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Assessment Framework of Eco-Compatible Management of River Basin Complex around a Bay

ASSESSMENT FRAMEWORK OF ECO-COMPATIBLE MANAGEMENT OF RIVER BASIN COMPLEX AROUND A BAY

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ABSTRACT

We are aware that it is necessary to reconstruct sustainable society and it must be supported by eco-compatible management of national land. River basin is a unit of its management, and we often take care that most of metropolises have developed around bays where multiple river basins are intimately connected. In this study, we develop assessment framework of eco-compatible management of river basin complex. Eco-compatibility is achieved to activate ecosystem service as much as possible to suppress consumption of fossil fuels. River basin complex is an assembly of flux networks of water as well as various matters, and various landscapes with ecosystem bring various ecosystem service locally while they change the flux and such local changes propagate in the whole river basin complex and finally to the bay area. A tool box to evaluate ecosystem service and flux change is developed for categorized landscapes, one of which a local side belongs to. Another tool box is prepared for flux network analysis, which informs the inflow flux at local site and is updated when the flux change appears. The other tool box is prepared to integrate locally evaluated ecosystem service for the basin level. The assessment framework is how to drive these three tool boxes.

Keywords: *Ecosystem, River basin management, Hydrological cycle*

1. INTRODUCTION

When we consider a national land planning toward sustainability particularly for us who are strongly aware of environmental degradation to threaten our sustainability, eco-compatible management of river basin complex is an attractive and possible efficient scenario. In order to enhance feasibility, it is necessary to achieve assessment techniques, and first of all, several concepts should be clearly defined.

River basin is a unit of hydrological cycle, which itself is quite global. In a river basin, runoff process dominates and it drives sediment transport and fluvial process, material cycle (transport of various materials and changes through bio-geo-chemical processes), and ecosystem. It implies each sites in a river basin is connected each other by flux network of various materials (water, sediment and other materials including biomass). The end of fluxes pour into sea, and if there is a bay, multiple rivers pour into it and we have to consider a complex of multi-river basins. And, artificial networks (not only irrigation canals and drainage channels but also transportation routes to carry various materials) are considered as well as natural rivers, and they sometimes exceed the border of river basins.

Ecosystem is recognized as an interrelating system of physical basement, bio-aspect and material cycle. Physical basement provides habitat for various organisms and fields for various geo-chemical processes. There may be reactions such as change of physical indices of the fields by bio-activities and material cycle. Meanwhile, bio aspect and material cycle are interacted each other: production and assimilation, and metabolism and decomposition. We can find advantage from the viewpoint of human activity, which works instead of artificial function, and it is called “ecosystem service”. In eco-compatible river basin scenario, “ecosystem service” should be reserved as much as possible, and it can restrain consumption of fossil fuels to contribute the sustainability.

As above-mentioned, eco-system service will be extracted to conserve (preserve and restore or rehabilitate) the ecosystem for each site in a river basin, and on the other hand it reflects the change of fluxes and the local effect propagates everywhere in a river basin. In order to evaluate the locally generated ecosystem service and the flux change, we have to prepare a tool box. When we consider making a tool box, a concept of “categorized landscape” is effective. Then, a river basin is composed of several typical landscapes, and each local site belongs one of several “categorized landscapes”. At first a river basin is divided into aquatic and terrestrial areas. A river is divided into “segments” such as mountainous river, fluvial fan river, river in alluvial plain, estuary and so on. Relating to this segment, a part of terrestrial area is divided into valley, fluvial fan, alluvial plain, delta and so on besides forest or hill slope and mountain. For each category of landscapes, it forms a peculiar ecosystem and we expect peculiar ecosystem service and devise policies and/or measures. The methods to evaluate ecosystem and the subsequent change of fluxes must be similar for the same category of landscape, and its development is one of the major parts of the assessment.

The other stem of the assessment is to provide flux network analysing model which gives the information of flux inflow to each local site, and the change of fluxes at the local site can be fed back and the flux network can be updated. The outflow of the fluxes to pour into the bay is calculated depending on the policies and/or measures in the river basin, and the dynamics of water and its quality such as behaviour of oxygen deficient water in the bay can be analysed by using a numerical simulation model to be developed. And, there is a feedback system between the bay and the coastal zone where peculiar ecosystem related to fishery particularly for bivalve such as short necked clam. The fishery production and filtering effect by bivalves to purify water are “ecosystem service” there to be evaluated. The latter is fed back to the water quality of the bay.

The ecosystem service produced at individual sites in the river basin as well as along the coastal zone of the bay might be integrated as how they can suppress the consumption of fossil fuels, which is an index to measure the eco-compatibility.

2. IMPORTANT CONCEPTS

2.1 River-Basin and River-Basin Complex

In hydrology and geography, a river basin is defined as a area of watershed surrounded by water divide and is a unit of hydrological cycle on a surface of a globe, where precipitation is converted to flow discharge in a river system. Hydrological system is composed of precipitation-river-sea-evapotranspiration-clouds and it moves as convection-diffusion in an atmosphere, and in this sense hydrological cycle is global. Runoff is a converting system from rainfall to river discharge. River is a conveyance of water, but it transports sediment as well to bring about fluvial processes. Water and sediment transport various materials. So, we would say a river basin is an assembly of natural fluxes of several matters, and a river system provides its routes.

In a river basin, human activity has been developed mainly alluvial area, and a river has been separated in human-developed area by flood levees. Such activities have made a river basin narrowly limited in an alluvial part, however, such areas supplied water from that river and drained to it artificially, In this sense, they are included in socially defined river basin. Furthermore, sediment transported by the river forms the coastal zone and with stop of sediment the coast line cannot be maintained. In this sense, coastal area is also included in a widely defined river basin. There are bays surrounded by several river basins, and metropolises are located around such bays such as Tokyo, These metropolises and human activities on them have polluted bay environments and in order to support them such river basins have been degenerated. Furthermore, most of them are connected by artificial fluxes: irrigation and drainage channels, water supply and waste water. Even roads and rail roads provides fluxes of materials by cars and trains. These river basins are a collective with a same lot, and here we define such a collective as a "river basin complex" (see Figure 2). The fluxes from the river basin complex to the bay are subjective to the dynamic behaviour of the bay which is also influenced by the ocean behaviour. The dynamics of the bay affects the ecosystem of coastal zone where fishery activity and the subsequent ecosystem are expected.

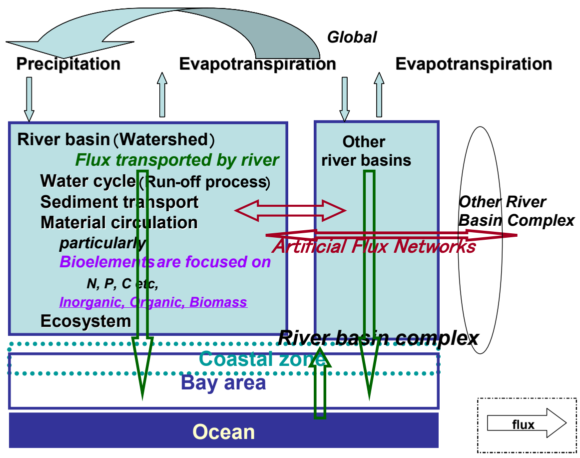

Fig.1 River basin complex and ecosystem

2.2 Ecosystem

As aforementioned, a river basin is an assembly of various flux, and when they pass many landscape elements within a river basin they are somewhat changed. Here a "landscape element" is a site characterized by interactions among three subsystems (see Figure 2): (A) physical basement, (B) biological aspect and (C) material cycle as for which we focus on biophilic elements which change forms in inorganic, organic matters and even in biomass such as N, P, C, O, *etc*., which is closely related to biological aspect of ecosystem. Such an interrelating system forms a "landscape" and it is often considered as "ecosystem". Ecosystem is not merely a set of organisms.

Subsystem (A) is an interrelating system in a river, constituted by geomorphology, flow and sediment transport (subjected to fluvial processes). Subsystem (A) is intensively affected by vegetation. Subsystem (B) may include life history of individuals, breeding of a species and society of several species subjected to food-web, competition-coexistence and species diversity. The subsystem (A) contributes the subsystem (B) to provide habitat for various stages of various species. The subsystem (C) is transport of biophilic elements and change in forms between inorganic and organic matters through such as filtering, trap and flash, nitrification and denitrification, *etc*. There are several processes in the subsystem (C) and they require in peculiar conditions respectively which are provided by various physical background ((A) to (C)). Nutrients (inorganic bioelements) relate to primary production and assimilation to produce biomass ((B) from (C)), while decomposition and metabolism cause inorganic matters and decay and death bring non-alive organic matters ((C) from (B)). As mentioned here, the subsystems (A), (B) and (C) are mutually interrelated.

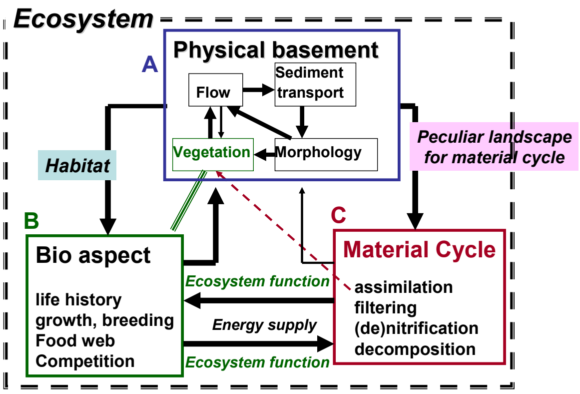

Fig.2 Ecosystem in a river

There are various landscape elements characterized by peculiar physical backgrounds with peculiar bio- and material cycle aspects in a river basin and various fluxes make networks on it. When the fluxes pass through such peculiar landscape, various "ecosystem services" are expected. The concept of ecosystem services is summarised as follows (Constanza *et al*. 1990): (i) Production, (ii) Regulation, (iii)….., and so on. In addition, when a flux ϕ_j (j designates one material to be transported) pass through them, the change of the flux $\Delta\phi_j$ is brought about and it is propagated by the flux network throughout the river basin to the sea. The ecosystem service ES_{jk} and $\Delta\phi_{jk}$ appearing locally (k designates a landscape element) can be evaluated depending on the inflow flux conveyed through the flux networks and the characteristics of the landscape described through the modelling of the ecosystem, in other word, the modelling of the above three subsystems (A), (B) and (C) and interactions among them. $\Delta\phi_{jk}$ is fed back to the flux network.

2.3 Categorized Landscape

It is necessary to estimate the ecosystem service and the change of the flux which appear locally, and in order to standardize the tools to evaluate them a concept of "categorized landscape" is introduced. Among the same category, the mechanism to produce ES_j and $\Delta\phi_{jk}$ are expected to be similar.

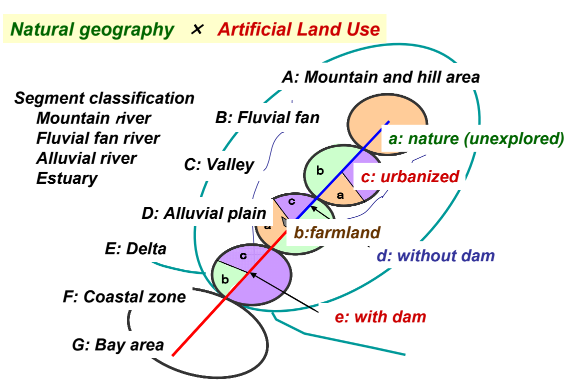

Fig.3 Categorized landscapes

When a river area is focused on, the concept of "segment" is introduced and it can be applied to the alluvial area: valley, fluvial fan, alluvial plain. Moreover, mountainous area, table land, and forest are added. These are further divided depending on human activities, and the land use is a useful index.

Depending on a category of landscape, the development of human activities have been different each other, and the near future policies must be similar for the same category. Thus, this categorization must be significant on river-basin assessment.

3. TRANSITION OF QUALITY OF RIVER BASIN COMPLEX

In a river basin, we developed human society to keep safety against disasters, necessary resources and good environment. The population of Japan reached around 35million and stable at the beginning of Meiji era, and through modernization and industrialization it has reached 130milion with economic growth. The former was supported by ecosystem service which was brought about by natural landscape elements and natural flux networks in a river basin, and it required an environmental capacity. In order to exceed the limit, we have constructed various facilities and artificial flux network to compensate functions of the natural landscape elements and natural flux network driven by hydrological cycle (see Figure 4). Furthermore, efficient functions that artificial facilities and flux network posses had replaced ecosystem enjoyment of ecosystem services and natural network more than those required for compensation. Modernization has been accompanied with urbanization developed along bays, and it has brought environmental problems in bay area. In addition, protection against floods and the excess of water consumption for urban water and for provision of food for the urbanized area have suppressed the upstream environment in the river basin. These have brought about degradation of river basin ecosystem and impoverishment of river basin as well as urban areas. Furthermore, the operations of artificial facilities and flux networks have required high energy mainly depending upon fossil fuels which have threatened the sustainability through global warming.

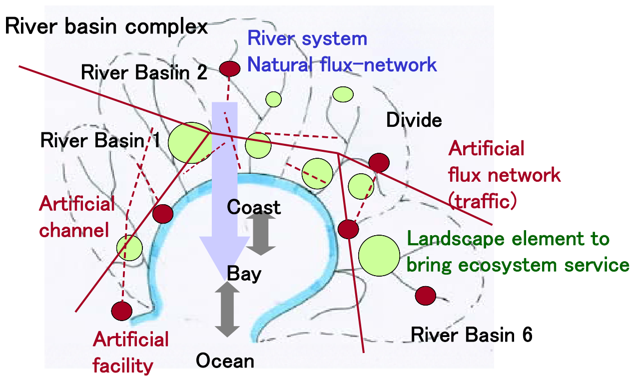

Figure 4 Development of river basin complex

The emergent issues as for a river basin complex are restoration of bay environments including ecosystem and fishery, mitigation of degraded river basin ecosystem and design of a sustainable human society, and "eco-compatible river basin complex" is a scenario to accomplish. Urbanization had brought conversion from ecosystem service and natural flux network driven by hydrological cycle to facilities and artificial network to overcome the limit of growth of population and economy, and the reverse conversion may answer the above issues, where co-compatible design should be considered for river-basin ecosystem mitigation to enjoy ecosystem service. The enjoyment of ecosystem services as much as possible are expected to save fossil fuels and to reduce green gas release, and thus this direction may bring sustainability.

4. ECO-COMPATIBILITY ASSESSMENT – ELEMENTARY TOOL BOXES

When we look through the qualitative transition of river-basin complex, we have recognized ecosystem degradation in river basins, deterioration of water quality and ecosystem and fishery decline in a bay, and we should challenge to restore river-basin complex toward the sustainability. The key is "eco-compatibility", and it implies how the ecosystem is conserved and how we can replace the fossil fuels consumption with "ecosystem service" which is brought about by sound ecosystem.

This study aims to design a framework of eco-compatibility assessment of river basin, which evaluates how the eco-compatibility of the river basin has been degraded through urbanization with the development of population and economies and how it will be restored or rehabilitated through several scenarios. Here scenario means a set of menus of programs (facilities, operations, institutional measures and so on). The assessment requires the following items:

(1) Flux network analysis

It clarifies the natural flux network driven by the hydrological cycle not only for water but also various materials. Here, biophilic elements such as N and P are taken into account. In addition to the natural network, artificial networks are connected to the natural system, and furthermore artificial transports (by cars and/or train) are devised to be added. Flux network connects various landscape elements and artificial facilities to bring about the change of flux and the functions required in a river-basin complex. The combination of landscape elements and artificial facilities is variable in assessment process, and the flux network model should prepare a proper interface with the local changes of flux.

(2) Description of landscape elements

At each local site, a landscape element constitutes a peculiar ecosystem and it brings ecosystem service and the local change of the flux, which depend upon the inflow flux to the landscape element. In order to evaluate them, we need a model to describe ecosystem mechanism.

(3) Integration of ecosystem service from on-site level to river-basin complex level

Ecosystem service evaluated locally may be different in quality should be integrated for comprehensive evaluation or assessment through river-basin complex, and we have to devise how to integrate them from the view point how to replace fossil fuels with them. It is also an important view how the local effect propagates through the river-basin complex. In addition, artificial facilities treating water and materials are taken into account as similarly as natural landscape with ecosystem, which also bring the functions we require and the change of the flux. The local change of the flux accompanied with creation of local ecosystem service should be taken account of for updating the flux network analysis.

4.1 Flux Network Model

The runoff model is a basis of flux network model, which converts rainfall into water flux (discharge). Most of materials including sediment and biophilic elements are principally transported with water flow. By employing an existing model for runoff process, the natural water flux network for the present river-basin complex is analysed where the present fluxes in artificial networks such as irrigation and drainage canals and water-supply and sewage system are reproduced, and the parameters have been fixed for the present situation in a form of hourly variation. After analysing the water flux, the fluxes of N and P are calculated with considering the change of the forms. The solutions are called "0-order approximations" of the flux networks because these can be modified by refinements of accuracy of evaluations of the flux change at several landscapes elements or the enhancement of the data set for artificial facilities and networks. Moreover, several scenarios should be checked in assessment process: the previous situation before construction and/or operating artificial facilities and flux networks and degradation of ecosystem service, and the future predictions for several scenarios with different menus. With changes of functions of landscape elements and/or facilities, the local changes of the fluxes are evaluated and those effects should be reflected properly and easily to the flux networks by versatile interface. This type of flux network analysing procedure is prepared as the "Tool Box 1" (see Fig.5)

In order to obtain the 0-order approximated solutions, there are two keys: how to evaluate the source of them and the change of their forms on the process. These should be evaluated by clarified by the process of landscape elements, but they depend upon the inflow flux. Thus, iterative procedures are required, and for the 0-order calculation we adopt empirically assumed relationship which gives the source (or the change) of fluxes per unit area for some categorized landscape elements.

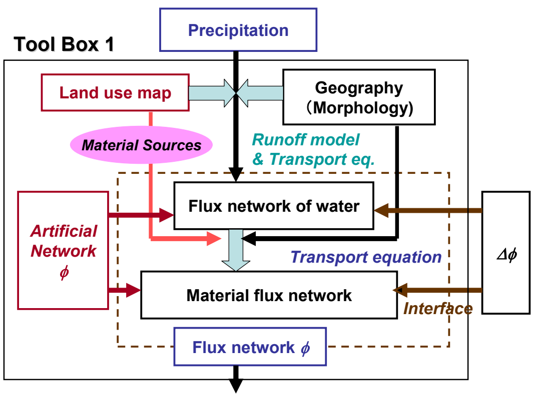

Fig.5 Tool Box 1 – Flux network analysing model

4.2 Ecosystem Modelling

We have introduced the concept of "categorized landscape" which includes several landscape elements. One landscape is constituted by a peculiar combination of landscape elements. For example, a sandy river segment possesses aquatic route with riffles and pools and alternate bars with sandy mound, gravel belt, vegetated area and temporary waters. These are in a sense a physical basement, but it provides habitat for bio-aspect of ecosystem and the physical basement also provides peculiar sites for peculiar process in material cycle. In other words, each "categorized landscape" is a peculiar ecosystem, and it changes the flux flow and brings peculiar ecosystem service. The key of the procedure (2) in the assessment framework is to make a model describe a fundamental mechanism of ecosystem and to evaluate how it brings ecosystem service and the change of fluxes quantitatively. The mission is to prepare a tool box which can evaluate *ES* and $\Delta\phi$ for each categorized landscape.

The framework of ecosystem modelling in assessment must be composed of the following processes to make various maps, and the "Tool Box 2" (see Fig.6) is prepared:

(1) <u>Map for physical parameter</u>

Indices for the physical characteristics of landscape (ecosystem) should be quantitatively evaluated for given influx. In an aquatic area, velocity, depth, substratum and so on are the physical indices, and they can be evaluated by using fluvial hydraulics with the dynamics of vegetation (grow and decay). The fluvial hydraulics is a mapping function to convert morphology to hydraulics parameters. Anyway, this process provides maps of physical indices.

(2) <u>Map for biomass of organism</u>

In order to make a habitat map for a peculiar species of organisms, preference curves are prepared, which relate the habitat suitability with the physical parameters. In other words, the preference curves are mapping functions to convert maps of the physical indices to a habitat-suitability map which shows spatial distribution of habitat potential. The preference curve $f_s(\xi_s)$ implies habitat suitability ranging in [0,1] against a physical parameter, ξ_s (*s* designates one of the physical parameters). Considering multiple parameters, the composite habitat suitability Ξ_z is obtained as

$$\Xi_z = \prod_{s=1}^{N} [f_s(\xi_s)]^{p_s}, \quad \sum_{s=1}^{N} p_s = 1$$

where *N*=number of physical parameters included in consideration (*s*=1, 2, …, *N*); and *z* designates the landscape elements. The above technique follows the so-called PHABSIM (Physical Habitat Simulation, 1989).

There is a population dynamics modelling. If a single species is focussed on, its temporal change on biomass per unit area, $M(t)$, can be expressed as follows, for example.

$$M(t) = \mu M_0 \left(1 - \frac{M_{eq}}{M}\right) + D(t)$$

where M_0=initial biomass per unit area, μ=growth rate, M_{eq}=maximum biomass per unit area (environmental capacity); and $D(t)$=loss of biomass (death) due to disturbance, for example; and *t*=time. Habitat suitability implies habitat potential to suggest μ and M_{eq}, and these are related to Ξ, such as $\mu = \Xi \mu_{max}$ and $M_{eq} = \Xi M_{eqmax}$, where μ_{max} and M_{eqmax} are the values of μ and M_{eq} at the most suitable conditions. Population dynamics model is a mapping function to convert the habitat suitability to the biomass, and we can obtain a biomass map which indicates spatial distribution of biomass density $M_z(t)$. When the area of the designated landscape elements is expressed by ΔA_z, the biomass $B(t)$ of the categorized landscape is expressed as

$$B(t) = \sum_z M_z(t) \Delta A_z$$

(3) Map for the flux change $\Delta\phi$

The suitability for a designated process of material cycle (such as trap and flash of particulate organic matter, nitrification or denitrification, *etc*), Θ_z^r (*r* designates a peculiar process), can be analysed as similarly as habitat suitability. Thus, Θ_z^r ranges in [0, 1], and it depends on the physical indices, thus, on the landscape element as similarly as the reference curve in habitat suitability analysis.

When the maximum change of the flux due to the process *r* at the landscape element *z* is represented by $\Delta\phi_j^r{}_{max}$, it is related to the influx ϕ_j, and the required biomass and then the followings are formulated.

$$\Delta\phi_j^r = \sum_z (\Delta\phi_{jmaz}^{rz} \Theta_z^r)$$

$$\Delta\phi_{j\max}^{rz} = func(\phi_j, B_z)$$

(4) Map for habitat of ecosystem service *ES*

The ecosystem service ES_i (*i* indicates an interest designated in a peculiar landscape) is various and it is related to the local change of various flux $\Delta\phi_j$.

$$ES_i^r = func(\Delta\phi_j^r)$$

Various combinations of *i* and *j* exist. In order to integrate the ecosystem service through a river basin and/or a river-basin complex, ecosystem service should be somehow normalized. It is proposed herein that they are converted to the potential to replace the fossil fuel and thus it is represented by ES^*.

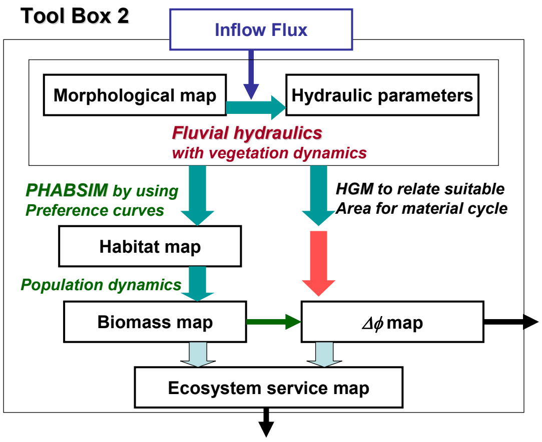

Fig.6 Tool Box 2 – Ecosystem service modelling

4.3 Integrated Evaluation of Ecosystem Service from on-Site Level to River-Basin Complex level

Even in a landscape, various ecosystem services may replace the fossil service (ES^*) and they can be added up, and finally all the ecosystem service can be integrated through a river basin and/or a river-basin complex. In the meantime, it is not clearly formulated but it would be called as a “Tool Box 3”.

5. ECO-COMPATIBLE RIVER BASIN ASSESSMENT FRAMEWORK

In the preceding chapter we have prepared the tool boxes necessary for ecosystem assessment in particular reference with “ecosystem service”. Here we show a framework of a scenario-driven assessment for a river-basin complex.

We know that the several artificial facilities and the artificial flux network operation which have supported our activities with high population, consume high energy and they have often caused ecosystem degradation, and we aware that it should be somehow restored. To support such a challenge, we have prepared the eco-compatible river basin assessment framework (see Fig.7).

At first, the present situation of a river-basin complex as an assembly of flux network would be represented by using the Tool Box 1, and it is simply accomplished as 0-order approximated flux network. If our research proceeds, the accuracy of the flux network described the present situation should be enhanced through the same framework as described for assessment process.

To restore the river basin, we will prepare several scenario composed of menus in various sites in the river basin which can be proposed depending on the characteristics of the categorized landscape which the peculiar site belongs to: for example river restoration programs in various segments, operation changes of dams and headworks (irrigation intakes), devices for sediment through from dam-reservoirs, changes in farmland management, land use and operations of artificial network, and lifestyle changes. We will conduct an eco-compatibility assessment proposed in this study for each scenario (alternative), and it can be compared each other by an index, “integrated ecosystem service”. The main purpose of the assessment here is relative comparison among scenarios, and thus 0-order assumption can be employed as an expression of the present situation.

As mentioned in chapter 2, we consider a river-basin complex as a complex of categorized landscapes connected by the networks of water and materials, natural and man made. We prepare the tool box to evaluate the ecosystem service and the change of flux there for each categorized landscape (Tool Box 2). It is based on the characteristics of the categorized landscape. For each program in individual scenarios, Tool Box 2 can evaluate onsite ecosystem service and local change of flux for inflow flux on that site given by Tool Box 1.

The change of flux as one of the outputs of the Tool Box 2 for individual sites is fed back to flux network updating analysis (to the Tool Box 1), and ecosystem service produced in categorized landscapes are added up as replacement of fossil fuels for integrated assessment by using the Tool Box 3.

Integrated ecosystem service is employed to compare various scenarios one another.

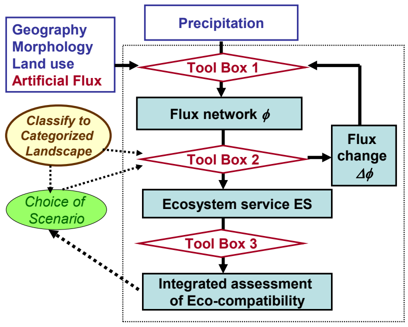

Fig.7 Total system of eco-compatibility assessment

CONCLUSION

In this paper, the framework for eco-compatible river basin assessment is introduced with three tool boxes to support it. Here, a river-basin complex is considered to be composed of categorized landscapes connected one another by flux network, natural and man made. Tool Box 1 can describe flux network, Tool Box 2 can evaluate ecosystem service for each landscape, and Tool Box 3 is prepared for integrated evaluation through river basin. We assume that the eco-compatibility should be evaluated among various scenarios (alternatives) composed of several programs, and the framework discussed here will be able to do so reasonably. Principally the three tool boxes have been prepared. Though they have been applied them to actual river basins (Tool Boxes 2 and 3 have been tested partially), we have not yet apply them to any river basin complex for total assessment, and we are now tackling with a project to design an eco-compatible river basin complex around Ise bay, Japan.

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