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Models for Analyzing Water Quality Environment

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Abstract

Models for analyzing water quality environment should be developed and used properly according to the objectives of analysis, the degree of water pollution, hydrological and hydraulic properties and topographic conditions of the research area, the target of water quality improvement (items, concentration, reference points, etc.), the measures for conserving water quality, the type and amount of data which can be acquired, required accuracy, time, money, the number of persons and computers which can be used. Therefore, a number of model types have been developed and classified by constancy of time, methods for dividing the space of a water body and handing of biological reactions. In this paper, the authors classified the models for water quality analysis. Then, the prerequisites and the processes for constructing the models were defined. Finally, examples of analysis were introduced. Objective areas included watersheds and water bodies, such as irrigation and drainage canals, rivers and lakes. It is important for analyzing the water quality to constrict a balanced model that simulates the process of pollutants flowing into a water body, hydraulic motion and reactions within the water body itself, because the accuracy of a system or a model as a whole is determined by the least accurate subsystem.

Discipline: Irrigation, drainage and reclamation/ Agricultural environment
Additional key words: water pollution, water conservation, watershed, water quality diagnosis, biological reaction

Introduction

Recently rural areas in Japan have been confronted with the problem of deteriorating water quality. In the field of irrigation, drainage and reclamation engineering, it is important to conduct a preliminary survey on water quality to evaluate the influence of various land improvement projects or to analyze their effect.

Pollutants are generated, partially removed on site, discharged into the water body, and they alter water quality through physical, chemical and biological reactions. The load which reaches the water body being investigated is called the "reaching load". The ratio of reaching load to discharged load is the "reaching ratio". The points for the calculation of reaching ratios vary with the ranges of models and objectives for water quality analysis. Fig. 1 shows typical flows of pollutants within a watershed.

Material cycles in the entire watershed must be considered as a total system in analyzing water quality. Models for water management methods, fluctuation of water quality within a water body[9], and unsteady inflow or discharged loads[11] which are caused by rainfall, or irrigation and drainage, all constitute subsystems. Investigation of the water balance is a prerequisite for analyzing water quality.

The following practical measures may be effective for conserving water quality: 1) reduction of the load generated from "point sources" before reaching water bodies using sewerage treatment facilities, 2) strict control of fertilizer and water management in farmland, 3) construction of a system in which resources are effectively utilized, such as recycling of livestock wastes and cyclic irrigation, 4) utilization of purification function of natural ecosystems, 5) use of clean water if available to dilute polluted water, 6) exchange of polluted water with water in bodies with a higher water-purifying capacity by controlling operations in irrigation facilities, and 7) reduction of generating sources through the

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This paper was based on Yuyama et al. "Water quality analysis" series in Journal of the Japanese Society of Irrigation, Drainage and Reclamation Engineering (JSIDRE) (1993-1994) and some results of analysis reported by Yuyama[16,17] were added.

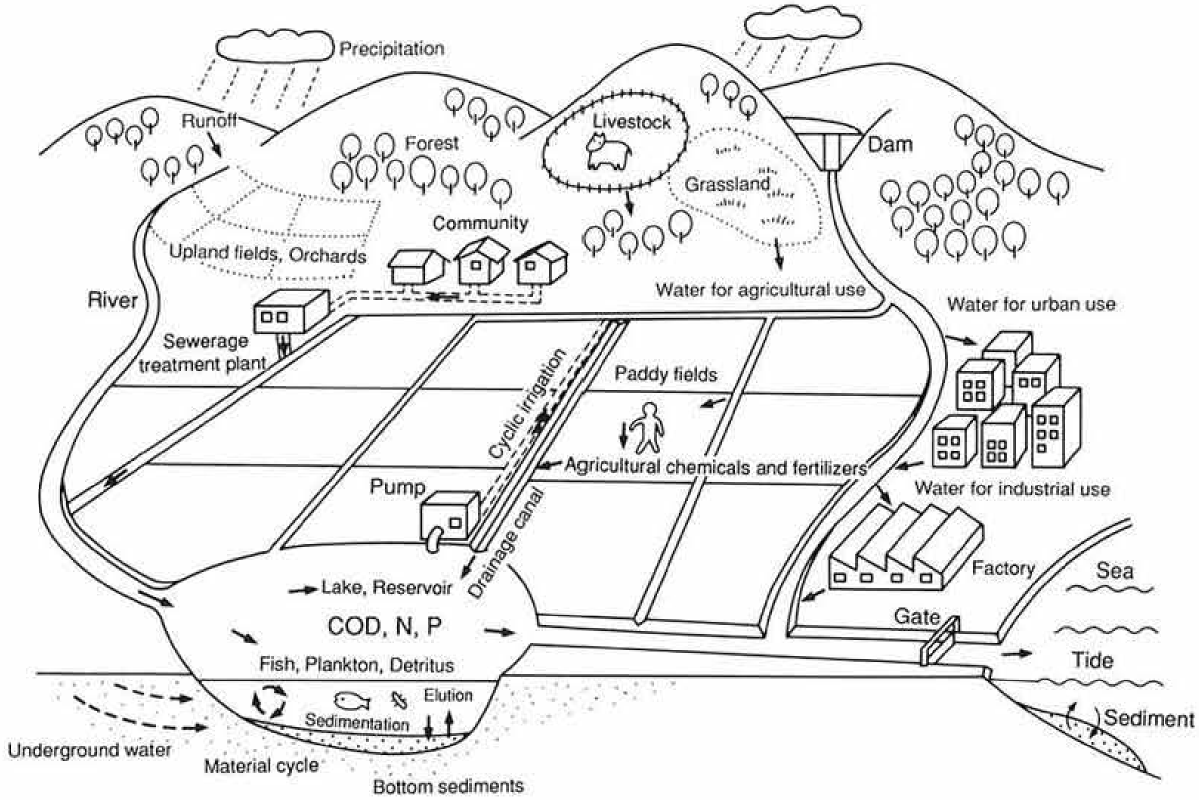


Fig. 1. Flows of pollutants within a watershed

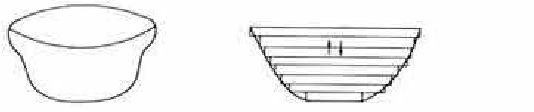
implementation of land use and other regulations.

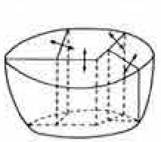
In this paper, the authors classified the models for water quality analysis which were developed based on objectives of analysis, items of water quality, hydrological conditions, topographical conditions, characteristics of pollutant runoff, etc. Then, the prerequisites and the processes for constructing the models were defined. Finally, examples of analysis were introduced. Objective areas included watersheds and water bodies, such as irrigation and drainage canals, rivers and lakes.

Classification of models for water quality analysis

Models for analyzing water quality environment should be developed and used properly according to the objectives of analysis, the degree of water pollution, hydrological and hydraulic properties and topographic conditions of the research area, the target of water quality improvement (items, concentration, reference points, etc.), the measures for conserving water quality, the type and amount of data which can be acquired, required accuracy, time, money, the number of persons and computers which can be used. Therefore, a number of model types have been developed and classified by constancy of time, methods for dividing the space of a water body and handling of biological reactions.

Items generally considered when analyzing water quality include: 1) conservative dissolved substances such as Cl, 2) non-conservative dissolved substances such as BOD, COD, N, P and agricultural chemicals, 3) plant plankton represented by chlorophyll-a,


ⓐone-box, one-layer model ⓑone-box, multi-layers model


ⓒmulti-boxes, one-layer model

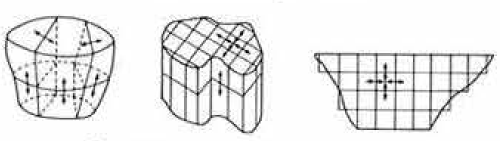

ⓓmulti-boxes, multi-layers models

Fig. 2. Methods for dividing water bodies

and 4) sedimenting and floating materials, i.e. soil and SS. Water temperature and pH are also important.

Fig. 2 shows the methods applied for dividing the space of a water body: ⓐ one-box, one-layer, ⓑ one-box, multi-layers, ⓒ multi-boxes, one-layer, and ⓓ multi-boxes, multi-layers. Each water body is divided in considering the conditions of inflowing pollutants, distribution of water quality within the body, topographic characteristics and principal points for water management. Above classification was reported by the Environmental Agency[1]..

Fig. 3 shows a classification of models for water quality analysis. The terms are those most commonly used. Yuyama[14] compared the characteristics as shown in Fig. 4 and consequently supplied the information on how to select the model.

Methods for estimating flow are broadly classified into "box models", which consider only material balance as continuous conditions, and "mesh models", which solve the equation of motion. Flow can usually be estimated only from the water balance when a water body is represented by either ⓐ, ⓑ or ⓒ in Fig. 2. Equation of motion should be solved when a water body is divided into smaller spaces as in ⓓ. Actual numbers of divided spaces

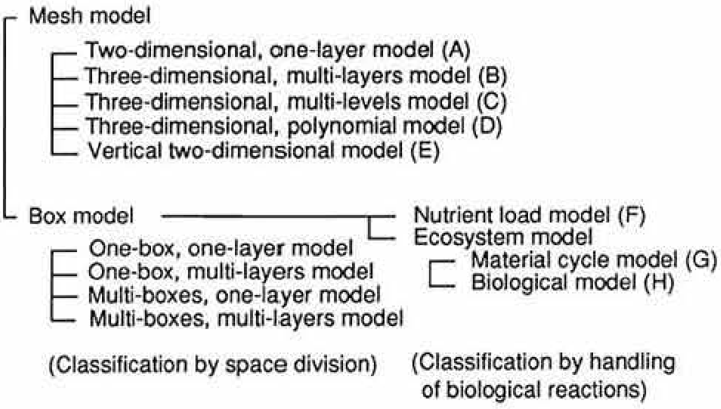


Fig. 3. Classification of models for water quality analysis

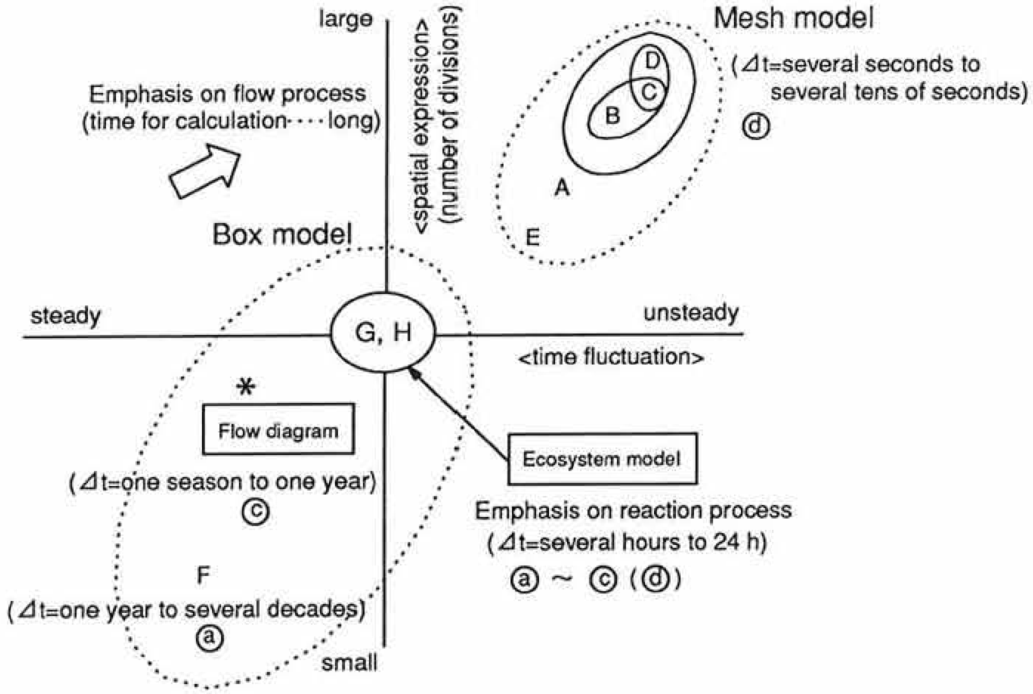


Fig. 4. Characteristics of model for water quality analysis (Refer to Figs. 2 and 3 for symbols.)

are less than ten in box models, while more than several dozens in mesh models. "Flow diagram"[7] corresponds to ⓒ and is effective for analyzing the linkage between discharge and inflow loads within a watershed.

Two-dimensional one-layer mesh models, in which the flow velocity to the horizontal direction is represented by average cross-sectional velocity, are appropriate for analyzing shallow water bodies which are entirely mixed by wind and do not form salt or temperature layers. Canal systems, such as rivers and irrigation and drainage canals, are mostly analyzed as one-dimensional models, in which flows to the direction of their main streams are based only on horizontal movement.

In layer models, momentum transfer among layers is neglected, and the water movement is treated as in box models. In level models, hydraulic quantities are calculated for each lattice point at each level. Three-dimensional polynomial models[5] enable to calculate continuously hydraulic quantities in vertical directions by approximating them to polynomials and are more widely applicable than layer or level models, in which hydraulic quantities among vertically subdivided meshes must be computed discretely.

Vertical two-dimensional models convert two-dimensional planes into one dimension and divide space into horizontal and vertical dimensions. They are appropriate for analyzing water bodies in which exact vertical circulation must be known, such as dam reservoirs.

In mesh models, water bodies are analyzed by solving partial differential equations. The finite differential method (FDM) and finite element method (FEM) are most commonly used for numerical analysis. Unit time for calculation is generally less than several tens of seconds. Takaki & Onishi[10] and Hiramatsu[3] discussed the method of numerical analysis using FDM, and Kawachi[6] discussed FEM.

Box models can be subdivided into "nutrient load models", which act as a black box and pay directly attention to the input-output relationships, and "ecosystem models", which analyze physical, biological and chemical changes. In the former, water quality is expressed as average values in both time and space, whereas the latter treats them as fluctuating values in both time and space. In ecosystem models, simultaneous ordinary differential equations for each substance must be solved. Unit time for analysis generally ranges between several hours and 24 h.

The "phosphorus load model" developed by Vollenweider is a well known nutrient load model. The approximate expression for yearly average concentration of phosphorus [P] ($\mathrm{mg \cdot m^{-3}}$) is:

$$[P] = (L(P)/qs) \cdot \frac{1}{1 + \sqrt{\tau\omega}} \quad \cdots\cdots\cdots\cdots\cdots\cdots \ (1)$$

Here, $L(P)$ represents the phosphorus load accumulated during one year ($\mathrm{mg\ P \cdot m^{-2} \cdot y^{-1}}$), qs is the specific inflow load ($\mathrm{m^3 \cdot m^{-2} \cdot y^{-1}}$), and $\tau\omega$ is the hydraulic retention time (y).

"Material cycle models" are ecosystem models which estimate water quality by separating organic and inorganic substances. Some of them subdivide organic substances into dissolved and suspended matter. The models often have two layers which are vertically split due to the effect of sunlight. In these models, the interactions considered between various kinds of organisms and inorganic nutrients include production and decomposition. Therefore, their structure is simple, and calculations are easy. The models also consider the sedimentation/decomposition of organic nutrients and the elution of inorganic nutrients from sediments as the mass transfer between water and sediments.

"Biological models" are distinctive in analyzing organic nutrients for various kinds of organisms. In all these models, inorganic nutrients and plant plankton are essential. Animal plankton, detritus and dissolved organic substances are considered if necessary. Plant plankton may be treated as one factor or two, i.e. blue-green algae and/or diatoms.

Changes in water quality by physical and biological reactions within a water body are expressed most simply as equation of continuity using the only parameter "removal speed coefficient" in mesh model (two-dimensional, one-layer) and box models as shown in equations (2) and (3), respectively. Equation (2) is an advection / variance formula. Equation (3) has the same structure as the classic equation of Streeter-Phelps.

$$\frac{\partial C \cdot h}{\partial t} + \frac{\partial C \cdot Q_x}{\partial x} + \frac{\partial C \cdot Q_y}{\partial y} = \frac{\partial}{\partial x}\left(K_x \cdot h \cdot \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \cdot h \cdot \frac{\partial C}{\partial y}\right) - k \cdot h \cdot C \quad \cdots\cdots\cdots\cdots \ (2)$$

$$\frac{\mathrm{d}C}{\mathrm{d}t} = -k \cdot C \quad \cdots\cdots\cdots\cdots\cdots\cdots \ (3)$$

Here, C is the concentration of a substance ($\mathrm{mg \cdot l^{-1}}$),

k is the removal speed coefficient, Q_x is the flow per unit width to x direction ($m^2 \cdot s^{-1}$), Q_y is the flow per unit width to y direction ($m^2 \cdot s^{-1}$), h is the depth (m), K_x is the dispersion coefficient to x direction ($m^2 \cdot s^{-1}$), K_y is the dispersion coefficient to y direction ($m^2 \cdot s^{-1}$), and t is time. Removal speed coefficient, also referred to as the "self-purification coefficient", expresses production or removal in a water body in the dimension of [T^{-1}]. Units such as [d^{-1}] or [s^{-1}] are used. Its concept is completely different from that of the removal ratio represented as [%].

Biological reactions are differentiated in water bodies whose hydraulic retention time exceeds 2 weeks. It is useless to apply an ecosystem model to a water body with a retention time of several hours or to use a mesh model in estimating yearly average for water quality. In analyzing a complex topography, it is theoretically possible to utilize mesh models in considering complicated reactions of ecosystem models, but it is more practical to classify and limit objectives and use proper types of models.

Prerequisites and processes for constructing models

A series of preliminary surveys, evaluation of water quality and investigations on measures for conserving water quality are referred to as "water quality diagnosis". The locations of reference points are important. In analyzing the water quality for agricultural use, the intake becomes the reference point, whereas the central points of lakes and canals may be considered to be reference points to analyze the degree of water pollution. The entire line along a canal or the entire water body may be selected as reference points when water amenity is studied. Reference points must be defined clearly when conducting water quality analysis.

The conditions of a good model are as follows: 1) have a clear objective, 2) be based on a clear assumption, 3) have an adjusted range for application, 4) be able to determine, as much as possible, each parameter through investigations and experimentation, and 5) be easily handled.

An ecosystem model, for example, becomes more precisely descriptive as the number of stated variables increases. However, reaction coefficients which show relationships between the variables must also be increased and may not all be estimated through experiments or investigations. An excessively complex system is not practical.

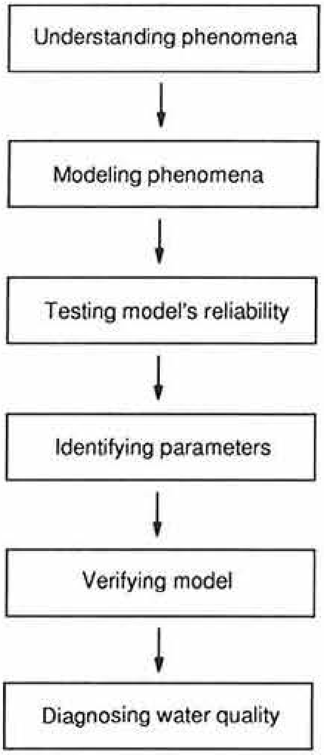


Fig. 5. General process for constructing models for water quality analysis

Fig. 5 shows the general procedure applied for constructing a model to estimate time fluctuation in water quality. The phenomena of water pollution in the concerned watershed must be first understood.

After the construction of a model, the calculations should be tested for their reliability by investigating the material balance, constancy and sensitivities of parameters used. Parameters are identified by first selecting hypothetical parameters whose values can be determined under continuous conditions and theoretically. Next, the parameters whose values can be determined by field research, experiments or steady analysis are selected. After the elimination of unknown parameters, most appropriate values for each parameter should be determined by comparing calculation using unsteady models and values actually measured. This is the process of calibration.

A model of which parameters are identified may reproduce the water quality for the period under analysis, but it is only an output of simulation. The model must be tested by comparing the output during the period used for identifying parameters with independent data from the past. The model is "verified" if the degree of conformity is high. When the model shows a low conformity, parameters must be modified, and the design of the model itself must be reconsidered if the conformity is not improved.

Data in target years of projects and measures for conserving water quality must be considered in diagnosing water quality using models.

Yuyama[15] and Yoshino[13] referred to the data collection. Tanji[12] analyzed the pre- and post-processes using computers. Yuyama[15] also arranged and classified many references and journals. These undertakings may contribute to the efficiency of water quality analysis.

Examples of water quality analysis

Following examples could be considered based on the above water quality analysis:

(1) Prediction of seasonal changes in nitrogen concentration in a stream network, classified by the degree of sewerage work and expected self-purification ability of the streams.

(2) Examination of the possibility of water pollution in a stream network improved by the flush effect of pouring river water associated with heavy rainfall. Estimation of the maximum discharge of flush water which will not cause flood damage.

(3) Estimation of the changes in water quality in rivers when a cyclic irrigation system is introduced.

(4) Calculation of the quantity of water necessary to dilute polluted water to fulfill the water quality standards for agricultural use. Examination of the locations appropriate for the intake.

(5) Estimation of the concentration of chlorophyll-a at a diversion ditch, where water-bloom grows, when the hydraulic retention time is reduced from 3 weeks to 1 week.

(6) Estimation of the changes in vertical distribution of water quality at a dam when an agitator and intermittent aerator are installed.

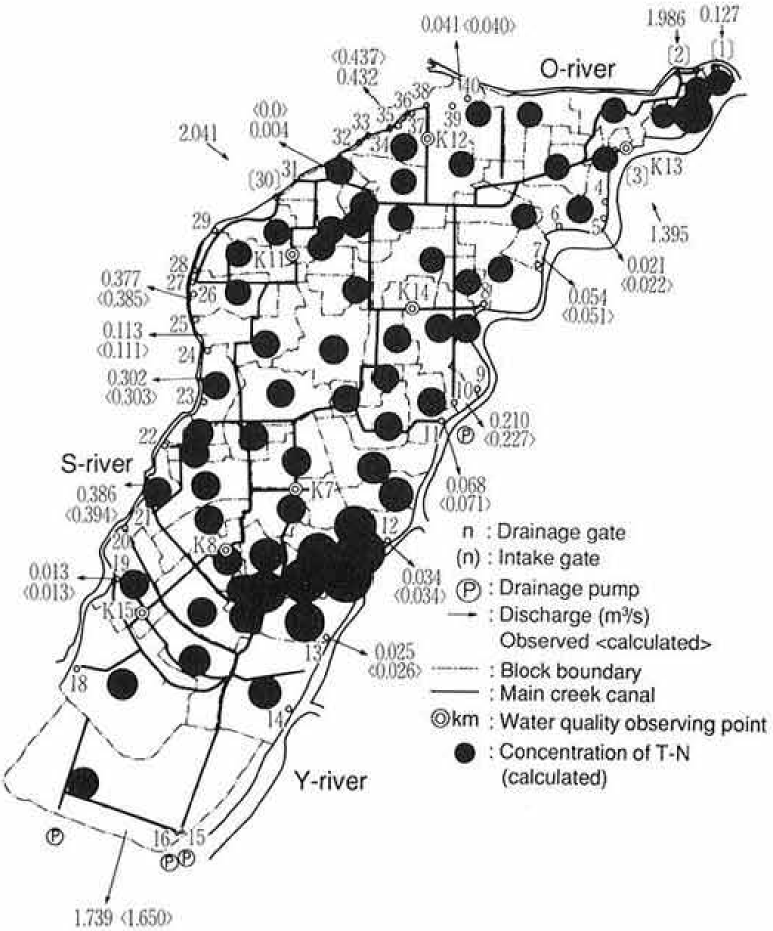


Fig.6. Distribution of nitrogen concentration obtained by a kind of flow diagram analysis

(7) Examination of the possibilities for establishment of guiding dike, maintenance of gut and operation of gate that can improve water quality by accelerating water movement.

(8) Examination of methods for operating tidal gates so that the salt concentration in a brackish lake is maintained between 1,000 and 1,500 mg.l^{-1}.

(9) Estimation of the movement of SS in gulf where floating sediment inflows from the hinterland, settles and refloats by tidal movements.

A part of each example has already been introduced for actual use. Yuyama[17)] showed that it was possible to solve examples (1) and (2). Fig. 6 is an example where the spatial distribution of nitrogen concentration was calculated by a kind of flow diagram. Yuyama[16)] obtained results for example (4), using the simplest material cycle model and mesh model. Figs. 7 and 8 show the results obtained by the use of the former model. Fig. 7 shows a comparison of nitrogen concentration among calculated values by three removal speed coefficients and observed values. Fig. 8 shows the effect of pouring clean water for improving the COD concentration. Influence of pouring point must be analyzed using a mesh model. Fig. 9 shows an example of flow vector in another project area. Shiratani[9)] indicated the way of analyzing example (5). Katoh[4)] and Mori[8)] indicated the way of analyzing example (6). Hiramatsu[3)] dealt with the problem presented in example (9). Hirabayashi[2)] arranged the ecosystem models used for drafting conservation plans in designated lakes.

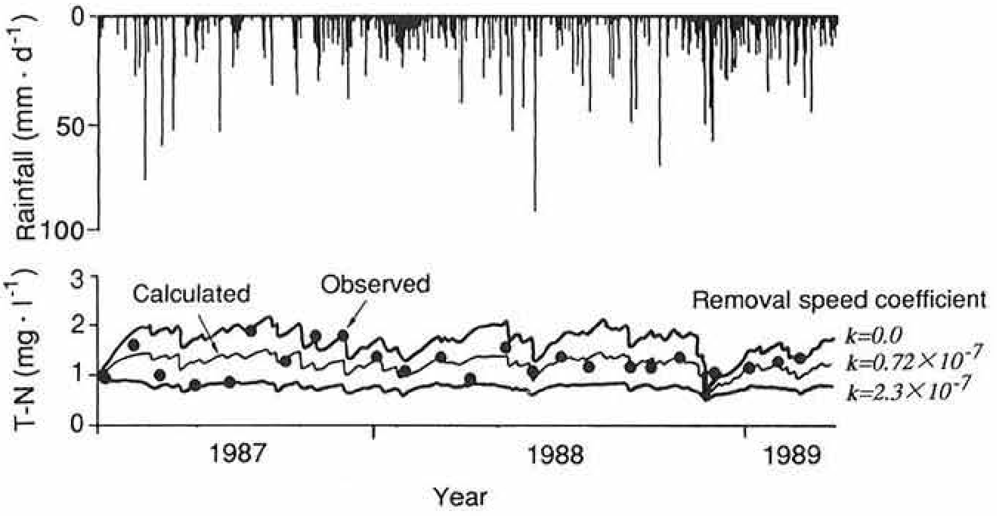


Fig.7. Comparison of nitrogen concentration between observed values and calculated values obtained by a kind of material cycle model

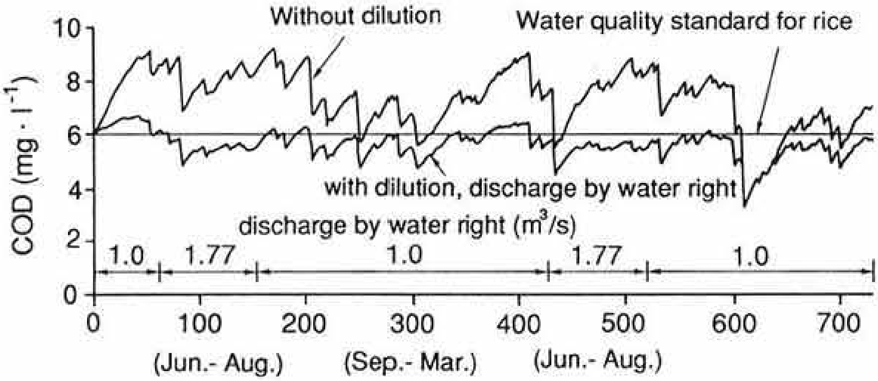


Fig. 8. Effect of dilution on COD concentration obtained by a kind of material cycle model

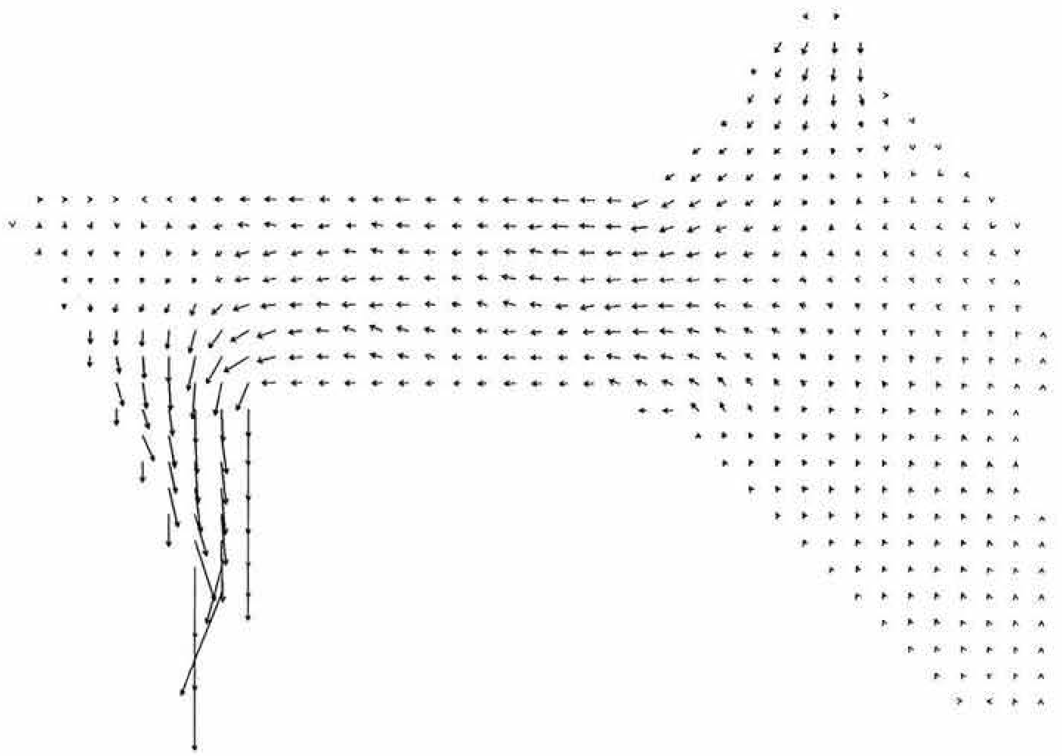


Fig. 9. Flow vector obtained by mesh model of FDM

Conclusion

It is important for analyzing water quality to construct a balanced model of the process of pollutants flowing into a water body, hydraulic motion and reactions within the water body itself. The accuracy of a system or a model as a whole is determined by the least accurate subsystem, though the other components may be adequate.

The collection of highly reliable data which are based on carefully planned studies is a prerequisite for the construction of effective models. Actual research, however, must be conducted with limited manpower, time and money, and it is impossible to comprehensively collect all necessary data with the same degree of accuracy. The need for data, the kinds of data which must be emphasized in the collection of data become apparent after working through a series of operations for water quality analysis.

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