Available online at www.sciencedirect.com
SciVerse ScienceDirect
Procedia Environmental Sciences 13 (2012) 1246 – 1253
Procedia Environmental Sciences

The 18th Biennial Conference of International Society for Ecological Modelling

Nutrient Transport and Change Driven by Sub-surface Flow in Alternate Bar Reach

Makiko Obana*, Yuji Toda, Tetsuro Tsujimoto

Nagoya university, Furo-cho Chikusa-ku, Nagoya, Aichi 464-8603, Japan

---

Abstract

The landscape of a river sandbar is composed of several elements, including vegetation, bare areas, side-pools and so on. For sandy river management, it is necessary to determine the contributing factors for the ecosystem functions of alternate bar segments. In recent years, it has been reported that sandbars have a water purification function involving denitrification driven by sub-surface flow, but the details are still unknown. The objective of this study was to develop a model that could be used to examine how the nitrogen is trapped and retained by several elements of a sandbar in an alternate bar reach. We also developed a framework to analyze the temporal change in the denitrification by using a numerical simulation, aerial photos, and a water quality information system. The numerical simulation was performed under the discharge and morphological conditions of the Yahagi River in the Chubu region of Japan. The main results of this study are that the temporal change in the denitrification ecosystem function in a sandbar reach can be quantified using the proposed model and the denitrification activity has increased over the past 40 years. In addition, it was clearly shown that differences in the vegetation distribution and sandbar shape affect the nitrogen dynamics. Thus, the numerical simulation has made it possible to determine the most effective vegetation patterns to maximize the ecosystem function in a sandbar.

Keywords: Nutrient transport; sub-surface flow; denitrification; temporal change; numerical simulation

---

* Corresponding author. Tel.: +81-52-789-4626; fax:+81-52-789-3727.
E-mail address: mobana@civil.nagoya-u.ac.jp.

doi:10.1016/j.proenv.2012.01.118

1. Introduction

In Japan, ecosystem conservation has been an issue for river management since 1997. To ensure ecosystem management, it is necessary to set some clear standards for ecosystems, similar to what has been done for flood control and water resource utilization. For the time being, the goal for a river environment is still ambiguous. Although landscape conservation is an example that is used in plans, it is only a term and does not designate quantitative goals. In this paper, we focus on a downstream segment with alternate bars in a sandy river. In a river ecosystem, it is very important to conserve a sandbar landscape because sandbars provide habitat, as well as, an appropriate space for the peculiar elementary processes of the material cycle, the exchange of biophilic elements between biomass and non-biomass and other actions. Sandbar landscape conservation demands a clear understanding of the role played by the sandbars in a river by quantifying the sandbar ecosystem value. For this quantification, the "ecosystem service [1]" concept may be useful for ecosystem conservation. According to the "UN Millennium Assessment" [2], such ecosystem services can be divided into several categories: (i) environmental regulation, (ii) food production, (iii) habitat provision, and (iv) cultural resources, including amenities and recreation. We focus on "water purification" in this paper, which involves the removal of nitrogen (denitrification) from river flow.

As for denitrification in a sandbar, various studies have been done recently. Shade *et al.* [3] reported the assimilation and reduction of inorganic nitrogen and organisms in the exchange process for the surface-subsurface water flow in a sandbar. A sandbar landscape is composed of sub-bar-scale landscape units that are smaller than the sandbar scale including vegetation, bare areas and so on. Several reports [4], [5], have shown that the behavior of sub-surface water flow and material transport in a sandbar are affected by the relationship between the sub-bar-scale landscape units and physical conditions (grain size, sandbar elevation, etc.). Another report [6] clearly showed that the denitrification potential can be distinguished in the vegetation area of a sandbar, and the authors developed a numerical simulation model that considered sub-surface water flow and the distribution of the vegetation forms [7].

The research mentioned above showed that it is important to focus on the connections between the respective landscapes by the water/material flux network. In an aquatic area, some landscape units such as riffles and pools are connected by a flux network of surface flow, while in a terrestrial area, various landscape units are connected by flux networks of subsurface flow. In this sense, the subsurface network plays a great role in a sandbar ecosystem.

The objective of this study was to develop a model that could be used to examine how the nitrogen is trapped and retained by several sandbar elements in an alternate bar reach. We also developed a framework to analyze the temporal change in denitrification using a numerical simulation, aerial photos, and a water quality information system.

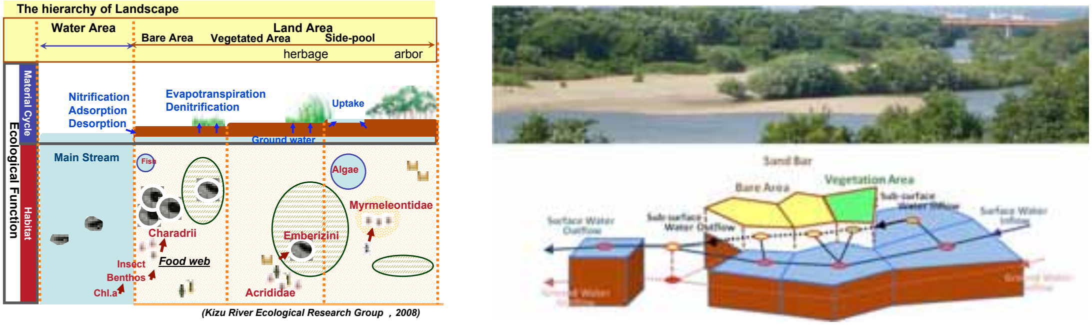
2. Some basic concepts

2.1. Structure and function of river ecosystem

We considered a river ecosystem to be a natural unit consisting of the following three subsystems [8]: (A) the physical basement, (B) biological aspect, and (C) material cycle aspect. The physical basement involves the sediment transport, morphology, and vegetation in the water flow. The biological aspect refers to the dynamics such as the population, community structure, energetics, predation, and competition among various species. As for the material cycle, bio-elements (N, C, O, P, etc.) are transported in the water flow and exposed to various fundamental processes. The ecosystem contains various interacting subsystems. When assessing a river ecosystem, it is important to clarify which parts of the sandbars have an ecological function. The physical basement provides habitats corresponding to life cycles (from (A) to (B)) and characteristic places for ecological processes (from (A) to (C)). We here define these (habitat and material cycle) as “ecological functions”(EF) of the physical basement. The “ecosystem service (ES)” concept is defined as an ecosystem function that provides some benefit to humankind.

2.2. Landscape elements and their connectivity

River landscapes consist of a physical background such as the morphology and hydraulics, as well as the material cycle and biological aspect. They are also characterized by a diverse array of surface waters, alluvial aquifers, riparian systems, and geomorphic features. These landscapes have a spatial hierarchy composed of segments, reaches, and units that are classified by scale in the river system. In river management in Japan, we often recognize the scale hierarchy, and the segment scale is very large. We often classify segments as follows: mountain river, valley, gravel-bed river, sandy river, delta, and estuary. These are principally categorized by using the bed slope and sediment size of the bed materials, and are often characterized by the bed forms. The reach scale is composed of a couple of sand-bars formed by the river flow and bed condition. Moreover, a sandbar is consists of several sub-bar-scale landscape units, such as fine sand mounds, gravel belts, grass covered areas, forests, shore-line, secondary channels, side-pools, and side-arms. These spatial divisions within the hierarchy have individual time scales. Previous studies for a sandy river showed that these sub-bar scale landscape units support the typical ecological functions [9]. Fig.1 (a) summarizes the relationships between the sub-bar-scale landscape units and ecological functions. Furthermore, all the landscape units are connected by surface and sub-surface water flow, as shown by Fig.1 (b).



(Kizu River Ecological Research Group , 2008)

Fig.1. (a) Relationship between landscapes and ecological functions; (b) connectivity of sandbar landscapes by sub-surface water flow

3. Sandy River Segment in Yahagi River as Study Field

An investigation was conducted on the Yahagi River (Chubu region, Japan), which has a sandy river segment with alternate bars, as shown in Fig.2. The length was around 6km, the average bed slope was 1/1200, and the bed was composed mainly of coarse sand mixed with fine sand and gravels. The channel width was around 250m, and around 6 alternate bars in a length of about 1 km. Some of these were appreciably vegetated, while some were less vegetated (rather bare). Because of the construction of dams in the upstream region, this segment is exposed to appreciable bed degradation and the excessive growth of riverine trees. As for the water quality in the target segment, industrialization and urbanization peaked around 1955 and water pollution became severe in connection with these trends. One of the main causes of this pollution was industrial and human activities. As one water quality index, the nutrient concentration tripled in 50 years in spite of various efforts to improve the water quality by some communities along the Yahagi River. In this study, we selected a couple of sandbars, named No.3 and No.4, as our study site.

Fig.2. Study site in Yahagi River basin

4. Temporal and Spatial Distributions of Landscape Elements

A new procedure has been introduced to distinguish and calculate each landscape as a sub-bar-scale landscape [5]. This procedure uses several aerial photos taken since 1976. By employing this procedure, each sandbar was classified into several landscape categories using the difference in the surface cover condition (terrestrial, vegetated, or bare areas). The results are shown in Figs.3 (a) and (b). The cumulative change in the vegetated area during the approximately 40-year period was 50%. The sandbars in 2010 are 1.5 times larger for a long time. It was clearly seen that the vegetated area in the target reach was significantly expanded. Moreover, the physical characteristics of the landscape elements were investigated by field observations in 2010. The categorization of the sub-bar-scale landscapes mentioned above facilitates the management of all landscape elements as one unit to conserve the ecosystem.

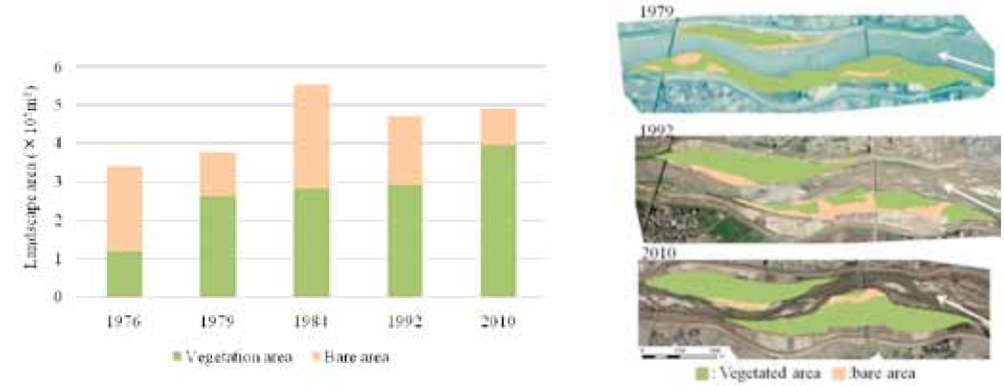


Fig.3. (a) Temporal distribution of topographical features of sand bar at study site; (b) examples of temporal distribution of sandbar landscape

5. Numerical Simulation Method

A numerical computation was conducted to quantify the denitrification rate driven by sub-surface water flow in relation to this sub-surface flow and nutrient transport in a sandbar. This computation was composed of two parts, which were used to calculate the sub-surface flow and nutrient transport of a sandbar using our developed model [7].

5.1. Sub-surface water flow

A two-dimensional sub-surface flow analysis was conducted by regarding the sub-surface flow in a sandbar as unconfined aquifer flow. At our study site, there was an impermeable layer one meter below the sub-surface water level. Hence, we assumed that the sub-surface flow was planar and considered the Dupuit-Forchheimer hypothesis using the following equation:

$$\lambda \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(kh \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y}\left(kh \frac{\partial h}{\partial y} \right), \tag{1}$$

where h is the height of the ground water, λ is the porosity rate, and k *is* the hydraulic conductivity.

5.2. Nutrient transport

A schematic view of the process of the nitrogen cycle and definitions of the symbols used are shown in Fig.4. The nitrogen form considered in our analysis consisted of three kinds of inorganic nitrogen, ammonium, nitrate, and nitrite ion. Their concentrations were represented as $C_{NH4\text{-}N}$, $C_{NO3\text{-}N}$, and $C_{NO2\text{-}N}$, respectively. These inorganic nitrogen concentrations ($C_{NH4\text{-}N}$, $C_{NO3\text{-}N}$, $C_{NO2\text{-}N}$) were estimated using the advection-dispersion equation, considering the microbial process, as follows:

$$\frac{\partial C_i}{\partial t} + u\frac{\partial C_i}{\partial x} + v\frac{\partial C_i}{\partial y} = \frac{\partial}{\partial x}\left(D\frac{\partial C_i}{\partial x} \right) + \frac{\partial}{\partial y}\left(D\frac{\partial C_i}{\partial y} \right) + R_i, \tag{2}$$

where u is the velocity of the ground water, D is the variation coefficient and R_i is the biochemical reaction term. As for the biochemical reaction term, we considered its formularization by combining it with each reaction of the nitrogen cycle. For further details, the reader should refer to [7].

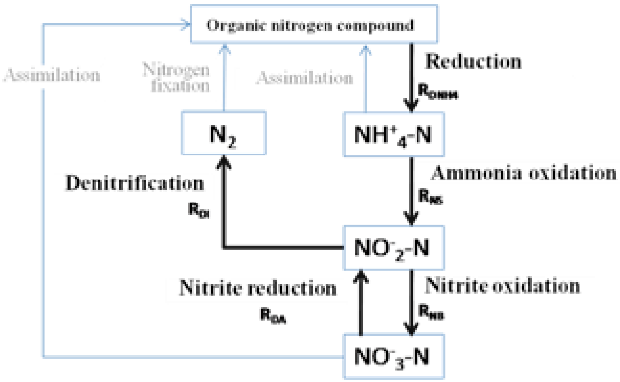


Fig.4. Process of nitrogen cycle

5.3. Computational conditions

When determining the boundary condition of Eq. (1), the boundary between the surface flow and sandbar is used as the surface water level, and the transverse direction of boundary on the side of the levee in sandbar is given a zero surface slope. Based on the field observation [7], the hydraulic conductivities used for the vegetated and bare area sub-bar scale landscapes in our calculation were $k = 5.0 \times 10^{-3}$, and $2.0 \times 10^{-5} (m/s)$,respectively.

When determining the other side, the boundary condition of Eq. (2), the boundary part of the sub-surface inflow to sandbar is given as the stream water quality value ($C_{NH4\text{-}N}$, $C_{NO3\text{-}N+NO2\text{-}N}$), the boundary part of the sub-surface outflow to surface flow is given a zero concentration gradient, and the transverse direction of boundary on the side of levee in sandbar is given as zero for the surface slope. The values of the parameters for the biochemical reaction term used in the present computation are summarized in [7].

6. Transition of denitrification activity as ecosystem service

6.1. Supposition of sandbar landscape transition in numerical simulation

In this study, it was very important to quantify the ecosystem service change in the target area during the 40-year period by using the GIS technique presented in chapter 4 and the numerical simulation presented in chapter 5. From the point of view described above, we considered the denitrification activity change as a water purification function along the landscape transition process mentioned above. The sandbar landscape transition was simplified as a change in the plane shape of the sandbar and the distribution of the vegetated area. With these assumptions, a numerical computation was performed under the conditions of the six cases presented in chapter 4, based on the characteristics of the sub-bar-scale landscapes for each year.

Regarding the stream water quality during the 40-year period, several observations have been reported about the long-term transition of the water quality [10], [11]. The numerical calculation was conducted under a stream water quality based on field observation results as follows: $C_{NH4\text{-}N}$=0.023(mg/l), $C_{NO3\text{-}N+NO2\text{-}N}$=0.55(mg/l) after 1992 and $C_{NH4\text{-}N}$=0.023(mg/l), $C_{NO3\text{-}N+NO2\text{-}N}$=0.40(mg/l) before 1992.

6.2. Calculation results and discussion

The calculation results were used to estimate the temporal distribution of the denitrification activity. Fig.5 shows that the denitrification activity tended to increase over a long period as an effect of the expansion of the vegetation area. This was because a vegetation area has higher potential denitrification activity than a bare area [6]. As a reason the maximum value was seen in 1984, it is considered that the effect of the sandbar landscape area appeared sensitively. Moreover the upstream part of the vegetated area of a sandbar had a higher denitrification activity than the downstream part based on the results of the spatial distribution of each sandbar. The denitrification activity differed according to the length from the waterside [7]. The results mentioned above showed that the denitrification activity rate is significantly affected by differences in the sandbar area, especially the vegetated area.

The results for 1992 and 2010 showed almost the same ecosystem service value in spite of the difference in landscape area. The distribution of the vegetation in sandbar No.4 had several small vegetation masses along the waterside, as shown in Fig.4. Previous research [7] showed that multiple vegetation masses along the waterside enhance the denitrification activity. Therefore, from the viewpoint of the water purification function, what is important in river management is not so much the size of the vegetation area, but rather how many small vegetation masses exist.

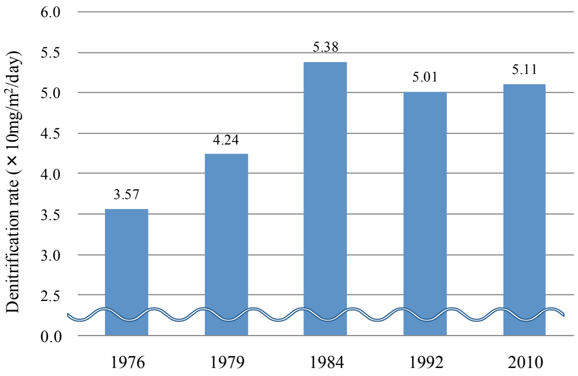


Fig.5.Temporal change in denitrification rate

7. Conclusion

A landscape assessment method based on an evaluation of ecosystem service in a sand bar segment was proposed in the preceding chapters. We focused on the ecosystem service in particular through the material cycle. An ecosystem service is brought about by an ecosystem function, which has been clarified as an interaction among the three subsystems composing the ecosystem. Furthermore, the ecosystems of a unit and segment are composed of scattered landscape units connected by water/material flux networks driven by subsurface flow as well as surface flow.

The main results of this study are that the temporal changes in an ecosystem function such as denitrification in a sandbar reach can be quantified by using the proposed model and the denitrification activity has increased during the past 40 years. Moreover, it was clearly shown that differences in the vegetation distribution and sandbar shape affect the nitrogen dynamics. Thus, it has become possible to propose vegetation patterns that are effective at maximizing an ecosystem function in a sandbar. Although it has been suggested based on the results of this study, that the temporal changes in river landscapes such as the expansion of vegetation areas play an active role in mitigating the water pollution caused by an increase in environmental loads, it is speculated that the original landscape (sandy river) of the target river was changed by the expansion of vegetation. This may have caused a degradation of the river ecosystem. Hence, it is evident from the general overview that more work using different approaches is necessary.

Acknowledgements

This study was conducted as a part of the project, “Research and Development in Assessment and Restoration for Eco-compatible Management of River Basin Complex around Ise Bay”, a program of the Special Coordination Fund for Promoting Science and Technology for Sustainable National Land Management, provided by the Ministry of Education, Culture, Sports, Science & Technology, Japan.

References

[1] Constanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M. The value of the world's ecosystem services and natural capital. *Nature*, 1997; **387**, 253-60.

[2] United Nations. Ecosystem and human well-being synthesis, *Millennium Ecosystem Assessment Reports*, 2005.

[3] Shade JD, Fischer SG, Grimm NB, Seddon JA. The influence of a riparian shrub on nitrogen cycling in a Sonoran Desert stream, *Ecology*, 2001; **82**(12), 2263-3376.

[4] Katakai K, Kamei T, Sumi T, Tsujimoto T. Subsurface water transport and nitrogen behavior in a sandbar with vegetation in Kizu River, *Advances in River Engineering,* JSCE, 2006; **12**, 489-94. (in Japanese)

[5] Jacobs TC, Gilliam JW. Riparian losses of nitrate from agricultural drainage waters, *Journal of Environmental Quality*, 1985; **14** (4), 472-8.

[6] Tsujimoto T, Obana M, Anbutsu K. Spatial-temporal distribution of ecosystem service potential from viewpoint of biophilic elements cycle in Sand River segment with alternate bars, *Proc. 8th International IAHR Symposium on Ecohydraulics*, 2010, Seoul, Korea, CD-ROM.

[7] Obana M, Toda Y, Tsujimoto T, Nojiri K. Denitrification activity through subsurface flow in sandbar with vegetation, *Annual Journal of Hydraulic Engineering*, JSCE, 2011; **55**, 1363-8. (in Japanese)

[8] Tsujimoto T, Toda Y,Obana M. Assessment framework of eco-compatible management of river basin complex around a bay, *Advances in Hydro-Science & Engineering*, 2008; **8**, ICHE, CD-ROM.

[9] Obana, M., Inoue K, Tsujimoto T. Approach to ecosystem management according to landscape changes in a sandy river with alternate bars, *Proc. 11th International Summer Symposium.*, 2009, JSCE, Tokyo.

[10] Shirogane A. Water quality of the Yahagi River II –long term changes of the water quality and the comparison with other rivers-, *Journal of Yahagi River Investigation*, 2001; **8**, 219-28. (in Japanese)

[11] Miyachi S, Yagi A. Water characteristic of Yhagi River, *Journal of Nagoya Women's University, Home Economics・Natural Science, Humanities・Social Science*, 1992; **38**, 129-36. (in Japanese)