INTEGRATED WATER QUALITY ANALYSIS FOR WATER MANAGEMENT IN THE CHIKUGO BASIN AND THE ARIAKE SEA

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by

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ABSTRACT

In this dissertation, integrated water quality analysis is proposed for water management in the Chikugo Basin and the Ariake Sea. Various interests and numerous groups of water users make water quality problems in the Chikugo Basin more complicated. These problems affect water environment not only in the Chikugo River but also in the Ariake Sea. There are very few researches on water quality in the Chikugo Basin and the Ariake Sea, and the analytical tool for decision-making has not been developed. In this study, numerical models to analyze water problems and water policies are developed in the Chikugo Basin and then linked with that of the Ariake Sea. Feasibility of existing policies is evaluated and discussed through the application of the integrated model.

In Chapter 2, concepts of policy analysis and implementation of water management in various types of water bodies are reviewed. Solution of problem in one area may lead to new or more serious problems in other areas. As a result, water management focusing on the interrelation between the river and its receiving water is found to be necessary. In the process of policy analysis, impacts of the proposed alternatives should be assessed in both river basin and sea area before evaluating the alternatives and presenting to the decision-makers. Overview of the application of numerical models indicates that these models have been improved in analytical capability and become powerful instruments for water management in many areas. From water quality approach, it is pointed out that numerical models for water quality analysis become indispensable for water management.

In Chapter 3, problem analysis is performed in the Chikugo Basin and the Ariake Sea based on observed data of water use and water quality. Characteristics of water quality observed in the Chikugo Basin can be described as high organic and nutrient loadings during irrigation period. Loading analysis indicates that large amount of loadings is generated from paddy field in irrigation period while those from non-irrigation activities are lower and steady. Unknown parameters of non-point sources, such as unit loading of paddy field and urban area, are obtained from this loading analysis. The observation in the Ariake Sea shows that organic and nutrient concentrations in its innermost area are high during rainy season. These concentrations become lower in the middle area and near the open sea.

In Chapter 4, the tank model and one-dimensional river model are proposed for the simulation of water quantity and water quality in the Chikugo Basin. Water quality parameters concerned in these models are COD, SS, T-N and T-P. The simulated results prove that the proposed models are effective for the comprehensive simulation in the Chikugo Basin. Water quantity analysis indicates that most of irrigation water withdrawn along the middle reach returns to the main river within the reach. Good correlation between the observed loadings and the simulated ones confirms the effectiveness of the proposed models in estimating the loadings discharged from the Chikugo Basin into the Ariake Sea.

In Chapter 5, water quality model in the Ariake Sea is developed based on the finite-volume model. Besides the loadings from land area, this model also takes into account productivity of algae and natural loadings from mud bed in the Ariake Sea. After verification, the finite-volume model is integrated with the developed models in the Chikugo Basin. The integrated model succeeds in simulating water quality in the Ariake Sea in 1991-2000. In sensitivity analysis, it is found that natural loadings from mud bed predominate in COD, orthophosphate and SS in the innermost area during dry period. The simulated results show that high discharged loadings from land area in rainy season increase organic and nutrient concentrations in the vicinity of the river mouth. The productivity of phytoplankton is another control factor of the nutrients in the innermost area. On the other hand, the analysis points out that inorganic nitrogen concentration is the growth-limiting factor for algae and laver in the Ariake Sea.

In Chapter 6, policy analysis on the existing measures of water quality control is evaluated from the viewpoint of the feasibility. For water quality control in the Ariake Sea, master plans for implementation of wastewater treatment are being drafted to decrease the loadings from land area. The analysis remarks that the influences of natural loadings from mud area are also significant and cannot be neglected in the achievement of environmental quality standard in the Ariake Sea. Feasibility of loading reduction in the Chikugo Basin is evaluated at 50% and 80% removal. These alternatives are found to be effective only in rainy season. However, it may be practically infeasible because wastewater treatment system is unable to handle non-point source loadings that dominate in rainy season. With the purpose of nutrient supply, the minimum flow rate in the Chikugo River is secured for fisheries, mainly for laver cultivation, in the Ariake Sea. The simulated results give the new insight that contribution of nutrient supply from mud bed in the innermost area of the Ariake Sea is as high as that from the Chikugo Basin. From the results mentioned above, it is proposed that new concept for management of river flow and water quality should be established by taking into account the natural loadings from mud bed and the loadings from land area.

The integrated water quality analysis makes great contribution to the policy analysis in the Chikugo Basin and the Ariake Sea. The integrated model can be adapted for the analysis of the problems related to other water quality indices. The new information obtained from the analysis in this study calls for revision of the selected policies.

In Chapter 7, concluding remarks and recommendation for further research are given.

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CHAPTER 1

INTRODUCTION

1.1 Background

When discussing about water problems in one country, it is necessary to take into account the particular characteristics of that country such as location, topography, climate, population, economic condition, culture, etc. These individual characteristics are important factors that lead us to the clues of the water problems. For example, people in cold area tend to consume less water than those in warmer area. Despite such different characteristics among each country, some existing water problems are more or less in common.

Flooding is recorded as one of the oldest water problems that human have faced. Since the ancient time, people prefer to settle their community near rivers where water can be conveniently withdrawn for their daily life and growing crops. Archaeological evidences indicate that many civilizations were established along rivers. Flooding is unavoidable for ones who stay close to the river.

Major causes of flooding can be defined as inland water and coastal water. The inland water means high intensity or long duration of precipitation or rapid discharge from mountainous area including melting snow or overflow from upper reach of the river or even the water accidentally released from the reservoir. The coastal area, estuary and low-lying area near river mouth are more vulnerable to flooding caused by the coastal water than that of the inland water. The coastal water refers to a high tide or a storm surge that occurs during strong storm like typhoon, tornado, etc. including a tsunami, which occurs after the earthquake.

Facing with a number of flood disasters, people have tried to protect their lives and properties in various ways. Infrastructures like reservoirs, weirs and sluices, are constructed to control water level in rivers while dikes and barrages are built to decrease degree of damage from flooding.

After securing their lives and properties, people have to face another problem – water demand. We consume water for various purposes during a day. Generally, human cannot survive longer than a few days without drinking water. One person basically requires at least 20-50 liters of water each day. We need clean water for drinking and cooking. We need water for bathing, washing and cleaning. We need water for growing crops and producing food. We need water for generating power, industry, etc. In daily life, people may use less water in winter and more water in summer. The amount of water used in one factory maybe constant until the order for products changes or the production process is modified. Farmers may need large amount of water for their crops during cultivation season and less water during harvest season. Water demand varies from time to time according to the purpose of each water user.

Because of water pollution and the increase in water demand, available freshwater becomes limited. Sooner or later we will face difficulty in supplying sufficient water for all water users. Water shortage problem sometimes occurs in a drought year and it will become more serious if the drought continues for a long time. There are many areas in this world already suffering with low precipitation and inadequate water supply. According to the Global Water Supply and Sanitation Access 2000 Report (WHO and UNCEF 2000), there were 1.1 billion people lacking of access to improved water supply in 2000 although the number of people served with improved water supply increased from 4.1 billion in 1990 to 4.9 billion in 2000. An additional 1.5 billion people will need to gain the water supply service by 2015 and the number of people without improved water supply is forecasted to be 0.6 billion.

The rapid increase in water demand also refers to the increase in wastewater generated from human activities. Insufficient management of wastewater can lead to contamination problems in receiving water bodies. Not only wastewater, but solid wastes and hazardous wastes can also cause water pollution in both surface water and groundwater as well, if they are not handled appropriately. Groundwater can be contaminated by diffused sources of pollutants such as waste dumping sites, agricultural areas where fertilizer and chemicals are heavily used, etc.

Water quality problems are getting serious in many areas especially in developing countries. Industrialization in developing countries is one of the major causes of water pollution as well as the inadequate sanitation system. The polluted water relates with health problems in many ways. Many diseases are caused by consumption of water contaminated with pathogens and heavy metals. Toxic metals such as mercury, lead, cadmium and arsenic are harmful to human health. These metals are dissolved in water and cumulative in fish and shellfish. The well-known water-borne diseases are diarrhea, cholera, typhoid, polio, hepatitis A and E, etc. The price per unit of drinking water in many countries is increasing because of depletion in quality of raw water.

Besides the major problems mentioned above, there are some specific water problems, such as groundwater problems or seawater intrusion, which cannot be neglected in some areas. In the area where freshwater is insufficient or quality of surface water is not desirable, groundwater becomes attractive for drinking water supply, industry and irrigation. Without appropriate control on usage of groundwater, excessive groundwater consumption occurs. Excessive pumping of groundwater links to land subsidence, decrease in soil moisture, etc. Problem on saltwater intrusion often occurs in the coastal area and sometimes extends up to 100 kilometer upstream if river discharge is very low. Flushing by freshwater or installation of barrage are the measures widely used to protect against seawater intrusion.

To solve water problems in these present days is not easy since a large number of water users with various interests have made the water system complicated. Water quality problem in one watershed can affect water quality in receiving water body like sea and lake. On the other hand, water quality problem in the sea area can influence on water quality in the discharging river as well. To handle water problems systematically, water management with integrated aspect is necessary.

In water management, problem is identified and analyzed according to the desires of socio-economic system. The possible actions or policies are then formulated based on results of problem analysis. In the process of policy analysis, attention is paid to interaction of the action with the water system, natural environment and other water users. After screening of actions, impacts of these actions are evaluated and presented to decision-makers. With assistance of analytical tools, the policy will finally be selected and implemented.

Several water problems arise from conflict interests of agriculture, drinking water supply and environmental protection in the country with developed water management system like the Netherlands (NHV 1998). The similar problems also occur in many areas in Japan including the Chikugo Basin and the Ariake Sea where numerous interests exist. However, it is difficult to deal with such problems by applying the same countermeasures with those in the Netherlands because the legislative system of Japan is different and stakeholders involve greatly in decision-making in this country. To develop water management system for such individual legislative structure, researches on water management for the water bodies with large number of water users are necessary.

1.2 Research objectives and scope of study

A river basin and the connected sea area like the Chikugo Basin and the Ariake Sea tend to be considered as a distinct system in water management in Japan. As a result, most of water problems in both areas are solved separately. Influences of the measures taken in one area on the environmental system in other area are likely to be overlooked.

Taking into account the interrelation between the Chikugo Basin and the Ariake Sea in water management, it is necessary to analyze water quality in both areas from integrated point of view. Simultaneous researches on water quality in the Chikugo Basin and the Ariake Sea are very few and there is no analytical tool developed for the decision-making process. To provide essential information for water quality management in the Chikugo Basin and the Ariake Sea, integrated water quality analysis is proposed in this research.

The final goal of this dissertation is to implement integrated water management system in the Chikugo Basin and the Ariake Sea, Japan. In the process of water quality analysis, the specific objectives that should be achieved are listed below.

- To analyze water problems in the Chikugo Basin and the Ariake Sea.
- To propose an integrated numerical model as an analytical tool for integrated water quality analysis.
- To carry out water quality analysis in the Chikugo Basin and the Ariake Sea from an integrated point of view.
- To conduct policy analysis on existing measures for water quality management in the Chikugo Basin and the Ariake Sea.

Focusing on the interrelation between the Chikugo Basin and the Ariake Sea, integrated water quality analysis is carried out in the middle and lower parts of the Chikugo Basin and the innermost area of the Ariake Sea. Secondary data from reliable sources are utilized in this study. Because of inadequate information, only basic analysis is conducted in the upper part of the Chikugo Basin. The proposed models of water quality analysis in the Chikugo Basin are developed based on the tank model and one-dimensional river model. In water quality modeling in the Ariake Sea, two-dimensional finite-volume model, so-called the box model, is developed under the assumption of no density current in each element. Deposition in the tidal flat is not included in this study. Aiming at environmental aspects, economical evaluation for policy analysis is out of the scope of this study.

1.3 Thesis organization

In Chapter 2, water management in various types of water body is discussed. Concepts of policy analysis are described through the study on Policy Analysis of Water management for the Netherlands (PAWN). As the analytical tools, development of numerical models and their application in water management are reviewed. Finally, background on legislative system, master plans involving in water management as well as history of water in Japan are summarized to give an idea on water management in Japan.

In Chapter 3, at first water problems in the Chikugo Basin are analyzed based on available data. Quantitative and qualitative information of this watershed such as observed data of flow rate, water quality and water use are collected and summarized. Characteristics of water quality in the Chikugo Basin are determined. In the policy analysis, it is necessary to evaluate impacts of the proposed policy throughout the watershed including its receiving water, the Ariake Sea. In the same manner, the problem analysis is carried out in the Ariake Sea. Receiving high discharge from the Chikugo River, water situation in the innermost area of the Ariake Sea can point out related problems in the Chikugo Basin.

In Chapter 4, two numerical models are proposed for the Chikugo Basin. The tank model is developed to estimate base flow and loadings from the catchment area and one-dimensional river model is developed for the main river. Despite the fact that available data in the upstream area of Arase is inadequate, discharge from this area is represented by observed data of the reservoir located near Arase. The developed models are used to simulate water quantity and water quality in the Chikugo Basin. Effectiveness of the proposed models is verified through comparison with the observed data. These models are then applied in the quantitative and qualitative analysis to obtain information about water use and loadings generated in the Chikugo Basin.

In Chapter 5, development of two-dimensional finite-volume model for the Ariake Sea is described. The finite-volume model and the developed models of the Chikugo Basin are integrated together to represent the interrelation between the Chikugo Basin and the Ariake Sea. With application of the integrated model, contributions of natural loadings from mud bed, algal productivity and discharged loadings from land area to water quality in the Ariake Sea are examined in the sensitivity analysis.

In Chapter 6, the integrated model is applied in feasibility study on selected measures in the Chikugo Basin and the Ariake Sea. Environmental quality standard in the Ariake Sea and reduction of loadings from the Chikugo Basin are analyzed from the viewpoint of water quality control. From water quality management aspect, the minimum flow rate at downstream of the Chikugo River for fishery especially laver productivity in the Ariake Sea is selected. The contributions of discharged loadings from the Chikugo Basin and natural loadings from mud bed in the Ariake Sea are taken into account in the feasibility study of each measure.

The concluding remarks and recommendation for further research are given in Chapter 7.

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CHAPTER 2

POLICY ANALYSIS IN WATER MANAGEMENT

2.1 Introduction

Final goals of water management are defined from the demand and interests of the society. In these present days, more attention is paid to water quality of the water system especially in developed countries. For recreation, people prefer the rivers with good water quality and rich environment. Frequently, water quality becomes one of the important keywords in determination of the final goals. To achieve the desired water quality, water quality standards are sometimes applied as a target of water quality management.

To achieve the targets of water management, possible actions are designed. Usually, there is more than one alternative that can approach to the final goals. It is a difficult task to decide which alternative is the most suitable one. Reviewing water management carried out in the past with the same or similar goal can give an idea in how to formulate and select the alternatives. Moreover, disadvantages and problems of the proposed alternatives are sometimes reported in the former management. Taking the relationship between all related factors into account, water management requires various kinds of experts as analysts for policy analysis.

Policy analysis plays an important role in assisting the decision-makers to select feasible and acceptable solution. In policy analysis, the alternatives are screened, evaluated and finally presented to the decision-makers and the public. The presentation should be clear and easy to understand for the decision-makers who may have very little scientific knowledge. Many analysts make an extensive use of mathematical models in evaluating the proposed alternatives for water management.

After basic concepts of policy analysis are summarized, development of numerical models and their application as analytical tools in water quality analysis and policy analysis are reviewed in this chapter. Finally, legislative system for water management and water quality related issues in Japan are discussed.

2.2 Water management

In order to provide a comprehensive water management system, integrated water management takes into account all the factors that influence and are influenced by the water system. The words "integrated" or "comprehensive" refer to the concept of considering the compound uses and functions of the water (including flood control) in one or more basin (Koga et al. 1994a).

Existing government power over national water bodies is not able to solve the problems of transboundary river basins. The obvious examples are the Rhine in Western Europe and the Ganges in South Asia. For deltaic areas involved by many riparian countries, corporation among the involving countries becomes necessary in water management. Lacking of international river authorities has made sensible international river planning impossible. The only solution in such cases is to plan for the downstream country by taking consequences of upstream policies into account as boundary conditions (CUR 1993).

In 1957, an international commission of the riverine countries was established under the auspices of what is now the Economic and Social Commission of Asia and the Pacific (ESCAP) with a view to coordinating the activities of technical and economical development of various parts of the Mekong delta. At present, this commission is known as the Interim Committee for the Coordination of Investigations in the Lower Mekong Basin. One of the important programs of the Mekong Committee is the introduction of an appropriate flood control and water management system in order to create the optimum hydrologic conditions in the Mekong delta. Being an island country, Japan is isolated from such a problem with neighbor countries.

Takebayashi (1993) characterized the water management in Japan by comparing the systems used for river administration in Japan and the Netherlands. Some similarities between the systems used in both countries such as procedures for drawing up the policies were pointed out. Case study of comprehensive development project in Lake Biwa was demonstrated to give an idea of water management in Japan.

Usage of river basin resources depends on the development and structure of society (CUR 1993). It is necessary to consider about the consequences of human activities on the river environment. Impacts of various types of water use that may take place on hydrology and biota are listed in Table 2.1. Degree of the impact caused by same kind of hydraulic works may be different depending on characteristics of the basin, purpose of the project, etc. With appropriate countermeasures, these impacts are sometimes avoidable. The predicted impacts should be weighed with the advantages that will be obtained. To handle with unavoidable impacts that may occur, mitigation measures should be defined.

In order to evaluate the proposed alternatives and their impacts on the water body, policy analysis with assisting from numerous types of academic experts is necessary for water management.

Table 2.1 Hydraulic works and their possible impacts

Types of hydraulic works	Possible effect on hydrology	Possible effect on biota
dams in river valleys	stagnation	loss of running water species
	changing groundwater table	loss of hygrophytes
lowland reservoirs	isolation	managed populations
decapitation of rivers	decreasing discharge	loss of spawning grounds
canalisation	changing of flow	loss of biotope diversity
locks, barrages	intermittent flow	migration disturbance
diversion of rivers	changing drainage	alteration of biocommunity
communication of waters	water quality affected	biotic forgery
flushing measures	water quality affected	removal of biota
level manipulations		
a. groudwater drawdown	loss of volume	loss of hygrophytes,wetlands
groudwater-rise	gain of volume	gain of hydrophytes,wetlands
b. surface water	shore erosion	loss of shore biota
c. fixed tidal water level	stagnation	changing brackish biota
bottom lowering(mining)	increase of volume stratification	loss of bottom fauna,fish and birds
transport from low to high lands	water quality	loss of specific biocommunities
recharge of aquifers	quality and quantity	alteration of vegetations
drainage of soils	loss of sources	loss of hygrophytes
polders	controlled system	loss of aquatic system
		gain of aquatic systems(ditches)
agricultural irrigation	flow regulation	harm to wild flora and fauna
agricultural sprinkling	surface and groundwater balance	affects wild flora and fauna
agiricultural drainage	quality and quantity loss of ditches	loss of aquatic habitats
heating(cooling water)	stratification	fish damage
dredging	favours transport	resists moorland communities and favours aquatic biota
specific industries	acidification of rain	damage to specific species
salt water wedge repulsion	desalination	loss of salt marshes
control of floods	flow regulation	loss of spawning grounds and changing vegetation
dumping	turbidity and decrease of volume	depends on quality and quantity of dumped material
bank protection	wave energy dissipation	loss of biota depending of kind of artificial substratum used
shore and bank profile	circulations in the water	limits use of substrata by flora and fauna

Source: CUR (1993)

2.3 Policy analysis

Policy analysis is an important procedure in water management before the final decision will be made because complexity of the water system limits an insight in impacts of the policies. With policy analysis, it is possible to gain the better insight in the impacts of the proposed policies. The objective of this procedure is to obtain various measures in which all water users and functions of water are comprehended. This procedure involves an analysis of the water system and its existing problems and should be carried out by the representatives of water users, stakeholders, the involving authorities and academic experts. In this section, basic concepts of policy cycle are summarized and an insight in policy analysis is given through the review of Policy Analysis of Water Management for the Netherlands (PAWN).

2.3.1. Policy cycle

As a part of policy cycle, policy analysis is demonstrated in Fig.2.1. It should be noted that decision-making is not included in policy analysis. Some explanation about basic concepts of the policy cycle (Koga et al. 1994a) is listed below:

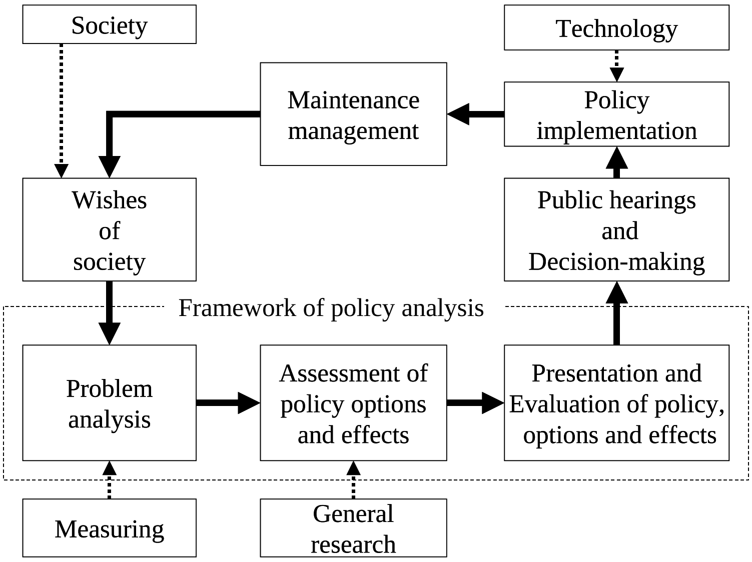


Figure 2.1 Policy cycle

Source: Koga et al. (1994a)

- Determine of water users and functions of the water.

Each water user has one own interest. Function of the water for one user may differ from others. However, this difference can be changed depending on how much the user can compromise with other users. Naturally, most users try to protect their interests as much as possible. Determination of all water users and water functions provides an insight in current situation of the water system, which leads to problem analysis.

- Problem analysis

Through the consideration of water users and functions of the water, some valuable details of water environment can be obtained. Utilizing this information, water problems at present as well as future situation can be pointed out in this step.

- Determine of the goal and objective

Desires of the water users can be defined upon the determination of water users and functions of the water. The desired situation or wishes of the society leads to a certain evaluation criteria for the proposed policy.

- Design and pre-selection of alternatives

An alternative is composed of measures that are believed to solve the existing problems. Pre-selection of alternatives helps reduce the number of alternatives and screen unreasonable measures.

- Impact assessment

It may be unavoidable to adopt modern computer-aided analysis methods in system analysis or policy analysis when the water body is involved by many interests, authorities and policy makers. Obviously, application of these methods may vary from relatively simple one to very complex and extensive one. When possible, it is better to choose the simplest method that can complete the task (CUR 1993).

In order to select the best choice, impacts of each alternative on the water system are assessed. Numerical models and expert opinion are effective tools for impact assessment. Based on scientific and technological aspects, prediction approach that can give a quantitative insight of following factors is required.

  - Impact assessment of policy alternatives and various measures
  - Cost-benefit analysis
  - Risk evaluation

The proposed alternatives must have political and bureaucratic feasibility and be acceptable by the involving parties, who are in control of a part of water system. If one of the involving parties cannot accept the alternative then that alternative is not feasible and can be neglected, even if it is very promising in other ways. It is suggested that the alternatives that are not feasible due to these reasons should be eliminated as much as possible in the pre-selection phase to prevent unnecessary research.

- Comparison and evaluation of the alternatives

The analysis results of each alternative are then compared with each other. After that the alternatives are evaluated with the evaluation criteria.

- Presentation of the results

In this step, results of the evaluation are presented to the decision-makers and the public. The presentation assists the decision-makers by providing an insight in advantages and disadvantages of the proposed alternatives. It may consist of scorecard, cost-benefit analysis, etc. Many decision-makers have very little technical knowledge. Therefore, the presentation should be done as clear as possible and easy to understand without using many technical expressions.

Being involved by many complicate processes and uncertainty of the nature make policy analysis unable to give an exact prediction of the future, just a prediction of future trends. Generally, implemented policies must be evaluated and adjusted if necessary. Unforeseen side effects and changes in the demand of the society lead to the need for new policies and policy analysis, thus making the policy cycle round.

- Decision-making

As mentioned before, the procedure of decision-making is excluded from policy analysis. It is left for political groups or bureaucratic groups. The decision-makers have a difficult task to judge on the importance of the different units and select the preferred alternatives. Providing uncomplicated and adequate information obtained from policy analysis step can support the decision-makers to make better decisions. This is why the policy analysis is considered important in water management.

2.3.2. Policy Analysis of Water Management for the Netherlands (PAWN)

In the country that has long history of facing water related problems like Netherlands, many measures and authorities are available for handling with water problems. A large number of models and approaches are developed and effectively used for conducting sophisticated policy analysis with the integrated strategy for water management. PAWN system is developed for integrated water management during the 1970s. Scope of PAWN is demonstrated in Fig.2.2.

In the Netherlands, water management policy is under the responsibility of the Ministry of Transport, Public Works and Water Management (Rijkswaterstaat). PAWN was developed by Rand Corporation from the United States, Delft Hydraulics Laboratory and Rijkswaterstaat in order to design the policy guidelines. Objectives of PAWN are to develop a methodology for assessing multiple consequences of national water management policies and to apply this methodology in generating and analyzing the alternatives of water management policies (Goeller 1983).

Van Beek (1993) described about PAWN as a coherent computational framework in which various models and databases are integrated with the objective to support the Netherlands government in their decision-making process on integrated water management. Water use functions are taken into account in this system. The relation between two components, user-function (demand of water and discharge of pollutant) and water-system (condition of water system including water supply), is used to evaluate the impacts of human activities. The models and databases are used to represent each component. Occasionally, some models represent more than one component.

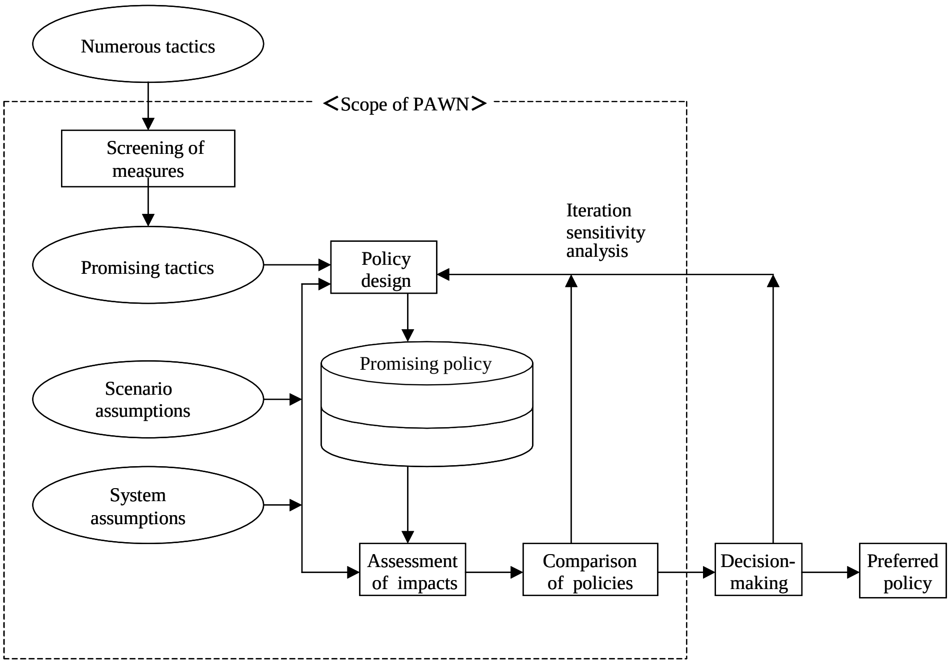


Figure 2.2 Stages of policy analysis

Source: Ankum et al. (1988)

There are three types of modeling for ecological aspect in PAWN (Van de Ven 1994).

1. Mass balance modeling

   Mass balance models represent the mechanism of mass change of constituent in the water. Example of mass balance models in PAWN is DBS (Van der Molen et al. 1994).

2. Empirical relation among ecopopulation, vegetation types and abiotic parameters

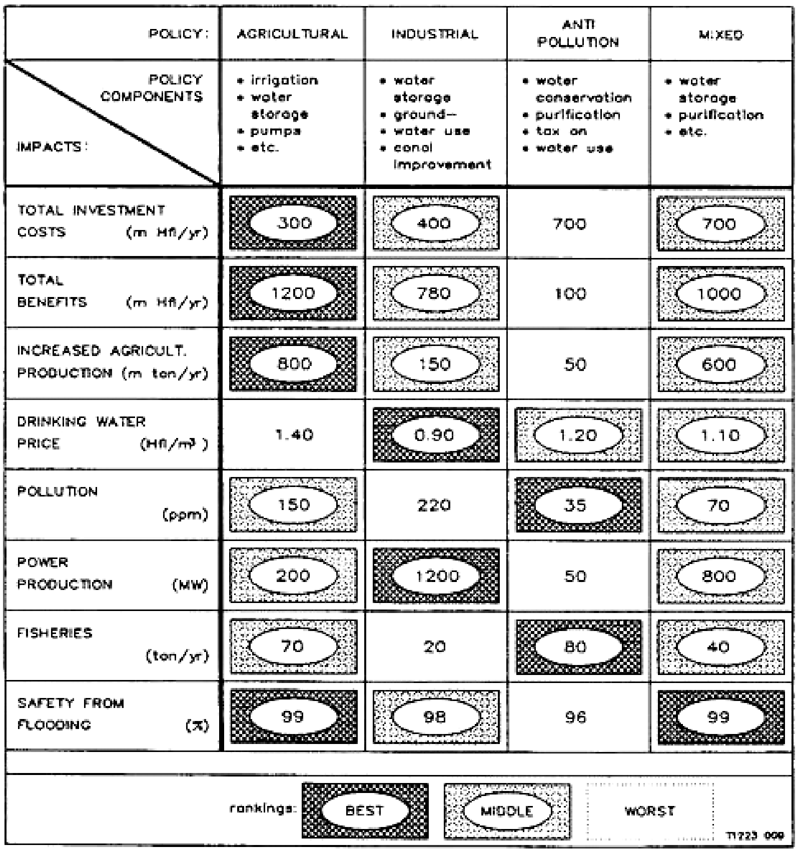
   This type of models can be listed as DEMNAT (Witte and Claessen 1991), DEMAQUA and HEP/HSI. Impacts of human activities on ecosystem can be evaluated by these models.

3. Structured (dynamic) ecosystem modeling

   By taking into account physiological and ecological processes, structured ecosystem models quantify ecopopulations in the water system.

The presentation of evaluation result should be clear and easy to understand so that it can provide the decision-makers an insight in impacts of the policies. There are many ways to present the results effectively. The methods such as measuring rods, scorecards, multi-criteria evaluation technique, AMOEBA and mondriaan presentation technique are employed in PAWN.

The scorecard method of presentation of analysis results was introduced by Rand Corporation in policy analysis with respect to the Eastern Scheldt closure. Calculation results of the effects of the proposed strategies are organized in a set of scorecards, listing in a vertical direction the considered criteria and horizontally one or more alternatives (Fig.2.3). Different scorecards are drawn up for different scenario conditions or system assumptions (Goeller 1983).



POLICY:	AGRICULTURAL	INDUSTRIAL	ANTI POLLUTION	MIXED
POLICY COMPONENTS IMPACTS:	• irrigation • water storage • pumps • etc.	• water storage • ground– • water use • canal improvement	• water conservation • purification • tax on • water use	• water storage • purification • etc.
TOTAL INVESTMENT COSTS (m Hfl/yr)	300	400	700	700
TOTAL BENEFITS (m Hfl/yr)	1200	780	100	1000
INCREASED AGRICULT. PRODUCTION (m ton/yr)	800	150	50	600
DRINKING WATER PRICE (Hfl/m³)	1.40	0.90	1.20	1.10
POLLUTION (ppm)	150	220	35	70
POWER PRODUCTION (MW)	200	1200	50	800
FISHERIES (ton/yr)	70	20	80	40
SAFETY FROM FLOODING (%)	99	98	96	99

rankings: BEST MIDDLE WORST

T1223 009

Figure 2.3 Sample scorecard

Source: Van Beek (1993)

Development, maintenance and application of PAWN summarized by Van Beek (1993) are described as follow:

PAWN was first introduced as PAWN-I by the end of 1979. The first version of PAWN mainly concerned in water quantity and economics. In water quality, only salinity and water temperature were considered. During 1980-1985, PAWN-I was improved and transferred into the responsibility of Rijkswaterstaat from Rand Corporation and Delft

Hydraulics. In 1985, the Second National Policy Document on Water Management was prepared from information provided by PAWN-I.

The third phase of PAWN (1986-1990) is called PAWN-3rd Note because it was used in preparing the Third National Policy Document on Water Management released in 1989. Water quality and ecology components of PAWN were improved.

Objective of the Third National Policy Document is integrated water management. Concept of integrated water management is to create a balance between economic interests and desires of society for environment. Many projects for improving the water system such as REGIWA (REGional Integrated WAter management) were initiated under the Third National Policy Document in order to promote the integrated approach in regional water management. This policy has been implemented in provincial regulations and in plans of water boards.

In 1991-1994, PAWN was improved in groundwater model, emission model and aquatic ecology model. A Geographic Information System (GIS) was introduced. Because it was applied in the Aquatic Outlook Project (WSV), this PAWN is referred as PAWN-WSV.

The fifth phase of PAWN was employed for the Forth National Policy Document on Water Management in 1997.

Most of development and maintenance tasks are mainly carried out by external agency like Delft Hydraulics. Rijkswaterstaat, who is in charge of PAWN, takes care of guidance in development and application of models in policy analysis and translates results of the analysis into policy statement.

Delft Hydraulics has applied PAWN approach in various countries such as Taiwan, Greece and Indonesia. Although Japan and the Netherlands are different in geographic and morphological conditions, Van Beek (1993) indicated that general approach and philosophy of PAWN were applicable in Japan. However, the author suggested that some specific aspects according to the main policy of Japanese government were required. It was recommended to apply PAWN in a pilot area such as island or river basin in order to investigate the applicability. The proposed alternatives need to be evaluated in both Japan and the Netherlands but the difference between two countries in policy analysis is the evaluation in Japan is separately made for flood control and water use by different organizations (Takebayashi 1993).

Many authors had reviewed about PAWN in their works. Nishida (1993) had mentioned about an overview of PAWN in water management in the Netherlands through the study project of Public Works Research Institute (PWRI) of Japan. Most recent developments according to PAWN-study are summarized in the National Policy Document on Water Management (Rijkswaterstaat 1989).

With the increase in water demand and interests, water system becomes more complicated than in the past. To evaluate the proposed alternatives, various analyses are required in policy analysis. As a result, many kinds of academic experts and analytical tools are necessary. According to technological development, numerical models become ones of effective analytical tools for water management.

2.4 Development and application of numerical models in water management

In the present days, computers are greatly developed in computational capability and widely employed in various branches of works. As analytical tools, numerical models play important roles in water management. General concepts in development and application of numerical models in water quality management are summarized below:

1. A simple model is preferable if it can sufficiently solve the problem and provide accurate results. It is not necessary to include all parameters and variables in the analysis. However, interrelation among various water quality parameters must be clearly understood.

2. It is preferable to use a specific model to solve the problem rather than a generalized multipurpose model because the generalized model is expensive, difficult to understand, requires a number of data and sometimes cannot handle the problem in micro level.

3. Not only the mathematical method used in model development, but attention should also be paid to the validity of each parameter in the model. Too many assumptions on the model parameters will result in unreliable and useless outputs.

4. Modeling and data collection process should proceed in parallel. Modeling often gives a better insight to the type of data that should be collected. Besides the existence of the data, its accessibility, accuracy and usability are also important. Raw data often require a great deal of messaging before it can be converted to a form where it can be used as input to a model (Biswas 1976).

5. The model should be developed in a way that obtained results can be linked to the current decisions. It should be able to provide answers to the decision makers' questions such as what decision should be made to meet the final goal and what would be the effects on water quality resulting from the current decision.

6. The developed model should be up-to-date and useful for current application. It should be updated when more information is available or understanding in the processes and relation between parameters in the model gets improved.

7. It is important that the users clearly understand in principle and assumptions of the model as well as applications and limitation of the model.

8. A good document manual is very useful for users in providing detail of how to use the model. Principal concepts, assumptions used in the model and limitation of the model should be clearly given in a manual.

Not only in water quality management, some of these concepts are also applicable to other kinds of works in which the models are applied.

Until these days, many mathematical models have been developed and applied as effective tools in water management. Roles of mathematical models in water management and related fields are summarized as follows.

Watershed models

Wurbs (1998) classified generalized water resources models into (1) watershed models, (2) river hydraulics models, (3) river and reservoir water quality models, (4) reservoir/river system operation models, (5) groundwater models, (6) water distribution system hydraulic models and (7) demand forecasting models.

Singh and Woolhiser (2002) summarized historical perspective of watershed modeling, recently used models, new development and challenges for watershed models and predicted the direction of watershed hydrology modeling in the future. The authors stated that watershed models were used to evaluate the impacts of watershed management strategies, linking human activities within the watershed to water quantity and quality of the receiving water (Mankin et al. 1999; Rudra et al. 1999) for environmental and water resources. The rational method developed by Mulvany (1850) and an “event” model by Imbeau (1892) for relating storm runoff peak to rainfall intensity are referred as an origin of mathematical modeling on hydrology. Some of the watershed models from Singh and Woolhiser (2002) are listed below.

The MMS model of the U.S. Geological Survey (USGS) is used for water resources planning and management works, especially in the works of the U.S. Bureau of Reclamation (Singh and Woolhiser 2002). Besides the MMS model, other examples of currently used watershed models are HEC-HMS (HEC 1981, 2000; Feldman 1981) which is a model for drainage system design and evaluating effects of change in land use on flooding, NWS for flooding forecast, UBC (Quick and Pipes 1977), WATFLOOD

(Kouwen et al. 1993), SHE and SHESED (Abbott et al. 1986a, 1986b; Bathurst et al. 1995).

The tank model

The tank model is a mathematical model developed by Sugawara (1967). Main purpose of this model is to estimate the amount of runoff originated from the catchment area. Though the tank model has been qualified for both short-term and long-term runoff models, its performance in simulating of long-term runoff is more outstanding. The parameters used in short-term model are different from those in long-term model. As a result, it is difficult to apply both models together (Kadoya and Nagai 1988a).

After the development of LST I in 1983, Kadoya and Nagai (1998a) developed another long- and short-term runoff model, LST II, with the same basis of the tank model. The upper tank was modified in order to improve its capability in short-term runoff simulation. Inside of the upper tank was replaced with two small tanks lying in vertical. Each small tanks represents flood surface runoff. The developed models were performed for runoff simulation in the Kama experimental basin in 1975-1982. The obtained results were compared with those obtained from Sugawara’s tank model. Relative errors in the long- and short-term runoff models were smaller than in the tank model. The authors also stated that both LST I and LST II had less parameters than the tank model. The long- and short-term runoff model LST II (Kadoya and Nagai 1988b) was applied for flood analysis and long-term runoff analysis in the reservoir basin. Precipitation data was estimated from the observed data obtained from telemeter gauge stations. The simulated results agree well with the observed runoff hydrographs in both identification and verification period.

Tada et al. (2002) compared two runoff models in the simulation of short- and long-term runoff of small-forested catchment. LST II has better performance for long-term runoff while the modified TOPMODEL can account better for rapid storm. The authors mentioned that TOPMODEL was more preferable for water quality modeling because fewer parameters and less storage in the model were required. TOPMODEL is a watershed hydrology model developed in 1979 by Beven and Kirkby. It was developed to contain more information of catchment, more physically based processes and improved parameter estimation. At present, TOPMODEL is the standard model for hydrologic analysis in many European countries.

Ministry of Construction, Republic of Korea organized the study of hydrological characteristics of three representative basins in Korea under the International Hydrological Program, IHP in 1982-1989. Yoon (1993) applied linear models such as runoff function and nonlinear models such as storage function and the tank model for runoff analysis in the study basins. The author suggested storage function model for prediction of flood hydrograph.

The box model

The water quality models based on the box model were adopted by many researchers for the analysis in various estuary and seas in Japan. Sekine et al. (1995) examined the influence of development activities on shallow sea ecosystem of the Seto Inland Sea using a Shallow Sea Ecological Modeling tool (SSEM) based on the box model. It was found to be difficult in estimating local deficit oxygen using SSEM because of its large water volume. Nitrogen budget was examined in an artificial tidal flat in Osaka Bay in September of 2000 and 2001 by Yamochi et al. (2003). From observation and application of the box model, nitrogen uptake by the algal growth in the artificial tidal flat was around 72% of total nitrogen fixed in one day. Algae and benthic animals were found to have large contribution in nitrogen cycle in the experimental tidal flat area of Osaka Bay. Yanagi (1999) applied budget models (Yanagi 1997) in nutrient budgets analysis in Hakata Bay and compared with nutrient budgets in Mikawa Bay (Matsukawa and Susuki 1985) and Tokyo Bay (Matsukawa and Sasaki 1990). Matsunashi and Imamura (1998) estimated the reduction effects of pollutant load on water quality in Tokyo Bay using the box model.

Water quality models

Koga et al. (1994b) classified water quality models based on (1) water quality parameters that are involved; (2) time-scale condition; (3) spatial dimensionality; (4) particular aspects of hydrologic system that are simulated; and (5) numerical techniques used in model formulation or computational methods used to obtain the solution.

Pollutant control is one of important processes in water quality management in a river. Yamamoto et al. (1995) developed a simple one-dimension dispersion model for carbonaceous BOD, nitrogenous BOD and DO simulation and an optimization model for BOD loading control in a river. The optimization model was applied in determining the maximum loading that can be discharged into the receiving water. As a case study, the developed models were applied to the Kase River, Japan. Chihara and Sadako (1993) analyzed pollutant loading, self-purification in rivers and eutrophication in lakes. Self-purification functions in a river system, such as utilization of nitrogen removal in paddy field and purification of polluted river water through ground seepage, were proposed for loading reduction. A simulation model of self-purification was developed to evaluate the proposed functions. In order to select the optimal technique, the expert system, based on the information of the pollutant sources in a basin, was applied.

In estuarine area and seas, water movement and mass transport are more complicated than in rivers or lakes. In order to understand and simulate the phenomena in coastal and sea area, many efforts have been paid to development of mathematical models. There are various kinds of models available for different objectives of the analysis.

Numerical model of nutrient behavior between water and sediments was developed by Ukita et al. (1985) based on the experiment and in-situ survey in eutrophic seas. Amount of adsorbed phosphates released from the sediment layer was found to be dependent on the dissolved oxygen in the water layer above the sediment layer. Release rates of nitrogen and phosphates were determined by the developed model. Three-dimensional layer integrated model was applied to predict water elevations, layer averaged velocity components, distribution of conservative and non-conservative materials and sediment transport fluxes in estuarine and coastal waters in the Humber Estuary in the U.K. (Falconer and Lin 1997). Futawatari and Kusuda (1993) developed a two-layered sediment transport model using a Lagrangian reference frame. The advection term in this model can be eliminated and numerical dispersion can be reduced because the frame travels with water movement up and down the estuary. Finite element method has been used in developing multi-layered models for stratified flow problems in strongly stratified water bodies (Wang and Connor 1975; Simons 1973; Cheng et al. 1976; McNider and O'Brien 1973).

Because of its complicate water movement, simulation in a semi-closed sea like the Ariake Sea is attractive to the analysts. A hydrodynamic model was developed for studying the dispersion of pollutants and transport of sediment in the Ariake Sea using finite element method (Oshita et al. 1994). The Galerkin weighted residual technique was used in formulating this model. Patterns of current and profiles of water level in the Ariake Sea were obtained from the simulation. Araki et al. (2001) simulated the tidal flow and material transport in the Ariake Sea by using two-dimensional flow/mass transport model (MIKE21). Simulated water movement and salinity before and after the closure dam installation were compared. The obtained results demonstrated slight change in tide level and tidal current due to the closure dam. MIKE21 was also applied in water quality simulation in the Ariake Sea (Araki et al. 2002). Important phenomena in the shallow sea such as resuspension were taken into account. The author suggested that MIKE21 was more effective when simulating water quality in the innermost area.

Water quality modeling is also described in the literatures of Biswas (1976), Loucks et al. (1981), Orlob (1983), Thomann and Mueller (1987), and others.

Ecological models

Impacts of the proposed alternatives on ecosystem are another important factors that should be concerned in water management. In order to simulate the aquatic ecosystem, many ecological models have been developed (Chen 1970; Thomann et al. 1974, 1975; Larsen et al. 1974; O'Connor et al.1969, 1976; Chen and Orlob 1975; Di

Toro et al. 1975; Di Toro and Connolly 1980; Najarian and Harleman 1975; Walsh 1976; William and Hinwood 1976; Baca and Arnett 1976; Jorgensen 1976, 1983; Jorgensen and Harleman 1978; Harleman 1978; Orlob 1983; Thomann and Mueller 1987). In the ecological models, mass transport by convection and diffusion is taken into account together with chemical and biological transformations in the water.

Application of numerical models in water management

Making use of Decision Support System (DSS) enhances operational water management. The DSS is useful for assisting the managers and operators in decision making for day-to-day operation. The DSS is often a mathematical model that simulates the quantity and quality parameters in the water system. The model is applied in order to find out possible operation strategies before actual execution. With the application of DSS, the decision-makers are facilitated in selecting the best strategy for specified objectives. Such models are recommended with data assimilation techniques (e.g. Kalman filtering) to incorporate real-time field data. Further refinements in the DSS can be obtained through usage of expert systems or optimization models (CUR 1993). The decision support tool named PRIMAVERA model (Van Sluis et al. 1994) was developed to help the decision-makers in technical aspects of alternatives and aspects of acceptance in the Netherlands. By allocating weights to different aspects, the PRIMAVERA makes alternatives comparable for the decision. It also assists in the communication with other experts and related persons.

In the Netherlands, many kinds of models are used in policy analysis to evaluate impacts of the proposed alternatives on ecology, economy, agriculture, safety, etc. Van de Ven (1994) reviewed the numerical models employed in the Netherlands with some examples listed as follows. The IMPAQT model (IMPAQT 1993) was used for the simulation of organic micropollutants, heavy metals and radionuclides in rivers and lakes. For eutrophication problems, DBS (Van der Molen et al. 1994) was developed for simulating nutrients, sediment-water-interaction and algal growth. This model can simulate the growth of nine species of algae concerning the growth limiting by nutrients and light. It was applied for the simulation of algal concentration in Lake Veluwe, the Netherlands in 1985-1986. Making use of the database of numerous lakes, BASIS (Van Nes and Scheffer 1993) can predict ecological conditions of a lake based on analogies with lakes having similar physical and chemical characteristics. The database utilized in this model is composed of physical and chemical parameters of the lakes, morphology data, information of algae, zooplankton and fish. It is used to estimate effects of a reduction of phosphate load on chlorophyll-*a* concentrations. Witte and Claessen (1991) developed DEMNAT for estimating effects of changing groundwater levels, changing seepage water supply and additional surface water supply on groundwater dependent ecosystems. DEMNAT was applied for the evaluation of policy in the National Policy

Document for the Drinking and Industrial Water Supply issued in 1993 (Witte et al. 1993).

Van Dijk (1994) introduced integrated water management system for Ushizu area. Ushizu Town has a typical Japanese water system. Under the storm, water is drained very quickly through canals. On the other hand, water will become stagnant when there is no rain for long period. Two main problems investigated in Ushizu area are inundation and water pollution. The author purposed three alternatives for flood and water quality control. Impacts of the purposed measures were assessed using a branch-node model named DUFLOW. The branch-node model is one-dimensional finite element model, which is applied for analyzing unsteady flow and dispersion problem in a hydraulic network system (Booij 1980; Koga et al. 1988; Spaans et al. 1989, etc.). The evaluation indicated that improvement and increasing in the inlet from irrigation canals can improve the water quality in short period and construction of sewerage system for solving long-term problem was suggested.

Embanking of overland longitudinal flow and overbank storage can cause a rise in flood level of rivers. To predict this rise for various options of dyking and provision of floodways, a mathematical model presented by SOGREAH under the auspices of UNESCO was applied to the Mekong River. This model simulated flood conditions in the non-tidal reach of the river (upstream of Can Tho). Magnitude of the rise at a certain location depends on magnitude of flood and extent of dyking. It was found that in the case of complete dyking the 100-years' flood would increase by not less than 2.7 m in Kompong Cham, 2.6 m at Phnom Pehn and 0.4-0.6 m in downstream stations. Partial embanking and provision of floodways lead to much smaller effects (UN-ECAFE 1969)

One-dimension water quality model was applied for water quality management in tidal rivers by Sudjono (1998). In the problem analysis, low dissolved oxygen was observed in the study river. Flushing measure was purposed to increase the dissolved oxygen and control deposited mud. The alternative evaluation showed that, together with pollutant load reduction, flushing with fresh water can improve the dissolved oxygen and decrease deposited mud in the study area.

Lee et al. (1996) developed the water-sediment quality model with the basis of the box model for water quality management in the Seto Inland Sea. The developed model was applied to examine influences of discharged loadings from land area in 1957-1987. It indicated that T-N and T-P loadings greatly affected the water quality in the Seto Inland Sea. Two alternatives loading abatement were proposed and evaluated using the developed model. It suggested that 30%-80% reduction of T-N loading and 60%-65% of T-P loading was required in the area of Bisan Seto and Osaka Bay.

Nakatsuji et al. (2003) proposed three-dimensional models for evaluating the policy of Area-wide Total Pollutant Load Control on COD in Osaka Bay in 1950-2000. The proposed models consisted of the flow model ODEM (Osaka Daigaku Estuarine Model), water quality model and sediment quality model, which interact to each other. The study indicated that COD and nutrients loadings discharged into Osaka Bay increased rapidly since the 1940s. COD and T-P loadings were highest during the economic growth in the 1970s. In the analysis on the effect of discharged loading, water quality in Osaka Bay was simulated under various conditions. The policy of loading control on COD together with nutrients gave a better result in improvement of water quality than the policy of controlling COD loading alone. This is because nutrients can accelerate the productivity of biomass, which leads to high COD concentration. Besides COD, it is necessary to control nutrient loadings as well.

2.5 Legislative system for water management in Japan

Legislative system is one of the most important instruments in the policy cycle in water management. Without approval and permission from legislative organs, the final goal of water management cannot be achieved. Because of long history of cultural and political background, Japan has different legislative system from those of the countries in Europe, the United States or even in Asia. History of development and management of water resources in Japan is summarized to give clear understanding in characteristics of legislative system for water management in Japan. After that, master plans for water management in Japan are introduced.

2.5.1. History of water resources development and management in Japan

Until the end of the Shoen era (15th century), objective of river development was flood control. People tried to protect their lives and properties from flood and drought. Although they knew that living near riverbanks was dangerous, people moved from valleys and settled down along rivers because it was convenience to get water for producing food and the soil was fertile.

The law which allowed inhabitants to own the land where they had settled as private property was issued in 742. This law led to the “Shoen” system in which manors were governed by aristocrat landowners.

During the Sengoku era (16th century), people learned to construct dikes, levees and dig channels in order to improve and control rivers for flood control and irrigation. After the flood in 1542, a feudal lord named Shingen Takeda initiated river works to control the Kamanashi River to protect the Kofu area, which is Yamanashi Prefecture at present. Hideyoshi Toyotomi conducted many river improvement works such as relocation of channels of the Kiso River and construction of levees along the Yodo River.

A lord in Kyushu region, Kiyomasa Kato, installed retarding basins to mitigate flood damage from the Midori, Kikuchi and Shira rivers.

Rice production was a power indicator of the country in the Edo era (1603-1807). Agriculture was promoted at the beginning of this era. Cultivation areas were expanded under the supervision of the Tokugawa Shogunate. In order to support farmers, water works for irrigation were rapidly developed. Low water channels were installed next to flood control facilities. Channels were excavated in the Tone, Kiso and Edo rivers as inland navigation routes for transporting rice. After moving to Edo in the early 17th century, Ieyasu Tokugawa executed many river works to divert the Tone River in order to protect the Edo area from flooding.

"To build a wealthy, strong and modernized Japan and catch up with the western European countries" was the national aspiration and political goals after Japan had opened itself to the world in the Meiji era (1868-1911). The Meiji government heavily promoted agricultural productivity especially rice by giving the rights of water and land use to farmers. Land was defined as private property while rivers were defined as public property. The government was responsible for flood control and water management. At the same time, they can get tax from landowners. Dutch engineers were invited to give an advice for river works. Channel dredging and sand control were introduced for the improvement of navigation. The first River Law was enacted in 1896 after big floods in 1893 and 1896. Main purposes of the River Law are to organize legal system for flood protection and water privilege permission. River improvement was carried out in the Edo, Yodo and Chikugo rivers. To promote agricultural production, the River Law strengthened the priority of irrigation over drinking water supply and industry. The first Flood Control Plan was authorized in 1911 after several floods had occurred during 1902-1910.

From the Taisho era (1912-1926) to the beginning of the Showa era (1926-1989), agricultural system was changing by the modernized machinery. Using new technology and chemical fertilizer increased crop yields. Flood control works were carried out under the Second Flood Control Plan (1921) and the Third Flood Control Plan (1933). These works were finally removed from national projects according to World War I in 1941-1945.

After World War II, General Head Quarter (GHQ) organized by the United States introduced economic revival plans and agricultural revolution. Farmers had a right to own the paddy field. The selective rivers were managed by Ministry of Construction (MOC), which is Ministry of Land, Infrastructure and Transport (MLIT) in present.

Water demand was raised due to rapidly industrial development during the period of economic growth. Pattern of water use was also changed. The River Law was revised in order to catch up with the increase in population and economical development. The second River Law was drafted in 1964 in which the water use concern was added. Rapid growth in economical and industrial activities has increased pollution and diseases. The Water Pollution Control Law was enacted, and environmental quality standards were established.

Since the beginning of the Heisei era (1989), the pollution problems in the period of economic growth have drawn the attention about the environment of the people. Besides safety in life and property, the demand for good river environment has increased. Environmental oriented was included in the revision of the River Law in 1996. The third River Law put an emphasis on nature, landscape and recreation. The legal framework are provided for environmental plans. Master plans for river works are divided into two steps. In the first step, information is opened to the public, which allows people to participate in planning. The second step is public hearing. With opinions from local residents, the government will be able to create a better river environment. Ecohydrological system analysis is introduced in water management in order to restore sound environment.

Recently, many environmental related topics have been brought up to the society. People pay more attention to environment problems. Reclamation and relationship between local residents and water are promoted continuously. The River Law provides the legal framework for environmental plans and programs of central government, the municipalities and lays down regulatory procedures for planning and permission. Many water resources development projects have been developed in order to meet the increasing demand due to economical development and the increase in population. Some conflicts occur during developing the plan or even in the progress of construction according to the difference in interests.

The closure of Isahaya Bay has brought up such a conflict among the government and water users in the Ariake Sea. Problem of laver productivity in the Ariake Sea occurred in 2000-2001, which leads to many public discussions related to the bay closure and ecosystem in the Ariake Sea. A number of committee and researcher groups are organized in order to handle with this problem. According to the environment oriented, policy analysis and water resources management are necessary and should be carried out in water resources development project. Demand of water user, opinion of local residents and functions of the water should be concerned when determining objectives and goals. Public participation in the plan development defines the real desire of involving parties and leads to the better agreement.

2.5.2. Characteristics of legislative system in Japan

Koga et al. (1994b) quoted about policy analysis and differences between Japan and the Netherlands as "Japan differs in many ways from the Netherlands. …Geographical differences give different water related problems but can be tackled with policy analysis. The legislative and social differences have many big impacts on the water management but cannot be tackled with policy analysis. These impacts should be carefully considered in a policy analysis."

Existing political, bureaucratic and legal systems of the country impose great influence on water management. Before analyzing policies, it is important to have knowledge about these systems.

An old Chinese proverb is: "One who can manage the water of the river can manage the country". Van Wolferen (1992) stated in his publication: "'Bring me to your leader', Japan had none". "If there is nobody who can manage the country then who can manage the water?" The answer is the same, "In Japan there is no one".

In European countries, the government has the highest power to make a decision in national policy. In the United States, this power is divided over a number of councils, institutes, boards, etc. The central government takes action in pushing these authorities to pass and implement a policy. Having a ministry with overall power in water field eases water planning on a national scale. Unfortunately, there is no one who makes the final decision in Japan. Japan has many semi-autonomic components with their own political power and is not represented by one central body that is in charge. There is no highest authority with the ultimate power in policy defining (Van Wolferen 1992). In Japan, there are many organizations that involve in policy making for water including private sectors like farmers and industries and very few corporations between each semi-autonomic component. Corporation will occur only for benefits or interests of their own not for the benefits of society which makes it difficult to apply integrated water management in this country. The ultimate power in decision-making and negotiation is necessary for water management in Japan.

2.5.3. Master plans for water management in Japan

Takebayashi (1993) reviewed about master plans for water management in Japan, which are based on the Comprehensive National Development Plan. Objectives of the Comprehensive National Development Plan are to ensure comprehensive use and development, conservation of the national land, appropriate use of industrial land and improvement of social welfare.

According to the second River Law (1964), rivers in Japan are classified into two classes: class A rivers and class B rivers which are managed separately. The rivers that relate to the national land conservation and the national economy are designated as class A rivers while the other rivers are class B rivers. Master plans for class A rivers are administrated by MLIT whereas master plans for class B rivers are under the responsibility of prefectural governments.

- Master Plans for Implementation of Work

Main purpose of the Master Plans for Implementation of Work is to establish integrated flood control measures for the whole river system and secure the usage of water resources. Under the Comprehensive National Land Development Law, these master plans are related with the Master Plans for Water Resources Development and any plans of national land development.

Before the revision of the River Law in 1997, river administrators drew up a master plan for each river and evaluated it by themselves, and details of river improvement and public hearing were not clearly described in the former Master Plans for Implementation of Work. According to the revision, the Master Plans for Implementation of Work are separated into two components: the Basic Policy for River Improvement and the Plans for River Improvement. Conservation of river environment was added in the basic policy component.

The adoption of these master plans for class A rivers is described below:

1. The Basic Policy for River Improvement is drafted by the Regional Development Bureau for each river and submitted to Social Capital Improvement Council.

2. Referring to the deliberation of Social Capital Improvement Council, the Minister of Land, Infrastructure and Transport is responsible for the final approval.

3. After the final approval, the basic policy is opened to the public.

4. To create concrete plans for the Basic Policy for River Improvement, the Plans for River Improvement is drafted by taking into account opinions of academic experts and local residents.

5. Referring to the opinion of the head of local government, final approval is done by the Minister of Land, Infrastructure and Transport. The approved plans are finally announced to the public.

For class B rivers, a draft of the basic policy must be deliberated by the local river council. The prefectural governors are the ones who make the final approval of the master plans.

- Master Plans for Water Resources Development

According to the Law for Promotion of Water Resources Development, the Master Plans for Water Resources Development are drawn for “water resources development river system” where new water resources need to be developed to cove the increase in water demand.

In the adoption of the master plans, demand on water from local governments is prepared as a draft proposal for the plans by the National Land Council and submitted to the Prime Minister. Besides the National Land Council, there are other two advisory councils: the Water Resources Development Council and the Electric Power Development Coordination Council. The Prime Minister will pass the plans to the Cabinet who is in charge of the final approval.

- Master Plans for Management of River Environment

Objectives of the Master Plans for Management of River Environment are to improve and preserve the environment of each river from long-termed viewpoint. The River Environment Management Council draws a draft proposal taking into account opinions from local residents. This council consists of academic experts from various fields, river administrators and local governments. The draft plans are submitted for the approval from the River Council and finally passed to the Minister of Land, Infrastructure and Transport or the prefectural governors. There are two major plans in the Master Plans for Management of River Environment: the Plans for Water Environment Management and the Plans for River Space Management. The Plans for Water Environment Management cover control and monitoring of discharge and water quality and the policies for improvement of water environment while the Plans for River Space Management relate with conservation, improvement and utilization of river space including consideration of effects on river space by the river projects.

2.6 Water quality

Water and sediment quality are major indicators of the environmental situation. Water pollution has unacceptable consequences for biological balance, human health and even for the very quality of life. In most countries, many measures have been and are being taken to improve the environmental situation. In these measures, a marked development is evident. The first approach was the emission approach aimed at stimulating or enforcing purification of wastewater. Then came the water quality approach in which standards were set for quality of receiving waters. The latest ideas point to an approach comprising integrated management of water systems (CUR 1993)

Loading generated within a watershed is one of important information for water quality control in a river basin and receiving water bodies like seas or lakes. Characteristics of loadings discharged from one river basin depend on the characteristics of water use in its basin area.

Runoff rate of loadings (COD, N, P) in the Ibo Basin, the Kako Basin and the Kotoh Basin was determined by Ukita and Nakanishi (1985). Runoff rate of pollutant load in flow-out stage ranged from 0.7 to 1.0. Unit loading from various types of activities in the river basin was estimated. The relationship between discharged loadings and flow rate was also indicated. Good correlation between measured and calculated runoff load of pollutant was observed.

Lee et al. (1995) studied about COD and nutrient loadings discharged into the Seto Inland Sea. The discharged loadings were estimated from the unit loading defined by Ukita et al. (1985). For water quality management in the Seto Inland Sea, Lee et al. (1996) predicted impacts of loadings using a numerical model. The authors indicated that the increase in discharged loading could lead to the increase in primary production in the Seto Inland Sea and indirectly to the increase of fish catchment.

Shoji et al. (1998) developed a framework for pollutant load analysis in the Onga Basin with application of Geographic Information System (GIS). The distribution of point and non-point sources in the Onga Basin was determined by using GIS data. It was found that the ratio of paddy field area to forest area influenced on nutrient concentrations of the Onga River whereas the ratio of population to forest area influenced on COD concentration.

Mikuriya et al. (2000) examined the characteristics of nitrogen loadings in the Chikugo Basin using observed data and GIS data. The study pointed out that ammonia nitrogen was mainly discharged in the form of domestic waste loading while nitrate nitrogen loading was generated from paddy field and forest area.

Unit loading in the discharge from household, forest area and agricultural area in Japan is classified in Table 2.2-2.5.

Table 2.2 Unit loading of domestic wastewater in Japan

Domestic wastewater	Unit loading (g/capita-d)					Discharge (l/capita-d)
	SS	COD	BOD	T-N	T-P	
Grey water Average	8 - 24 14	7 - 21 15	11 – 34 27	0.9 – 2.4 1.45	0.23 – 1.06 0.54	89 – 357 176
Night soil	20	9	16	7.15	0.68	64
Domestic wastewater Average	12 – 51 34	15 - 31 24	19 – 59 43	4.3 – 12.2 8.6	0.82 – 1.65 1.22	172 – 397 240

Source: Kunimatsu and Muraoka (1989) (investigated in 1970-1984)

Table 2.3 Unit loading of discharge from forest area in Japan

Discharge from forest area	Unit loading (kg/ha-y)		
	COD	T-N	T-P
Range	10.7 – 13.9	1.83 – 12.7	0.06 – 0.55
Average	12.3	7.265	0.305

Source: Kunimatsu and Muraoka (1989) (investigated in 1970-1987)

Table 2.4 Comparison of loadings generated from precipitation inside and outside of the forest area in Kyoto and Shiga prefectures, Japan

Area		Precipitation (mm)	Unit loading (kg/ha-y)		
			NO_3-N	NH_4-N	T-P
Kyoto Prefecture	Cypress forest	1,231	1.9	4.4	0.12
	Broadleaf forest	1,015	1.6	4.1	0.42
	Non-forest area	1,973	1.4	2.1	0.24
Shiga Prefecture	Red pine forest	1,455	2.2	2.2	1.09
	Non-forest area	1,931	1.4	4.0	0.63

Source: Somiya (1990)

Table 2.5 Unit loading of discharge from paddy field in Japan

Discharge from paddy field	Unit loading (kg/ha-y)	
	N	P
Surface runoff	8.0	0.26
Groundwater runoff	11.7	0.19
Total	19.7	0.45

Source: Kunimatsu and Muraoka (1989)

2.7 Summary

Researches on water resources management remarked that an international commission is necessary for river planning and river basin management when there are many countries involving in the river basin. The Rhine delta and the Mekong delta are presented as the case study. Concepts of policy analysis are explained through the review of PAWN, Policy Analysis for the Water management of the Netherlands. It indicates that policy analysis is necessary in selecting the policy that has less impacts weighing with advantages. There are many attempts to apply PAWN with water management in Japan. Various analytical tools including numerical models are necessary for policy analysis.

Development and application of numerical models for water management in several types of natural water is summarized. The overview reveals that numerical models are improved in analytical capability due to technological development. In water management, many types of mathematical models are developed for specific purposes. Purposes of mathematical models can be classified into two groups, that is, simulation and analysis. In the analysis, the developed models are used to explain quantitative and qualitative properties of water system while they are used to represent behaviors of the water system in the simulation. In policy analysis, numerical models are utilized to evaluate the alternatives for the problems of both water quantity and water quality. It is found that numerical models are effective tools and widely used for water management in several countries. In water quality management, numerical models for water quality analysis become indispensable.

An insight of water management in Japan is given in the summary of legislative system and history of water management as well as the master plans for water management in Japan. It is pointed out that the authority with ultimate power in making national decision is essential for water management in Japan.

The review of water quality related issues shows that loadings from land area play important roles in water quality of receiving water body. Estimation of discharged loading has been made in many river basins. Most of the researches have focused on BOD, COD and nutrient loadings because organic matters and nutrients are the important water quality parameters in natural water system. High organic loading can increase the consumption of dissolved oxygen in the water while nutrient loadings may accelerate the growth of algae and, in the worst case, lead to eutrophication problem in the surface water. Many researchers determined total loading of one river basin from unit loading of the existing sources in the basin. The summary of unit loading of three major sources in Japan, namely household, paddy field and forest area, is provided.

In this chapter, it is clear that most researches about water management treated a river basin and sea area separately as an individual system. Although water problems in both areas are closely related to each other, there are very few researches in which the river basin and the sea area are concerned as an integrated system. Thus, integrated water management taking into account the interrelation between the river and its receiving water is necessary. The impacts of proposed measures should be evaluated simultaneously in both areas.

Aiming at integrated water management in the Chikugo Basin and the Ariake Sea, an integrated approach for water quality analysis and policy analysis in both areas is proposed. To identify water users, characteristics of water use and existing water problems, problem analysis will be carried out in the Chikugo Basin and the Ariake Sea in Chapter 3.

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CHAPTER 3

PROBLEM ANALYSIS IN THE CHIKUGO BASIN AND THE ARIAKE SEA

3.1 Introduction

“ Make sure you know the problem well before solving it!” No matter what kind of problem we are dealing with, it is important to understand clearly what is the problem so that we can handle it correctly.

One of the most important procedures in water management is problem analysis. Before carrying out problem analysis for water management in a watershed, it is necessary to determine water users and functions of the water. Details of the watershed such as topography, climate, characteristics of water quantity and water quality, land use, etc. are necessary information that can provide an insight in current situation of that watershed. Not only present situation of the watershed, recorded data in the past is also essential. With these typical features of the watershed, we can trace back to causes of the problem or search for appropriate solutions of the problem. Besides available data, water users and their interests including desires of local residents on their river basin should be taken into account in this process. Determination process for final goals and objectives are frequently done based on the detail obtained from problem analysis.

Since the scope of this dissertation covers water quality in the Chikugo Basin and the Ariake Sea including an interrelation between water quality in both areas, problem analysis is conducted in the Chikugo Basin in parallel with the Ariake Sea. In this chapter, general information such as geographical and morphological properties, climate including observed data of water quantity and quality of the Chikugo Basin is collected and analyzed to determine characteristics of the watershed and the existing problems. Same procedures are conducted in the Ariake Sea. It should be noted that the information of the Chikugo Basin and the Ariake Sea obtained from this step is useful for policy analysis as well because it can be utilized in developing of analytical tools and evaluation process of the proposed alternatives.

3.2 Problem analysis in the Chikugo Basin

3.2.1. General information

The Chikugo Basin is located in Kyushu Island, which is the southern one among four major islands in Japan. The origin of the Chikugo River is in Senomoto Heights, Aso District, Kumamoto Prefecture. The Chikugo River becomes larger in size when it meets the Kusu River, which flows down from the Kuju Mountains, at Hita City in Oita

Prefecture. Many rivers join the Chikugo River while it travels downstream, i.e. the Sada River; the Koishiwara River; the Kose River and the Homan River. Before discharging into the Ariake Sea, the Chikugo River splits and forms another river named the Hayatsue River. Total length of the Chikugo River is about 143 km. The Chikugo Basin covers four prefectures: Kumamoto, Oita, Fukuoka and Saga prefectures. Catchment area of this basin is 2,860 km^2, which is almost one-tenth of Kyushu Island. The Chikugo Basin is the biggest basin in Kyushu Island and the Chikugo River itself is the longest one in Kyushu Island as well. In Japan, the Chikugo Basin is the 21st biggest basin and the Chikugo River is the 22nd longest river. According to the 2000 Population Census of Japan (Statistics Bureau 2000), total population in the Chikugo Basin is around 1,440,000 people. Details of this basin are demonstrated in Fig.3.1. According to its topography, the Chikugo Basin can be divided into three parts, that is, upper part, middle part and lower part. The upper part is the upstream area of Arase, which is the catchment area of Yoake Dam. The middle part is situated between Arase and Senoshita. The low-lying area at downstream of Senoshita is referred as the lower part. Around 56% of the Chikugo Basin is mountainous and covered by forest. Lying densely along the middle reach of the Chikugo River, agricultural area covers 27% of the basin area. The remainder is an urban area and others, which is around 23% of the basin area. Big cities such as Kurume, Tosu and Okawa cities are located near the middle and lower reaches of the Chikugo River.

3.2.2. Climate

Average annual precipitation of Japan is around 1,800 mm, which is almost twice of the world’s average annual precipitation (MLIT 1992). Average annual precipitation of the Chikugo Basin is about 2,000 mm. Monthly precipitation at Hita Station and Chikugo Barrage Station is shown in Fig.3.2. Around 60% of this precipitation can be observed in June to September. In the south of Japan, during June to July is rainy season while during August to September is a period of typhoons. In this study, the period between June and September is considered as rainy season whereas the period from October to March is considered as dry period. Pattern of precipitation in 2003 is different from pattern of average precipitation. In 2003, precipitation in July, August and November is higher than an average value while the precipitation in June, September and October is much lower. Rainfall in January-May is low because of the drought during July 2002 to May 2003.

3.2.3. Disasters

Another name of the Chikugo River is “Chikushi-jiro”. This name is well known as one of three rivers that often overflow the riverbanks. The other two rivers are Bando-taro (the Tone River) and Shikoku-saburo (the Yoshino River). Although precipitation of the Chikugo Basin is high, average precipitation per capita is around 4,000 m^3/capita-y, which is approximately two-third of average precipitation per person of Kyushu Island. Major disasters in the Chikugo Basin are inundation and drought. History of disasters in this watershed is listed in Table 3.1.

Table 3.1 Major disasters in the Chikugo Basin

Date	Type	Affected region	Damage
1978.5.20 – 1979.3.25	Drought	Northern Kyushu	Water usage restrictions in Fukuoka City for 287 days. Affecting 3.28 million people in Kyushu Region at peak.
1990.6.28 – 1990.7.3	Rain front	Kyushu overall	27 dead, 536 buildings partially or totally destroyed, 44,571 buildings flooded. Major mudslides in Ichinomiya Town (Kumamoto), Taketa City (Oita) and Yame-gun (Fukuoka). Flooding damage in Karatsu City, Saga (the Rokkaku Basin), Saga City (the Chikugo Basin).
1991.9.2 – 1991.9.4	Typhoon No.19	Northern Kyushu	Some 37,000 ha of forest in northern Kyushu subjected to severe tree toppling to wind.
1993.7.31 – 1993.9.3	Heavy rainfall Typhoon No.13	Kyushu overall	After heavy rainfall from the rainy season (June through August), typhoon No.7 and 13 crossed Kyushu Island. Heavy rainfall caused river flooding and mudslides in Kagoshima with considerable loss of life. Damage from June through September throughout Kyushu Region amounted to 146 dead/missing, 2370 buildings partially or totally destroyed, and 100,558 buildings flooded.
1994.7.7 – 1995.6.1	Drought	Northern Kyushu	Scale of drought exceeded major drought of 1978. Water usage restrictions on 2.73 million people in 16 cities, 30 towns and one village in Fukuoka and Saga prefectures.
1995.12.23 – 1996.4.30	Drought	The Chikugo Basin	Drought lasted for 129 days.
1999.2.25 – 1999.6.26	Drought	The Chikugo Basin	Drought lasted for 122 days.
2002.7.11 – 2003.5.1	Drought	The Chikugo Basin	Drought lasted for 92 days in Amagi City from 2002.4.11–2002.10.10 and 264 days in many cities including Fukuoka City (2002.8.10–2003.5.1).

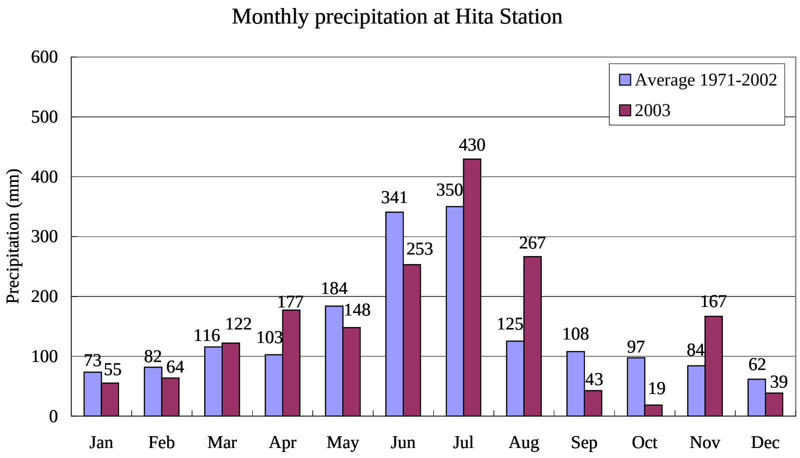
Source: MLIT (1994, 2002)

3.2.4. Hydraulics structures

To meet high water demand in the Chikugo Basin, many projects of water resources development have been carried out. Not only for water supply, these hydraulic structures also serve for flood control, power generation and environmental conservation as well. Details of hydraulic structures in the Chikugo Basin are summarized in Table 3.2.

Figure 3.1 The Chikugo Basin

Source: WRDPC (2002)


Monthly precipitation at Hita Station

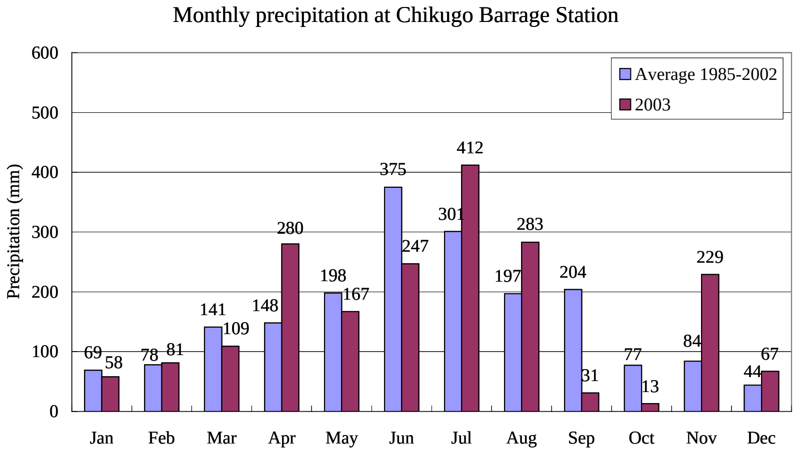

Monthly precipitation at Chikugo Barrage Station

Figure 3.2 Monthly precipitation at Hita Station and Chikugo Barrage Station

Source: Hita Station - Japan Meteorological Agency (2004),
Chikugo Barrage Station - The Chikugo Barrage Operation Office (2004)

Shimouke Dam is located on the Tsue River. It is an arch dam constructed from concrete and was completed in 1973. This multipurpose dam is under the control of MLIT. The original purposes of this dam were flood control and electricity generation. The increase in population had raised the water demand for maintaining flow condition and water quality in the river. With additional purposes on water supply, Shimouke Dam was reconstructed and the operation was started again in 1979. Having effective capacity of 52.3 million m^3, this dam receives water from catchment area of 185 km^2. The maximum output of Shimouke hydroelectric power plant is 15,000 kW. This dam is designed to store high runoff from upstream and release at 350 m^3/s in order to prevent the flood at downstream during rainy season.

According to big damage on agriculture caused by the flood in 1953, Matsubara Dam was constructed and finished at the same period with Shimouke Dam. It is a concrete gravity dam located near the point where the Tsue River joins the Chikugo River. As same as Shimouke Dam, this dam belongs to MLIT. It is also a multipurpose dam and was designed for power generation and flood control. In the revision of its functions, drinking water supply and flow maintenance were added. Matsubara dam was modified and operated again in 1979. During dry season, this dam supplies water at rate of 0.1 m^3/s for drinking water in Hita City. Catchment area of Matsubara Dam is 491 km^2 and effective capacity is 47.1 million m^3. For flood control, inflow from upstream is stored and adjusted to be 1,100 m^3/s. This dam generates electricity at the maximum output of 50,600 kW, which is around 3.4 times of Shimouke Dam. In order to maintain the stability of water supply and appropriate condition for fishery in the Ariake Sea, MLIT has introduced a measure of securing the minimum flow rate of 40 m^3/s at Senoshita. During winter, low flow at Senoshita is augmented by the discharge from Shimouke Dam and Matsubara Dam.

Yoake Dam belongs to Kyushu Electric Power Company (KEPC). Its main purpose is power generation. This dam is gravity type made of concrete. Catchment area of this dam is 1,440 km^2. Total storage volume is 4.05 million m^3. Maximum release rate of Yoake Dam for hydroelectric generation is about 80 m^3/s. Observation station in the Chikugo River named Arase is located at downstream of Yoake Dam. Average flow rate at Arase is about 84 m^3/s.

Oishi Weir, Yamada Weir and Eri Weir were constructed for irrigation according to the droughts in 1660s and 1710s. With the length of 180 m, Yamada Weir lines obliquely across the Chikugo River. This weir serves irrigation water for 7 km^2 of paddy field in the middle part of the Chikugo Basin. To support irrigation water during the drought in 1663, Oishi Weir came from an idea of five village headmen. Rokuuemon proposed the construction of Eri Weir after seeing farmers suffering from the drought in 1710s. As a foundation of this weir, workmen had to sink an old boat by filling it with rocks. Eri Weir finished in 1712.

Gosho Dam has total catchment area of 42 km^2. This dam is an embankment dam. It was constructed crossing the Kumanoue River and completed in 1988. Effective capacity of Gosho Dam is 6.7 million m^3. This dam is under the responsibility of Ministry of Agriculture, Forest and Fisheries (MAFF). Major functions of this dam are irrigation, drinking water and industrial water.

Terauchi Dam is an embankment dam holding water from the Sada River in the middle part of the Chikugo Basin. The construction was completed in 1977. This dam has catchment area of 51 km^2 and effective capacity of 16 million m^3. Besides flood control, Terauchi Dam supplies water for irrigation, drinking water, industrial water, for environmental conservation and keeping the flow rate stable. This multipurpose dam is operated by Water Resources Development Public Corporation (WRDPC). Cooperating with Egawa Dam, Terauchi irrigates agricultural area of around 59 km^2 in Fukuoka Prefecture at rate of 2.51 m^3/s. Discharge of 3.65 m^3/s is served for drinking water in some parts of Saga and Fukuoka prefectures. When the flow rate at Chikugo Barrage is low during summer, water will be released from Terauchi Dam and Egawa Dam to maintain the flow.

Egawa Dam was completed in 1975. This concrete gravity dam is located on the Koishiwara River. Belonging to WRDPC, main purposes of this dam are irrigation, drinking water and industrial water. Effective storage capacity of this dam is 24 million m^3. Catchment area of Egawa Dam is 30 km^2. The construction of a new dam is now carried out at upstream of Egawa Dam. This new dam will supply water for Amagi City in Fukuoka Prefecture and will be collaborated with Egawa Dam and Terauchi Dam to sustain flow rate in the lower reach of the Chikugo River.

Yamagami Dam is a concrete gravity dam stretching across the Homan River. Total storage capacity is 2.98 million m^3. This dam serves for flood control, drinking water and maintaining flow condition. Catchment area of Yamagami Dam is 9.1 km^2. Administrator of this dam is Fukuoka Prefecture.

The construction of Chikugo Barrage was carried out during 1978 to 1984 at 23 km upstream of the estuary of the Chikugo River (Water Resources Development Public Corporation (WRDPC)). Chikugo Barrage is a moveable dam with total length of 501.6 m. Total capacity of the barrage is 5.5 million m^3 receiving water from 2,315 km^2 of catchment area. Main functions of Chikugo Barrage are irrigation, drinking water supply and flood control. This barrage is operated by WRDPC.

After the completion of Chikugo Barrage, new water distribution system is adopted. Water supply for downstream of the barrage is withdrawn by large pumping stations and distributed to the water users in the east and the west of the Chikugo River. Instead of the traditional water intake using the tidal level in the lower reach of the Chikugo River, irrigation water is now distributed more stably through open channels.

This new system supplies irrigation water for 348 km^2 of agriculture area at the maximum rate of 28.08 m^3/s during June to October. At rate of 0.35 m^3/s, Chikugo Barrage serves for drinking water supply in many big cities in Fukuoka and Saga prefectures. Prior to the construction of Chikugo Barrage, Council of environmental impact assessment of Chikugo Barrage was found in 1977. The council consists of academic experts and the representatives from Ministry of Construction (MLIT at present), MAFF, Fukuoka Prefecture, Saga Prefecture and WRDPC. Environmental impact assessment of Chikugo Barrage was started in 1978. According to the impact assessment program, environment monitoring is carried out in the Chikugo River at both upstream and downstream of the barrage as well as in its estuarine area and the Ariake Sea.

To stabilize water supply in the lower part and to supply nutrients for fishery in the Ariake Sea, MLIT is now making an effort to maintain the minimum flow rate at Senoshita at 40 m^3/s. Integrated management system is proposed with the cooperation among Shimouke Dam, Matsubara Dam, Egawa Dam, Terauchi Dam, Koishiwara River Dam (under construction) and Chikugo Barrage.

Table 3.2 Important hydraulic structures in the Chikugo Basin

Infrastructure	River	Purposes	Catchment area (km^2)	Total volume (x10^6 m^3)	Administrator
Dam					
Shimouke	Tsue	F N P	185.0	59.3	MLIT
Matsubara	Chikugo	F N P W	491.0	54.6	MLIT
Yoake	Chikugo	P	1,440.0	4.05	KEPC
Gosho	Kumanoue	A W I	42.0	7.66	MAFF
Egawa	Koishiwara	A W I	30.0	25.3	WRDPC
Terauchi	Sada	F N A W I	51.0	18.0	WRDPC
Yamagami	Homan	F N W	9.1	2.98	Fukuoka
Weir					
Oishi	Chikugo	A	-	-	-
Yamada	Chikugo	A	-	-	-
Eri	Chikugo	A	-	-	-
Chikugo Barrage	Chikugo	F N W	2,315.0	5.5	WRDPC

A: Irrigation, F: Flood control, I: Industrial use, N: Maintaining flow, P: Hydro-power, W: Drinking water

MLIT: Ministry of Land, Infrastructure and Transport

KEPC: Kyushu Electric Power Co., Inc.

MAFF: Ministry of Agriculture, Forest and Fisheries

WRDPC: Water Resources Development Public Corporation

Fukuoka: Fukuoka Prefecture

Besides the structures described above, the other hydraulic structures are operated by prefectural government or private agency such as power generation company. At present, some construction projects are carried out in the Chikugo Basin and some plans are developed to meet the increase in water demand. The structures under planning or under construction are listed in Table 3.3.

Table 3.3 Future plans for hydraulic structures

Infrastructure	River	Purposes	Catchment area (km^2)	Total volume (x10^6 m^3)	Administer
Dam					
Jobaru River	Jobaru	F N W I	42.5	15.8	MLIT
Shishimuta	Kusu	F N A W I	113.0	38.5	MLIT
Oyama	Akaishi	F N W I	33.6	19.6	WRDPC
Koishiwara River	Koishiwara	F N W I U	20.5	40.0	WRDPC

A: Irrigation, F: Flood control, I: Industrial use, N: Maintenance flow, U: Water shortage countermeasures, W: Drinking water

MLIT: Ministry of Land, Infrastructure and Transport

WRDPC: Water Resources Development Public Corporation

3.2.5. Water use and land use

Since the Chikugo River originates in mountainous area, flows through valleys and passes along plain area before discharging into the Ariake Sea, topography of the Chikugo Basin can be described as mountainous area in the upper part and lowland in the lower part. The Chikugo River supplies freshwater for various kinds of water users dwelling within its watershed and in some area outside the watershed i.e. some cities in Fukuoka, Saga and Oita prefectures. Functions of the Chikugo River are irrigation, drinking water, industrial water, power generation as well as recreation and environmental conservation. Hita City, Kurume City, Tosu City and Okawa City are the cities with large population located in this watershed. Development of residential and business area near the Chikugo River is high in Hita City and Kurume City. Irrigation service area of the Chikugo River is around 550 km^2 and capacity of drinking water supply including the supply for Fukuoka City is for 3.4 million people. Located outside of the Chikugo Basin, more than 40% of drinking water in Fukuoka City is supplied from the Chikugo River. Average water supply for Fukuoka City from the Chikugo River is around 80 million m^3/y. This amount is only 2% of annual volume of the reservoir of Chikugo Barrage. In the Chikugo Basin, there are 23 power plants with the maximum generation capacity of 225,000 kW.

Not only in water supply, the Chikugo River also plays an important role in environmental conservation in its own basin and in the Ariake Sea. The nutrients loaded from this watershed are more or less utilized by aquatic life in the vicinity of the river mouth. As mentioned before, the minimum flow rate in the Chikugo River is determined in order to supply nutrients for fishery and laver cultivation in the Ariake Sea. Feasibility study on this maximum flow rate will be discussed in Chapter 6. Recently, people visit the riverside of the Chikugo River for recreation. There are many events held to relate people and the river, for example, Chikugo Firework Festival, the River Day, etc. Several areas in banks of the river become sport grounds or riverside parks.

In the past, one of the major functions of the Chikugo River was navigation. From the Edo era until the middle of the Showa era (1600s-1950s), logs of Japanese cedar were transported as rafts from Hita City in Oita Prefecture to Okawa City in Fukuoka Prefecture for wood industry. Until the beginning of the Heisei era (1994), ferry service had been available along both sides of the Chikugo River for transporting people and goods. At the peak period of this business, there were more than 62 service points of ferry from Hita City to the mouth of the Chikugo River and the Hayatsue River. According to the construction of Yoake Dam and river improvement, the cedar rafts and ferry finally vanished from the Chikugo River. At these days, most of the boats in the upstream of the Chikugo barrage are for tourism, and fishing boats can be seen only in the vicinity of the river mouth.

The Chikugo Basin is divided into 14 blocks as shown in Fig.3.3. Information of population and land use in each block is defined by Geographic Information System (GIS) utilizing Grid Square Statistics of 1990 Population Census of Japan (Statistics Bureau 1990) and National Land Information 1990 (MLIT 1990). Figure 3.4 shows population and details of land use in the Chikugo Basin obtained from GIS. The number shown in each block is an accumulated value from upstream. Characteristics of land use and functions of the Chikugo River from the upper part to the lower part are summarized below.

As shown in Fig.3.4, total upstream area of Arase is around 1,440 km^2, which is the biggest one among the three parts. Most of this area is mountainous area. Almost 70% of forest in the Chikugo Basin is situated here. Total residents of this area are only 10% of total population in the Chikugo Basin. Hita City is a big city in this mountainous area. Comparing with the middle and lower parts, agricultural area in the upper part of the Chikugo Basin is small. Major water use in this area is for hydroelectric power generation and irrigation.

Being mountainous makes it feasible to construct reservoirs in this area. Many reservoirs have been installed and some hydraulic structures are under construction at present. One of main purposes of these reservoirs is power generation. In Japan, as well as the construction of hydroelectric power plants, the electric power company has also invested in the construction of reservoirs. Another important function of these reservoirs is flood control in order to protect lives and properties in downstream area.

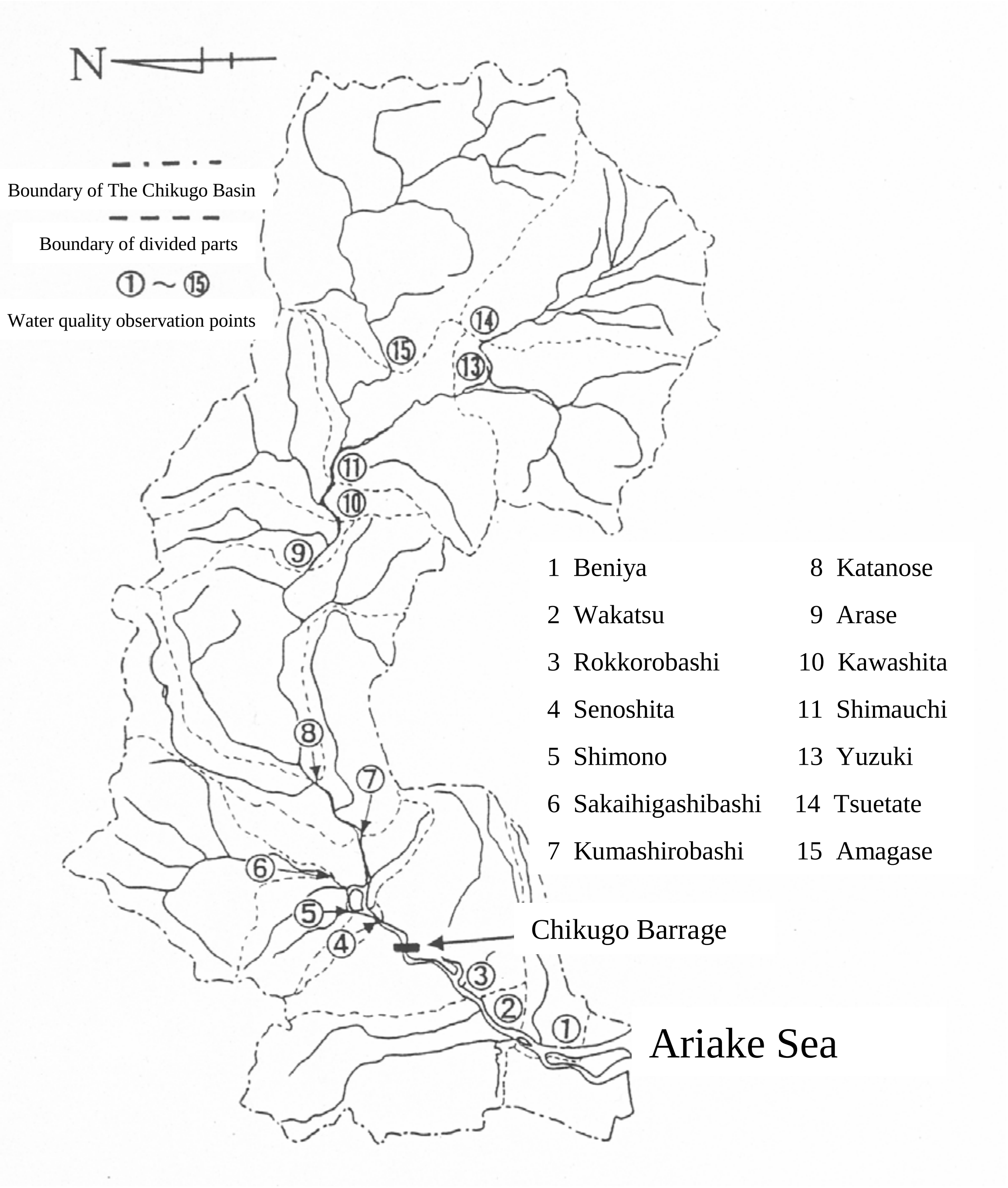


Figure 3.3 Observation points in the Chikugo Basin and divided area for GIS application

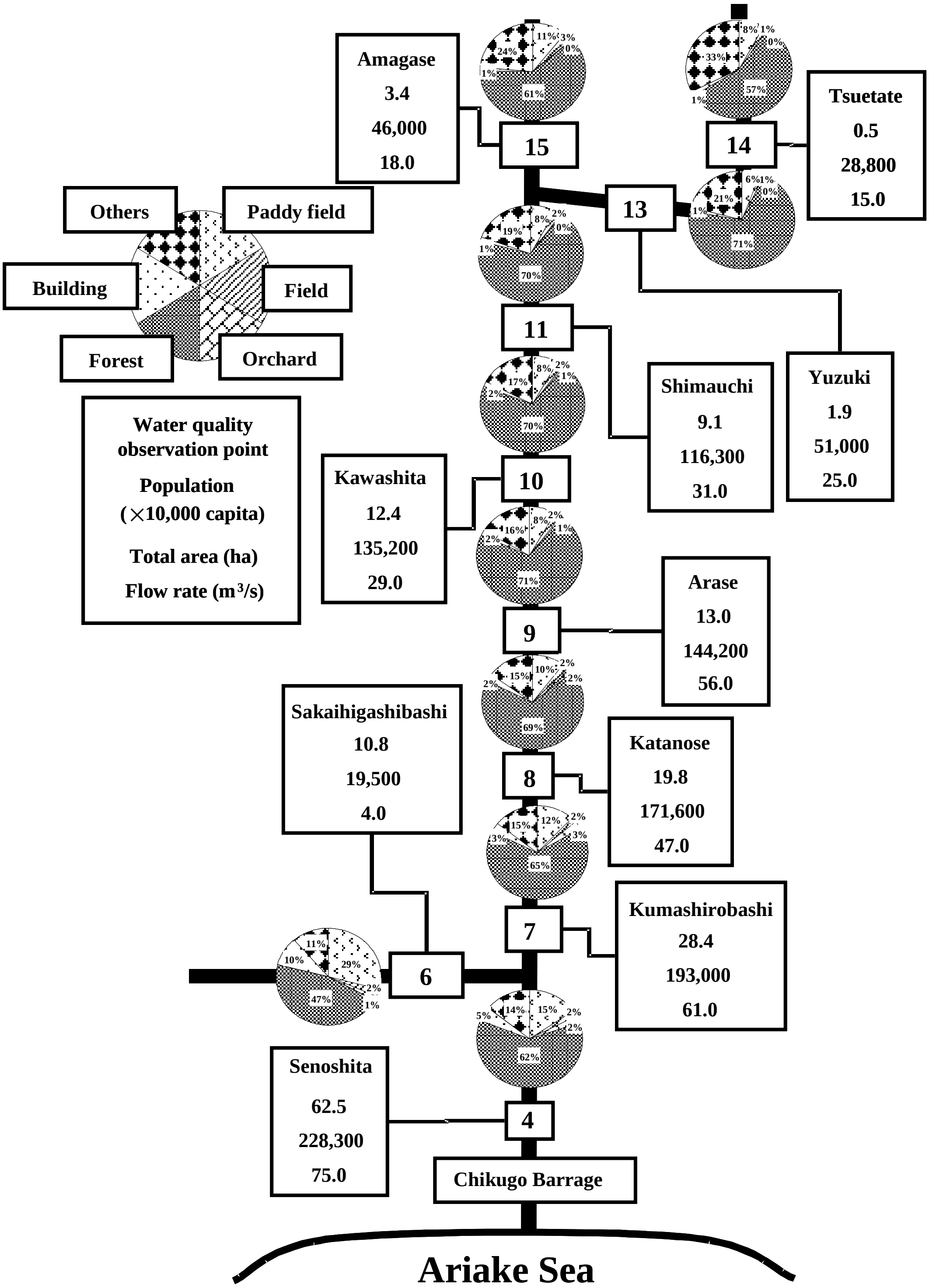


Figure 3.4 GIS data of the Chikugo Basin

Source: Statistics Bureau (1990) and MLIT (1990)

Catchment area between Arase and Senoshita is about 840 km^2. More than 40% of total population in the Chikugo Basin inhabit in this area. Big cities with dense population such as Kurume City and Tosu City are located in this area. The paddy field in this area is about 41% of total paddy field of the Chikugo Basin. With high population and large agricultural area, main water use in the middle part is for irrigation, drinking water and industry. In every second, around 51 m^3 of water is utilized in this area. Around 89% of this water is for irrigation, 12% is for drinking water and the rest is for industry. MLIT has planned to develop an integrated reservoir system in this area in order to maintain the flow rate at downstream of the main river and to provide water for Amagi City. Located at downstream of this area, the Chikugo Barrage supplies water for irrigation and drinking water in several cities in Saga and Fukuoka prefectures.

At downstream of the Chikugo Barrage, slope of the Chikugo River becomes gradual. The Hayatsue River separates from the Chikugo River at Okawa City before discharging into the Ariake Sea. Being the smallest part, total area of this lower part is only 20% of the Chikugo Basin. Topography of this area is flat plain. Less than one-tenth of forest area in the Chikugo Basin is located here. Population in this area is around 45% of total population in the Chikugo Basin. As a result, density of population becomes very high. Not only residential area, but paddy field area in this area is also very large. More than 40% of this area is paddy field and agricultural area. There are many open channels for irrigation existing in this area. Water demand for irrigation and drinking water in this area is as high as the water demand in the middle part.

With the length of 23 km, the Chikugo River between the river mouth and the Chikugo Barrage is influenced by the tide in the Ariake Sea. In the past, farmers in this area utilized the advantage of tidal effect in their traditional intake system for irrigation. Under the high tide, seawater enters the river and elevates freshwater layer, which is lighter in density. The farmers opened water gates to let the freshwater fill in their channels. Depending on the tide, this traditional system was unstable. At present, paddy field and open channel systems are modified, and a new distribution system is equipped in order to improve the stability of water supply in the lower part of the Chikugo Basin. Irrigation and drinking water is now supplied by the freshwater from upstream of the Chikugo Barrage.

Although large tidal range in the Ariake Sea makes the water in the lower reach of the Chikugo River unsuitable for consumption, it has created the valuable and unique ecosystem. There are many aquatic animals that can be found only in the vicinity of the river mouth of the Chikugo River and other rivers that flow into the Ariake Sea. Etsu anchovy is one of those rare species in this area. They swim upstream to spawn during June to August. Vulnerable species such as *Salanx ariakensis* and *Neosalanx reganius,* which are “Ariakeshirauo” and “Ariakehimeshirauo” in Japanese, inhabit only in the estuary of the Chikugo River and the Midori River. These fish spawn their eggs on coarse sand in the riverbed. Laver cultivation is widely carried out in the tidal flats near the river mouth during autumn and winter (October to March). The laver production of the Ariake Sea is very famous in Japan.

3.2.6. Characteristics of water quantity in the Chikugo River

In Japan, class A rivers are administrated by MLIT. Figure 3.5 shows daily flow rate of the Chikugo River at Arase, Katanose and Senoshita in 1981-2000 observed by Kyushu Regional Development Bureau, MLIT. Catchment area and distance from the river mouth of each point are listed in Table 3.4.

Table 3.4 Details of three observation points in the Chikugo River

Name	Catchment area (km^2)	Distance from the river mouth (km)
Arase	1,443.0	62.0
Katanose	1,727.0	41.3
Senoshita	2,315.0	25.9

Source: Kyushu Regional Development Bureau, MLIT (2001)

It is clear that flow condition of the Chikugo River has a seasonal pattern that is high flow rate during rainy season and low flow rate during dry season. Low flow rate was observed at every point during the rainy season of 1994 due to the drought in 1994-1995. Average flow rate at Arase, Katanose and Senoshita are 84, 88 and 125 m^3/s, respectively.

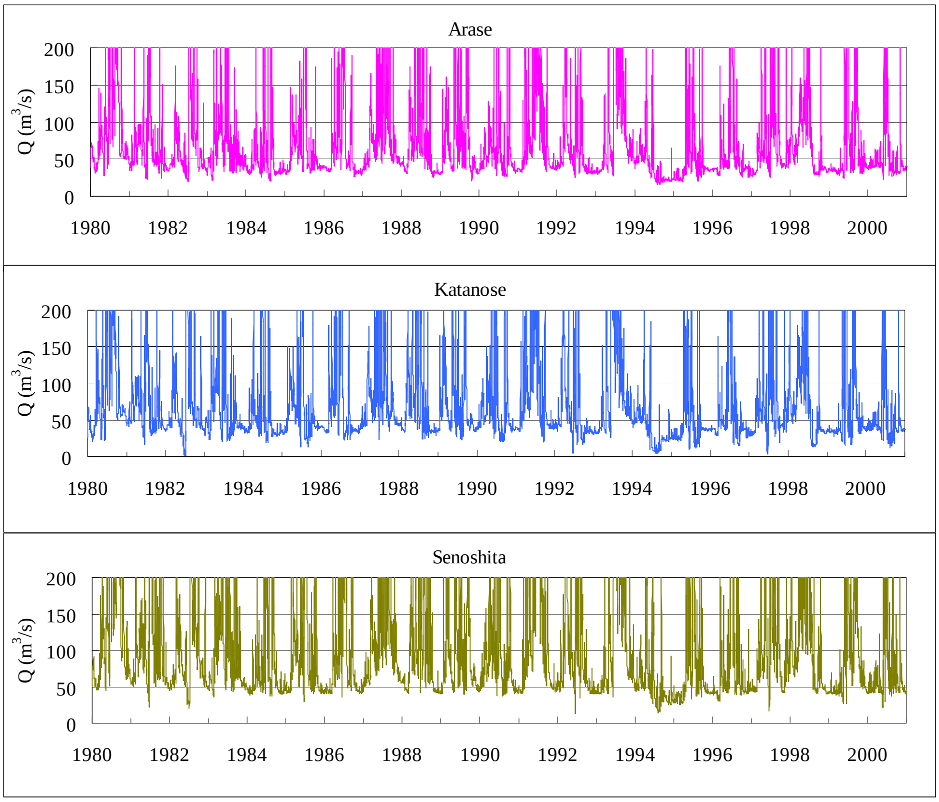


Figure 3.5 Flow rate of the Chikugo River at Arase, Katanose and Senoshita

The observed flow rate is averaged to define the pattern of flow rate in each month. Monthly flow rate of the Chikugo River is demonstrated in Fig.3.6. It is clear that monthly flow rate has a similar pattern at all stations. Flow rate is high from June to September and becomes low and almost constant in November to February. High precipitation during June and July shown in Fig.3.2 is one factor that results in high flow rate in the Chikugo River. Monthly flow rate at Katanose is almost same with the flow rate at Arase even in rainy season whereas the flow rate at Senoshita is much larger.

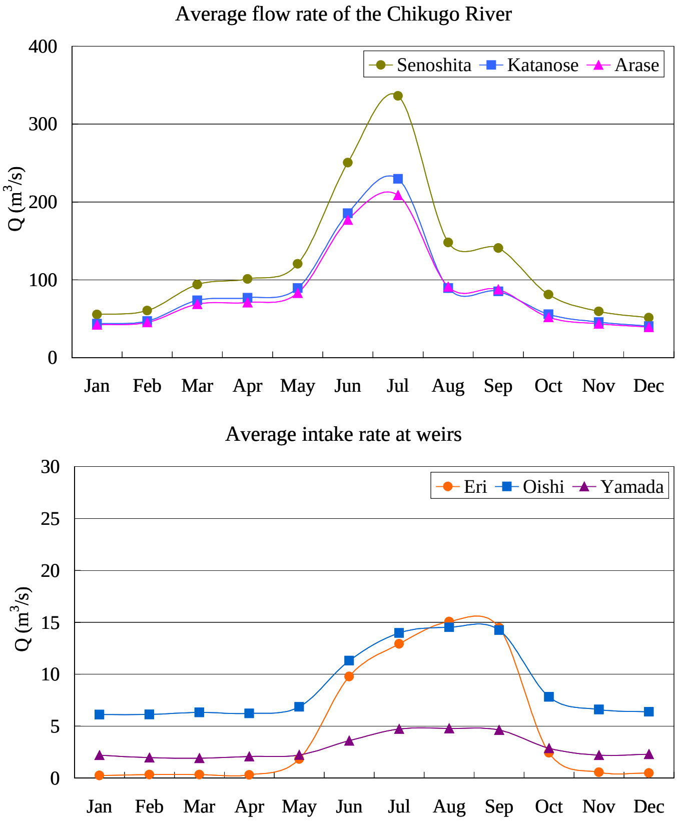


Figure 3.6 Trends of flow rate and irrigation intake in the Chikugo River

Figure 3.6 also demonstrates monthly averaged water intake at three weirs located between Arase and Katanose. Major purpose of these weirs is for irrigation. It is shown that irrigation water is highly withdrawn during June to September whereas the withdrawal is lower and steady in November to April. As a result, the period between June and September can be defined as irrigation period in the Chikugo Basin. High water consumption for irrigation is one of the reasons of small difference between the flow rate at Katanose and that Arase in irrigation period. In spite of large agricultural area between Arase and Senoshita, the flow rate at Senoshita during irrigation period is much higher than at Katanose. High consumption of irrigation water does not decrease the flow rate at Senoshita. It indicates that characteristics of water use in agricultural area in the area between Arase and Katanose may be different with those in the area between Katanose and Senoshita.

Watershed model such as the tank model is necessary for an analysis on characteristics of irrigation water use and the relation between water use and water quantity in the Chikugo Basin. Moreover, the tank model is also effective in analyzing base flow, which is important for water management during dry period. Development of numerical models and water quantity analysis in the Chikugo Basin will be discussed in Chapter 4.

3.2.7. Characteristics of water quality in the Chikugo River

As same as in the water quantity analysis, water quality at Arase, Katanose and Senoshita is analyzed. Water quality parameters, namely, water temperature, BOD_5, COD, total nitrogen (T-N), total phosphorus (T-P), suspended solids (SS) and dissolved oxygen (DO), are considered in this study. Observation of water quality in the Chikugo River is conducted by Kyushu Regional Development Bureau, MLIT. Except T-N and T-P, the water quality mentioned above is measured once a month. T-N and T-P are measured in every three months. As shown in Fig.3.7, water quality standard of the Chikugo River at upstream of Yoake Dam is in category AA while the water quality standard for the river segment between Yoake Dam and Senoshita is in category A. Water quality standard of the estuary of the Chikugo Basin belongs to category B. The observed water quality from 1980-2001 at each observation point is shown in Fig.3.8 to Fig.3.10. After that, monthly averaged concentration is analyzed.

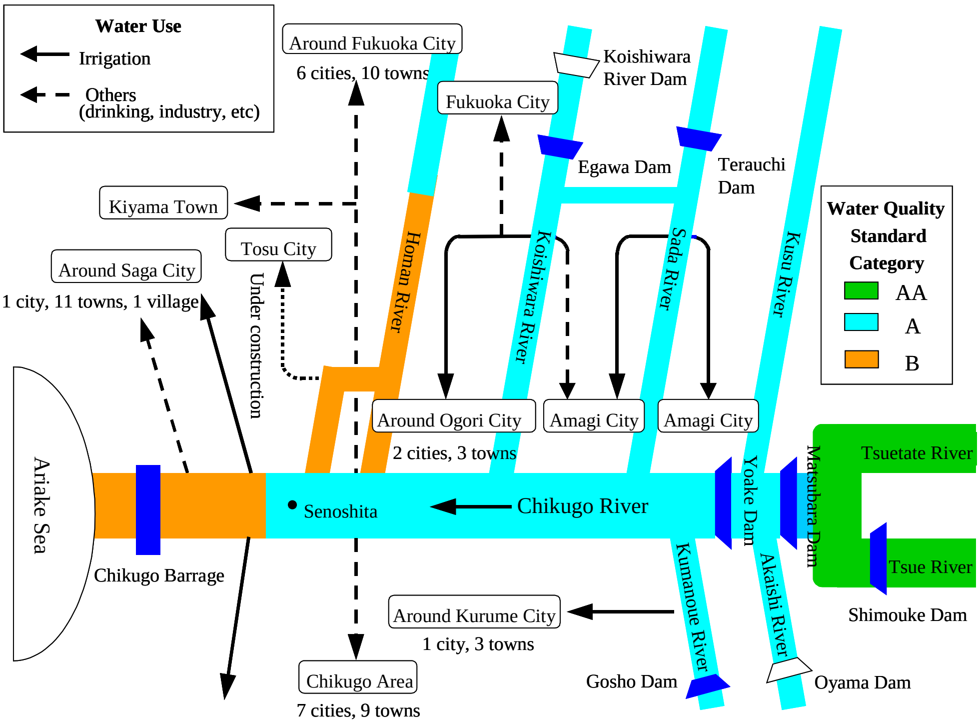


Figure 3.7 Water quality standard for water quality and water distribution in the Chikugo Basin

Source: WRDPC (2002)

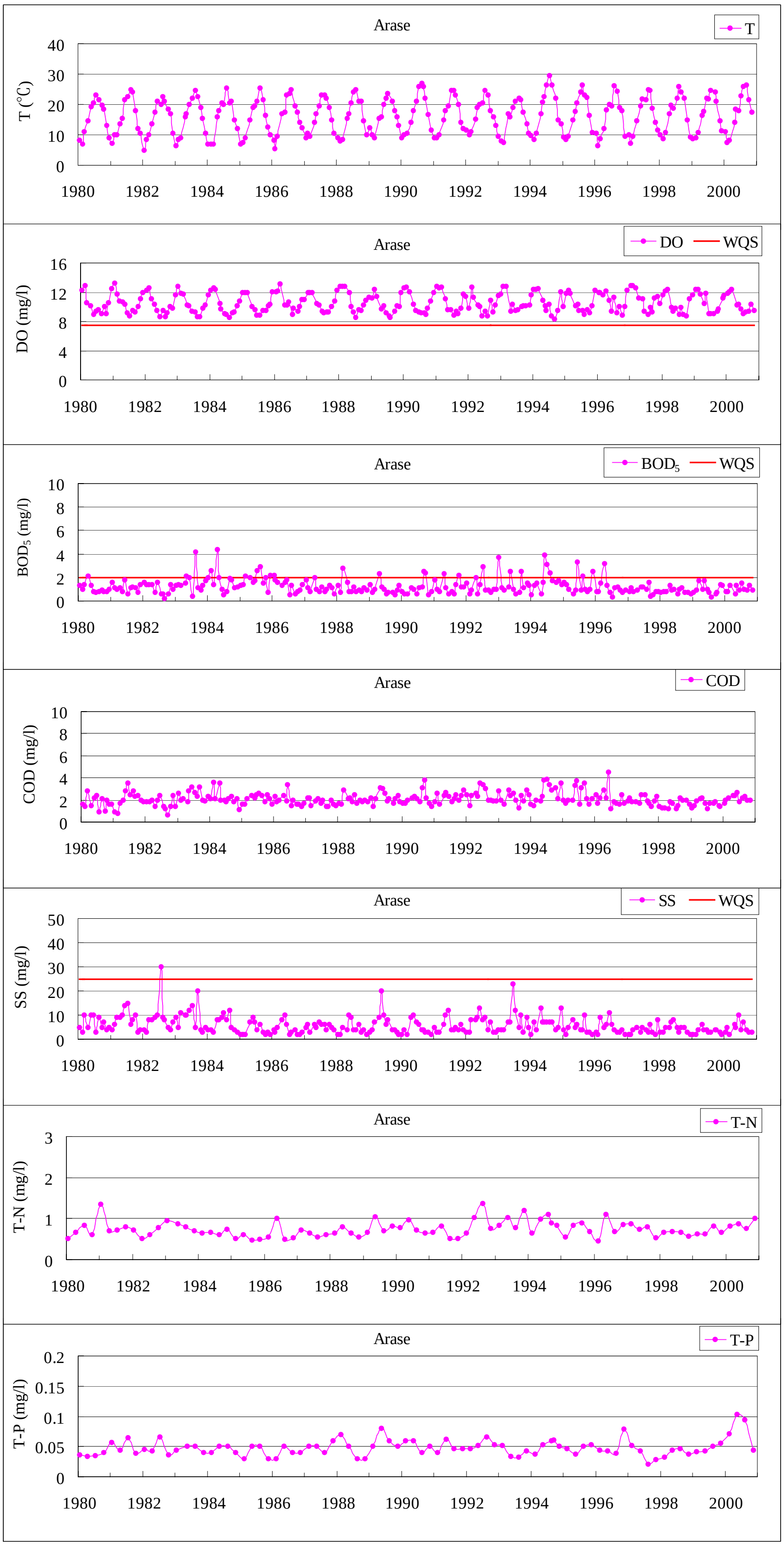


Figure 3.8 Water quality of the Chikugo River at Arase

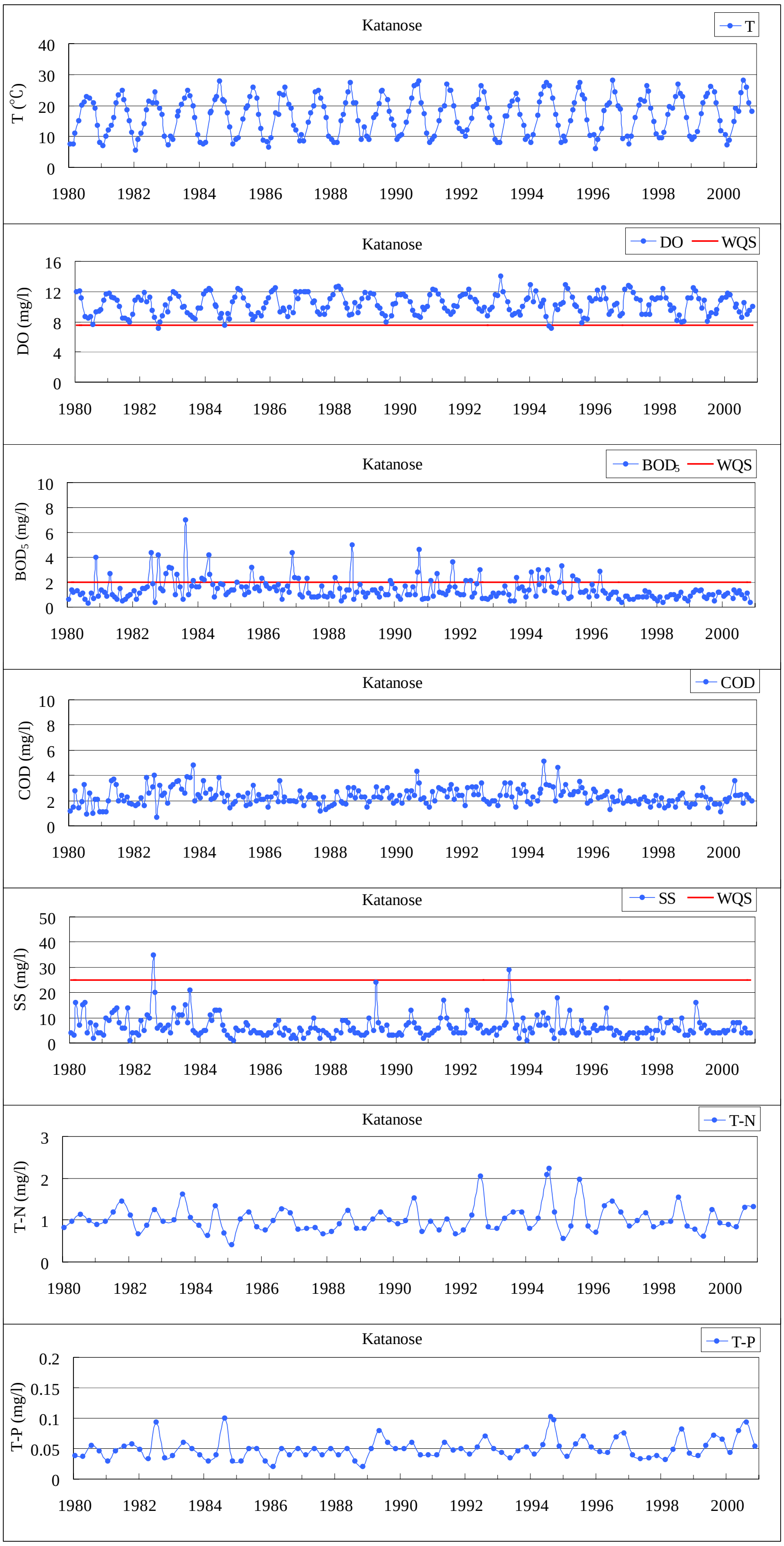


Figure 3.9 Water quality of the Chikugo River at Katanose

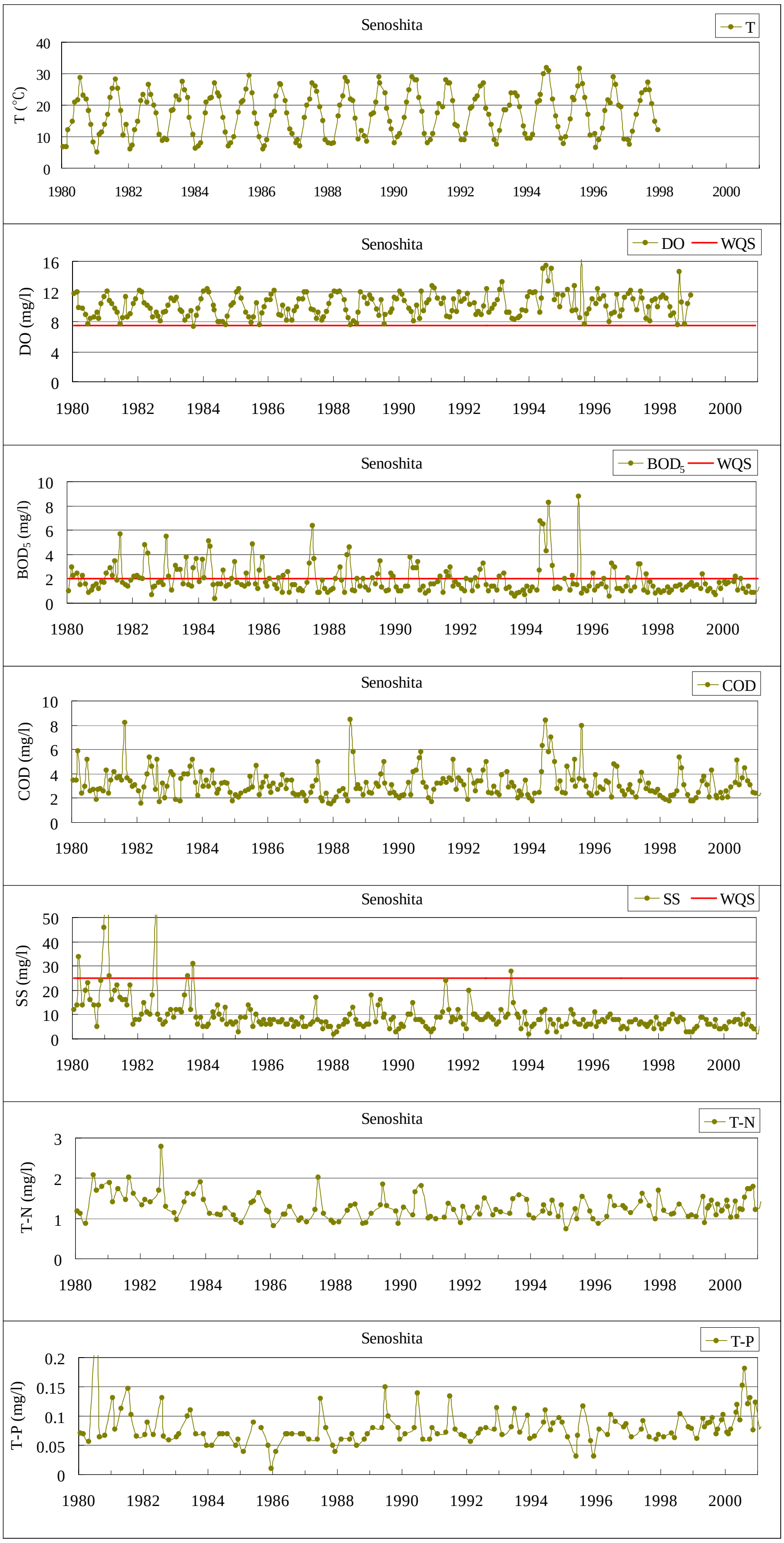


Figure 3.10 Water quality of the Chikugo River at Senoshita

The minimum water temperature at Arase has increased since 1986. Average water temperature is 16.3°C. In Fig.3.8, the maximum water temperature higher than 25 degree was observed after the drought year of 1994. Average BOD_5 and SS are about 1.25 and 5.8 mg/l, which are below the water quality standard of category A. Average COD concentration at Arase is 2.1 mg/l. Dissolved oxygen ranges between 8-13 mg/l which is higher than 8 mg/l in the water quality standard. Average T-N and T-P are 0.8 and 0.05 mg/l, respectively. T-P in summer of 2000 was around 1.0 mg/l.

Trend of water temperature at Katanose has also increased. Comparing with water temperature at Arase, average water temperature at Katanose is 0.5 degree higher. Water quality concentration at Katanose is higher than at Arase since number of water users is higher and functions of the water in this area are more various than at upstream of Arase. Average BOD_5 and SS are 1.4 and 6.5 mg/l, respectively. COD concentration at Katanose has increased since 1981. The minimum COD concentration of each year is around 2 mg/l. Except in 1994, DO concentration is above the standard. DO value in 1994 was less than 8 mg/l due to high water temperature, BOD_5 and COD concentrations. Nutrient concentrations have increased since 1998. Average T-N is 1.2 mg/l and average T-P is 0.07 mg/l. High T-P concentration was observed in 2000.

After the drought in 1994, average water temperature at Senoshita has been rising. BOD_5 concentration exceeding the standard is frequently observed at Senoshita in rainy season. From 1990 to 2000, BOD_5 concentration in winter was low and varied very slightly. Average BOD_5 and SS at Senoshita are 1.9 and 9.6 mg/l, respectively, which are within the water quality standard. Average COD concentration is 3.2 mg/l. BOD_5 and COD concentrations were very high during the drought in 1994. Nutrient concentrations are high during rainy season, which is irrigation period in the paddy field. High nutrient concentrations were observed at downstream of the Chikugo River in summer of 2000.

It is concluded that average water quality concentration of the Chikugo River between Arase and Senoshita is within the water quality standard of category A. Nutrient concentrations and average water temperature of the Chikugo River have increased. High T-P concentration was observed at every point in 2000. Besides DO concentration, water quality concentration at Katanose and Senoshita is higher than at Arase.

Observed data is averaged monthly in order to determine the change of water quality in the Chikugo River around the year. As shown in Fig.3.11, patterns of monthly water temperature and dissolved oxygen are similar at all points. Water temperature of the Chikugo River increases after March and reaches the peak in August. During May to September, water temperature at Senoshita is higher than at Katanose and Arase. Dissolved oxygen of the Chikugo River declines along with the increase in water temperature from March. DO concentration at every point is around 10 mg/l in the period of high water temperature.

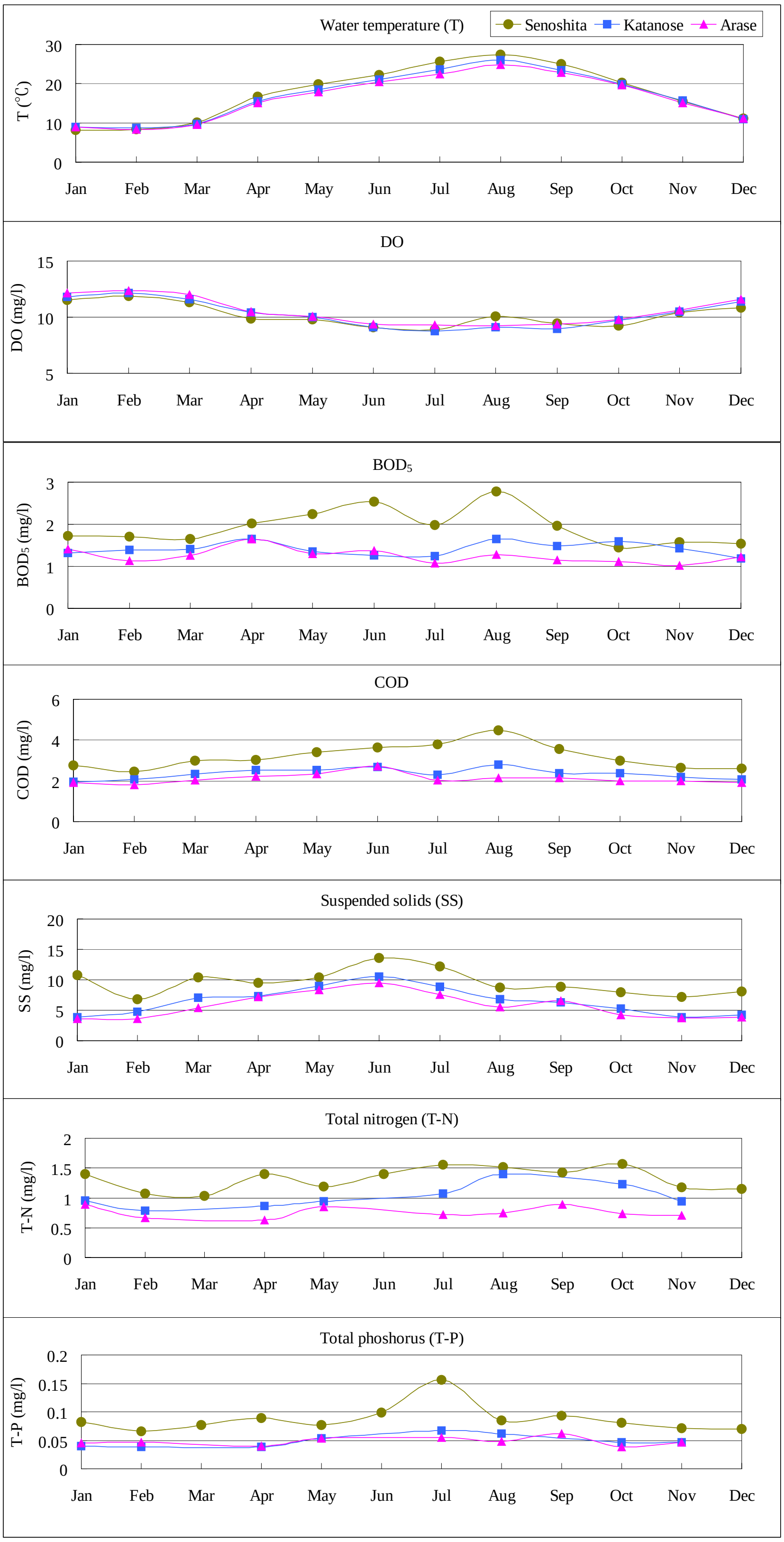


Figure 3.11 Monthly water quality concentration of the Chikugo River

At Arase, BOD_5 is high in March to June. In this period, BOD_5 at Arase and Katanose is in the same level. From July to December, BOD_5 at Arase is around 1 mg/l. BOD_5 at Katanose decreases between May and July. Besides the period of low BOD_5, concentration of BOD_5 at Katanose is approximately 1.5 mg/l. In April to September, BOD_5 at Senoshita is 2-3 times higher than BOD_5 at Katanose and Arase. BOD_5 at Senoshita in October to March is constant and much lower than that in April to September.

Except the peak COD in June, COD at Arase is constant at around 2 mg/l. COD at Katanose is highest in August. Besides high COD in August, COD at Katanose in the same level with COD at Arase. Similar to the pattern of BOD_5, COD at Senoshita is high during May to October and is highest in August. It is shown that BOD_5 and COD concentrations at Senoshita are in the same level with those at Arase and Katanose and become high during irrigation period.

Suspended solids at Arase and Katanose are in the same level whereas suspended solids at Senoshita are higher. Because of erosion, SS at every point increase with the increase in flow rate in Fig.3.6. T-N at Arase is low comparing with T-N at Katanose and Senoshita. T-N at Arase and Katanose are high in May to October whereas T-N at Senoshita is high in April to October. T-N at Katanose in August and September is as high as that at Senoshita. T-P of the Chikugo River is around 0.05 mg/l at Arase and Katanose. In spite of high T-N concentration in irrigation period, T-P at Katanose is much lower than T-P at Senoshita. T-P at Senoshita ranges between 0.07 and 0.16 mg/l. The period of high T-P at Senoshita is from June to August.

It is clear that BOD_5, COD and nutrient concentrations at Senoshita are high during irrigation period. The concentrations in non-irrigation period are low and almost constant. Irrigation and fertilization in agricultural area result in high concentrations in irrigation period. Since Arase is located near the outlet of Yoake Dam, the influence of irrigation activities on water quality at this point is very small. The difference in characteristics of irrigation and fertilization in agricultural area is one possible cause of different patterns of nutrient concentrations at Katanose and Senoshita.

Water in the Chikugo Basin is used for many purposes and the number of water users is large. Loadings are discharged into the Chikugo River from various kinds of point sources and non-point sources. Because it is difficult to define non-point source loadings by field observation, the information of non-point sources in the Chikugo Basin is hardly available. Therefore, loading analysis is necessary. In loading analysis, characteristics of loadings and non-point sources in the Chikugo Basin are determined from available field data.

3.2.8. Loading analysis in the Chikugo Basin

In loading analysis, characteristics of loadings of BOD_5, COD, SS, T-N and T-P are studied. Figure 3.12 shows monthly loadings at Arase, Katanose and Senoshita. Monthly loadings are determined by multiplying monthly flow rate with monthly water quality concentration. Observed data of flow rate and water quality in 1980-2000 is utilized in this analysis (Kyushu Regional Development Bureau, MLIT 2001).

As shown in Fig.3.12, patterns of loadings at every point are similar. From October to May, loadings of the Chikugo River between Arase and Senoshita are almost uniform. It is shown that loadings become high in June to September. In this period, loadings at Senoshita are higher than those at Katanose and Arase. Except T-N loading, loadings at Katanose in June to September are in the same level with those at Arase. The maximum BOD_5 and COD loadings at Senoshita are 2-3 times higher than the maximum loadings at Katanose. The peak SS loading at Senoshita is twice of the peak loading at Katanose. Ratio of T-N loading to T-P loading at Katanose is higher than the ratio at Senoshita. It indicates that, at every unit of T-P loading discharged into the Chikugo River, higher T-N loading is discharged at Katanose.

Because of cold weather, it is not suitable to grow crop in winter. Few irrigation activities are held in this period. In this study, it is assumed that there is no irrigation and fertilization in the paddy field area during November to February, so-called non-irrigation period. During non-irrigation period, loadings originate from the activities that do not involve in agriculture. Loading sources in this period are household, industry, etc., which generate waste at steady rate. High loadings in irrigation period are predominated by loadings from irrigation and fertilization in the agricultural area. Erosion during high flow period is another cause of high SS loading in irrigation period. Higher ratio of T-N loading to T-P loading at Katanose is probably caused by the difference between irrigation systems in the catchment area of Katanose and Senoshita. Characteristics of water use in agricultural area in the middle part of the Chikugo Basin will be analyzed by numerical models in Chapter 4.

Because of large number of water users, there are many kinds of loading sources in the Chikugo Basin. Point source loadings can be controlled by wastewater treatment system. To handle with non-point source loadings is more difficult since they cannot be controlled by wastewater treatment system and the information of non-point sources is rarely available. Major non-point sources in the Chikugo Basin are forest area, urban area and agricultural area. From data of land use, more than 70% of agricultural area in the Chikugo Basin is paddy field. In this study, paddy field is used as a representative of agricultural area in the Chikugo Basin. Characteristics of non-point sources are determined by analyzing available data of water quality and land use of the Chikugo Basin. This analysis focuses on characteristics of urban area and paddy field area.

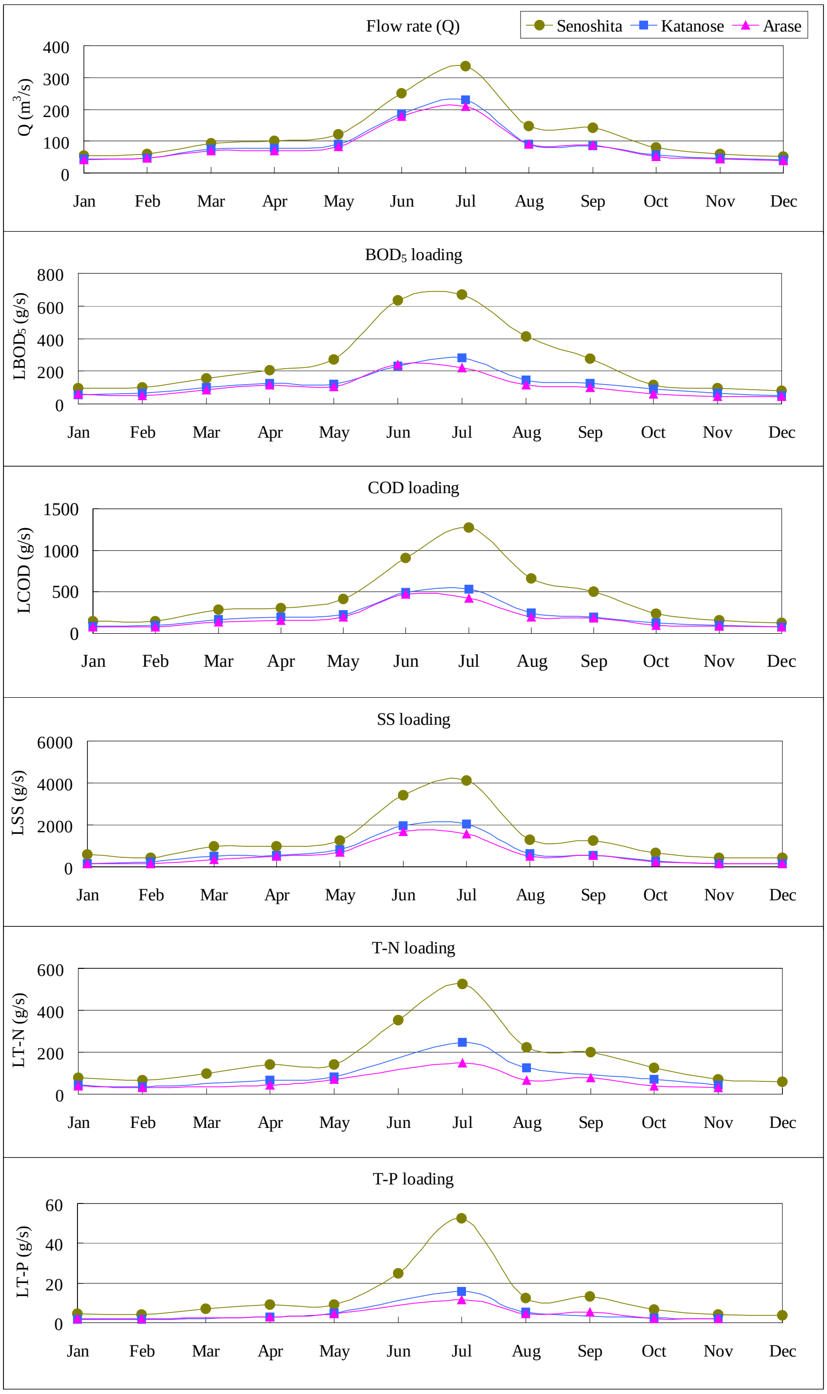


Figure 3.12 Monthly loadings of the Chikugo River

Relationships between COD, T-N and T-P concentrations and population are linear as shown in Fig.3.13. Since the population of the Chikugo Basin is proportional to paddy field area, it is recognized that the relationships between these water quality concentrations and paddy field area are also linear. It is pointed out that COD and nutrient concentrations from forest area at upstream of the river, where there is no influence of human activities existing, are constant and can be estimated through getting intercept values at the axis of concentration in this figure.

After subtracting the concentrations from forest area, discharge from urban area and paddy field can be evaluated in form of loadings. To determine unit loading of each source, loadings are considered in two periods. The first period is irrigation period (June to August). The second one is non-irrigation period (November to February).

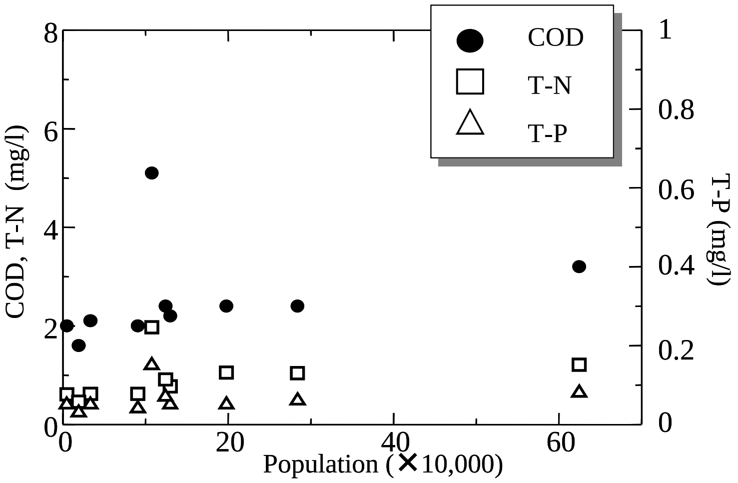


Figure 3.13 Relationship between population and water quality in the Chikugo Basin

Loadings in each period are shown with paddy field area and population in Fig.3.14. As mentioned before, loadings from paddy field are assumed to occur only in irrigation period whereas loadings from urban area are discharged at steady rate in both periods. Relationship between COD loading and paddy field area is linear in both periods. Relationships between nutrient loadings and paddy field area are similar to COD loading. The difference between loadings in both periods can be evaluated as the loadings generated from irrigation and fertilization in paddy field area. It is suggested that loading per hectare of paddy field area can be obtained through dividing the difference between the loadings (b’) by paddy field area (a’).

Loadings from urban area can be evaluated from the loadings in non-irrigation period. Relationships between loadings and population are also linear. As shown in Fig.3.14, loading per capita can be estimated from the gradient of the line.

Figure 3.14 also shows results of loading analysis in the Onga Basin, Fukuoka Prefecture (Shoji et al. 1998). Length of this river is 61 km and basin area is about 1,030 km^2. Population of the Onga Basin is 630,000. The Onga River flows to the Genkai Sea in the north of Kyushu Island. Annual average flow rate at downstream is 30.15 m^3/s.

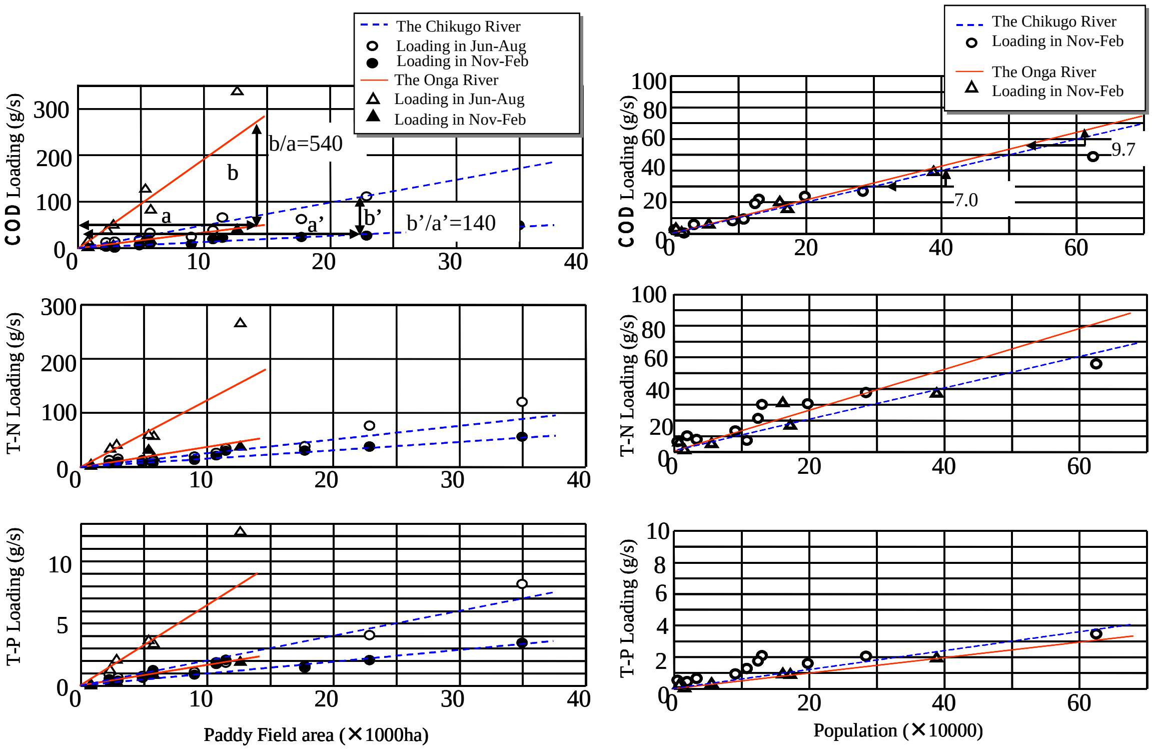


Figure 3.14 Relationship between loadings and paddy field area and relationship between loadings and population in the Chikugo Basin and the Onga Basin

The comparison of unit loading of urban area and paddy field in the Chikugo Basin and the Onga Basin is shown in Table 3.5. Unit loading of urban area in the Chikugo Basin and that in the Onga Basin are in the same level. However, unit loading of paddy field area in the Chikugo Basin is less than one-third of that in the Onga Basin. One possible cause is the difference in characteristics of irrigation water use in paddy field area in both areas. In the Onga Basin, many weirs are installed along the river for irrigation water intake. After returning to the main river, water is withdrawn again at next weirs and distributed to paddy field. Because the Onga River is shorter, water is repeatedly used for irrigation several times and more frequent than water in the Chikugo Basin. The study on nutrient runoff process carried out by Moriyama et al. (2003) indicated that discharge from agricultural area predominated nitrate nitrogen runoff in the Onga Basin whereas main source of ammonium nitrogen and phosphate phosphorus was municipal wastewater from urban area. The unit loading obtained in this analysis is useful in evaluating discharged loadings from the Chikugo Basin into the Ariake Sea.

Table 3.5 Unit loading of non-point sources in the Chikugo Basin and the Onga Basin

Water Quality	River	Unit loading of paddy field area (kg/ha-y)	Unit loading of urban area (g/capita-d)
COD	The Chikugo River	140.0	7.0
	The Onga River	540.0	9.7
T-N	The Chikugo River	40.0	8.6
	The Onga River	280.0	10.8
T-P	The Chikugo River	3.4	0.5
	The Onga River	16.0	0.45

3.3 Problem analysis in the Ariake Sea

3.3.1. General information

The Ariake Sea is a semi-closed sea located in the west of Kyushu Island. A bay outlet of 6 km long at Hayasaki Strait connects the Ariake Sea with the open sea. Total area of this L-shaped sea is about 1,700 km^2. Length of the Ariake Sea is about 100 km, average width is 15 km and average water depth is 20 m. According to salinity level, the Ariake Sea is divided into three parts, namely, innermost part, central part and gulf mouth (Fig.3.15). Tidal range of the Ariake Sea is the greatest one in Japan. At the spring tide, tidal difference reaches almost 6 m at the head of the gulf. Tidal flat with the length of 6-10 km appears during ebb tide. The tidal flat in the Ariake Sea covers about 40% of total tidal flat in Japan. Because of the enclosure of Isahaya Bay in 1997 and land reclamation project, the tidal flat in the Ariake Sea is decreasing. The investigation of condition of mud bed in the innermost part of the Ariake Sea by Yamanishi et al. (2002) indicated that bottom deposits in the west side were composed of fine particles like silt and clay. The deposits with larger particle size such as fine sand were observed in the east side of the innermost area. Results of the investigation agree with characteristics of water movement in the Ariake Sea. Seawater from the open sea flows counterclockwise along the coast before leaving the Ariake Sea from the west of Hayasaki Strait (Gan et al. 2000). Watershed area of the Ariake Sea is about 8,450 km^2 composing of five prefectures: Fukuoka, Saga, Kumamoto, Nagasaki and Oita prefectures. Most of discharged water from land area flows into the Ariake Sea through eight class A rivers including the Chikugo River. Fishery and laver production in the innermost area of the Ariake Sea are productive and famous in Japan.

3.3.2. Major rivers in catchment area of the Ariake Sea

As shown in Fig.3.15, there are eight class A rivers located in the catchment of the Ariake Sea. Total basin area of these rivers is 6,852 km^2, which is more than 80% of the basin area of the Ariake Sea. Total amount of water discharged from all rivers are around 8.5 km^3/y. More than 40% of this discharge comes from the Chikugo River, which is the largest amount among these eight rivers. Details of each river basin except the Chikugo Basin are described below.

The Midori River discharges into the central part of the Ariake Sea at Kumamoto City. This river is one of two large rivers that flow through Kumamoto Plain. Length of the Midori River is 76 km. Basin area of the Midori Basin covers 1,100 km^2 of Kumamoto Prefecture. Because of the urbanization in its tributaries, water quality of the Midori River frequently fails to meet the water quality standard.

The Shira River is other large river running through Kumamoto Plain. Length of this river is 74 km. As same as the Midori River, the Shira River flows into the Ariake Sea at Kumamoto City. Total area of the Shira Basin is 480 km^2. This river basin is located in the north of the Midori Basin. The origin of this river is in Mt. Aso. Influenced by volcanic ash, high content of fluoride in the Shira River makes it unsuitable for consumption.

The Kikuchi Basin is another watershed located in Kumamoto Prefecture. With the length of 71 km, catchment area of this river basin is 996 km^2. The Kikuchi River discharges into the Ariake Sea at Tamana City.

Discharging into the innermost part of the Ariake Sea, the Yabe River is 61 km long. Basin area of the Yabe Basin is 620 km^2. Population of this watershed is 188,000. The Yabe River originates in the boundary of Fukuoka, Oita and Kumamoto prefectures. Major function of this river is irrigation water supply.

Total length of the Kase River is 57 km. Located in Saga Prefecture, basin area of the Kase Basin is 368 km^2. Almost 70% of this watershed is mountainous area. Major water use is irrigation, drinking water and hydroelectric generation. Agricultural area in this watershed is 136 km^2. The Kase River supplies water at rate of 1.2 m^3/s for drinking water service.

The Rokkaku Basin is located in the west of Saga Prefecture. Total area of this river basin is 341 km^2. The Rokkaku River meets the Ushitsu River before flowing into the Ariake Sea. Tidal range reaches 5-6 m at the river mouth. Length of the tidal reach is approximately 29 km. Because of high consumption of groundwater and soft soil, land subsidence is a big problem in this watershed.

With basin area of 87 km^2, the Honmyo Basin located in Isahaya City, Nagasaki Prefecture. Total length of the Honmyo River is 21 km. This river is the shortest class A river in Japan. The Honmyo River discharges into Isahaya Bay in which the reclamation project is now carried out. Because of low flow rate as well as the wastewater from food industry and household, water quality at downstream of this river is deteriorating.

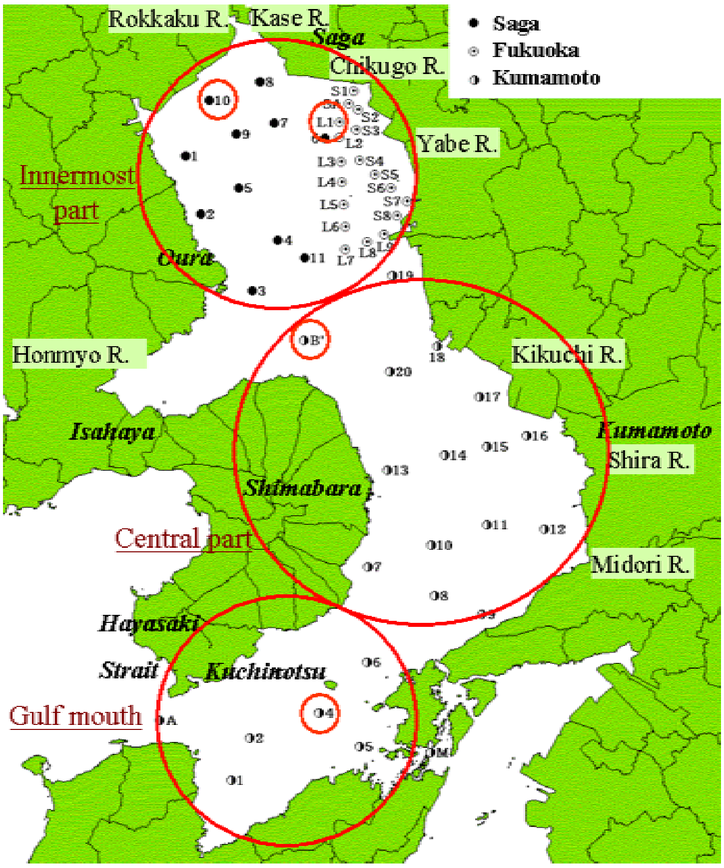


Figure 3.15 The Ariake Sea

3.3.3. Characteristics of water quantity and quality in the Ariake Sea

Water quality investigation in the Ariake Sea has been carried out at 61 fixed observation stations. Sampling is carried out at the high tide of every spring tide. Characteristics of water quality in the Ariake Sea are determined from observed data and related researches.

Araki et al. (2001) stated that the tidal range increased along the gulf axis from the mouth to the innermost part. Figure 3.16 shows tide level of each part of the Ariake Sea. Independent with season, the tide level has a cyclic pattern with a period of approximately 28 days. As shown in Fig.3.17, levels of high tide and low tide in winter to early summer are almost constant whereas low tide level rises during summer to fall. As a result, tidal flat is large during winter to early summer and becomes largest in the low tide of a spring tide in spring season.

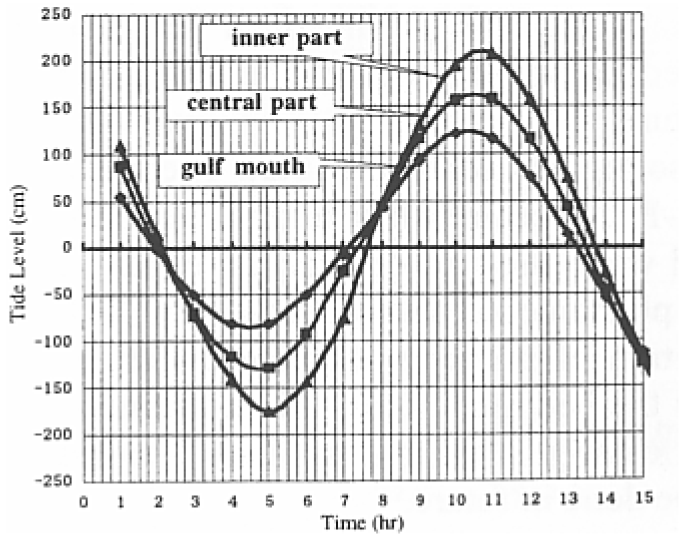


Figure 3.16 Tide level in the Ariake Sea

Source: Araki et al (2001)

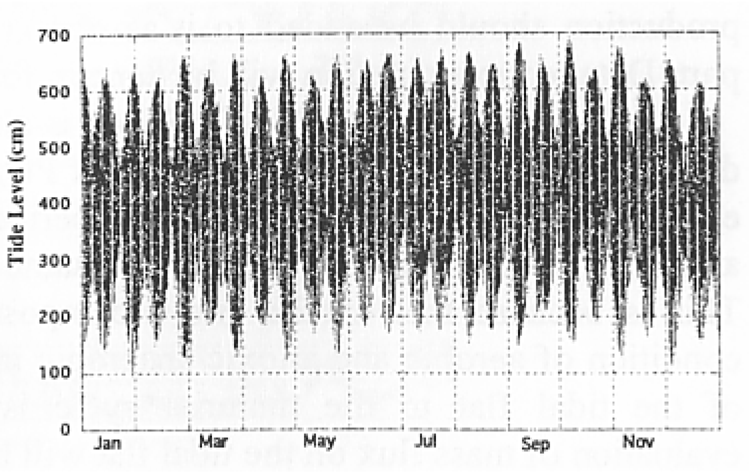


Figure 3.17 Pattern of tide level at a monitoring tower

Source: Araki et al. (2001)

From the environment monitoring of Chikugo Barrage, tide level and water temperature in the vicinity of the mouth of the Chikugo River are rising (WRDPC 2003).

Observed data of tide level at Oura Station and Kuchinotsu Station in 1991-2000 (Japan Meteorological Agency 2001a, 2001b) is averaged over 24 hours. In Fig.3.18, daily tide level is low in winter to summer whereas the tide level in summer to fall is high. Average level of tide at Oura Station is higher than at Kuchinotsu Station. The increase in tide level at Oura Station agrees with the report of WRDPC. Tide level at Kuchinotsu Station has increased as well. In spite of the increase in tide level, average tide level at both stations was low in summer to fall of 2000. Fluctuation of average tide level in 2000 was small comparing with those in other years.

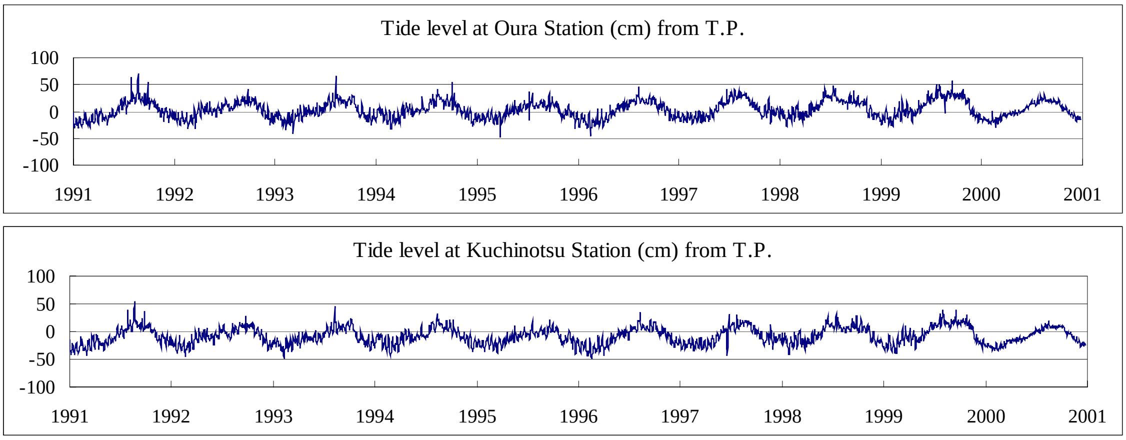


Figure 3.18 Daily tide level in the Ariake Sea

Water quality in the Ariake Sea from the innermost part to the mouth of the gulf is shown in Fig.3.19 to Fig 3.24. Average water temperature rises in every part of the Ariake Sea. The certain cause of the increase in water temperature is still unknown. One of possible causes is an impact of global warming. Salinity in the innermost part is lower than the salinity observed in the central part and the area near the open sea. Salinity in the gulf mouth is approximately 35 ppt during dry period whereas salinity in the innermost part is about 30 ppt. Salinity near the river mouth decreases during rainy season because of high discharge of freshwater.

Transparency is low and constant near the river mouth and in the innermost part because of suspended solids discharged from land area, resuspension by tidal movement and algal productivity. However, this low transparency may have controlled eutrophication in the innermost area of the Ariake Sea. Transparency is high in the central part and near the open sea. Concentrations of COD and inorganic nutrients in the head of the gulf are higher than those in the central part and the gulf mouth. COD in the innermost part slightly increases in these ten years. Because the relation between inflow loading and COD is unobvious, the increase in COD is probably caused by organic matter released from mud bed and secondary productivity in the Ariake Sea. Inorganic nutrients of the innermost part are low in winter to early summer, which is an expansion period of the tidal flat. During the expansion, active productivity in the tidal flat leads to the increase in nutrient uptake. It is clear that the tidal flat contributes to water quality in the innermost part of the Ariake Sea. Nutrient contents become high during summer to fall when irrigation is carried out in paddy field and nutrient loads are discharged into the rivers. It is believed that nutrients for productivity of laver in the Ariake Sea are mainly supplied from the Chikugo River.

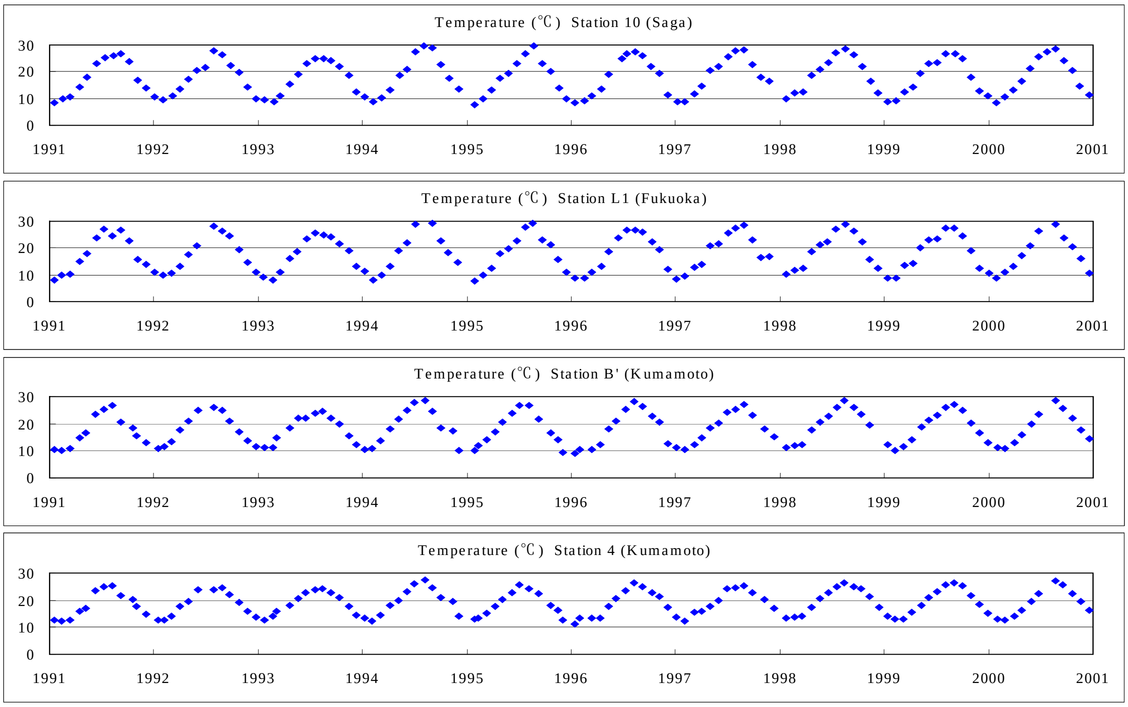


Figure 3.19 Water temperature in the Ariake Sea

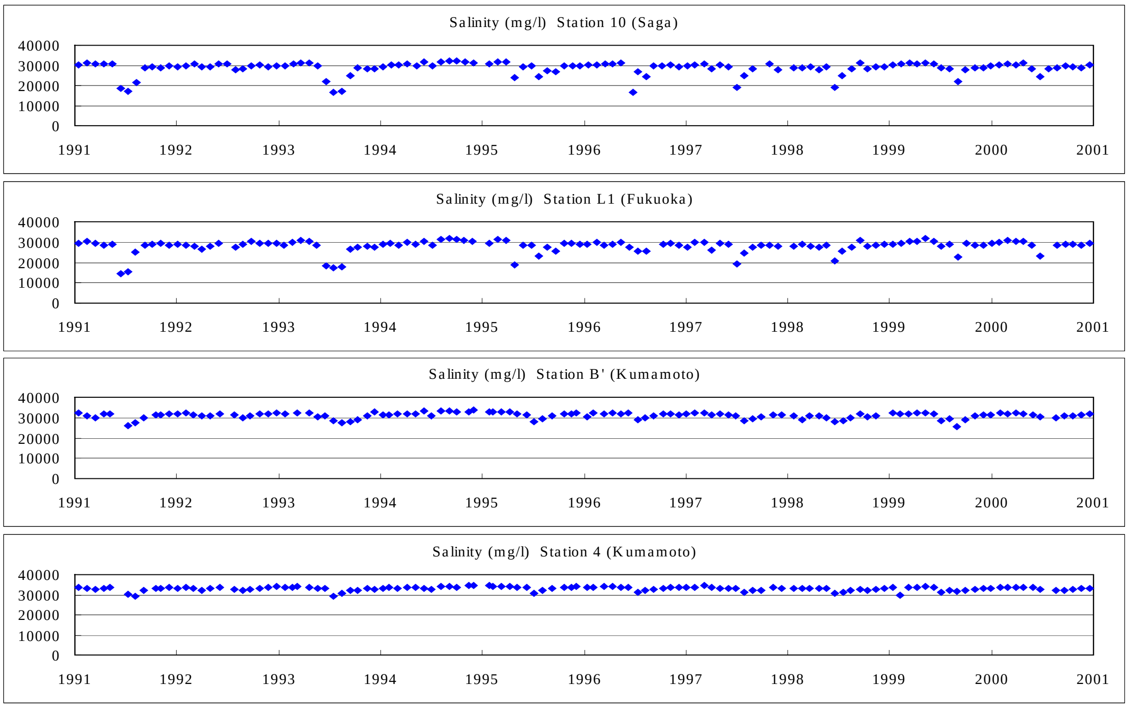


Figure 3.20 Salinity concentration in the Ariake Sea

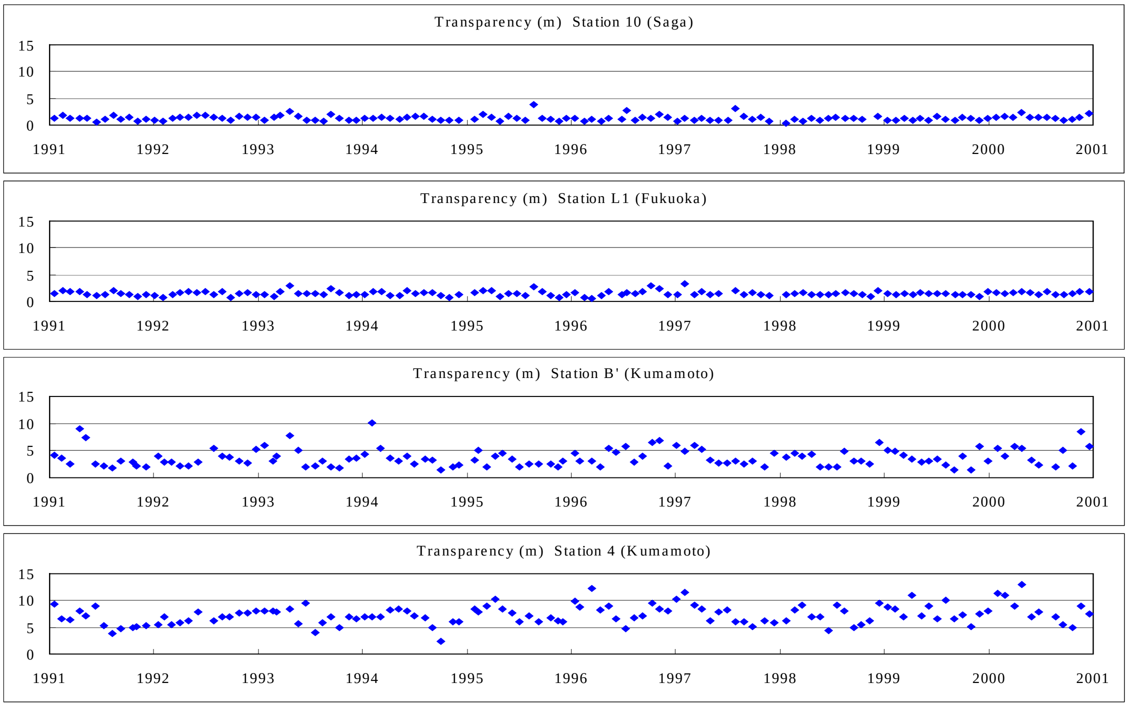


Figure 3.21 Transparency in the Ariake Sea

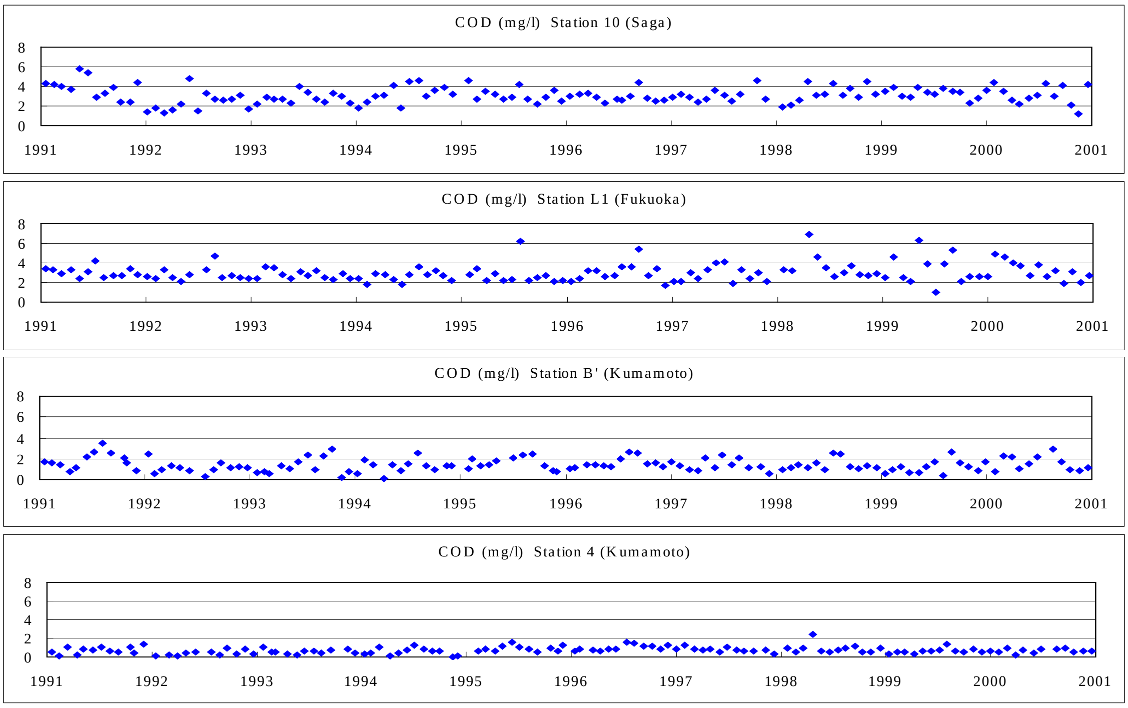


Figure 3.22 COD concentration in the Ariake Sea

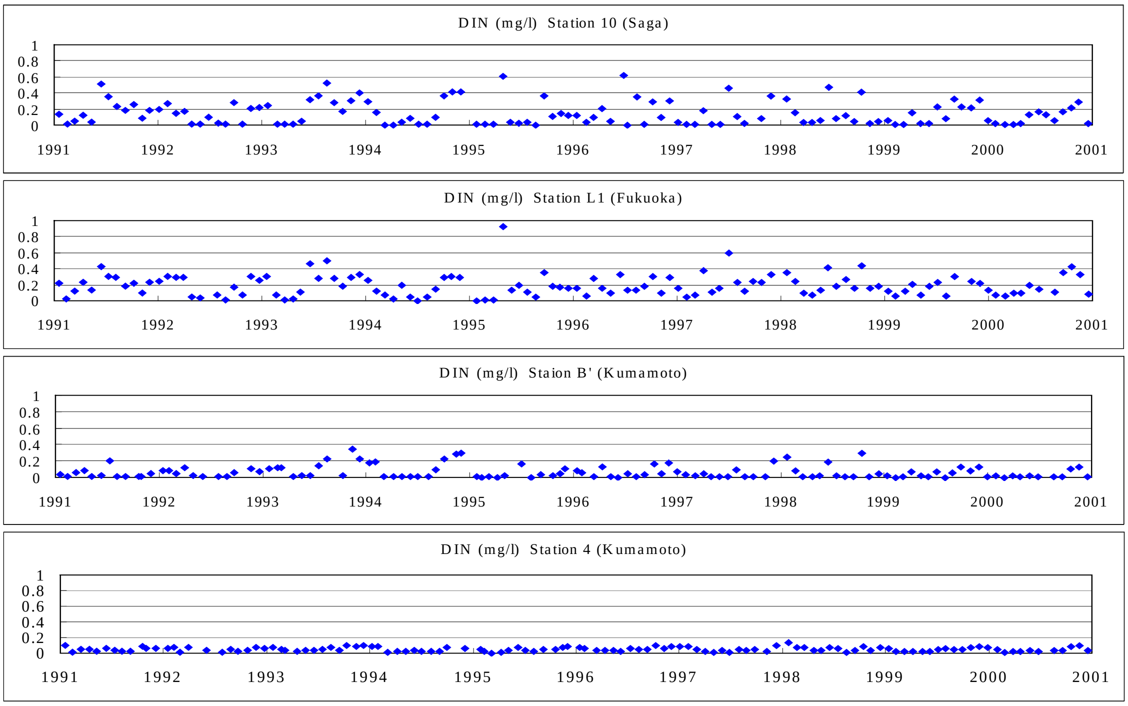


Figure 3.23 DIN concentration in the Ariake Sea

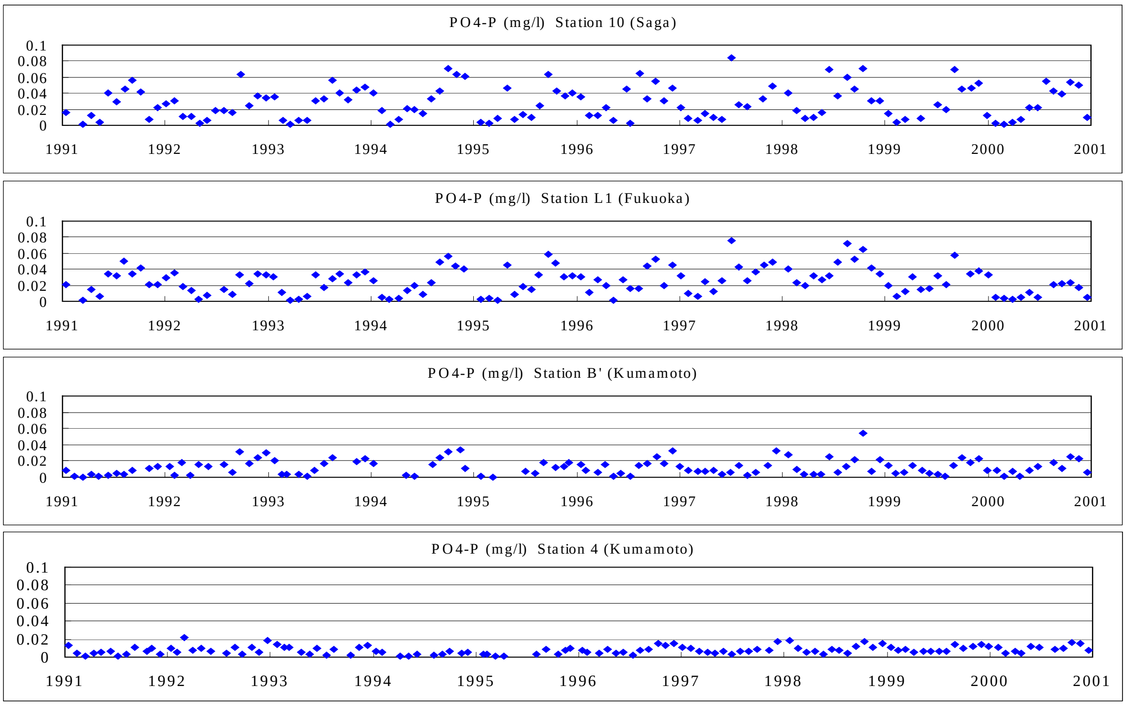


Figure 3.24 PO_4-P concentration in the Ariake Sea

Koh (2003) investigated microphytobenthos in terms of chlorophyll-*a* (Chl-*a*) in the tidal flat of the Ariake Sea and its contribution to the coastal ecosystem. The investigation indicated that the resuspension from the tidal flat contributed to Chl-*a* in the overlying water whereas the Chl-*a* in the central part of the Ariake Sea was predominated by biological process.

From results of the investigation and researches above, it is pointed out that there is some relationship among water quality in the innermost part, discharged loadings from land area and ecosystem in the tidal flat in the Ariake Sea. It is suggested that information of the tidal flat and inflow loadings including loadings from the Chikugo Basin should be taken into account when analyzing water quality of the Ariake Sea. In this study, inflow loadings from land area and condition of mud bed are considered as important factors in water quality modeling in the Ariake Sea. On the other hand, relationship between discharged loadings and water quality in the Ariake Sea emphasizes that the impact assessment of proposed measures for water management in the Chikugo Basin needs to be conducted in the Ariake Sea as well. In order to analyze such impacts simultaneously in both areas, it is recommended to integrate the water quality model of the Chikugo Basin with the model of the Ariake Sea. In Chapter 5, water quality model is developed in the Ariake Sea and integrated with the developed model of the Chikugo Basin.

Laver productivity in the Ariake Sea was very low during cultivation period from autumn of 2000 to spring of 2001. Laver lost its black color and turned paled yellow because of red tide, which occurred during that period. This problem affected large number of laver cultivation groups and brought environmental situation of the Ariake Sea to public concern. At present, many researches are carried out in order to investigate the environmental situation in the Ariake Sea and the causes of the red tide. Although this study does not aim at solving the problem of laver productivity, the analytical tools developed in this study and the information obtained from water quality analysis can give some explanation about the situation of the Ariake Sea, which may lead to solutions of the problem.

3.4 Summary

In this chapter, the Chikugo Basin is divided into three parts. General characteristics such as topography, climate, land use and water use in each part are summarized. Observed data of water quantity and water quality of the Chikugo River is analyzed, and characteristics of water quantity, water quality and loadings in this watershed are pointed out.

The upper part of the Chikugo Basin is mountainous area. Agricultural area in this part is small comparing with those in the other parts. Water use in this area is mainly for power generation and irrigation. Because of more population and larger paddy field area, water demand for irrigation, drinking water and industry is high in the middle and the lower parts. Flow rate between Arase and Senoshita is high during June to September, which is rainy season and irrigation period in the Chikugo Basin. Water quality of the Chikugo River in this reach achieves the water quality standard of category A. However, water temperature and nutrient concentrations in this reach have increased. During the drought in 1994, BOD_5 and COD concentrations of the Chikugo River were high. Concentrations of BOD_5, COD, SS and nutrients at Senoshita become high in rainy season. In August and September, T-N at Katanose is as high as T-N at Senoshita whereas T-P at Katanose is much lower. The difference between patterns of nutrient concentrations at Katanose and Senoshita is probably caused by the difference in irrigation water use.

Due to high flow rate, loadings in the middle reach of the Chikugo River are high during irrigation period. Loading analysis states that large amount of loadings is generated from paddy field in irrigation period while those from non-irrigation activities are lower and steady. Unknown parameters of non-point sources such as unit loading of paddy field and urban area are determined and compared with those in the Onga Basin. It is found that annual loadings from one hectare of paddy field in the Onga Basin are more than three times of those in the Chikugo Basin whereas unit loading of urban area in both watersheds is in the same level. The difference in characteristics of irrigation system is one of possible causes of high loadings from paddy field in the Onga Basin. Unit loading of the Chikugo Basin obtained from loading analysis is useful for estimating loading in water management in the Chikugo Basin and the Ariake Sea. Because it is difficult to determine characteristics of irrigation water use and non-point source loadings by using only observed data, analytical tools such as numerical models are necessary. Based on results of problem analysis, numerical models of the Chikugo Basin are developed in Chapter 4. The developed models are then applied in the analysis on water quantity and water quality in the Chikugo Basin.

In the second part of this chapter, problem analysis is performed in the Ariake Sea. Being a receiving water body for many rivers, details of the rivers situated in the watershed of the Ariake Sea are summarized to give an idea about the loadings discharged into the Ariake Sea. Loadings from the Chikugo Basin are the biggest ones among loadings from all rivers. The increase in high tidal level and water temperature are reported near the mouth of the Chikugo River in these recent years. Not only in the innermost part, water temperature is rising in the whole parts of the Ariake Sea. The increase in water temperature is probably an influence of the global warming. From the investigation, transparency in the innermost part is lower than that in the central part and gulf mouth. Resuspension from tidal flat, secondary productivity and loadings from land area are the causes of low transparency in this area. COD and nutrient concentrations are high in the innermost part. These concentrations become lower in the central part and near the open sea. The analysis results reveal the relationship among inflow loadings from land, the tidal flat and water quality in the Ariake Sea. It is suggested taking into account contributions of inflow loadings and ecosystem in the tidal flat in water quality analysis in the Ariake Sea. Contribution of inflow loadings to water quality in the Ariake Sea also points out the necessity of evaluating impacts of the proposed measures on water quality of the Ariake Sea in integrated water management in the Chikugo Basin. As a decision-support instrument, an integrated model for water quality analysis in the Chikugo Basin and the Ariake Sea is recommended.

In Chapter 5, water quality model is developed for the Ariake Sea concerning the discharged loadings from land area and ecosystem in the tidal flat. This model is linked with the developed models of the Chikugo Basin and applied in sensitivity analysis in the Ariake Sea.

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CHAPTER 4

QUANTITATIVE AND QUALITATIVE ANALYSIS IN THE CHIKUGO BASIN

4.1 Introduction

Not only the analysis of available observed data described in Chapter 3, there are also many ways to provide necessary information for water management. One of the effective methods is an application of numerical model. The purpose of system analysis is to provide systematic quantitative and qualitative information for water management, which can support decision-makers to pick up the better choice among the proposed alternatives (CUR 1993). Due to scientific and technological development, calculating instruments and analytical methods become more powerful and widely available for all types of analyses. With capability of making prediction, numerical models are now playing an important role in analytical tasks for water management.

Based on general details obtained from problem analysis, numerical models are developed for the simulation of water quantity and water quality in the Chikugo Basin. These simulation models function as analytical tools for water quality analysis and evaluation of the proposed alternatives in water management. Representing the Chikugo River and its catchment, the river model and the tank model are introduced to the Chikugo Basin in this chapter. Water quality parameters concerned in the water quality models are COD, SS, T-N and T-P. In the model development, both models are calibrated with observed data of flow rate and water quality at three observation points in the Chikugo River in 1986-2001.

The developed models are employed in water quantity and water quality analysis in order to clarify characteristics of water use and loadings generated in the Chikugo Basin, which are difficult to determine by field observation. Relationship between amount of water use and discharged loadings is one important factor required for the control and management of water quality in a river basin, for example, establishment of wastewater infrastructures or countermeasures against pollutant loads. Economical evaluation in policy analysis needs output of the efficiency of water quality improvement while impact assessment may need predicted result of the changes in flow rate or water quality at downstream. As a result, the developed models are necessary as facilitating tools for decision-making process in water management in the Chikugo Basin.

4.2 Water quantity and water quality modeling in the Chikugo Basin

In water quantity management, it is important to secure the river flow to meet water demand and to maintain the river environment during dry period. Under low precipitation, flow rate in dry period is predominated by base flow from the basin area. Because of different hydrological condition, modeling is performed separately in the main river and the catchment area of the Chikugo Basin. The simulation model for the catchment area is based on the tank model in which base flow is taken into account in determining runoff from the catchment area. To simulate flow rate and water quality in the river, one-dimensional river model is developed. Water quality parameters such as COD, SS, T-N and T-P are considered in water quality modeling. Basic concepts of the tank model and the river model in Chikugo Basin are described below:

4.2.1. The tank model

The tank model developed by Sugawara (1967) is a simple model, which has been widely used for long- and short-term runoff analysis. One good point of this model is the mechanism of rainfall loss is considered in water balance in the basin area. The tank model consists of a vertical series of tanks with one orifice at the bottom and one or more lateral orifices. Composed of four tanks, the typical tank model of Sugawara is shown in Fig.4.1. The lateral flow from an upper tank represents surface runoff of the catchment area while the lateral flow from lower tanks associates with subsurface runoff and groundwater. As water infiltrates from an upper soil layer to a lower layer, water from the upper tank flows through the orifice at the bottom into the lower tank.

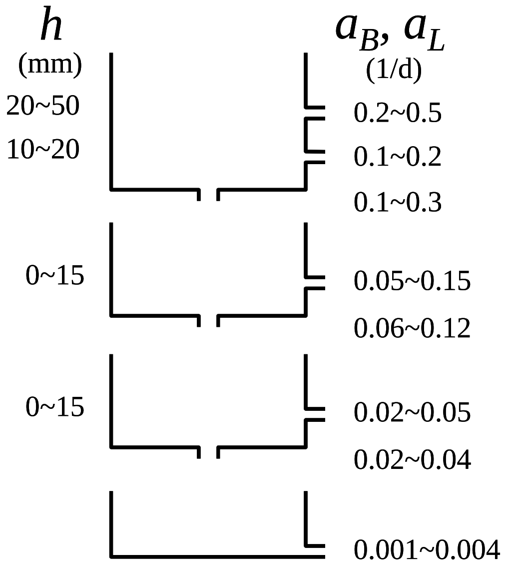


Figure 4.1 Details and parameters of a typical tank model

Source: Sugawara (1973) and Japan Society of Civil Engineers (JSCE) (1980)

In this study, the tank model composed of three tanks is developed for the catchment area of the Chikugo Basin. Time step of this model is one day. Details of the developed tank models are described below:

- Water balance in a catchment area

During rain, some of precipitation infiltrates into the ground becoming subsurface runoff or recharging into the groundwater layer, some of them is retained in ponds or lakes while the rest flows over the surface of the ground, called surface runoff, to the lower area or receiving water body like river and sea. Amount of water discharged from the catchment area is determined by the developed tank model. Water evaporates from surface water body and ground to the atmosphere during a fine day, and another form of water loss in the soil is transpiration by plants. These two processes are often considered together as evapotranspiration. The balance of water in one catchment area is described in Eq.(4.1).

$$\frac{dY_{(k)}}{dt} = p_{(k)} - e_{(k)} - q_{T(k)} + i_{(k)} \tag{4.1}$$

where Y = amount of water in the basin (m);

p = precipitation (m/d);

e = evapotranspiration (m/d);

q_T = total runoff flowing into the river (m/d) and

i = irrigation water (m/d).

Subscript k = basin number.

As shown in Fig.4.2, irrigation water in one basin area is supplied in form of water directly withdrawn from the main river at the weirs located inside the basin. Another form of irrigation water is the water conveyed in open channel system from upstream area. Eq.(4.2) describes amount of irrigation water entering the basin in unit of depth. The remaining of irrigation water is collected into open channels and distributed to the downstream area as $i_{C(k+1)}$ in Eq.(4.3).

$$i_{(k)} = \frac{\gamma_{(k)} \cdot Q_{W(k)} + \alpha_{r(k)} \cdot i_{C(k)}}{A_{(k)}} \tag{4.2}$$

$$i_{C(k+1)} = (1-\gamma_{(k)}) \cdot i_{W(k)} + (1-\alpha_{r(k)}) \cdot i_{C(k)} \tag{4.3}$$

where Q_W = total intake water withdrawn at weirs (m^3/d);

γ = percentage of irrigation water supplied directly from weirs (%);

i_C = total irrigation supply in the open channel (m^3/d);

α_r = distribution ratio of irrigation water from the open channel (%) and

A = basin area (m^2).

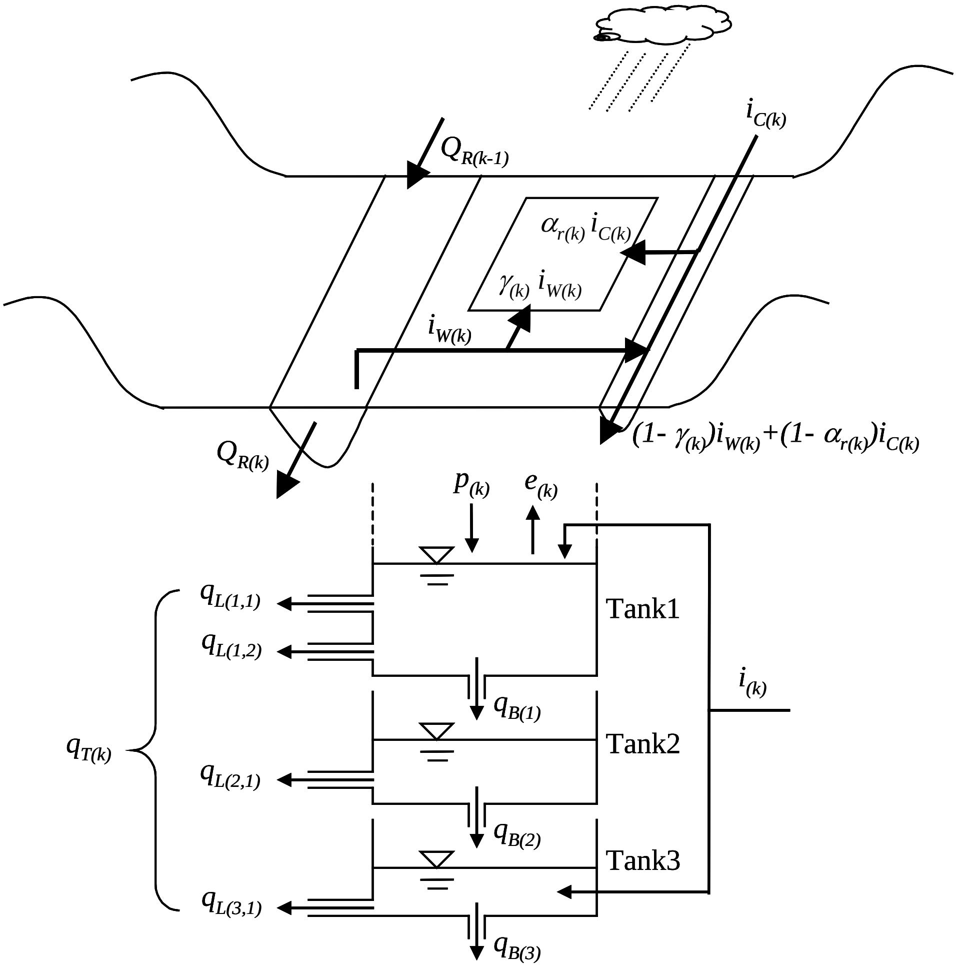


Figure 4.2 Water balance in the catchment area

- Water balance in the tank model

Composed of three tanks, the developed tank model represents inflow and outflow of one catchment area. As mentioned above, some of precipitation and irrigation water flows to the lower area, some is retained in an open water body called surface water and some infiltrates into the ground. The loss in surface water occurs in form of evapotranspiration. After entering the soil profile, water becomes a part of subsurface flow or infiltrates into the deeper soil layer. Subsurface water moves through porous soil to the lower area discharges into river or sea or percolates into the aquifer. These mechanisms are revealed through the water balance in each tank of the tank model.

With time step of one day, water balance inside a tank is described in Eq.(4.4). Representing the loss in surface water, evapotranspiration occurs only in the most upper tank that is filled with water. Some part of precipitation and irrigation water is rapidly drained into a river through an outflow of the topmost tank and the rest is gradually discharged to the river as base flow from lower tanks. Outflow through each orifice is proportional to amount of the water above the orifice as shown in Eq.(4.5).

Water infiltrates to the lower layer through the orifice at the bottom of the tank. Amount of infiltrate is proportional to the water depth inside the tank. The infiltration of each tank is described in Eq.(4.6).

$$i = 1; \qquad \frac{dy_{(i)}}{dt} = p_{(k)} - e_{(k)} + i_{T(i)} - \sum_j q_{L(i,j)} - q_{B(i)}$$

$$i > 1; \qquad \frac{dy_{(i)}}{dt} = -e_{(k)} + i_{T(i)} - \sum_j q_{L(i,j)} - q_{B(i)} \tag{4.4}$$

$$q_{L(i,j)} = a_{L(i,j)}(y_{(i)} - h_{(i,j)}) \tag{4.5}$$

$$q_{B(i)} = a_{B(i)} \cdot y_{(i)} \tag{4.6}$$

where y = water depth (m);

i_T = irrigation water entering the tank (m/d);

q_L = runoff flowing through the lateral orifice (m/d);

q_B = seepage (m/d);

h = height of the lateral orifice (m);

a_L = discharge coefficient of the lateral orifice (1/d) and

a_B = seepage coefficient (1/d).

Subscripts i = tank number; j = lateral orifice number and k = basin number.

Generally, discharge coefficients are related to soil moisture but the soil in the area of frequent precipitation like Japan can be considered as saturated soil and soil moisture can be neglected (Sugawara et al. 1975). Parameters of a typical tank model suggested by JSCE (1980) are also shown in Fig.4.1.

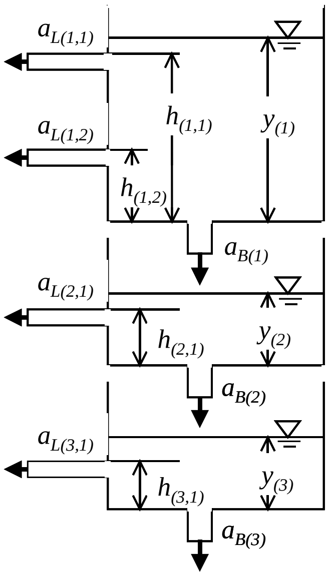


Figure 4.3 Details of the developed tank model

In this study, parameters h, a_L and a_B shown in Fig.4.3 are calibrated with observed flow rate at the observation points by trial and error method. Values of h, a_L and a_B in each basin are described later in the application of the developed models.

4.2.2. The river model

The river model in this study is one-dimensional model. The equation of continuity and mass balance in each river segment are described in Eq.(4.7) and Eq.(4.8), respectively. Similar to the tank model, time step of the river model is one day. To meet water demand for drinking water and industrial water in the Chikugo Basin, the required water is supplied from the reservoirs. During irrigation period, additional water is released from reservoirs for irrigation in downstream area. In the area between Arase and Senoshita, irrigation water is withdrawn from the river at weirs and distributed to agricultural area. The minimum flow rate at Senoshita is maintained in order to supply nutrients for fishery activities in the Ariake Sea. Because the river flow in dry period is predominated by base flow from the catchment area, additional water supply from the reservoirs at upstream is necessary. The information of water use mentioned above is taken into account in developing of the river model as shown in Fig.4.4.

- Continuity equation in a river segment

$$\frac{dV_{R(k)}}{dt} = (Q_{R(k-1)} + Q_{T(k)} + Q_{D(k)}) - (Q_{R(k)} + Q_{W(k)}) \qquad (4.7)$$

where V_R = water volume in the river segment (m^3);

Q_R = flow rate at downstream of the river segment (m^3/s);

Q_T = total runoff from the basin (m^3/s);

Q_D = total discharge from reservoirs (m^3/s);

Q_W = total water intake at weirs (m^3/s);

Subscript k = river segment number and basin number.

Volume of the river segment is a product of length and average flow cross-sectional area of the segment. Flow cross-sectional area is obtained from the relationship between flow rate and water level (Q-H curve) and the relationship between water level and flow cross-sectional area (H-A curve) of each observation point in the Chikugo River (MLIT 2000). An advantage of Q-H curve is it can satisfy the momentum balance in the river segment. Therefore, the momentum equation is not necessary for the river model.

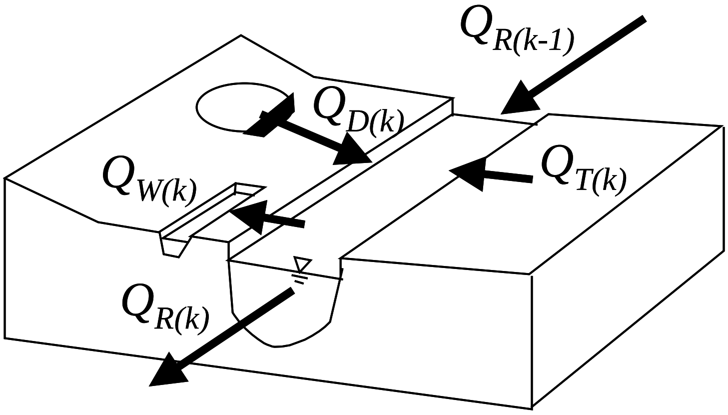


Figure 4.4 Water balance in the river segment

- Mass balance in a river segment

In this study, diffusion can be neglected because flow rate of the Chikugo River is high. Major non-point sources of loadings in a basin area considered in this study are urban area, forest area and paddy field area. It is assumed that loadings of paddy field are discharged at constant rate during irrigation period. Rapid runoff during heavy rainfall leads to high loadings from forest and urban area. These high loadings are estimated from the relationship between loading and runoff rate (L-Q relationship). On the other hand, steady loadings generated by non-point sources are estimated from unit loading and frame of each source. Total loading discharged from the basin is shown in Eq.(4.9).

The mass balance equation in river segment k, neglecting the diffusion term, can be written as below.

$$\frac{d\,c_{(k)} \cdot V_{R(k)}}{dt} = (c_{(k-1)} \cdot Q_{R(k-1)} + L_{T(k)} + L_{D(k)}) - c_{(k)}(Q_{R(k)} + Q_{W(k)}) \pm S_{(k)} \quad (4.8)$$

$$L_{T(k)} = aQ_{L(k)}^{b} + (N_{U(k)} \cdot L_{U(k)} + N_{F(k)} \cdot L_{F(k)} + N_{P(k)} \cdot L_{P(k)}) \qquad (4.9)$$

where c = concentration in the river segment (g/m^3);

L_D = total loading discharged from reservoirs (g/s);

S = reaction term (g/s);

a, b = constant (-);

Q_L = total runoff from basin area during heavy rainfall (m^3/s);

N_U = number of population (capita);

L_U = unit loading rate of population (g/capita-s);

N_F = forest area in the basin (m^2);

L_F = unit loading rate of forest area (g/m^2-s);

N_P = paddy field area in the basin (m^2) and

L_P = unit loading rate of paddy field area (g/m^2-s).

Subscript k = river segment number and basin number.

The left side of Eq.(4.8) can be rewritten as

$$\frac{d\,c_{(k)} \cdot V_{R(k)}}{dt} = c_{(k)} \cdot \frac{dV_{R(k)}}{dt} + V_{R(k)} \cdot \frac{d\,c_{(k)}}{dt} \qquad (4.10)$$

Substitution of Eq.(4.7) and Eq.(4.10) into Eq.(4.8) gives

$$V_{R(k)} \cdot \frac{d\,c_{(k)}}{dt} = L_{Sum} \pm S \qquad (4.11)$$

in which

$$L_{Sum} = (Q_{R(k-1)}) \cdot (c_{(k-1)} - c_{(k)}) - (Q_{T(k)} + Q_{D(k)}) \cdot c_{(k)} + L_{T(k)} + L_{D(k)} \qquad (4.12)$$

In a small segment, total inflow volume during high flow period may be larger than the water volume of the river segment. As a result, the water in that segment will be flushed out and the segment will be exchanged by inflow water.

The reaction term in Eq.(4.8) is generally negligible because the detention time in the river segment is short and inflow loading of the segment is normally much higher than the reaction rate. In this case, the concentration in the river segment should be same as average concentration of inflow $(\bar{c}^*_{(k)})$. The average inflow concentration can be expressed as follow:

$$\bar{c}^*_{(k)} = \frac{\text{Total inflow loading}}{\text{Total inflow rate}}$$

$$= \frac{c_{(k-1)} \cdot Q_{R(k-1)} + L_{T(k)} + L_{D(k)}}{Q_{R(k-1)} + Q_{T(k)} + Q_{D(k)}} \tag{4.13}$$

$\bar{c}^*_{(k)}$ can also be assigned in other ways depending on the climate and activities carried out in the river basin as some examples described below:

In a period of strong rainfall, $\bar{c}^*_{(k)}$ is equal to the concentration of surface runoff in that period.

In dry period, $\bar{c}^*_{(k)}$ is almost same with the concentration of upstream discharge and/or the concentration of discharge from reservoirs.

In irrigation period when the influence of loadings from paddy field is strong, $\bar{c}^*_{(k)}$ may be close to the concentration of the discharge from paddy field.

4.3 Application of the developed models

Located at downstream of Yoake Dam, flow rate at Arase depends on the release from Yoake Dam. Characteristics of water intake in the upstream area of Arase are complicated because there are several power plants located in this area. Due to the complex water intake system and inadequate information of water use, inflow from the basin area at upstream of Arase is replaced by the discharge from Yoake Dam. The developed models are applied in the Chikugo Basin from Arase to the mouth of the river. Observed data of flow rate and water quality at Arase is employed as a boundary condition of the developed models.

According to the topography and available observation points, the middle part of the Chikugo Basin is divided into four basins, and the Chikugo River between Arase and Senoshita is divided into three segments. Under an assumption that runoff from the lower reach is directly discharged into the Ariake Sea, the downstream area of Senoshita is represented by one tank with one lateral orifice at the bottom of the tank. Figure 4.5 demonstrates details of the developed models.

Parameters of the developed tank model in each basin area are calibrated through the simulation of flow rate at Esonoshuku, Katanose, Hatama and Senoshita. The obtained results from water quantity simulation are utilized in the estimation of discharged loadings from the basin area. Water quality simulation is carried out at Esonoshuku, Katanose and Senoshita. Unknown parameters of non-point sources such as unit loading of forest, urban area and paddy field area can be obtained.

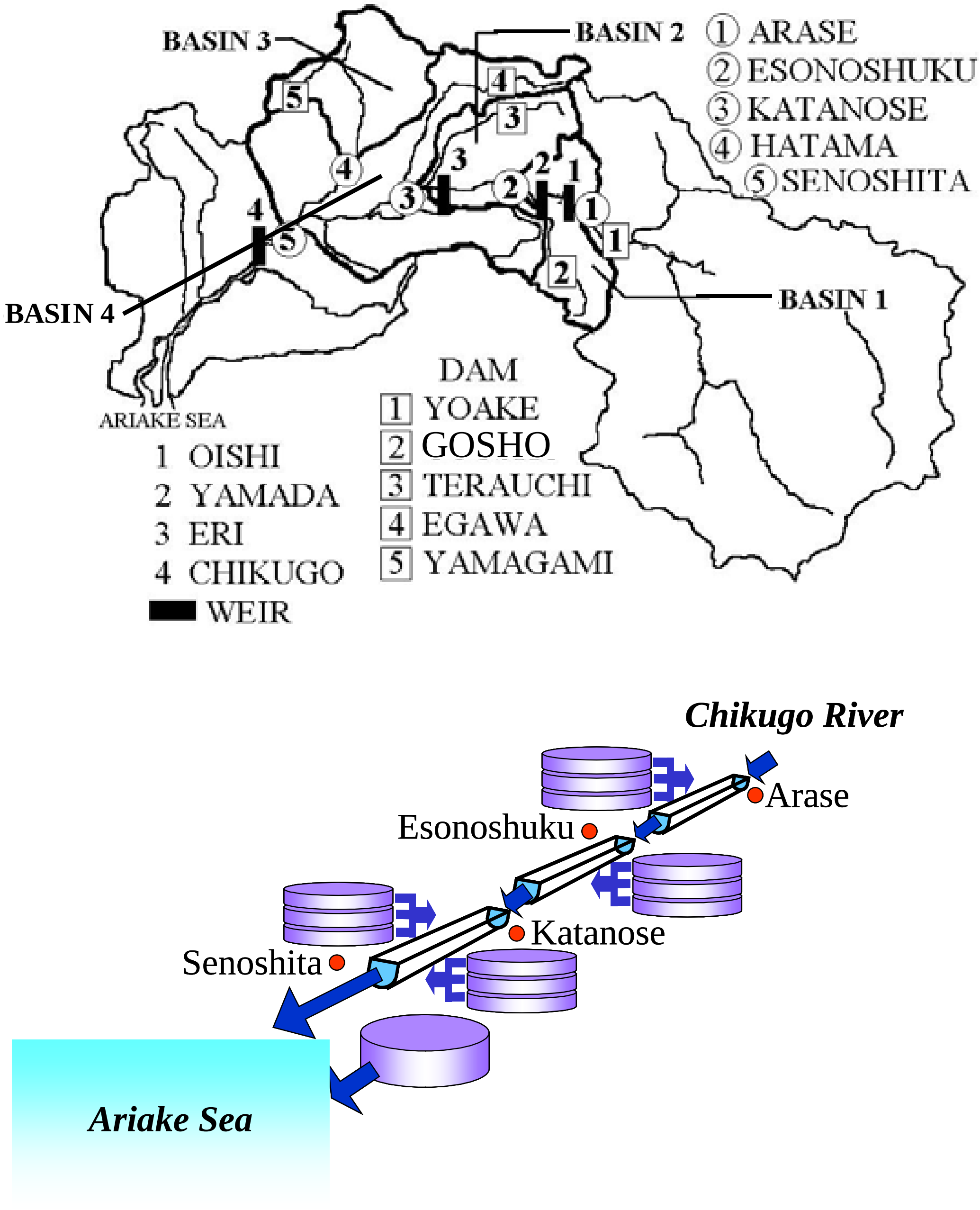


Figure 4.5 The developed models of the Chikugo Basin

After the calibration, the developed models are applied in the analysis of water quantity and water quality in the Chikugo Basin. As well as contribution of existing hydraulic structures to flow rate in the Chikugo River, characteristics of irrigation water use in the middle part of the Chikugo Basin are made clear in water quantity analysis. Using simulated results of the developed models, loadings at each observation points are determined in water quality analysis. The analysis results of water use and loadings are important information for policy analysis for the implementation of wastewater facility. Providing an insight of impacts of the proposed alternatives, the developed models are useful tools, which support the decision-makers in determining the policy.

General information and details of water use of four divided basins between Arase and Senoshita are summarized below:

Basin 1 is located between Arase and Esonoshuku. Total area of this basin is 123 km^2. Population in this area is 30,504. Hydraulic structures located inside this basin are Gousho Dam, Oishi Weir and Yamada Weir. Main purpose of Oishi Weir and Yamada Weir is irrigation water supply. Length of the Chikugo River in this basin is 9.55 km.

Basin 2 is the area between Esonoshuku and Katanose. With population of 38,713, catchment area of this basin is 156.1 km^2. Length of the Chikugo River in this basin is 11.9 km. Terauchi Dam and Eri Weir are major hydraulic structures located in this area. Similar to Oishi Weir and Yamada Weir, Eri Weir was constructed for irrigation water supply.

Located in the northwest of Arase, Basin 3 is the catchment area of the Homan River. Total area is 172.3 km^2. With population of 94,937, population density of this area is approximately three times higher than those of Basin 1 and Basin 2. The Homan River meets the Chikugo River at Hatama. In this basin, there is one dam administrated by Fukuoka Prefecture named Yamagami Dam. Purposes of this dam are for flood control, irrigation and drinking water supply. Runoff and loadings from this basin enter the Chikugo River at the river segment between Katanose and Senoshita.

Located between Katanose and Senoshita, Basin 4 is the biggest basin among four basins. Total area of this basin is 400.6 km^2. Number of population in this area is 344,115. Kurume City, which is one of several big cities in the Chikugo Basin, is located in this area. Downstream of this basin locates Chikugo Barrage which controls flow rate and supplies water for irrigation and drinking water in many cities in Fukuoka and Saga. Length of the Chikugo River in this basin is 15.1 km.

Loadings generated by non-point sources in the catchment area of each basin are estimated from frame and unit loading of existing loading sources. Frames of loading sources in the each basin are summarized in Table 4.1.

Table 4.1 Frames of loading sources in the middle part of the Chikugo Basin

Basin	Population	Forest (ha)	Paddy field (ha)	Total area (ha)	Length of river segment (km)
1	30,504	6,544	2,829	12,300	9.55
2	38,713	8,305	3,590	15,610	11.9
3	94,937	7,874	5,031	17,230	-
4	344,115	14,536	12,419	40,060	15.1

Source: Statistics Bureau (1990) and (MLIT 1990)

4.3.1. Water quantity simulation

Daily flow rate at Esonoshuku, Katanose and Senoshita is simulated by using the developed models in 1986-2001. Water supply from reservoirs and rates of irrigation water withdrawn at weirs are taken into account in the simulation. Daily precipitation data used in the tank model is the observed data in 1983-1999 and the data obtained from Automated Meteorological Data Acquisition System (AMeDAS) in 2000-2001 (Japan Meteorological Agency 2001). It is assumed that evapotranspiration in the tank model occurs at a constant rate of 0.5 mm/d and there is no evapotranspiration when the precipitation is higher than 0.5 mm/d (JSCE 1980).

Parameters of the developed tank model in each basin calibrated in the water quantity simulation are listed in Table 4.2 to Table 4.5.

Table 4.2 Parameters of the tank model in Basin 1

Tank	Orifice	h (mm)	a_L , a_B (1/d)
1	Lateral 1	50	0.5
	Lateral 2	15	0.2
	Bottom	0	0.1
2	Lateral 1	0	0.07
	Bottom	0	0.06
3	Lateral 1	0	0.05
	Bottom	0	0

Table 4.3 Parameters of the tank model in Basin 2

Tank	Orifice	h (mm)	a_L , a_B (1/d)
1	Lateral 1	50	0.5
	Lateral 2	15	0.2
	Bottom	0	0.1
2	Lateral 1	0	0.08
	Bottom	0	0.06
3	Lateral 1	0	0.03
	Bottom	0	0.005

Table 4.4 Parameters of the tank model in Basin 3

Tank	Orifice	h (mm)	a_L , a_B (1/d)
1	Lateral 1	50	0.2
	Lateral 2	15	0.1
	Bottom	0	0.2
2	Lateral 1	0	0.15
	Bottom	0	0.1
3	Lateral 1	0	0.03
	Bottom	0	0.02

Table 4.5 Parameters of the tank model in Basin 4

Tank	Orifice	h (mm)	a_L , a_B (1/d)
1	Lateral 1	50	0.3
	Lateral 2	15	0.2
	Bottom	0	0.3
2	Lateral 1	0	0.05
	Bottom	0	0.06
3	Lateral 1	0	0.03
	Bottom	0	0.02

Simulated flow rate at Esonoshuku, Katanose and Senoshita is shown in Fig.4.6-Fig.4.8, respectively. It is clearly seen that the developed models can simulate the season pattern of flow rate in the Chikugo River effectively. Correlation between the simulated flow rate and the observed one at each observation point is shown in Fig.4.9.

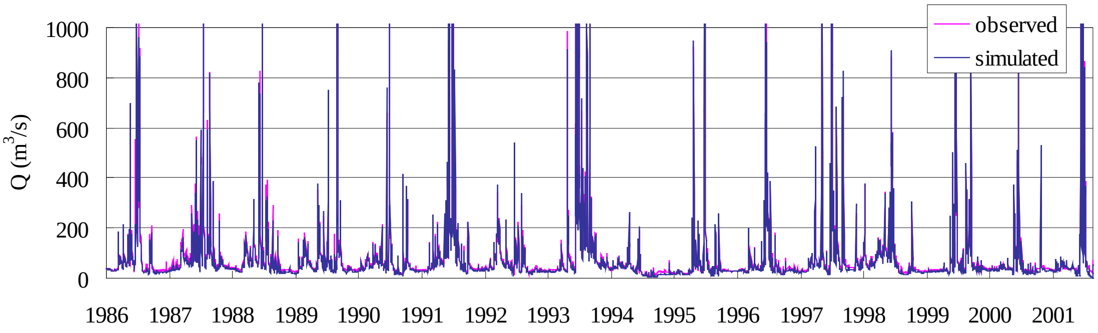


Figure 4.6 Flow rate of the Chikugo River at Esonoshuku from 1986 to 2001

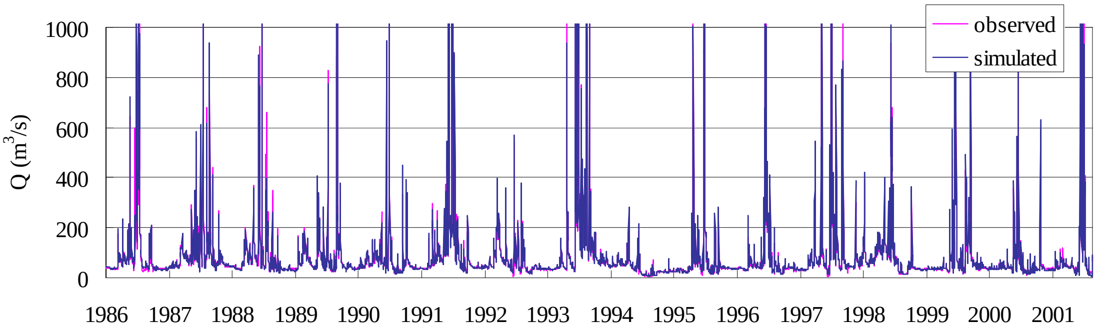


Figure 4.7 Flow rate of the Chikugo River at Katanose from 1986 to 2001

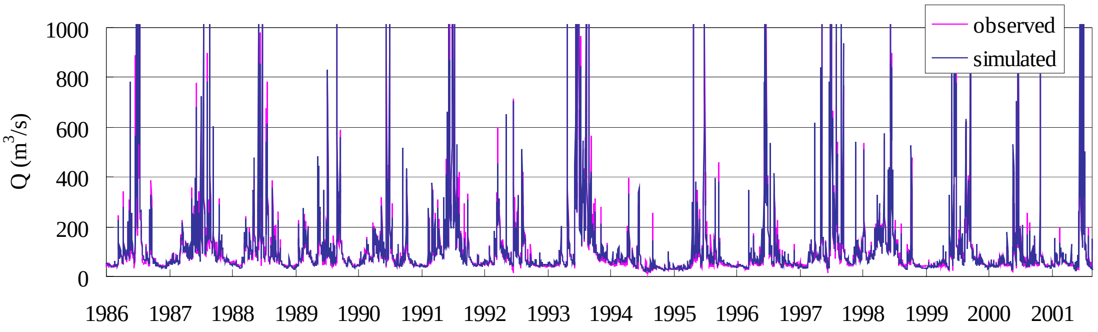


Figure 4.8 Flow rate of the Chikugo River at Senoshita from 1986 to 2001

It reveals that the obtained results at Esonoshuku and Katanose have good correlation with the observed data in high flow period whereas the simulated flow rate in low flow period is slightly lower than the observed data. The obtained result and observed data at Senoshita have good agreement in both high and low flow. Small difference of flow rate during dry period at Esonoshuku and Katanose indicates that there may be some additional water supplied from the reservoirs located between Arase and Katanose to secure the flow rate at Senoshita.

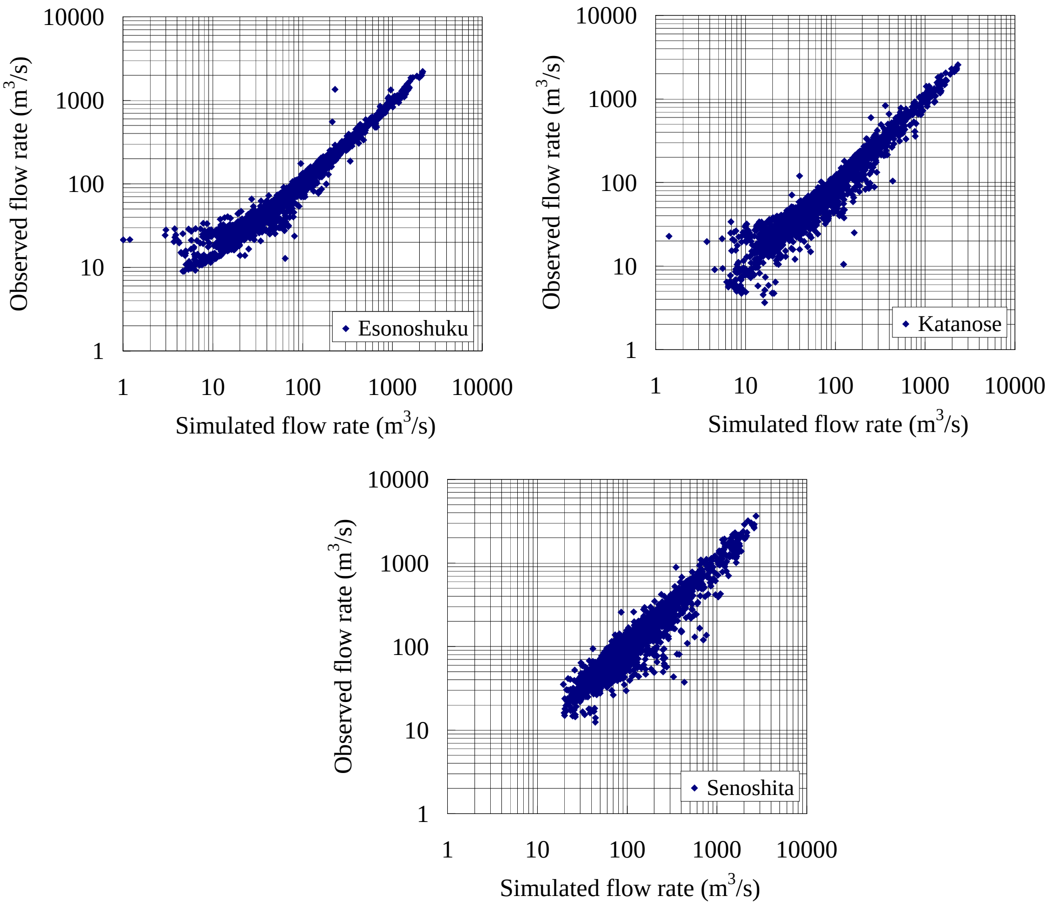


Figure 4.9 Correlation between simulated flow rate and observed data

For river flow management, influences of existing hydraulic structures and characteristics of water use on flow rate of the Chikugo River need to be determined. In water quantity analysis, contribution of existing structures to flow rate and characteristics of irrigation water use are analyzed by the developed models.

4.3.2. Water quality simulation

Water quality in the middle part of the Chikugo Basin is simulated at Esonoshuku, Katanose and Senoshita from 1986-2001. High concentrations of COD, SS, T-N and T-P are observed in the Chikugo River during irrigation period when irrigation and fertilization are carried out in paddy field. Under an assumption that irrigation and fertilization are not carried out in dry season, loadings from the basin come from non-irrigation activities such as household, industries, etc. Miscellaneous wastewater from households is one of major non-point source loadings in the middle and lower parts of the Chikugo Basin. Daily loadings from these sources are almost constant through the year. Natural loadings are generated at low and steady rate from forest area. High loading from forest and urban area during heavy rainfall is determined from L-Q relationship and runoff from two upper tanks. Steady loadings are estimated from unit loading and frame of each source. L-Q relationship and unit loading of COD, SS, T-N and T-P obtained from the calibration of the developed models in water quality simulation are listed in Table 4.6-Table 4.9.

Table 4.6 Unit loading of COD from forest, urban area and paddy field

	Forest (kg/ha-year)		Urban area (g/capita-d)		Paddy field area (kg/ha-year)	
	Rainy Day	Fine Day	Rainy Day	Fine Day	Irrigation	Non-irrigation
Tank 1	$L = aQ^b$ a = 1.0 b =1.0	-	$L = aQ^b$ a = 2.0 b = 1.0	-	70.0	-
Tank 2		-		-		
Unit loading	10.0	10.0	5.0	5.0		

Table 4.7 Unit loading of SS from forest, urban area and paddy field

	Forest (kg/ha-year)		Urban area (g/capita-d)		Paddy field area (kg/ha-year)	
	Rainy Day	Fine Day	Rainy Day	Fine Day	Irrigation	Non-irrigation
Tank 1	$L = aQ^b$ a = 4.0 b =1.0	-	$L = aQ^b$ a = 10.0 b = 1.0	-	140.0	-
Tank 2		-		-		
Unit loading	10.0	10.0	2.0	2.0		

Table 4.8 Unit loading of T-N from forest, urban area and paddy field

	Forest (kg/ha-year)		Urban area (g/capita-d)		Paddy field area (kg/ha-year)	
	Rainy Day	Fine Day	Rainy Day	Fine Day	Irrigation	Non-irrigation
Tank 1	$L = aQ^b$ a = 0.7 b =1.0	-	$L = aQ^b$ a = 1.0 b = 1.0	-	40.0	-
Tank 2		-		-		
Unit loading	7.0	7.0	2.5	2.5		

Table 4.9 Unit loading of T-P from forest, urban area and paddy field

	Forest (kg/ha-year)		Urban area (g/capita-d)		Paddy field area (kg/ha-year)	
	Rainy Day	Fine Day	Rainy Day	Fine Day	Irrigation	Non-irrigation
Tank 1	$L = aQ^b$ a = 0.05 b =1.0	-	$L = aQ^b$ a = 0.15 b = 1.0	-	0.4	-
Tank 2		-		-		
Unit loading	0.1	0.1	0.1	0.1		

Results of water quality simulation at Senoshita are compared with the observed data in Fig.4.10 and Fig.4.11. Correlation between the simulated water quality and the observed one is shown in Fig.4.12.

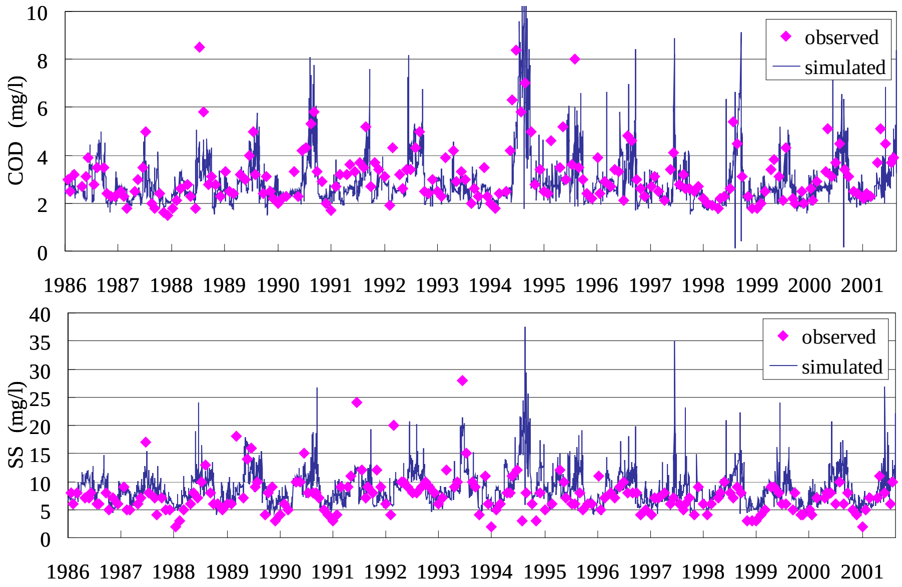


Figure 4.10 COD and SS at Senoshita from 1986 to 2001

As shown in Fig.4.10 and Fig.4.11, pattern of the simulated water quality is high concentration in rainy season and low in dry season, which is similar to the pattern of the observed data. It is realized that simulated COD concentration has good agreement with observed data not only in dry season but also in rainy season as well. Simulated SS during dry season is higher than the observed one. It indicates that deposition of sediments probably occur in the stagnant water of Chikugo Barrage, and reaction terms such as settling during low flow period may be necessary for the simulation of suspended solids. Simulated T-N and T-P in dry season are in the same level with the observed ones.

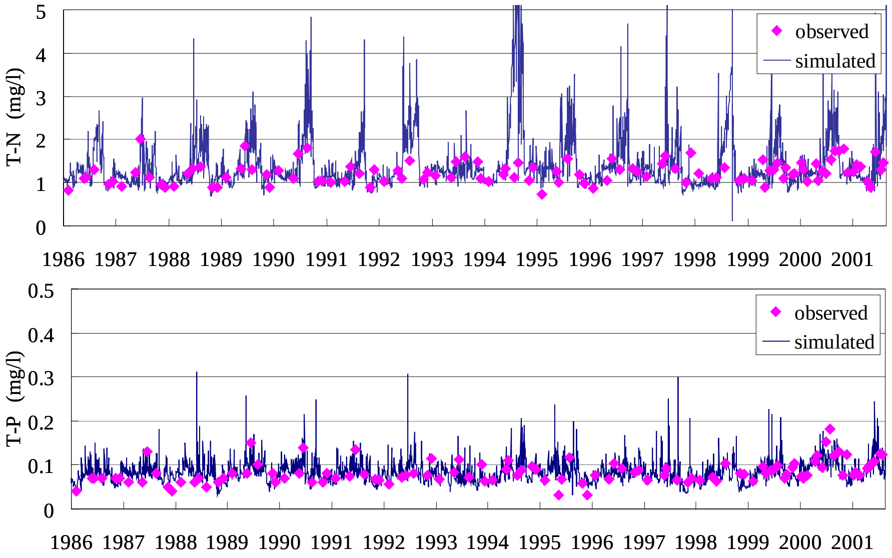


Figure 4.11 Nutrient concentrations at Senoshita from 1986 to 2001

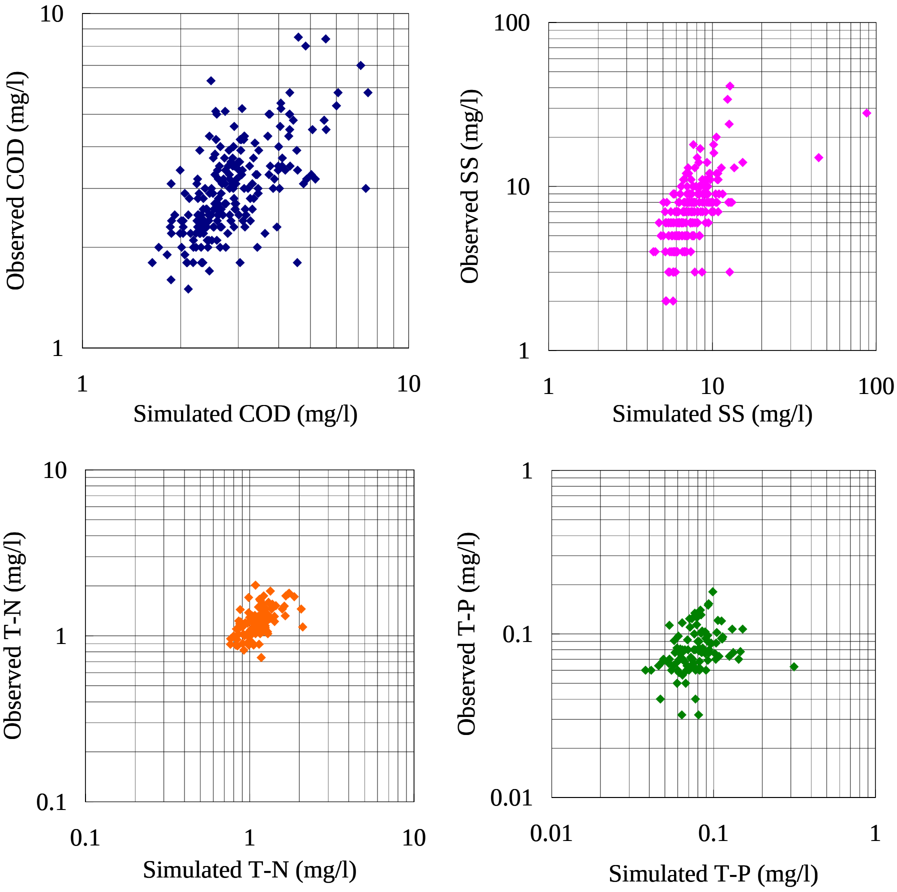


Figure 4.12 Correlation between simulated water quality and observed data at Senoshita

In Fig.4.12, it is obvious that the simulated T-N has good correlation with the observed data whereas the correlation of T-P is not clear. Information of nutrient concentrations in the Chikugo River is very few and range of the available data is narrow because the observation of nutrient concentrations in the Chikugo River is conducted every three months. To improve the simulation of T-P, more observed data is required for the calibration.

Water quality obtained from the developed models is used in the estimation of loadings in water quality analysis. In order to evaluate the effectiveness of the developed models, simulated loadings will be compared with those obtained from L-Q relationship of the observed data.

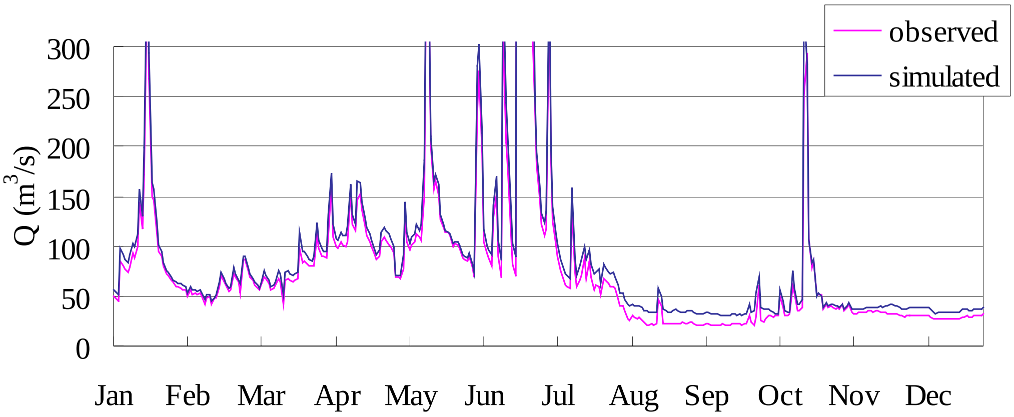
4.3.3. Water quantity and water quality analysis

Many kinds of hydraulic structures such as reservoirs and water intake structures are situated in the middle part of the Chikugo Basin. Main purposes of these structures are flood control, water supply for irrigation and non-irrigation activities and securing flow rate in the Chikugo River for environmental preservation and fishery in the Ariake Sea. Contribution of existing hydraulic structures to flow rate in the Chikugo River is examined using developed tank model.

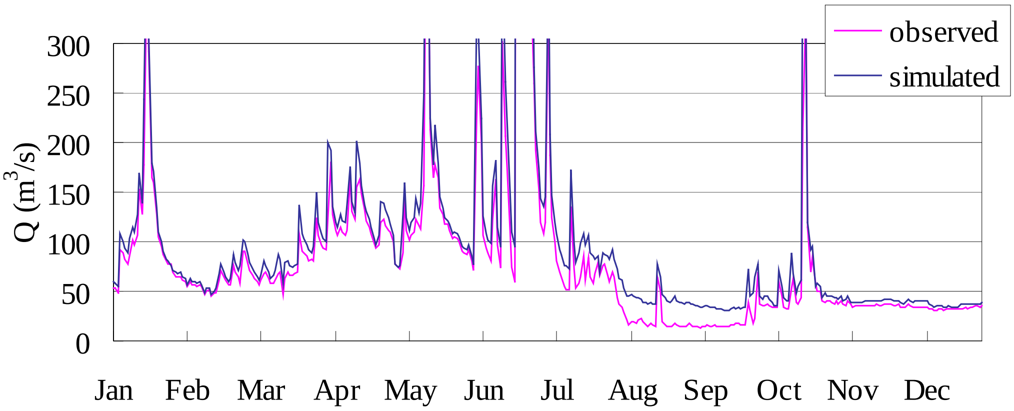
Characteristics of water use for irrigation are necessary information for water management in the Chikugo Basin. This information is complicated and difficult to determine by field observation. With the application of the developed models, characteristics of irrigation water use are determined in water quantity analysis.

To examine the contribution of hydraulic structures, flow rate is simulated by neglecting the existing structures in the Chikugo Basin. Figure 4.13 indicates that the operation of hydraulic structures affects flow rate in the middle reach of the Chikugo River especially in irrigation period. Under the condition of no hydraulic structures, the simulated flow rate at Esonoshuku and Katanose becomes higher than the observed data. The increase in the simulated flow rate emphasizes that water is highly withdrawn from the Chikugo Basin between Arase and Katanose for irrigation. On the other hand, the difference between the simulated flow rate and the observed one at Senoshita is very small even in irrigation period. It indicates that irrigation water is withdrawn while traveling along the middle reach, however, used irrigation water finally returns to the main river within the end of the reach.

Flow rate at Esonoshuku 1998 (without hydraulic structures)



Flow rate at Katanose 1998 (without hydraulic structures)



Flow rate at Senoshita 1998 (without hydraulic structures)

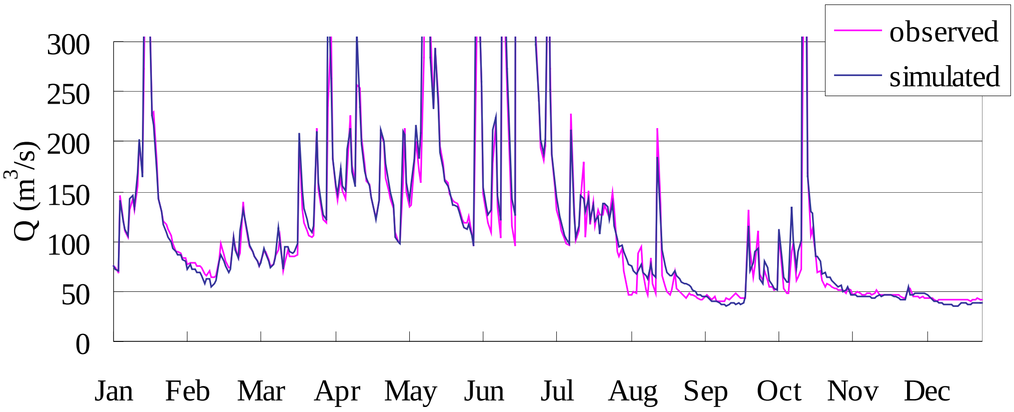


Figure 4.13 Contribution of hydraulic structures to flow rate in the Chikugo River

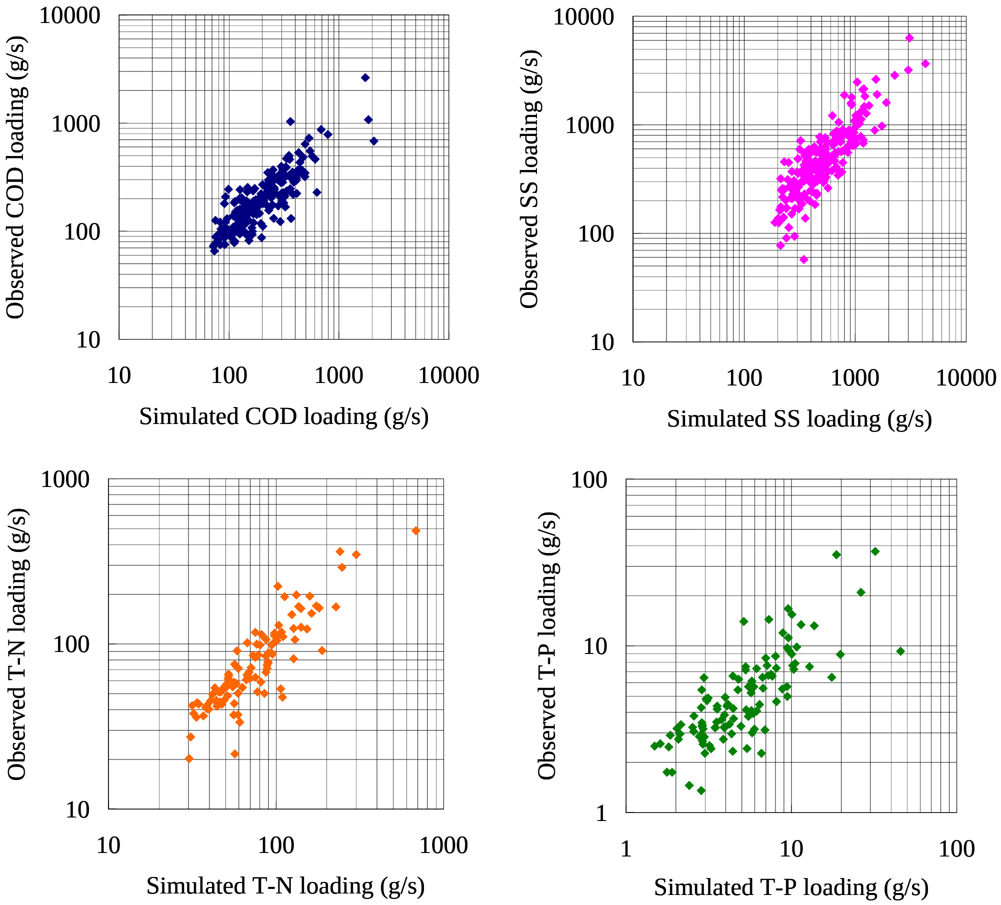


Figure 4.14 Correlation between simulated loading and observed data at Senoshita

In water quality analysis, water quality loadings at Esonoshuku, Katanose and Senoshita are estimated from flow rate and water quality obtained from the developed models. The simulated results at Senoshita are plotted with the observed data in Fig.4.14.

Water quality loadings at Senoshita estimated by the developed models show good correlation with the observed data. It shows that the developed models can effectively simulate loadings of COD, SS and T-N than T-P loading. As mentioned in the water quality simulation, the observed data of T-P concentration is inadequate for the calibration.

Annual loadings of the Chikugo River obtained from the developed models are estimated and compared with those of L-Q relation. Table 4.10 shows the comparison between annual loadings obtained from the developed models and L-Q relation at Senoshita. Simulated annual loadings of COD and T-N are in the same level with the annual loadings obtained from L-Q relation whereas the simulated annual T-P loading is slightly lower. Although the simulated SS are higher than the observed one, the simulated annual SS loading is less than 50% of the annual loading of L-Q equation.

Table 4.10 Annual loadings of the Chikugo River at Senoshita obtained from the developed models and L-Q equation

Annual loading	The developed models (t/year)	L-Q relation (t/year)
COD	10,904	11,302
SS	37,561	81,284
T-N	5,372	5,471
T-P	360	495

Since there is very few observed data during heavy rainfall, it is possible that loadings obtained from L-Q relation during high flow period are higher than usual. Good correlation between the observed loadings and the simulated ones including SS loadings shown in Fig.4.12 confirms that the developed models can be used as analytical tools in determining discharged loadings from the Chikugo Basin, which is necessary for water management in the Chikugo Basin and the Ariake Sea.

In Chapter 3, the relationship between the discharged loadings from the Chikugo Basin and water quality in the innermost part of the Ariake Sea is pointed out. It is suggested that environmental evaluation of the proposed alternatives for water management in the Chikugo Basin should be carried out in the Ariake Sea as well. Therefore, an analytical tool that is applicable for water quality analysis in the Chikugo Basin and the Ariake Sea is necessary. In Chapter 5, water quality model of the Ariake Sea is developed and integrated with the developed models of the Chikugo Basin. Contribution of discharged loadings to water quality of the Ariake Sea is analyzed by an integrated model. Same analysis is done with natural loadings from mud bed and algal productivity in the Ariake Sea.

4.4 Summary

In this chapter, the simulation models of the Chikugo Basin are developed based on the tank model and the river model. In water quantity simulation, flow rate simulated by the developed models has good correlation with the observed data. Small difference between the simulated and observed flow rate at Esonoshuku and Katanose during dry period points out that additional water may be supplied from reservoirs in the middle part of the Chikugo Basin in order to secure the flow rate at Senoshita. The results obtained from the water quantity simulation such as total runoff from the catchment area are applied as input data in water quality simulation. Major non-point sources in the Chikugo Basin considered in this study are forest area, urban area and agricultural area (paddy field). Parameters concerned in water quality models are COD, SS, T-N and T-P. Simulated result of suspended solids at Senoshita is higher than the observed data during dry season. It is pointed out that deposition problem probably occur in the stagnant water of Chikugo Barrage and reaction terms such as settling are suggested for the developed models. Except T-P, the simulated water quality shows good agreement with the observed data. Since there is very few observed data and range of the available data is narrow, more data is required for the calibration of T-P. Unknown parameters of non-point sources such as unit loading are also defined in water quality simulation.

As an important part in the basic study of water management, the analysis of water quantity and water quality is conducted in the Chikugo Basin. As well as characteristics of irrigation water use, contribution of existing hydraulic structures to flow rate of the Chikugo River is examined in the water quantity analysis. The analysis results indicate that existing hydraulic structures play important roles in controlling of flow rate in the middle reach of the Chikugo River. By neglecting the existing structures, the simulated result at Senoshita points out that the water withdrawn for irrigation along the middle reach finally returns to the main river within the reach. In water quality analysis, loadings of the Chikugo River are estimated and compared with the observed data at each observation point. Annual loadings obtained from the developed models are compared with those obtained from L-Q relation at Senoshita. It is found that simulated annual SS loading is lower than that of L-Q relation. Because of inadequate data during heavy rainfall, loading obtained from L-Q relation tends to be higher than usual. Good correlation between the simulated loadings and the observed ones confirms the effectiveness of the developed models. With the application of the proposed models, total amount of loadings discharged into the Ariake Sea from the Chikugo Basin can be evaluated.

According to the relationship between water quality in the innermost part of the Ariake Sea and discharged loadings from the Chikugo Basin found in Chapter 3, it is recommended that the environmental evaluation of the proposed alternatives for water management in the Chikugo Basin needs to be conducted in the Ariake Sea as well. The information obtained from the developed models is an important key for water management in the Chikugo Basin and the Ariake Sea because it can support the decision-makers in determining the policy for implementation of wastewater facility. The developed models will be integrated with water quality model of the Ariake Sea developed in Chapter 5 as an analytical tool for water quality analysis and policy analysis in the Chikugo Basin and the Ariake Sea. Finally, contribution of discharged loadings to water quality in the innermost of the Ariake Sea is evaluated by an integrated model.

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CHAPTER 5

INTEGRATED WATER QUALITY MODEL IN THE CHIKUGO BASIN AND THE ARIAKE SEA

5.1 Introduction

In Chapter 3, it is found that there is some relationship among water quality in the innermost part of the Ariake Sea, inflow loadings from land area and ecosystem in the tidal flat. Therefore, information of inflow loadings and ecosystem in the tidal flat need to be considered in water quality analysis in the Ariake Sea. From a viewpoint of integrated water management in the Chikugo Basin, this relationship emphasizes the necessity of environmental evaluation of the proposed alternatives in the Ariake Sea. An integrated analytical tool for water quality analysis in the Chikugo Basin and the Ariake Sea is recommended.

In this chapter, two-dimensional water quality model of the Ariake Sea is developed based on the finite-volume model, so-called the box model. Information of discharge from the rivers is given as the boundary condition in the developed model. The water quality in the Ariake Sea concerned in this study includes COD, SS, dissolved inorganic nutrients and chlorophyll-*a*. Concepts of water quality modeling in the Ariake Sea as well as functions of the developed model are described. In the verification of model, water quality in the Ariake Sea is simulated from 1991 to 2000.

In the implementation of wastewater treatment in the Chikugo Basin, output of water quality improvement in the Chikugo Basin and the Ariake Sea is necessary for evaluating the proposed measures. In order to develop an analytical tool for water quality management in the Chikugo Basin and the Ariake Sea, water quality model of the Ariake Sea are integrated with the developed models of the Chikugo Basin. The observed data of the Chikugo Basin is replaced by the simulated results obtained from the developed models.

The integrated model is applied in sensitivity analysis in order to make clear the contributions of discharged loadings from land area and other important factors, such as algal productivity and natural loadings from mud bed, to behaviors of water quality in the Ariake Sea. The analysis results obtained from the integrated model are useful and can be utilized in policy analysis for the Chikugo Basin and the Ariake Sea. The application of the integrated model in feasibility study of existing measures of the Chikugo Basin and the Ariake Sea will be discussed in Chapter 6.

5.2 Water quality modeling in the Ariake Sea

Being a semi-closed water body, water movement in the Ariake Sea is complicated. Water quality in the Ariake Sea is affected by such complicated water movement. Two-dimensional finite-volume model (Rich 1973) is proposed for water quality analysis in the Ariake Sea. The finite-volume model is effective for describing characteristics of the water quality that vary significantly from one point to another. This two-dimensional model is composed of discrete fluid volumes, called “element”. Other common name of this model is the box model. Materials are transported passing from one element to another. Each element is considered to be homogeneous along the fluid depth. The advantage of the finite-volume model is it does not require the governing equation of water movement. Instead of water movement information, calibrated coefficients of advection and dispersion using conservative materials should be estimated.

It is assumed that there is no effect of density current in each element. Therefore, even if a vertical distribution exists, water quality in each element can be treated as an averaged value over the water element. Besides being averaged over the water depth in the element, water quality and water movement handled in the developed box model are averaged over the specific time constant. The specific time constant used in this study is one day, which is approximately two tidal cycles. Observed data is also treated as an averaged value as well. Concentrations of COD, SS, inorganic nutrients and chlorophyll-*a* are water quality parameters considered in the developed box model.

With given boundary conditions, a net flow rate between two adjacent elements can be obtained from the continuity equation in Eq.(5.1). The mass balance equation in each element of the finite-volume model (Rich 1973) is described in Eq.(5.2).

$$\frac{dV_{(n)}}{dt} = \sum Q_{nm} + Q_{B(n)} \tag{5.1}$$

$$\frac{dc_{(n)} \cdot V_{(n)}}{dt} = \sum \left\{ Q_{nm} \left[\delta_{nm} \cdot c_{(m)} + (1 - \delta_{nm}) c_{(n)} \right] + E'_{nm} \left(c_{(m)} - c_{(n)} \right) \right\} \pm S_{(n)} \tag{5.2}$$

where V = water volume of element (m^3);

Q_{nm} = net flow rate between element n and m (m^3/s);

Q_B = boundary condition of flow rate of the element (m^3/s);

c = average concentration in the element (g/m^3);

δ_{nm} = net advection factor between element n and m (-);

E'_{nm} = mixing coefficient between element n and m (m^3/s) and

S = reaction term (g/s).

Subscripts n and m denote the considered element and the adjacent element, respectively.

Rich (1973) described the advection factor as a constant representing the average concentration within adjacent elements. Therefore, the advection factor and mixing coefficient between two adjacent elements in this model are constant. Inflow from land area and open sea is given as the boundary condition of Eq.(5.2). Natural loadings from mud bed and inflow loadings from land area and open sea are considered as boundary conditions in the mass balance equation. The reaction term (S) of each water quality is described as follow.

Water quality standards of nutrient concentrations are established to prevent eutrophication in many coastal areas in Japan including the Ariake Sea. Algae utilize nutrients during the growth process and those nutrients will be released when algae are decomposed after decay. Together with the investigation, Yamochi et al. (2003) applied the box model to measure nitrogen uptake in an artificial tidal flat in September. It was found that algae and benthic animal greatly contributed to nitrogen cycle in the experimental tidal flat. Since algae consume nutrients in inorganic forms, nutrient parameters in this model are dissolved inorganic nitrogen (DIN) and orthophosphate phosphorus (PO_4-P).

Two kinds of algae, diatoms and green algae, are considered through the examination of the observed water quality. The growth period of diatoms is between winter and spring while the growth of green algae is optimum during spring to summer. Concentrations of algae are estimated in terms of chlorophyll-*a* (Chl-*a*). As the boundary condition, nutrient supply from mud bed is a function of mud bed area in an element. Nutrient concentrations in mud bed are assumed to be constant. Contribution of the natural loadings to behaviors of nutrient concentrations in the Ariake Sea will be examined later in sensitivity analysis. The reaction terms of DIN and PO_4-P of element n are described as S_N in Eq.(5.3) and S_P in Eq.(5.4). The substantial change in biomass of algae (AG) is shown in Eq.(5.5).

$$S_N = -\sum_{x=1}^{2} Y_{N(x)} \cdot AG_{(x)} + K_{RN} \cdot DIN_B \cdot R_M \cdot A \tag{5.3}$$

$$S_P = -\sum_{x=1}^{2} Y_{P(x)} \cdot AG_{(x)} + K_{RP} \cdot PO4_B \cdot R_M \cdot A \tag{5.4}$$

$$AG_{(x)} = (\mu_{(x)} - K_{D(x)} \cdot \theta_{(x)}{}^{(T-T_D(x))})CH_{(x)} \cdot V \tag{5.5}$$

$$\mu_{(x)} = \mu_{MAX(x)} \cdot T_{G(x)} \frac{DIN}{(K_{N(x)} + DIN)} \frac{PO4}{(K_{P(x)} + PO4)} \tag{5.6}$$

where Y_N = DIN: Chl-*a* (mg DIN/μg Chl-*a*);

Y_P = PO_4-P: Chl-*a* (mg PO_4-P/μg Chl-*a*);

K_{RN}, K_{RP} = release rate of DIN and PO_4-P (g/m^2-d), respectively;

DIN_B, $PO4_B$ = DIN and PO_4-P in mud bed (g/m^3);

R_M = ratio of mud bed area in the element (-);

A = element area (m^2);

K_D = specific decay rate (1/d);

θ = temperature coefficient for decay (-);

T_D = critical temperature for decay (°C);

T = water temperature (°C);

μ_{MAX} = maximum specific growth rate (1/d);

T_G = temperature coefficient for algal growth (-);

K_N, K_P = saturation constant of DIN and PO_4-P (g/m^3), respectively;

CH = Chl-*a* (mg/m^3);

DIN = dissolved inorganic nitrogen (g/m^3) and

$PO4$ = orthophosphate phosphorus (g/m^3).

Subscript x refers to species of algae.

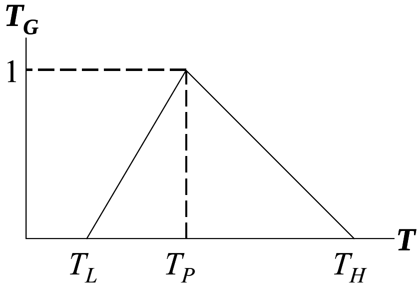
Vongthanasunthorn et al. (2003) determined temperature coefficient for algal growth in the Ariake Sea as a function of optimal, maximum and minimum water temperatures. In order to reveal the optimal growth period of each type of algae, the temperature coefficient (T_G) described below is adopted in the developed model.

For $T < T_L$ $\quad T_{G(x)} = 0$

For $T_L \le T \le T_P$ $\quad T_{G(x)} = \dfrac{T - T_L}{T_P - T_L}$

For $T_P < T \le T_H$ $\quad T_{G(x)} = \dfrac{T - T_H}{T_P - T_H}$

For $T > T_H$ $\quad T_{G(x)} = 0$



Suspended solids (SS) in the coastal area near the river mouth are an important parameter in the relationship among discharged loadings from land area, water quality of seawater and ecosystem of the tidal flat. The suspended solids from land area come from erosion of riverbanks and loadings generated in the basin area. After being discharged into the Ariake Sea, some coarse suspended materials are likely to deposit in the tidal flat. Transported by advection and dispersion, fine suspended materials travel offshore to the central part and the mouth of the gulf. Influences of tidal movement and wind on resuspension in shallow area are considered in this model. The reaction term of suspended solids (S_S) in element *n* is expressed in Eq.(5.7)

$$S_S = SS_{RS} - K_{SS} \cdot B_S \cdot SS \cdot A \tag{5.7}$$

$$SS_{RS} = (R_T \cdot K_{RT} + K_{RW})\frac{R_M \cdot A}{D} \tag{5.8}$$

For $v_W > v_W^*$ $$K_{RW} = \phi \cdot K_W[(\frac{v_W}{v_W^*})^2 - 1]$$

in which $$\phi = 1 - \frac{\phi_W}{2}\left[1 - Cos(\varpi^* - \varpi)\right]$$

For $v_W \le v_W^*$ $$K_{RW} = 0 \tag{5.9}$$

where K_{SS} = settling velocity of SS (m/d);

B_S = settling coefficient (-);

SS = suspended solids (g/m^3);

R_T = resuspension coefficient due to tidal movement (-);

K_{RT} = resuspension rate due to tidal movement (g/m-d);

K_W = resuspension rate due to wind (g/m-d);

D = water depth of the element (m);

v_W = maximum wind speed (m/d);

v_W^* = critical wind speed (m/d);

ϕ_W = wind direction factor (-);

ϖ^* = critical wind direction for resuspension (m/d) and

ϖ = direction of maximum wind speed (radian).

Equation (5.9) describes influence of wind on resuspension from mud bed. Maximum wind speed and its direction are employed as factors of wind. During strong wind when the maximum wind speed exceeds the critical wind speed, wind shear force at surface of seawater raises the flow velocity of seawater. This momentum transport phenomenon leads to high shear force between seawater and the surface of mud bed where bottom deposits are resuspended from the bed. The critical wind speed is set to be constant in every point of the Ariake Sea. At a certain maximum wind speed, resuspension becomes largest when the wind has same direction with the critical wind direction of an element. Each element has individual critical wind direction depending on direction of the shore. Wind direction factor (ϕ_W) ranges between 0 to 1. Factor of wind direction is shown in Fig.5.1.

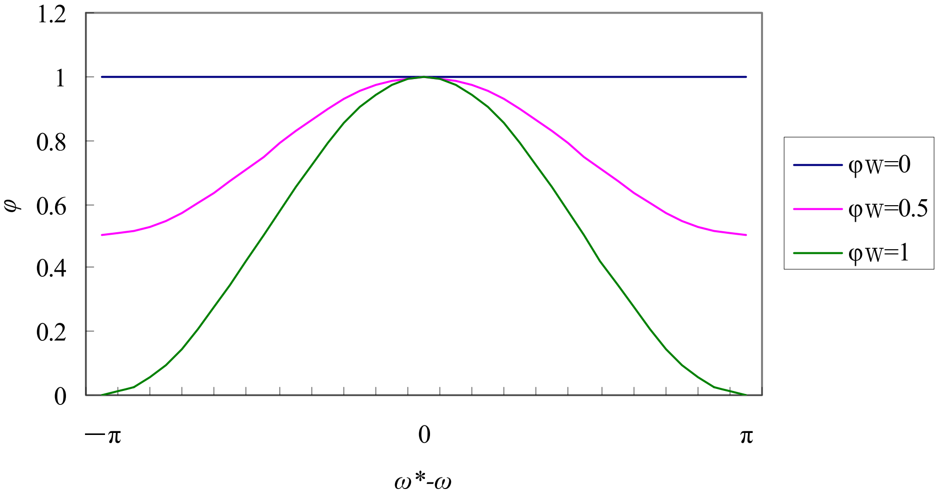


Figure 5.1 Influence of direction of maximum wind speed on resuspension

During strong rainfall, large amount of coarse materials such as gravels and sand is discharged from land area through the river flow. These coarse materials settle more rapidly than lighter materials such as colloidal particles. In order to reveal this phenomenon, two different values of settling coefficient (B_S) are given for high and low flow period in the developed model. The larger one is given during high flow period when salinity is less than 30,000 g/m^3 to represent higher settling velocity of coarse particles.

Suspended organic solids like algae (SS_{ALGAE}) are also considered in this model. The simulated result in the developed model is the concentration of total suspended solids including SS_{ALGAE}.

$$SS_{ALGAE} = \sum_{x=1}^{2} Y_{S(x)} \cdot CH_{(x)} \tag{5.10}$$

where Y_S = SS: Chl-*a* (mg SS/μg Chl-*a*).

Subscript x refers to species of algae.

COD concentration is considered as particulate COD (PCOD) and dissolved COD (DCOD). Particulate COD includes PCOD discharged from land area and PCOD generated in algal productivity. The reaction terms of PCOD and DCOD are described as S_{CP} in Eq.(5.11) and S_{CD} in Eq.(5.13), respectively. Resuspended PCOD is related with resuspended solids from the mud bed. Amount of PCOD resuspended from mud bed is estimated from the PCOD content ratio of particulate materials in the mud bed (Y_{SC}). The settling transport of algal form of PCOD ($SCOD_{ALGAE}$) is explained in Eq.(5.12). The release from mud bed contributes to DCOD. Similar to nutrient concentrations, it is assumed that concentration of DCOD in mud bed is constant.

$$S_{CP} = Y_{SC} \cdot SS_{RS} - (K_{SC} \cdot PCOD + SCOD_{ALGAE})A + \sum_{x=1}^{2} Y_{C(x)} \cdot AG_{(x)} \tag{5.11}$$

$$SCOD_{ALGAE} = \sum_{x=1}^{2} Y_{C(x)} \cdot K_{SA(x)} \cdot CH_{(x)} \tag{5.12}$$

$$S_{CD} = K_{RC} \cdot DCOD_B \cdot R_M \cdot A \tag{5.13}$$

where Y_{SC} = PCOD content of particulate materials in mud bed (mg COD/ mg SS);

K_{SC} = settling velocity of PCOD (m/d);

$PCOD$ = particulate COD (g/m^3)

Y_C = PCOD: Chl-*a* (mg COD/μg Chl-*a*);

K_{SA} = settling velocity of algae (m/d);

K_{RC} = release rate of DCOD (g/m^2-d) and

$DCOD_B$ = DCOD in mud bed (g/m^3).

Actually, COD concentration of rivers is measured by acid process whereas one of seas is measured by alkali process. In this study, value of COD measured by acid process is used in both the Chikugo River and the Ariake Sea to examine the impacts of COD loading from land area. From water quality observation in the Ariake Sea, COD measured by acid process is 1.65 times of COD measured by alkali process (Saga Prefectural Ariake Research and Development Center 2002).

As shown in Fig.5.2, total area of the Ariake Sea is divided into 11 elements in the developed box model. Surface area of each element is fixed. The Chikugo River discharges into the Ariake Sea at element 9.

Water volume used in the continuity equation is estimated from daily tide level at Kuchinotsu Station and Oura Station (Japan Meteorological Agency 2001a, 2001b). Flow and loadings from land area as well as loadings at Hayasaki Strait are used as boundary conditions in the developed model. Discharged loadings from land area are estimated from L-Q equation of each river. It is assumed that loadings generated in the basin area near the river mouth are discharged directly into the Ariake Sea. In such area, the discharged loadings are estimated from unit loading. It is noted that Chl-*a* content in the river water is low, and loading of Chl-*a* from land area can be neglected.

Water quality data of the Ariake Sea in 1991-2000 is obtained from the investigation carried out by Fukuoka, Saga and Kumamoto prefectures (Fukuoka Fisheries & Marine Technology Research Center 2002; Saga Prefectural Ariake Fisheries Research and Development Center 2002; Kumamoto Prefectural Fisheries Research Center 2002). Maximum wind speed and wind direction are obtained from AMeDAS (Japan Meteorological Agency 2002).

Figure 5.2 The Chikugo Basin and the Ariake Sea

5.3 Water quality simulation in the Ariake Sea

The advection factor and mixing coefficient can be obtained from the calibration of conservative materials such as chlorides. Besides the calculation, these coefficients can be measured by using tracers (Fischer 1968). The advantage of the box model is it does not require the governing equation of water movement. Water quality can be simulated without flow parameters such as flow velocity, etc. Instead of water movement parameters, the calibrated advective factor and mixing coefficient are used. Good correlation between simulated salinity and observed data means the satisfied solution of governing equations of mass balance and momentum.

As mentioned above, both coefficients between two adjacent elements are constant. The advection factor ranges between 0.5-1.0 depending on nature of the considered environmental system (Rich 1973). Araki et al. (2002) calibrated the advection factor and mixing coefficient of two-dimensional box model from the simulation of salinity in the Ariake Sea in 1991-1999. Table 5.1 shows the advective factor and mixing factor obtained from the developed box model. It is indicated that the mixing factor is related with average water depth of the element. Salinity obtained from the developed model in the innermost part, the central part and the gulf mouth are shown in Fig.5.3.

Table 5.1 Advective factor and mixing coefficient used in the finite-model

n	m	δ_{nm} (-)	E'_{nm} (m^3/s)	n	m	δ_{nm} (-)	E'_{nm} (m^3/s)
1	2	0.8	15,000	2	1	0.2	15,000
2	3	0.8	2,500	3	2	0.2	2,500
2	4	0.8	15,000	4	2	0.2	15,000
4	5	0.5	3,000	5	4	0.5	3,000
4	7	0.5	5,000	7	4	0.5	5,000
5	6	0.5	750	6	5	0.5	750
5	8	0.5	2,000	8	5	0.5	2,000
7	8	0.5	3,000	8	7	0.5	3,000
7	9	0.5	500	9	7	0.5	500
8	9	0.5	500	9	8	0.5	500
8	10	0.5	1,000	10	8	0.5	1,000
8	11	0.5	1,500	11	8	0.5	1,500
9	10	0.5	200	10	9	0.5	200
10	11	0.5	200	11	10	0.5	200

The simulated salinity in Fig.5.3 has good agreement with the observed data which means the mass balance equation and the momentum equation are satisfied. The simulated salinity and the observed data in the other elements also have good correlation. The obtained results indicate that the developed box model can effectively simulate the process of dilution according to the freshwater discharged through the rivers and direct runoff from land area. The calibrated advective factor and mixing coefficient are applicable for water quality simulation in the Ariake Sea.

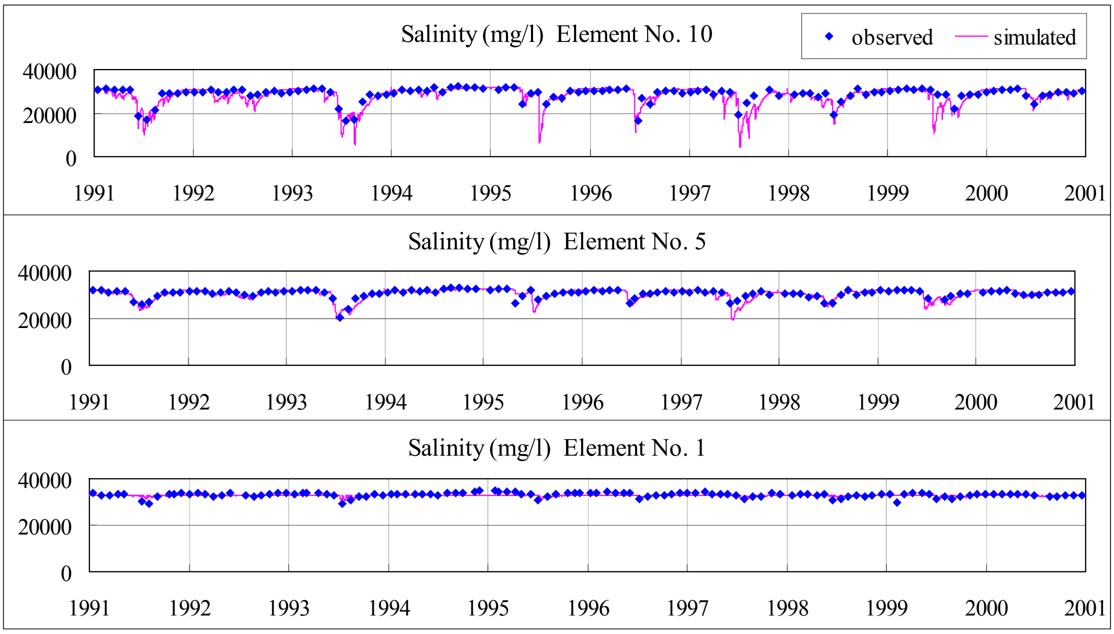


Figure 5.3 Simulated salinity in the Ariake Sea in element 1, 5 and 10

The developed box model is applied in water quality simulation in the Ariake Sea in 1991-2000. Parameters of the developed box model obtained from the calibration are listed in Table 5.2. Figure 5.4 demonstrates the optimal condition for algal productivity in the Ariake Sea obtained from the developed model.

Table 5.2 Parameters of the finite-volume model of the Ariake Sea

μ_{MAX}	maximum specific growth rate	0.25* (0.20)	1/d
K_N	saturation constant of nitrogen	0.05* (0.05)	g/m^3
K_P	saturation constant of phosphorus	0.01* (0.02)	g/m^3
K_D	specific decay rate	0.005* (0.005)	1/d
θ	temperature coefficient for decay	1.04* (1.06)	-
T_D	critical temperature for decay	25.0* (30.0)	°C
K_{SS}	settling velocity of SS	0.1	m/d
K_{SC}	settling velocity of PCOD	0.1	m/d
K_{SA}	settling velocity of algae	0.1* (0.1)	m/d
B_S	settling coefficient of SS	1-10 (high flow) 1-8 (low flow)	-
K_{RT}	resuspension rate due to tidal movement	10.0	g/ m-d
K_W	resuspension coefficient for wind	2.0	g/ m-d
v_W^*	critical wind speed	4.0	m/s
K_{RN}	release rate of DIN	0.06 - 0.12	g/ m^2-d
K_{RP}	release rate of PO_4-P	0.002- 0.02	g/ m^2-d
K_{RC}	release rate of DCOD	0.01 - 0.5	g/ m^2-d

* diatoms; ( ) green algae

Table 5.2 Parameters of the finite-volume model of the Ariake Sea (continued)

DIN_B	DIN concentration in mud bed	2.5	g/m^3
$PO4_B$	PO_4-P concentration in mud bed	1.2	g/m^3
$DCOD_B$	DCOD concentration in mud bed	10.0	g/m^3
Y_N	DIN: Chl-*a*	0.015* (0.015)	mg DIN /μg Chl-*a*
Y_P	PO_4-P: Chl-*a*	0.0012* (0.0012)	mg PO_4-P /μg Chl-*a*
Y_S	SS: Chl-*a*	0.1* (0.1)	mg SS /μg Chl-*a*
Y_C	PCOD: Chl-*a*	0.035* (0.035)	mg COD /μg Chl-*a*
Y_{SC}	PCOD content of particle materials in mud bed	5.0	%

* diatoms; ( ) green algae

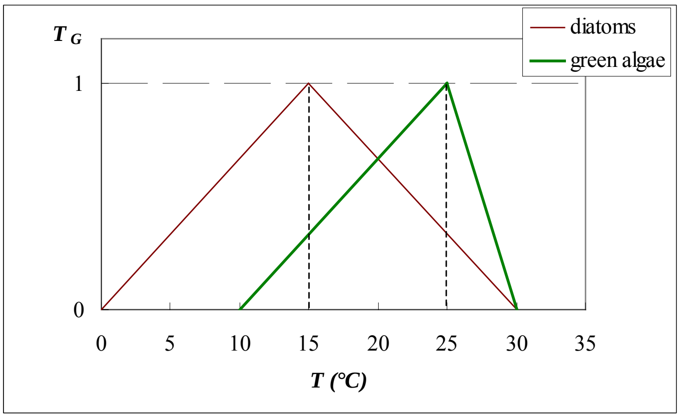


Figure 5.4 Optimal condition for algal growth in the Ariake Sea

In Fig.5.5, the simulated water quality in element 9 is shown together with the observed data. Since there is very few observed data of SS in the Ariake Sea, observed SS used in this study is estimated from the relationship between transparency and SS (Kumamoto Prefectural Fisheries Research Center 2002). COD and SS in algal form are demonstrated in Fig.5.5 as well. It is clearly seen that COD has similar pattern with Chl-*a* in rainy season. It refers that algal productivity contributes to COD concentration in the innermost part of the Ariake Sea during rainy season. On the other hand, algal productivity has no contribution to suspended solids. In shallow area, resuspended materials from mud bed predominate in suspended solids during dry period whereas SS loading from land area leads to rapid increase in SS concentration during rainy period. Effect of high discharged loading on suspended solids during heavy rainfall appears for a short period. It is found that resuspension in the coastal area is mainly influenced by tidal action.

DIN is high during rainy season, which is the period of high nutrient loadings from land area. The period of high PO_4-P is longer than DIN. It is pointed out that besides high loadings, the increase in PO_4-P is influenced by release from mud bed. The simulated results indicate that nutrients are released from mud bed at higher rate in summer.

Koh (2003) stated that resuspension of Chl-*a* from the tidal flat contributed to Chl-*a* in the coastal area of the Ariake Sea whereas biological activity predominated the Chl-*a* in the central of the Ariake Sea. From the simulation, it is found that the contribution of Chl-*a* in the tidal flat to Chl-*a* in the overlying water is low and can be neglected. Contribution of the tidal flat to the behaviors of water quality in the Ariake Sea will be discussed later.

The simulated results in the other elements also have good correlation with the observed data. The developed box model is proved to be an effective tool for the water quality simulation in the Ariake Sea.

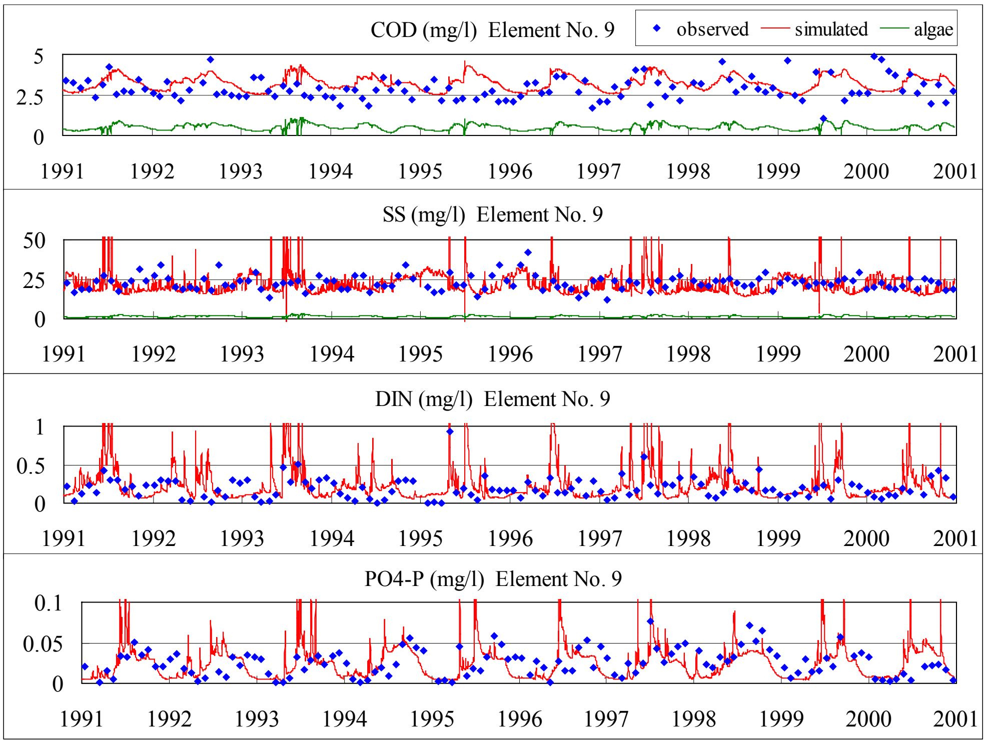


Figure 5.5 Water quality of the Ariake Sea simulated by the developed box model

5.4 Integrated model in the Chikugo Basin and the Ariake Sea

For integrated water management in the Chikugo Basin, it is necessary to evaluate impacts of the proposed measures on the water quality not only in the Chikugo Basin but also in the Ariake Sea. Therefore, the developed box model and the developed models in the Chikugo Basin are combined together in order to represent the interrelation between the Chikugo River and the Ariake Sea. Observed flow rate and discharge loading of the Chikugo Basin are replaced by the simulated results from the developed models of the Chikugo Basin. The integrated model is shown in Fig.5.6.

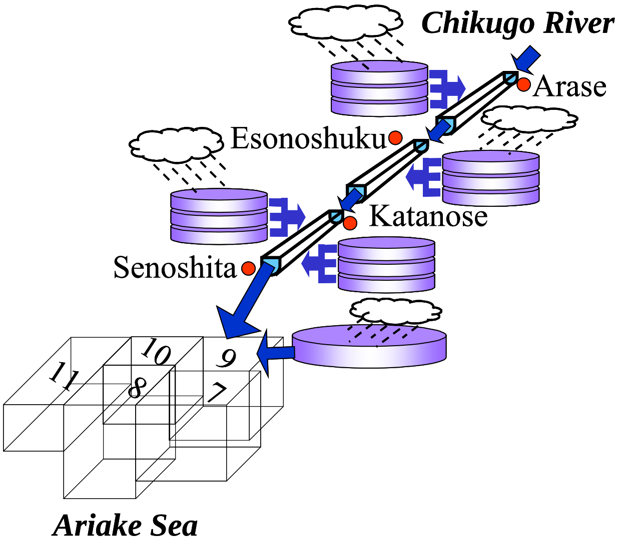


Figure 5.6 The integrated model in the Chikugo Basin and the Ariake Sea

Because the prototype of water quality model in the Chikugo Basin is developed for simulating nutrients in forms of total nitrogen and total phosphorus, the interpolation is required. Loadings of dissolved inorganic nitrogen and orthophosphate phosphorus of the Chikugo Basin are interpolated from simulated T-N and T-P loadings using the ratio of DIN to T-N and the ratio of PO_4-P to T-P listed below:

DIN: T-N = 0.735

PO_4-P: T-P = 0.388

The relationship between DIN and T-N and the relationship between PO_4 and T-P are obtained from the observed data at Senoshita (Kyushu Regional Development Bureau, MLIT 2001).

To verify the capability of the integrated model, it is applied in the simulation of water quality in the Ariake Sea in 1991-2000. Figure 5.7 shows the obtained results of the integrated model.

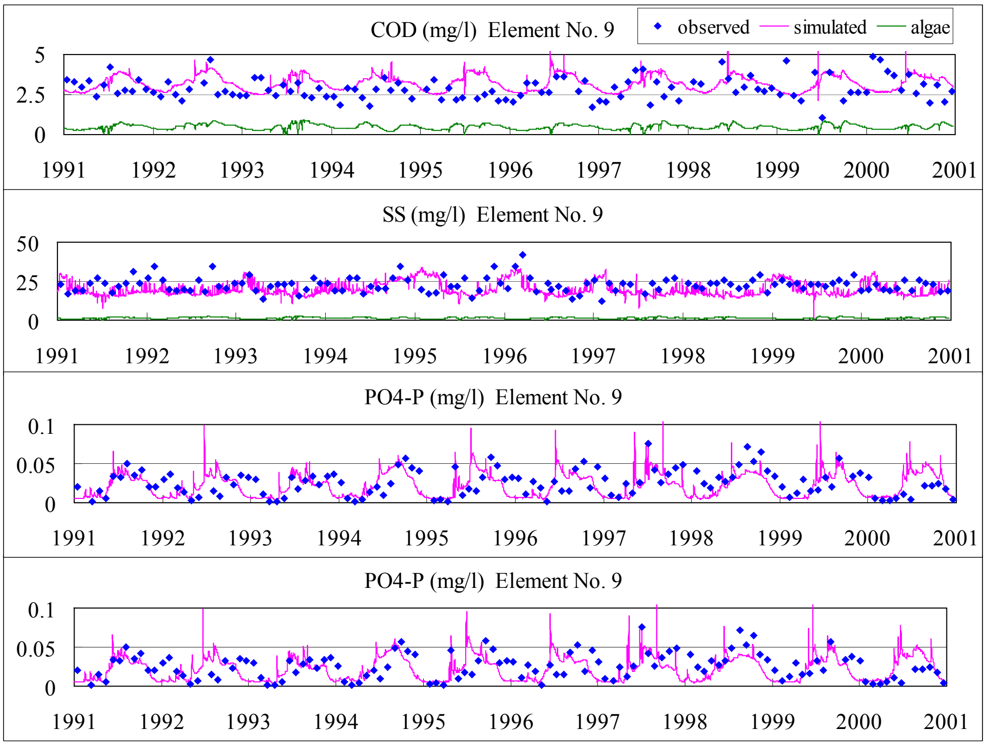


Figure 5.7 Simulated water quality of the Ariake Sea by the integrated model

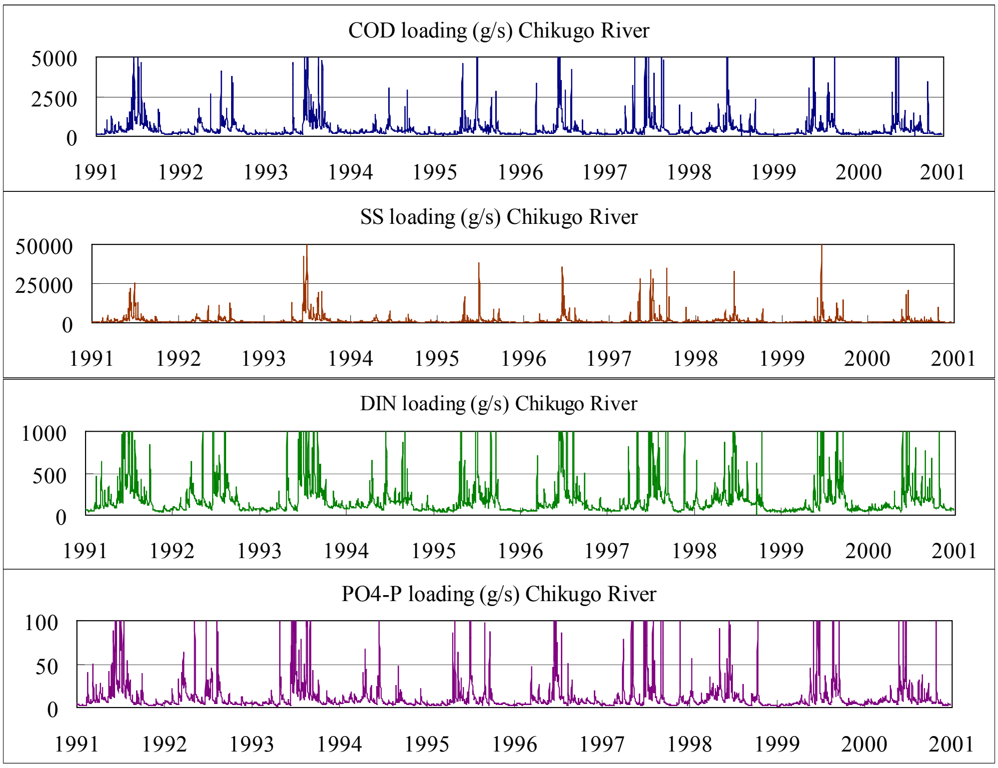


Figure 5.8 Total loadings from the Chikugo Basin simulated by the integrated model

The simulated water quality has a good agreement with the observed data. Compared with the simulated results of the developed box model in Fig.5.5, SS during the rainy season obtained from the integrated model is lower. It is because of the difference between SS loadings obtained from L-Q relation and the developed model in the Chikugo Basin. Referring to Table 4.10, it is found that average annual SS loading obtained from L-Q relation is twice of the simulated one. However, the loading from L-Q relation is probably higher than usual because observed data during heavy rain is not available. It is suggested L-Q relation of the Chikugo River should be recalculated if there is more information of water quality during heavy rain. Good correlation between the simulated loading and the observed data in the Chikugo Basin confirms that the simulated loading is reliable (Fig.4.14). Therefore, the integrated model is applicable for water quality analysis in the Chikugo Basin and the Ariake Sea.

The discharged loadings from the Chikugo Basin are demonstrated in Fig.5.8. Referring to the simulated results in Fig.5.7, some relationships between behaviors of water quality in the innermost part of the Ariake Sea and discharged loadings can be pointed out. It is clearly seen that simulated COD concentration is high in the same period with high loading from the Chikugo Basin whereas SS are high in the period of low discharged loading. The possible cause of high SS in the shallow sea during dry period is resuspension due to tidal movement and wind. As mentioned in water quality modeling, deposited materials are highly resuspended when water level is low.

High nutrient concentrations are observed during high loading period. It is mentioned in water quality analysis in the Chikugo Basin that high nutrients are discharged from land area due to irrigation activities in the agricultural area. After irrigation period, PO_4-P is still high although when the discharged loading becomes lower. Another source of PO_4-P in the innermost area of the Ariake Sea is the tidal flat with large content of clay. The important phenomenon is that the PO_4-P in dry period results from the release from mud bed.

The simulated results points out that there is some relationship exists among water quality in the innermost of the Ariake Sea, ecosystem of the tidal flat and discharged loadings from land area, which agrees with the results of problem analysis in Chapter 3. In order to examine the relationship mentioned above, sensitivity analysis is necessary.

5.5 Sensitivity analysis

The discharged loadings from land area especially from the Chikugo Basin are believed to have great influence on water quality and ecosystem in the Ariake Sea. To evaluate the contribution of the discharged loadings from land area, sensitivity analysis is carried out with the application of the integrated model. Contributions of algal growth and natural loadings from the mud bed are also analyzed in order to give more explanation about the relationship among these factors and water quality in the Ariake Sea.

5.5.1. Contribution of algal productivity

In the Ariake Sea, algal productivity in the innermost area is normally high because large amount of nutrients is available and sunlight can reach sea bottom easily. The cultivation of laver in this area is also effective. In order to evaluate the contribution of the algal productivity, water quality is simulated by neglecting the algal growth in the Ariake Sea.

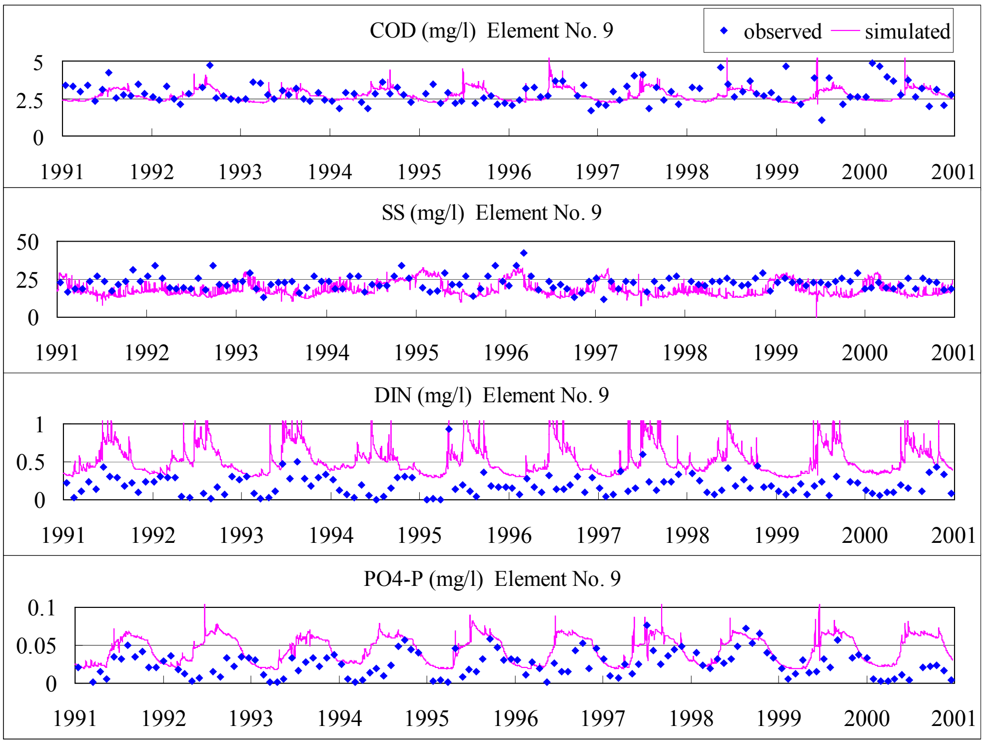


Figure 5.9 Water quality in the innermost area of the Ariake Sea simulated by neglecting algal productivity

Figure 5.9 shows that, without algal productivity, nutrient concentrations greatly increase while COD and SS concentrations decrease slightly. Compared with PO_4-P, the increase in inorganic nitrogen is higher during dry period, which is the growth period of algae. It indicates that nitrogen concentration is a growth-limiting factor for algal productivity in the Ariake Sea. For water quality control, it is recommended to carry out the research on sources of nitrogen in the Ariake Sea including the sources situated in the Chikugo Basin.

5.5.2. Contribution of natural loadings from mud bed

Mud bed is another important source of nutrients and organic matter in the innermost area of the Ariake Sea. Coarse matters discharged through the rivers tend to sediment and accumulate in the vicinity of the river mouth. Being disturbed by tidal movement and wind, mud bed makes an addition of dissolved and particulate materials in the overlying water through the process of release and resuspension. Release and resuspension from mud bed are neglected in the simulation of water quality shown in Fig.5.10.

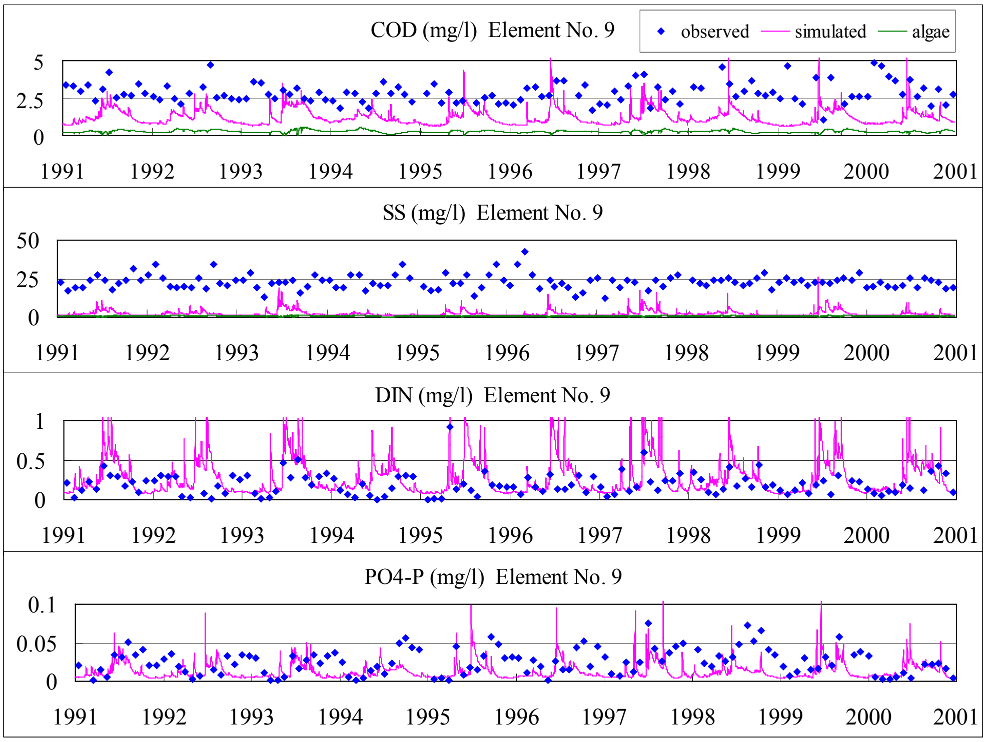


Figure 5.10 Water quality in the innermost area of the Ariake Sea simulated without release and resuspension from mud bed

Neglecting the natural loadings from mud area, concentrations of COD, SS and PO_4-P decrease obviously. It is clear that SS and PO_4-P concentrations become very low especially in dry period. Without the contribution of mud bed, DIN concentration slightly increases because PO_4-P becomes a limiting factor of algal growth. It can be concluded that the natural loadings from mud bed play an important role on SS and PO_4-P concentrations in the innermost area. Contribution of mud bed to algal productivity will be studied in Chapter 6. As it is assumed in this study that concentrations of dissolved COD and inorganic nutrients in mud bed of the Ariake Sea are constant, further study on the condition of the tidal flat in the Ariake Sea and long-term contribution of loadings from land area to the tidal flat is necessary.

5.5.3. Contribution of discharged loadings from land area

In water quality control, master plans for wastewater treatment in the watershed of the Ariake Sea are drafted at current. The loadings generated in each basin area are being examined in order to determine the appropriate reduction measures. To evaluate the contribution of discharged loadings from land area, water quality in the Ariake Sea is simulated by neglecting all discharged loadings. The simulated results are shown in Fig.5.11. Without loadings from land area, it is clear that water quality concentration in the area near the river mouth becomes lower in rainy season. Water quality concentration in the central part and the gulf mouth also decreases but lower in degree. COD and nutrient concentrations greatly decrease in the rainy season while the decrease in SS concentration is smaller. The decrease in PO_4-P during rainy season is smaller than DIN because some PO_4-P is supplied from mud bed in this period. Without the nutrient supply from land area, it is found that concentration of Chl-*a* also decreases. It indicates that high discharged loadings in rainy season are ones of the main causes of high concentrations of organic matters and nutrients in the vicinity of the river mouth.

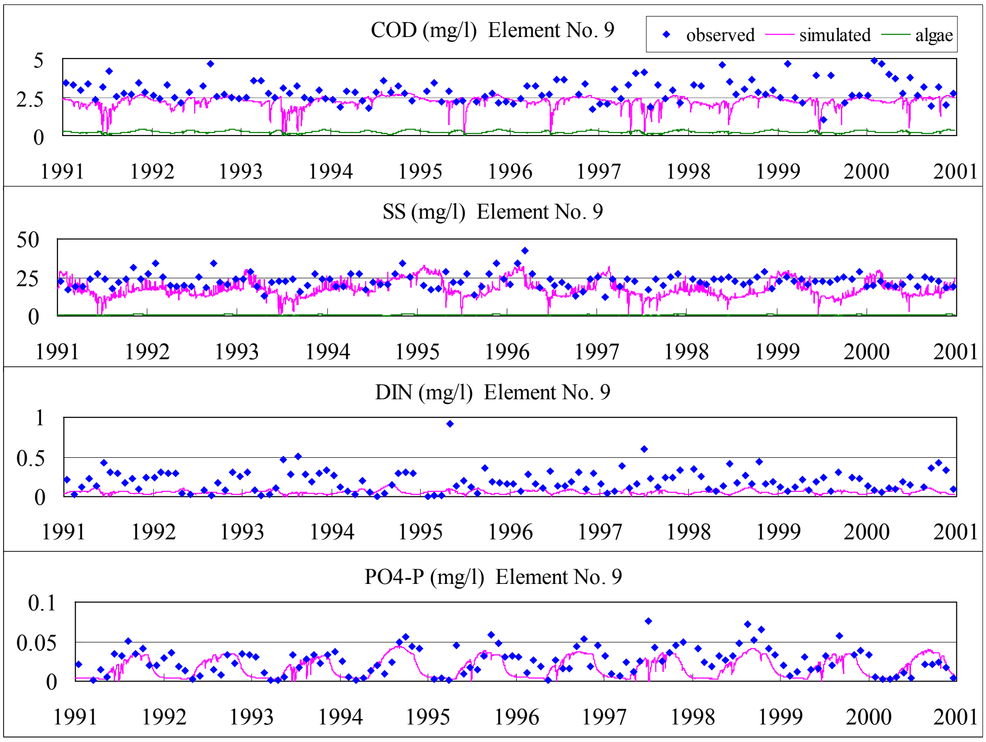


Figure 5.11 Water quality in the innermost area of the Ariake Sea simulated without discharged loadings from land area

The simulated results indicate that there is some relationship between Chl-*a* concentration and discharged loadings from land area. For water quality control, further analysis on the contribution of discharged loadings on algal productivity is necessary. The analysis results will be useful for maintaining the minimum flow rate at downstream of the Chikugo River for fishery in the Ariake Sea.

Results of sensitivity analysis indicate that the integrated model effectively represent behaviors of water quality and important phenomena in the Ariake Sea and the Chikugo Basin. This model is applicable as an analytical tool for integrated water management in the Chikugo Basin and the Ariake Sea. The integrated model will be applied in policy analysis for the Chikugo Basin and the Ariake Sea in Chapter 6.

5.6 Summary

As the water quality model in the Ariake Sea, the finite-volume model is developed with an assumption that there is no density current inside each element. Under this assumption, even if a vertical distribution exists, observed data and the calculated results in each element can be treated as an averaged value over the water depth and specific time constant. The coefficients of advection and mixing, which are constant between two adjacent elements, are calibrated through the simulation of salinity. The advantage of this model is there is no governing equation of water movement required. The governing equation of water movement can be satisfied by the calibration of salinity. Water quality considered in this model is COD, SS and inorganic nutrients.

The water quality obtained from the developed model has good correlation with the observed data. It is found that resuspension due to tidal effect and wind mainly contributes to SS in dry period, and nutrients are released from mud bed at high rate in rainy season. The finite-volume model is combined with the developed models in the Chikugo Basin. In the integrated model, the simulated loadings of the Chikugo Basin are applied as the boundary condition in the water quality model of the Ariake Sea.

The simulated results show that the integrated model can simulate water quality in the Ariake Sea effectively. The relation between discharged loadings from the Chikugo Basin and water quality in the Ariake Sea near the river mouth is defined from the simulated results. During the period of high loadings from the Chikugo Basin, COD and nutrient concentrations are high comparing with those in dry period. Suspended solids in the vicinity of the river mouth are high in dry period. It is found that the natural loadings from mud bed dominate the concentrations of suspended solids and orthophosphate phosphorus in the innermost area of the Ariake Sea during dry period.

The advantage of using the tank model in the integrated model are less observed data of the Chikugo Basin is required in water quality simulation and its capability of predicting influences of the change in water use in the Chikugo Basin enables simultaneous impact assessment of the proposed alternatives in the Chikugo Basin and the Ariake Sea. The developed tank model is effective in the simulation of base flow from the catchment area. Since base flow predominates the river flow in dry period, the tank model is very useful for river flow management and water quality management. When all information of boundary condition such as water use in the Chikugo Basin is available, the tank model will be more powerful. Influences of water resources development in the Chikugo Basin can be evaluated in the Chikugo Basin and the Ariake Sea simultaneous by the integrated model.

The integrated model is applied in sensitivity analysis. The relationship among water quality in the innermost part of the Ariake Sea, the tidal flat and discharged loadings from land area is examined. Algal productivity contributes to nutrients in the innermost part of the Ariake Sea. Under the condition of no algal growth, COD and SS slightly decrease. It is found that nitrogen is a growth-limiting factor for algal productivity in the Ariake Sea.

Natural loadings from mud area highly contribute to SS and PO_4-P concentrations in the innermost part of the Ariake Sea especially in dry period. Simulated COD concentration also decreases slightly. Contribution of natural loadings to inorganic nitrogen is found to be small. It is recommended to examine the contribution of mud bed to algal productivity for laver cultivation in the Ariake Sea.

When loadings from land area are completely eliminated, it is found that contribution of discharged loadings to COD and nutrient concentrations is high during irrigation period. It seems that contribution to inorganic nitrogen is greater orthophosphate phosphorus. Influence of discharged loadings on Chl-*a* concentration is clearly seen. For water quality control, further analysis on the contribution of discharged loadings to algal productivity is necessary.

In this chapter, the integrated model is proved to be an effective analytical tool for water quality analysis in the Ariake Sea and the Chikugo Basin. The integrated model will be applied in policy analysis for selected measures in Chapter 6.

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CHAPTER 6

APPLICATION OF THE INTEGRATED MODEL IN POLICY ANALYSIS IN THE CHIKUGO BASIN AND THE ARIAKE SEA

6.1 Introduction

Using the information obtained from problem analysis in Chapter 3, numerical models are developed and performed in water quality analysis in both the Chikugo Basin and the Ariake Sea. Characteristics of water quality in both areas are determined, and the interrelation between water quality at downstream of the Chikugo River and water quality in the Ariake Sea near the river mouth is pointed out.

In water management, proposed alternatives need to be evaluated through the process of policy analysis and presented to the decision-makers before new policy will be adopted. For the Chikugo Basin and the Ariake Sea, it is necessary to examine influences of the proposed alternatives in both areas simultaneously.

From a viewpoint of feasibility study, the integrated model developed in Chapter 5 is applied as an analytical tool in policy analysis in the Chikugo Basin and the Ariake Sea in this chapter. The analysis focuses on water quality in the middle and lower parts of the Chikugo Basin and the innermost part of the Ariake Sea. Several existing measures for water quality control and water quality management in the Chikugo Basin and the Ariake Sea are selected and analyzed in the feasibility study. Because water quantity and water quality are interrelated, it is found that water quantity management approach is also important as a measure of water quality management.

6.2 Water quality control aspect

For water quality control in the Ariake Sea, master plans for implementation of wastewater treatment are being drafted in order to reduce the loadings from land area. In this dissertation, feasibility of environmental quality standard (EQS) and reduction of loadings in the Chikugo Basin is analyzed.

6.2.1. Environmental quality standard in the Ariake Sea

From a viewpoint of water quality control, environmental quality standards are established for various types of water body in Japan according to the Basic Environment Law. Each EQS differs from each other depending upon water usage and type of water body. In order to achieve and keep EQS, many countermeasures are formulated against waste loads generated from human activities in land area. In the conservation of water quality in rivers and streams, regulations on effluent from factories and measures against domestic effluent are drawn up under Water Pollution Control Law. In the same manner, countermeasures against eutrophication and discharged loadings from land area are established for the conservation of water quality in oceans.

Several measures are adopted to decrease loadings from the Chikugo Basin and other rivers that discharge into the Ariake Sea in order to accomplish the EQS in the Ariake Sea and the Chikugo River. On the other hand, loading or contamination that is naturally occurred with no relation to human activities such as natural loadings from mud bed and productivity of algae in the Ariake Sea should not be overlooked. Contribution of loadings from these non-human sources to natural system is an important factor in the implementation of water quality control.

With the application of the integrated model, contributions of loadings from land area and natural loadings to water quality in the innermost area of the Ariake Sea are evaluated through sensitivity analysis.

Sensitivity analysis on water quality in the Ariake Sea

In Chapter 5, contributions of natural loading and discharged loadings from land area are determined in broad scope through the application of the integrated model. In order to examine the degree of contribution of each loading on water quality in the Ariake Sea, another analysis is necessary. Sensitivity analysis is carried out under two conditions below:

Case 1: Contribution of natural loadings from mud bed

(without the algal productivity and discharged loadings from land area)

Case 2: Contribution of discharged loadings from land area

(without the algal productivity and natural loadings from mud bed)

In order to evaluate the contribution of natural loadings from mud bed, all discharged loadings from land area including those from the Chikugo Basin as well as algal growth in the Ariake Sea are eliminated in case 1. The simulated results in the area near the mouth of the Chikugo River (element 9) are shown in Fig.6.1. The simulated results reveal amount of organic matters and nutrients supply from mud bed and resuspension of deposited materials.

SS and orthophosphate concentrations are high during rainy season although there is no discharged loading from land area. It indicates that natural loadings from mud bed predominate on SS and orthophosphate in the innermost area of the Ariake Sea.

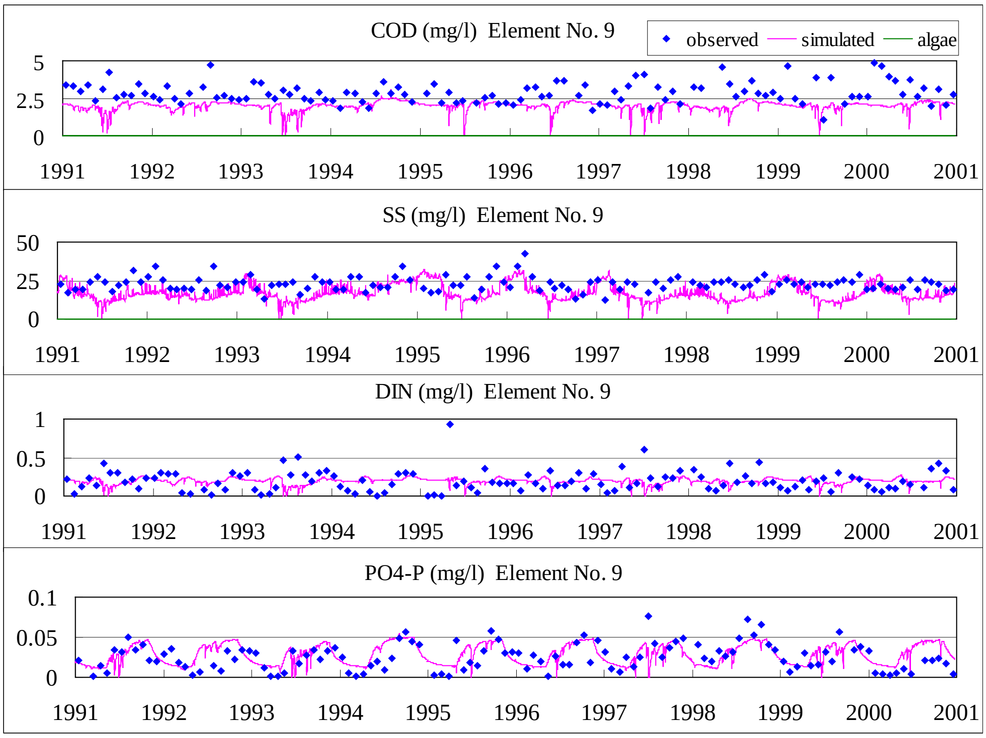


Figure 6.1 Water quality near the mouth of the Chikugo River under the condition of no algal productivity and discharged loadings from land area (case 1)

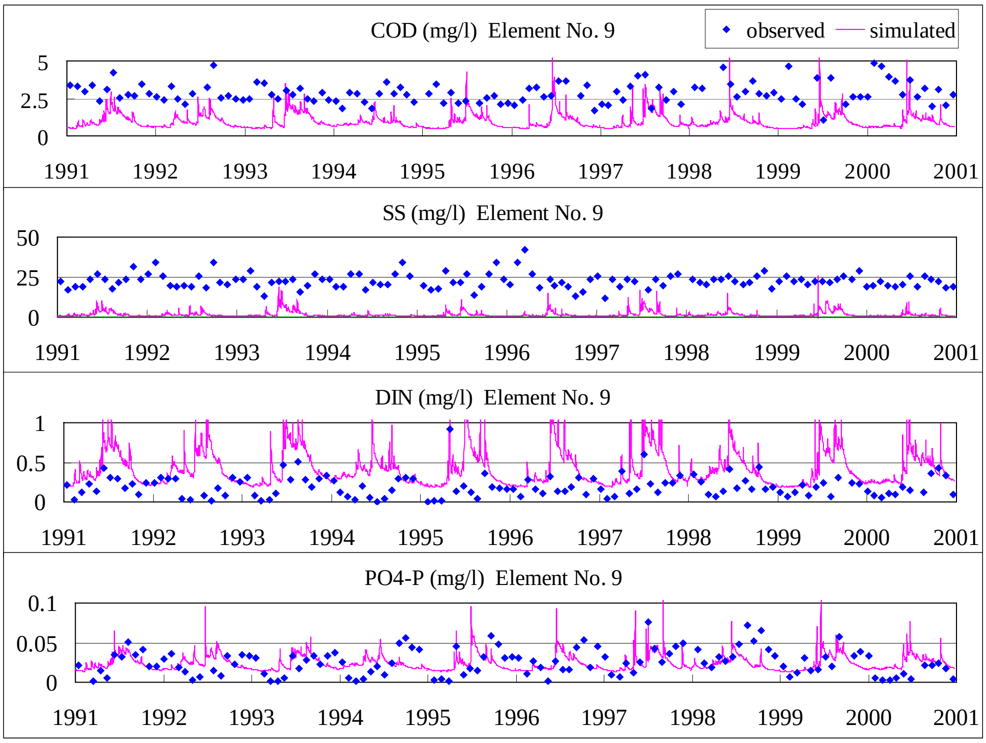


Figure 6.2 Water quality near the mouth of the Chikugo River under the condition of no algal productivity and natural loadings from mud bed (case 2)

The objective of case 2 is to determine contribution of discharged loading from land area. Only discharged loadings from land area are concerned in this simulation. In Fig.6.2, the simulated nutrient concentrations during dry period (October to March) are in the same level with those of case 1 whereas the simulated nutrient concentrations in rainy season are higher than those of case 1. In dry season, observed inorganic nitrogen and orthophosphate are low because this period is cultivation season of laver and growth period of algae. The results of sensitivity analysis in Chapter 5 indicate that nutrient concentrations in the shallow sea area are controlled by nutrient consumption of algae. Contribution of the natural loadings like the release from mud bed should be concerned in the achievement of the EQS in the Ariake Sea. Only countermeasures against pollutant loads from land area might be inadequate to achieve the environmental quality standard in the area where contribution of natural loadings is large. Installation of wastewater treatment system may not be able to handle the loadings, which occur naturally in the Ariake Sea.

6.2.2. Measure of loading reduction in the Chikugo Basin

In Chapter 5, feasibility study on the installation of wastewater treatment system in the watershed of the Ariake Sea shows that the contribution of wastewater treatment to the Ariake Sea is high in rainy season comparing with the contribution in dry season. Since the discharge of the Chikugo Basin is the largest one among the discharge from all river basins, it is necessary to consider about the influences of discharged loadings from this basin especially in the area near the river mouth.

Matsunashi and Imamura (1998) analyzed influences of pollutant load reduction on water quality and release rate of nutrients from mud bed in Tokyo Port. The results indicated that the response of water quality and release rate of nutrients from mud bed to pollutant load reduction was linear. When comparing with reduction rate of pollutant load, it is found that reduction rate of water quality and release rate from mud bed were smaller. Lee et al. (1996) applied water-sediment quality model based on the box model to analyze the influence of discharged loadings on water quality in the Seto Inland Sea. It is found that T-N and T-P loadings greatly affected water quality in the Seto Inland Sea. Around 30-80% reduction of T-N loading and 60-65% of T-P loading were recommended.

From the analysis on water quality in previous chapters, characteristics of loadings in the Chikugo Basin are classified as high discharged loadings in rainy season and low and almost steady loading in dry period. Loadings in dry period are discharged from household, industry, wastewater treatment plants, etc. The analysis also defines that these non-irrigation activities generate waste at almost constant rate all the year. High loadings in rainy season include non-point sources loadings such as irrigation activities in agricultural area and surface runoff during heavy rainfall, etc.

An effect of loading reduction in the Chikugo Basin is evaluated by using the integrated model. Water quality in the vicinity of the river mouth after 50% and 80% removal of loadings from the Chikugo Basin is shown in Fig.6.3 and 6.4. Because the loadings discharged from the Chikugo Basin are low in dry period, the improvement on water quality concentration is effective mostly in rainy season. These results agree with contribution of discharged loadings from land area determined in Chapter 5 that without loadings from land area, water quality concentration reduces at higher proportion in rainy season. In practice, efficiency of this reduction may be lower because it is difficult to control the non-point source loadings, which dominate in total loadings in rainy season. However, the measure of wastewater treatment is still necessary and should be implemented in order to reduce loadings from human activities.

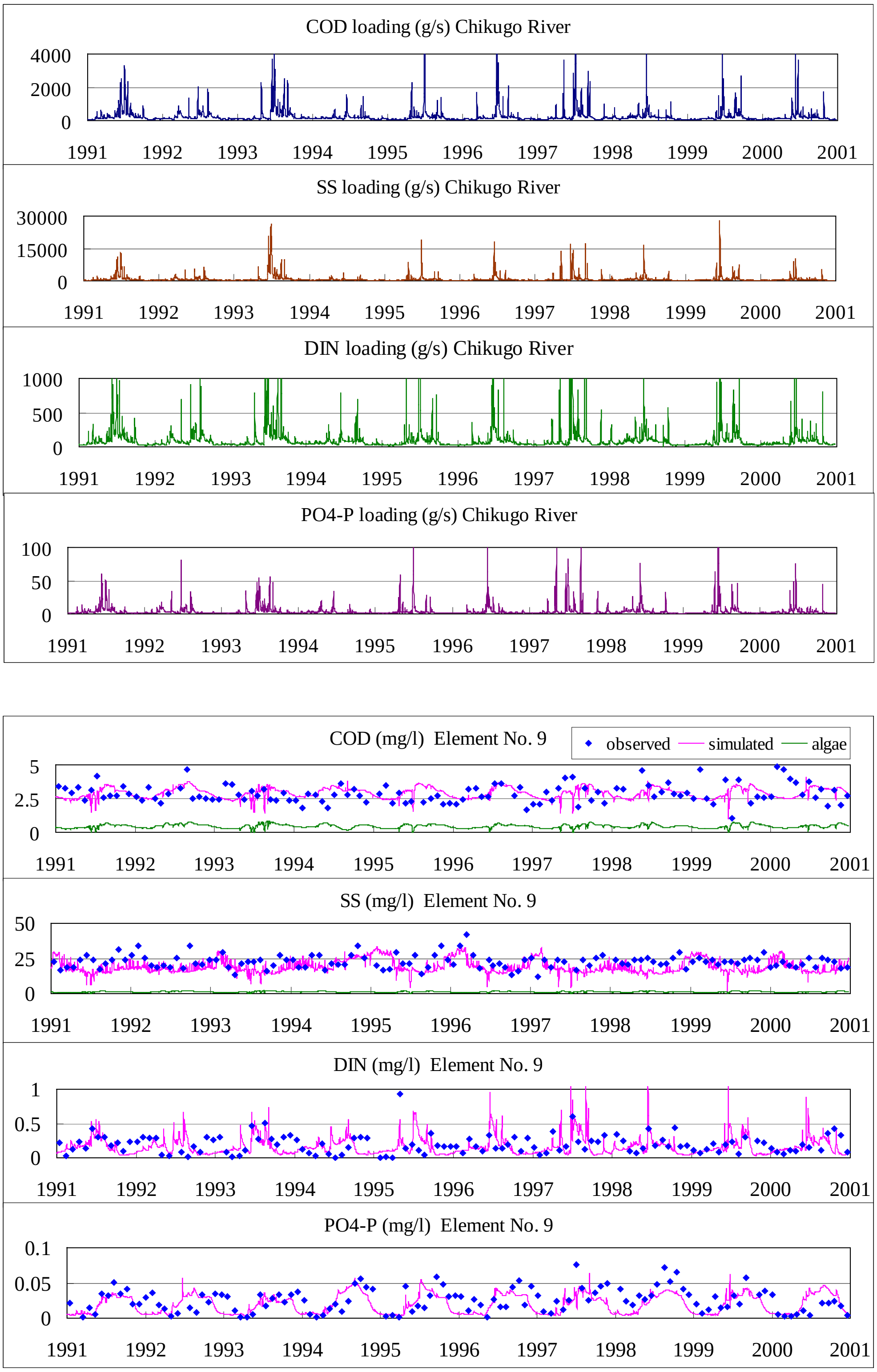
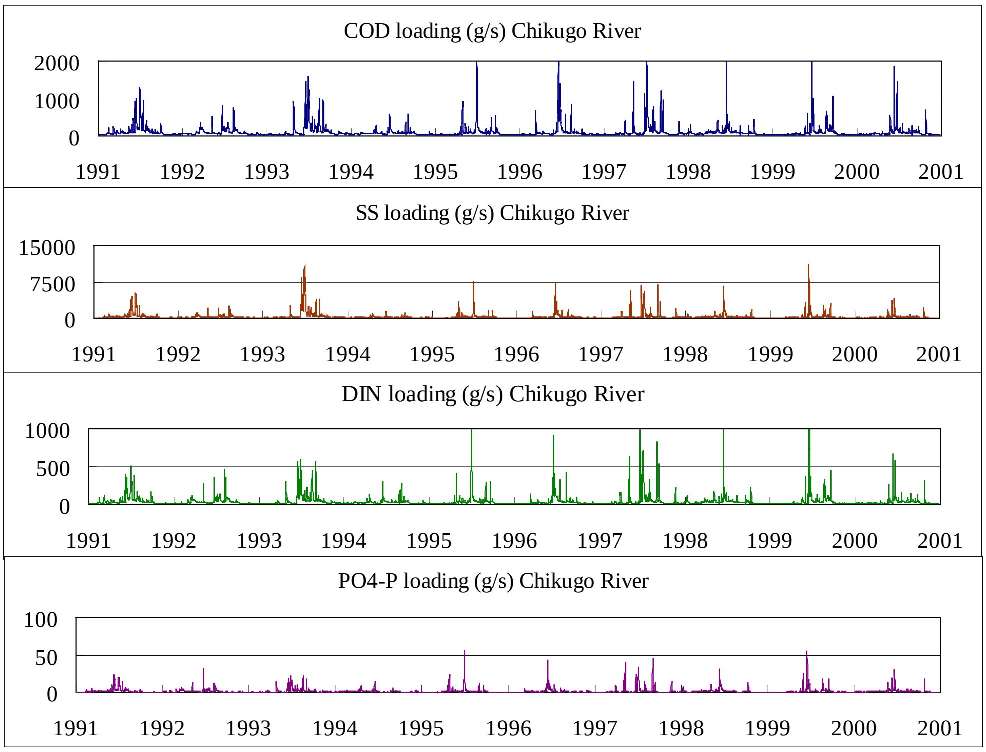


Figure 6.3 Results of 50% reduction of loadings from the Chikugo Basin



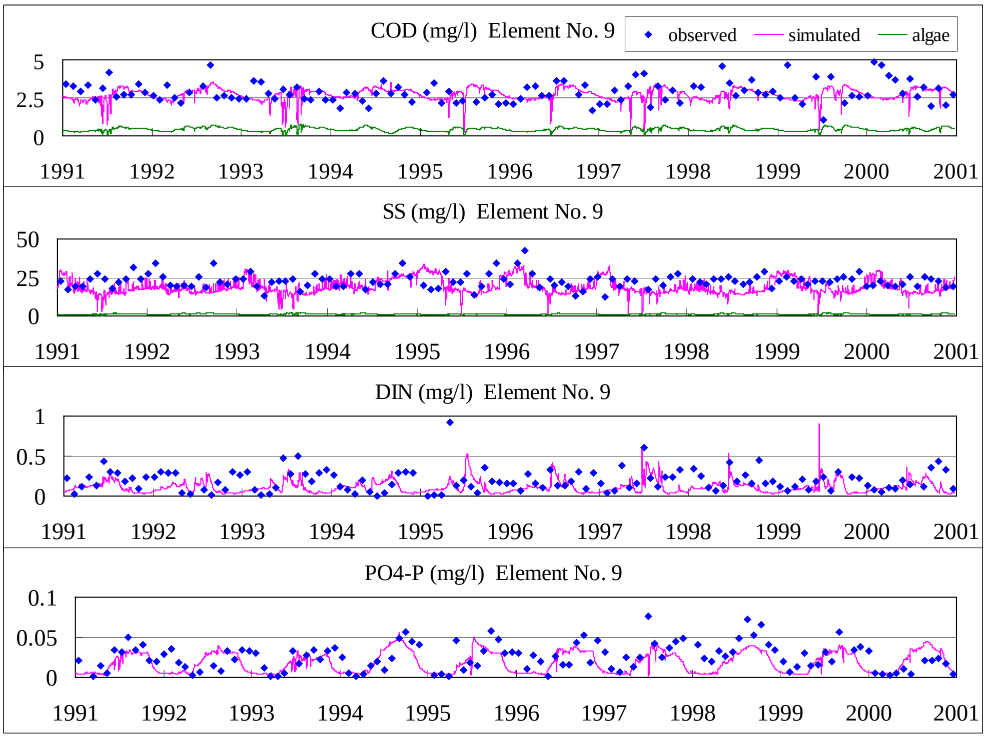


Figure 6.4 Results of 80% reduction of loadings from the Chikugo Basin

6.3 Water quality management aspect

The Master Plans for Water Resources Development in the Chikugo Basin were approved by the cabinet in January of 1999. According to these master plans, water demand from the Chikugo River was estimated from data of 1986-2000. Amount of water use from Yoake to Senoshita is at rate of 5.531 m^3/s for drinking water, 0.245 m^3/s for industrial water and 45.2 m^3/s for irrigation water (River Bureau, MLIT 2003).

In the Chikugo River, the minimum flow rate at 40 m^3/s is assigned at Senoshita according to an agreement between MLIT and fishery and laver cultivation groups. The purpose of this flow rate is to maintain the appropriate condition for fishery and laver productivity. These groups require essential nutrients especially nitrogen to be supplied from the Chikugo River and other rivers. From sensitivity analysis, it is pointed out that inorganic nitrogen concentration under the contribution of mud bed is almost same as those of the contribution of discharged loading during cultivation season (October to March). It means mud bed plays as important role as the loadings of the Chikugo River in supplying nitrogen for algal growth in the vicinity of the river mouth and the innermost area of the Ariake Sea. The nutrients supplied from mud bed in the Ariake Sea seem to be underestimated by fishery and laver cultivation groups.

In the Basic Policy for River Improvement (former Master Plans for Implementation of Work) reported by River Bureau, MLIT (2003), standard flow rate is determined in order to maintain flow condition for environmental conservation, etc. in each river system. From the investigation on river flow rate for all water users, ecosystem, growth of plants and animals, navigation, etc., the standard flow rate of the Chikugo River at Yoake is assigned at 35-40 m^3/s during irrigation period. However, this standard flow rate does not always secure the flow rate at Senoshita. In order to maintain the flow rate at downstream, it is important to set more reference points for the flow control between Yoake and Senoshita and assign the flow rate that should be maintained at those points.

MLIT has planned for water resources development such as construction projects and integrated management of reservoirs in order to make the flow in the Chikugo River meet the minimum flow rate. However, because all the projects cannot be carried out within one time, MLIT is facing the difficulty in maintaining the minimum flow rate in the Chikugo River during dry period. Some water is supplied from the reservoirs at upstream to increase the flow rate at Senoshita in this period.

As mentioned above, inorganic nitrogen supplied from mud bed is as high as that from discharged loadings. Therefore, nutrient supply from the Chikugo River can be compensated by nutrients from mud bed, and the minimum flow rate at Senoshita can be reduced. Natural loadings from mud bed should be considered in determining of the minimum flow rate. It is essential to investigate how much nutrients are supplied through discharge of the rivers and how much are supplied from mud bed. With results of the investigation, new minimum flow rate, which is more feasible than the current one, can be determined.

From the analysis, it suggests that new concept for river flow management and water quality management should be set up by taking into account the natural loadings from mud bed and the discharged loadings from land area. In order to maintain sustainable water environment in the Chikugo River, it might be more feasible to draw up the measures with water use aspect in policy analysis.

It is important to understand clearly about the water system and what is happening inside the water system before focusing on the how to solve the water problems. In water management, all of the necessary information of the watershed including data of water use and results of water quality analysis should be opened to public. In case of the Chikugo Basin, it is difficult to perform water management system because some information is still closed and some information such as contributions of discharged loadings in the Chikugo River and natural loadings in the Ariake Sea is not clear. Another reason is there are many parties such as local residents, stakeholders, responsible authorities, etc. involving in the decision-making in this watershed. As a result, it is hard to get a satisfying agreement among all parties. However, with all necessary data available, the conflicts in interests can be reduced. For example, if nutrient supply from mud bed were realized, the problem on more water demand for fishery and laver cultivation would never happen in the Chikugo Basin.

6.4 Summary

From the viewpoint of the feasibility, policy analysis on the existing measures in the Chikugo Basin and the Ariake Sea is performed in this chapter with the application of the integrated model. Aiming at water quality control, the environmental quality standard in the Ariake Sea and loading reduction in the Chikugo Basin are analyzed. In sensitivity analysis, it is pointed out that contribution of natural loadings from mud bed in dry period is as large as that of discharged loadings from land area. It is necessary to take natural loadings into account in the achievement of the EQS in the Ariake Sea or the investment in wastewater treatment plants in the Chikugo Basin.

In feasibility study on the measure of loading reduction, water quality in the vicinity of the river mouth is simulated under 50% and 80% reduction of loading in the Chikugo Basin. These alternatives are found to be effective only in rainy season. Because SS in the innermost part are predominated by natural loadings from mud bed, loading reduction is not effective in controlling suspended solids in the Ariake Sea. The loading analysis in previous chapters indicates that non-point source loadings dominate in discharged loadings of this watershed during rainy season. As a result, loading reduction may be practically infeasible because wastewater treatment system can handle only point source loadings. However, wastewater treatment is necessary for the reduction of loading generated from human activities. In winter of 2000, the red tides placed great damage on laver productivity in the Ariake Sea. Many researches and investigation are organized to determine the causes of red tides and low productivity of laver. Policy analysis on this problem will be carried out in the near future.

With the purpose of nutrient supply, the minimum flow rate in the Chikugo River is secured for fishery especially laver cultivation in the Ariake Sea. The feasibility of this measure is evaluated. At present, additional water supply from reservoirs at upstream is necessary for maintaining the flow rate in the Chikugo River during dry period. It indicates that the minimum flow rate may need to be reconsidered, and more sustainable flow rate is required. Sensitivity analysis brings out new viewpoint that the nutrient supply from mud bed in the innermost area during cultivation season is as high as that from the Chikugo Basin. It is proposed that new concept for the management of river flow and water quality should be established by considering natural loadings from mud area and discharged loadings from land area.

The integrated water quality analysis makes contribution to policy analysis by providing useful information of the Chikugo Basin and the Ariake Sea. New information obtained from policy analysis in this chapter calls for revision of the selected policies. It is recommended that, in order to reach the final goal of integrated water management in the Chikugo Basin and the Ariake Sea, all necessary information should be opened.

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CHAPTER 7

CONCLUSIONS

Water problems can be classified into two groups, that is, water quantity problems and water quality problems. The major and traditional problems related to water quantity are flooding and water shortage. Flooding can be referred as the first water problem in human history. Human learned how to protect their lives and properties from flooding since the ancient time. The causes of water shortage are drought and excessive water use.

Water quality problem can lead to shortage of clean water and health problems. Many diseases originate from waste contamination in water. Nowadays, water problems become more complicated compared with problems occurred in the past because the number of water users has increased and lifestyle has been changed. There are two types of measures for water problems, namely, technical measures and non-technical measures. The technical measures include the construction or modification of infrastructures such as flood control structures, wastewater treatment plants, etc. On the other hand, the non-technical measures refer to laws, promotion campaigns, etc. The influences of the proposed measure on other water problems, water users and natural environment should be taken into account when solving water problems involved by several water users. Therefore, integrated water management is necessary.

This dissertation describes about integrated water quality analysis in the Chikugo Basin and the Ariake Sea. In Chapter 1, background of general water problems and the problems in the Chikugo Basin and the Ariake Sea are expressed. According to the problem statement, objectives and scope of the study are determined. Being involved by many water users in the Chikugo Basin, the water quality problems are very complicated. These problems are not only limited within the basin area but also expands into the Ariake Sea. However, very few researches on water quality have been carried out in the Chikugo Basin and the Ariake Sea.

Objective of this dissertation is to analyze water quality in the Chikugo Basin and the Ariake Sea from integrated viewpoint. Characteristics of water quality in each area are the important information for integrated water management as well as how water quality in both areas is related to each other. The integrated model is developed and utilized for water quality analysis, policy analysis in the Chikugo Basin and the Ariake Sea. Taking into account the interrelation between water quality in both areas, this dissertation focuses on water quality in the middle and lower reaches of the Chikugo Basin as well as the innermost area of the Ariake Sea.

In Chapter 2, water management in various water systems and basic concepts of policy analysis are discussed. The policy analysis is composed of problem analysis, impact assessment and evaluation of policy. The development and application of numerical models for water management are reviewed. With technological development, numerical models are improved in analytical capability and become the powerful instruments for establishment of water management system. From the viewpoint of water quality, it is shown that water quality models become a significant analytical tool for water management.

The study on legislative system in Japan indicates that authority with ultimate power in making the final decision is required for water management in Japan. The water quality related issues reveals that organic and nutrient loadings generated in a river basin play an important role on water quality in receiving water body. Focus has been placed on estimation of discharged loading from land area. It is found that most of water problems in river and sea are handled separately. Solving water problems in one water body may cause new or more serious problems in the nearby areas. Impacts of the proposed measures need to be evaluated in both river basin and sea area in the policy analysis. Therefore, water management concerning with the interrelation between the river basin and sea area is essential for the water problems in the Chikugo Basin and the Ariake Sea.

In Chapter 3, problem analysis is carried out in the Chikugo Basin and the Ariake Sea. Main water use in the upper part of the Chikugo Basin is for hydroelectric generation and irrigation. Large population and agricultural area result in high water demand for irrigation, drinking water and industrial water in the middle and lower parts. Characteristics of water quality at downstream of the Chikugo River can be described as high organic and nutrient concentrations during rainy season, which is irrigation period, whereas concentrations in dry period are lower. Loading analysis indicates that high loadings are generated from paddy field in irrigation period while loadings from non-irrigation activities are low and steady. Unit loading of non-point sources such as paddy field and urban area, which is difficult to define by field observation, is determined through the analysis of loadings in both periods.

Water quality observation in the Ariake Sea indicates that concentrations of COD and nutrients are high in the innermost area. These concentrations become lower in the central area and near the mouth of the gulf. It is found that there is some relationship existing among inflow loadings, ecosystem in the tidal flat and water quality in the Ariake Sea. Therefore, contributions of the tidal flat and discharged loadings including those of the Chikugo Basin cannot be neglected in water quality analysis in the Ariake Sea. On the other hand, impact assessment of the proposed measures in the Chikugo Basin should be conducted in the Ariake Sea as well. As a conclusion of this chapter, the development of an integrated model is proposed for water quality analysis and policy analysis in the Chikugo Basin and the Ariake Sea.

In Chapter 4, the numerical models based on the tank model and the river model are proposed for simulation models of the Chikugo Basin. Water quality parameters concerned in these models are COD, SS, T-N and T-P. Total discharge from the catchment area and unknown parameters of non-point sources such as unit loading are determined through the calibration of models. Good correlation between the simulated results and the observed data shows the effectiveness of the developed models in comprehensive simulation in the Chikugo Basin. Small difference between the simulated and observed flow rate at Esonoshuku and Katanose during dry period indicates that additional water from reservoirs is supplied to secure the flow rate at Senoshita. The simulated SS at Senoshita points out the possibility of deposition problem in the stagnant water of Chikugo Barrage and the necessity of reaction term such as settling during low flow period.

Characteristics of water use for irrigation and discharged loadings are made clear in the analysis of water quantity and water quality in the Chikugo Basin. Water quantity analysis indicates that most of the water withdrawn for irrigation along the middle reach returns to the main river within the end of the reach. Annual loadings of the Chikugo River at Senoshita are determined in water quality analysis. Good agreement between simulated loadings and the observed data shows that the proposed models can effectively estimate the loadings discharged into the Ariake Sea. The discharged loadings from the Chikugo Basin are important information for pollution control and water quality management in the Ariake Sea.

Because the necessary data has not been completely disclosed yet, water quality analysis in the upper reach of the Chikugo Basin cannot be done completely in this dissertation. It is suggested to carry out the analysis in the upper reach of this watershed if information of water use and water quality is available. The tank model and the river model are also applicable for this area.

In Chapter 5, two-dimensional finite-volume model is developed in the Ariake Sea. Under the assumption of no density current in each element, water quality in each element is averaged over the water depth and specific time constant. After being verified, the finite-volume model is combined with the developed models of the Chikugo Basin. The integrated model effectively simulates water quality in the Ariake Sea in 1991-2000. The advantage of employing the tank model in the integrated model is that it can predict influences of human activities such as water resources development on water quantity and water quality in the Chikugo Basin. It can be recommended that the developed tank model is a powerful tool for water management in the Chikugo Basin and the Ariake Sea when all necessary information of the Chikugo Basin is available.

The sensitivity analysis on water quality in the Ariake Sea indicates that natural loadings from mud bed plays an important role in COD, SS and orthophosphate concentrations in the innermost area. Further study on the contribution of mud bed to algal productivity is recommended. The simulated results point out that high discharged loadings from land area increase organic and nutrient concentrations in the vicinity of the river mouth during rainy season. Without nutrient supply from land area, it is found that Chl-*a* concentration becomes lower. Analysis on the contribution of discharged loadings to algal productivity in the innermost part of the Ariake Sea is necessary for water quality control. Besides the release from mud bed, growth of phytoplankton is another control factor of the nutrients in the Ariake Sea. It is found that inorganic nitrogen is the growth-limiting factor for algae and laver in the Ariake Sea.

In Chapter 6, policy analysis is carried out on the existing measures for the Chikugo Basin and the Ariake Sea from the viewpoint of feasibility study. For water quality control in the Ariake Sea, master plans for implementation of wastewater treatment are being drafted in order to reduce the loadings from land area. The feasibility study on measures of water quality improvement in the Ariake Sea mentions that the contribution of the natural loadings from mud bed is significant and should be concerned in the achievement of the environmental quality standard. The effect of 50% and 80% loading reduction in the Chikugo Basin is evaluated by using the integrated model. It is found that these alternatives are effective only in rainy season. However, they may not be feasible in practice because the loading in rainy season is predominated by the non-point source ones which are difficult to control by wastewater treatment system.

With the purpose of nutrient supply, the minimum flow rate at downstream of the Chikugo River is secured for fishery activities, mainly for laver cultivation, in the Ariake Sea. The results of the sensitivity analysis indicate that not only the loadings from the Chikugo Basin, natural loadings from mud bed also play an important role in nutrient supply during the cultivation season. It is necessary to take into account the additional nutrient supply from mud bed in estimating the available nutrients for fishery in the Ariake Sea before determining the minimum flow rate in the Chikugo River. Finally, it is proposed that new concept for management of river flow and water quality should be established by considering natural loadings from mud bed and discharged loadings from land area.

Providing useful information for decision-making process, the integrated water quality analysis makes great contribution to policy analysis in the Chikugo Basin and the Ariake Sea. With some modification, the integrated model can be applied for the analysis of other existing problems. New information obtained from water quality analysis in this dissertation calls for revision of the selected policies.

After Chikugo Barrage was completed, new irrigation water supply system is introduced in downstream area of the Chikugo Basin. To evaluate impacts of this new system, it is suggested to carry out further investigation on water quality in the lower reach and estuary of the Chikugo Basin because long-term observed data are not available.

The problem of laver productivity during cultivation season in 2000 has brought out the environmental situation of the Ariake Sea to public concern. Investigation is still carried out to determine the environmental change in the Ariake Sea. In order to propose the feasible measures for this problem, policy analysis will be performed in near future.

APPENDIX A

WATER QUALITY STANDARDS IN JAPAN

In this appendix, water quality standards established for each type of water body in Japan are demonstrated.

Table A.1 Environmental Water Quality Standards for protecting human health

Item	Standard Values
Cadmium	0.01 mg/l or less
Cyanide	Not detectable
Organic phosphorus[2]	Not detectable
Lead	0.1 mg/l or less
Chromium (hexavalent)	0.05 mg/l or less
Arsenic	0.05 mg/l or less
Total mercury	0.0005 mg/l or less
Alkyl mercury	Not detectable
PCB	Not detectable

Source: Environmental Water Quality Standards (Dec. 28, 1971, Amendments 1974, 1975, 1982, 1985) (Environmental Agency, Japan 1992)

Notes: 1. Maximum values. But with regard to total mercury, standard value is based on the yearly average value.

2. Organic phosphorus includes parathion, methyl parathion, methyl demeton and E.P.N.

3. Standard value of total mercury shall be 0.001 mg/l in case river water pollution is known to be caused by natural conditions.

Table A.2 Environmental Water Quality Standards for conservation of the living environment in rivers

Category	Item Purposes of water use	Standard values[1]				
		pH	Biochemical Oxygen Demand (BOD)	Suspended Solids (SS)	Dissolved Oxygen (DO)	Number of Coliform Groups
AA	Water supply class 1; conservation of natural environment, and uses listed in A-E	6.5-8.5	1 mg/l or less	25 mg/l or less	7.5 mg/l or more	50 MPN / 100 ml or less
A	Water supply class 2; fishery class 1; bathing and uses listed in B-E	6.5-8.5	2 mg/l or less	25 mg/l or less	7.5 mg/l or more	1,000 MPN / 100 ml or less
B	Water supply class 3; fishery class 2; and uses listed in C-E	6.5-8.5	3 mg/l or less	25 mg/l or less	5 mg/l or more	5,000 MPN / 100 ml or less
C	Fishery class 3; industrial water class 1; and listed in D-E	6.5-8.5	5 mg/l or less	50 mg/l or less	5 mg/l or more	—
D	Industrial water class 2; agricultural water[2] and uses listed in E	6.0-8.5	8 mg/l or less	100 mg/l or less	2 mg/l or more	—
E	Industrial water class 3; conservation of the environment	6.0-8.5	10 mg/l or less	Floating matter such as garbage should not be observed	2 mg/l or more	—

Source: Environmental Water Quality Standards (Dec. 28, 1971, Amendments 1974, 1975, 1982, 1985) (Environmental Agency, Japan 1992)

Note: 1. The standard value in based on the daily average value. The same applies to the standard values of lakes and coastal waters

2. At intake for agriculture, ph shall be between 6.0 and 7.5 and DO shall not be less than 5 mg/l. The same applies to the standard values of lakes.

3. Conservation of natural environment: Conservation of scenic spots and other natural resources.

4. Water supply class 1 – Water treated by simple cleaning operation, such as filtration.
Water supply class 2 – Water treated by normal cleaning operation, such as sedimentation and filtration.
Water supply class 3 – Water treated through a highly sophisticated cleaning operation including pretreatment.

5. Fishery class 1 – For aquatic life, such as trout and bull trout inhabiting oligosaprobic water, and those of fishery class 2 and class 3.
   Fishery class 2 – For aquatic life, such as fish of salmon family and sweet fish inhabiting oligosaprobic water, and those of fishery class 3.
   Fishery class 3 – For aquatic life, such as carp and crucian carp inhabiting mesosaprobic water.
6. Industrial water class 1 – Water given normal cleaning treatment such as sedimentation.
   Industrial water class 2 – Water given sophisticated cleaning treatment by chemicals.
   Industrial water class 3 – Water given special cleaning treatment.
7. Conservation of the environment – Up to the limits at which no unpleasantness is caused to people in their daily life including a walk by the riverside, etc.

Table A.3 Environmental Water Quality Standards for conservation of the living environment in coastal waters

Category	Item / Purposes of water use	Standard values				
		pH	Chemical Oxygen Demand (COD)	Dissolved Oxygen (DO)	Number of Coliform Groups[1]	N-hexane Extracts
A	Fishery class 1; bathing; conservation of the natural environment, and uses listed in B-C	7.8-8.3	2 mg/l or less	7.5 mg/l or more	1,000 MPN / 100 mg/l or less	Not detectable
B	Fishery class 2; industrial water, and the uses listed in C	7.8-8.3	3 mg/l or less	5 mg/l or more	—	Not detectable
C	Conservation of the natural environment	7.0-8.3	8 mg/l or less	2 mg/l or more	—	—

Source: Environmental Water Quality Standards (Dec. 28, 1971, Amendments 1974, 1975, 1982, 1985) (Environmental Agency, Japan 1992)

Note: 1. With regard to the water quality of fishery class 1 for cultivation of oysters, the number of coliform groups shall be less than 70 MPN/100 ml.

2. Conservation of natural environment – Conservation of scenic points and other natural resources.

3. Fishery class 1 – For aquatic life, such as red sea-bream, yellow tail, seaweed and for those of fishery class 2.
Fishery class 2 – For aquatic life, such as gray mullet, laver, etc.

4. Conservation of the environment – Up to the limits at which no unpleasantness is caused to people in their daily life including a walk along the shore.

Table A.4 Environmental Water Quality Standards for nitrogen and phosphorus in coastal waters

Category	Items / Purpose of water use	Standard values	
		Total nitrogen	Total phosphorus
I	Conservation of the natural environment and users listed in II-IV (excluding fishery classes 2 and 3)	0.2 mg/l or less	0.02 mg/l or less
II	Fishery class 1 and the uses listed in III-IV (excluding fishery class 3)	0.3 mg/l or less	0.03 mg/l or less
III	Fishery class 2 and the uses listed in IV (excluding fishery class 3)	0.6 mg/l or less	0.05 mg/l or less
IV	Fishery class 3, industrial water, and conservation of habitable environments for marine biota	1 mg/l or less	0.09 mg/l or less

Source: Environmental Water Quality Standards (Aug, 1993) (Environmental Agency, Japan)

Notes: 1. Standard values are set in terms of annual averages.

2. Standard values are applicable only to marine areas where marine phytoplankton blooms may occur.

3. Fishery class 1 – For aquatic life, such as red sea-bream, yellow tail, seaweed and for those of fishery class 2.
Fishery class 2 – For aquatic life, such as gray mullet, laver, etc.

4. Conservation of the environment – Up to the limits at which no unpleasantness is caused to people in their daily life including a walk along the shore.

Table A.5 Environmental Quality Standards for Water Pollution for protecting human health

Item	Standard Values
Cadmium	0.01 mg/l or less
Total cyanogen	Not detectable
Lead	0.01 mg/l or less
Chromium (hexavalent)	0.05 mg/l or less
Arsenic	0.01 mg/l or less
Total mercury	0.0005 mg/l or less
Alkyl mercury	Not detectable
PCB	Not detectable
Dichloromethane	0.02 mg/l or less
Carbon tetrachloride	0.002 mg/l or less
1.2-dichloroethane	0.004 mg/l or less
Dichloroethane	0.002 mg/l or less
Cis 1.2-dischloroethane	0.04 mg/l or less
Trichloroethane	1.0 mg/l or less
Trichloroethane	0.006 mg/l or less
Trichloroethylene	0.03 mg/l or less
Tetrachloroethylene	0.01 mg/l or less
1.3-dischloropopane	0.002 mg/l or less
Thiram	0.006 mg/l or less
Simazine	0.003 mg/l or less
Thiobenearb	0.02 mg/l or less
Benzene	0.01 mg/l or less
Selenium	0.01 mg/l or less

Source: Environmental Quality Standard (March, 1993) (Environmental Agency, Japan)

Table A.6 Environmental Quality Standards for Water Pollution for protecting living environment

Categories	Target values
Chloroform	0.06 mg/l or less
Trans 1.2-dichloroethylene	0.04 mg/l or less
Dichlorpropane	0.06 mg/l or less
P-dichlorobenzene	0.3 mg/l or less
Isoxathion	0.008 mg/l or less
Diazinon	0.005 mg/l or less
Fenirothin	0.003 mg/l or less
Isoprothiolane	0.04 mg/l or less
Oxine copper	0.04 mg/l or less
Chlorothalonil	0.04 mg/l or less
Propyzamide	0.008 mg/l or less
EPN	0.006 mg/l or less
Dichlorovos	0.01 mg/l or less
Fenobucarb	0.02 mg/l or less
IBP	0.008 mg/l or less
CNP	-
Toluene	0.06 mg/l or less
Xylene	0.4 mg/l or less
Ethylhexy phtalate	0.06 mg/l or less
Boron	0.2 mg/l or less
Fluoride	0.8 mg/l or less
Nickel	0.01 mg/l or less
Molybdenum	0.07 mg/l or less
Antimony	0.002 mg/l or less
Nitrate-N and nitrite-N	10 mg/l or less

Source: Environmental Quality Standard (March, 1993) (Environmental Agency, Japan)

Table A.7 National Effluent Standards for substances related to the protection of human health[1]

Toxic substances	Permissible limits
Cadmium and its compounds	0.1mg/l
Cyanide compounds	1 mg/l
Organic phosphorus compounds (parathion, methyl parathion, methyl demeton and EPN only)	1 mg/l
Lead and its compounds	0.1 mg/l
Sexivalent chrome compounds	0.5 mg/l
Arsenic and its compounds	0.1 mg/l
Total mercury	0.005 mg/l
Alkyl mercury compounds	Not detectable[2]
PCBs	0.003 mg/l
Trichloroethylene	0.3 mg/l
Tetrachloroethylene	0.1 mg/l
Dichloroethylene	0.2 mg/l
Carbon tetrachloride	0.02 mg/l
1,2-dichloro ethane	0.04 mg/l
1,1-dichloroethlene	0.2 mg/l
cis-1,2-dischloro ethylene	0.4 mg/l
1,1,1-trichloro ethane	3 mg/l
1,1,2-trichloro ethane	0.06 mg/l
1,3-dichloropropene	0.02 mg/l
Thiram	0.06 mg/l
Simazine	0.03 mg/l
Thiobencarb	0.2 mg/l
Benzene	0.1 mg/l
Selenium and its compounds	0.1 mg/l

Source: National Effluent Standards (June 21, 1971, Amendments 1974, 1975, 1976, 1977, 1981, 1985, 1986) (Environmental Agency, Japan 1992)

Notes: 1. Prefecture may, by decree, set more stringent standards.

2. By the term “not detectable” is meant that the substance is below the level detectable by the method designated by the Director-General of the Environment Agency

Table A.8 National Effluent Standards for substances related to the protection of living environment[1, 2]

Item	Permissible limits
Hydrogen ion activity (pH)	5.8-8.6 (for effluent discharged into public water bodies other than coastal waters) 5.0-9.0 (for effluent discharged into coastal waters)
Biochemical Oxygen Demand (BOD)[3]	160 mg/l (daily average 120 mg/l)
Chemical Oxygen Demand (COD)[3]	160 mg/l (daily average 120 mg/l)
Suspended solids (SS)	200 mg/l (daily average 150 mg/l)
N-hexane extracts	5 mg/l (mineral oil) 30 mg/l (animal and vegetable fats)
Phenols	5 mg/l
Copper	3 mg/l
Zinc	5 mg/l
Dissolved iron	10 mg/l
Dissolved manganese	10 mg/l
Chromium	2 mg/l
Fluorine	15 mg/l
Number of coliform groups (per cc)	3,000 (daily average)
Nitrogen[4]	120 mg/l (daily average)
Phosphorus[4]	16 mg/l (daily average)

Source: National Effluent Standards (June 21, 1971, Amendments 1974, 1975, 1976, 1977, 1981, 1985, 1986) (Environmental Agency, Japan 1992)

Notes: 1. Prefecture may, by decree, set more stringent standards.

2. The standard values in this table are applied to the effluents from industrial plants and other places of business whose volume of effluents per day is not less than 50 m^3.

3. The standard value for BOD are applied to public waters other than coastal waters and lakes, while standard value of COD is applied only to effluents discharged into coastal waters and lakes.

4. Standard values for nitrogen and phosphorus are applied to lakes and reservoirs in which problems due to eutrophication may occur.

The phosphorus standards are applicable to lakes and reservoirs where water stays for 4 days or longer (excluding those with a chlorine ion content of more than 9,000 mg/l and those where special dam operations are conducted) out of lakes and reservoirs with a drainage area of more than 1 km^2 and a total surface area of more than 0.1 km^2 (this limitation does not apply to lakes and reservoirs used as source of tap water). Also covered are rivers and other water bodies designated as “public water areas” flowing into the above lakes and reservoirs.

The nitrogen standards are applicable to lakes and reservoirs where the figure obtained by dividing the nitrogen content of water by the phosphorus content is less than 20 and the phosphorus content of water exceeds 0.02 mg/l out of the lakes and reservoirs subject to the phosphorus regulation. Also covered are rivers and other water bodies designated as public water areas flowing into those lakes and reservoirs.

APPENDIX B

DATA OF THE CHIKUGO BASIN

Details of the Chikugo Basin such as observation points, GIS data, etc. are listed in this appendix.

Table B.1 Flow observation points in the Chikugo River

Observation Point	Administrator	Area (km^2)	Location
Senoshita	MOC	2295.0	Fukuoka, Kurume City
Arase	MOC	1443.0	Fukuoka, Ukiha County
Kobuchi	MOC	1120.8	Oita, Hita City
Katanose	MOC	1722.1	Fukuoka, Ukiha County
Esonoshuku	MOC	1566.0	Fukuoka, Asakura County
Ogase	MOC	530.5	Oita, Hita City
Ohira	MOC	533.7	Oita, Hita County
Yunoki	KEPC	27.8 (~1990) 28.3 (1991~)	Kumamoto, Kamoto County
Hazama	KEPC	32.3	Oita, Kusu County
Sakuradake	KEPC	456.0	Oita, Hita County
Saruoshi	KEPC	74.1 (~1967) 61.7 (1968~)	—
Mameikuno	KEPC	37.2	—
Nukumi	KEPC	492.0	—
Ichiino	KEPC	195.2 (~1960) 282.2 (~1962) 277.0 (1963~)	—
Oyama Reservoir	WRDPC	33.6	Oita, Hita County
Bunda	MOC	546.0	Kumamoto, Kamoto County
Yamaga	MOC	572.3	Kumamoto, Yamaga City
Furukawa	KEPC	(91.6)	Data of Tatsumon
Kamihanjaku	MOC	22.3	Kumamoto, Kikuchi City

MOC: Ministry Of Construction (Present: Ministry of Land, Infrastructure and Transport (MLIT))
KEPC: Kyushu Electric Power Co., Inc.
WRDPC: Water Resources Development Company
Fukuoka : Fukuoka Prefecture
Oita = Oita Prefecture
Kumamoto = Kumamoto Prefecture

Table B.2 Reservoirs and electric power plants in the Chikugo Basin

Infrastructure		Authority	Area (km^2)	Location	Memo
Reservoirs	Matsubara	MOC	491.0	Oita, Hita County	
	Shimouke	MOC	185.0	Oita, Hita County	
	Egawa	WRMPC	30.0	Fukuoka, Amagi City	
	Terauchi	WRMPC	51.0	Fukuoka, Amagi City	
	Yamagami	Fukuoka Prefecture	9.1	Fukuoka, Chikushino City	
	Gosho	MOA	42.0	Fukuoka, Ukiha County	
	Yoake	KEPC	1440.0	Oita, Hita City	Intake max. 80.0 m^3/s
	Hyugami	Fukuoka Prefecture	84.3	Fukuoka, Yame County	
Electric power plants	Yanagimata	KEPC	—	Fukuoka, Hita County	Max. 68.0 m^3/s
	Koshio	KEPC	—	Fukuoka, Ukiha County	Max. 0.83 m^3/s
	Onagohata	KEPC	—	Oita, Hita County	Max. 36.7 m^3/s
	Miyoshi	KEPC	—	Oita, Hita County	Max. 48.97 m^3/s

MOC: Ministry of Construction (Present: Ministry of Land, Infrastructure and Transport (MLIT))
WRDPC: Water Resources Public Company
MOA: Ministry of Agriculture (Present: Ministry of Agriculture, Forest and Fisheries (MAFF))
KEPC: Kyushu Electric Power Co., Inc.
Fukuoka: Fukuoka Prefecture
Oita: Oita Prefecture

Table B.3 Intake rate for water supply in the Chikugo Basin

Intake point	River	Service area	Reservoir	Intake quantity (m^3/s)	
				Summer	Winter
Meotoishi	Koishiwara	Amagi City	Egawa	0.256	
		Fukuoka City	Egawa	1.075	
Yamagami	Homan	Yamagami	Yamagami	0.290	
Chikugo Barrage	Chikugo	Eastern Saga	Egawa, Terauchi, Gosho	1.124	1.124
		Kenminamikouiki		1.086	1.055
		Fukuoka Area*		2.192	2.064
Kyomachi	Chikugo	Hita City	Matsubara	0.100	

* Including Kiyama Town in Saga Prefecture

Table B.4 Land use data of the Chikugo Basin

Water quality observatory	Average flow rate (m^3/s)	Water quality* (mg/l)			Population (capita)	Land use (ha)											
		COD	T-N	T-P		Paddy field	Field	Orchard	Other trees	Forest	Wasteland	Building	Land for main traffic	Other use	Inner drainage pond	Beach	Total
1. Beniya	-	-	-	-	104,024	2,985	42	30	48	7	1	1,432	17	100	290	0	4,952
2. Wakatsu	-	7.0	2.12	0.20	84,858	9,586	308	984	21	6,872	657	2,490	135	328	656	0	22,037
3. Rokkorobashi	-	4.1	1.56	0.11	327,118	9,638	596	1,964	696	4,381	214	3,893	125	1,021	924	0	23,451
4. Senoshita	74.53	3.2	1.21	0.08	40,973	789	53	113	1	526	30	485	43	173	151	0	2,365
5. Shimono	12.74	3.9	1.60	0.13	191,956	5,588	501	270	285	2,672	87	2,411	301	725	539	0	13,379
6. Sakaihigashibashi	4.43	5.1	1.97	0.15	107,742	5,706	485	277	161	8,930	618	1,925	271	717	447	0	19,538
7. Kumashirobashi	60.80	2.4	1.04	0.06	85,951	5,148	273	1,668	1,205	10,276	129	1,704	45	217	725	0	21,389
8. Katanose	46.99	2.4	1.05	0.05	67,974	6,260	364	2,317	630	14,574	236	1,627	61	205	1,135	1	27,409
9. Arase	56.26	2.2	0.77	0.05	5,727	744	78	329	17	7,441	37	161	27	71	122	0	9,027
10. Kawashita	29.33	2.4	0.91	0.07	33,409	1,720	542	253	73	14,933	208	778	39	152	227	0	18,924
11. Shimauchi	-	2.0	0.62	0.04	37,807	1,206	345	288	70	16,027	416	468	13	90	346	0	19,269
12. Mikumaoohashi	31.05	2.2	0.69	0.04	-	-	-	-	-	-	-	-	-	-	-	-	0
13. Yuzuki	25.42	1.6	0.46	0.03	14,352	686	250	35	14	19,749	647	222	3	19	581	0	22,206
14. Tsuetate	14.98	2.0	0.61	0.05	5,078	2,236	380	2	39	16,397	9,113	402	6	56	164	0	28,795
15. Amagase	18.15	2.1	0.62	0.05	33,720	4,868	1273	105	78	28,337	10,093	502	65	247	417	0	45,986
Total	-	-	-	-	1,140,689	57,159	5,490	8,635	3,340	151,122	22,487	18,499	1,149	4,121	6,724	1	278,727

* Average concentration of 12 years (1986-1997) (MLIT 1998)

Source: Population: Grid Square Statistics of 1990 Population Census of Japan (Statistics Bureau 1990)

Land use: National Land Information 1990 (MLIT 1990)

Table B.5 Land use data of the Chikugo Basin (accumulated from upstream)

Accumulation from upper area	Water quality* (mg/l)			Population (capita)	Land use (ha)											
	COD	T-N	T-P		Paddy field	Field	Orchard	Other trees	Forest	Wasteland	Building	Land for main traffic	Other usage	Inner drainage pond	Beach	Total
Σ1 (1+2+3+4+5+6+7+8+9 +10+11+13+14+15)	-	-	-	1,140,689	57,159	5,490	8,635	3,340	151,122	22,487	18,499	1,149	4,121	6,724	1	278,727
Σ2 (2+3+4+5+6+7+8+9+10 +11+13+14+15)	7.0	2.12	0.20	1,036,665	54,174	5,448	8,605	3,291	151,115	22,486	17,067	1,133	4,022	6,434	1	273,775
Σ3 (3+4+5+6+7+8+9+10+11 +13+14+15)	4.1	1.56	0.11	951,807	44,587	5,140	7,621	3,271	144,243	21,829	14,577	998	3,694	5,778	1	251,738
Σ4 (4+5+6+7+8+9+10+11+13 +14+15)	3.2	1.21	0.08	624,689	34,950	4,544	5,657	2,574	139,862	21,615	10,684	873	2,673	4,854	1	228,287
Σ7 (7+8+9+10+11+13+14+15)	2.4	1.04	0.06	284,018	22,866	3,505	4,996	2,127	127,734	20,880	5,863	257	1,057	3,717	1	193,004
Σ8 (8+9+10+11+13+14+15)	2.4	1.05	0.05	198,067	17,719	3,232	3,328	922	117,458	20,750	4,159	213	841	2,992	1	171,616
Σ9 (9+10+11+13+14+15)	2.2	0.77	0.05	130,093	11,459	2,868	1,011	292	102,885	20,515	2,532	152	636	1,857	0	144,207
Σ10 (10+11+13+14+15)	2.4	0.91	0.07	124,366	10,715	2,790	682	275	95,444	20,477	2,372	125	564	1,735	0	135,180
Σ11 (11+13+14+15)	2.0	0.62	0.04	90,957	8,995	2,248	429	202	80,511	20,269	1,594	87	413	1,508	0	116,255
Σ13 (13+14)	1.6	0.46	0.03	19,430	2,921	630	37	53	36,147	9,760	623	8	76	745	0	51,000

* Average concentration of 12 years at downstream of each part (1986-1997) (MLIT 1998)

Source: Population: Grid Square Statistics of 1990 Population Census of Japan (Statistics Bureau 1990)

Land use: National Land Information 1990 (MLIT 1990)

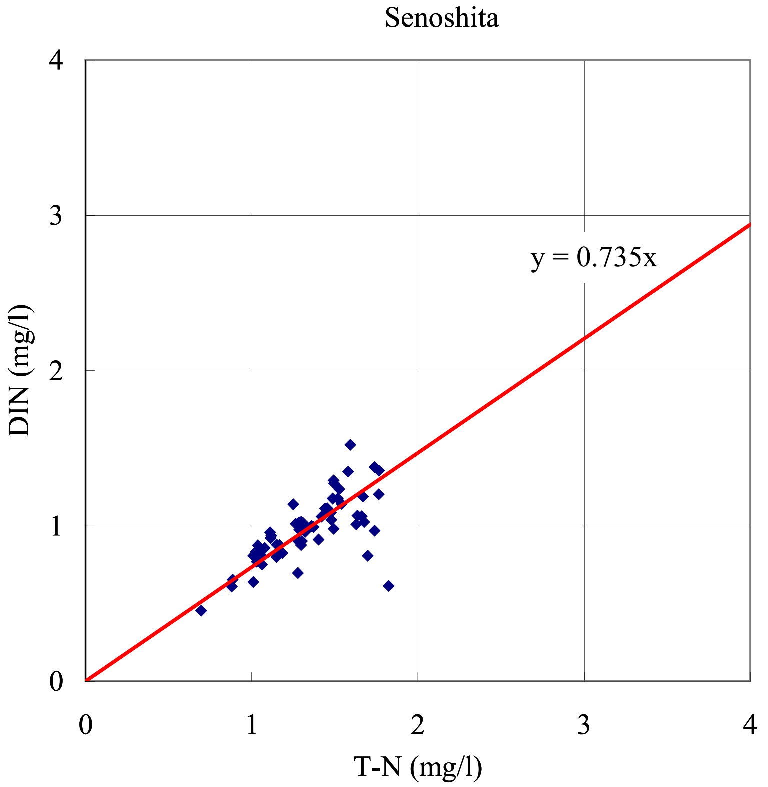
Table B.6 Land use data of three parts of the Chikugo Basin

Summation in each part	Water quality* (mg/l)			Population (capita)	Land use (ha)											
	COD	T-N	T-P		Paddy field	Field	Orchard	Other trees	Forest	Wasteland	Building	Land for main traffic	Other usage	Inner drainage pond	Beach	Total
The upper part Σ1 (1+2+3)	-	-	-	516,000	22,209	946	2,979	765	11,259	872	7,816	277	1,448	1,870	0	50,440
The middle part Σ2 (4+5+6+7+8)	3.2	1.21	0.08	494,596	23,490	1,676	4,645	2,282	36,978	1,100	8,152	721	2,038	2,997	1	84,080
The lower part Σ3 (9+10+11+13+14+15)	2.2	0.77	0.05	130,093	11,459	2,868	1,011	292	102,885	20,515	2,532	152	636	1,857	0	144,207
Total	-	-	-	1,140,689	57,159	5,490	8,635	3,340	51,122	2,487	18,499	1,149	4,121	6,724	1	78,727

* Average concentration of 12 years at downstream of each part (1986-1997) (MLIT 1998)

Source: Population: Grid Square Statistics of 1990 Population Census of Japan (Statistics Bureau 1990)

Land use: National Land Information 1990 (MLIT 1990)



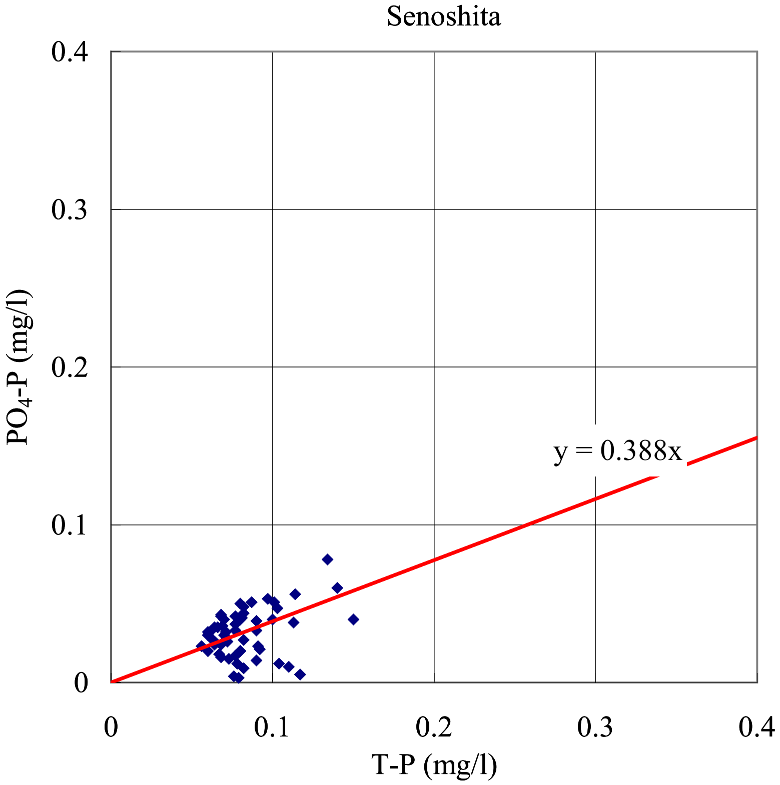


Figure B.1 The relationship between DIN and T-N and the relationship between PO_4-P and T-P at Senoshita

Source: observed data in 1989-1998 (Kyushu Regional Development Bureau, MLIT 2001)

APPENDIX C

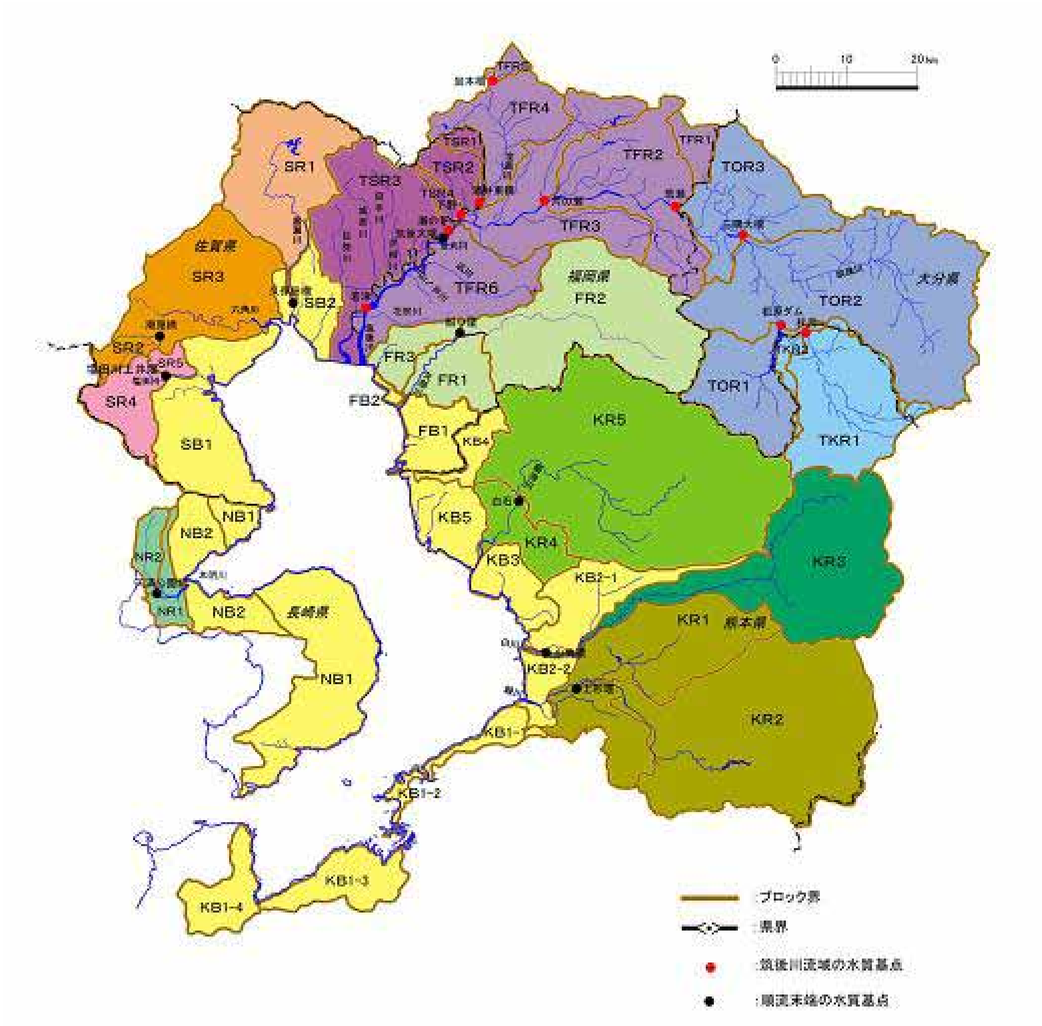
DATA OF THE ARIAKE SEA

Details of watershed of the Ariake Sea such as basin area, information of inflowing rivers are provided in this appendix.

Table C.1 Observation points for flow rate and water quality at downstream of inflowing rivers in watershed of the Ariake Sea

River	Observation point	Catchment area of observation point (km^2)	Total basin area (km^2)
Midori	Jonan	680.9	1100
Shira	Yotsugibashi	477	480
Kikuchi	Tamana	906	996
Yabe	Funagoya	460	620
Chikugo	Senoshita	2315	2860
Kase	Kawakami	225.5	368
Rokkaku	Myokenbashi	95	341
Honmyo	Urayama	35.8	87

Figure C.1 Watershed of the Ariake Sea



Block		Area (km^2)
Rokkaku Basin	Upper part (SR-2)	32.30
	Estuary (SR-3))	308.70
Kase Basin	Upper part (SR-1)	276.36
Chikugo Basin	Upper part (TFR-1, TFR-2, TFR-3, TFR-4, TFP-5, TSR-1, TSR-2, TSR-4, TKR-1, TKR-2, TOR-1, TOR-2, TOR-3)	2,316.63
	Estuary (TFR-6, TSR-3)	537.04
Yabe Basin	Upper part (FR-2)	450.88
	Estuary (FR-1, FR-3)	166.92
Kikuchi Basin	Upper part (KR-5)	897.77
	Esturary (KR-4)	102.46
Shira Basin	Upper part (KR-3)	480.00
Midori Basin	Upper part (KR-2)	680.90
	Estuary (KR-1)	378.80
Honmyo Basin	Upper part (NR-2)	37.95
	Estuary (NR-1)	48.70
	Shiota Basin-Upper part (SR-4)	101.82
	Shiota Basin- Estuary	18.98
Direct discharge part	FB-1	84.62
	FB-2	11.79
	SB-2	91.64
	SB-1	267.41
	KB-1-1	50
	KB-1-2	101.86
	KB-1-3	79.22
	KB-1-4	141.7
	KB-2-1	63.59
	KB-2-2	41.38
	KB-3	17
	KB-4	111.71
	KB-5	93.3
	NB-1	335.13
	NB-2	128.33
Total		8,454.89

Loadings from land area

L-Q equation

$$L = a \cdot Q^b$$

L: loading (g/s), Q: flow rate (m^3/s), a, b: constant

Table C.2 L-Q equation of eight rivers that flows into the Ariake Sea

River	COD		NH_4-N		NO_2-N		NO_3-N		PO_4-P		SS	
	a	b	a	b	a	b	a	b	a	b	a	b
Midori	1.0	1.211	0.03	1.123	0.004	1.194	0.5	1.0	0.004	1.322	1.19	1.613
Shira	2.228	1.026	0.02	1.477	0.035	0.987	0.552	1.171	0.036	1.107	5.742	1.271
Kikuchi	2.0	1.106	0.025	1.236	0.015	1.085	0.8	1.179	0.035	1.228	3.583	1.24
Yabe	1.5	1.151	0.05	1.151	0.015	0.867	1.0	1.153	0.007	1.427	1.785	1.389
Chikugo	3.002	1.0	0.04	1.194	0.009	1.174	0.45	1.152	0.0065	1.344	0.136	1.94
Kase	1.2	1.179	0.04	1.199	0.0012	1.81	0.3	1.151	0.012	1.261	1.218	1.715
Rokkaku	2.8	1.126	0.15	1.174	0.015	1.125	0.6	1.204	0.02	1.239	5.952	1.206
Honmyo	5.787	1.0			0.737*	1.0*			0.179**	1.0**	4.167	1.946

* Calibrated from L-Q equation of T-N (DIN: T-N = 0.6)

** Calibrated from L-Q equation of T-P (PO_4-P: T-P = 0.9)

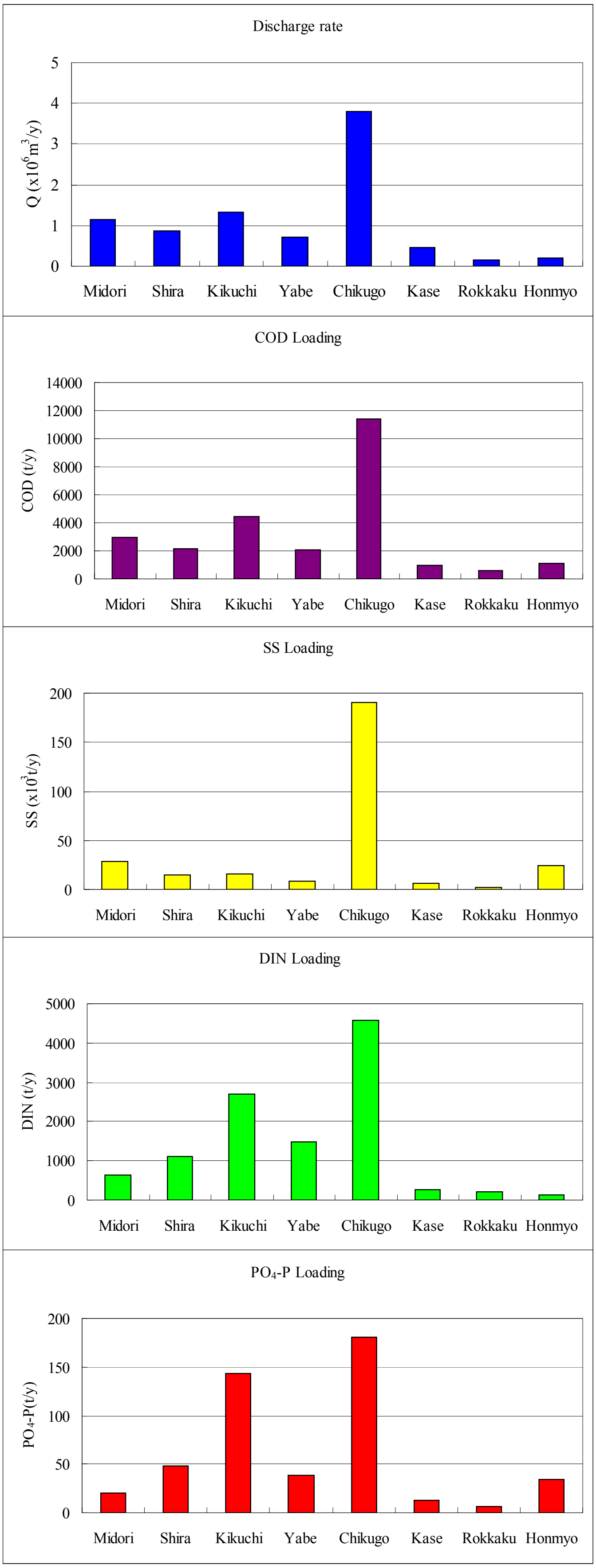
Source: observed data in 1978-1998 (Kyushu Regional Development Bureau, MLIT 2001)

Table C.3 Unit loading for directly discharge from the coastal area

	Unit loading (t/ha-y)
COD	900.0
DIN	460.0
PO_4-P	35.0

Source: Master plans for implementation of wastewater treatment in watershed of the Ariake Sea (according to total inflow loadings of the Ariake Sea in 1995)

Notes: Based on characteristics of land use, most of loadings from this area are domestic wastewater. Since there is no evaluation of SS loading carried out, SS loading of this area is calibrated from the ratio of catchment area to basin area of observation point.


Discharge rate

COD Loading

SS Loading

DIN Loading

PO$_4$-P Loading

Figure C.2 Annual loadings of eight rivers obtained from L-Q equation

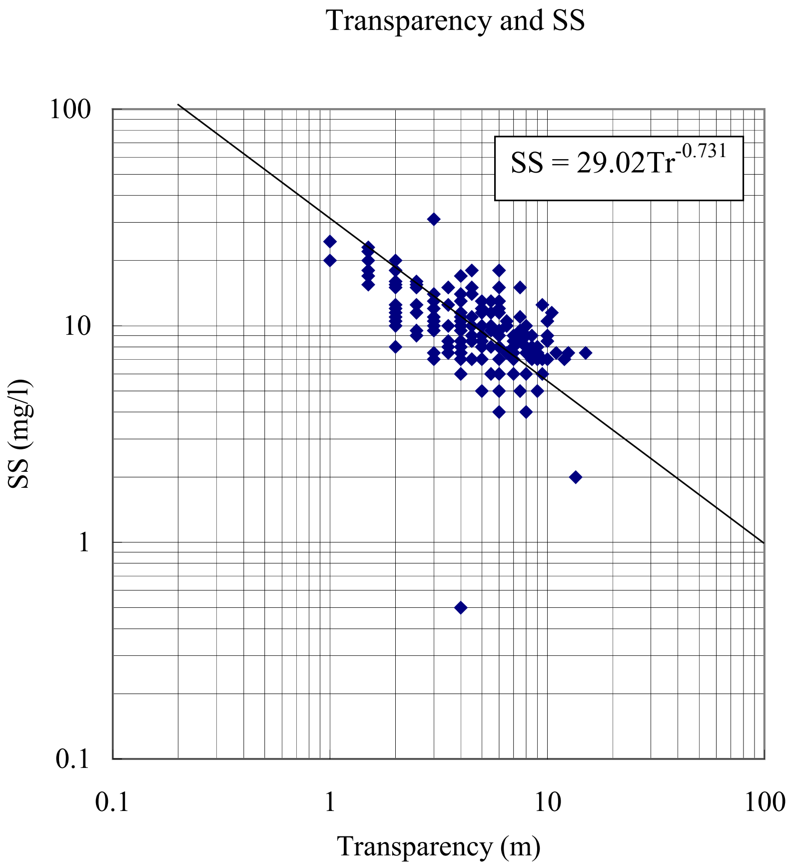


Figure C.3 Relationship of transparency and suspended solids in the Ariake Sea (Kumamoto Prefecture)

Source: Observed data of transparency and SS in 1995-1999 (Kumamoto Prefectural Fisheries Research Center 2002)

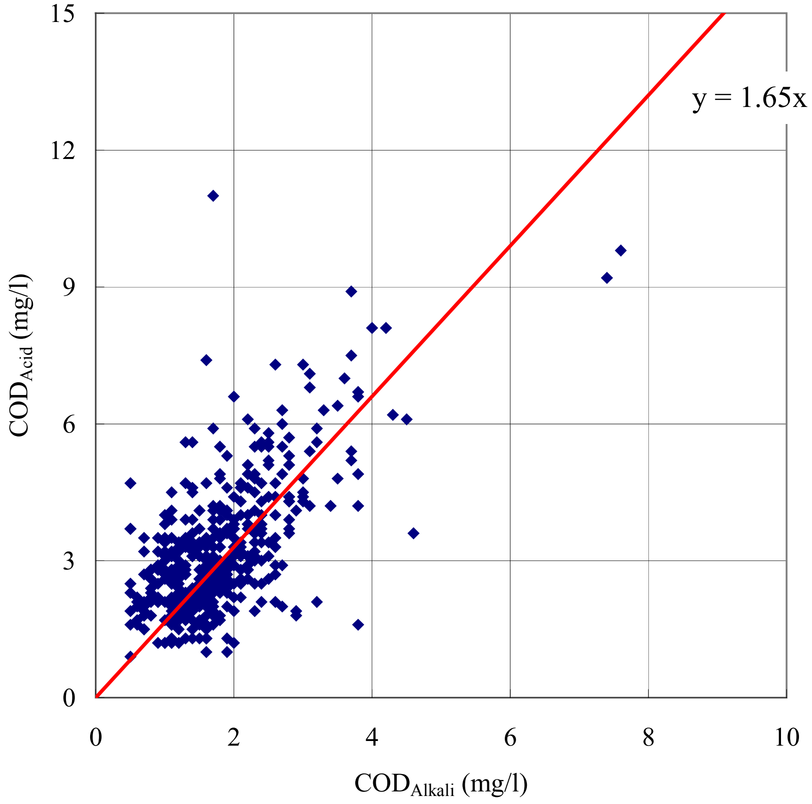


Figure C.4 Relationship between COD measured by acid process and alkali process

Source: Observed data in 1985-1993 (Saga Prefectural Ariake Research and Development Center 2002)

APPENDIX D

DETAILS OF THE INTEGRATED MODEL AND SIMULATED RESULTS

Table D.1 Relationship between flow rate and water depth (Q-H curve) in the Chikugo River

Arase	Esonoshuku	Katanose	Senoshita
$0 \le Q < 40$ $H = \sqrt{\frac{Q}{45.28}} - 0.17$ $40 \le Q < 966.8$ $H = \sqrt{\frac{Q}{89.32}} + 0.1$ $Q \ge 966.8$ $H = \sqrt{\frac{Q}{114.19}} + 0.48$	$0 \le Q < 33.41$ $H = \sqrt{\frac{Q}{56.35}} - 2.64$ $33.41 \le Q < 41.53$ $H = \sqrt{\frac{Q}{127.83}} - 2.38$ $41.53 \le Q < 239.93$ $H = \sqrt{\frac{Q}{131.65}} - 2.36$ $Q \ge 239.93$ $H = \sqrt{\frac{Q}{66.48}} - 2.6$	$0 \le Q < 33.57$ $H = \sqrt{\frac{Q}{31.04}} - 0.04$ $33.57 \le Q < 266.5$ $H = \sqrt{\frac{Q}{59.86}} + 0.29$ $266.5 \le Q < 1231.62$ $H = \sqrt{\frac{Q}{89}} + 0.63$ $Q \ge 1231.62$ $H = \sqrt{\frac{Q}{52.12}} - 0.51$	$0 \le Q < 42.76$ $H = 4.1$ $Q \ge 42.76$ $H = 4.9$

Source: MLIT (2000)

Table D.2 Relationship between water depth and flow cross-sectional area (H-A curve) in the Chikugo River

Arase	Esonoshuku	Katanose	Senoshita
$0 < H < 2.65$ $A = 133.67 + \frac{H - 0.5}{0.011}$ $H \ge 2.65$ $A = 329.12 + \frac{H - 2.65}{0.007}$	$H > 0$ $A = 60.15 + \frac{H + 2.01}{0.0063}$	$0 < H < 2.72$ $A = 87.09 + \frac{H - 0.69}{0.009}$ $2.72 \le H < 6.5$ $A = 306.42 + \frac{H - 2.72}{0.006}$ $H \ge 6.5$ $A = 904.09 + \frac{H - 6.5}{0.004}$	$1.45 < H < 7.5$ $A = 170(H - 1.45)$ $H \ge 2.65$ $A = 367(H - 7.5) + 1105$

Source: MLIT (2000)

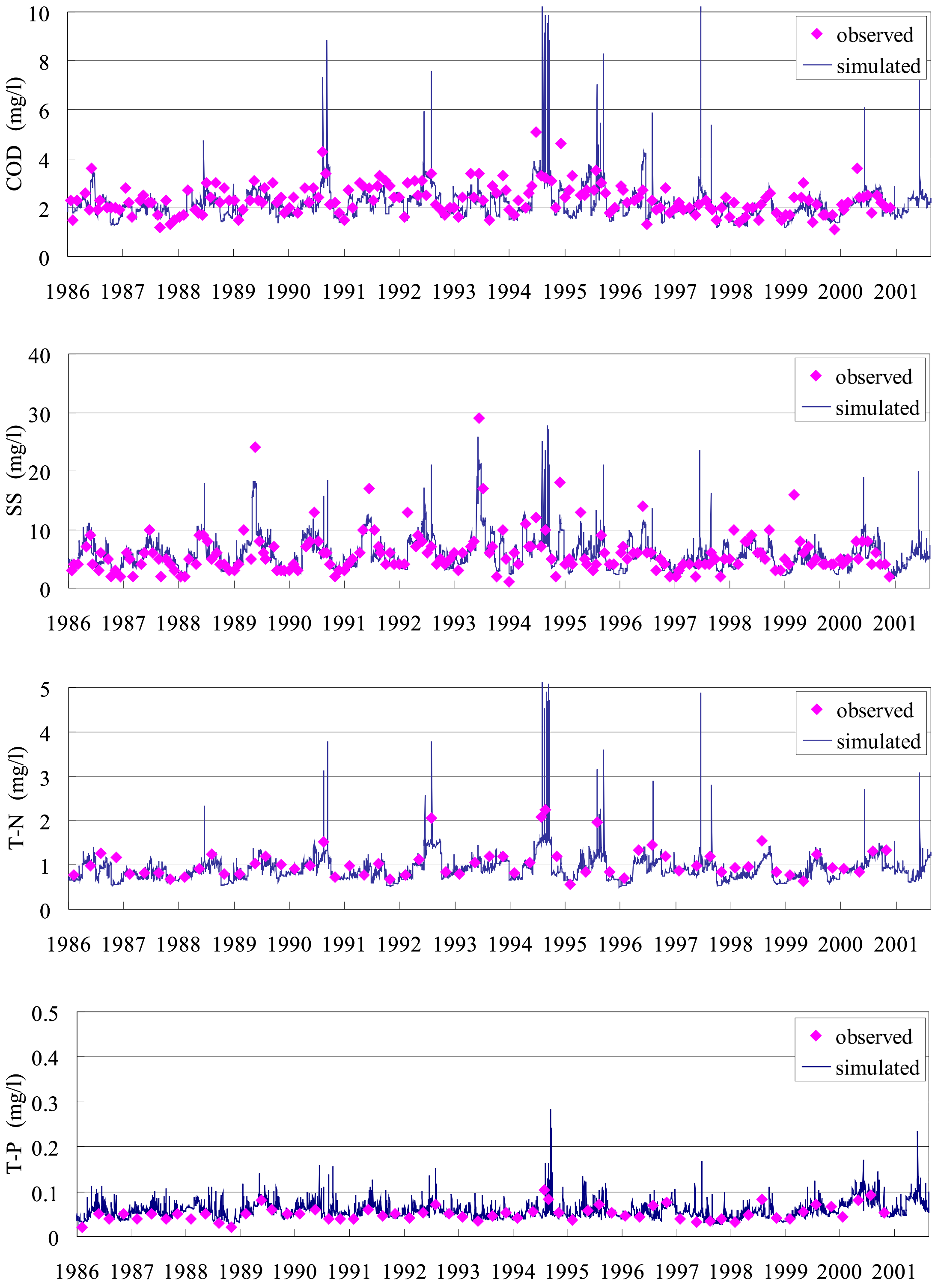


Figure D.1 Simulated water quality at Katanose

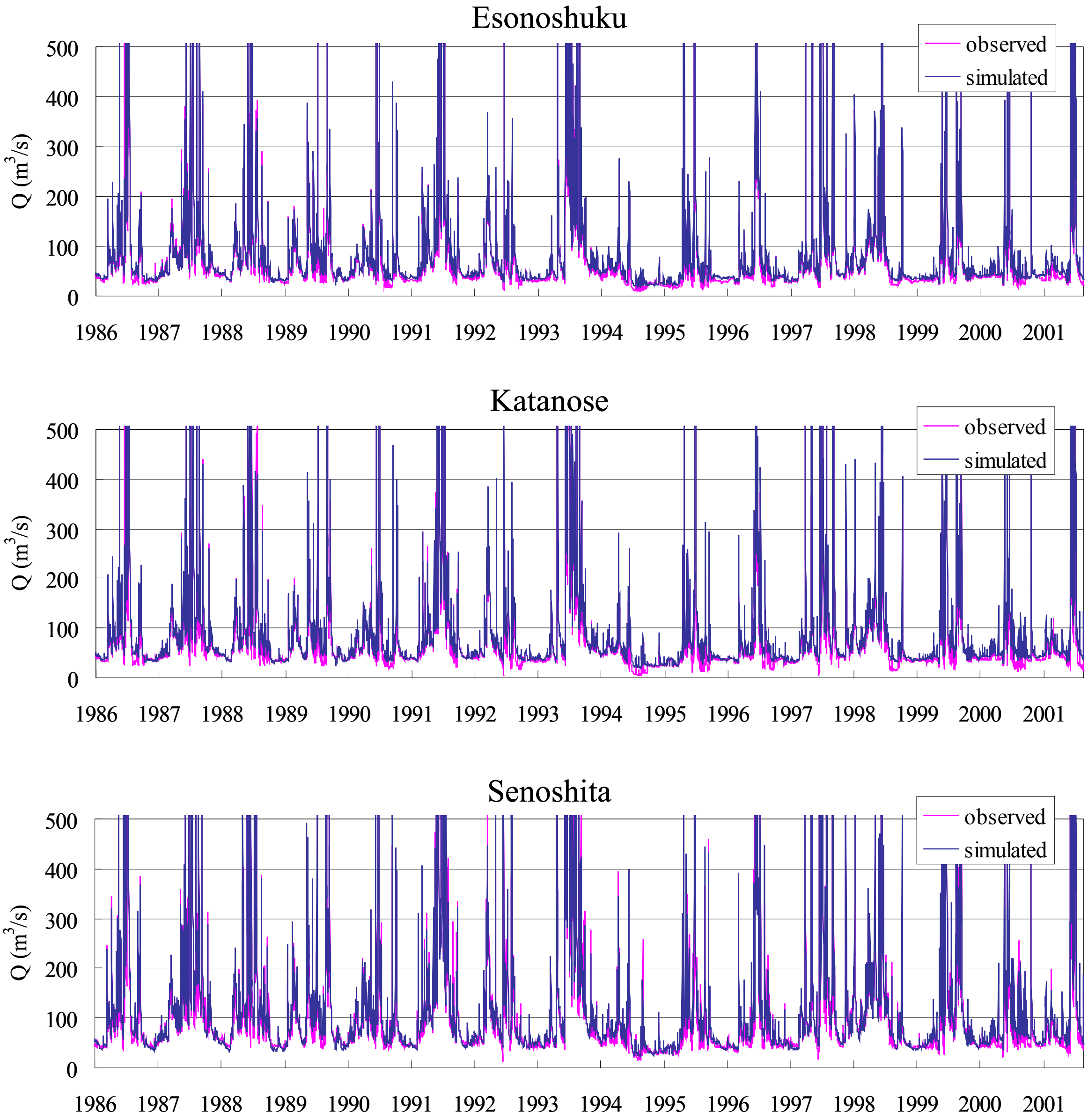


Figure D.2 Contribution of hydraulic structures to flow rate of the Chikugo River

Table D.3 Details of elements in the Ariake Sea (the finite-volume model)

Element	Area (km^2)	Inflow rivers
1	314.5	-
2	400.0	-
3	53.5	Midori, Shira
4	208.0	Kikuchi
5	125.25	-
6	17.75	Honmyo
7	175.75	Yabe
8	145.0	-
9	51.0	Chikugo
10	60.5	Kase, Rokkaku
11	43.25	-
Total	1594.5	

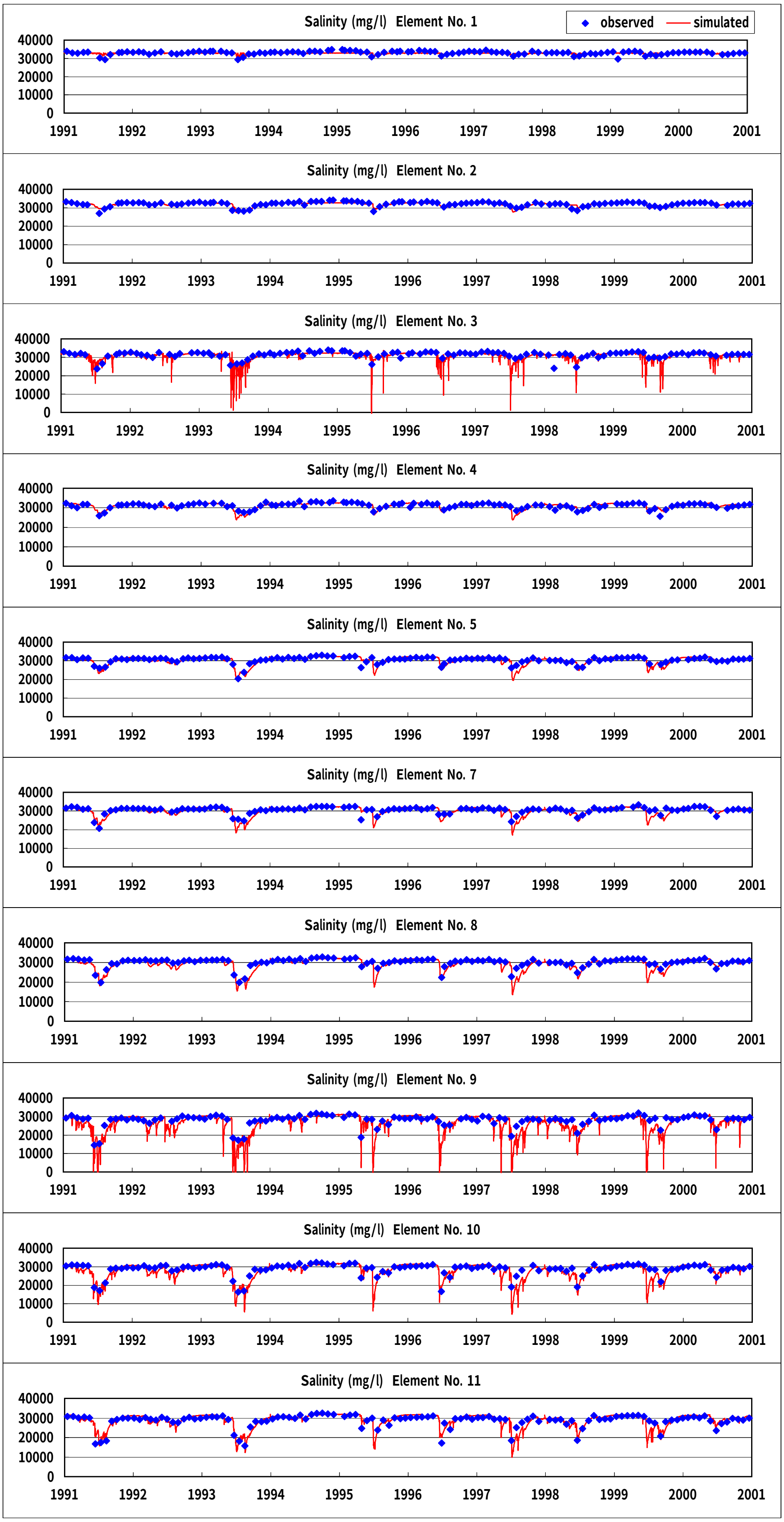


Figure D.3 Simulated results of the finite-volume model (Salinity)

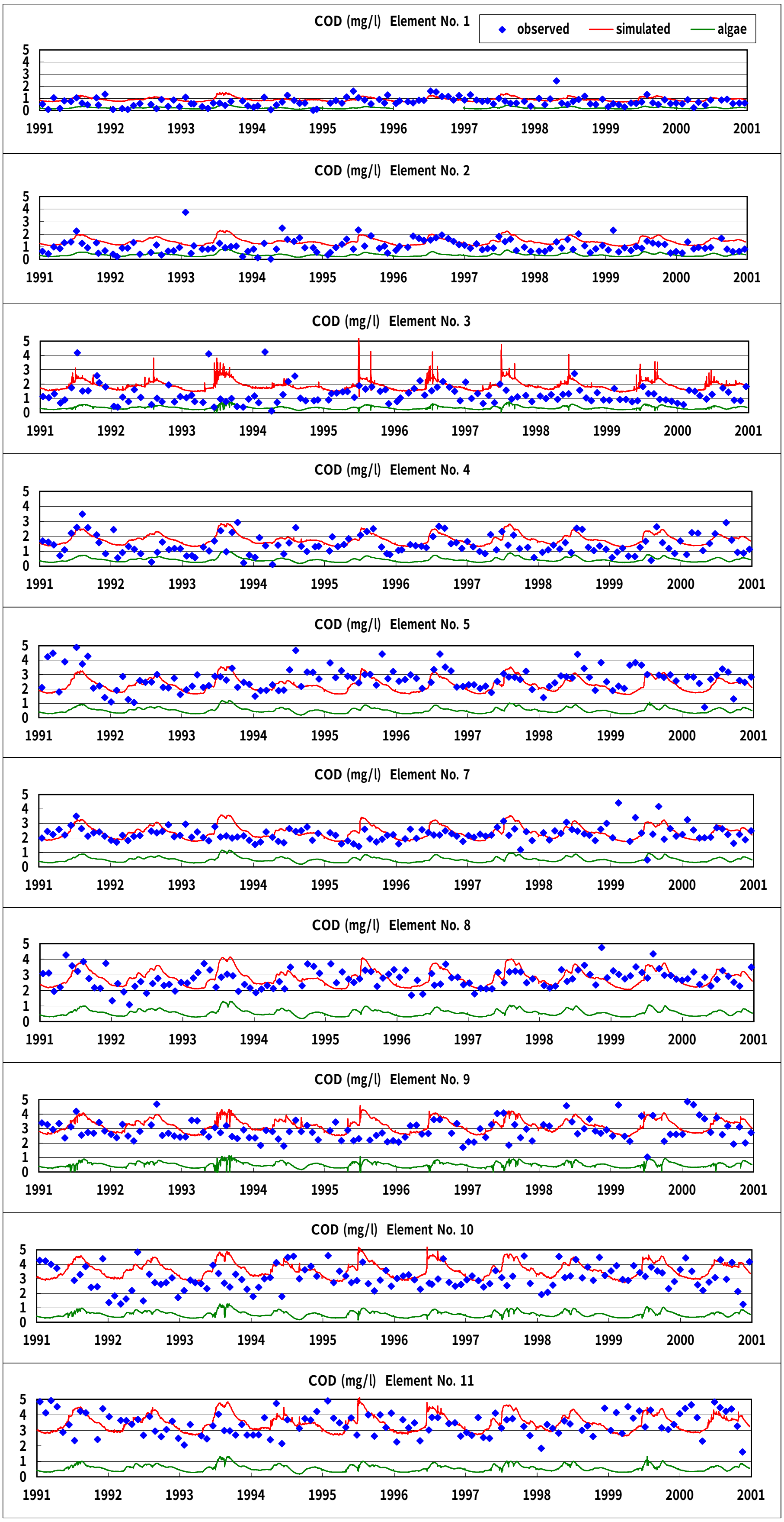


Figure D.4 Simulated results of the finite-volume model (COD)

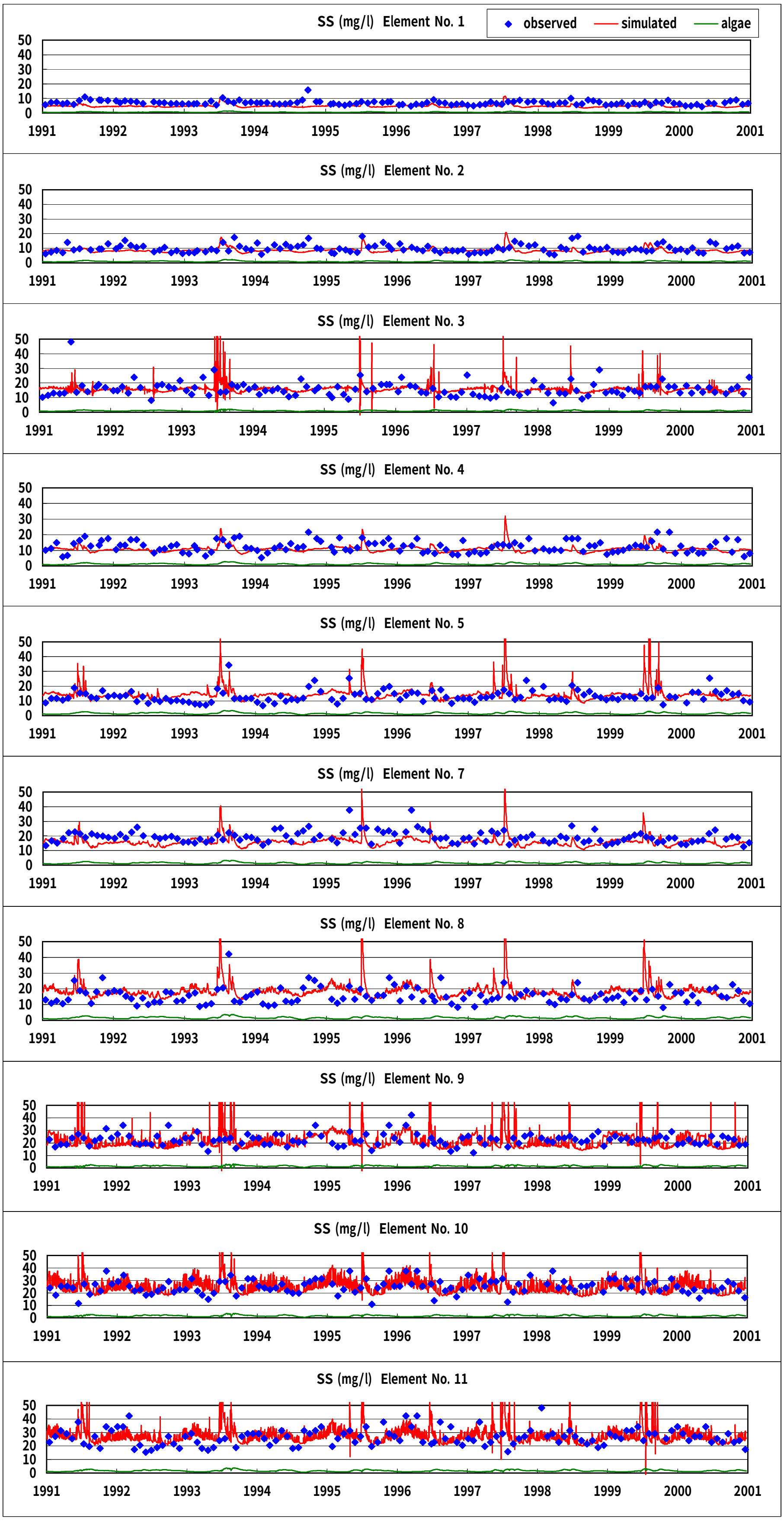


Figure D.5 Simulated results of the finite-volume model (SS)

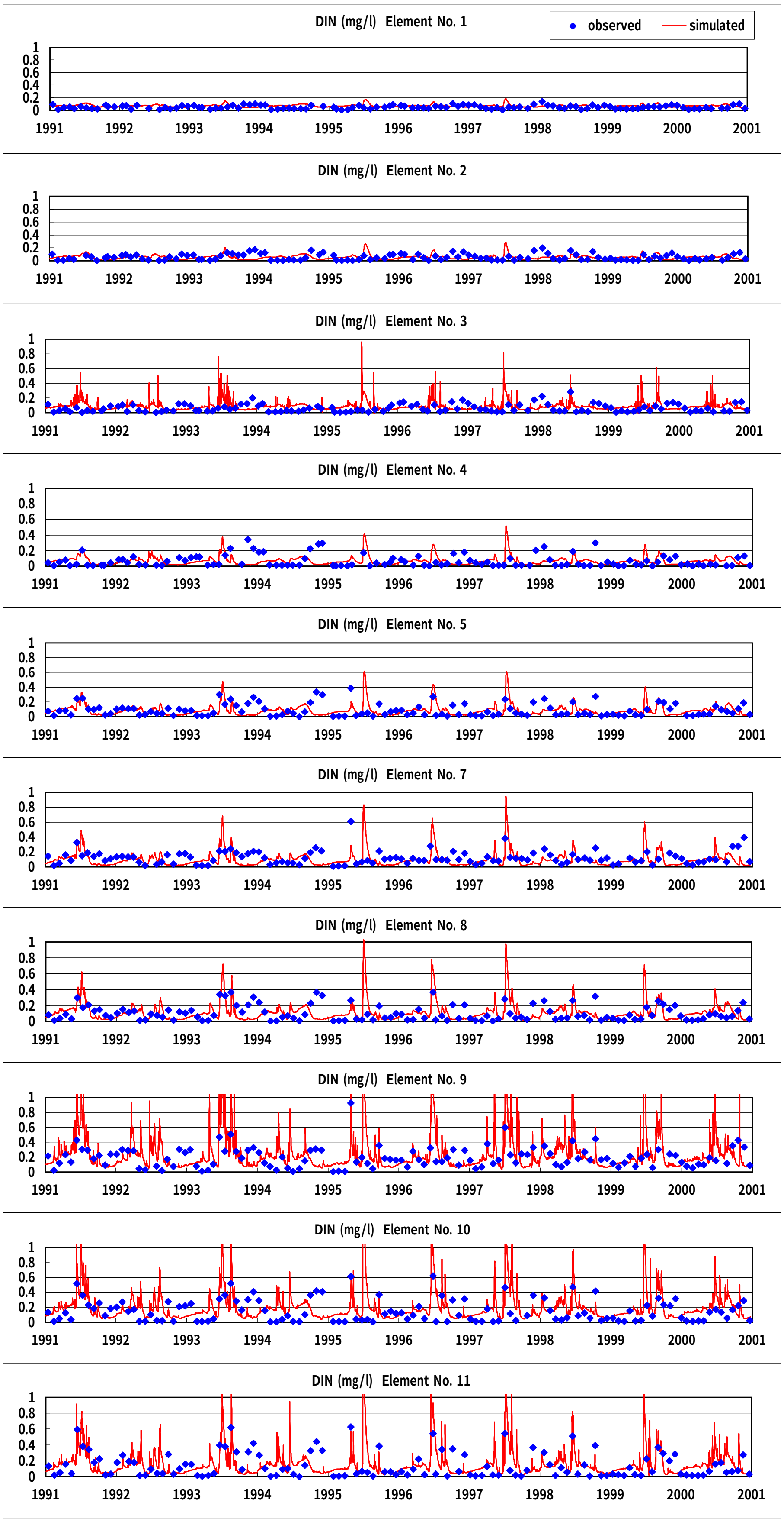


Figure D.6 Simulated results of the finite-volume model (DIN)

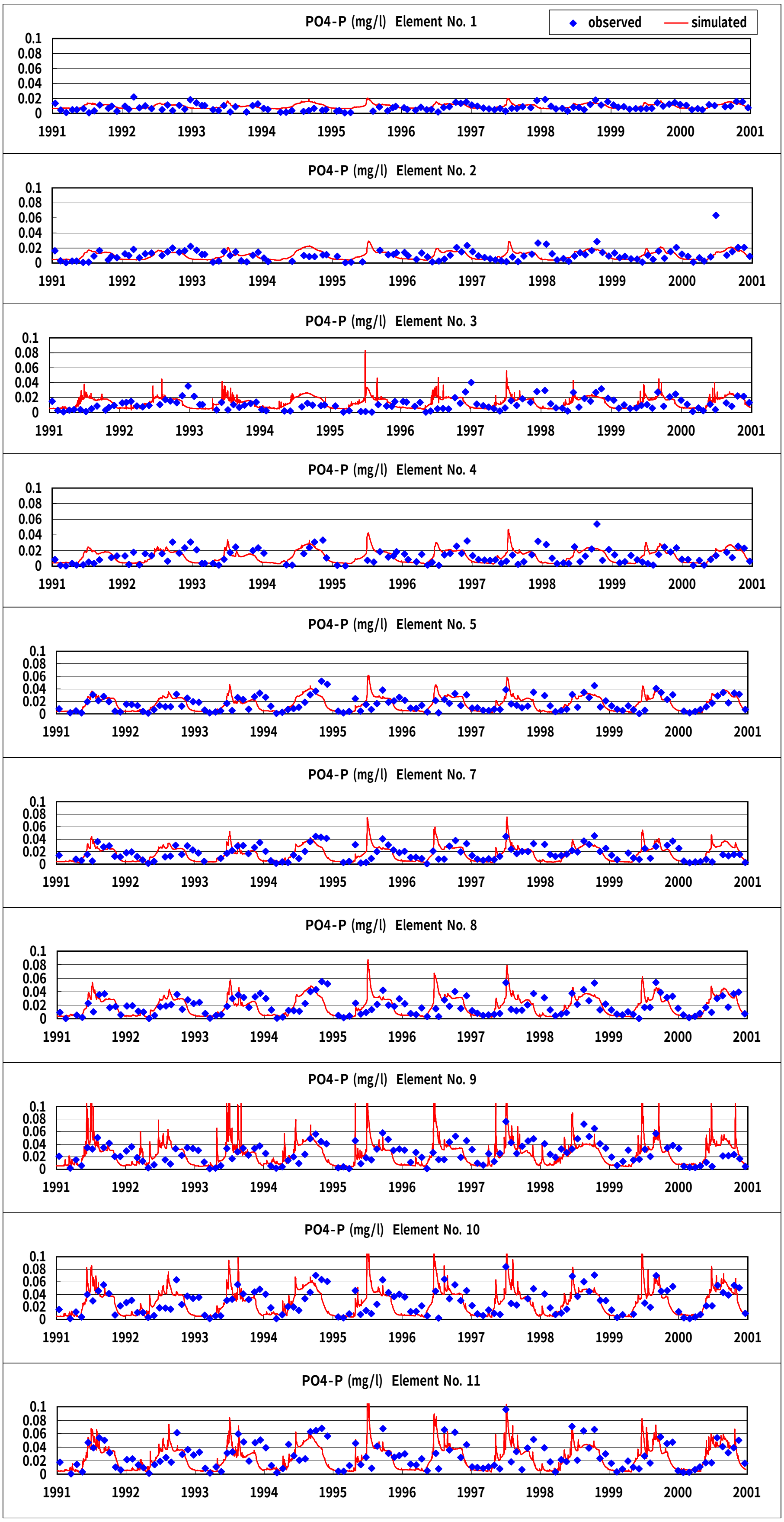


Figure D.7 Simulated results of the finite-volume model (PO_4-P)

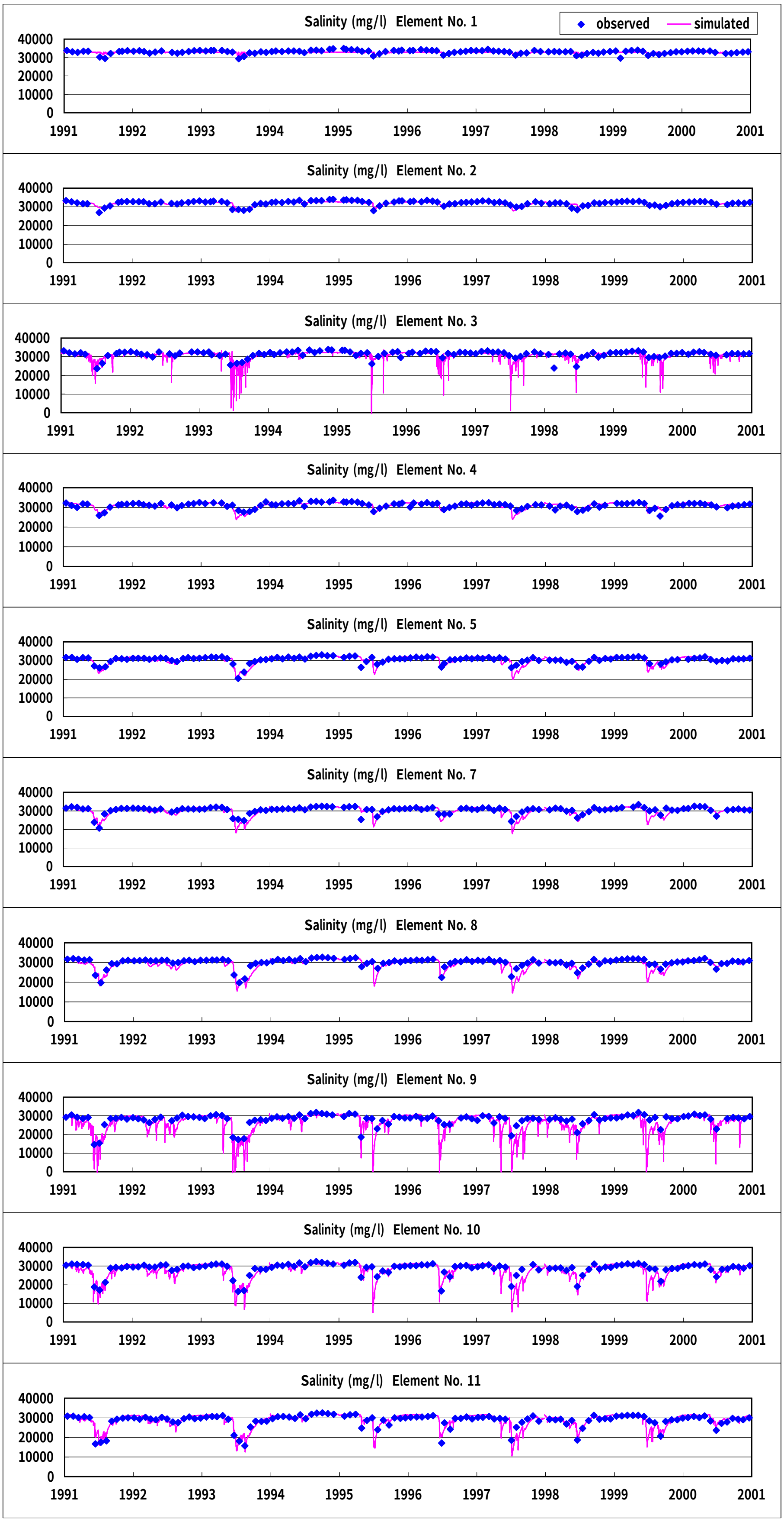


Figure D.8 Simulated results of the integrated model (Salinity)

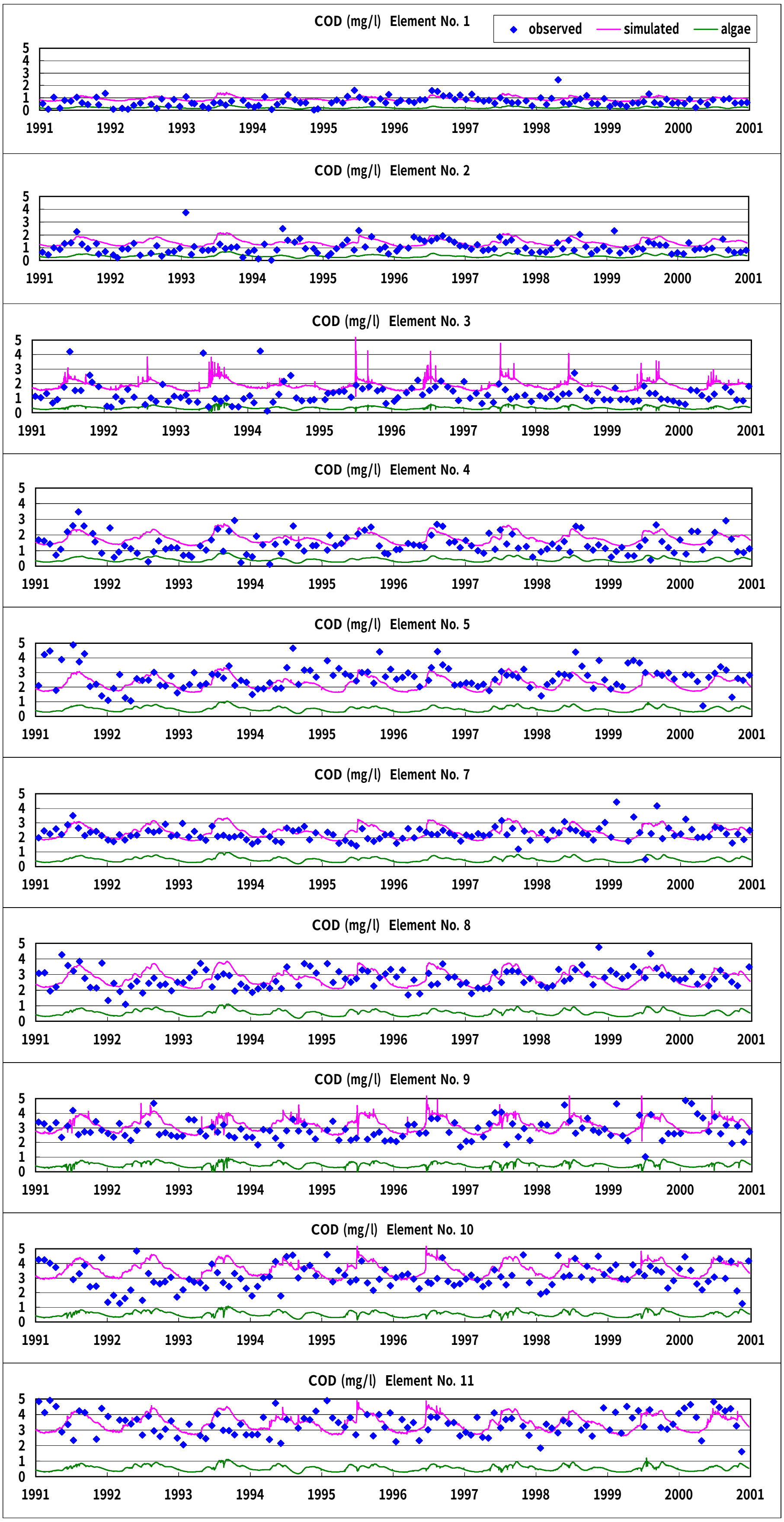


Figure D.9 Simulated results of the integrated model (COD)

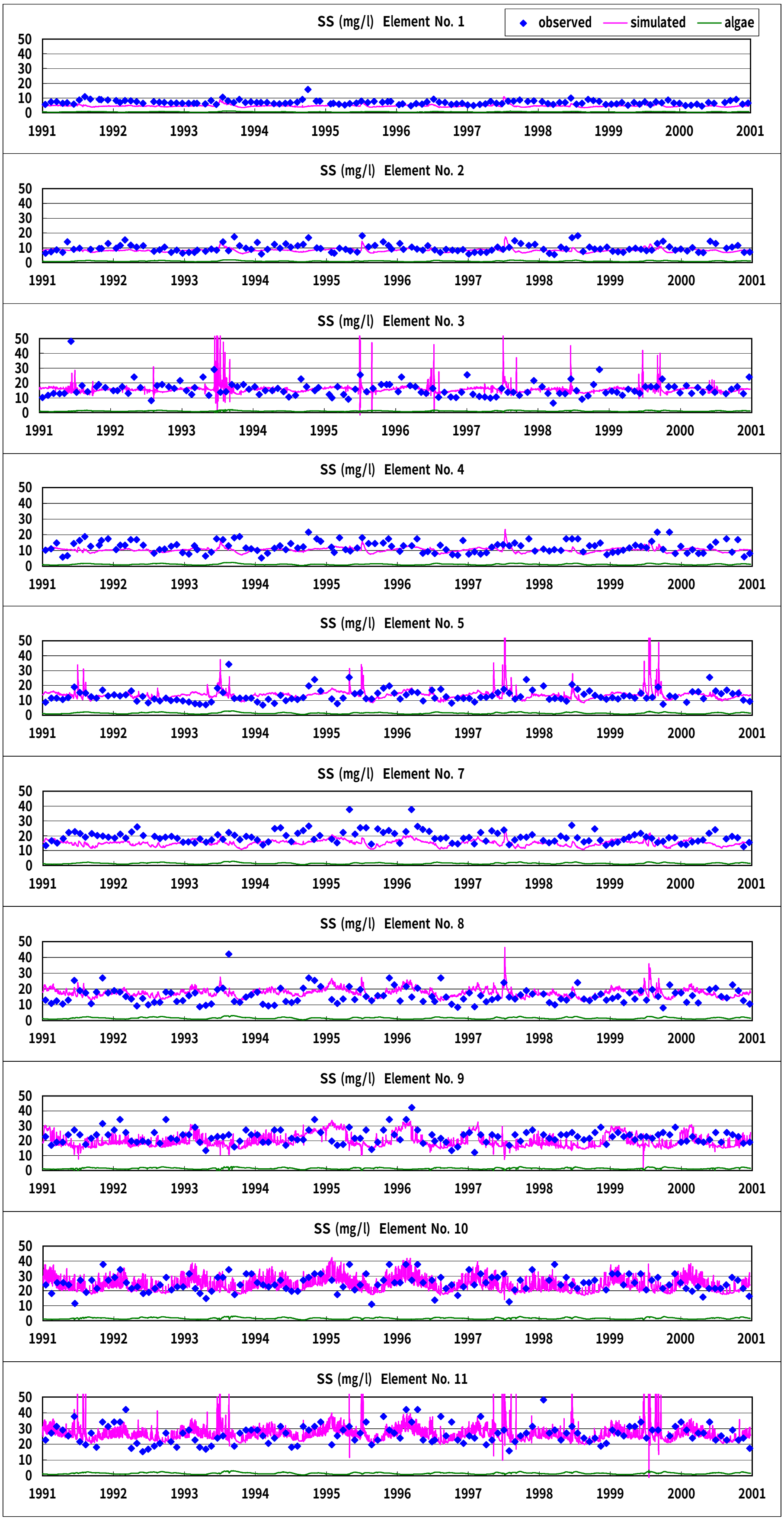


Figure D.10 Simulated results of the integrated model (SS)

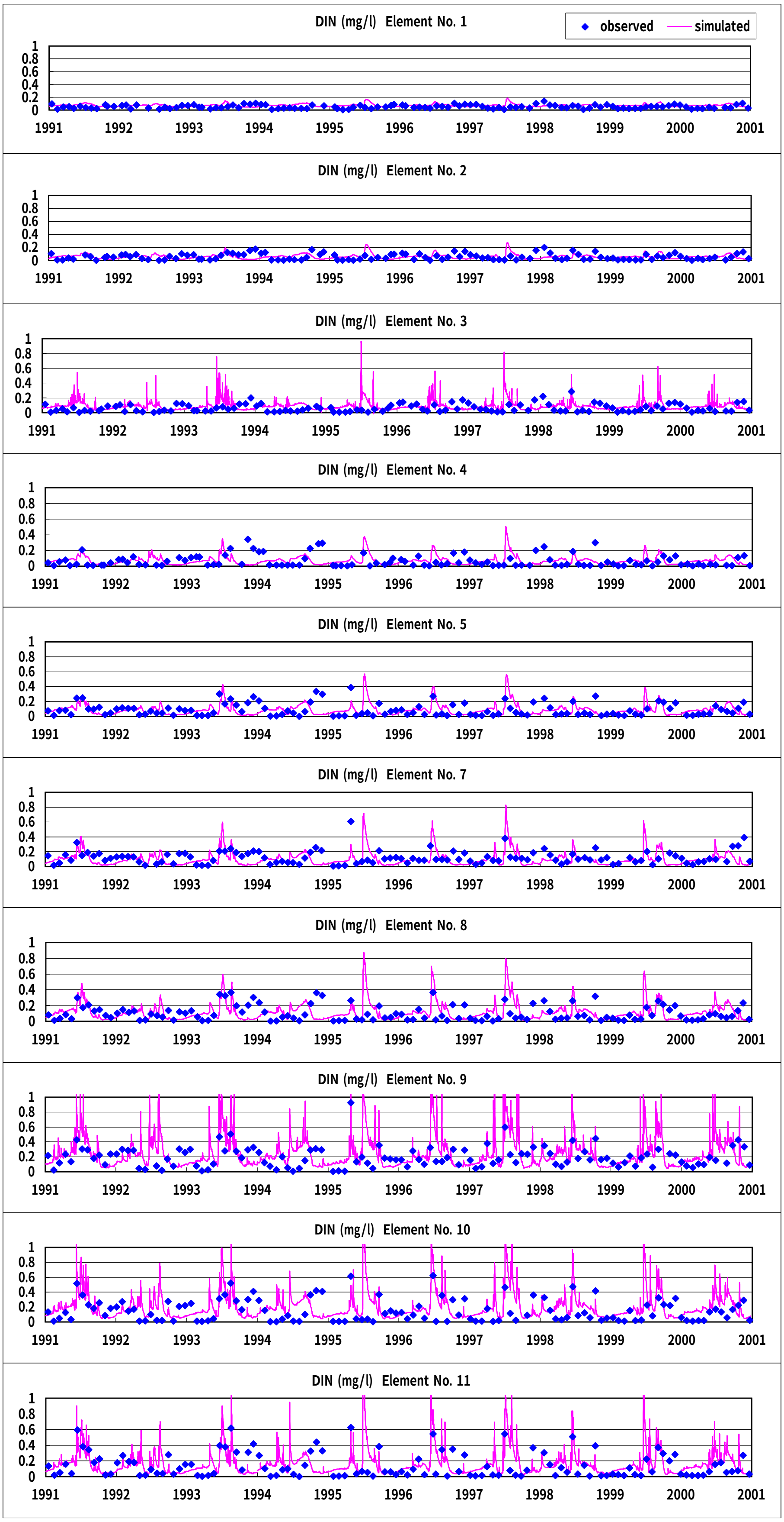


Figure D.11 Simulated results of the integrated model (DIN)

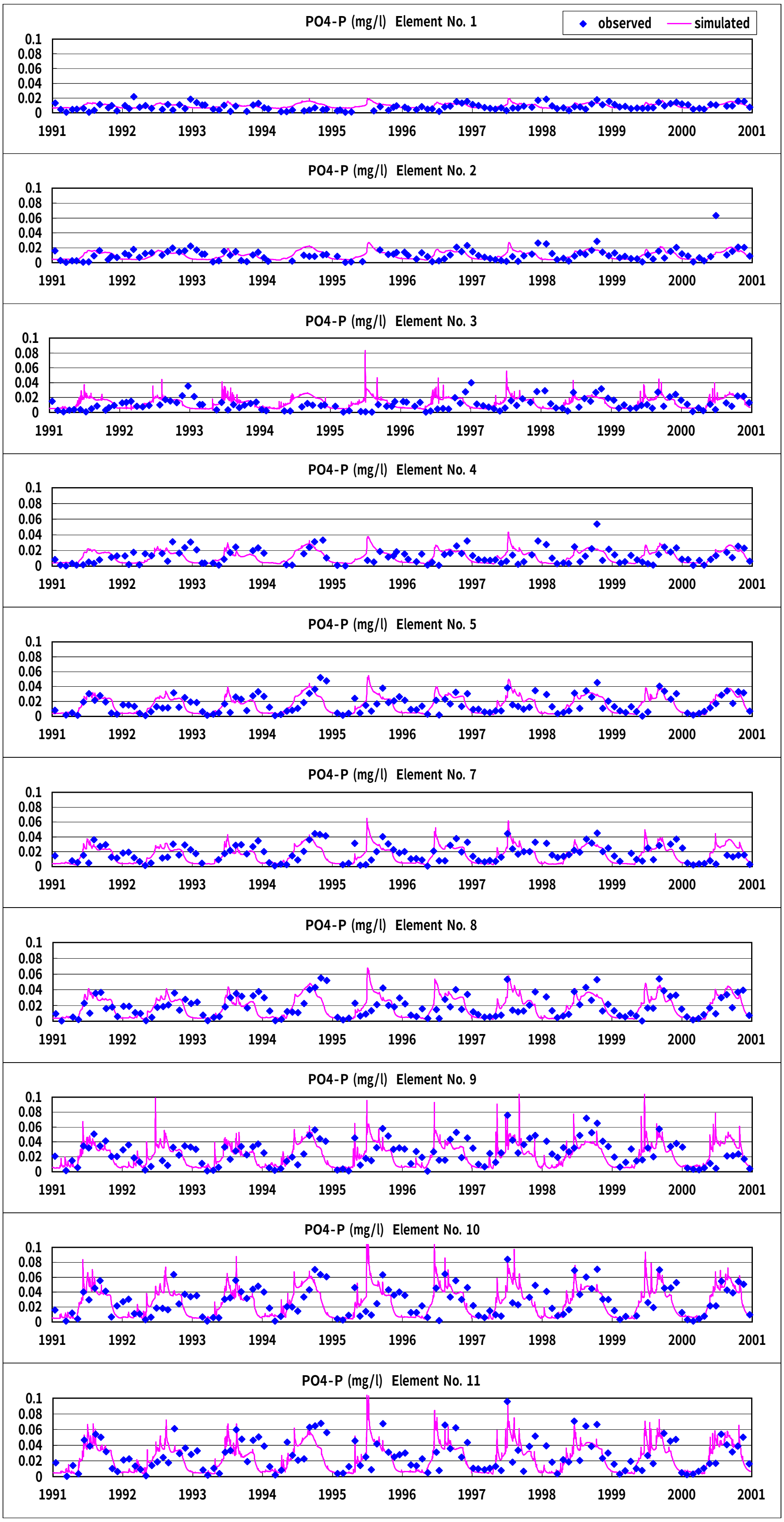


Figure D.12 Simulated results of the integrated model (PO_4-P)

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NOTATION

Dimensions are given in parenthesis after the description. Numbers in brackets after the dimension refer to equations in which symbols are first used or defined.

A = basin area (m^2), [4.2]
A = area of element (m^2), [5.3]
B_S = settling coefficient (-), [5.7]
a, b = constant of L-Q relation (-), [4.9]
a_B = seepage coefficient (1/d), [4.6]
a_L = discharge coefficient of lateral orifice (1/d), [4.5]
c = concentration in the river segment (g/m^3), [4.8]
c = average concentration in the element (g/m^3), [5.2]
$\bar{c}^*$ = average concentration of inflow (g/m^3), [4.13]
CH = Chl-*a* (mg/m^3), [5.5]
D = water depth (m), [5.8]
$DCOD$ = dissolved COD (g/m^3) [5.13]
$DCOD_B$ = DCOD in mud bed (g/m^3), [5.13]
DIN = dissolved inorganic nitrogen (g/m^3), [5.6]
DIN_B = DIN in mud bed (g/m^3), [5.3]
E'_{nm} = mixing coefficient between element *n* and *m* (m^3/s), [5.2]
e = evapotranspiration (m/d), [4.1]
h = height of lateral orifice (m), [4.5]
i = irrigation water (m/d), [4.1]
i_C = total irrigation supply in the open channel (m^3/d), [4.2]
i_T = irrigation water entering the tank (m/d), [4.4]
K_D = specific decay rate (1/d), [5.5]
K_N = saturation constant of DIN (g/m^3), [5.6]
K_P = saturation constant of PO_4-P (g/m^3), [5.6]
K_{RC} = release rate of DCOD (g/m^2-d), [5.13]
K_{RN} = release rate of DIN (g/m^2-d), [5.3]

K_{RP} = release rate of PO_4-P (g/m^2-d), [5.4]
K_{RT} = resuspension rate due to tidal movement (g/m-d), [5.8]
K_{SA} = settling velocity of algae (m/d), [5.12]
K_{SC} = settling velocity of PCOD (m/d), [5.11]
K_{SS} = settling velocity of SS (m/d), [5.7]
K_W = resuspension rate due to wind (g/m-d), [5.9]
L_D = total loading discharged from the reservoirs (g/s), [4.8]
L_F = unit loading rate of forest area (g/m^2-s), [4.9]
L_P = unit loading rate of paddy field area (g/m^2-s), [4.9]
L_U = unit loading rate of population (g/capita-s), [4.9]
N_F = forest area in the basin (m^2), [4.9]
N_P = paddy field area in the basin (m^2), [4.9]
N_U = number of population (capita), [4.9]
$PCOD$ = particulate COD (g/m^3), [5.11]
$PO4$ = orthophosphate phosphorus (g/m^3), [5.6]
$PO4_B$ = PO_4-P in mud bed (g/m^3), [5.4]
p = precipitation (m/d), [4.1]
Q_B = boundary condition of flow rate of the element (m^3/s), [5.1]
Q_D = total discharge from reservoirs (m^3/s), [4.7]
Q_L = total runoff from basin area during heavy rainfall (m^3/s), [4.9]
Q_{nm} = net flow rate between element *n* and *m* (m^3/s), [5.1]
Q_R = flow rate at downstream of river segment (m^3/s), [4.7]
Q_T = total runoff from the basin (m^3/s), [4.7]
Q_W = total intake water withdrawn at weirs (m^3/d), [4.2]
Q_W = total water intake at weirs (m^3/s), [4.7]
q_B = seepage (m/d), [4.6]
q_L = runoff flowing through lateral orifice (m/d), [4.4]
q_T = total runoff flowing into the river (m/d), [4.1]
R_T = resuspension coefficient due to tidal movement (-), [5.8]
R_M = ratio of mud bed area in each element (%), [5.3]
S = reaction term (g/s), [4.8]
S = reaction term (g/s), [5.2]

SS = suspended solids (g/m^3), [5.7]

T = water temperature (°C), [5.5]

T_D = critical temperature for decay (°C), [5.5]

T_G = temperature coefficient for algal growth (-), [5.6]

T_H, T_L, T_P = optimal water temperature for algal growth (°C), [5.6]

V = volume of element (m^3), [5.1]

V_R = water volume in river segment (m^3), [4.7]

v_W = maximum wind speed (m/d), [5.9]

v_W^* = critical wind speed (m/d), [5.9]

Y = amount of water in the basin (m), [4.1]

Y_C = PCOD: Chl-*a* (mg COD/μg Chl-*a*), [5.12]

Y_N = DIN: Chl-*a* (mg DIN/μg Chl-*a*), [5.3]

Y_P = PO_4-P: Chl-*a* (mg PO_4-P/μg Chl-*a*), [5.4]

Y_S = SS: Chl-*a* (mg SS/μg Chl-*a*), [5.10]

Y_{SC} = PCOD content of particulate materials in mud bed (mg COD/ mg SS), [5.11]

y = water depth (m), [4.5]

α_r = distribution ratio of irrigation water from the open channel (%), [4.2]

γ = percentage of irrigation water supplied directly from weirs (%), [4.2]

δ_{nm} = net advection factor between element *n* and *m* (-), [5.2]

θ = temperature coefficient for decay (-), [5.5]

μ_{MAX} = maximum specific growth rate (1/d), [5.6]

ϕ_W = wind direction factor (-), [5.9]

ϖ^* = critical wind direction for resuspension (m/d), [5.9]

ϖ = direction of maximum wind speed (radian), [5.9]

あとがき

ついに帰国の予定が決まった。昨年の半ばからずっと学位論文の作成で忙しく、気が付けばあと一ヶ月でこの六年間の留学が終わってしまう。学位論文が完成する喜びと同時に、何だか胸の中が空っぽで寂しくなった。国から、家族から、慣れている環境から離れて失ったものも当然あったが、得たものも数えられない程あった。この六年間得たものを身につけ、自分のできることがいろんな人の役に立てばいいなと思っている。今日に辿り着くまでたくさんの方々にお世話になり、すぐにお返しはできないかもしれないけれど、心を込めて感謝の言葉を言います。

初めて日本に来た日から今日までずっと面倒を見てくださった古賀先生、研究を始め、どの教科書にも載ってないことまで教えてくださいました。言葉にできないぐらい感謝しています。長い間、特にこの最後の一年間、迷惑や面倒なことばかりかけてすみませんでした。先生から学んだことはタイに帰って学生に教え、研究のことも先生に近づくように精一杯頑張りますので見守っていてください。これから何十年経っても多分まだお世話になっていると思いますので (笑) これからもよろしくお願いします。

いつもお忙しい荒木先生、会うたびにいろんなアドバイスしてくださってありがとうございます。勉強になることはもちろん、先生の面白い話も大好きです。悩み事まで相談に乗ってくださいました。学会や研究室の飲み会で気軽に先生と会話ができる機会はいつも楽しみにしています。長い間、本当にお世話になりました。お仕事忙しくても体のことも気をつけてださい。

古賀先生のもとに留学を勧めてくださったウィナイ先生、先生のご指導がなければ今日の私はないかもしれません。貴重なチャンスをくださいまして心から感謝しています。先生のもとに帰って少しでも先生の役に立てればうれしいです。

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渡辺先生と大串先生、学位論文のご指導及び副査していただきまして、ありがとうございます。特にこの一年間、大変お世話になりました。

森山先生、筑後川の研究がきっかけで修士のときから最後までずっとお世話になりました。研究のことから日本の文化までいつもやさしく教えてくださいました。先生のお宅までお邪魔しに行ったときは楽しかったです。本当に感謝しています。

ドクターの同級生小島さん、最後まで一緒に頑張りましたね。お仕事で忙しくて会う機会が少なかったですが、小島さんが研究室に来るたびに私は新しい知識を得ました。日本の会社員のことから誰も気づかないことまで教えてくれました。本当に小島さんと知り合ってよかったなと思いました。

アパートより過ごした時間が長かった、北棟4階の古賀研究室。まさに自分の家でした。この研究室に入っていろんなことと出会いました。いい思い出になったのもあるし、きついことも経験しました。ともだちも後輩もたくさんできました。その中で、人のやさしさと心遣いということが一番心に染み込んでいます。

学位論文で一番大変だった時期にずっと手伝ってくれたべっちゃん、本当にお世話になりました。私のドクターコースが始まったと同時にこの研究室の4年生になって、修士まで入ったべっちゃんは、きっと運が悪かったと思う (笑) 。この三年間、楽しかったことつらいこともほとんど一緒だったね。学校に来ると必ず院生部屋に住み込んでいたべっちゃんがいた。べっちゃんがいなければ誰が研究室を片付けてくれるんだろう。一緒に卒業できてうれしい。べっちゃん、本当にありがとう。

学位論文の最後まで毎晩遅くまで手伝ってくれたまつやまくんとまさきくん、感謝しています。ぺたろうで日本語講座やってくれたまつやまくん、勉強になったよ。仕事が終わるまで待っててくれて毎日一緒に帰ってくれて、ありがとうね。まさきくん、有明海の研究がんばれ！あとは頼むね。

めぐみちゃんと董くん、研究は大変だと思いますががんばってください。応援しています。

じゅんちゃん、忙しかった頃、手伝ってくれたり、晩ごはん作ってくれたり本当に助かった。競馬好きはいいけど、ぜひ万馬券取ってね。その時のご馳走いつまでも楽しみに待ってるよ！！！

まだまだお世話になった OB の方々がたくさんいますが、六年間いい思い出ありがとう。皆さんのやさしさは忘れません。

日本語の先生（酒井先生、古井先生、福井先生）、先生方が日本語を教えてくださったおかげで人との会話もでき、研究がうまくいきました。さらに日本語能力試験1級までとれました。特にいつも心配してくれた酒井先生、私にとって先生はお母さんのような存在でした。

愛情たっぷりで育ててくれた両親、いつも応援してくれて心から感謝しています。

タイに帰っても日本で出会った人々とのいろんな思い出を大切にしていきたいと思っています。

平成16年3月3日