial water withdrawal. Because of extensive range of industrial water usage, it is simplified the relationship between water deficit multiplier and industrial output as a linear relation as follows;

Table 1 Perspective of Views for Industrial Import (*POV_ind_impo*)

Importing/ Invested Exporting / Investing	Africa	Asia	Australia	Europe	N_America	S_America
Africa		0.4	0.14	1	0.14	0.14
Asia	0.22		0.13	1	0.9	0.13
Australia	0.1	1		0.625	0.625	0.125
Europe	0.5	1	0.125		0.75	0.575
N_America	0.125	0.75	0.125	1		0.75
S_America	0.04	0.4	0.04	0.7	1	

$$ws\_def\_mlt\_for\_ind = 1 - \frac{ind\_water\_demd - ind\_water\_wdraw}{ind\_water\_demd} \cdots (6)$$

3.4 Water Quantity Sector

The objective of the water quantity sector is to model the balance between water supply and water demand in each continent, and the effects of water deficiencies on the other sectors of activities. Water withdrawals are calculated from the volumes of agricultural, municipal and industrial activities. Three sources of water supply are considered: renewable water resources, water reuse and desalinization of sea water. Withdrawals of nonrenewable groundwater resources are omitted because data is only limited to certain water-scare regions, mostly Africa and Arab countries where such resources are exploited extensively. The deficit in water resources is then found by subtracting withdrawals from the supply volumes. Restrictive effects of water deficit are fed back to the respective sectors. This implies that growth will be retarded if there is a deficit in water resources, causing future demand of water to be reduced. The simplified causal loop diagram of the water quantity sector is shown in Fig. 5. Arrow with a "+" sign denotes reinforcing relation between the two linked components while arrow with a "-" sign means a restrictive relation between the linked components. Feedback loop is indicated by a curved arrow with a "+" or a "-" sign in it depending on whether it is a negative or a positive feedback loop. In this sector, there are three negative feedback loops as shown.

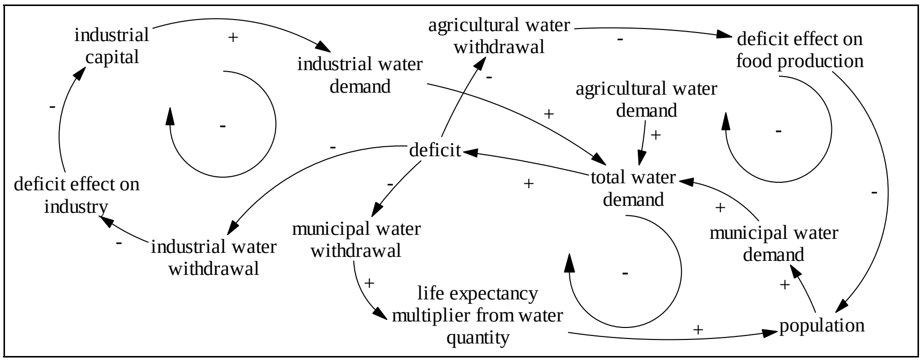


Fig. 5 Simplified Casual Loop Diagram of Water Quantity Sector

3.5 Water Quality Sector

Water quality is designed as parameters affecting human life-expectancy. A water quality variable called "life-expectancy multiplier from water quality" is statistically derived from the percentage of population that has access to improved sanitation and water supply in rural and urban areas. Definitions of improved sanitation and water supply follow the guidelines set by World Health Organization (WHO, 2000). It is found that the percentage of population with access to improved sanitation and water supply has the strongest correlations with industrial output per capita and renewable water resources per capita. Populations in richer regions and regions with abundant precipitation have better access to improved sanitation and water supply. The simplified causal loop diagram of the water quality sector is shown in Fig. 6.

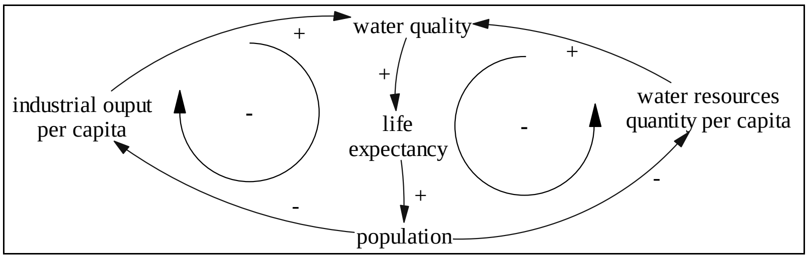


Fig. 6 Simplified Casual Diagram of Water Quality Sector

4. Simulation Results

4.1 Overall Development of the World from the Standard Run

The standard run is a simulation run of the model assuming that the current conditions remain the same. It is apparent that the results do not reflect the exact stage of the future world. The results are meant for comparisons with other scenario runs when changes to the model are introduced. Fig. 7 shows five important outputs representing the world development in a multi-axes graph. Unlike the results in World3 and WorldWater model whereby limits of growth and decline are sharp and prominent, a world divided into continents linked by trading activities give more attenuated development patterns. Irregular fluctuations in industrial output per capita and food per capita seen after 2015 are due to water resources shortage in certain regions of the world.

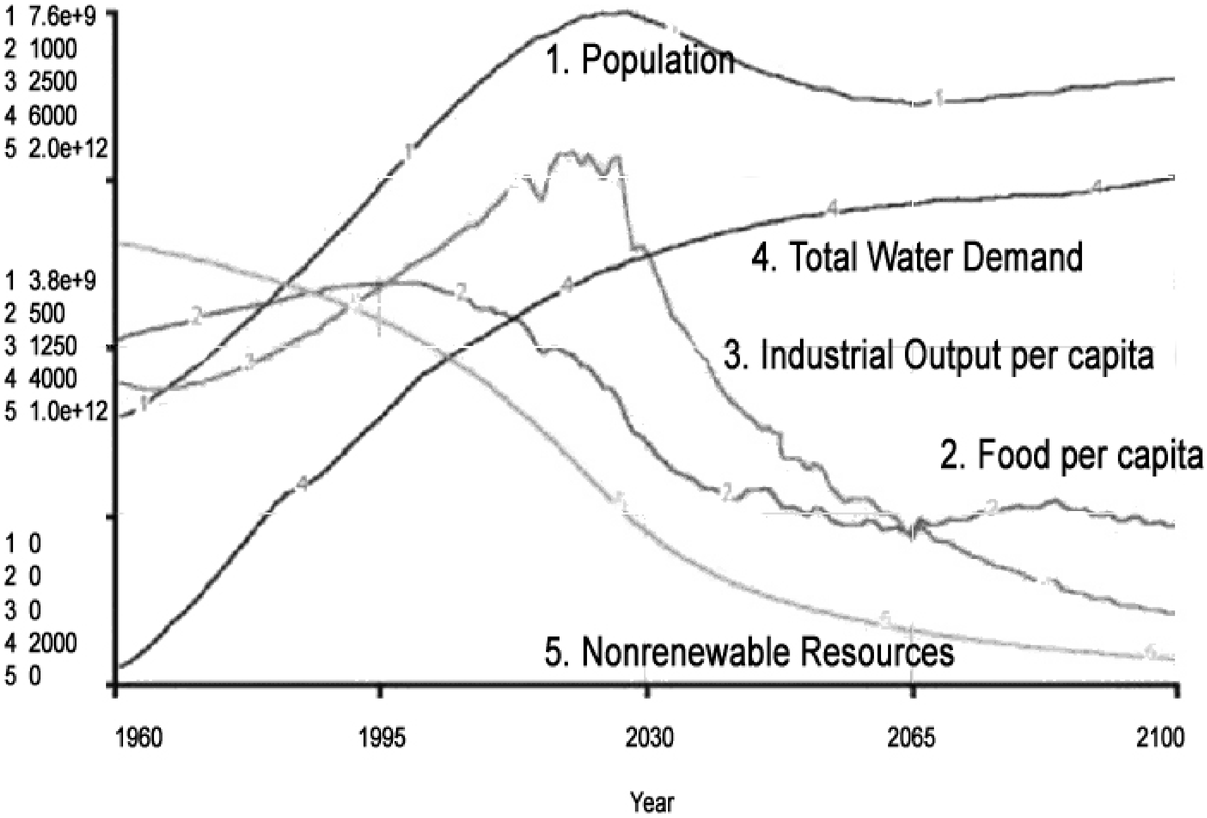


Fig. 7 Five important outputs representing world development: population; total water demand (km^3); industrial output per capita (1995 US$); food per capita (vegetable equivalent kg); nonrenewable resources (capita year at 1970 use-rate).

Fig. 8 shows the five important outputs representing Asia development in a multi-axis graph. From the Fig. 8, Asia has more than half of the world population. Population in Asia is forecasted to meet a maximum of about 5 billion inhabitants in 2020. Then, it starts to decline to 2.1 billion in 2100 due to the emergence of food shortage which starts from 2030. Food supply begins to climb from its trough at around 2060 due to the population decrease and food recovery processes which try to allocate industrial output into food production to sustain the human life shown in Line 2 in Fig. 8. Fluctuations shown in the results of industrial output per capita and adjusted food per capita are restrictive effects of water deficit in Line 2,3 in Fig. 8. Water shortage in Asia is predicted to occur from around 2010 in Asia.

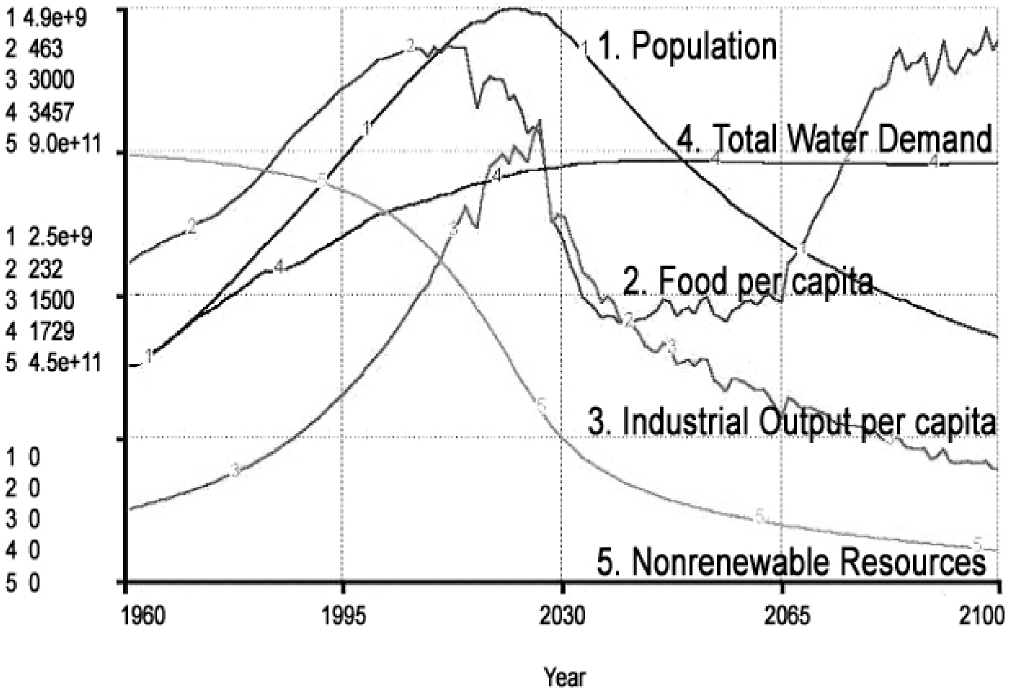


Fig. 8 Results of the Five Main Factors for Asia

Fig. 9 shows the the results of the water availability between water supply and water demand for the standard run. The zero in the vertical axis is indicated as a black bold line. Negative water availability means deficit of water resources. Water deficit is expected to occur by 2010 in Asia and by 2030 in North America. In Asia, this problem is not abated immediately despite the decrease in industrial development and population. This shows the difficulty of dealing with the problem of water scarcity.

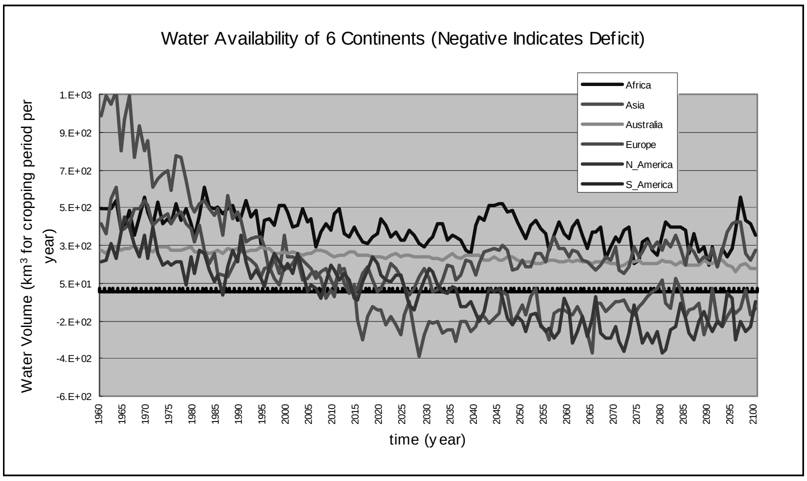


Fig. 9 Water Availability for the Six Continents

4.2 Continental Interactions

Results of material movements across continents can be examined to identify the major importing, exporting; and immigrating, emigrating continents. Results of net food imports are shown in Fig. 10. As shown in Fig. 10, fluctuations in the graphs are influences of water shortages on food production which lead to irregular trade patterns. Although water shortages occur only in Asia and North America in the standard run, their impacts on trade over all regions are seen. This shows that water scarcity has widespread effects on the world even when its occurrence is local.

4.3 Runs under Global Warming Scenarios

Besides the standard run using the reference GCM data, two GCM scenario results are used to examine the effects of greenhouse gases (GHG) on water resources and the human society. One assumes 1% per annum increment in CO^2 while the other assumes 1% per annum increases in CO^2 and aerosol.

Fig. 11 shows the results of the water balance between water supply and water demand for the six continents. Red line represents the results of the standard run, while Blue line represents the results of 1% per annum increment in CO^2.

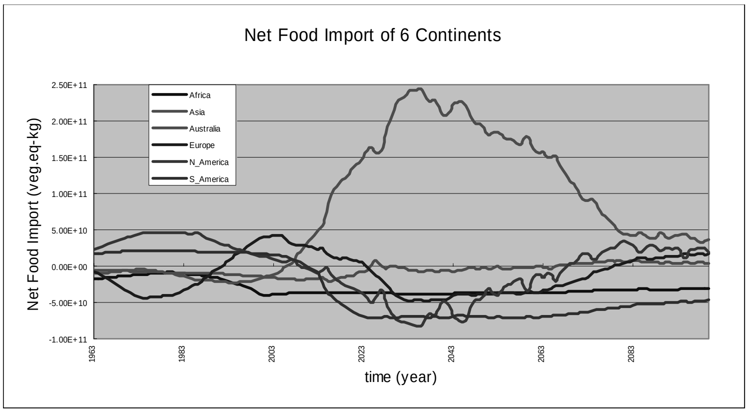


Fig. 10 Net import of food (import – export) of the six continents

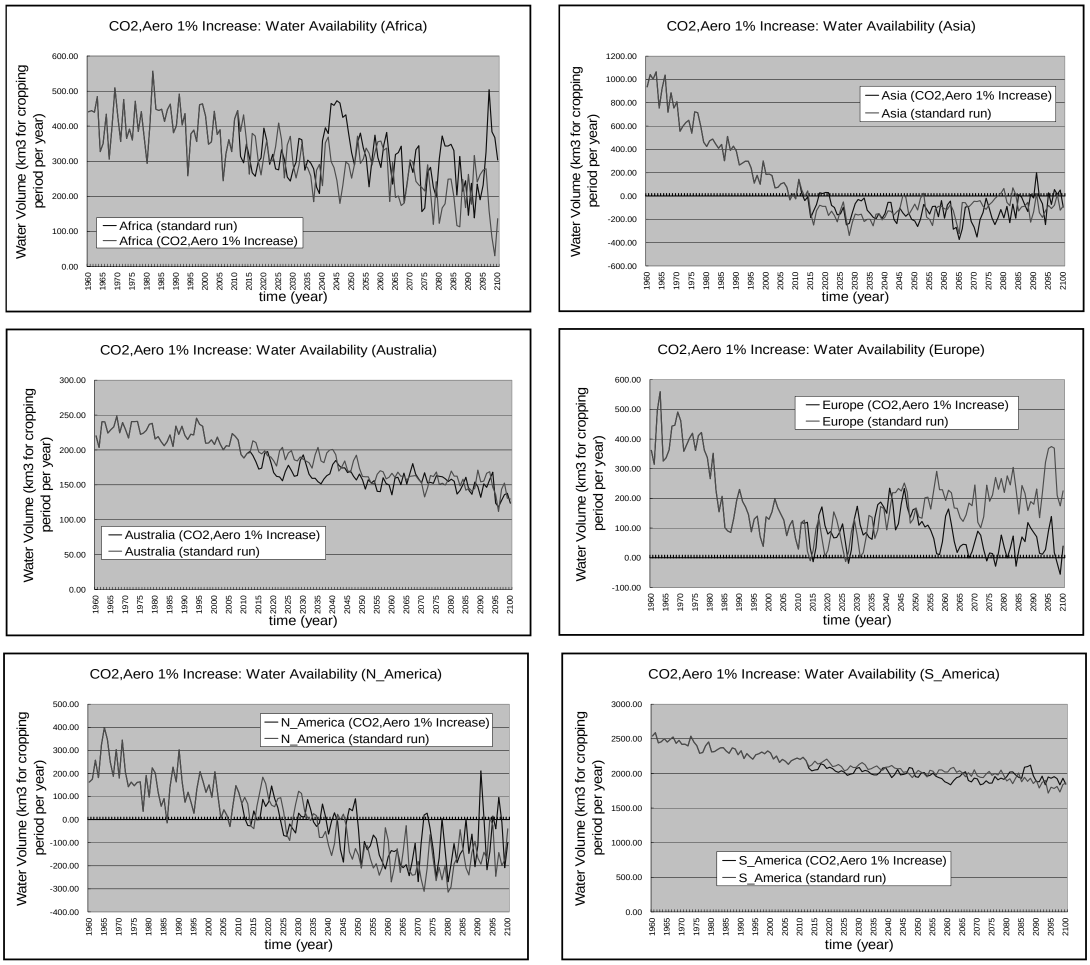
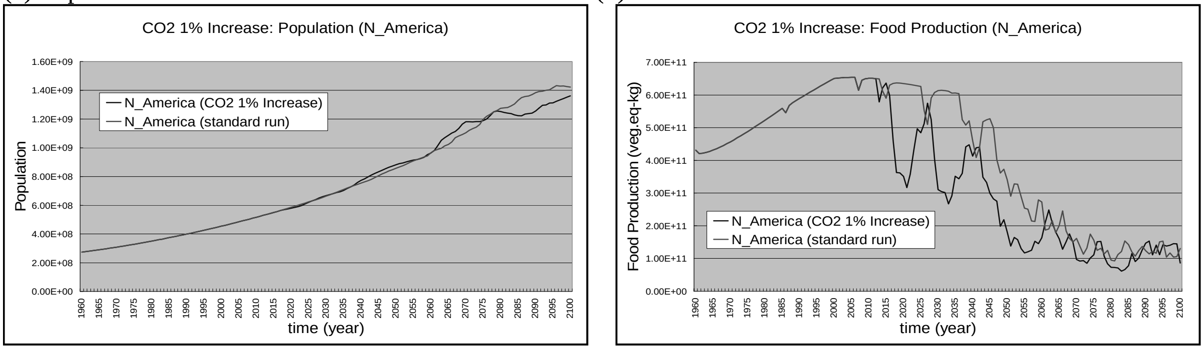
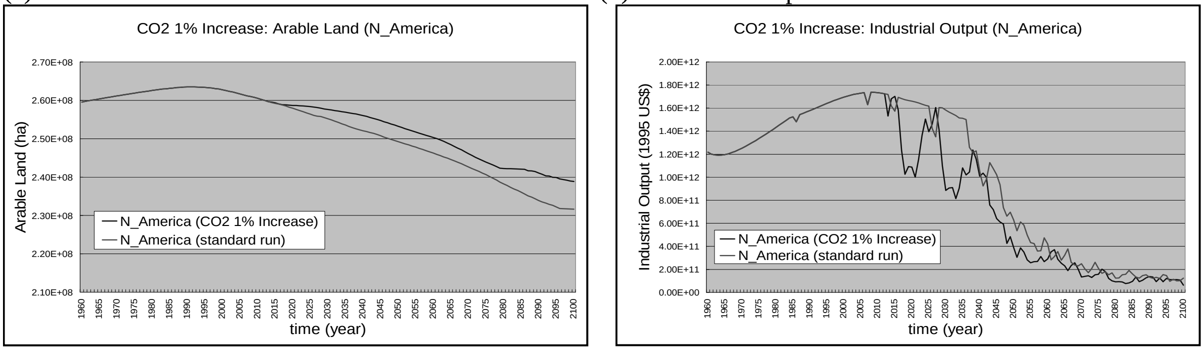


Fig. 11 Water Availability of 1% CO^2 Increase for Six Continents

In Fig. 11, it is noticed that the Results of some continents are shown up above the standard run and on the other hand, the results of other continents are drawn below the standard run. In Africa, Australia and South America, since there are sufficient water, the effects of global warming related to water resources are assumed to be a quite few. However, in Europe, water deficit occurs under 1% CO^2 increase, though there is not deficit under the situation of standard run. Also North America has more serious water deficit under 1% CO^2 increase than on the standard run. By contrast, in Asia, under the 1% CO^2 increase situation, water deficit is alleviated as against the standard run.

These aggravation or alleviation of water deficit affects the other socio-economic activities. Fig. 12 shows the results of some variables compared with the standard run in North America.


(a) Population
(b) Food


(c) Arable Land
(d) Industrial Output

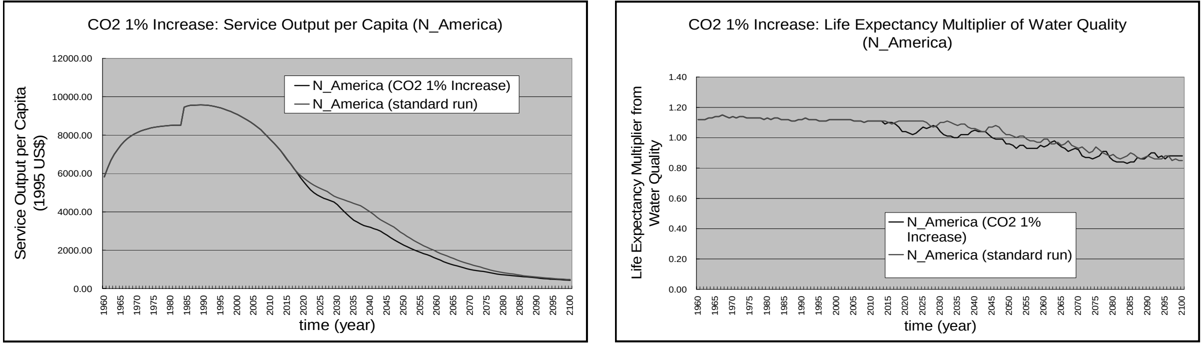

(e) Service Output
(f) Life Expectancy Multiplier of Water Quality

Fig. 12 Results of Some Variables under 1% CO^2 Increase in North America

Owing to the water deficiency, food production and industrial output in Fig. 12 (b), (d) decrease from around 2015 comparing with the standard run. The fluctuation drawn in the results under 1% CO^2 increase represents the effect of water deficiency. The reduction of food production drives the amplification of arable land to alleviate the food reduction. Moreover, the water shortage generates the water quality aggravation as shown in Fig. 12 (f). Aggravation of water quality drives the reduction of population shown in Fig. 12 (a).

From above results, it is apparent that the effects of water deficiency are quite sensitive to the other socio-economic activities. And 1% CO_2 increase gives the aggregative influence for the social development in North America.

4.4 Unlimited Resources Scenarios

Through the standard run, it is apparent that the greatest restriction of the human development is the limitation of nonrenewable resources. However, the technological improvement has been achieved and there are possibilities new resources would be discovered. Furthermore, Raphael and Sanjay (2000) describe that renewable energies will become the main form of energy resource in the world. It is the quite interesting issues whether we can develop the sustainable society under unlimited resources.

This scenario gives the run of the world under the assumption of unlimited resources. The stocks of nonrenewable resources in all continents are kept constant throughout the entire run.

Results under unlimited resources are compared with the standard run. Some results in Africa are shown in Fig. 13. Blue line represents the results of the standard run, while red line represents the results under unlimited resources.

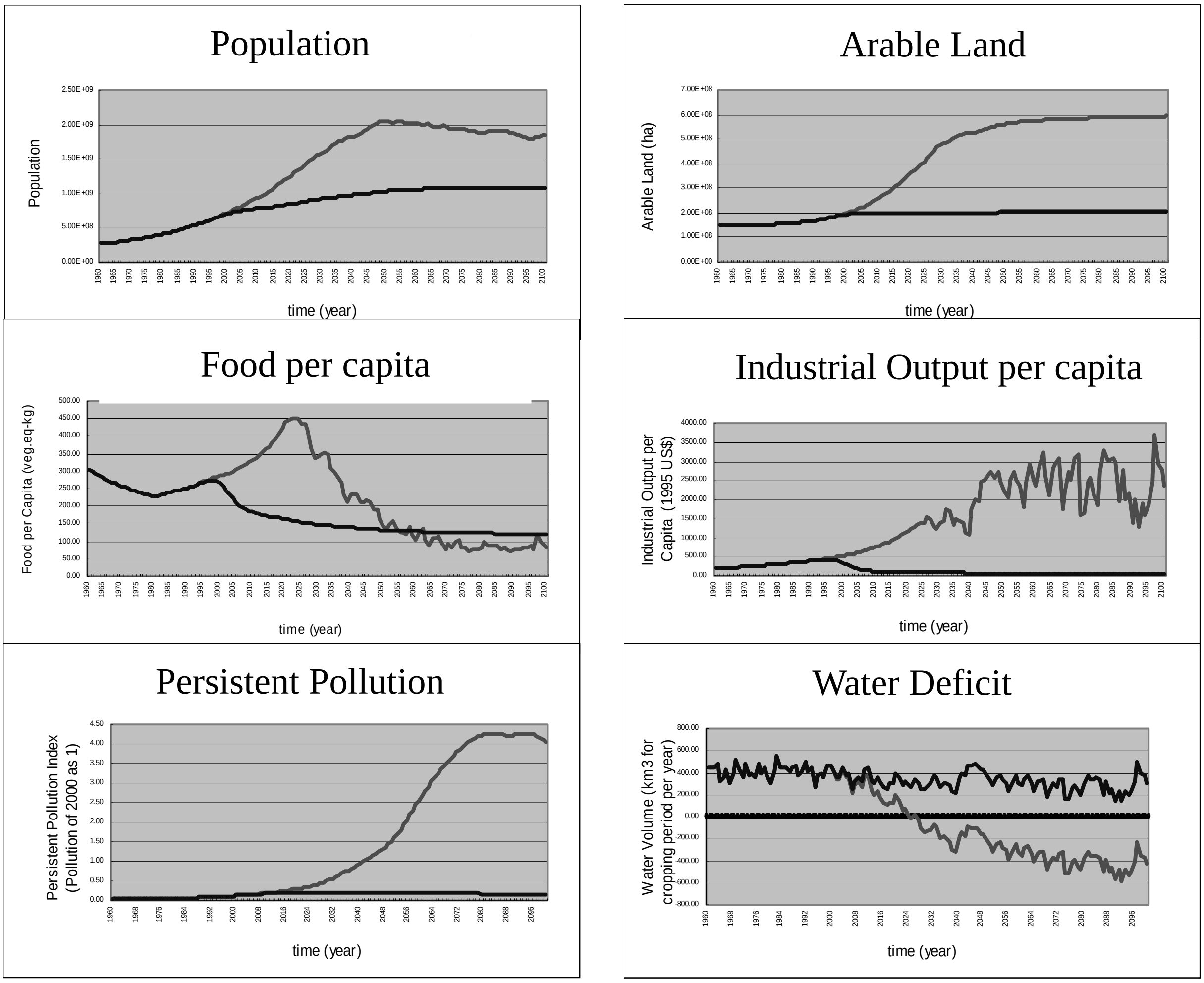


Fig. 13 Some Variables under Unlimited Resources in Africa

Generally, the trend given on scenario with no restrictions on resources is that the industrial outputs of all continents are extremely above the results of the standard run. These increase of industrial output drives the enhancing the growth of other sectors. Food production increases as a result of more agricultural inputs, and more new arable lands are exploited at the same time. Growth of industrial and agricultural activities generates the strain on water resources. On the whole, the world faces the extensive water shortage. Furthermore, vast increase in industrial output leads to very high pollution index which restrict population growth through life expectancy. From these results, even though there is no limitation of resources, water pollution, water shortage and arable land area become the great limitation. Under unlimited resources, the world is expected to head towards a serious global water crisis at the end of same century. Especially, Africa, Asia and North America are assumed to face increasing threats of water scarcity.

4.5 Deterioration of Water Quality Scenario

The scenario assumes that there is going to be increasing difficulties in securing safe water supply due to pollutant emissions and salinization in the 21st century. Usable water resources are restricted to half of that in the standard run by 2100 starting from 2015. Fig. 14 shows the world population under the influence of deteriorating water quality. The world population falls under the standard run level due to shortened human life-expectancy and decrease in food output. This implies that water quality is an important issue and its impact must not be ignored. Blue line represents the results of the standard run, while red line represents the results of scenario on deterioration of water quality.

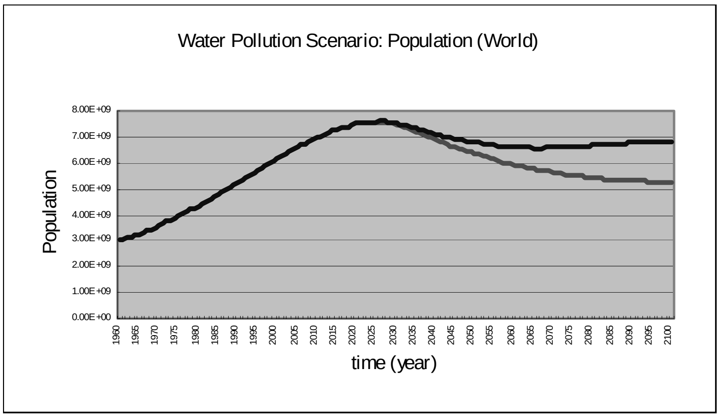


Fig. 14 Results of World Population in the Deterioration of Water Quality

5. Conclusion

In this research, the world water simulation model is proposed to grasp the dynamical interrelationship between the socio-economic activities concerning the water demand and the water supply in the world using System Dynamics concepts. Moreover, the regional interconnection is considered to identify the gap of each region. In the proposed model, socio-economic-activities consist of several sectors, such as population, capita, agriculture, nonrenewable resource, persistent pollution, water quantity and water quality. Spatially, the model is divided into six continental regions, such as Africa, Asia, Australia, Europe, North America and South America. Future situation of water resources are estimated through the simulation with some scenarios.

Some important aspects are concluded through the results of the standard run. First of all, the biggest restraint factor of world development is nonrenewable resources reduction. However, water resources also constrain to world development which is confirmed by the comparison between the standard run and the scenario 3. The effects of water resources deficiency appear in small fluctuations on some results. This indicates that the effects of water resources deficiency are quite sensitive to the development of the world. Notably, the effects of water resources deficiency affect agriculture product and population increase. Furthermore, the local water deficiency affects all regions through the food and goods trade. It is claimed that the local water problems becomes the problems all over the world.

Some future trends in the 21st century of all continents under the standard run are summarized.

i) Africa: Extensive water deficiency does not occur. However, living conditions such as food production and industrial output get into the collapse level due to the depletion of nonrenewable resources.
ii) Asia: Extensive water deficiency occurs from around 2015. After getting to the peak of 5 billion people around 2020, it is assumed to start to decrease up to 2 billion in 2100. Because of large population, water deficiency and nonrenewable resources decrease, industrial output is decreasing gradually from around 2020. However, the living condition is expected to be kept at the sustainable level until 2100.
iii) Australia: Although water deficiency does not occur during this century, industrial output is assumed to collapse due to the nonrenewable resources depletion. Food production is kept to be sustainable level.
iv) Europe: The balance between water supply and water demand is equipoise, though there is no water deficiency through the entire run. The population growth is likely stabilized from 2000. The living condition is assumed to get at the limit of the sustainable level in the end of this century.
v) North America: Extensive water deficiency occurs from around 2030. As well as in Europe, the living condition is expected to reach at the limit of the sustainable level in the end of this century.
vi) South America: There are sufficient water resources through the entire run. However, same as in Africa, living conditions is expected to reach at the collapse level due to the depletion of nonrenewable resources.

The effect of global warming for the future situation is analyzed through the scenario 1, 2. It is expected that global warming might give more serious water resources condition in some place, and give better water resources condition in other places. In Europe and North America, it is assumed that there is a possibility of the aggravation of water deficiency due to the global warming. Furthermore, in Asia, there is a possibility of water supply increment.

In terms of the water qualitative aspects, it is suggested that problems related to water quality is not negligible even as macro scale through the results of scenario 4 which assume we have much further water quality deterioration in the future. It is also confirmed through the scenario 5 that even though there is no limitation of resources, water pollution, water shortage and the capacity of arable land become the great limitation. The world is assumed to face serious water crisis by the end of this century.

Regarding regional characteristics, the development gaps between the developing and developed regions would continue to keep wider before each continent stable optimum growth or collapses. As noticed above, Asia and North America are expected to encounter the water deficiency near future even in macro view. When we take more down scaling on water distribution, water deficiency is assumed to be more quite extensive. Since local water deficiency might affect all over the world, co-operational measures for the water related problem are strongly needed.

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大陸規模世界水資源ダイナミックスモデル

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要旨

本研究は、将来の水資源問題を検討するため、大陸規模での人間活動を考慮したしステムダイナミックスのモデル化と適用をまとめたものである。大陸における人間活動に関しては、人口、資本、農業、資源、汚染、水量、水質の 6 要素を導入した。大陸間の相互作用には人間の移動や貿易を考え、社会・経済活動を表現した。適用においては、1960年から2000年の資料でパラメータを決め、GCM 出力を用いて 2100 年の水資源状況を推定した。

キーワード：大陸モデル、システムダイナミックス、貿易と移住、GCM