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Application of Landscape Ecology to Watershed Management – How can We Restore Ecological Functions in Fragmented Landscape ? –

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유역관리에서 경관생태학의 응용 – 절개된 경관의 생태적 기능을 어떻게 회복시킬 수 있을까? –

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ABSTRACT

This paper describes the ecological structure and function of riparian zone, and their historical changes with land-use. The riparian zone consists of valley floor landform and riparian vegetation. The functions discussed are attenuation of sunlight energy, input of leaves and needles, contribution of woody debris to streams, and retention of flowing material out of transport. These primary functions directly or indirectly influence water and sediment qualities of streams, bars and floodplains, and thereby aquatic biota. Temporal changes in a hydrological system and riparian ecosystem were examined with reference to land-use conversion in order to understand the linkages between these two systems in Toikanbetsu River. The influences of channelization and land-use on discharge of suspended sediment and wetland vegetation was also investigated in Kushiro Marsh. These two examples suggested that the ecological functions of riparian zone have been degraded as flood control and reclamation works have expanded in the past twenty years. The author proposes river restoration planning by preserving or creating landscape elements based on the concepts of sustaining physical and ecological linkages.

Key words: Flood control, Land-use, Riparian zone, Stream ecology, Watershed.

INTRODUCTION

The landscape of Japan displays very steep and undulating terrains. Annual precipitation is considerable, ranging from 1,000 to 3,000 mm. Heavy rains and subsequent floods are generally caused by typhoons in summer. These natural conditions strongly influence Japanese river management policy, which has historically focused on flood control.

Since the 1970s, public opinion with respect to river management has greatly shifted from flood prevention to environmental preservation, in part in relation to pollution in many industrialized regions. Presently, preservation of the natural environment has become a key issue for the management of Japanese rivers. Thus new management perspectives which involve not only flood control but also conservation of riparian ecosystems are urgently needed. This problem cannot be solved only by the implementation of a conservation project at the riparian fringe, rather restoration of the hydrogeomorphological and ecological watershed systems is strongly required.

Temporal changes in a hydrological system and riparian ecosystem were examined with reference to land-use conversion in order to understand the linkages between these two systems in Toikanbetsu River. The rainfall-runoff process is an integrated hydrological system within a landscape, and land-use development substantially alters the spatial heterogeneity of landscape elements, which in turn changes the rainfall-runoff system. Shortening of river channel, construction of dikes, implementation of open and underground drainage ditch system are common engineering works used in agricultural development. As a result, streamside forests have been destroyed and heterogeneous pool-riffle channel morphologies were altered into a flat, uniform morphology (Takahashi and Higashi 1984, Brookes 1988, Inoue and Nakano 1994). For the last few decades, little attention has been given to studying the holistic environmental impact despite the close relationship between these systems.

The influences of channelization on discharge of suspended sediment and wetland vegetation was also investigated in Kushiro Marsh. Wetlands provide essential habitats for many species of birds, fish and other wildlife (Harris 1988, Weller 1988). They also affect water quality (Johnston *et al.* 1984, Cooper *et al.* 1987) and provide flood abatement (Winter 1988). Development has had the cumulative effect on the watershed of producing suspended sediments including nutrients (Whigham *et al.* 1988). The excessive production of suspended sediment in association with agricultural development is one of the most serious environmental issues in the Kushiro Marsh. The cumulative impact of suspended sediments from uplands may deteriorate the quality of wetlands and accelerate their loss despite the fact that they are designated as a National Park and are supposed to be protected from development. The objectives of this study are to clarify the structure and function of hydro-geomorphological system and riparian ecosystem and to examine their connections using time-series analysis in association with land-use development.

GENERAL CONCEPT

The riparian zone is structured by river and hillslope geomorphologies providing a template and by vegetation on that template (Fig. 1). Valley floor landforms consist of terraces, alluvial fan, floodplains, bars and streams. Riparian forests are able to establish on all these geomorphic surfaces except streams. The forests on hillslopes and the valley floor have several ecological functions such as attenuation of sunlight energy, input of leaves and needles, contribution of woody debris, and retention of flowing materials out of transport, which results in the alteration of water and soil qualities of streams, bars and floodplains (Fig. 1).

Shading provided by tree crowns hanging over the stream strongly influences water temperature and primary production in lotic ecosystems. The research carried out in a deciduous stream showed that the daily maximum and total solar radiation was reduced to approximately 1/4 and 1/7 of full sun by crown-shading in summer, respectively (Nakamura and Dokai 1989).

Leaves and twigs falling into streams are critical food resources especially in forested headwater streams where light is limited. Fisher and Likens (1973) clarified the importance of allochthonous detritus in aquatic ecosystems, indicating that over 90% of organic matter was supplied by the surrounding forests. Litter-fall to stream measured in the Tomakomai Experimental Forest was about 2.5 tons/ha, which is slightly lower than the volume of leaf fall on the forest floor.

Coarse woody debris (CWD) pieces from adjacent slopes and floodplains function as obstructions in streams, providing storage sites for sediment and or-

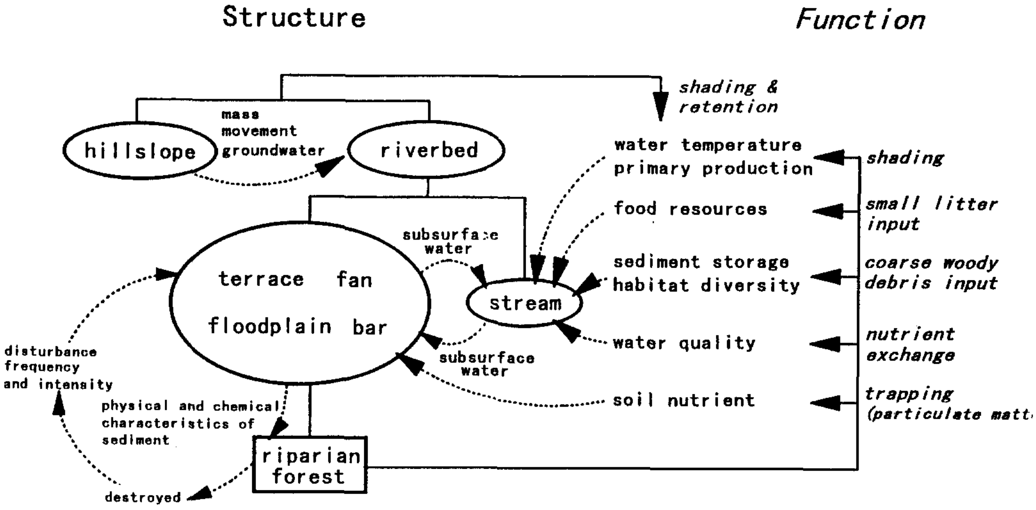

Fig. 1. Conceptual model of structure and function of riparian zone.

ganic matter and enhancing habitat diversity for aquatic organisms. Pools and structures that provide hiding cover are important component of habitat structure for aquatic organisms, especially fish (Bisson *et al.* 1982). Approximately 40% of pools and 50% of habitat cover structures were created by CWD fragments in the Sarufutsu River (Abe and Nakamura 1996). Thicker, longer pieces oriented perpendicular to the channel were effective in forming pools and cover. Moreover, stems and roots of riparian vegetation comb inorganic and organic matter transported from upstream when the floodplain is inundated, which increases the soil nutrients of floodplain deposits. They, in turn, supply organic matter and nutrient during flooding. The interaction between floodplains and streams through surface- and subsurface-water drainage systems is not well understood, but recent studies indicate the importance of floodplain vegetation in improving the nutrient quality of flowing water (Jones and Holmes 1996).

Historical changes in hydrological and ecological functions in Toikanbetsu River basin

1. General description

The Toikanbetsu River basin is a branch of the Teshio River, which drains the northern part of Hokkaido. The 60 km^2 central part of the basin consist of floodplains and terraces. Historically, most of this basin was covered by peat land and pristine forest, and has been converted to grassland since the 1960s. The 220 km^2 upper part of the basin is owned by the Teshio Experimental Forest of Hokkaido University. *Picea glehnii* dominates the east side while conifer and broad-leaved mixed forests dominate the west. From 1870 to 1930 several fires burned the natural forests extending about 70 km^2, resulting in 20 km^2 of bamboo bush (*Sasa* spp.) regeneration. The mean annual temperature is 5.7℃, and the annual precipitation is about 1,000 mm, half of which falls as snow (Hokkaido Experimental Forest 1992).

The reclamation of Toikanbetsu River basin begun in 1904. Since 1960, most agricultural land has been converted to grassland with agricultural modernization projects. The population has rapidly decreased because mechanized farming encouraged poor farmers to emigrate to urban areas (Horonobe Town 1974). Flood control works had began in 1952, and small-scale dikes had placed in the first decade. The severe flooding in 1970 initiated large-scale engineering works such as channelization and sequential dike systems and were continued until finished in the

1980s.

2. Hydrological changes

The water retention area varied with land-use development. The decrease in forested area was mostly caused by several wild fires which occurred in 1910, 1924, 1926, 1929, 1930, 1940.

Thereafter, these 70 km^2 burned areas had been replaced by bamboo bushes by the end of World War II. Since the 1960s, the forested areas have been maintained because they were designated as the Experimental Forest of Hokkaido University.

Rainfall-runoff was simulated using the Tank Model (Sugawara 1974), which is one of the lumped models explaining non-linear responses between rainfall and runoff. Two Tank Models corresponding to the past and present hydrological conditions were constructed.

Tank Models were built in 1970~1974 and 1984~1993 to elucidate the temporal changes in rainfall-runoff system. The overall structures of the two models differ markedly. The 1970~1974 model consists of tanks which have high infiltration coefficients (bottom holes), large storage capacity (depth of tanks) and low runoff coefficients (side holes), whilst the 1984~1993 model consists of shallow tanks having low infiltration coefficients, meaning that it generates a quick runoff even if the rainfall intensity is relatively small. The structural differences in these two models can be attributed to the development of agricultural lands over the floodplains and footslopes and channelization of river system.

We inputted hyetograph data from October 1970 into the 1984~1993 model and hyetograph data from August 1989 into the 1970~1974 model in order to examine the differences in height and arrival time of peak discharges between the 1970s and the present. The peak discharge calculated by the 1984~1993 model was 9.66 mm/hr whilst the obsered one in 1970 was 6.62 mm/hr, and 7 hours ahead of the 1970 peak (Fig. 2A). On the other hand, the observed peak discharge in 1989 was 2.17 mm/hr and the 1970~1974 model generated 0.93 mm/hr in peak discharge (Fig. 2B). These results indicate that the hydrological process is highly dependent on the amount of land-use in a basin, and potential flood hazards may be historically enhanced with increasing peak discharge even if engineering counter measures are employed.

3. Riparian environment

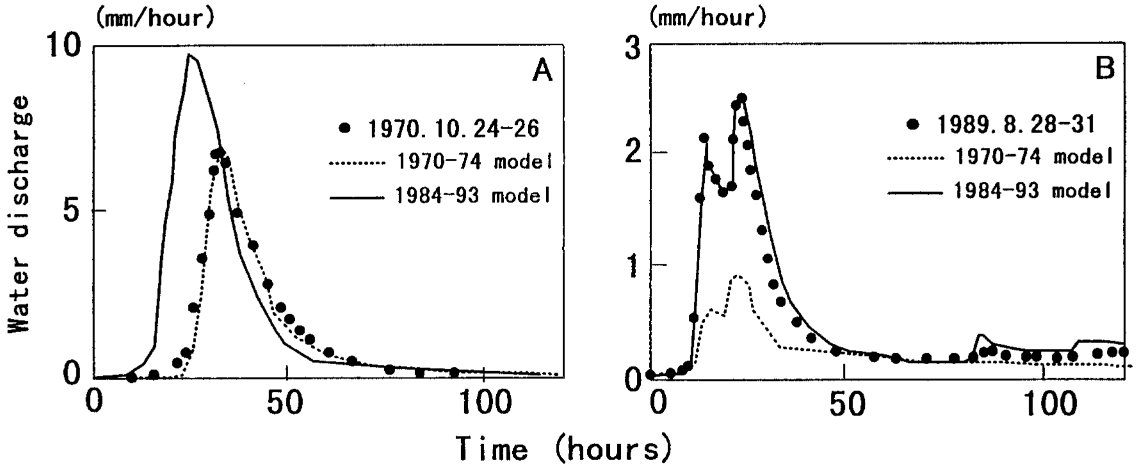

Fig. 2. The results of the Tank model analysis. Graphs A and B were generated by inputting hyetograph data observed in October 1970 into the 1984~1993 and hyetograph data from August 1989 into the 1970~1974 model, respectively.

Riparian forests along the main stem of Toikanbetsu River were delineated from aerial photographs taken in 1947, 1960, 1969, 1977 and 1989. Characteristics of the forest patches were evaluated from the total area, number of patches and ratio of the perimeter to the area of the patch (Forman and Godron 1986).

The riparian forests were shrunk rapidly and were fragmented from 1947 to 1969 (Fig. 3). This reduced, fragmented pattern was prominent in the 1970s when agricultural lands fully extended over the floodplain and river regulation projects were intensively executed. The pattern has continued until present although a slight increase in forest areas can be recognized from 1977 to 1989. The total area of the riparian forests has decreased from 4 km² to 1 km², and the number of the patches has increased from 10 to 75. As indicated by area-perimeter ratio, the shape has varied from broad patches to elongated patches.

The water temperature was measured at eleven locations in tributaries using maximum-minimum mercury thermometers in mid-June to late September in 1993 and 1994. The independent variables considered to control water temperature are watershed area, elevation and open channel length. Open channel length refers to the channel length that is not under the riparian canopy. The correlation between maximum summer stream temperature and other variables were examined. Of all the variables, watershed area and open channel length showed significant correlation with maximum stream temperature ($p<0.05$) and open channel length accounted for 79 % of variation in the maximum stream temperature ($p<0.001$, $r^2=0.79$). Multiple regression analysis using the step-wise method chose only open channel length as the variable accounting for temperature variation (Fig. 4A), because the three variables correlated with each other.

This regression equation was validated from the results of heat budget analysis applied to the Juyonsen Creek, one of the tributaries. The summer maximum temperatures estimated from the regression analysis reasonably coincided with those from the heat budget, and their differences range within 0.5℃. We therefore concluded that regression analysis is an accurate means of determining stream temperature in this basin. Historical changes in stream temperature in Juyonsen Creek were estimated by measuring the open lengths from aerial photographs and by applying these data to the regression equation (Fig. 4B). Almost no development was observed in 1947. The maximum summer temperature in 1947 was about 22.5℃, about 6℃ lower than at present. Further, a sharp increase in water temperature was identified from 1947 to 1960. During this period, extensive development of agriculture lands took place on the floodplain, and channelization was accelerated, resulting in the disappearance of riparian forests. The 6℃ increase in water temperature is detrimental to fish favoring cool water. Masu salmon is an important species in the area whose maximum thermal tolerance is about 25℃ (Tamai *et al.* 1993). At present,

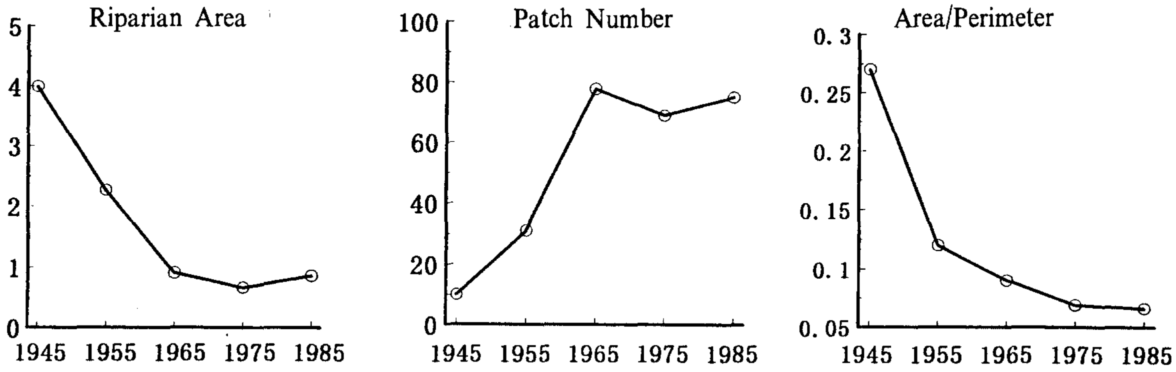

Fig. 3. The shrinkage and fragmentation of the riparian forests of the Toikanbetsu River. The area and number of forest patches were evaluated from aerial-photograph interpretation.

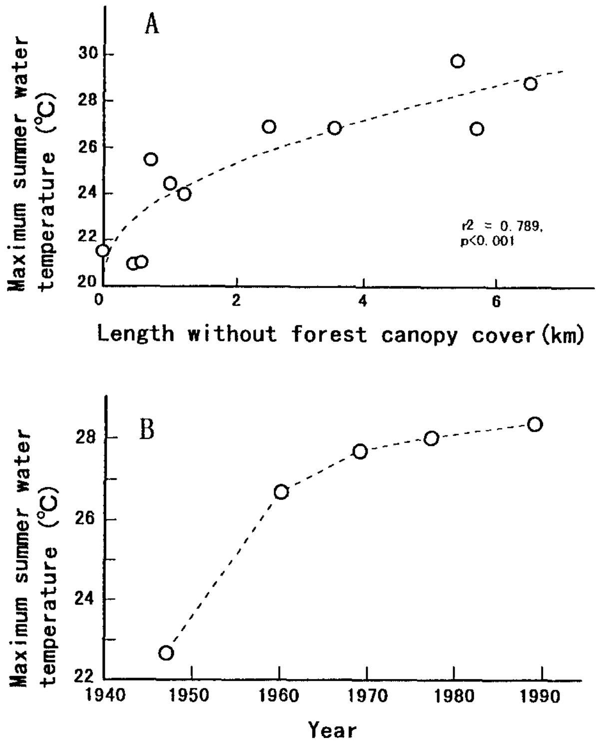

Fig. 4. The results of multiple regression analysis of maximum stream temperature (A). The only significant variable accounting for variation in the maximum summer water temperature was the open channel length ($r^2=0.789$, $p<0.001$). Temporal changes in the maximum summer water temperature in the Jyuyonsen Creek based upon regression analysis (B). The open channel lengths were estimated using aerial photographs.

this species cannot survive in the downstream section of the Juyonsen Creek, the fish is forced to migrate to headwaters where the water is cooler. However, the estimation of historical temperature indicated that the maximum water temperature can be lowered to approximately 23℃ by restoring riparian canopy over the stream.

River sedimentation and its effect on wetland vegetation in Kushiro Marsh

1. General description

The Kuchoro River drains into the Kushiro Marsh. The watershed area of this river above the downstream end of the channelized reach is 123 km^2. It has an elongated shape and the length of its main channel is about 45 km. Forests remain in the upper watersheds above 100 m in elevation, but mid-basin areas are intensively cultivated for livestock. In the downstream areas, the wetlands are distributed over the lowlands on both sides of the river channel. The average annual precipitation between 1958 and 1987 was 1140 mm. The downstream wetlands have been gradually altered into pasture with underground and open-ditch drainage systems. One of the big projects for this alteration of land-use was the channelization of the meandering river to drain water more rapidly and efficiently. Channelization occurred between 1965 and 1970, and 1972 to 1980. The total length of the channelized reach is about 10 km. Gauging stations were established at four sites to investigate the variations in sediment load along the river. *Alnus japonica, Fraxinus mandshurica* var. *japonica, Spiraea salicifolia, Phragmites communis* and sedges dominate the wetlands although willows (*Salix* spp.) are sporadically distributed along the river channel. Undulating features called "tussock" consisting of the accumulation of undecomposed sedges are common over the wetlands.

2. River sedimentation

The budgets of suspended sediment between St. 1 and St. 4 demonstrated that the wash load was the predominant component of total suspended load that likely has the greatest cumulative impact on the wetland (Fig. 5). Moreover, most of the wash load delivered into the wetland during the study period was observed to be produced by a single heavy rainfall event and transported by the associated high discharge. Although source areas of wash load production are not identified in the present study, the measurements indicate that wash load was produced from the entire watershed. Complex factors such as

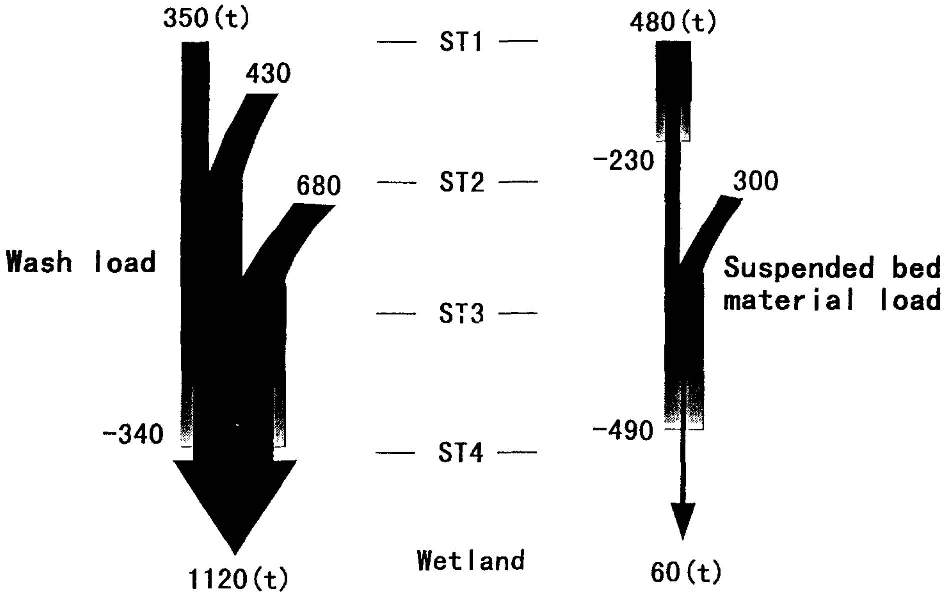

Fig. 5. Budgets of wash load and suspended bed material load in the larger flood.

landslides occurring at the outside of river bends, erosion of agricultural lands and banks, and degradation of small ditch networks may be source areas of these fine sediments.

25 % of the wash load and 75 % of the suspended bed material load were deposited between St. 3 and St. 4 in the channelized reach, and so contributed to the aggradation at the end of channelized reach (Fig. 5). In general, upstream of the channelized reach, the river channel is degraded because of a high flow velocities associated with a steeper bed slope, and downstream it is aggraded because of flatter natural reach (Emerson 1971, Parker and Andres 1976, Griggs and Paris 1982). About two meters of aggradation has accumulated on the downstream bed since the original channelization of the river. This has reduced the cross-sectional area of the channel by about 50 %. As a result, water discharged by a heavy rainfall cannot be conveyed within the channel, but spills over, carrying the suspended sediment deep into the wetlands. Such over-bank flows were confirmed by our field observations and other researchers (Japanese Environmental Agency 1993).

3. Changes in wetland vegetation

Successive deposits of wash load into the wetlands appear to have altered the structure and composition of wetland vegetation. Tree communities were classified into four groups dominated by *Alnus japonica, Salix* spp., *Fraxinus mandshurica* var. *japonica* with *Alnus japonica* and other tree species. Four plant communities were recognized in the wetland. *Salix* spp. *Alnus japonica-Artemisis princeps* community (Comm. A), *Salix* spp. *Alnus japonica-Cyperaceae lyngbyei, Artemisis princeps* community (Comm. B), *Alnus japonica-Cyperaceae caespitosa* community (Comm. C), and *Alnus japonica-Cyperaceae lyngbyei* community (Comm. D). Tree communities and plant communities were seperately distributed along the variation of ground-water level and total nitrogen, and along the water level and redox potential, respectively (Fig. 6). These four parameters are highly related to the river channelization and land-use developments in the watershed. In general, river channelization enhances the variation of water-level, and sedimentation of wash load decreases the water level. The use of fertilizer in the upstream agricultural lands supplies the nitrogen into the wetland and

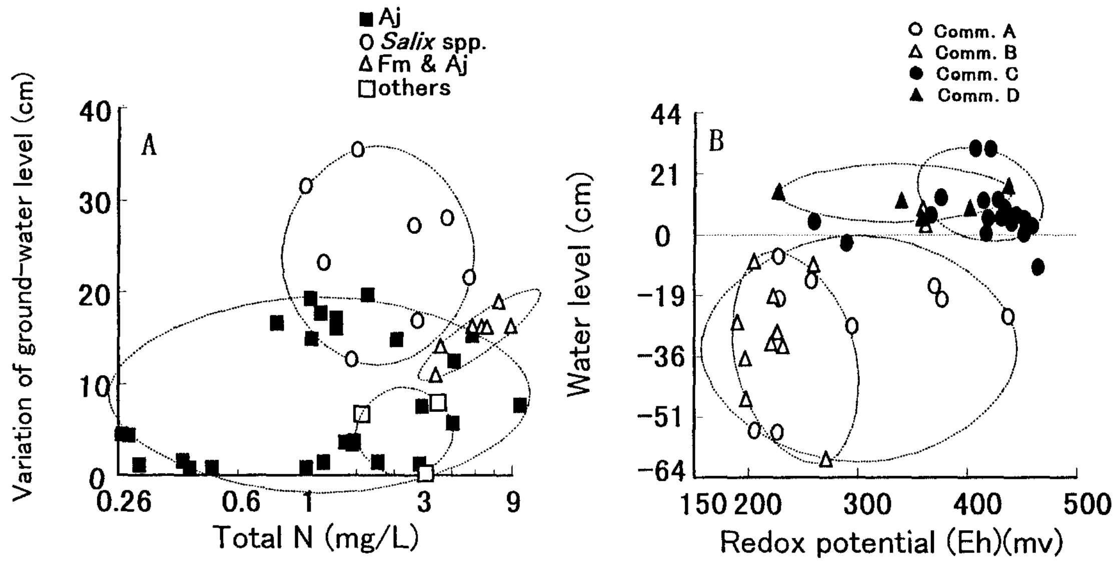

Fig. 6. Site conditions of dominant tree speices and plant communities. Aj; *Alnus japonica*, Fm; *Fraxinus mandshurica* var. *japonica*. Communities A-D in Graph B were explained in the text.

decrease the redox potential due to the oxygen consumption during decomposition of organic materials by micro-organisms. This alternation of site conditions clearly promote the changes in the composition of vegetation. The areas strongly influenced were covered by *Salix* spp.-*Artemisis princeps* community which rarely occurs the interior environment of wetlands. On the other hand, the areas being located far from the river channel and not being affected were dominated by *Alnus japonica-Cyperaceae* community.

Wetland vegetation serves as an efficient filter for removing fine sediments and sediment associated nutrients (Peterjohn and Correll 1984, Johnston *et al.* 1984, Cooper *et al.* 1987). On the other hand, sediment can also impose a physical barrier that may bury organisms (van der Valk *et al.* 1983). Sediment deposition, therefore, may have positive or negative impacts on various stages of wetland vegetation such as seed germination, seedling survival, and growth of adults (Jurik *et al.* 1994, Wang *et al.* 1994, Smith *et al.* 1995). In a study of Alaskan wetland species, van der Valk *et al.* (1983) found a range of responses of adult plants to sediment, from extirpation to more vigorous growth. The even-aged structures of *Salix* trees indicate their simultaneous establishment at the time of extensive and intensive disturbance. This broad distribution of *Salix* trees means that the original wetland vegetation such sedges and *Alnus japonica* have been gradually replaced by the river riparian trees after repeated inundations of sediment ladened water.

In conclusion, the shortening of channel length during channelization of the meandering river steepened the slope and enhanced the stream power to transport sediment (Brookes 1994). This shifted the depositional zones of fine sediment 5 km downstream and aggraded the riverbed by 2 m at the downstream end of the channelized reach. Development of land in the watershed may have further increased the discharge of the total suspended load and this may have accelerated aggradation (Nagasawa *et al.* 1987, Nagasawa 1992). Consequently, the carrying capacity of the channel has been substantially reduced and turbid, sediment ladened water frequently has invaded the wetlands. The fine sediment accumulated on the wetlands has gradually altered the edaphic conditions and thereby vegetation species. Given on-going catchment development, and further reductions in channel flood capacity, these trends are likely to continue.

CONCLUSION

I have demonstrated the links between the hydrogeomorphological system and the riparian ecosystem as affected by land-use. The alteration of one system definitely affects another system. Future watershed management, therefore, should focus on structural and functional linkages and seek to ensure they are protected. The orderly planning of land-use in a basin is essential for keeping balanced hydrogeomorphological and ecological systems. I propose that the water retention and inundation functions should be restored. Particularly the retention and inundation functions can be restored by creating flood control ponds and wetland distributed over the floodplains, by restoring side-channels to drain waters, and by removing dikes in association with the re-naturalization of meandering streams. Riparian buffer forests along the river will function to filter suspended sediment from the agricultural lands. These mitigating measures should contribute to a decrease in flood peaks, which would make it possible to restore the natural river systems and connected riparian ecosystems. However, these restoration projects need a certain extent of lands along the river channels and over the basin. In general, these lands in Japan had been already developed for other land-use and privately owned. How we can obtain or rent these areas is a key issue in the future restoration project.

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적 요

본 논문은 하천유역의 생태적 구조와 기능, 그리고 토지이용에 따른 그들의 역사적 변화를 기술하고 있다. 하천유역은 그 기반이 되는 토지유형과 식생으로 이루어진다. 기능으로서 수계 내에서 태양에너지의 절감, 낙엽의 유입, 목재파편의 영향 및 유동물질의 체류가 검토되었다. 이러한 1차적 기능들이 수계, 주 및 둔치의 물과 침전물의 질에 직·간접적 영향을 미쳐 수계 생물상에 영향을 미친다. 토이칸벳츠강의 수문학적 시스템 및 하천생태계의 연결성을 검토하기 위하여 이 두 시스템에서의 시간적 변화를 토지이용변천에 따라 조사하였다. 쿠시로 습지에서 부유 침전물의 방출 및 습지식생에 대한 직강화 및 토지이용의 영향도 조사하였다. 이들 두 가지 예는 과거 20년 동안의 홍수조절과 매립이 늘어남에 따라 훼손되었음을 보여주고 있다. 이에 본 저자는 물리적 부분과 생태적 부분의 지속적인 연결개념에 근거하여 경관요소를 보전하거나 창조하는 하천복원계획을 제안하고자 한다.

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