

Trends in Research toward Integrated Water Management Based on the Water Cycle

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9.1 Introduction

Japanese cities have developed in river basins and the water cycle of nature has been the center of people's lives. However, growing social and economic activities have imposed a heavy burden on the environment, damaging it in many ways.

This is in fact a global issue occurring not only in Japan. Interaction between the water cycle and human activities such as modification of landscapes results in world water problems from both quantitative and qualitative aspects.

The water problem is attracting people's

attention today. The current status and prospects of world water supply and demand were presented in the World Summit on Sustainable Development (Johannesburg Summit 2002) held in August 2002. Also, reports on water problem research will be set forth, and debate based on studies will be conducted in the Third World Water Forum, which will be held in Japan in March 2003.

Effective use of water resources and establishment and maintenance of a sound water cycle, in which pure and abundant water circulates continuously, are crucial in solving the water problem.

Research and development for creating a sound

Table 1: Principal goals in the field of the environment

Principal goals	Initiative	Outline
Research on technology for restoring cities in river basins in terms of coexistence with nature	Program for monitoring the urban and river basin environment	Technological development for observing and evaluating the current status of ecosystems and cities from the viewpoint of both the natural environment, such as the water cycle, matter flow and biodiversity, and the social environment, such as urban rivers and coasts.
	Program for developing urban and watershed management models	Improvement of element models, such as water cycle models and ecosystem models, and integration and management models
	Program for improving technology encouraging coexistence with nature	Development of technology for revitalizing ecosystems and our living space focusing on the water cycle
	Creation of scenarios toward coexistence with nature	Creation of scenarios for comprehensively encouraging coexistence with nature and development of practical technologies based on them
Research on global water cycle dynamics	Program for monitoring the global water cycle	Improvement of monitoring systems and management of databases
	Program for developing models of water cycle dynamics	Clarification of mechanisms of energy transportation and natural dynamics of the water cycle, and development of models for estimating fluctuation in the water cycle and the environment caused by human activities
	Program for estimating the effects of fluctuation in the water cycle on human society	Assessment of effects of fluctuation in the water cycle on food production, society, and the economy
	Program for comprehensive evaluation of scenarios and technological development for tackling the water problem	Provision of the optimum scenario for tackling the water problem

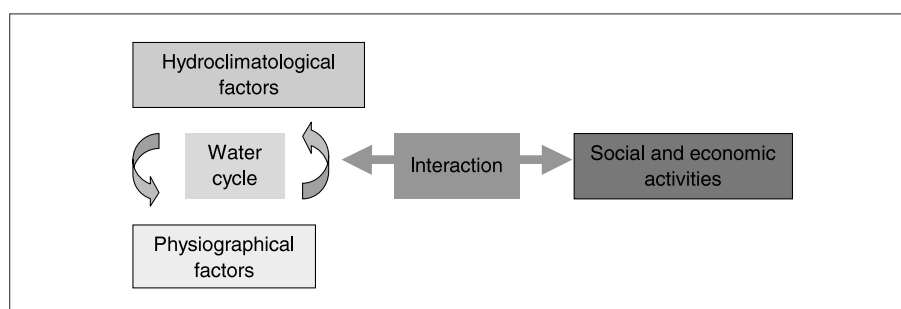
Sources: Promotion Strategy of Prioritized Areas of the Science and Technology Basic Plan

Table 2: Keynotes in the field of urban infrastructure

Keynotes	Research themes	Goals in research and development
Restoration of beautiful Japan and establishment of a high-quality infrastructure	Establishment of a sound water cycle in river basins and realization of integrated water management	Research and development for establishing sound water cycles in important water systems, rivers in major small- and middle-sized cities, areas specified by the government in the Land Subsidence Prevention Rules, i.e., the northern part of the Kanto plains, the Nobi plains and the Chikugo and Saga plains, and major river basins of the world

sources: the same reference as in Table 1

Figure 1: Concept of the water cycle and water resources system



Source: Lecture No.93 of the National Institute of Science and Technology policy: Water Cycle and Water Resources—From Local to Global Views

water cycle in river basins and conducting integrated water management have been promoted vigorously in the field of the environment and urban infrastructure under the Promotion Strategy of Prioritized Areas of the Second Science and Technology Basic Plan adopted at the Council for Science and Technology Policy of Japan's Cabinet Office.

In an effort to reveal the entire mechanism of the water cycle, basic models of urban river basins and analysis models of global demand and supply of water have been improved, and quantitative estimation of the water cycle is becoming possible. It is hoped that highly accurate models in which sediment movement and complex landscapes can be taken into consideration will be developed. Such development will help to establish models of water cycle dynamics and contribute greatly to the estimation of water resources and fluctuation in the water cycle in Asia including Japan.

Meanwhile, integrated water management has been advanced based on case studies of urban river basins. Yet, environmental indicators and estimation methods, which are deeply related to water management, have not been fully researched compared to flood control and water utilization.

In this report, I will introduce to you trends in

research toward integrated water management in respect to the water cycle, such as improvement of analysis models of global demand and supply of water, focusing on the field of study dealing with the water cycle, which is prioritized in the Second Science and Technology Basic Plan.

9.2 Research goals in the promotion strategy of prioritized areas

The promotion strategies of the Second Science and Technology Basic Plan set principal goals in water cycle research in the field of the environment and social infrastructure as shown in Table 1 and 2, respectively.

9.3 The water cycle and water resources system

The water cycle and water resources system comprises water, land and people. This is a dynamic system determined by hydroclimatological factors, such as rainfall, evapotranspiration, temperature and irradiation, physiographical factors, such as landscapes, geological features and soil, and artificial factors, such as social and economic activities. Hydroclimatological and

physiographical factors fluctuate through interaction with artificial factors, and these three factors characterize the water problem.

9.4 Trends in research for revitalizing the watershed water cycle and achieving integrated water management

9.4.1 *Technology helping to revitalize the water cycle*

Storage and infiltration are basic technologies for establishing and maintaining the sound water cycle.

Forests and farmland can be deemed as water storage and infiltration facilities with large capacities. Meanwhile, in river basins in highly urbanized areas, how to store and infiltrate water in the ground and return it to rivers through groundwater flow are essential in maintaining the cycle of clean and abundant water. Infiltration facilities such as a seepage pit and a seepage trench serve as infrastructures for realizing this favorable water cycle. Topographical and geological conditions are crucial in building infiltration facilities with sufficient infiltration capacities. Generally, tablelands, alluvial fans, hilly terrains and sands are suitable, while solid ground with low air porosity, viscous soil and places with high groundwater elevation are unfavorable. The infiltration facility is built into each house and rainwater is guided into the ground. This equipment is also connected to rainwater main pipes of the sewer system, so that excessive water may escape to these pipes upon downpours.

In the meantime, in the construction of sidewalks, permeable pavement is spreading instead of conventional pavement especially in urban areas. This provides surface asphalt with adequate porosity and makes water infiltrate into and under the ground through the roadbed.

9.4.2 *Environmental estimation methods in river basin water management*

A sound water cycle is defined as the sustainable, effective and balanced functioning of water in the water cycle with river basins as its center from the viewpoint of flood control, water

utilization and environmental conservation, and this is becoming a worldwide concept. The relationship between the water cycle and people concerns flood control, water utilization and environmental conservation, which have different values and interests, and how to assess the balance with the environment is crucial. The environment is sometimes an abstract concept and is often estimated subjectively. Thus, it is hard to build a consensus among people in this field of study.

A primary goal for the improvement of water management in river basins is to establish a good relationship between the water cycle and people by harmonizing differences in requirements among various entities and easing conflicts of interests through adopting new technologies and altering political systems properly.

Currently, the Ministry of the Environment and the Ministry of Land, Infrastructure and Transport conduct surveys on ecosystems, water analysis and census in river basins every year, accumulate basic data and analyze data properties and distribution. Also, they estimate the recharge and heat-shielding ability of forests, farmland and wooded areas.

By determining environmental indicators based on these basic data, they try to establish an estimation method for comprehensively evaluating the characteristics of species living in river basins and their habitats in terms of the relationship with flood control and water utilization. Such a method will help to boost environmentally friendly projects and nature-restoration programs.

9.4.3 *Water cycle models*

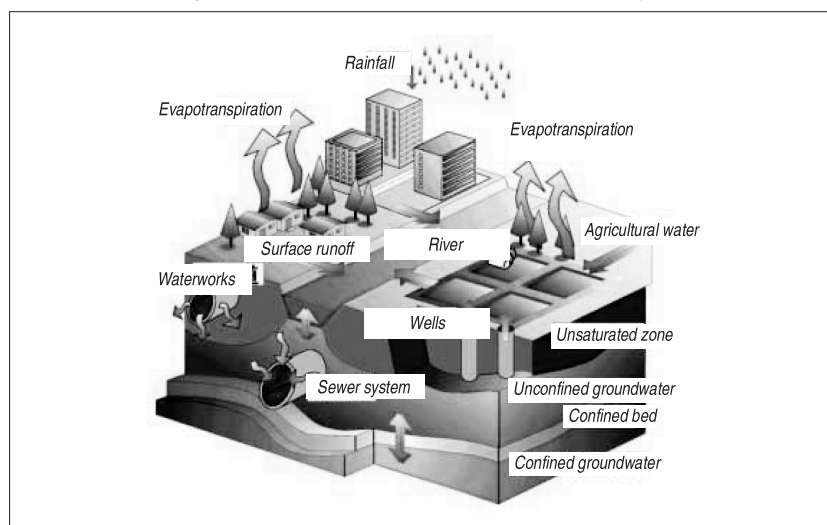
In improving river basin water management based on the sound water cycle, we need to develop analysis models in which related observation data are accumulated and the effects of water management projects are grasped and evaluated quantitatively based on these data.

In this section, I introduce to you water cycle modeling, which helps in the understanding and estimation of water dynamics in river basins from data on land usage and hydrological, geological and topographical properties.

The distributed physically based model is one of the most precise methods for analyzing the water cycle.

In this model, the water cycle in a river basin is

Figure 2: A conceptual model of the water cycle



Source: Material from the Tsurumi watershed committee

Table 3: Data to be inputted in water cycle modeling

Elements comprising the water cycle	Natural system	Precipitation, evapotranspiration
	Artificial system	Waste water, leakage from waterworks and sewer systems, agricultural water, pumped groundwater, runoff-controlling facilities
Information on the river basin	Land surface	Altitude, gradient of elevation, drainage direction, distribution of impermeable layers, mulch, storing capacity of depressions
	Surface soil	Surface soil properties
	Aquifer	Hydrogeological structures, boundary conditions
	Natural system	Various elements in river channels

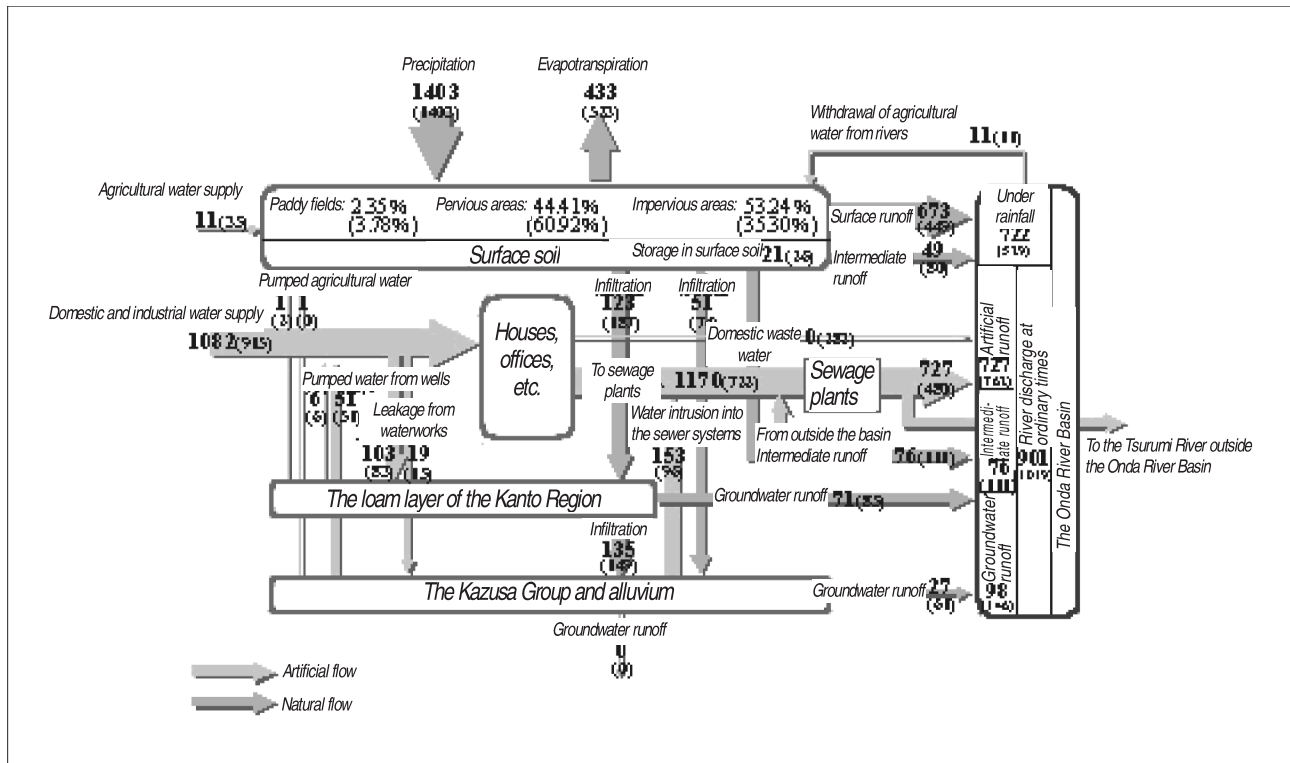
Source: the same reference as in Figure 2

Table 4: Watershed conditions to be set

	Present (1994)	Future (with an urbanization rate of 95%)
Impervious area ratio	Refer to detailed digital information	Presume that all land other than legally guaranteed natural land is developed
Population in the basin	Refer to the resident register	Estimate the population of new urban areas from the population densities of current urban areas
Consumption of supplied water	Multiply the water consumption per capita by population	Multiply current water consumption per capita by presumed population
Waste water volume	Calculate from the diffusion rates of sewer systems and flush toilets	Presume the diffusion rate of sewer systems as 100% and the waste water volume as 0
Leakage of supplied water	Estimate from non-effective supply	Presume that the current non-effective supply is maintained
Volume of pumped groundwater	Refer to the municipality's data	Presume that the current volume is maintained
Agricultural water withdrawal	Multiply paddy field area by water requirement depth*	Calculate in the same way as in "present"
Volume of pumped agricultural water	Refer to the municipality's data	Presume that the current volume is maintained
Volume of water intruding into the sewer system	Calculate from unaccounted water volume	Presume that the current unaccounted water volume is maintained
Outflow rate from sewage plants	Refer to the municipality's data	Presume from water consumption

*The water required depth indicates the decrease of stored water. Water requirement depth per day is generally used.
Source: the same reference as in figure 2

Figure 3: An example of an estimation deduced by water cycle modeling.(Values in parentheses indicate future estimations.)



(Value: mm/y)

Source: the same reference as in Figure 2

explained by representing the basin as a uniform grid of cells and surveying water movement in each cell. Figure 2 shows a conceptual model of the mechanism of the water cycle.

We can analyze water movement on the land surface including river channels, in the ground such as surface soil, and in the groundwater zone using a conventional flood analysis method, a saturated-unsaturated flow model, and a quasi-three-dimensional groundwater model, respectively.

Table 3 shows major data to be inputted.

Table 4 shows an example of an analysis at the Tsurumi River. In this table, “present” indicates the basin status in 1994, while “future” indicates when massive exploitation is conducted in the basin and its urbanization rate becomes 95%.

Figure 3 shows the results of a prospective analysis conducted based on the above conditions.

This estimation of water budget in a small basin of the Onda River, a tributary stream of the Tsurumi River, indicates that; (1) infiltration of precipitation will drop, while surface runoff will jump, (2) groundwater runoff into the river will plunge, and (3) the ratio of treated sewage water to river discharge will surge. In this way, we can

quantify the change in the water cycle. Moreover, we can quantitatively estimate how projects on river basins may affect the water cycle. Thus, water cycle modeling helps us to prepare effective projects. Furthermore, qualitative estimation of the water cycle is becoming possible, as the distributed pollutant flow model for water quality estimation has been developed.

9.5 Trends in research on global water cycle dynamics

9.5.1 Social background

World Water Vision 2000, a report of the Second World Forum held in The Hague, the Netherlands, anticipates that world water withdrawal will surge from 3,800km³ in 1995 to 4,300-5,200km³ in 2025, because of the increase in demand for irrigation water. Moreover, it warns that economic growth will cause excessive water consumption, heavily damage the ecosystem, and further, may trigger international conflicts and tensions as well as the water problem.

While global water resources have been evaluated based on the amount of water roughly calculated for each country, researchers have

recently launched the establishment of models for estimating water resources in each river basin, in which regional properties can be taken into consideration.

9.5.2 Water supply model

In evaluating water supply, water outflow and water resource availability are calculated. By using the Land Surface Model (LSM) in 0.5 degree by 0.5 degree longitude/latitude resolution, outflow from each unit is estimated with the presumption that the water volume calculated by taking evapotranspiration from precipitation equals to the amount of water reaching rivers through surface runoff and underground infiltration. Then, the water resource availability (See Footnote 1) is estimated by assessing discharge in each river based on the world landscape distribution. Annual river discharge is regarded as the maximum volume of water resources available.

Basically, tropical regions, east coasts of continents and Asian monsoonal areas, which have high precipitation, have rivers with high discharge. Also, the Nile Basin in Egypt and other countries contains a large amount of water available because of the flow from its upper stream.

9.5.3 Water demand model

In estimating water demand, consumption rate of domestic and industrial water per unit population is calculated for each nation, and its total water withdrawal is assessed in accordance with the population distribution. Also, consumption rate of agricultural water per unit irrigated area is evaluated for each nation, and its total water withdrawal is estimated in accordance with the distribution of irrigated farmland. Farmland distribution is assessed based on statistical data of not countries but states or counties for India, China and the U.S., which

account for 47% of the world irrigated area.

According to this calculation, large amount of water is withdrawn in the West Coast of the U.S., Europe including Eastern Europe, West Asia, the northern part of India, China and Japan.

9.5.4 Current status of supply-and-demand distribution of water resources

Water scarcity index (R_{ws}) is used as an indicator of the current supply and demand of water resources. R_{ws} is defined as $R_{ws} = (W - S) / Q$ where W is annual water withdrawal, S is annual water resource supplied by desalination of seawater, and Q is annual water resource availability. The extent of water scarcity is evaluated from R_{ws} . $R_{ws} < 0.1$ indicates no water stress, $0.1 < R_{ws} < 0.2$ indicates low water stress, $0.2 < R_{ws} < 0.4$ indicates moderate water stress, and $0.4 < R_{ws}$ indicates high water stress, or water shortage.

Figure 4 explains the distribution of R_{ws} calculated from the above method. This figure implies that actual water demand exceeds water resource availability in the Western U.S., the Middle East, the border between India and Pakistan, the region in the northern part of India and the southern part of Tibet, and the region from the Huanghe River Basin to the North China Plain. These areas are probably undergoing water stresses, having little resistance to fluctuation in the water cycle.

Another indicator of supply and demand of water resources is annual water demand per capita which is defined as $(W - S) / C$ where C is population. As shown in Figure 5, water demand in the Western U.S. is significant, because much water is consumed in the production of crops to be exported to other regions.

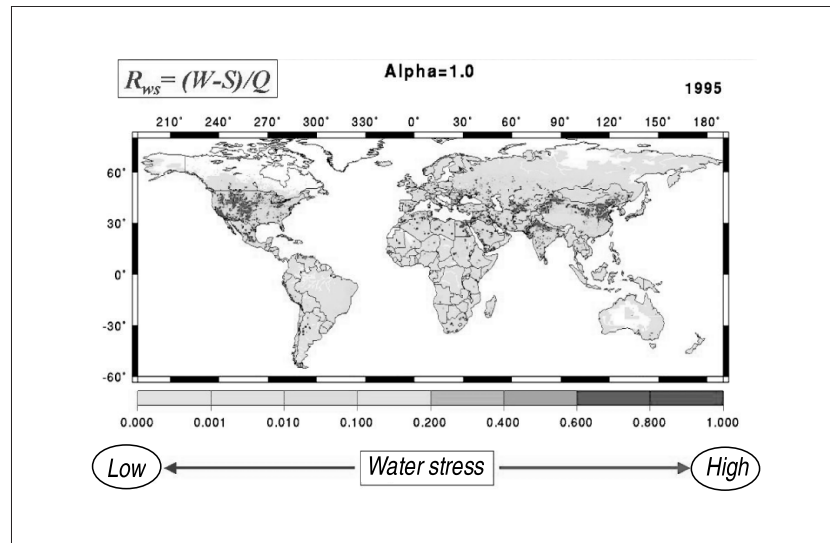
Water consumed in agricultural production is called virtual water. Japan is deemed as importing large amounts of water along with the import of crops, that is, relying on imported virtual water. Therefore, we must think of returning this benefit to the world.

9.5.5 Prospect of supply and demand of water resources

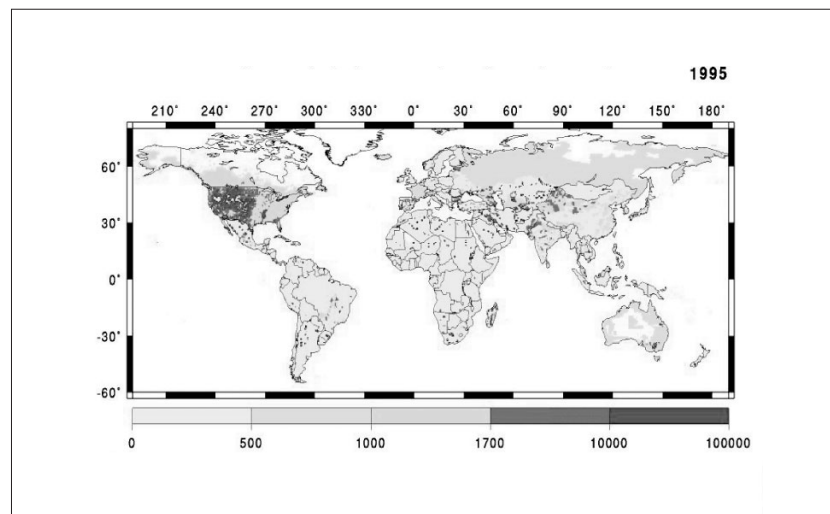
We consider the balance between water resources and demand in the estimation of future

Footnote 1:

Water resource availability is evaluated by multiplying the water volume (calculated by taking evapotranspiration from precipitation) by the area. This indicates the maximum water volume available for people.

Figure 4: Water stress indicator (annual withdrawal to availability ratio)

Source: the same reference as in Figure 1

Figure 5: Annual water demand per capita ($\text{m}^3/\text{year}/\text{person}$)

Source: the same reference as in Figure 1

supply and demand of water resources, as in the evaluation of the current water status.

In this analysis, future water resources in volume is estimated with the General Circulation Model (GCM), which was jointly developed by the Center for Climate System Research of the University of Tokyo and the National Institute of Environmental Studies, with the presumption that the CO_2 concentration will be doubled in around 2050. Runoff rate to rivers is calculated from prospected precipitation, and future river discharge is assessed as in the water supply model. The estimation result indicates that river discharge will increase in the northern part of China, India, and the region from the border between India and Pakistan to the Aral Sea, and it is expected that the

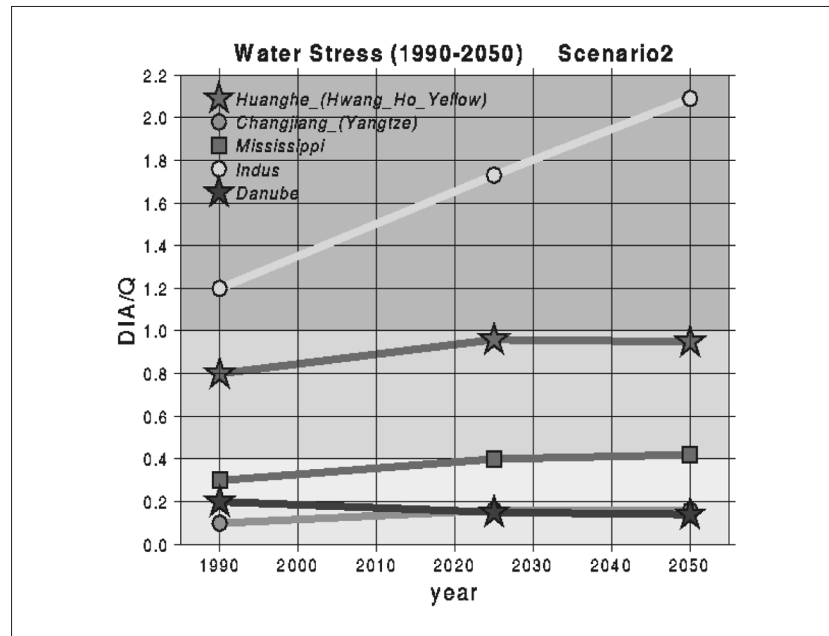
water problem from the viewpoint of supply of water resources will be alleviated.

Meanwhile, in evaluating water demand, it is postulated that the population will increase in accordance with the medium variant of the United Nation's world population prospects, while agricultural water withdrawal will rise proportionately to population growth. Whereas, increase in demand of domestic and industrial water per capita is presumed based on Raskin et al.

Figure 6 explains year-to-year changes in relative water demand, i.e., demand per discharge, by 2050 in several river basins deduced from the above hypothesis.

- Though discharge will probably rise in the

Figure 6: Year-to-year changes in relative water demand in several river basins



Source: the same reference as in Figure 1

Indus River as a result of global warming, relative water demand is estimated to surge linearly from 1990 to 2025 and 2050 because of continuous population growth. This implies that the impact of population growth surpasses that of climate change.

- Relative water demand will be stabilized from 2025 to 2050 in the Huanghe River Basin, because the population growth rate will decline in this area.

Meanwhile, there are similar reports that population growth affects relative water demand more than climate change does.

9.6 Essential themes of research on the water cycle and integrated water management in Asia including Japan

Understanding of water dynamics at the macro level by the establishment of models for estimating the global water cycle greatly helps to devise effective measures for tackling the impacts of global warming and so forth. Conventional analysis methods have been developed based on data in western countries, because water cycle research has been mainly conducted there. Yet, analysis of the water cycle and water resources

system is essential in Asia, where many cities are located in alluvial plains and are exposed to the direct effects of orogeny. Such research is also highly crucial in supporting sustainable development in developing countries. In order to fulfill this necessity, activities to set up the Asia Pacific Association of Hydrology and Water Resources have been launched with the leadership of researchers in Japan. The main themes of this field of study are as follows.

- (1) The distributed hydrological model, which was jointly developed in Europe for quantitative analysis of water infiltration, runoff, evapotranspiration and so forth, is for plain terrains, covering vertical infiltration only. Therefore, this model cannot be well applied to analysis of mountains and hills. We need to develop new models that include downhill flow parameters and thus can be applied to Asian mountains.
- (2) While karst hydrology for karsts with a peculiar water cycle has been established in western countries, volcanic hydrology needs to be systematized for Asian volcanic regions whose water cycle and processes of sediment production and transport are peculiar.
- (3) Sediment production in western countries has been formulated as being determined by sediment delivery by raindrops and erosion

by overland flow. In the meantime, discontinuous sediment production not only by erosion but also by mountain collapse, landslides, volcanic eruptions and mud flows has significant effects in Asia, thus analysis methods reflecting these parameters are necessary.

(4) Other research themes typical of Asian monsoonal areas are as follows.

- The precipitation mechanism, fluctuation of water resources and effects of the El Nino in Asian monsoonal areas.
- Irrigation and drainage technologies and water management in rice-growing areas.
- Flood control, water utilization and environmental issues in cities in alluvial lowlands.
- Water shortage and pollution in major cities resulting from the unbalance between water supply and demand in spite of large water supplies.
- Steps against mass production and runoff of sediment (e.g., soil erosion control and stabilization of alluvial channels).
- Selection of specific themes different from stable zones in western countries and their research and development in meteorology, agricultural engineering, river engineering, forestry, and groundwater hydrology among others.

9.7 Conclusion

In this report, I have introduced to you basic technology and water cycle models that contribute to integrated water management in respect to river basins in Japan and trends in research toward establishment of a sound water cycle, as well as studies at the global level. They will surely and significantly advance water management. While various efforts toward integrated water management can be deemed as groundbreaking experiments, we are facing many hurdles to overcome as shown below.

- It is essential to improve modeling methods like water cycle models for visually understanding various phenomena, so that these techniques may obtain high accuracy and

be used in various areas. In addition, we need to promote research and development of environmental evaluation because this is a key field of study in forming a consensus.

- It is preferable to introduce the viewpoint on water cycle into land use. If necessary, we need to consider taking social scientific steps such as enforcement of legal restrictions.
- As a matter of course, citizens, companies, municipalities and the national government must play their own roles and cooperate with each other in order to establish a sound water cycle. Especially, efforts by municipalities, which are in charge of various policies and public projects related to the development of cities in river basins, flood control, disaster prevention and so forth, will be critical. Moreover, the government needs to encourage decentralization and technical cooperation.
- Research in Japan has been carried out based on models developed in western countries, so characteristics that Japan has in common with other Asian countries have not been emphasized very much. We need to present other countries with various measures and technologies that Japanese researchers have fostered in studies of the water cycle and water resources system, and scrutinize their availability especially in Asian countries. Furthermore, we need to introduce to the world our findings on the water cycle and water resources system influenced by landscapes and social and economic activities particular to Asia, and invigorate the necessary research.
- The water problem is now a global issue. It is high time for Japan to pave the way for smoothly and appropriately transmitting to Asian countries social and technological systems that contribute to the establishment of a sound water cycle. We also need to respect the customs and climates in the countries we help in order to provide our technologies effectively and to advance overseas aid such as the Official Development Assistance.

Acknowledgements

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Global Views” by Professor Katsumi Mushiake of the Institute of Industrial Science, University of Tokyo, held at the National Institute of Science and Technology Policy on August 7, 2002, along with the addition of my findings.

My sincere thanks to Professor Mushiake, who contributed highly valuable information and advice

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