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Role Change of In-Channel Vegetation with Regard to Sediment Retention at the Decadal Scale

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ABSTRACT. Human modification to rivers may induce considerable barriers to sediment movement, whether directly and immediately or otherwise. For example, dams may prevent sediment from moving through the system once constructed. In-channel vegetation is a form of sediment trap, which could be an indirect consequence of human interference with river, and has received considerable attention. However, sediments retained in various landforms may be remobilized by one cause or another. Better understanding of sediment remobilization mechanisms and related time scales are needed for better sediment management. The present study is motivated by the fact that the long-term behavior of sediment trapped by in-channel vegetation is still poorly understood. It focuses on the temporally changing role of in-channel vegetation with its growth in regard to sediment retention in the lower Tenryu River, Japan. It reveals that although in-channel vegetation can trap sediment during growing stage, it could become a source of sediment supply at the decadal time scale, when the vegetation was well established. The mechanism behind is the formation and destruction of forested overhanging bank. The process can be characterized by the time period scale ratio of riparian forest growth to lateral channel migration. The findings can help identify the residence time of sediment stores and subsequently aid in planning to increase fluvial sediment delivery from river to the coast.

Keywords: riparian vegetation, storage-transport, bank erosion, time scale, Lower Tenryu River

1. Introduction

Human development of rivers often alters the natural flow regime and reduces the number of threshold flows that flush out in-channel vegetation during its early stages (Eschner, 1983; Johnson, 2000). As a result, vegetation in managed river channels colonizes large areas of exposed channel surfaces and influences channel morphology by increasing surface roughness. Vegetation zones trap sediment (Thorne, 1990; Carollo et al., 2002; Cotton et al., 2006; Rey, 2003), and furthermore, it enhances bank stability through root binding of sediment and increases the threshold shear stress needed to erode the sediment (Renard, 1997). As a matter of fact, vegetation has been used as an efficient mean of combating erosion. Studies have shown that erosion generally decreases with increased vegetation cover (Snelder and Bryan, 1995; Cerda, 1998, 1999). The impact of in-channel vegetation on flow structures has also been widely studied by modeling approaches (Shimizu and Tsujimoto, 1994; Wu and Wang, 2004; Wu et al., 2005; Van De Wiel and Darby, 2007). Besides, empirical approaches have been used to study the retention of organic matter, nutrients, and heavy metals by in-channel vegetation (Schultz et al., 2002; Brookshire and Dwire, 2003; Windham et al., 2003). In addition, laboratory experiments of vegetation effects were conducted (Jin and Römkens, 2001; Zong and Nepf, 2010). De Baets et al. (2006) studied experimentally the impact of root density and root length density of grass on the erodibility of saturated topsoils. These above-mentioned studies primarily addressed short-term effects, however, less is known about the effects of evolving vegetation on the retention and release of sediment in the longer-term.

Since the supply of fluvial sediment from river to the sea is a key factor affecting the sustainability of beaches and protection of coastal properties, the concern about sediment flux from river to the sea has been mounting in recent years. Studies have shown that human activities and climate change are the most important factors influencing riverine sediment flux (Syvitski, 2003; Walling and Fang, 2003). Therefore, better understanding on the turnover of vegetation role with regard to sediment retention can help formulate better planning for coastal conservation.

This paper addresses the issue of sediment remobilization in relation to in-channel vegetation. The objective is to highlight a mechanism of remobilization of sediment trapped in vegetation zone and its time scale over which the relation of sediment deposition with in-channel vegetation may turn over. Subsequently, attempt is made to discuss its implication for river sediment flux management in relation to coastal erosion pre-

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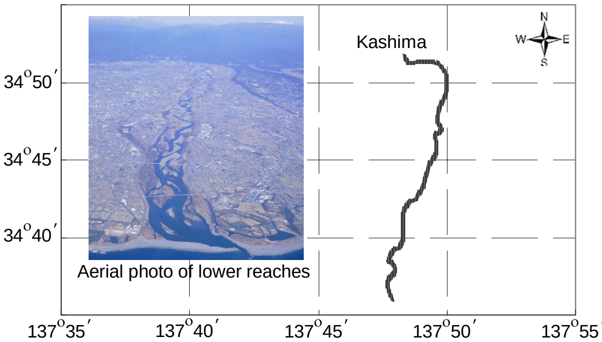

Figure 1. The lower Tenryu River.

vention.

2. Study Site Description

The Tenryu River (Figure 1) originates in the central Honshu Mountains at Lake Suwa (Okaya, Nagano Prefecture) and extends over 213 km down to the Enshu Sea. Total watershed area is 5,050 km². There are five dams along the mainstream-Yasuoka Dam, Hiraoka Dam, Sakuma Dam, Akiha Dam and Funagira Dam. The lower course of the Tenryu River stretches over 25 km from the Kashima gauging station to river mouth, approximately 25 km long. Lying upstream of Kashima, the Sakuma reservoir efficiently traps the sediment load of the upstream Tenryu River watershed, which is estimated to be 2.6 × 10^6 m^3/yr by evaluating reservoir sedimentation from 1956 to 2000. Since dam construction in 1956, most sediment conveyed in the lower Tenryu River is supplied from the Keta River, which joins the Tenryu River upstream of the Kashima site (Yoshii and Sato, 2010).

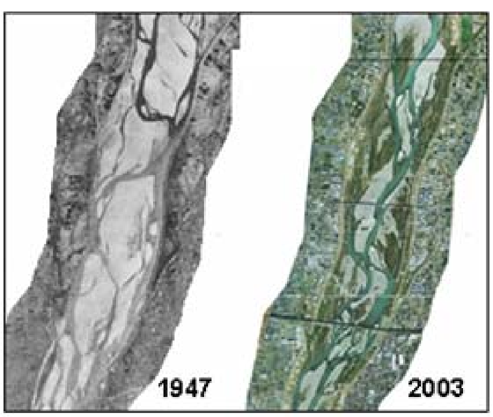

Figure 2. Plan view of the change in the lower Tenryu River.

Figure 2 shows the comparison of aerial photos taken in 1947 and 2003. It appears clear that the lower Tenryu River has been significantly transformed from a non-vegetated to vegetated channel. The dominant plant species are willow and Canada goldenrod. Figure 3 shows that the vegetated area covered less than 5% of the total river channel bed for more than three decades after dam construction, but then spread rapidly starting

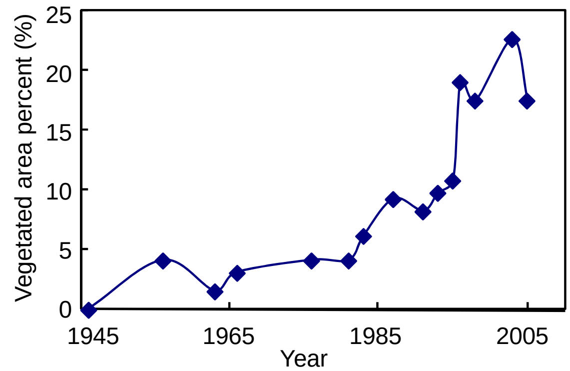

Figure 3. Spatial extent of vegetated channel surfaces in the lower Tenryu River from 1945 to 2005.

from 1989. At present, the vegetated area accounts for about 20% of the total channel surface of the lower Tenryu River. Sediment trapping in vegetated zones along the lower Tenryu River has been discussed by Toda et al. (2008) and Huang et al. (2008). Although Toda et al. (2008) simulated the long-term change of vegetated area and its effects on sediment trapping, the role of erosion processes as associated with vegetation removal during large flood events was not considered.

3. Data and Methods

Data of vegetation development and channel change along the lower Tenryu River were supplied by the Hamamatsu River and Road Administration Office. Flow discharge data at the Kashima gauging station were obtained from the River Association of Japan.

On August 9, 2003, a large flood with a peak discharge of 7,400 m^3/s occurred in the river. Flood frequency analysis based on daily discharge data from 1942 to 2006 and the Log-Pearson Type III distribution indicates that it was a 20-year flood event. Morphological change of the channel due to the 2003 flood was surveyed by the Hamamatsu River and Road Administration Office. The volumes of sediment that were removed by the flood event at different locations were estimated by comparing pre- and post-flood channel cross-sections.

To examine the long-term interaction between vegetation and sediment retention, the focus of the present study was on the vegetation height rather than the spatial extent of vegetated area. The reason is that the areal extent of channel vegetation is strongly correlated to flood activity at short time scales, whereas the variable vegetation height better reflects the long-term condition of in-channel vegetation. We assume that the period of remobilization for sediments trapped in tall riparian vegetation zones equal the period of cross-valley migration. The time scale for the characterization of cross-valley migration in the long-term can be defined as B/E, where E is the bank erosion rate (m/yr) and B is the channel width. When B/E is larger than the time period needed for vegetation colonization, riparian communities establish. Therefore, the ratio of the period of riparian vegetation colonization to lateral channel migration can be used as a measure of sediment remobilization and can

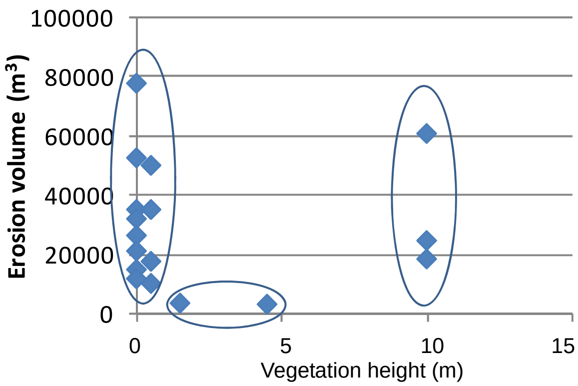

Figure 4. Relation between vegetation height and erosion volume.

also be used to discuss new strategy for in-channel vegetation management aiming at increasing sediment supply to the coast. For this purpose, bed material grain size distributions in vegetated zones are utilized to justify the discussion on the linkage between in-channel vegetation and coastal erosion.

4. Results and Generalization

To assess how sediment removal related to vegetation growth, erosion sites were classified according to vegetation height. The results are summarized in Figure 4 showing that the erosion volumes are larger in non-vegetation channel areas when compared to areas with vegetation heights of 2 ~ 4 m. Areas with 10 m high vegetation by contrast, reveal increased large erosion volumes. Figure 5 shows a typical setting where a part of a large point bar with tall vegetation was eroded. Erosion concentrated on the concave bank of a curved reach and the erosion volume was derived from bank erosion. The data and field observations suggest that vegetation retention of fine sediment is promoted during the early stage of vegetation development. Once the riparian vegetation is well established, it blocks overbank flow and generates high stream flow velocity in the main channel. This may lead to bank erosion through bank undercut below the root layer (Thorne et al., 1981). Crickmay (1960) showed that the erosivity of a river is related to:

$$F = \frac{MAV^2}{g} \tag{1}$$

where F is the inertial force of the flowing river, M is mass of a cubic meter of water, A is cross-sectional area of channel, V is current velocity, and g is acceleration due to gravity. The water force F varies along the length of the river. Along straight reaches, F is highest along the central axis of stream flow, but typically shifts to the outer side because velocity there is highest. Thus, channel erosion is most pronounced near the midpoint of a river bend where it promotes bank erosion. In addition, helical flow in curved channel section causes a downward flow that undercuts the channel bank.

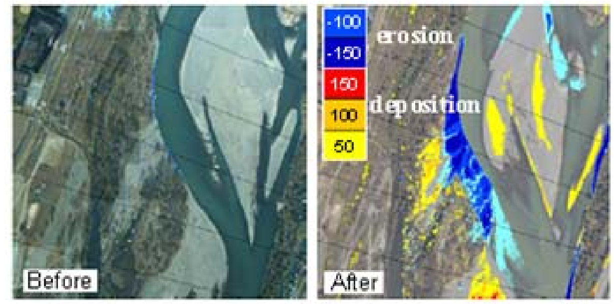

Figure 5. High-vegetation related bank erosion site.

The root reinforcement of soil can be described by the modified Coulomb equation:

$$S = c + \Delta S + N \tan\phi \tag{2}$$

where S is soil shearing resistance (kPa); N is the normal stress on the shear plane (Pa); φ is soil friction angle (degrees); c is the cohesion (kPa); ΔS is increased shear strength due to roots (kPa). However, root reinforcement could not be expected if the bank undercutting occurs below the depth of roots. We dug several pits at randomly chosen sites to record the lengths of willow roots. The zone of root penetration was found to lie within the range of 1m below surface. The main limiting factor of downward root penetration is the availability of aerated pore space. There is more oxygen in the top soil, so that is where the majority of the roots can be found.

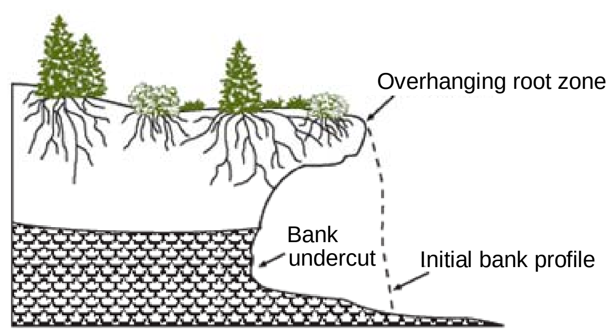

Figure 6. Mechanism of high-vegetation related bank erosion.

According to Ziemer (1981), soil strength can be expressed as:

$$Soil\,strength = 3.13 + 3.31 \times Root\,Biomass \tag{3}$$

Because the root penetration of riparian trees along the lower Tenryu River is shallow and river bank is high, the subsurface below the toot zone is exposed to bank undercut leading to lateral bank erosion. Then, it can be stated that during an early stage, in-channel vegetation promotes sediment retention, but established tall vegetation leads to the formation of overhanging bank as illustrated in Figure 6. Such a landform is unstable and can become a trigger of sediment removal once collap-

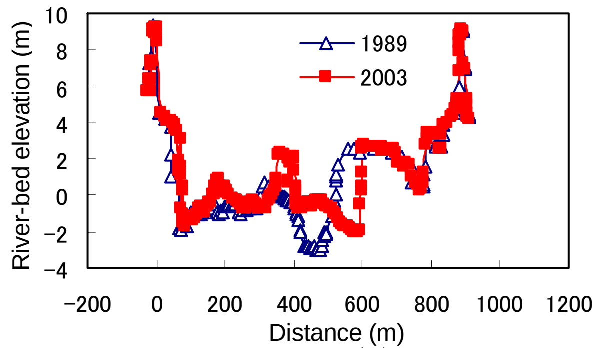

Figure 7. Cross-sectional changes at 16 km from the river mouth.

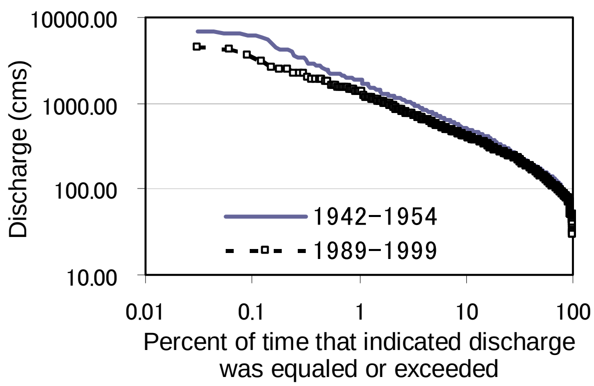

Figure 8. Comparison of flow regimes.

sed during a large flood. Consequently, the period of sediment retention on vegetated channel surfaces depends on the period of cross-valley channel migration.

Figure 7 shows cross-sectional channel change between 1989 and 2003 in the middle part of the lower Tenryu River, where channel morphological change was the largest during that period. As seen from Figure 7, lateral bank erosion accounted for about 100 m of the channel cross-sectional width between 1989 and 2003, As a result, the index value of B/E was calculated to be 100 years. Meanwhile, it can be noted from Figure 2 that the riparian forest along the lower Tenryu River was established over a decade starting from 1989. The study by Watanabe et al. (2005) also indicates that willows of ten meters high are about 10 years old. Therefore, the ratio of the period of tall riparian vegetation colonization to lateral channel change approximates 0.1. This indicates that the contemporary channel dynamism allows for the establishment of tall riparian vegetation. The reason is that the number of large floods was significantly less in the decade of 1989-1999 as shown in Figure 8.

Based on Figure 4, an attempt was made to develop a general description of storage-transport relation mediated by riparian vegetation. The hypothesis is that the relationship between vegetation height and sediment storage could be fit to a Gamma function being:

$$S / S_{\max} = CH^{\alpha}\{\exp(-\frac{H^{\beta}}{(H_{\max}-H)})\}^{\gamma} \quad (4)$$

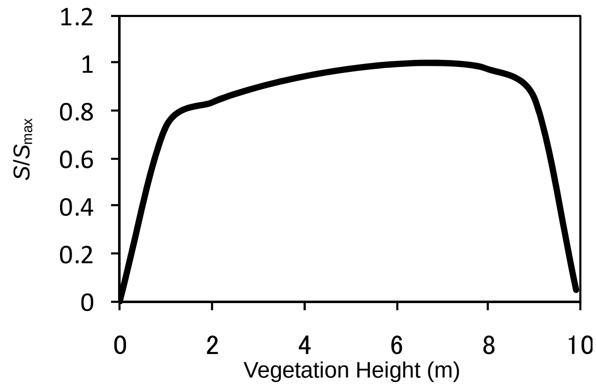

Figure 9. A mathematical generalization of in-channel sediment storage in relation to vegetation height.

where S is sediment storage in vegetated zone; S_{max} is maximum storage; H is vegetation height; H_{max} is maximum vegetation height. Using field data, the parameters in Equation 4 were determined for the lower Tenryu River as below:

$$S / S_{\max} = 0.75H^{0.2}\{\exp(-\frac{H^{0.2}}{(H_{\max}-H)})\}^{0.2} \quad (5)$$

The behavior of the above relation function is depicted by Figure 9. It reproduces qualitatively what was observed in the field. Storage increases with vegetation height, peaks around 5 m, then plunges at 10 m.

Developing a time-dependent functional relationship is fundamental to modeling the temporal variability of sediment storage in vegetated channel surfaces. More in-depth studies are needed in this direction.

5. Discussions

Previous studies have highlighted the decoupling between upstream sediment sources and lowland basins and estuaries due to either inefficient sediment delivery within the fluvial system and hence storage (Meade, 1982; Phillips, 1995). Valley constrictions and dams are more or less permanent sediment barriers. For in-stream sediment barriers of the local or zonal scales such as bedrock steps or woody debris, the breaching capacity concept has been employed by Brunsden (2001), which can be considered as the recurrence interval of the event required to breach the buffer, barrier or blanket, or as the residence time of these landforms. The present study however indicates that once a landform evolves close to a threshold of change, the breaching capacity concept becomes more relevant. That is to say, when a landform is in a stable state, it may require much higher or even extreme events to breach so that the concept may end up with no practical sense under such circumstances.

Sediment flux within river systems can be described as a "jerky conveyor belt" (Ferguson, 1981). The distribution of riverine sediment stores and sinks, and the frequency with which sediment is added or removed from these stores, reflects the degree to which a river system is coupled or decoupled (Harvey, 2002; Hooke, 2003).

Fryirs et al. (2007) described the changing landscape connectivity as analogous to the operation of a series of switches, which determine what parts of the landscape contribute to the sedimentary cascade over different time intervals. The findings of the present study suggest that the conceptual framework conveyed by Fryirs need to be modified to account for inherent change in the condition of barriers. It is not just the flow discharge that determines the switch on or off. The barrier evolving process gets the switch wired or not.

Wynn et al. (2008) showed that streambank erodibility during winter was more than twice that in either spring or summer for a study reach located in a pasture. Therefore, an interesting topic will be the seasonal change of streambank erodibility with the presence of tall vegetation.

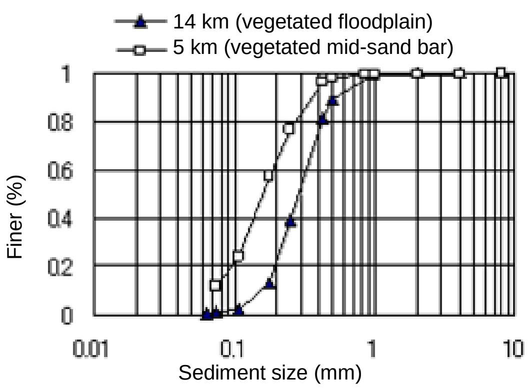

Figure 10. Sediment grain size distributions in vegetated zones.

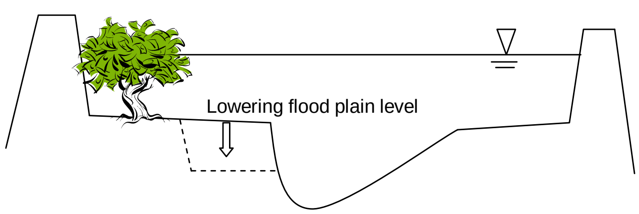

Figure 11. A management practice for in-channel vegetation reduction.

The findings of the present study also have implications for the management of sediment transport particularly when river-borne sediment supply is linked to issues of coastal erosion (Liu et al., 2009; Uda, 2009; Huang, 2010). Figure 10 shows the measured sediment grain size distributions on the vegetated floodplain 14 km from the river mouth and on the vegetated sandbar 5 km from the river mouth, respectively. A dominant feature is that a large portion of the Enshu beach-forming sands (0.1 ~ 1.0 mm) was found in vegetated zones. Based on measured sediment size distributions and deposition depths, the mean trapping rate for beach-forming sands (0.1 ~ 1 mm) in the lower Tenryu River was estimated to be 0.19 m^3/m^2/year. By multiplying this trapping rate with the total vegetation area along the Lower Tenryu River, it can be estimated that the storage of beach-forming sands along the lower Tenryu River could reach to more than 2×10^5 m^3 over a decade. Therefore, for the long-term sediment budget analysis, this storage should be taken into account since they become available source in the long-term. To increase sediment delivery to coast in a vegetated river course, channel width reduction of the main channel may help achieve the goal because it increases the frequency of inundation of vegetated zones, hence interrupting the development of in-channel vegetation. At present, a management practice is under discussion in Japan as a way for in-channel vegetation control. That is to lower flood plain level aiming at increasing inundation frequency of flood plain (Figure 11). However, this approach will widen river channel. According to the present study, channel widening may result in longer period of cross-valley migration. Consequently, it would allow for vegetation stabilization on remaining flood plain.

6. Conclusions

By studying the linkage between the duration of sediment retention and vegetation growth, it is found that in-channel vegetation efficiently traps sediment in the short-term but promotes sediment removal by bank erosion process in the long-term. This raises a question about what time scale should be considered in beach conservation planning. The time dependent change of the role of in-channel vegetation for sediment dynamics can be described by the ratio of the period of riparian forest growth to the period of lateral channel migration. The ratio was around 0.1 under present-day conditions in the lower Tenryu River, suggesting that currently low dynamism allowed for the full development of stable vegetation. It is postulated that the found storage-transport relation can be described mathematically by a Gamma function. The findings also suggest that some key concepts used in the present-day geomorphology such as breaching capacity and conveyor switch need modification. Besides, a potential issue is pointed out with regard to the application of an in-channel management approach to the river. Since downward trend of sediment yield was also reported in other river courses such as the Lower Reach of the Yellow River (Liu and Wang, 2008), the present study may provide some clue to studies elsewhere.

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