Tsujimoto, Tetsuro; Toda, Yuji; Takaoka, Hiroki; Obana, Makiko

Flux Network Modeling of Water and Materials In River Basin Complex For Assessment In Eco-Compatible Management

Proceedings of ninth International Conference on Hydro-Science and Engineering (ICHE 2010), IIT Madras, Chennai, India.
2 - 5 August 2010

FLUX NETWORK MODELING OF WATER AND MATERIALS IN RIVER BASIN COMPLEX FOR ASSESSMENT IN ECO-COMPATIBLE MANAGEMENT

Tetsuro Tsujimoto[1] , Yuji Toda[2], Hiroki Takaoka[3] and Makiko Obana[4]

Abstract: In a river basin represented by an assembly of natural flux networks of water and various materials driven by runoff process, various landscapes identified by specific ecosystems are distributed and have brought us various services to support human activities there. In order to compensate the rapid increase of population and to increase economic efficiency, we have added artificial networks and facilities there and It has brought an amalgamation of multiple river basins as a river basin complex. On the other hand, ecosystem in river basin has been seriously degraded and our sustainability is now threatened by exhaustion of resources, global warming and loss of bio-diversity. Conservation and restoration of ecosystem can mitigate the above threats. From this view point, we are developing an assessment framework to evaluate eco-compatibility as sustainability index of river basin complex which must become a driving force of policies and citizen movement toward sustainable development. First of all, an assessment framework requires a modeling of flux networks of water and materials in connected multiple river basins by artificial networks where natural ones bring ecosystem service and artificial ones sometimes degenerate a system. Furthermore, it requires modeling for role of local ecosystem which must bring the change of fluxes and ecosystem services to be accumulated locally, and such modeling must be combined with flux network model. This paper introduces a part of our research project concerned with eco-compatible management of river basin complex around the Ise bay, one of the three major bays in Japan.
Keywords: flux net work; river basin complex; eco-compatible management; categorized landscape; ecosystem service.

INTRODUCTION

In a river basin represented by an assembly of natural flux networks of water and various materials driven by runoff process, various landscapes identified by specific ecosystems are distributed and have brought us various services to support human activities there. In order to compensate the rapid increase of population and to increase economic efficiency, we have added artificial networks and facilities there and it has brought an amalgamation of multiple river basins and we define it as a “river basin complex”. The new system brings prosperity of more peoples, but on the other hand, ecosystem in river basin has been seriously degraded

1 Professor, Department of Civil Engineering, Nagoya University, Nagoya 464-8603, Japan,
Email: ttsujimoto@genv/nagoya-u.ac.jp (Member, IAHR).
2 Associate Professor, Department of Civil Engineering, Nagoya University, Nagoya 464-8603, Japan,
Email: ytoda@cc.nagoya-u.ac.jp (Member, IAHR).
3 Post Doctoral Fellow, Department of Civil Engineering, Nagoya University, Nagoya 464-8603, Japan,
Email: takaoka@civil.nagoya-u.ac.jp
4 Research Fellow, Department of Civil Engineering, Nagoya University, Nagoya 464-8603, Japan,
Email: mobana@civi.nagoya-u.ac.jp

and furthermore our sustainability is now threatened by exhaustion of resources, global warming and loss of bio-diversity. Conservation and restoration of ecosystem can mitigate bio-diversity loss and we will be able to obtain more ecosystem service to reduce consumption of fossil fuels and thus to reduce the emission of green house gasses. From this view point, we are developing an assessment framework to evaluate eco-compatibility as sustainability index of river basin complex which must become a driving force of policies and citizen movement toward sustainable development.

An assessment framework firstly requires a modeling of flux networks of water and materials in connected multiple river basins by artificial networks where natural ones bring ecosystem service and artificial ones sometimes degenerate a system. Furthermore, it requires modeling for role of local ecosystem which must bring the change of fluxes and ecosystem services to be accumulated locally, and such modeling must be combined with flux network model. In other words, the flux network model must include interfaces to artificial networks and local ecosystem model for distributed landscapes in the river basin complex.

We have organized the research project team from university and national institutes of government ministries serving national land management (ministry of land, infrastructure, transport and tourism, ministry of agriculture, forestry and fishery, and ministry of the environment) as shown in Table 1, and the project (2006-2010) is financially supported by the ministry of education, culture, sports, science and technology (Tsujimoto *et al*. 2008). Not only the land areas but also the bay area are included in this project, and the human behaviors and ecosystem function there are to be evaluated for previous days, at present and in the future. We have chosen the Ise bay area as a study field, which involves 10 basins of class-A rivers and the 3rd largest metropolis, Nagoya with 2 million population, is facing the Ise bay as a core of human activity. Figure 1 shows a satellite photo of this area and we can recognize a geographical feature with large contrast which is affected by Asia Monsoon climate. Thus, this is a most appropriate field to study for eco-compatible management toward the sustainability.

Table 1. Team of research project.

Assessment (Integration)	**NHRI, NILIM**
TB1 for River Basin	**NHRI**
TB2 for River Basin	
Forests	**NIES**
Rivers	**PWRI, NHRI**
Agricultural area	**NIRE, PWRI**
TB1 for Bay Area	**NIES**
TB2 for Bay Area	**NRIA, NRIFE, NIES**
TB3	**NHRI, NIES, NILIM**

***NHRI=Nagoya Institute for River Basin Management, Nagoya Univ.**
NILIM=National Institute for Land and Infrastructure Management
PWRI=Public Works Research Institute
NIES=National Institute for Environmental Studies
NIRE=National Institute for Rural Engineering
NRIA=National Research Institute of Aquaculture
NRIFE=National Research Institute of Fisheries Engineering

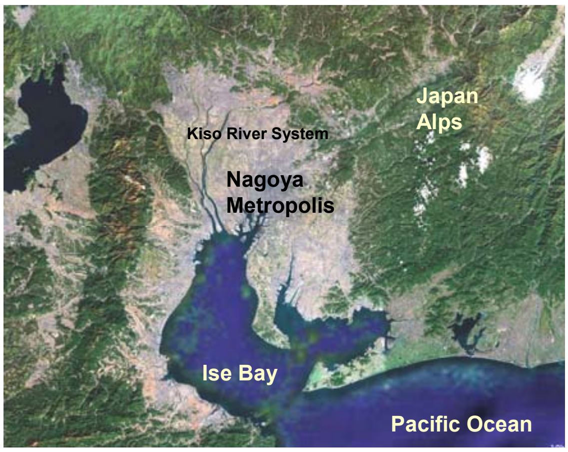

Fig.1. Photo of Ise bay river basin complex.

As already mentioned, flux network modeling is a key. And natural flux network is driven by runoff process of not only water but also various materials particularly related to biophilic elements. We have to consider the function of each ecosystem distributed locally in the basin which changes the fluxes and brings ecosystem services to be accumulated locally. Furthermore, artificial flux networks are connected with it as well as the facilities to bring functions to support human activities and sometimes to degrade the basin environment. Hence, the natural flux network model should have an interface with them as shown in Fig.2, and it is named Tool Box 1 (TB-1) in our research project.

In order to evaluate the ecosystem function, we have to prepare the Tool Box 2 (TB-2) for each landscape, where the change of fluxes and the ecosystem services accumulated to its landscape can be estimated for the influx. TB-2 is prepared for several "categorized landscapes" and applied to each landscape belonging to respective categories.. Categorization of landscapes is performed based on climatic, geological, geographical and ecological features with land-use patterns. Figure 3 is a standard flow-chart of TB-2, which is constituted by recognition of landscape as structure and function of ecosystem shown in Fig.4. As shown in Fig.4, the physical background of landscape provides habitats and place for peculiar elementary processes in biophilic elements cycle. TB-2 estimates the flux changes and ecosystem services: the former should be fed back to TB-1 and locally accumulated ecosystem services must be standardized and integrated by the Tool Box 3 (TB-3), which must be separately prepared. Figure 5 demonstrates this procedure.

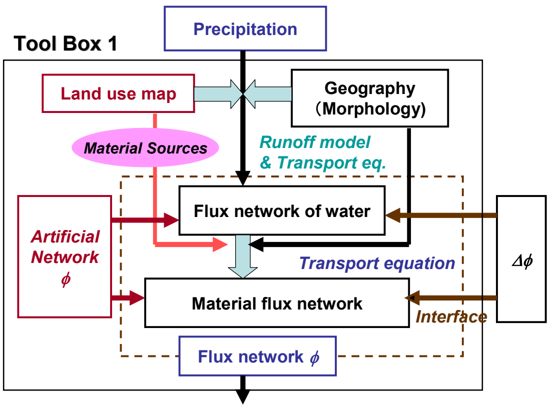

Fig. 2. Flux network model in land area.

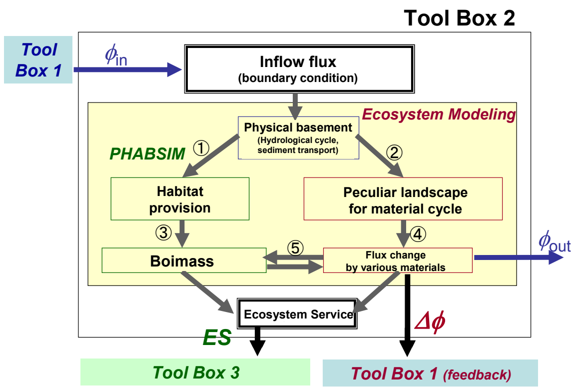

Fig.3. Ecosystem function modeling.

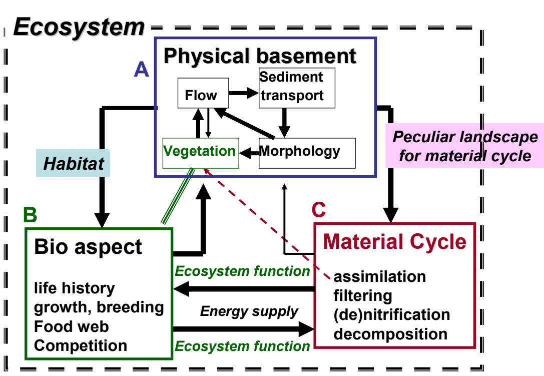

Fig.4. Structure and function of ecosystem.

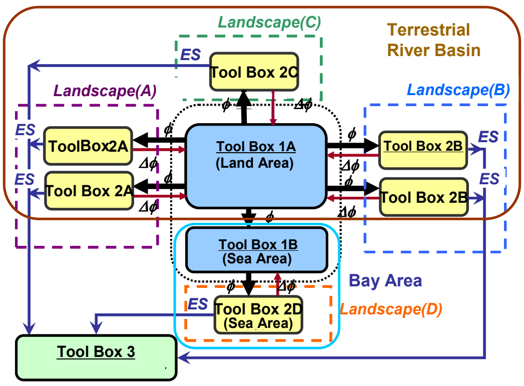

Fig.5 Description of river basin complex.

On the other hand, the bay area is affected by the out-flux from the river basin complex, and TB-1 there plays a model to describe the hydro-dynamics of water and materials and TB-2 in shallow coastal area where biological behavior is active and closely related to human life through fishery activities for example (Tsujimoto, 2010).

By analyzing the river basin complex by TB-1 with TB-2, we can evaluate how the various policies and actions degrade or promote the local ecosystem services. Through out-looking the framework of the present assessment framework, conservation and restoration of local landscapes (habitat mosaics) and rehabilitation of flux networks may play important roles in realizing eco-compatible river basin management.

Quantitative assessment of ecosystem service must become a driving force of eco-compatible management. Ecosystem service has been defined by economically positive value, but current value must be shifted to the value from the view point of sustainability such as how it replaces the consumption of fossil fuel and suppress the green house gas (GHG) emission. In this sense, benefit and cost must be counted by index concerning with the sustainability. The cost must be measured by the emission of GHG or consumption of fossil fuel. In this project, we are focusing on the ecosystem functions. The change of flux is one of the ecosystem functions, and it is taken into account in TB-1. While, such services as production of food, local improvement of environment including water quality, and absorption of CO_2, are provided by ecosystem, and they are accumulated locally. They must be standardized by replacing them to decrease of fossil fuel or GHG emission, and the total benefit maximization and/or spatially well balanced benefit must be a target in the river basin complex. In addition, improvement of habitat of typical species for categorized landscape is also recognized as ecosystem service accumulated locally. The benefit is how to recover the habitat of typical species and the recovery normalized by the potential might be an index which is standardized. From the view point of the river basin complex, normalized habitat area (usable area) of typical species which are different according to landscape categories can be utilized when the diversity index is investigated, and maximization of which must be a target of bio-diversity conservation.

The purpose of the research project is to develop an assessment framework procedure for eco-compatible management of river basin complex including the bay area by integrating various aspects with TB-1 through TB-3. This paper will explain a flux network modeling of water and materials in land area, but the above explanation has clarified the requirements of TB-1.

MODEL OF FLUX NETWORKS OF WATER AND MATERIALS

Natural Runoff Process

Our target is a wide river basin complex, roughly speaking $4000km^2$, which involves 10 basins of class-A rivers. We have divided this basin complex into sub-basins by using GIS technique, which are separated by confluence and divergence, and its scale is around 2km square. Each sub-basin is conceptually divided into a "channel" and a "slope". On the other hand, we have prepared a data base of various items (geographical properties, land-use, population, livestock and so on) as 1km mesh data. As for the rainfall, considering the distribution of monitoring stations, the Thiessen division is employed. Figure 6 shows the Yahagi river basin as a sample basin in the Ise bay river basin complex.

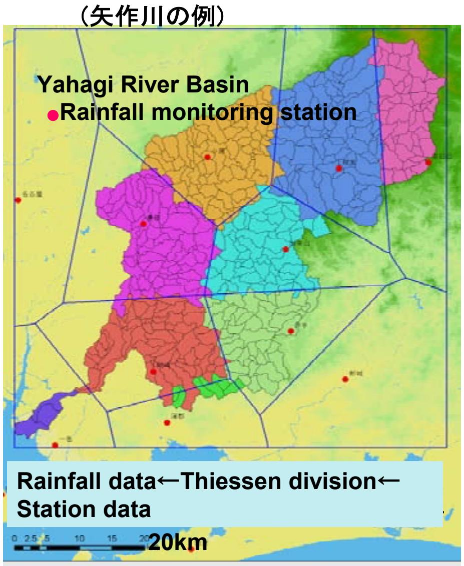

Fig.6 Sub-basin division in the Yahagi basin.

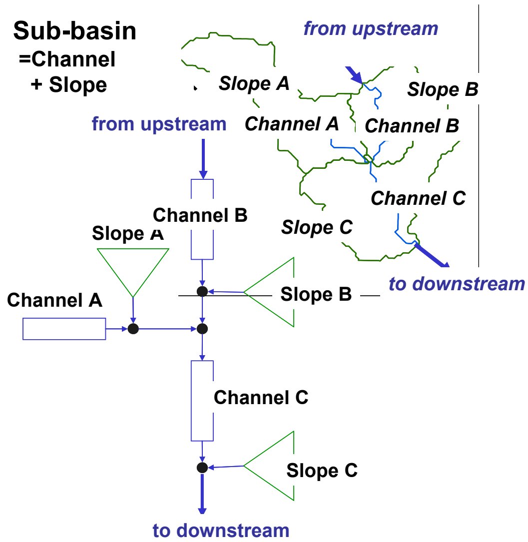

Fig.7 Sub-basin with channel and slope.

As for "slope" and "channel", we have prepared runoff models for water and materials respectively. As materials, SS (suspended sediment), TN (total nitrogen), TP (total phosphorus) and COD (chemical oxygen demand) are taken into account. These models constitute natural flux networks. Firstly, the followings are employed for a "slope". As for surface runoff of water,

$$u = \alpha h^m \tag{1}$$

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} = fr + r_a - r_f \tag{2}$$

where u=velocity of surface flow on slope; h=depth; α, m=hydraulic parameters in slope; f=runoff coefficient, r=rainfall, r_a=conceptual rainfall corresponding to irrigation (runoff parameter for field and target area are taken into account); and r_f=seepage loss. While, seepage to ground water runoff is considered by 2 layers tank model.

$$s_2 = k_{21} q_2 + k_{22} \frac{dq_2}{dt} \tag{3}$$

$$\frac{ds_2}{dt} = r_f - q_2 \tag{4}$$

where q_2=ground water runoff discharge from unit area; s_2=tank storage; k_{21}, k_{22}=parameters related to the tank outlets. On the other hand as for materials, the following equations are prepared by assuming non-linear relations of material load by surface runoff L_b with surface-runoff water discharge Q_1 (Q_c=critical discharge for runoff of materials) and considering that runoff material load is correlated with storage of material on the ground but it has the maximum limit S_{max}.

$$L_b = \begin{cases} k \times S^m \times (Q_1 - Q_c)Q^n & S < S_{max} \\ k \times S_{max}{}^m \times (Q_1 - Q_c)Q^n & S > S_{max} \end{cases} \tag{5}$$

$$S = S_0 - \int L_b dt + \Delta S \tag{6}$$

where m, n, k=parameters, S_0=initial storage; and ΔS=accumulation rate of material during period without rainfall. This model is prepared for each material by setting parameters m, n and k which are strongly related to land-use.

Next, transport in a channel is considered as follows: For the i-th channel, influxes of water and materials are coming from the (i-1)-th channel and from the (i-1)-th slope. Channel processes are formulated as follows conceptually in dimensionless version: As for water,

$$\frac{dH}{dt} = Q_{in} - Q \tag{7}$$

$$H = K_1 Q^{p_1} + K_2 \frac{d}{dT}\left(Q^{p_2}\right) \tag{8}$$

where Q= discharge: T= time, H=storage in channel (they are all dimensionlessed); K_1, K_2, p_1 and p_2=parameters. The parameters are set with reference to kinematic wave model.

As for materials, the governing equation is conceptually written as follows:

$$\frac{dC}{dt} + V\frac{dC}{dx} = -kC \tag{9}$$

where C=concentration of materials (=L/Q); V=average channel velocity; and k=coefficient of purification (dilution). As shown in Fig.8.

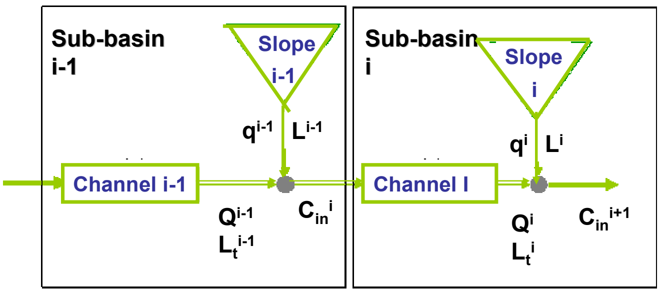

Fig.8. Connection of neighboring channels and slopes

Connection of Artificial Flux Networks

As for artificial flux networks, the following items are taken into account and connected to the natural flux network model. Principally, as point sources, at relevant joint of sub-basins the inflow flux is replaced after artificial operations: (i) dams, (ii) intakes for water resources utilization, and (iii) waste water treatments. At dams, according to model operation rule, inflow discharge is replaced by the outflow. A simple model is employed here: At each dam reservoir, a relation between the change of reservoir storage and the water surface elevation (depending on the reservoir geometry) is prepared as the data. During non-flood period, prefixed discharge is released for the downstream basin until the surface elevation reaches the limit. But when the reservoir surface level approaches the upper limit, inflow discharge is released. On the other hand, when the reservoir stage is lower than the lower limit, the out flow discharge must be zero. While during flood, some dams must play role for flood control. Fundamentally, flood control dams are categorized into two types as shown in Fig.9.

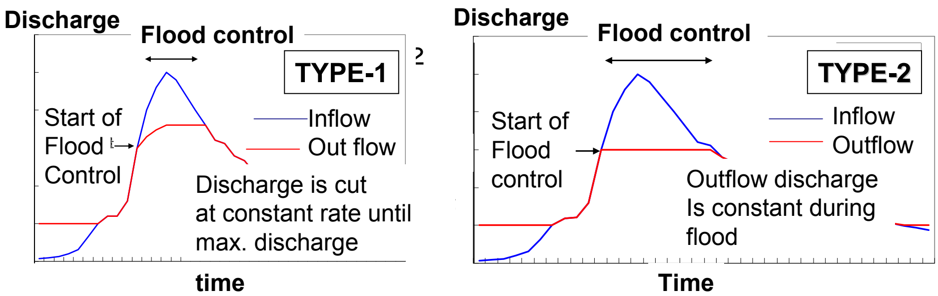

Fig.9. Two types of dams

At an intake for water resource, the water discharge is withdrawn based on rules for each facility. In case of agricultural intakes, the distributed water discharge is converted to additional hypothetical rainfall to the presumed (beneficial) area (r_a in Eq.2).

At waste water treatment (sewage) facilities, the rainfall for the presumed area is reduced from the runoff model and released at the relevant joint of sub-basins with planned (designed) load of materials. For the time being, the over flow of materials exceeding the planned load during heavy rainfall is not taken into account. Furthermore, non-point distributed load is taken into account by addition to the "slope" model in the runoff model. Load by human life is depending on the treatment level (no-treatment, individual treatments, collection, septic tanks for individual and/or combined treatment, and sewage treatment) and the population, and unit value method is employed. Animal waste (cattle, hog and fowl) are treated in the same manner by referring to their population data. As for the industrial waste water, discharge and material load are estimated for the area by using the data base of industrial sales.

EXECUTION OF CALCULATION OF FLUX NETWORKS

First of all, the two data files are prepared: (A) Data file of river includes, at first, sub-basin division with their arrangement, secondly, each sub-basin's area, slope, width of channel, then, population, industrial sales, numbers of cattle, hogs and fowls, and rainfall time series. Before preparing the data file (A), the mesh data (1km mesh) and rainfall data in the

Thiessen's divisions should be converted on the sub-basins by using GIS. (B) Data file for parameters includes those for runoff analysis (runoff parameters, resistance parameter, and unit values various materials) and they are set depending on geographical, land-use, waste-water treatment level and so on. These files can be arranged in Excel files (xls). Calculation is executed by Excel Macro (Microsoft Office), and the file (A) includes arithmetic based on the governing equations of runoff processes with artificial impacts explained in the preceding chapter.

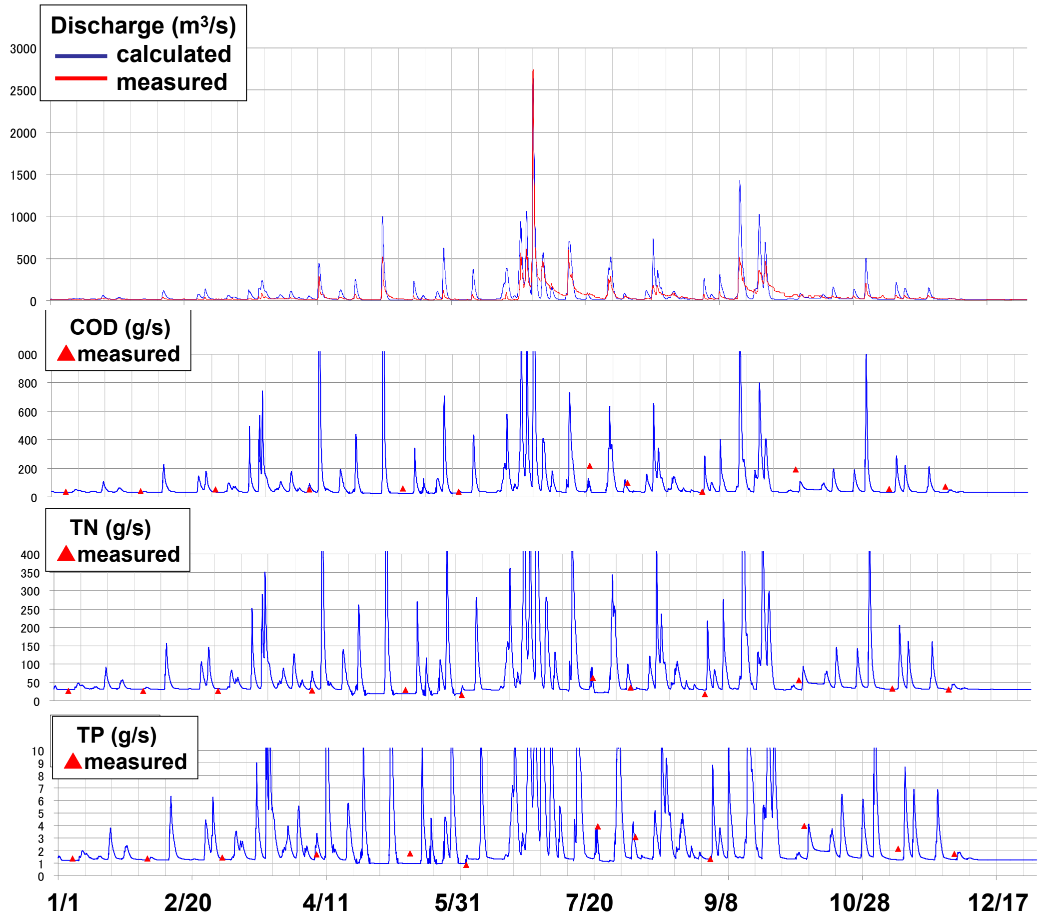

Fig.10. Calculated results of discharge and material loads in Yahagi River.

The calculated results are output to the files (C) and (D) for slopes and channel units respectively, which have output sheets for respective slopes and channel units. In a sheet of one slope, water discharge and material loads such as COD, TN, TP and SS at its outlet are listed with rainfall (input data) as time series, but if this slope area is investigated in detail and some policy menus are executed on this area, the output time-series must be modified by applying TP2. In a sheet of one channel unit, water discharge and material loads such as COD, TN, TP and SS from the confluent channel units are the upstream boundary condition, and the flowing processes are analyzed to obtain the outlet discharges. Then, the discharges of water and materials are respectively sum up with those from the slope of the same sub-basin, and it becomes the upstream condition of the downstream neighboring sub-basin. These discharges are listed as time series. If the details in the channel unit is analyzed and the effect of policy menus are effective, the outlet discharges must be modified by applying TB2 and then the upstream discharge of the downstream neighboring channel unit is modified. As mentioned above, if modifications by TB2 are added in some slopes and channel units, the total flux networks must be changed. After the necessary modifications are added in some columns, calculation of TB1 must be carried out again but only the assembly downstream, and it can be commanded from the file (A).

Some examples of calculated results for Ise bay basin-complex are shown in the following partially with the measured data. Figure 10 shows the time series of water discharge and loads of several materials for the Yahagi river in 1999 (standard year of this decade). The total annual discharges for various river basins in the Ise bay basin-complex are shown in Fig.11, and the total load of COD in Fig.12. The comparison of calculated results with the measured data suggests that the calculation system based of the proposed flux network model can provide fair description of flux network assembly in the basin complex.

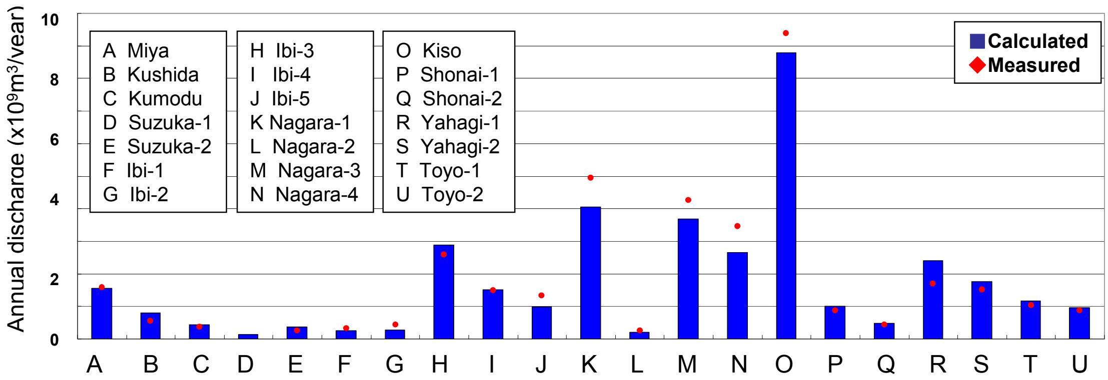

Fig.11. Annual discharge of water at stations in rivers of Ise bay basin-complex.

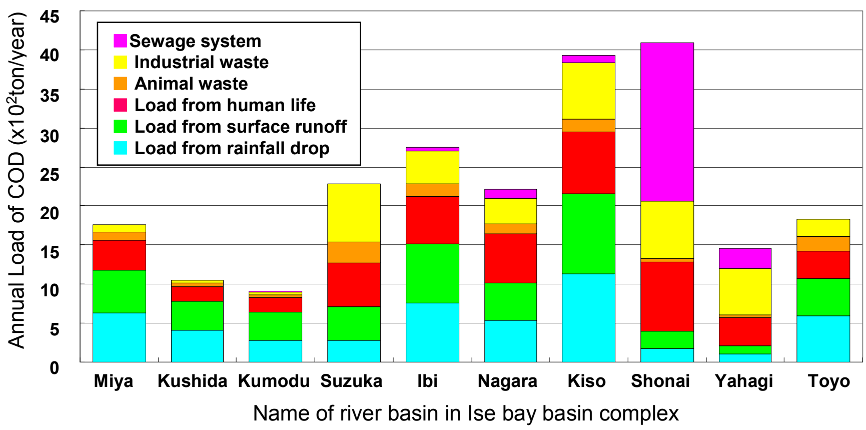

Fig.12. Annual load of COD at outlet of rivers in Ise bay basin-complex.

CONCLUSION

In the research project, we have constituted the framework of eco-compatibility assessment of river basin complex, where a model to calculate a flux network assembly with quick interfaces with artificial network of fluxes and with the output of ecosystem functions brought from distributed landscapes in river basins is emergently required. In this paper, a flux network calculation tool by using excel macro is proposed to satisfy the requirements mentioned above. The calculated results are compared with the measured data for the standard year in this decade to recognize sufficient reliability. This flux network calculating module will work efficiently in the total framework of the eco-compatibility assessment of river basin complex (see Fig.5) which evaluates various scenarios as sets of several policy menus.

Policy menus are classified into three categories: (i) change of population distribution and/or land-use, (ii) improvement of runoff properties of water and materials for each land-use, and (iii) ecosystem restoration of local landscapes. We can calculate the situation after carrying out the policy menus from the category (i) by changing the data file (A) in the flux network calculation module, and the situation after the policy menus from the category (ii) by changing the data file (B). While, if the menus belonging to the category (iii) are carried out, we can introduce the result of ecosystem modeling (TB-2) to the present flux network calculating module (TB-1) as easily as explained in this paper.

ACKNOWLEDGEMENTS

This study is conducted as a part of the special coordination fund for promoting science and technology for sustainable national land management (2006-2010), "Research and development in assessment and restoration for eco-compatible management of river basin complex around Ise bay" supported by Ministry of Education, Culture, Sports, Science and Technology, Japan.

REFERENCES

Tsujimoto, T. 2010. Restoration program of bay ecosystem through eco-compatible management of river basin complex around the bay. *XIèmes Journées Nationales Génie Côtier – Génie Civil*, Le Sabre Les Sables d'Olonne, France.

Tsujimoto, T., Toda, Y., Obana, M.. 2008. Assessment framework of eco-compatible river basin management around a bay. *Advancement of Hydro-Science & Eng.*, ICHE-Nagoya, Vol.8 (CD-ROM).

Tsujimoto, T., Toda, Y., Obana, M.. 2010. Eco-compatible management of river basins composed of assembly of flux networks and distributed landscapes. *Proc. 17th Congress of IAHR-APD*, Auckland, New Zealand (CD ROM).

United Nations. 2005. Millennium Ecosystem and human well-being synthesis. *Ecosystem assessment Reports*