GEOMORPHOLOGICAL EVOLUTION AND SEDIMENT BUDGET ANALYSIS WITH THE UJI RIVER, KYOTO

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This paper starts with presenting field evidences that illustrate the occurrence of significant bank erosion in a reach of the Uji River. It then demonstrates that the resulting escarpment was not a mere local adjustment, but is an indicator as to how extensively the Uji River has undergone appreciable amounts of channel erosion over the entire 15.2km-long section. The datasets on which the discussion is based include: the cross-channel topographical data (200m intervals along the river course) in 1967, 1979 and 2006 made available from the Yodogawa Office, MLIT. A careful geomorphological analysis of the datasets in terms of GIS, permitted the determination of tempo-spatial changes of areal sediment storage in the Uji River. When integrated over the entire river course, the overall volume of sediment loss due to erosion proved to amount to 3.1×10^6 m^3 in the period from 1967 up to 2006. A discussion is made to identifying its practical implications for future riverine management. Furthermore, a discussion is made of the linkage between the extent of the channel erosion and the depositional environments of the sediment that constitutes the boundary of the river channel.

Key Words : *Alluvial river, Channel erosion, Floodplain management, Sediment budget, Sediment routing system*

1. INTRODUCTION

In Japan, 70 percent of its landscape is a mountainous one and the population and property have concentrated on the less extensive alluvial plains, most of which are products of fluvial sedimentary actions. However, many of alluvial rivers in Japan have recently undergone channel erosion, due to river training for flood control, excessive riverine sand mining or reservoir sedimentation.

The question now arises as to consequences of channel erosion in an alluvial river. Are they always detrimental (to what if any)? The loss of sediment by erosion around bridge piers, for example, should be avoided or engineered, so as to ensure their integrity. What about the effect upon flood-control strategies on a river-basin scale? The prolonged loss of sediment by erosion in the low-water channel in a leveed river may add up to a considerable gain in accommodation space for flood water, thus it might be beneficial to the safety of the community in the river basin. This consideration will be of particular relevance if the floodplain has already been extensively urbanized and no space for levee retreat could be sought with reasonable resources. Also, the loss of sediment by erosion out of a reach may be regarded as a sediment production to a receiving body of water downstream. If an amount of clayey sediment is released through bank erosion, for instance, the fine-grained sediment might bring about a beneficial effect to the aquatic ecological environment in diversity. In essence, what has been described in this paragraph emphasizes a wide spectrum of possible channel-erosion issues.

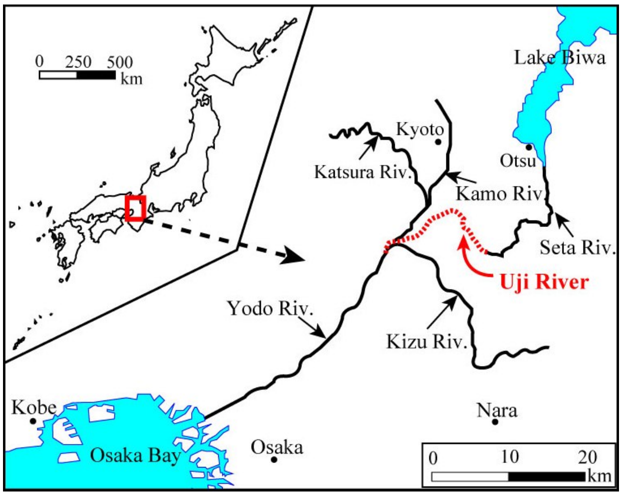

Fig.1 A map showing the location of Uji River

In what follows, the background to taking up the Uji River for the present discussion will be described first. This is followed by a description of findings obtained from a pilot study reach, providing an idea about the intensity of the channel erosion concerned. An attempt will then be made to provide a clear picture as to the extent of channel erosion in the entire river course of the Uji River, with relevant discussions.

2. FEATURES OF THE UJI RIVER

The Uji River 15.2km long is a relatively short alluvial river. However, it has a range of intriguing facets both from natural and societal standpoints (**Fig.1**). Note first that there is only one river (the Seta River) that emanates from Lake Biwa, the largest lake in Japan. The Seta River flows down mountainous valleys and changes its name into the Uji River at a location where Amagase Dam now stands. Then, the Uji River comes out to the low-lying southern Kyoto area and joins with the Katsura and Kizu Rivers, making the Yodo River. The confluence point is a geological constriction (a narrow lowland between two low-relief mountains of sedimentary rock), and highly engineered works have been performed over years so as to deal with the complex channel hydrodynamics concerned. Downstream the confluence point, there flows the Yodo River down to Osaka Bay. High- and low-water discharge characteristics of the Uji, Katsura and Kizu Rivers are listed in **Table 1**. As far as the maximum (flood) discharge is concerned, the Kizu River has a dominant quantity, exerting a significant influence on the flood-control strategies with the Yodo River system. Regarding low-water discharge, the Uji River stands out in quantity over the Kizu and Katsura Rivers. This is a clear manifestation of the benefit of Lake Biwa, a huge natural reservoir in the Yodo River basin.

Table 1 Discharge characteristics of the Uji, Katsura, Kizu Rivers (adapted from Kinki Regional Development Bureau, MLIT, 2000)

River name	Maximum discharge (m^3/s)	Low-water discharge (m^3/s)
Uji River	1,980	102.93
Katsura River	2,080	9.35
Kizu River	6,200	17.95

From a societal and cultural viewpoint, it will suffice herein to mention that Kyoto was a capital of Japan over 1000 years (from 794 up to 1868). One may imagine the importance of river waterways and river ports in those days when motorization has not yet been developed at all or only partly available. It is also of interest to note that this year (year 2008) cerebrates millennium of the Tale of Genji, a classic in which the landscape of the Uji River played a significant role at least behind the scene.

The plan form of the Uji River is detailed in **Fig.2**, together with cross-channel surveying stations set up by the Yodogawa Office, Ministry of Land, Infrastructure and Transport (MLIT). The surveying stations are spaced practically 200m intervals along the river course. Each surveying station joins two bench marks, which stand respectively on the right and left levees of the river. Note that on the upstream end of the Uji River, there stands Amagase Dam, a 73m-high arched concrete dam with a gross storage capacity of 26.28 million m^3. It was built in 1964 for purposes of flood-water regulation, water-power generation and urban irrigation. For purposes of the present discussion we regard the downstream end of the Uji River being at the 37.2km station. In fact the Uji River flows farther down a 2km-long reach with a well known dyke “SEWARI” on its right and joins the Kizu River.

The Uji River has undergone a range of anthropogenic actions over years. It is probably in 1590s when the first major river training works were performed by Lord Hideyoshi Toyotomi. He built a stretch of levee on the left-hand side of the Uji River and diverted its plan form so as to circumscribe a lake named Ogura Pond. Before that time, the Uji River directly flowed into Ogura Pond from the location shortly downstream of the 51.0km station or so. The extent of Ogura Pond in 1890s is indicated on **Fig.2** with a dotted line. Ogura Pond was completely separated from the Uji River in conjunction with the

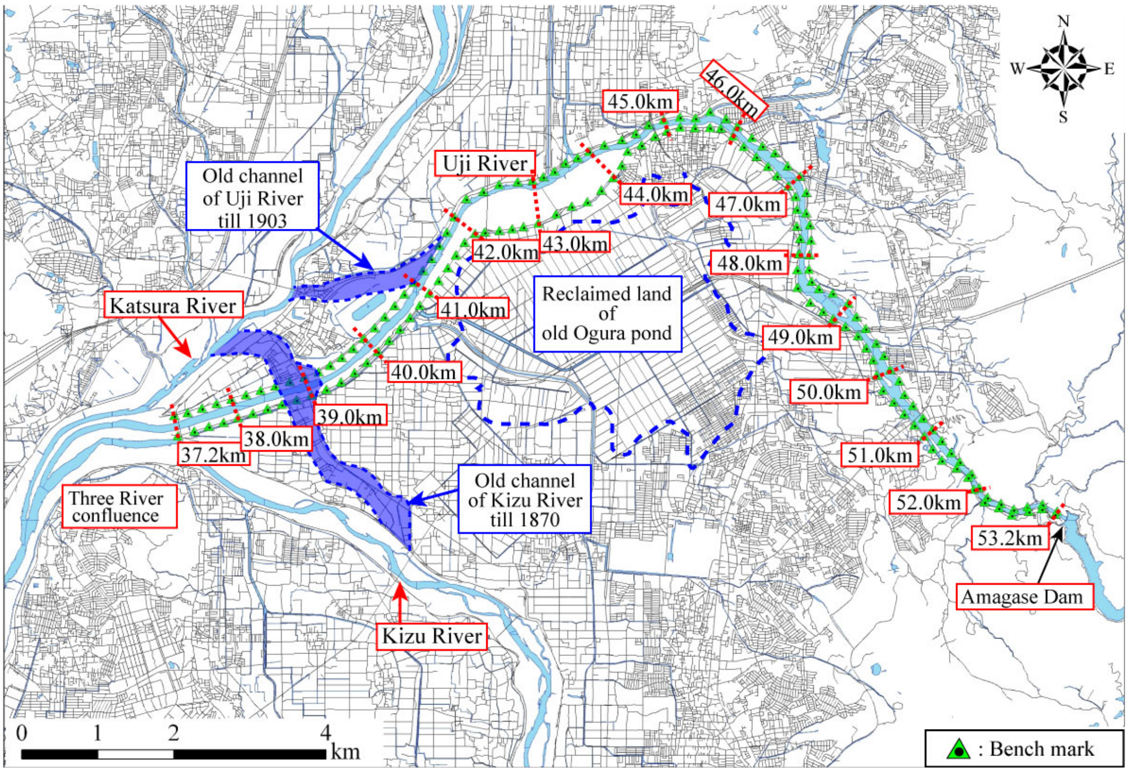

Fig.2 Plan form of the Uji River superimposed onto a Digital Map 2500 (Geographical Survey Institute)

modern levee works in 1920s. The quality of water in Ogura Pond became gradually deteriorated since then, eventually leading it to be reclaimed in 1941 for use as paddy fields. Ogura Pond itself was a shallow water body (water depths of 2m at most). However, there extends a thick deposit of unconsolidated sediments (over 700m thick) below the base of the pond. This fact is a manifestation that the Kyoto Basin is a structurally active, sedimentary basin, with its southern part subsiding over geological times due to crustal movements (Research committee for the active faults in Kyoto City, 2004).

3. A PILOT STUDY REACH FOR LOOKING AT CHANNEL EROSION

A pilot study reach was set up around the 43.0km station (**Fig.3**). On the left bank of the main channel, a length of escarpment stands out. This is clearly seen from **Fig.4**. In order to have an idea about the rate of advance of erosion by stream power, Azuma *et al.* (2007) carried out subaerial surveyings using a digital photo-theodolite system at two different times, namely on 17 January 2006 and 17 October 2006. The face of the escarpment surveyed was 5m high above the river water stage and 250m long streamwise. The subaerial volume of the sediment released during the 9 months proved to be equal to 3000m^3. It corresponds to either an areal rate of erosion of 16m^3/m per year or a rate of bank recession of 3.2m per year.

The question then arose as to whether the entire

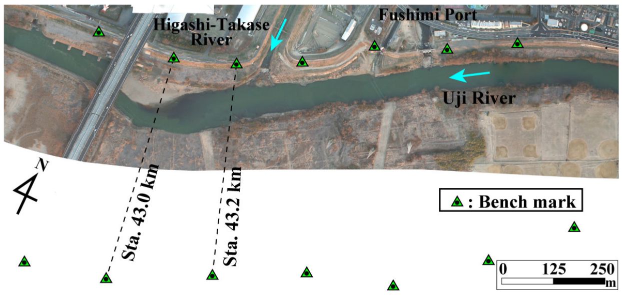

Fig.3 High-resolution aerial photograph of pilot study reach, taken on February 3, 2007 (courtesy of Yasuhiro Takemon)

Fig.4 Escarpment formed in left bank of the low-water channel, photograph taken on March 29, 2007

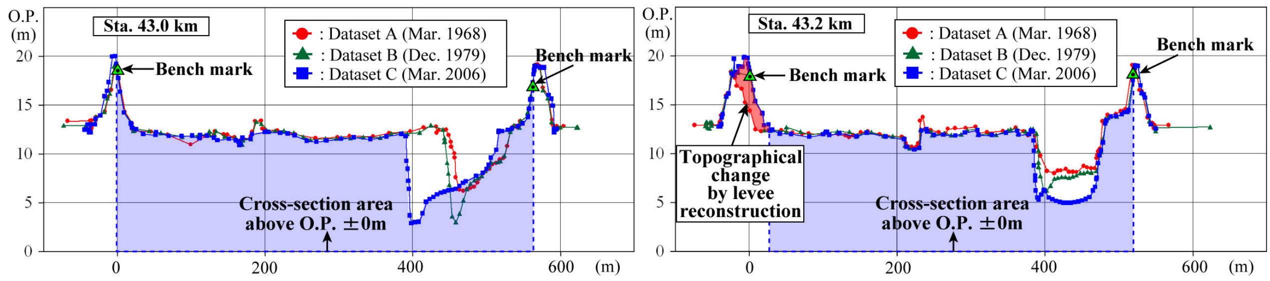

Fig.5 Evolution of cross-channel profiles in Stations 43.0km and 43.2km (looking downstream)

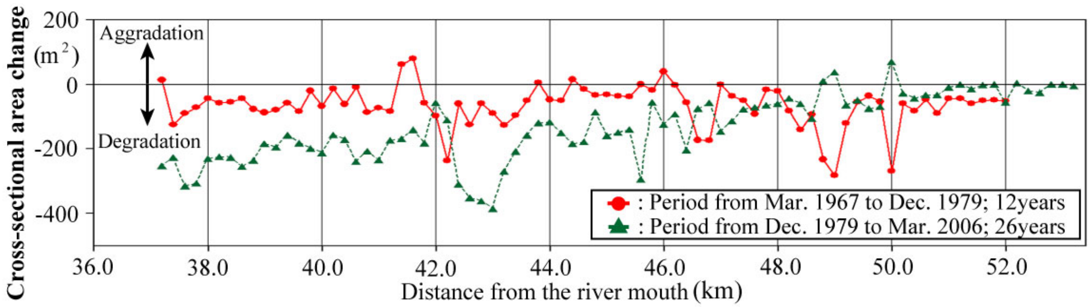

Fig.6 Plots of cross-sectional area changes against the along-channel distance

Uji River underwent such a significant rate of channel erosion. The issue has been addressed and an interim report for that will be described subsequently.

4. ASSESSMENT OF CHANNEL MORPHOLOGICAL EVOLUTION

(1) Cross-channel morphological changes over the entire river course

There are a total of 81 surveying stations in the Uji River, from the 37.2km to 53.2km stations (**Fig.2**). As far as the cross-channel surveying datasets of the Yodogawa River Office, MLIT are concerned, we learnt that it was possible to trace back to the dataset obtained in fiscal year 1967 (hereinafter referred to as dataset A); the actual surveying with dataset A was performed in March 1968, in relatively stable low-water conditions. The latest such dataset available (referred to as dataset C) was with fiscal year 2005 (the actual surveying in March 2006). For purposes of comparison, we decided to incorporate another dataset (referred to as dataset B) with fiscal year 1979 (the actual surveying in December 1979). Datasets A and B were originally in paper-based analog format. Thus we converted them into digital format and applied for the present discussion, along with dataset C, in terms of a Geographical Information System (GIS).

The way in which the cross-channel profile in a given station evolves, is typified in **Fig.5** for the 43.0km and 43.2km stations. Here O.P. stands for Osaka Peil which designates the local datum commonly used in the Osaka Bay area. Note herein that the elevation in terms of O.P. is 1.3m higher in value than the elevation in terms of T.P., the national datum. Let us now look at the performance with 43.0km first (the left panel of **Fig.5**). In each of the three topographical curves, one may readily read off the location and elevation of the deepest point in the channel bed (or thalweg). Certainly, the thalweg evolution is a good measure for representing the extent of riverbed aggradation/degradation (the latter in this case). However, such information cannot directly be used for a discussion of sediment budget. The procedure adopted in this study for volumetric calculations is a simple yet fundamental one. With a given topography curve (from dataset C, for instance), one can readily calculate an area of the domain (shaded on **Fig.5**) that is bounded by the topography curve from above, by a reference horizontal curve (elevation zero) from below and by the two vertical lines horizontally. It was found convenient to set the reference vertical lines such that they respectively go through the bench marks in the station concerned. In a situation where the levee reconstruction required a bench mark to be relocated, one may select a reference vertical line as appropriate, as illustrated in the right panel of **Fig.5**. In general, it is the relative value or evolution of the area of a boundary domain that matters for sediment budget analysis.

(2) Profiles of sediment volume changes along the entire river course

The extent of gain or loss of the sediment volume

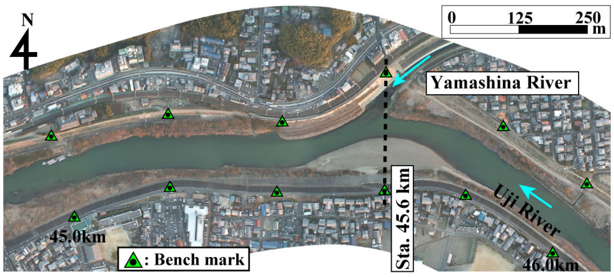

Fig.7 High-resolution aerial photograph of the confluence of Uji and Yamashina Rivers, taken on February 3, 2007 (courtesy of Yasuhiro Takemon)

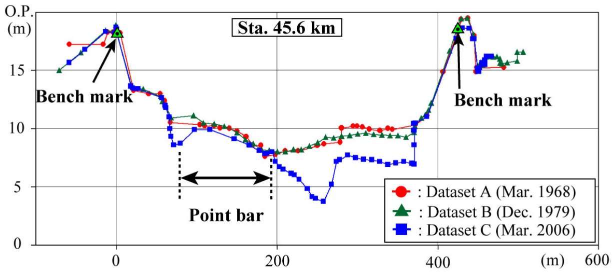

Fig.8 Evolution of cross-channel profiles in the station 45.6km (looking downstream)

for a given station (per running meter along the channel) during two different times may readily be calculated by following the procedure described above. By plotting the results for all the stations concerned, one can depict a set of two curves as shown in **Fig.6**. In a profile with the 1967-1979 period, one may note two marked troughs at stations 49.0km and 50.0km. The causes for these depressions are unclear at present, but they may be in association with the presence of distinct island-shaped sandbars at these locations in the stream channel. As far as the extent of erosion over the river course is concerned, the profile with the 1979-2006 provides a much clearer evidence. In the 26-year period, the lowermost reach around station 38.0km underwent the most significant erosion, namely a loss of 250m^2 or thereabouts in cross-sectional area. Furthermore, one may make the following observations: (1) the rate of erosion generally decreased towards upstream, approximately linearly with increasing stream-wise distance; (2) there are two apparent troughs at stations 43.0km and 45.6km where the erosion rates were excessively high; and (3) the rates of erosion were practically nil or of only minor extent in the uppermost reach of stations from 51.0km up to 53.2km. Possible factors that may relate to these features, especially to observation (1), will be discussed later in this paper, with emphasis on variations in depositional environment along the river course.

It may be instructive here to take a closer look at the performance of stations 43.0km and 45.6km. Let us first take up the case of station 45.6km (refer to **Fig.7**). The location coincides with the confluence of a tributary river (the Yamashina River) to the Uji River. Note that there is an anti-clockwise bend to the Uji River around this location, and a point bar develops to the left of the stream channel (**Fig.8**). The resulting steep velocity gradients in cross-channel directions may have promoted erosion in the 45.6km station.

Station 43.0km lies within the aforementioned pilot study reach. From **Fig.6** with the 1979-2006 profile, one may obtain an averaged rate of loss of sediment volume per annum being equal to 15m^3/m per year. The erosion rate included the subaerial and subaqueous contributions. However, it seems to be somewhat smaller than the value 16m^3/m that Azuma et al. (2007) obtained more recently through the subaerial surveying alone. Speeding up of erosion in the pilot study reach is one possibility. Note in this regard that there is a clock-wise bend at this location, facilitating the formation of a point bar to the right of the stream channel (refer to **Fig.3**). In this particular setting the stream flow tends to concentrate in a narrower space laterally away from the point bar, exerting an enhanced erosive power on the outer cutbank of the channel. This is where the escarpment now stands (**Fig.4**).

Overall, the extent of channel erosion in the Uji River may be well grasped from the two representative profiles shown in **Fig.6**.

5. A BOX MODEL FOR SEDIMENT BUDGET ANALYSIS

This section presents a box model that facilitates a holistic understanding of the linkage between channel morphological changes and sediment transport in a sediment routing system. Specifically, let us regard the entire Uji River as a 15.2km-long box model that comprises the accommodation space for stream flow and the boundary sediment domain. Let ΔV denote the change in the volume of the boundary domain. Then the mass balance of sediment in the box model over a period of time may be expressed as

$$\rho_s(1-n)\Delta V = Q_{in} - Q_{out} \quad (1)$$

where ρ_s is the mass density of sediment grains, n is the sediment porosity, Q_{in} represents the inflow of mass of sediment through the upstream end of the box and Q_{out} stands for the outflow of mass of sediment from the downstream end of the box.

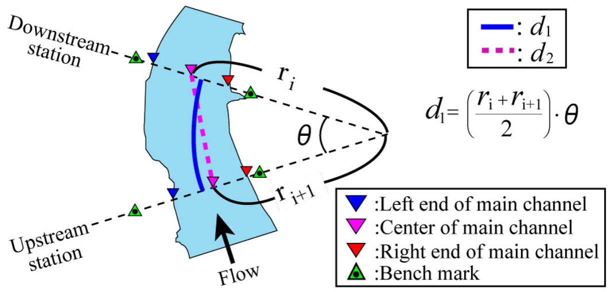

Fig.9 Sketch showing the parameters to allow for plan-form curvature

The ΔV value in the box model may be obtained by integrating the along-channel changes of sediment area that were already calculated, as illustrated in **Fig.6**. Let d be the channel-wise distance (nominally equal to 200m). Then the volume of the boundary sediment in a sub-box element between two stations may be calculated as

$$V = \frac{1}{3} \cdot d \cdot \left(A_i + A_{i+1} + \sqrt{A_i \cdot A_{i+1}} \right) \tag{2}$$

where A_i and A_{i+1} represent the areas of the boundary sediment in the downstream and upstream stations.

In order to assess the possible influence of plan form curvature on the sediment volume calculation with the box model, we introduced the following three definitions for d:

d_1; the distance allowing for the curvature between the two stations (refer to **Fig.9**)

d_2; the linear distance between the center points of the across-channel segment (refer to **Fig.9**)

d_3; the nominal distance 200m.

The calculated changes of the boundary sediment volume in the box model, ΔV, are listed in **Table 2** for the three periods of time indicated. It is seen that the use of either of d_1, d_2 and d_3 yields practically the same performance. For a logical clarity, we will subsequently refer to the ΔV value that was obtained in terms of d_1. What are the possible consequences or practical importance of the overall loss of 3.09×10^6 m^3 over the 38 years from 1967 to 2006? We will subsequently describe three related considerations in brief.

Fist of all, the loss of the boundary sediment volume means the gain of the accommodation space for flood water in the channel under discussion. Imagine that the 3.09×10^6 m^3 gain is equivalent to levee raising by 1m so as to create an in-channel accommodation space of 1m × 300m × 10000m. This surely is a substantial gain for risk management of the highly urbanized floodplain like the one in southern Kyoto.

Now that Amagase dam stands on the upstream end of the Uji River, one may put $Q_{in} \approx 0$ in Eq. (1). Accordingly, the mass of solid grains contained in

Table 2 Results of sediment budget analysis

Choice of d	ΔV (in 10^4 m^3) 1967～1979 12 years	ΔV (in 10^4 m^3) 1979～2006 26 years	ΔV (in 10^4 m^3) 1967～2006 38 years
d_1	-99	-210	-309
d_2	-99	-212	-312
d_3	-98	-210	-308

the sediment volume 3.09×10^6 m^3 that was lost over the 38 years, should have transferred to the Yodo River through the three-river confluence point. The consequences of the sediment transfer are yet to be examined closely. One interesting consideration may relate to inland navigation. There used to be cerebrated Fushimi Port in the Uji River around stations 43.6km-44.8km (refer to **Fig.3**). Although commercial ship transportation on the Uji River is inconceivable nowadays, there is a growing interest in the development of inland navigation on the Yodo River up to the Fushimi Port site for emergency relief operations in case of severe earthquake disasters. The presence of shoals in the reaches downstream the three-river confluence point, however, is a hurdle to manage toward safe possible navigation. The morphodynamics of such shoals is a subject for future studies in light of the sediment transport from the upstream regions including the Uji River.

The last consideration in this sub-section is concerned with the possible linkage with reservoir sedimentation. The volume of sediment stored in Amagase Dam in the period from March 1968 to February 2006 amounts to 3.99×10^6 m^3 . This quantity is practically comparable with (or only 30% larger than) the sediment loss in the box model, ΔV= 3.09×10^6 m^3. What is the underlying physics? Certainly, a future application of powerful sediment-transport analysis will be warranted with due consideration of fluvial depositional environments.

6. DISCUSSION

From a sedimentological point of view, the Uji River may be subdivided into four reaches. In order to make this statement clearer, we plot along-channel borehole logs (adapted from the Kansai Geo-informatics Network database) in a form as shown in **Fig.10**. In this figure we also plot thalwegs in March 1968 and in March 2006 that together represent the evolution of the longitudinal profile joining the deepest points of the channel bed (thalwegs) over the period of time concerned. Let us

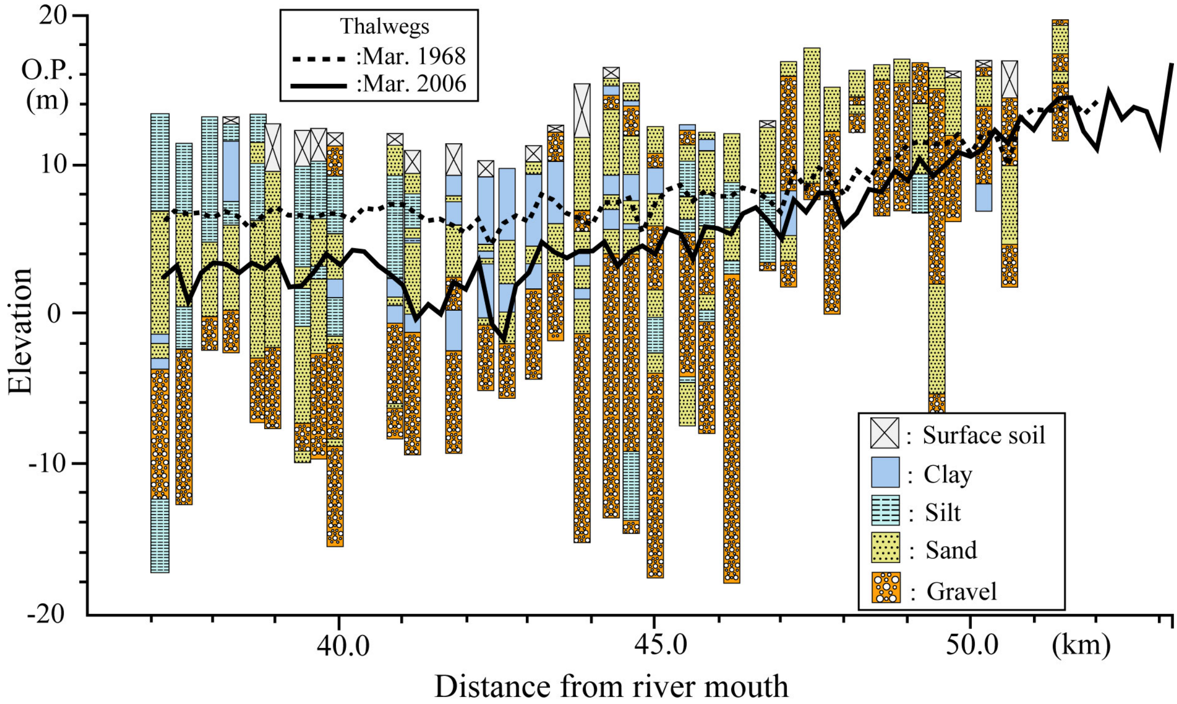

Fig.10 Plots of soil borehole logs (adapted from Kansai Geo-informatics Network) against the along-channel distance, together with thalwegs at two different times

start looking at the uppermost reach (Reach 1) that is located upstream of station 51km or so. Geologically, the reach is a confined rocky valley, thus undergoing least erosion. At the exit of the valley there occurs Reach 2 of alluvial-fan type or similar nature, extending down to station 47km or thereabouts. The associated material generally is coarse-grained, non-cohesive soil. Reach 3 of lacustrine nature, in close association with Ogura Pond, may be identified in a section around stations 42-43 km where well-defined clay layers are distributed at shallow depths (above O.P. +5m or so). The lowermost reach (reach 4) is of a backmarsh type. It extends farther down to station 37km or so, where silt layers are pronounced at shallow depths and are underlain by thick sand layers. Note that in Reaches 3 and 4, channel erosion has occurred at significant rates over the past forty years.

What will be the future tendency for erosion? We can make two related observations at this stage. First, in Reach 4 the riverbed has incised into the relatively thick sand layers, yet there remains a high potential for erosion. In Reach 3 the riverbed seems to have reached the base of the alluvium, which is underlain by a basal gravel layer. This is where a sort of rock control might have been operational. Indeed, we hypothesize that the riverbed degradation levels off when it has reached the basal gravel layer, thereby promoting lateral bank erosion where no revetment work was provisioned.

The just mentioned does not call for an immediate protection work. Rather, it emphasizes the importance of addressing the erosion issue from a broader perspective. This reasoning is in concert with the observation that the erosion in the Uji River has been occurring largely within the low-water channel, posing no direct threats to the integrity of the flood-control levees, somehow for the time being.

7. CONCLUSIONS

The channel erosion in the entire Uji River over the recent 38 years has been assessed and discussed, in terms of the cross-channel surveying results and related datasets of geoinformatics. The principal conclusions drawn may be summarized as follows:

1) The overall loss of sediment by erosion amounts to 3.1 $\times 10^6$ m^3 during the 38 years, which corresponds to a rate of 8 $\times 10^4$ m^3 per annum.

2) The loss of sediment by erosion has occurred largely within the low-water channel, resulting in a beneficial margin for accommodating flood water

3) The extent of the channel erosion is pronounced in the lower reaches passing through the lowland where lacustrine deposits or the like are distributed in association with Ogura Pond.

4) The channel erosion especially in the lower reaches is likely to accumulate appreciably, calling for dedicated monitoring and concerted analysis.

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REFERENCES

1) Azuma, R., Sekiguchi, H., Muto, Y. and Ono, T.: Bank erosion as an indicator of channel morphodynamical evolution, *Proc. of Int. Symp. on Mitigation & Adaptation of Climate-change-induced Natural Disasters*, Hue, pp.59-68, 2007.
2) Geographical Survey Institute, Digital Map (Spatial Data Framework), KINKI-1, 2005.
3) Kansai Geo-informatics Network, Kansai Geo-informatics Database, CD-ROM, 2007.
4) Ministry of Land, Infrastructure and Transport, Kinki Regional Development Bureau: Centurial History of the Yodo River, 1822pp., 1974 (in Japanese).
5) Ministry of Land, Infrastructure and Transport, Kinki Regional Development Bureau: Summary of the Yodo River, p.9, 2000 (in Japanese).
6) Research committee for the active faults in Kyoto City (Oike, K., Okada, A., Takemura, K., Uemura, Y., Yoshioka, T., Matsui, K., Furusawa, A., Sonoda, T., Sugimori, T., Umeda, T. and Saito, M.): Quaternary activity of the Ujigawa fault dividing the underground structure of the Kyoto basin into the north and south parts, central Japan, *Active Fault Research*, Vol.24, pp.139-156, 2004 (in Japanese).