River Management for Ecosystem Conservation
- Policy-Making Support through Mathematical Modelling -

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ABSTRACT

Human activity is developed on a river basin, which is a unit of hydrological cycle of the surface of a globe, In a river basin, rainfall is converted to flow regime in a river. Not only water but also various materials are transported along a river, and they support various organisms. Our activity is closely related to these processes and river basin management is a key for sustainability of human activity. In particular, management of rivers must be efficient where the above processes are dynamic.

Since the revision of River law in 1997, ecosystem conservation has become one of the objectives of river management, and we have tackled with the research topics how to recognize the mechanism of river ecosystem where it would be described quantitatively and mathematical modelling is one of powerful means.

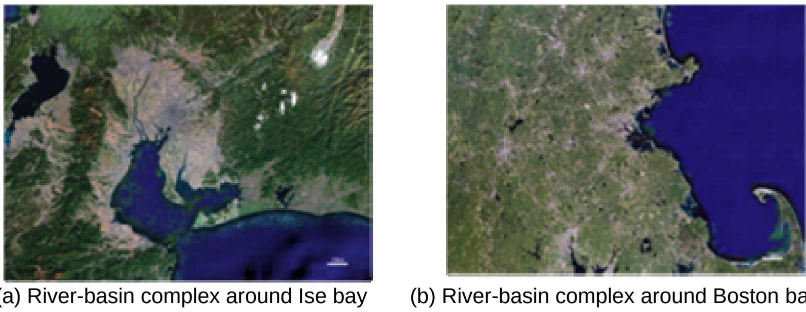
We regard ecosystem as an interrelating system among (1) physical basement, (2) material cycles focusing on the bioelements and (3) biological aspects, and mathematical models to describe respective subsystems are developed in addition the interactions among subsystems. This paper introduces the framework of mathematical modelling and some examples, where it is able to how we are able to recognize not only degradation of ecosystem by human impacts but also rehabilitation effects by new policies and measures of river management.

Keywords: *River basin management, Ecosystem, Habitat, Biophilic elements cycle, Mathematical modeling*

INTRODUCTION

The discipline of “civil engineering” has a mission to support national land grand design, construction and management which create various functions to sustain human activities, The functions are summarized as disaster prevention, resources development and environment management (against pollution and for ecosystem conservation), and these functions are accomplished by facilities (infrastructure), institutional framework and citizen behaviour. Civil engineering includes such wide aspects. In civil engineering, river engineering is responsible to river-basin management based on hydro-science and engineering (hydrology and hydraulics). National land is divided into many river basins, and water policy is to keep the following functions: flood control, water resources management and river-basin ecosystem conservation.

Figure 1 shows a comparison of river basins between Chubu district in Japan and Boston district in USA by satellite photos, and we can recognize intensive contrasts in Chubu river basin. The climatic and geographic characteristics of Japan bring such contrasts in landscape, and particularly in Japan, we have to take care about the river basin in grand design of our homeland. It implies that recognition of national land is a complex of river basins not a complex of merely administrative divisions.



(a) River-basin complex around Ise bay (b) River-basin complex around Boston bay

Fig.1 River basin characteristics

River basin is defined as a catchment in hydrology and/or geography, and it is a pan to receive precipitation where runoff process appears. Runoff implies the conversion from precipitation ($r(t)$=hyetograph) to flow discharge in river system ($Q(t)$=hydrograph), and it is a part of "hydrological cycle" which is constituted by precipitation, runoff and evapo-transpiration. Precipitation and evapo-transpiration sustains the hydrological cycle (water cycle), but between these two processes water travels globally (climatic circulation), but on the global surface a river basin limits the area of the behaviour of water. In this sense, a river basin is a unit of hydrological cycle on the surface of the globe. In a river basin, a conversion from $r(t)$ to $Q(t)$ is the first one when we discuss on mathematical modelling, and it is called "runoff model". In these hundred years, many runoff models have been developed based on modelling physical process and stochastic recognition (impulse response model), and some of them have been useful in policy making process depending on the purpose.

Hydrological cycle in river basin takes a role not only of conveying water but also sediment and various materials including biophilic elements. In transport process of biophilic elements, they change the form: inorganic (nutrients) to organic matters, and they sometimes form biomass. In this sense the hydrological cycle drives even bio-aspects related to various organisms. The word "ecosystem" includes physical basement and material cycles as well as bio-aspects, and it is driven by the hydrological cycle. Thus, a river basin is an assembly of fluxes where a flux implies not only a route but also include transport rate.

From the viewpoint of water policy, water is related to flood control and water resources, sediment is related to debris, erosion-deposition issues and fluvial morphology, and bioelement-transport is concerned with water quality and ecosystem. Thus, river basin management or water cycle management (integrated water resources management) is very important for human activity toward sustainability. However, we have not to forget the above-mentioned functions are most effective in a river as an axis of a river basin, and we can say that river management is efficient and in addition various policy can be applied in river areas most of which is owned by public while most of the other river basin by private. It should be added that river management brings fair polices for various functions: levee and flood-control dam constructions instead of special protection of limited areas, public water resources from river flow instead of limited sources (springs) and groundwater which causes severe ground subsidence. Few people occupying the area protected against flood agree that the owned area is utilized for ecosystem conservation. However, river management is insistently a part of river-basin management.

As for river management, the central government enacted "river law" in 1896 to strengthen the flood control countermeasures, then revised it in 1964 to establish river management for water resources development incorporated to flood control, and then in 1997 revised it again to add river environment in objectives of river management as well as flood control and water resources development.

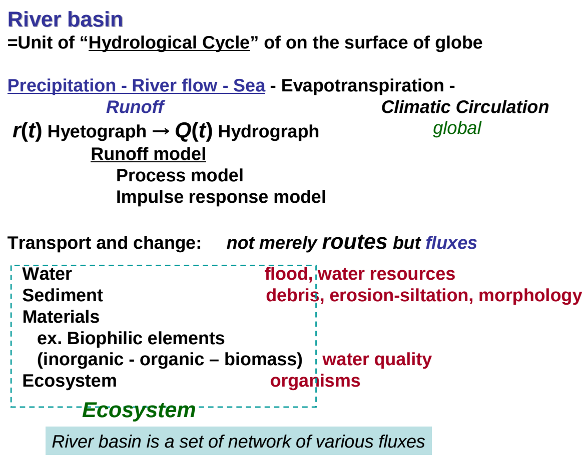


Fig.2 River basin as a unit of water policy

When we discuss a water policy, the following framework, the flow as vision-scenario-design-operation (see Fig.3), is focussed on. This framework should accompany the "accountability" and/or "assessment" which require fairness and transparency. In the visions, we have to clarify the functions necessary for sustainability of human activities. Functions are to be produced by processes in prepared infrastructures with natural system of river basin, and these processes should be reasonably described so that fair explanation how they create the required functions. We may say mathematical modelling is expected to be one of powerful means to keep fairness and transparency.

When we mention the functions, the required levels should be discussed from the social reality. For example, when we say the safety against flood, we set the level such as once 200 years and so on. That is an introduction of the concept of "return period", which needs an assistance of statistical modelling.

Because we often don't have enough datum, we would get a reasonably estimated value. In fact, various techniques have been developed in our fields, academically and practically. The return period concept has been employed when we discuss a designed drought in water resources policy, too. However, we have not proposed any standard for ecosystem yet, because we have not yet well understand ecosystem as a target for national land grand design. Hence, we, river engineers and researchers, started a cooperative study with other disciplines to hydrology and hydraulics such as biology, ecology and limnology. In addition to interdisciplinary cooperative study, river engineer had to make a framework how to recognize the ecosystem, otherwise innumerable information about ecosystem could not be taken into account in policy making.

RIVER ECOSYSTEM

We regard ecosystem as an interrelating system among (A) physical basement, (B) biological aspects, and (C) material cycles focusing on the bioelements such as N, P, C, O, *etc*. (see Fig.4). Subsystem (A) is also an interrelating subsystem among morphology, flow and sediment transport in a river, which is specified as "fluvial hydraulics", and it must not be forgotten that vegetation growth and decay affect the fluvial processes intimately. Subsystem (B) has three different aspects: Growth of individual, population change by breeding and interaction among species represented by "food web" and "species diversity". Subsystem (B) is supported by (A) as habitat, and related to (C) through production-assimilation and metabolism-decomposition. In subsystem (C), materials exist in some forms: inorganic (nutrients) or organic, furthermore in biomass, and they are transported and changed in forms through physical, chemical and biological processes. Transport and changing processes require peculiar morphology and flow dynamics, and in this sense (C) is supported by (A) as similarly as (B) by (A). Summarizing the above, we have three subsystems, which form interrelating systems respectively, and they are interacted one another.

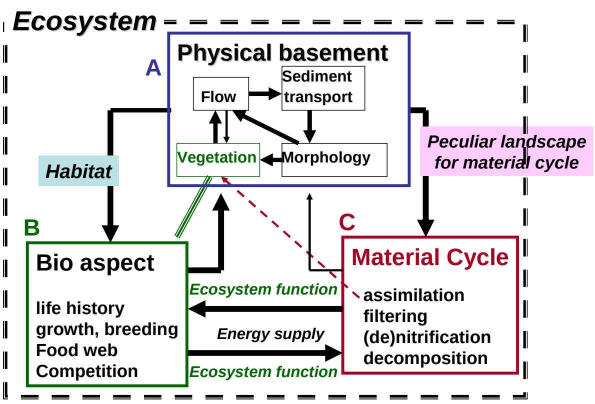


Fig.3 River ecosystem

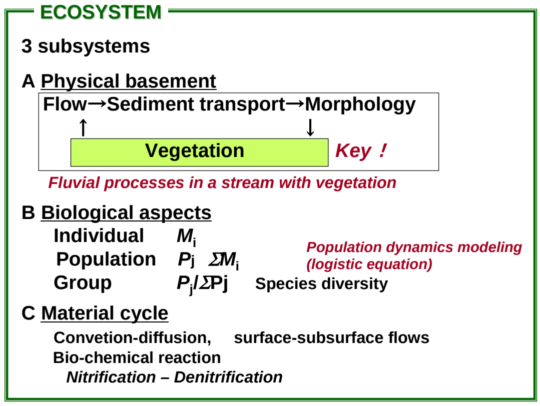


Fig.4 Three subsystems constituting river ecosystem

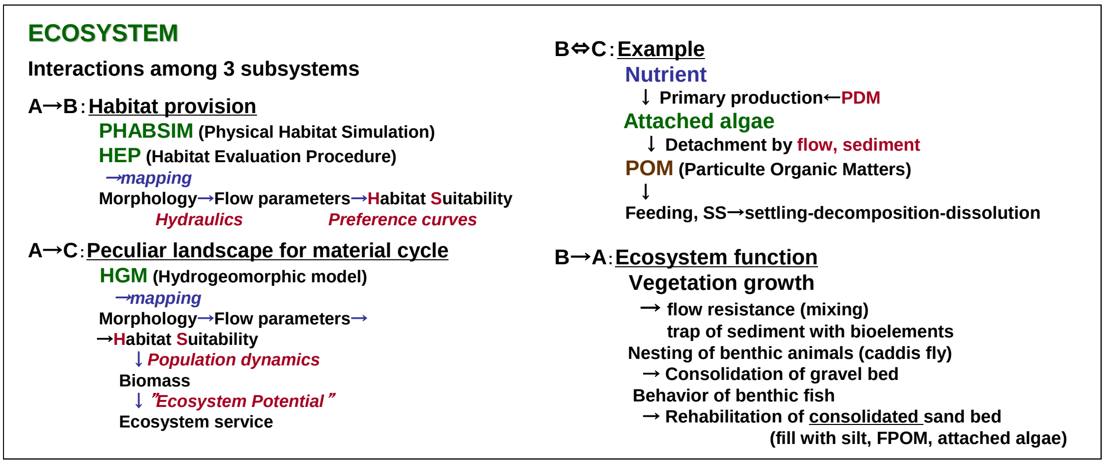


Fig.5 Interactions among 3 subsystems constituting ecosystem

As above-mentioned, we recognize the ecosystem as a complex of three subsystems (see Figs.3 and 4) and the interaction among them (see Fig.5). We should develop mathematical models to describe the respective subsystems: fluvial process, bio-material cycles, and behaviours of organisms; and in addition, we have to develop mathematical models to describe interactions among subsystems: Habitat provision ((A) to (B)), providing specialized landscape elements for peculiar processes in material cycles, changing of bioelements between biomass and non-biomass forms ((B)~(C), and biological actions to change physical process ((B) to (A)). In Fig.4, some interactions are shown. As for habitat suitability, the mathematical modelling was developed as PHABSIM (Physical Habitat Simulation) or HEP (Habitat Evaluation Method). In order to specify the morphology for respective processes in material cycle, HGM (hydro-Geo-Morphological modelling) is available.

Some examples from mathematical modelling for respective aspects will be introduced in the following part of this paper, where model for fluvial processes in streams with vegetation, habitat suitability evaluation and biomass dynamics are introduced based on the recent results from our laboratory. In particular, the author would show how we are able to recognize not only degradation of ecosystem by human impacts but also rehabilitation effects by new policies and measures of river management through applying such mathematical modelling. With suitable habitat and specially prepared site of material cycle, biomass must grow and its aspect can be analyzed by "Population Dynamics Modelling". Bio-aspects sometimes affect the physical basement: Vegetation growth and decay affect the flow resistance, some species of benthic animal brings consolidation of a bed, and behaviour of some species of benthic fish rehabilitates a sand bed degraded by silt deposition or by attached algae.

FLUVIAL PROCESSES IN STREAMS WITH VEGETATION

Physical basement of river ecosystem is subjected to fluvial processes, and proper description of fluvial process affected by riparian vegetation is a key. When a river is discussed, it is important to focus on the hierarchy of landscape in scales: river basin, river from headwater to sea, segment, reach, unit, and sub-unit scales. In particular, river management should be taken into account from upstream to down stream, but segment is an important scale, where physical processes are similar. Classification into mountain river, gravel-bed river (in fluvial fan), sandy river (in alluvial plain) and estuary is particularly significant. The physical processes are under similarity in a segment and it is mainly subjected to the substratum diameter and the stream slope. The detailed characteristics of segment are represented by those of reach which is repeated in a segment. For example, a photo in Fig.6 is a sandy river segment and sand bars appear aternately, and we say that it has such a "structure". When we close up into a unit of reach, a sand bar, we find more detailed morphology, which is sub-unit scale and is often called "texture" (see Fig.7). The "structure" is determined by fluvial process caused by major flood while the "textures" are by usual floods.

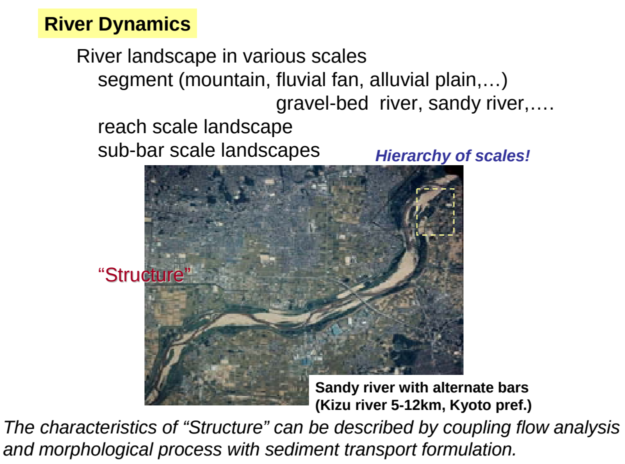


Fig.6 "Structure" in sandy-bed segment

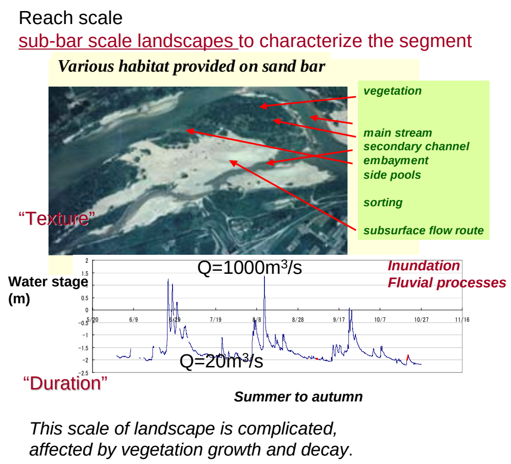


Fig.7 Reach scale characterized by "textures"

The structure can be analyzed by using depth-averaged 2D flow with transport equation of sediment, and in particular numerical simulation techniques have been developed. Fig.8 is an example of numerical simulation of alternate bars evolution, and such rather regular sand bars can be reproduced numerically.

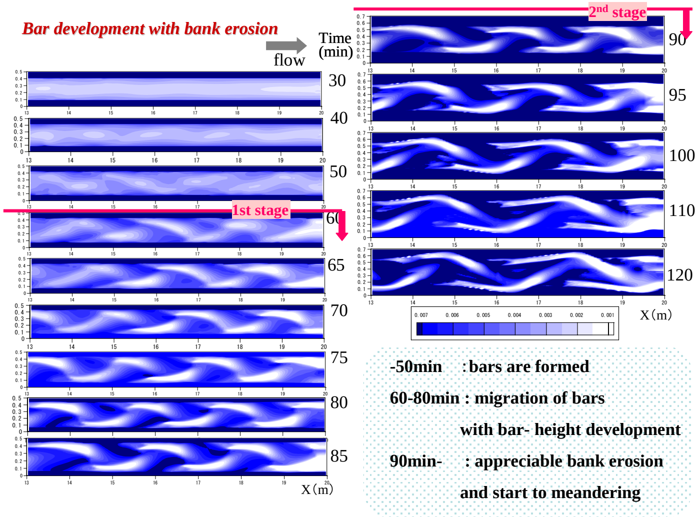


Fig.8 Numerical simulation of evolution process of alternate bars

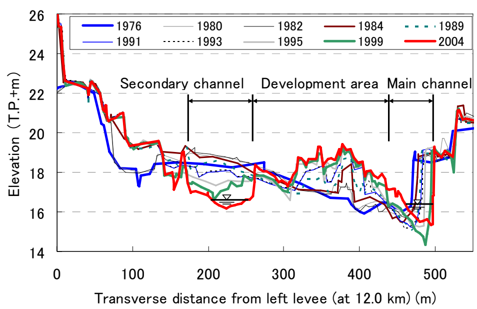


Fig.9 Transition of sand bar geometry affected by vegetation growth

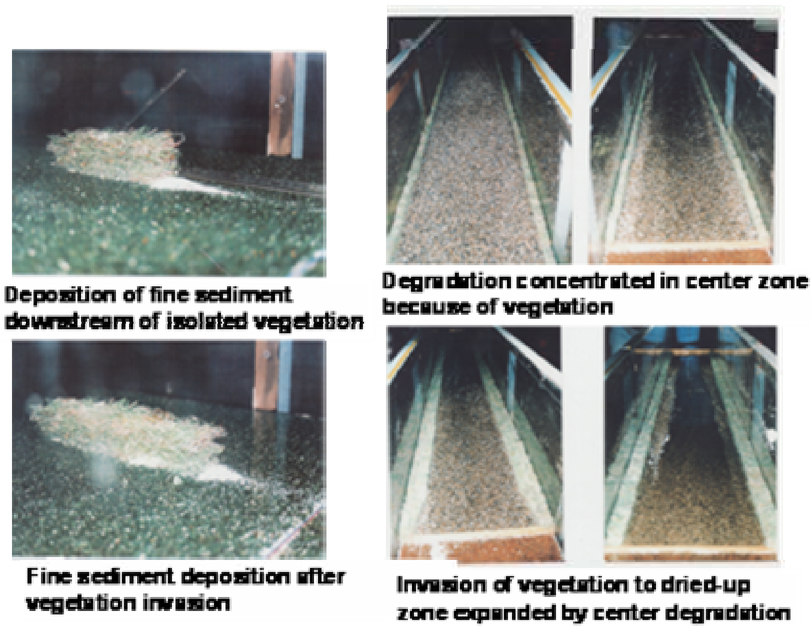


Fig.10 Laboratory experiment for fluvial processes affected by vegetation

Figure 9 shows the transition of bar geometry represented by cross-section survey of actual sand bar, and simple geometry in early 70's have changed to complicated one. The characteristics are formation and development (diversification) of longitudinal ridges with vegetation, which are examples of fluvial processes affected by vegetation growth, and the elementary processes have been checked by laboratory experiments shown in Fig.10. In fundamental laboratory experiments, artificial porous medium was employed instead of real vegetation, and polystyrene particles instead of sand. Such experiments where elementary processes are abstracted have been utilized for process modelling in mathematical calculation (for example, how to describe "vegetated region" and how to assume the location and its enlargement).

An approach to fluvial processes in streams with vegetation was well developed (Tsujimoto, 1999), and various processes governing river-landscape transition have been described mathematically. However, we often require an additional model concerning with vegetation strategy which is related to the subsystem (B) (growth-decay model). For example, Fig.11 shows the enlargement of vegetation-covered area after dam construction, which caused the decrease of magnitude of annual maximum flood discharge. In order to simulate such process, we derived the scenario to represent the strategy of vegetation growth, shown in Fig.12: Vegetation-covered area increases with G% annually, and individual trees grow gradually. While, major floods destructs vegetation without dam control, but minor floods after dam construction cannot destructs vegetation with grown trees.

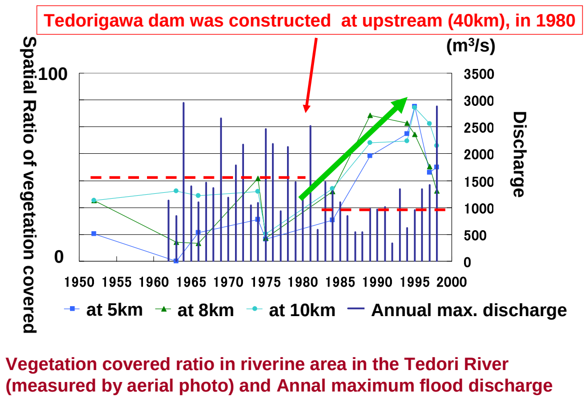


Fig.11 Enlargement of vegetation-covered area after dam construction (Tedori river)

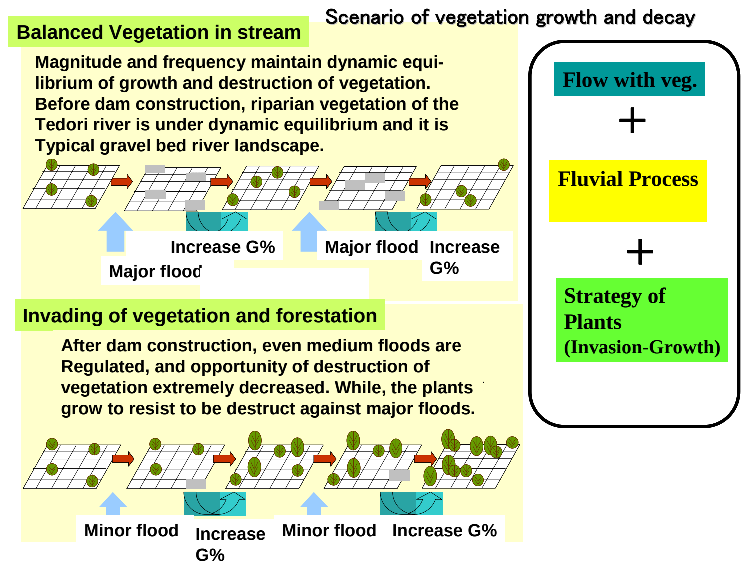


Fig.12 Scenario prepared for description of vegetation growth and decay

BIO-ASPECTS OF ECOSYSTEM

Bio-aspects are also represented by a mathematical model, particularly by the so-called population dynamics model (PDM). Its simple expression is written as follows for biomass of an individual or for population of one species. It often accompanies more terms, and multiple equations are prepared for different species. For example, 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.

Figure 13 shows an example for growth of attached algae in a gravel river. While, attached algae is detached eventually by bedload transport during flood, and the biomass shows temporal fluctuation (Tsujimoto & Tashiro, 2004).

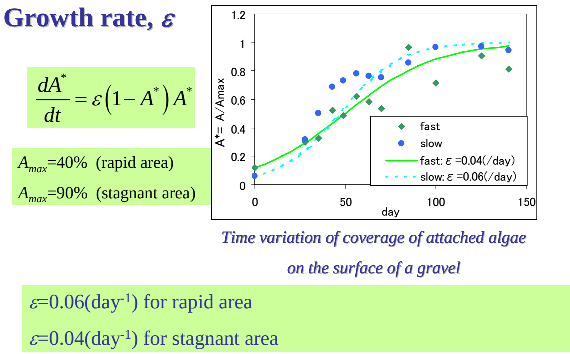


Fig.13 Application of PDM for attached algae

Sometimes the growth of organisms is not so simple. For example, we have developed the growth model of *Flagmites Japonica*, a plant growing on a sand bar, where the condition of supplying water with nutrients is not good. Active uptake during better condition and its storage in their roots are a strategy of those plants, and such a process is described by coupling a usual growth model with SPAC (Soil-Plant-Atmosphere Continuum) model.

HABITAT SUITABILITY ANALYSIS

In order to make a habitat map for a peculiar species of organisms, the preference curves are prepared, which relate the habitat suitability with the physical parameters. In other words, the preference curves are mapping functions to convert the 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 techniques follow the so-called PHABSIM (Physical Habitat Simulation) or HEP (Habitat Evaluation Procedure).

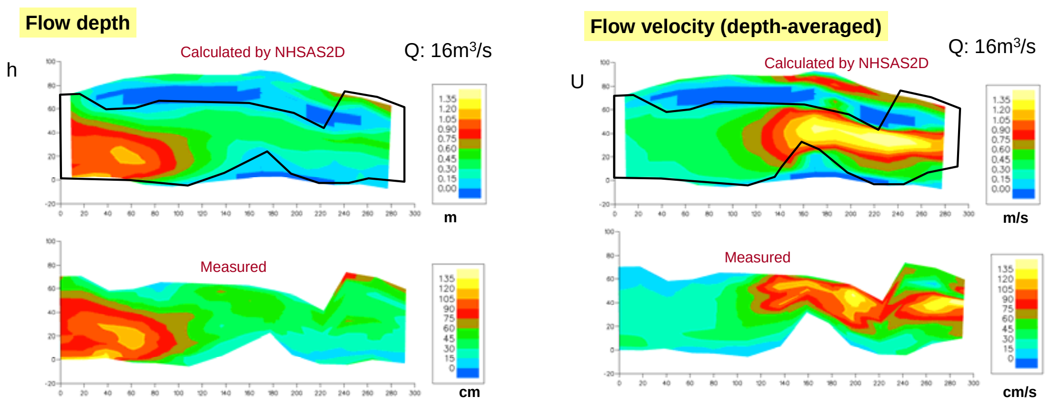
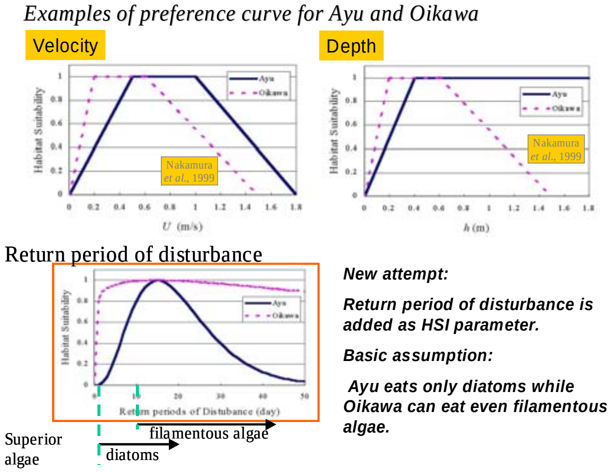


Fig.14 Physical parameters mapping in a reach of a gravel river segment (Yahagi river)



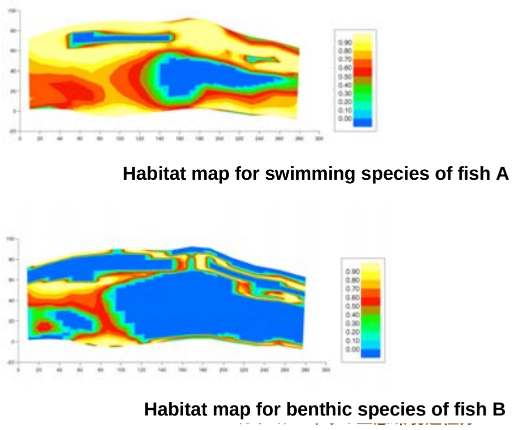
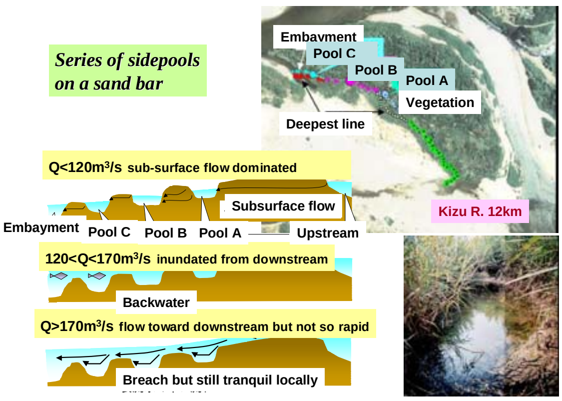


Fig.15 Examples of preference curves for some species of fish

Fig.16 Examples of habitat maps for fish

On discussion of habitat, we have to take care about the "life cycle" of the target organism. For example, an organism requires not only daily habitat but also spawning site, hatchery, nursery, feeding (hunting) site and emergency refuge for floods and/or draught. For example, "temporary waters" such as embayment and side pools provide emergency refuge during flood. Side pools are connected one another by subsurface flow usually, but during flood, they becomes submerged and connected from downstream opening back water area (embayment), and there are tranquil zones even when the upstream entrance breaches at the peak of flood (see Fig.17). Moreover, such temporary waters supply spawning site, hatchery, nursery for some species of fish. Particularly in this segment of the Kizu river, it is utilized by an endangered species, *Acheilognathus longipinnis Regan* (see Fig.18). For the above-mentioned argument, numerical simulation for detailed flow affected by complicated morphology and vegetation should be carried out to confirm the habitat suitability.



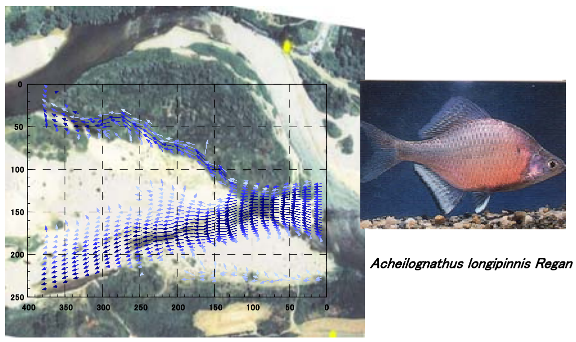
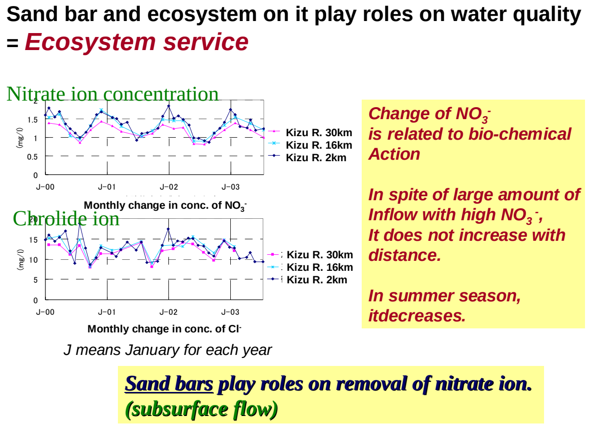


Fig.17 Temporary waters to provide habitat

Fig.18 Information on detailed flow and fish

MATERIAL CYCLE RELATED TO BIOASPECTS IN RIVER ECOSYSTEM

Figure 19 shows the time series of water quality monitored at longitudinally different three points of the Kizu river. Nitrate-ion and Chloride-ion concentrations are shown (In Fig.19, J-00 means January 2000, for example). As for the former (NO_3^-), a typical seasonal pattern can be recognized as it decreases in summer season, and there are small differences among the data monitored at different points though there are several tributaries in to the river with heavier ion load. On the other hand, the latter (Cl^-) hardly show a typical seasonal pattern. The former is affected by bio-chemical action and its activity is higher in summer, while the latter cannot be affected by bio-chemical action. Thus, the data shown in Fig.19 has become a motivation for a research on reaction of ecosystem to the river. River has a function to support ecosystem, while ecosystem brings a function, and that can be often regarded as "ecosystem service". Fig.19 suggests one of the examples of ecosystem service. The scenario is as follows: The segment in 2-30km of the Kizu river contains many sand bars, and water is conveyed not only by surface flow but also by subsurface flow which is stimulated by the existence of sand bars. Fig.20 shows the relation between the sand bar pattern (characterized by vegetation and secondary channel) and the subsurface flow behaviour, and we can recognize it by mathematical calculation of subsurface flow as well as excellent monitoring in the fields.



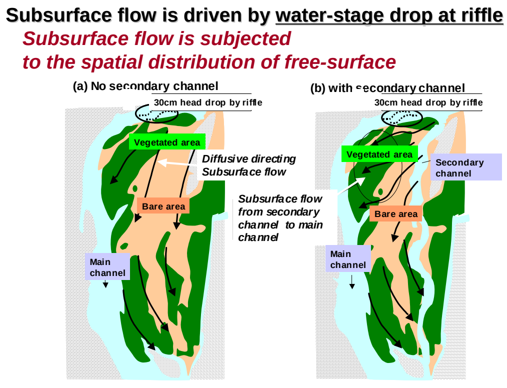


Fig.19 Temporal and spatial changes in water qualities along the Kizu river

Fig.20 Sand bar characteristics and subsurface flow

When we expect that the recognition of river ecosystem supports an ecosystem conservation policy, a concept "ecosystem service" is strategically employed: Physical basement of rivers supports bio-aspects or various organisms, and it reversely acts as an advantage for rivers or human activity, and one of examples are water purification through ecosystem service introduced in the above. If so, we can start an argument such what parts (elementary landscape units) of a bar are functionally efficient for water purification to be preserved, or how many bars must be preserved among many sand bars in a segment.

In order to clarify the function of elementary landscapes of a sand bar, various techniques to quantify the function are employed in the field study. Fig.21 shows one of them, where "stable isotope method" is applied. We measured not only nitrate-ion concentration (NO_3^-) but also the ratio of Nitrate isotope (heavier nitrogen), $\delta^{15}N$. Decreases of both the concentration and NO_3^- and $\delta^{15}N$ indicates denitrification (emission of nitrogen gas to the atmosphere), and it is pure purification (out release of N from the river system). Based on such field studies, we can specify the function of elementary landscapes of a sand bar. In a sand bar, vegetated area shows an intensive function of denitrification because the organic matters produced from vegetation requires Oxygen or the subsurface flow layer is intercepted from the atmosphere with impervious fine soil trapped by vegetation brings anaerobic condition (low dissolved oxygen condition), where is a good habitat for anaerobic bacteria to contribute denitrification.

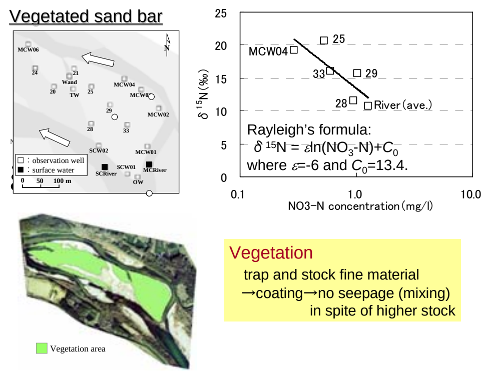


Fig.21 Stable isotope method to specify material-cycle process

For the time being, we cannot evaluate all the ecosystem service, but important ecosystem service can be added up as potential how it replaces fossil fuels and it may become an index of "value " to explain why the river ecosystem should be conserved.

As for a summary of this chapter, Fig.22 (Nohara 2007, from the report of the special coordination fund for promoting science and technology for sustainable national land management 2006-10, "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) .is an intuitive sketch which suggests where and how the respective elementary landscape units play roles for providing habitat, and how the biomass functions in various process of material-cycle regarded as "ecosystem service" in a river landscape.

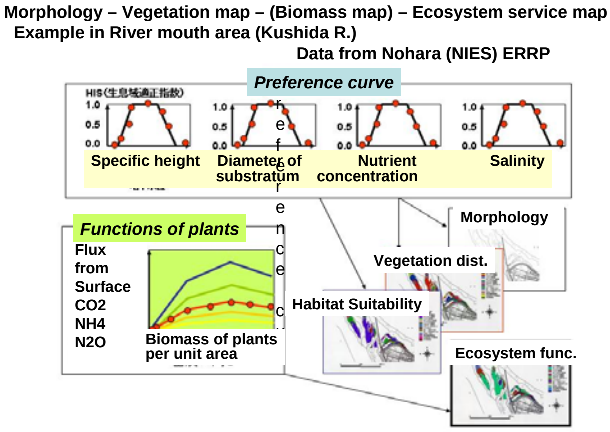


Fig.22 Elementary landscape units and their functions

CONCLUSION

The author sincerely appreciates Dr. T. Sakajo who provided him an opportunity to give an invited lecture on PRESTO Seminar in Hokkaido University, on the 13th June 2008, and this paper has been reproduced from the contents of this lecture. In this paper, it is explained how the river ecosystem is recognized as the process-complex or an interacting system. The research corporation among hydrology, hydraulics, biology, ecology and limnology has been efficient to bring various modelings, which is able to be employed in policy making for river and river-basin management, particularly in its accountability or assessment process. All processes included in the system have been clarified through not necessarily perfect observations or monitoring in the fields. Understanding of the field data is an important part, and various mathematical tools are expected such as data processing, statistical analysis, stochastic forecasting, and GIS techniques. On modeling the system, dynamism is an important aspect not only in physical processes but also in bio-processes, and various mathematical techniques are expected to be engaged. And, the process of policy making, based on the system, various conversions (morphology to flow characteristics, to habitat suitability, to biomass, to ecosystem service and so on) are necessary, and it requires mapping techniques in mathematics. Numerical tools have now become familiar to us, but meanwhile a kind of intuition for the processes or a system comes from rather based on mathematical relations for example relations among equations and solutions. In this sense, we expect interdisciplinary networks not only with several natural sciences in understanding of a system but also with mathematics in data processing, analyzing the processes, algorithm for accountability and intuition to the processes.

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