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Influence of Anthropogenic Activities on the Lower Tedori River, Japan

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Abstract

Long-term variations in the riverbed of the Tedori River, Japan, were investigated using a series of field surveys conducted between 1950 and 2007. The results showed that the sediment volume of the observed areas declined by 12.7×10^6 m^3 between 1950 and 1991. The riverbed has undergone serious and rapid erosion, lowering by 0.5–3.5 m, with an erosion rate of 0.06–0.10 m/year. In contrast, the riverbed sediment volume increased by 0.6×10^6 m^3 between 1991 and 2007. The temporal and spatial variation in the sediment volume and the corresponding riverbed response were related to anthropogenic activities such as gravel and sand extraction and dam construction. The variations between 1950 and 1979 were effectively identified using empirical orthogonal function analysis.

Key Words: Tedori River, erosion, anthropogenic impact, Empirical orthogonal function

I. Introduction

In many rivers worldwide, anthropogenic activities such as gravel-sand extraction and dam construction have disrupted the continuity of sediment transport and altered the downstream flow regime. The transport of sand and gravel sized sediment particles is particularly important in determining channel form, and a reduction in the supply of these sediments may induce significant channel changes (Kondolf, 1997). Consequently, any interruption in sediment movement by dams may cause accelerated erosion of the riverbed. Conversely, below dams, floods may not be sufficiently competent at entraining and transporting the incoming sediment from tributaries, so the riverbed begins to aggrade (Vericat *et al*, 2006). Therefore, it is important to investigate how anthropogenic activities in a river basin influence the sediment processes and the corresponding downstream morphological responses.

A variety of human induced morphological variations in rivers have been studied in the past few decades (*e.g.*, Kondolf, 1997; Yuhi, 2008; Isik, 2008). However, it is often difficult to fully understand the temporal and spatial variations that occur in a river basin and to quantify the effect of individual human interventions on such variations owing to the inherent complexity of the problem and the paucity of related data. A better understanding of the changes in the bedforms and corresponding sediment volumes of a river due to anthropogenic impacts could make a crucial contribution to the management of river watersheds.

This study was conducted to analyze the changes that

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have occurred in the bed of the lower Tedori River, Japan, with particular consideration of the human impacts on the changes in sediment volume. The main trends in the riverbed variation were simultaneously examined using empirical orthogonal function (EOF) analysis.

Ⅱ. Study Area

The Tedori River, which originates at Mt. Hakusan, has a catchment area of 809 km^2 and a channel length of 72 km (Fig. 1). The main tributary of the Tedori River is the Ushikubi River, with other tributaries being the Ozo River, the Danichi River and other small rivers. The Tedori River flows through the Tsurugi gauging station, on its westward journey through the Kaga Plain to the Japan Sea. The lower Tedori River referred to in the remainder of this paper (the reach downstream of the Tedorigawa Dam) is the portion of the river between the river mouth and 16 km upstream. The Tedori River is one of the steepest rivers in Japan, with average slopes of 1/27 and 1/145 for the entire river and the lower Tedori River, respectively. Based on homogeneity related to slope, width, and mean diameter of bed material, the lower Tedori River can be divided into four reaches located 0–2 km, 2–7 km, 7–13 km, and 13–16 km upstream of the river mouth (Teramoto *et al.*, 2003) (Table 1).

The drainage area is underlain by various lithologies, including ancient Hida metamorphic rocks and volcanic rocks from eruptions of Mt. Hakusan. Nobi rhyolites (pyroclastic rock) from the Mesozoic to the Cenozoic era are distributed around the Mt. Hakusan area while Tedori Layers are present in the area east of the Tedorigawa Dam and the Ozo River. Both the Tedori Layers and Nobi rhyolites are prone to massive collapse. Therefore, a large amount of gravel and sand sized sediment has been flowing into the Tedori River.

The climate of the catchment area is dominated by the monsoon winds blowing in from the Japan Sea. The mean annual rainfall in the Tedori River catchment is about 2,600 mm/yr on the plains, and 3,300–3,600 mm/yr in the mountain ranges. In 1980, the Tedorigawa Dam (Fig. 1) was constructed, resulting in changes in the flow regime of the lower Tedori River. The highest average daily discharges in the lower Tedori River typically occur from mid-March to late May (due to snow melt) and from mid-June to mid-July (owing to seasonal rainfall) both before and after the Tedori dam

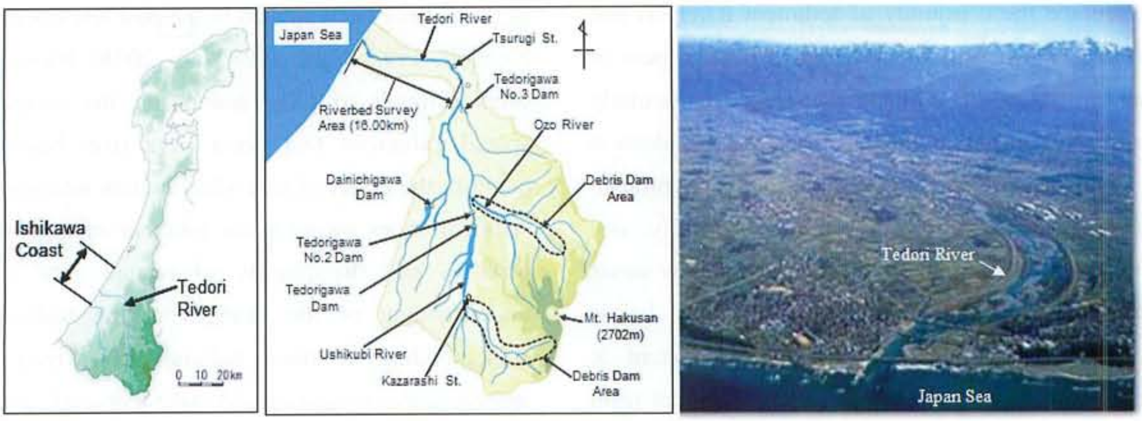


Fig. 1 Tedori River basin.

Table 1 Characteristics of the four distinct reaches in the lower Tedori River (Teramoto *et al.*, 2003).

	Reach 1	Reach 2	Reach 3	Reach 4
Distance upstream of river mouth (km)	0.0–2.0	2.0–7.0	7.0–13.0	13.0–16.0
Channel width (m)	350	358	289	146
Channel slope	1/365	1/190	1/140	1/130
Mean diameter of bed material (mm)	67	77	166	187

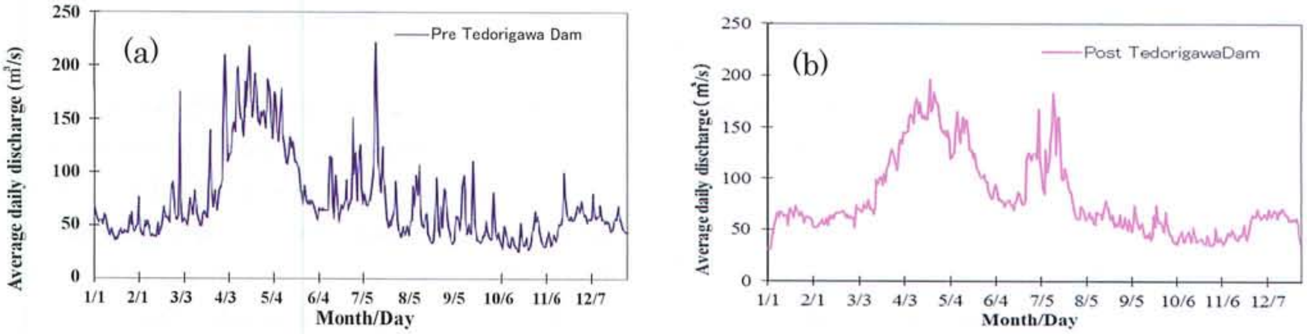


Fig. 2 Temporal variation in average daily discharge: (a) before (1968–1979); and (b) after dam construction (1980–2003).

construction (Fig. 2).

In recent decades, anthropogenic activities such as sand and gravel extraction, the construction of debris dams and multi-purpose dams, and dredging activities have significantly impacted the Tedori River basin. This has resulted in erosion of the riverbed in the lower reaches of the Tedori River by 0.5–3.5 m between 1950 and 1991, while a slight accretion has occurred in the study area from 1991 to 2007.

Ⅲ. Data Sets and Methods

1) Field Data

The temporal and spatial scale used to study an area should be closely related to the availability and quality of existing field records. Consequently, this study focused on investigating variations that occurred in the lower 16 km of the river during 1950- 2007. Data sets were provided by the Hokuriku Regional Development Bureau of the Ministry of Land, Infrastructure and Transport, Japan. These data sets consisted of: annual surveys of the topography at 81 river cross-sections at 200 m intervals along the 0–16 km reach in 1950–1979, 1991, 1997, 1998, 2002, 2003 and 2007; the permitted annual sand and gravel extraction volume from the river channel (1951–1991); the annual sediment deposition volume in debris dams (1936–1983, with some missing years); the volume of material dredged annually for maintenance activities (1949–1963); and the annual maximum river discharge (Q_{max}) data from 1928 to 2006 measured at the Tsurugi hydrological station, located 14 km upstream from the river mouth (Fig. 1). Sequential aerial photographs at 1:30,000 scales were also obtained for six dates from 1947 to 2007. In general, the range of surveyed data was sufficient to capture the main trends in changes in the river morphology and its controlling factors.

2) EOF Analysis

First, a comparative analysis of the existing survey data was conducted to detect and quantify the dominant trends in time and space. The long-term changes in the channel characteristics were then examined by EOF analysis. EOF analysis was initially used to describe the changes in beach profiles based on the lowest number of eigenfunctions (Winant *et al*, 1975). In this study, the riverbed level Z_{ki} (averaged for each cross-section) was explained by the summation of eigenmodes, as shown below.

$$Z_{ki} = \sum_{n=1}^{N} C_{nk} e_{ni} \text{ for the } i\text{th profile position and } k\text{th survey} \qquad (1)$$

where e_{ni} are the normalized spatial functions; C_{nk} are the temporal functions; and n indicates the variation modes. Subscript i ranges from 1 to I, the total number of points along the longitudinal profile of the riverbed where data are taken, and subscript k ranges from 1 to K, the total number of times when profiles were recorded. The spatial functions or eigenfunctions that best fit the data using the least squares method are determined with the following matrix equation:

$$\mathbf{A}e_n = \lambda_n e_n \qquad (2)$$

where $\mathbf{A}$ is a symmetric correlation matrix from a_{ij} and λ_n is the corresponding eigenvalue of the matrix A. The elements a_{ij} are calculated by

$$a_{ij} = \frac{1}{KI}\sum_{k=1}^{K} Z_{ik}Z_{jk} \quad i,j=1,2,\ldots,I. \qquad (3)$$

A dominant feature of eigenfunctions is that they are mutually orthogonal, so that

$$\sum_{i} e_{ni}e_{mi} = \delta_{nm}\,. \qquad (4)$$

where δ_{nm} is the usual Kronecker delta such that if $m=n$, then $\delta_{nm}=1$, otherwise $\delta_{nm}=0$. To obtain the value of the unknown C_{nk}, we minimize the mean square error in the fit of Z_{ki} using the eigenfunctions. The local error ξ_{ki} is defined as

$$\xi_{ki}=Z_{ki} - \sum_{n=1}^{N} C_{nk}e_{n_i}\,. \qquad (5)$$

The minimization is carried out using the least-squares method by minimizing the sum of the squares of the errors over the profile ($\sum_{i=1}^{I}\xi_{ik}^{2}$) with respect to C_{mk}

$$2\sum_{i=1}^{I}(Z_{ik} - \sum_{n=1}^{N} C_{nk}e_{ni})e_{mi} = 0. \qquad (6)$$

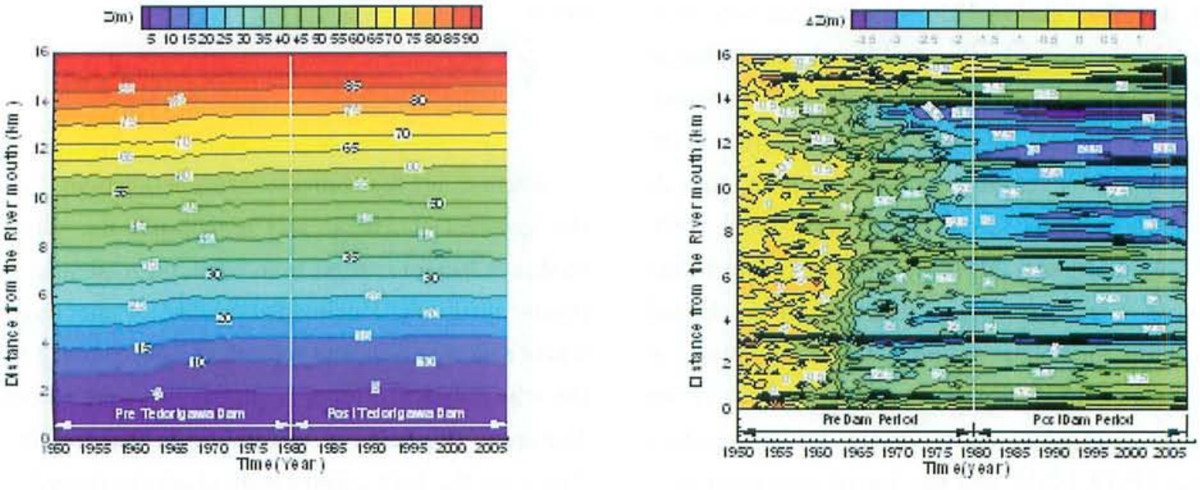
Using the orthogonality, we have:

$$C_{mk} = \sum_{i=1}^{I} Z_{ik}e_{mi}\,. \qquad (7)$$

Ⅳ. Results

1) General Features of Riverbed Response

Figure 3a describes the temporal variations in the riverbed elevation (Z) in the lower Tedori River. The bed elevation was measured relative to the Tokyo Peil (T.P.) datum, which is the standard ground elevation in Japan based on the mean sea level in Tokyo Bay. An overall trend of considerable erosion was evident during the period of 1950–2007. Fig. 3b indicates that the riverbed level decreased by 0.30–3.50 m over the period 1950-2007. Comparisons of longitudinal profiles from 1950, 1979 and 2007 (Fig. 4) and corresponding cross-sections at 1 km intervals (Fig. 6) indicate that the erosion during 1950–1979 was much more significant than during 1979–2007. In particular, the average erosion depth of 1.8 m during 1950–1979 was considerably higher than the average erosion depth of 0.16 m during 1979–2007. The mean erosion depths for reaches 2, 3 and 4 (2.10 m, 2.84 m and 2.02 m, respectively) were significantly greater than for reach 1 (0.84 m) (Table 2). This surprising result implies that construction of the Tedorigawa Dam did not aggravate the erosion in the lower Tedori River. In addition, Figure 5 illustrates the deposition/erosion distribution in plan form based on changes in real riverbed levels surveyed in the years between 1950 and 1979. The most intensive and



(a) Mean riverbed elevation

(b) Variation in mean riverbed elevation relative to 1950

Fig. 3 Temporal and spatial variation in elevation of the Tedori riverbed (T.P.).

Table 2 Temporal variation in average erosion depth for each reach.

Distance (km)	Erosion depth (m)		
	1950–1979	1979–2007	1950–2007
0–2 (Reach 1)	−1.26	0.39	−0.87
2–7 (Reach 2)	−2.01	−0.08	−2.10
7–13 (Reach 3)	−2.46	−0.38	−2.84
13–16 (Reach 4)	−1.45	−0.58	−2.02
Average	−1.80	−0.16	−1.96

Distances are measured upstream from the river mouth.

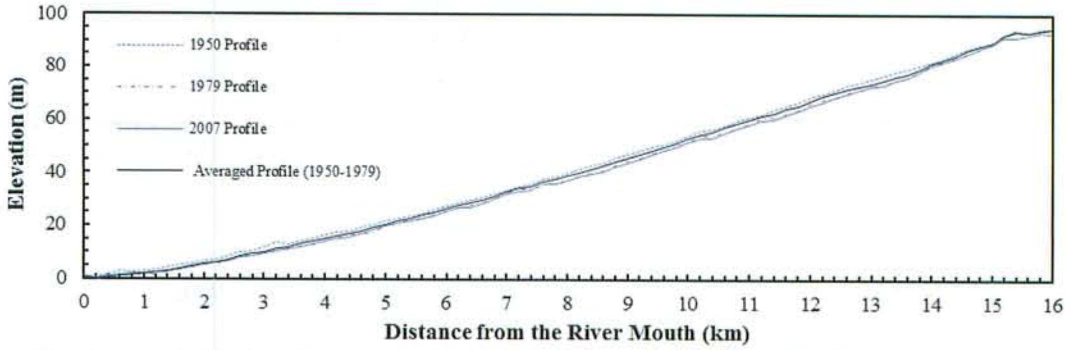


Fig. 4 Longitudinal profiles of the lower Tedori River surveyed in 1950, 1979, 2007 and average profile from 1950 to 1979.

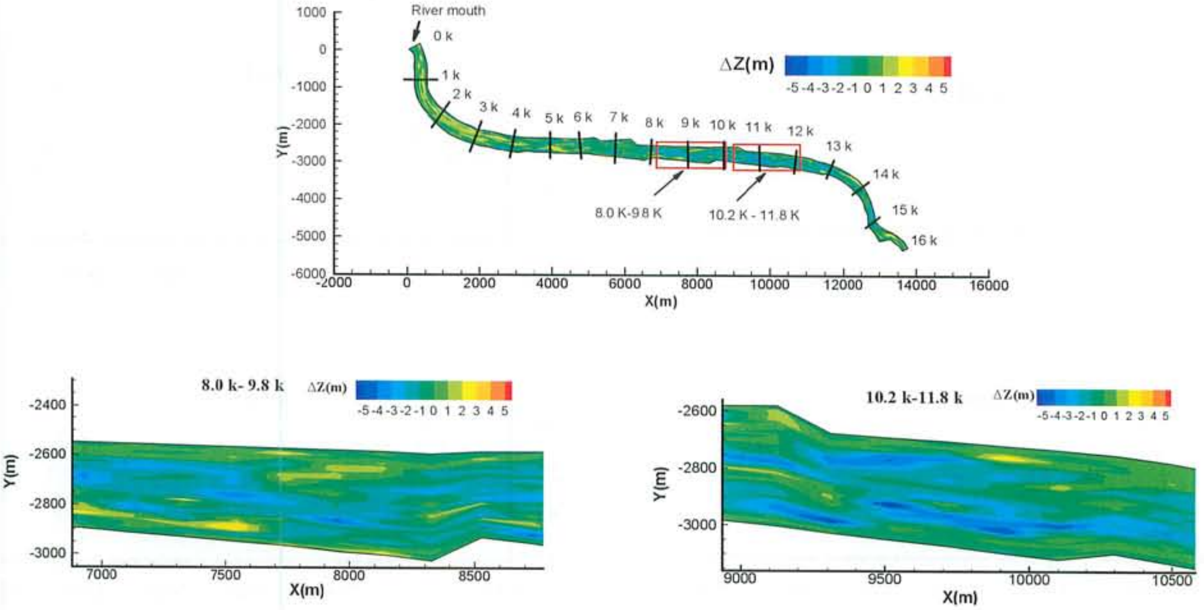
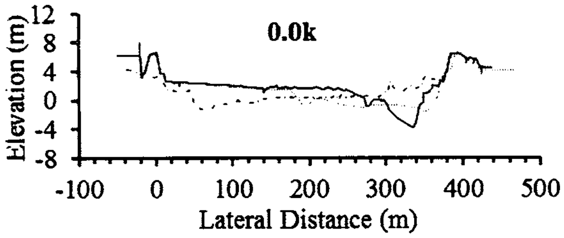


Fig. 5 Variation in riverbed level (1950–1979).

extensive erosion was observed in the region 8–12 km upstream from the river mouth.

Alluvial survey results along cross-sections at 1 km intervals were collated between 1950–1979 and 1979–2007, as shown in Fig. 6. The results indicate that from 1950 to 1979, significant erosion occurred along the entire river channel and floodplain, except at 0, 1, 4, 15 and 16 km upstream from the river mouth. At the five locations mentioned previously, erosion occurred intensively in the river channel but light deposition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400
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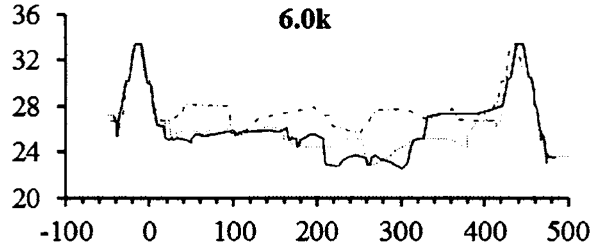
Lateral Distance (m)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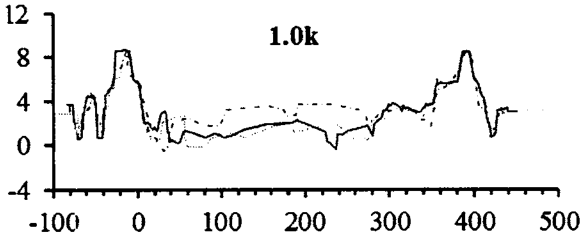
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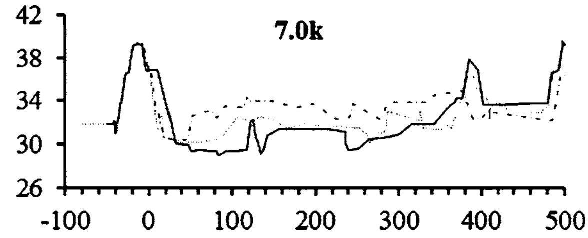
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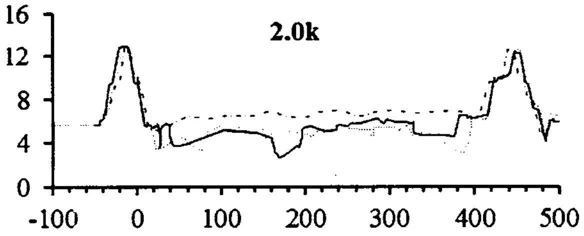
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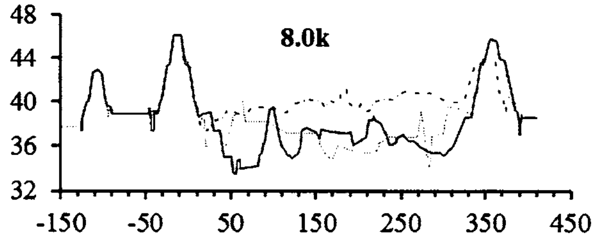
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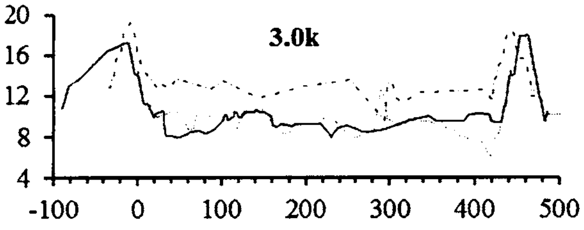
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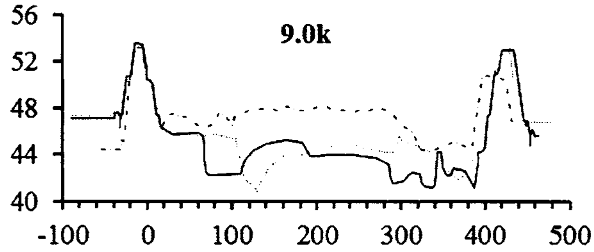
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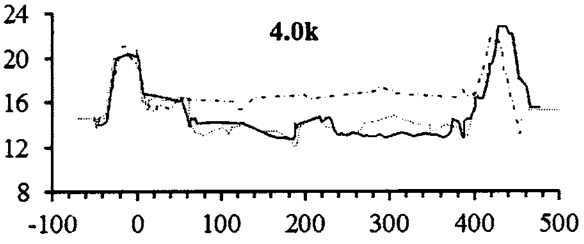
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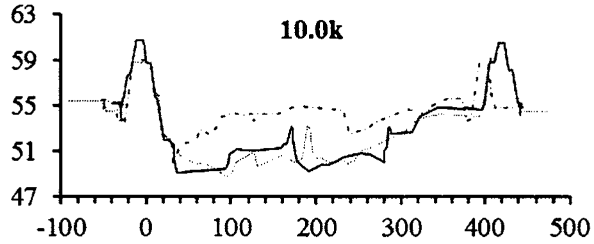
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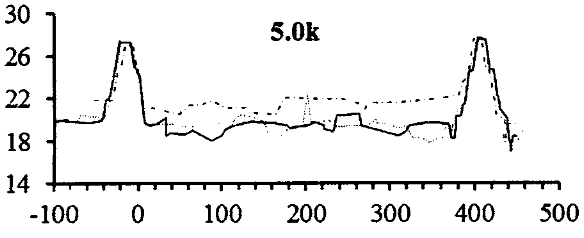
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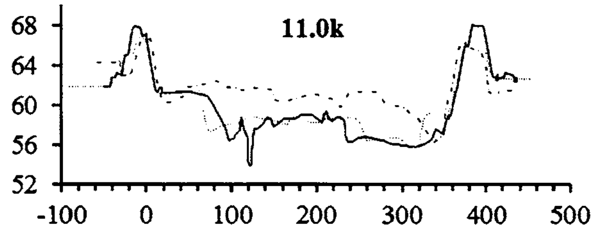
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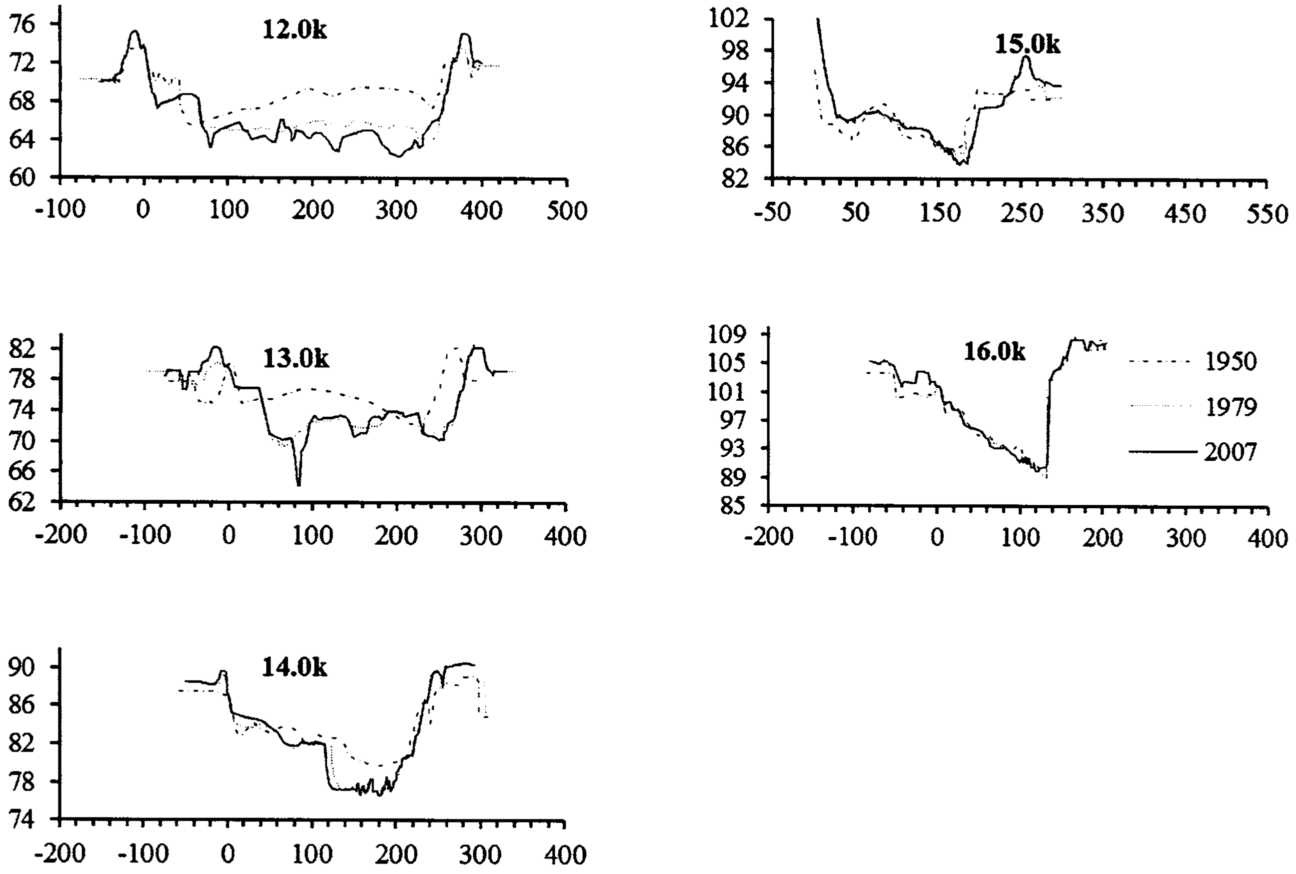


Fig. 6 Comparison of cross-sections from 1950, 1979 and 2007 at 1 km intervals.

occurred in the floodplain. For each cross-section during 1979–2007, accretion was clearly observed in the floodplain while both erosion and deposition occurred in the river channel.

The spatial distribution of the linear trends in variations in the riverbed level during 1950–2007 is shown in Fig. 7. The linear trends are calculated as the temporal gradient of the riverbed elevation at each cross-section, using the least squares method. Between 1950 and 1979, the average erosion rates at Reaches 2 and 3 were 0.1 m/yr and 0.09 m/yr, respectively; at Reaches 1 and 4 the average erosion rate was 0.06 m/yr (Table 3). The highest rate of erosion during 1950–1979 was 0.14 m/yr, 3.2 km from the river mouth, after which the erosion rate decreased steadily until the end of Reach 2. The trends in reach 3 fluctuated, with the second highest erosion rate during 1950–1979 measured in this reach, after which the erosion rate decreased considerably to the end of Reach 4. The corresponding trends during the sub-periods of 1950–1959, 1960–1969 and 1970–1979 are also included in Fig. 7. Between 1950 and 1959, significant erosion was observed from 0 to 5.5 km and in almost all of the 6.5–16 km reach, while minor deposition was observed at 5.5–6.5 km and about 15 km upstream from the river mouth. Between 1971 and 1979, accretion was evident in the reach 0–4 km upstream from the river mouth, with an accretion rate of 0.05 m/yr, which can be attributed to natural recovery of the sediment. However, strong erosion was observed in other areas, with a mean erosion rate of 0.07 m/yr. It is interesting to note that the variation in the riverbed in the 1960s was similar to the overall 1950–1979 period described above. In particular, significant erosion was evident along the longitudinal riverbed profile during both time periods, with the highest values occurring at the same location in Reach 2 (2–7km) at 0.24 m/yr (1960–1969) and 0.1 m/yr (1950–1979). These findings imply that the intensive sand mining that occurred in the 1960s dominated the change in riverbed elevations observed during the entire study period.

Table 3 Mean value of linear trends during different periods.

Distance (km)	Linear trend (m/year)				
	1950–1959	1960–1969	1970–1979	1950–1979	1980–2007
0–2 (Reach 1)	−0.07	−0.13	0.04	−0.06	0.03
2–7 (Reach 2)	−0.03	−0.24	0.01	−0.10	0.01
7–13 (Reach 3)	−0.06	−0.13	−0.10	-0.09	0.00
13–16 (Reach 4)	−0.05	−0.09	−0.03	−0.06	−0.02

Distances are measured from the river mouth.

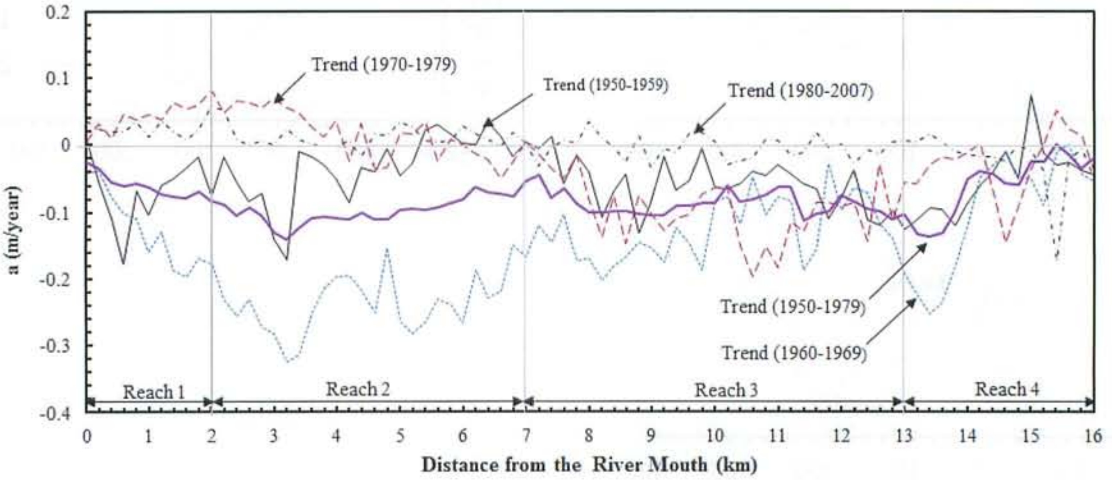


Fig. 7 Linear trends in riverbed variation.

In contrast to the 1950–1979 period, the linear trend in the riverbed level variation was minor from 1980 to 2007. A slight accretion trend was observed in the first two reaches with rates of 0.03 m/yr and 0.01 m/yr, respectively (Table 3). In Reach 3, the erosion rate of 0.00 m/yr was unvarying while Reach 4 experienced slight erosion at 0.02 m/yr.

2) Variation in Sediment Characteristics in the Lower Tedori River

Figure 8 shows the cumulative variations in sediment volume in the lower reach of the Tedori River from 1950 to 2007. The changes in the sediment volume of Reaches 1–4 were also examined. The cumulative variation in sediment volume was calculated with respect to the riverbed elevation in 1950. The overall trend in sediment volume in all reaches was a significant decrease during 1950–1979 and a slight decrease during 1980–2007. Overall in the lower 16 km of the river, the sediment volume decreased by 11.5×10^6 m^3 during the first 30 years at a rate of 0.38×10^6 m^3/yr, while the decrease in the following 29 years was 0.63×10^6 m^3, a rate of 0.02×10^6 m^3/yr. The greatest reduction in sediment volume occurred in the 1960s, with a reduction of almost 6.8×10^6 m^3 of sediment (0.68×10^6 m^3/yr). A similar trend was also observed in Reach 2 (2–7 km upstream) in the 1960s. This is considered to be due to the intensive sand excavation that occurred in the 1960s. In the 1970s, the cumulative sediment volume change in the entire study area was closely related to the change in Reach 3 (7–13 km upstream). From 1979 to 1991, the sediment volume declined by 1.23×10^6 m^3 (0.09×10^6 m^3/yr), and then increased by 0.6×10^6 m^3 (0.04×10^6 m^3/yr) between 1991 and 2007. A similar trend was also seen clearly in Reaches 1–3, while the steady erosion appeared to be occurring in Reach 4 throughout the whole period of 1979–2007.

An investigation of the variation in median sediment diameter (d_m) in both the river channel and floodplain was conducted by annual surveys of sediment samples from 1963 to 1971. Figure 9 shows the temporal variation in d_m in relation to the temporal variations in the slope and flood discharge product (Q.S). The Q.S may be representative of stream power per unit channel length (Bridge, 2003) and, consequently, may be an important factor that influences the variation in d_m. Thus, in Reaches 1, 2 and 3, the temporal variation in both d_{mc} (median sediment diameter in the river channel) and d_{mp} (median sediment diameter on the floodplain) is closely related to the temporal variation in Q.S during 1963–1971. In Reach 4, although a close relationship was also observed between d_{mc} and Q.S from 1963 to 1971, the variation in d_{mp} is opposite to the Q.S from 1966 to 1969. In particular, in 1966 and 1968, when the minimum values of Q.S were measured, maximum values of d_{mp} were recorded (Fig. 9d). This unusual

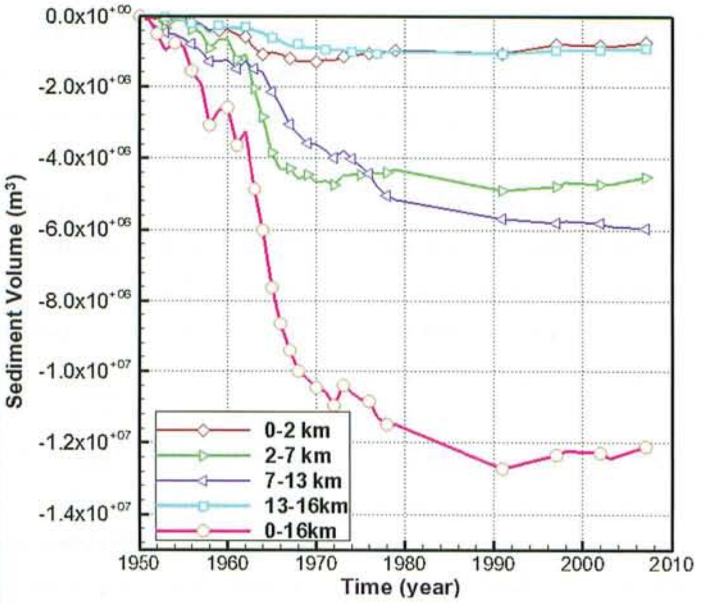


Fig. 8 Cumulative variations in sediment volume in the Tedori riverbed.

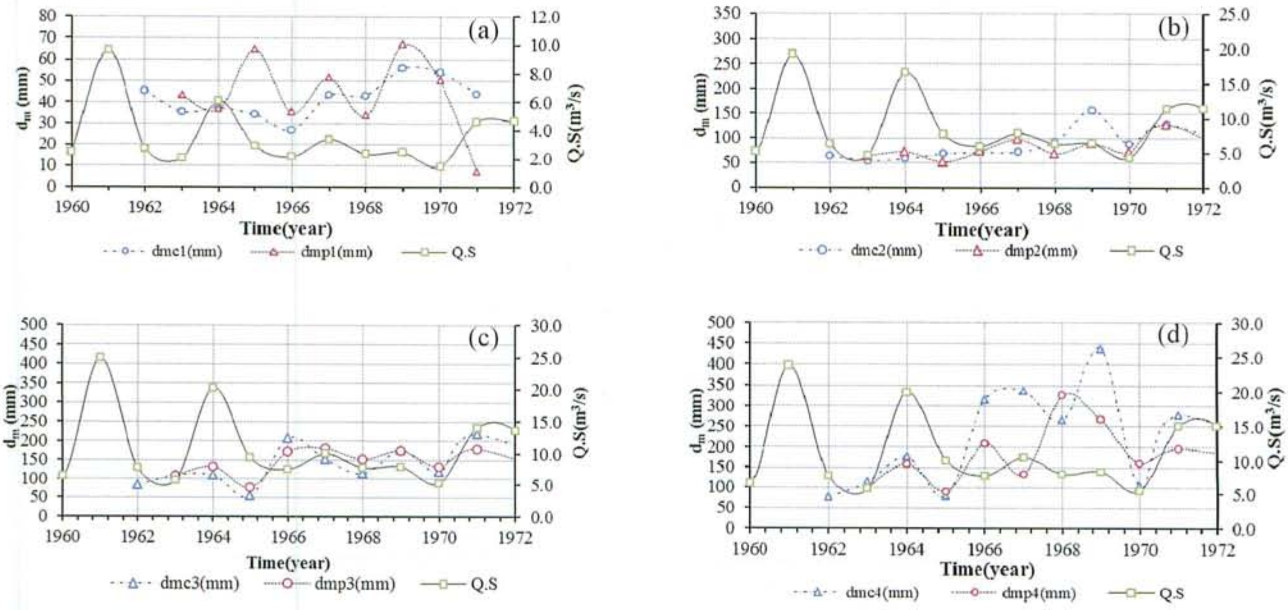


Fig. 9 Temporal variation in the slope and flood discharge product (Q.S) and D_m of the lower Tedori River: (a) Reach 1 (0–2 km); (b) Reach 2 (2–7 km); (c) Reach 3 (7–13 km); and (d) Reach 4 (13–16 km upstream of river mouth).

relationship could be related to the effect of intensive sand mining that occurred in the floodplain of Reach 4, as gravel and sand extraction may have made the bed surface more armored.

V. Discussion

1) Impacts of Anthropogenic Activities on Variations in River Morphology, 1950–1979

To investigate the effects of anthropogenic activities on changes in the cumulative sediment volume and the riverbed of the Tedori River, the cumulative volume of sediment in debris dams, and the cumulative volume of sediment extracted from the river (sand and gravel mining, and dredging activities) were determined (Fig. 10). During the post-World War II period, sand and gravel were mined from the alluvial section of the river for construction aggregate. This extraction was intensive in the area from the river mouth to 15 km upstream. During the mid-1960s, the most extensive mining activities occurred, resulting in a considerable reduction in the riverbed. The total amount of extracted sediment was estimated to be 6.4×10^6 m^3 based on licenses issued by local authorities from 1950 to 1979; however, it is difficult to determine the amount that was actually removed from the riverbed. Yamamoto *et al.* (2008) estimated that the extracted amount could be up to two times greater than the volumes determined from local permits. From 1949 to 1963, maintenance dredging of the river channel was conducted in the area from the river mouth to 4.8 km upstream, which resulted in the removal of 2.1×10^6 m^3 of sediment (Fig. 11). Between 1950 and 1969, the cumulative volume of extracted material increased by approximately 6.8×10^6 m^3, a rate of 0.34×10^6 m^3/yr. However, owing to legal enforcement of the sand mining permits starting in the mid-1970s, the rate of increase in the cumulative volume of extracted material in the 1970s was lower than that in the 1960s. The estimated amount of sediment removed by sand mining and channel dredging from 1949 to 1979 was 9.35×10^6 m^3, which is equivalent to 81% of the decreased riverbed sediment volume of 11.5×10^6 m^3. This clearly indicates that the sand mining had a crucial impact on the decrease in riverbed sediment volume as well as the corresponding riverbed level during 1950–1979.

In the upstream region of the river, in the Hakusan Mountains, where the Tedori system is composed of two major tributaries (the Ushikubi and Ozo rivers), approximately 150 debris dams have been constructed to monitor and control the production of debris and sediment runoff since the 1910s. Between 1955 and 1959, sediment deposition in the debris dams rapidly increased to approximately 3.24×10^6 m^3, at 0.65×10^6 m^3/yr, then

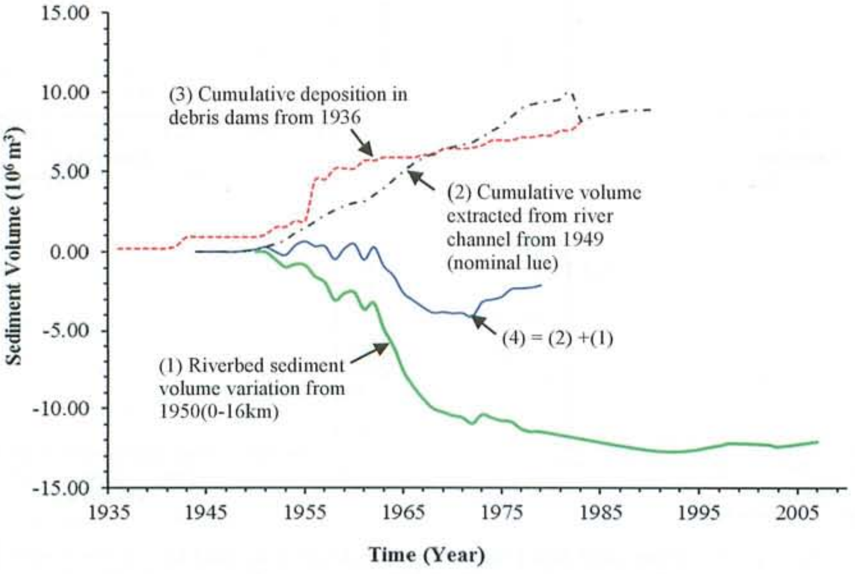


Fig. 10 Temporal variations in cumulative sediment volume in the Tedori River basin.

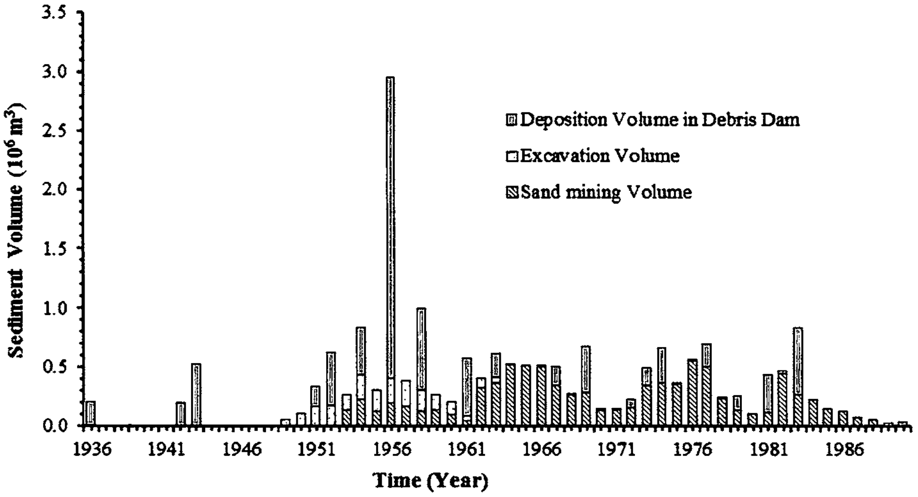


Fig. 11 Temporal variation in the volume of sediment trapped or removed from the sediment transport system due to anthropogenic activities.

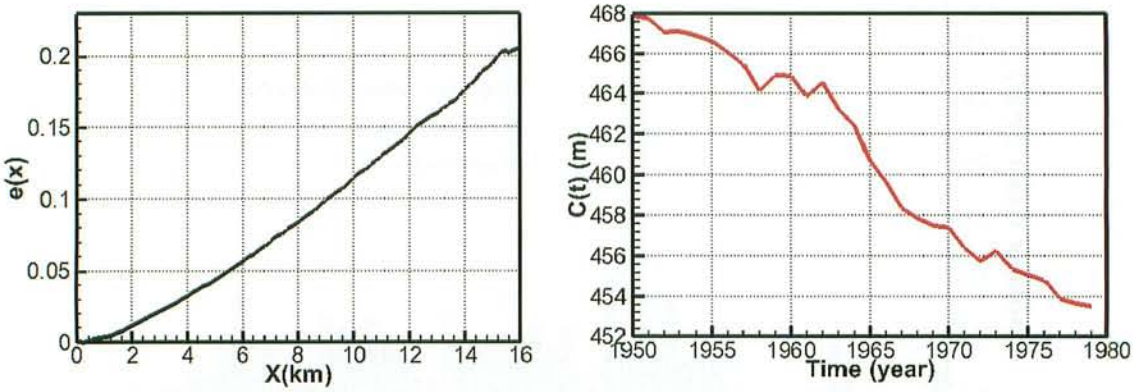
gradually increasing to 7.3×10^6 m^3 by 1979. The median grain size of sediment sampled in these dams in 1980 was 78.4 mm and 117.1 mm in the Ozo and Ushikubi river areas, respectively. The median diameters of sediment deposited in debris dams were found to be the same as those in the bed surface in the lower Tedori River. This implies that the debris dams have trapped the amount of sediment that may be transported to the lower Tedori river by flood events. Therefore, it was considered that debris dams may contributed significantly to the degradation of the riverbed level in the lower Tedori River.

2) EOF Analysis

EOF analysis was used to discuss the decadal variation in the mean riverbed levels as well as its controlling factors. Figures 12 and 13 describe the temporal and spatial functions for the first three modes. The variance associated with the first eigenfunction was 99.9854%, while the second and third eigenfunctions account for 0.0119% and 0.0008% of the variations, respectively. These findings clearly indicate that the spatial function of the first mode $e_1(x)$ corresponds to the mean riverbed profile during 1950–1979 (the averaged profile (1950–1979) in Fig. 4). The temporal function $C_1(t)$ was closely related to the curve describing the cumulative temporal variation in the sediment volume of the lower reach of the Tedori River. In addition, the spatial functions of the second mode $e_2(x)$ were found to reflect the linear trend of variations in the mean bed level from 1950 to 1979 and 1961 to 1970. The temporal function $C_2(t)$ gradually increased in the 1950s, then rapidly increased in the 1960s before becoming stable in the 1970s. The variation trend of such curve describes the trend in the cumulative deposition of sediment volume in debris dams with a lag time of about 5 years. For the third mode, the spatial function $e_3(x)$ was found to be positive in the 0–4 km reach, negative in Reach 3 (7–13 km) and fluctuated around zero in the remaining reaches, indicating that this curve corresponds to the linear trend of mean bed level variations during 1971–1979. The $C_3(t)$ curve had slight fluctuations in the 1950s, then decreased considerably in the early 1960s, before increasing until 1979. With a time lag of 3 years, this curve is related to curve (4) in Fig. 11 which describes the sum of the cumulative variation in sediment volume for the 0–16 km reach and the cumulative sediment volume extracted from the river (sand mining plus dredging). As the third mode of variation is the product of $e_3(x)$ and $C_3(t)$, the third mode describes the accretion at 0 to 4 km during 1971–1979.

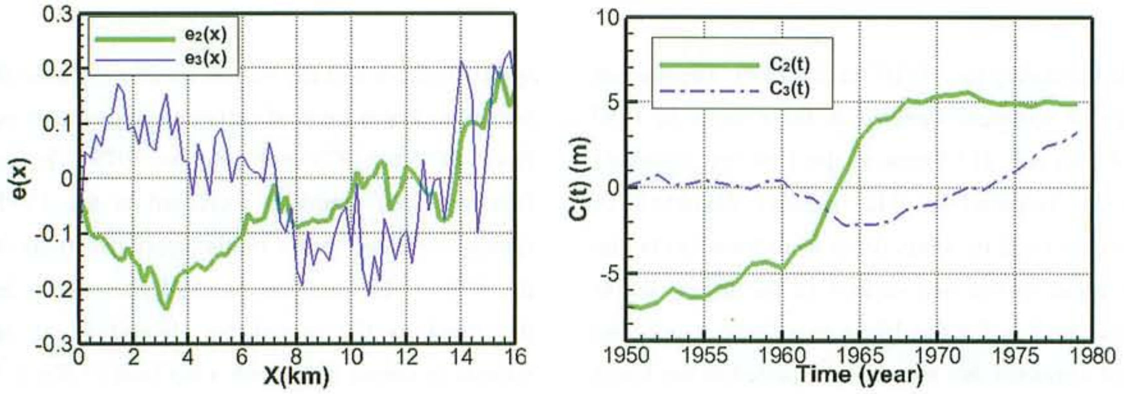
3) Impacts of Anthropogenic Activities on Variations in River Morphology, 1979–2007

A further gradual decrease in riverbed sediment volume occurred in the lower Tedori River from 1979 to



(a) Spatial eigenfunction $e_1(x)$ (b) Temporal Eigenfunction $C_1(t)$

Fig. 12 Temporal and spatial eigenfunctions for the first mode.



(a) Spatial eigenfunctions (b) Temporal eigenfunctions

Fig. 13 Temporal and spatial eigenfunctions for the second and third modes.

1991 (Fig.11), during which the bed sediment volume decreased by $1.23 \times 10^6 m^3$. In the period 1979-1991, the volume of sand extracted from the Tedrori river was about 1.75×10^6 m^3, at 0.13×10^6 m^3/yr while the incoming sediment volume was supplied by Ozo river was also nearly 0.13×10^6 m^3/yr. In this case, the sediment budget of Ozo river was roughly estimated based on a numerical analysis conducted by HRDB in 2007. Thus, the gravel and sand mining was a key driving force lowering the riverbed in that period.

Immediately following the cessation of gravel and sand mining in 1991, slight accretion was observed in the study area, and this has continued until the end of the study period in 2007. This trend was attributed to sediment supplied by the Ozo River during flood seasons and a substantial reduction in the sediment-carrying capacity of the lower river due to the Tedorigawa dam construction. Flood control operations have led to a decrease in the magnitude and frequency of floods in the post-dam period compared with the pre-dam period. Figure 15 shows that the average flood peaks in the pre- and post-dam periods were 1737 m^3/s and 1159 m^3/s, respectively. The expected probable flood discharges for 5, 10, 50 year return events (Table 4) were also calculated using the annual maximum discharges observed at Tsurugi gauging station and by using the Gumbel method. The results indicate that the volumes of the 5-, 10- and 50-year return flood events are forecast to decrease by 24%, 19% and 14%, respectively.

A summary of the flow characteristics for the pre-and post-dam periods is shown in Table 5. It indicates that, owing to increased rainfall, the average annual flow in

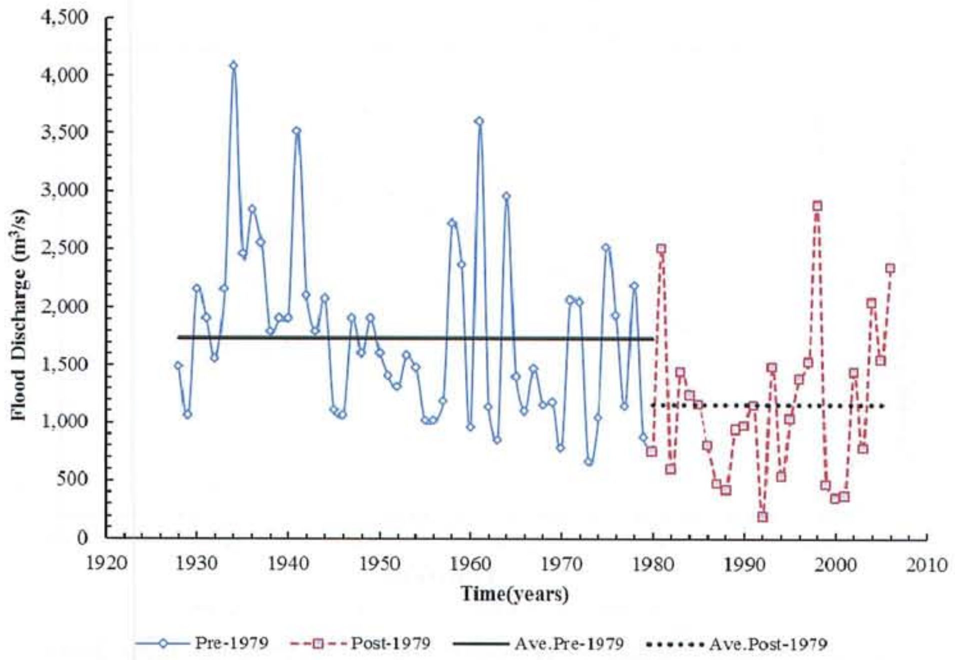


Fig. 14 Temporal variation in flood discharge at the Tsurugi gauging station before and after Tedorigawa dam construction.

Table 4 Expected maximum flood discharges corresponding to varying return periods.

Return period (year)	Flood Discharge		Reduction (%)
	PreDam (1928–1979) (m^3/s)	PostDam (1980–2006) (m^3/s)	
5	2357	1799	24%
10	2847	2293	19%
50	3924	3379	14%

Table 5 Flow characteristics of the Tedori River before and after dam construction.

Flow characteristics	Unit	PreDam (1968–1979)	PostDam (1979–2003)	Deviation
Average annual flow volume	m^3	26688.8	29484.3	10%
$Q_{daymean}$	m^3/s	72.9	80.6	10%
RMS (Q_{3d})		10.86	4.97	-54%

the post-dam period was 10% greater than before dam construction. The root mean square of deviations between the daily average discharge and the 3-day moving average discharges (RMS(Q_{3d})) was also determined. The results (Table 5) show that the RMS(Q_{3d}) in the post-dam period is over 50% lower than in the pre-dam period. This reduction in magnitude and frequency of flood events leads to a direct reduction in the sediment-carrying capacity of the flow, and also an increase in the vegetation cover along the river. In turn, the drag caused by vegetation increases the overall flow resistance and reduces the shear stress applied to the bed, resulting in reduced bed-load transport capacity and increased propensity for trapping, deposition, and stabilization of sediment (Wu *et al*, 2009).

After analyzing aerial photographs from 1984, 1995 and 2000, the temporal variation in vegetation cover in various sub-reaches including 0–2 km, 4–6 km, 9–11 km

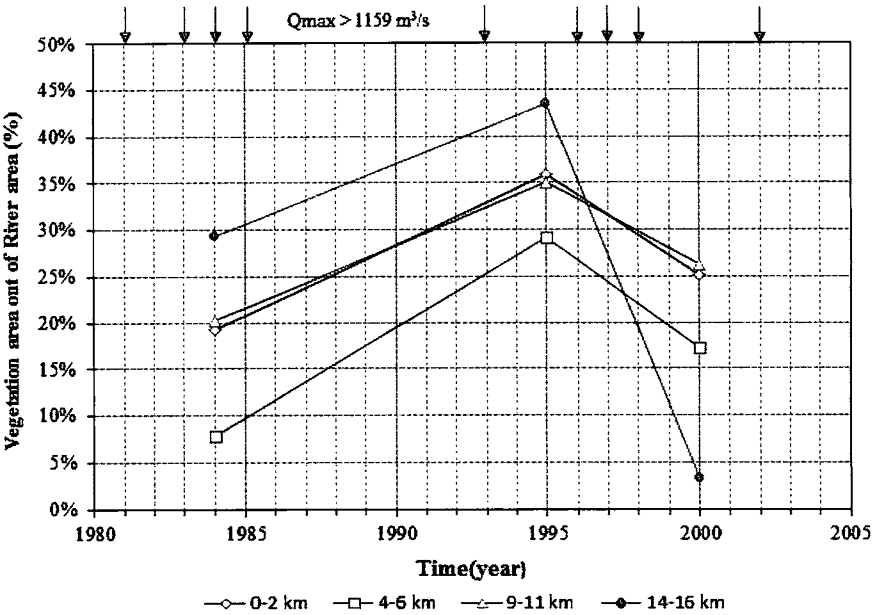


Fig. 15 Temporal variation in vegetation cover area along the Tedori River. Vertical arrows indicate years when Q_{max} exceeded 1159 m^3/s.

and 14–16 km upstream is shown in Fig. 16. Four years after completion of the Tedorigawa dam, the highest vegetation cover of 29% was measured in the 14–16 km sub-reach, and was 20%, 19% and 8% in the 9–11 km, 4–6 km and 0–2 km sub-reaches, respectively. Between 1984 and 1995, no large flood over 2000 m^3/s occurred, so the highest vegetation cover was measured in all sub-reaches with 44% in the 14–16 km sub-reach. A large flood event (2883 m^3/s) occurred in 1998, leading to a considerable decrease in the vegetation area in 2000. It is worth noting that the partial development of vegetation in a cross-section leads to a redistribution of the flow velocity along that cross-section, inducing simultaneous deposition and erosion in that cross-section, as seen in Fig. 6.

VI. Summary

A better understanding of the effect of human activities on changes in river morphology is fundamental for enabling the sustainable management of river basins. In this study, changes in the Tedori riverbed based on changes in the sediment volume induced by gravel and sand extraction and dam construction were analyzed using a series of field surveys from 1950 to 2007. The results show that accelerated erosion of the riverbed, leading to declines of 0.5–3.5 m, was observed from 1950 to 1991, while slight accretion was observed from 1991 to 2007. EOF analysis was then used to capture the variation trends in the river basin during 1950–1979, and the principal modes of variation clearly reflected the changes in both the riverbed and its controlling factors.

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Notation

Z = riverbed level averaged over each cross-section
$e(x)$ = the normalized spatial functions
$C(t)$ = the temporal functions
n = the variation modes
i = index for mean riverbed level
k = index for time
$\mathbf{A}$ = symmetric correlation matrix
ΔZ = variation with respect to mean riverbed elevation of 1950
a = linear trend
d_{mc} = median diameter in river channel
d_{mp} = median diameter in floodplain
Q = flood discharge

S = slope

$\mathrm{RMS}(Q_{3d})$ = deviations between daily average discharge and 3-day moving average discharges

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手取川流域の人為的改変が河床変動に及ぼした影響

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要　旨

長期間に渡る現地測量データに基づいて，石川県手取川の長期河床変動に関する解析を行った。解析対象領域は手取川河口部より16kmの区間である。対象領域における土砂量は，1950年から1991年にかけて約12.7×$10^6$$m^3$ 減少した。その間，河床は0.06-0.10 m/yearの速度で低下し，観測期間中におよそ0.5-3.5 mの侵食が確認された。一方，1991年から2007年にかけては，土砂量は0.6×$10^6$$m^3$ の微増を示した。河道内土砂量や河床高，河床構成材料の時空間変動について，ダム建設や砂利採取などの人為的影響との関連を検討した。河床変動が顕著に見られた1950年から1979年の期間を対象に経験的固有関数法に基づく解析を実施して，特徴的な変動モードを抽出し，人為的インパクトとの関係を検討した。

キーワード：手取川，侵食，人為的影響，経験的固有関数法

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