REGIONAL SEDIMENT MANAGEMENT BASED ON SEDIMENT BUDGET FOR GRADED SEDIMENTS -A CASE STUDY OF TENRYU WATERSHED AND ENSHU-NADA COAST

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For the planning of comprehensive sediment management of fluvial systems, a combination of a one-dimensional model of riverbed change and a model for predicting shoreline and grain size changes was applied to a fluvial system that extends from the Tenryu River to the Enshu-nada coast of Japan. Coarse materials with diameter d greater than 0.85mm are easily deposited on the riverbed and rarely reach the river mouth despite the high sedimentation yield in the upstream region. Sand with diameter in the range of $0.2 < d \leqq 0.85$mm is easily transported to the river mouth, with little being deposited on the riverbed. Sand supply of this grain size has been greatly reduced as a result of dam construction and riverbed excavation. Accordingly, the supply of sand to the coast becomes insufficient unless the necessary volume of sand is dredged from the reservoirs of dams and supplied to the river course downstream of these dams. The shoreline changes of the Enshu-nada coast from 1946 to 1995 were reproduced and the characteristic that grain size becomes finer further from the river mouth was reproduced well by the numerical model. The present method is an effective tool for analyzing the sensitivity of shoreline and grain size changes in response to sediment supply from rivers.

1. Introduction

In planning comprehensive sediment management of a fluvial system, it is extremely important to understand the changes of the fluvial system, to quantify the impact of the construction of dams and riverbed excavation on the fluvial system, and to select concrete executable measures appropriate for the fluvial system. Since sediment management affects not only the volume of sediment, but also the grain size, consideration of grain size changes is important. However, in the practical planning of comprehensive sediment management, a method by which the sediment transport in the entire fluvial system can be predicted, taking not only the volume but also the properties of the materials into account, has not yet been established.

In this study, a combined calculation of the one-dimensional model of riverbed change and Kumada et al.'s (2003) model for predicting shoreline and grain size changes was applied to a fluvial system extending from the Tenryu River to the Enshu-nada coast, Japan, as a typical example. We propose an investigative technique and a method of predicting the integrated fluvial system of both a river and the coast, and concrete measures for the comprehensive sediment management are discussed.

2. General Condition of Fluvial System of Study Area

The study area is the fluvial system ranging from the Tenryu River, with a catchment area of 4,971km^2, to the Enshu-nada coast facing the Pacific Ocean and extending on both sides of the river mouth. The study area of the river is the lower basin of Sakuma Dam located 76km upstream of the river mouth, and that of the coast is a 109km stretch of the coastline between Omaezaki and Irago Points at the east and west ends, respectively, as shown in Fig. 1.

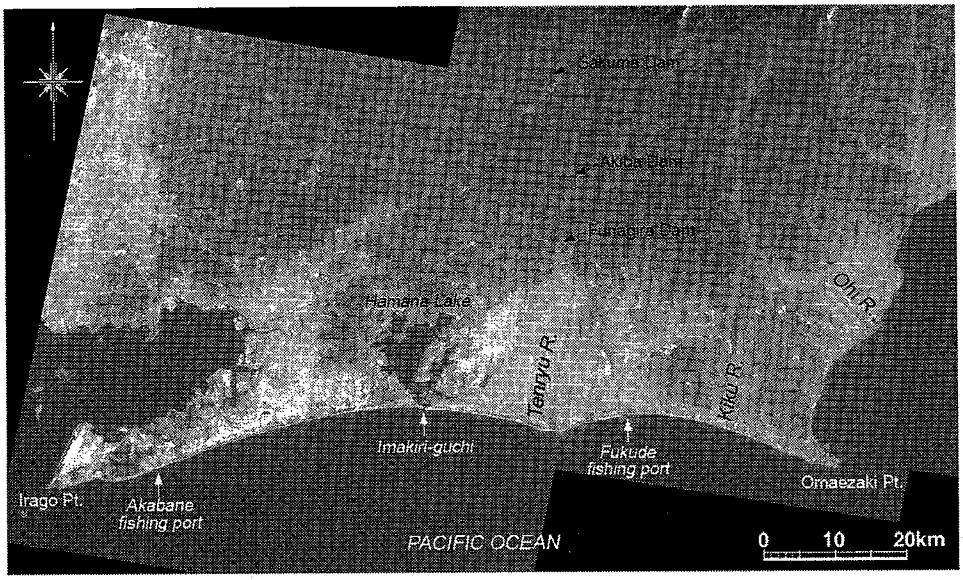

Figure 1. Satellite images of the study area taken in March 1988 by JERS-1.

The Enshu-nada coast, the main sediment source of which is the Tenryu River, has suffered serious erosion in recent years, because of the rapid decrease of the fluvial sand supply. Since the Tenryu River emerges from mountains with soft rock near the central tectonic line of the Japanese archipelago, it has supplied a large amount of sediment to the sea. Downstream of Akiba Dam, located 25km from the river mouth and covering about 90% of the catchment area, riverbed excavation amounting to approximately $2\times10^{7}\text{m}^{3}$ was carried out between 1960 and 1999. The Tenryu River is one of the steepest rivers in Japan and its sediment is composed of coarse materials with the median diameter of 12.2mm in the region from the river mouth to 8.6km upstream. The Enshu-nada coast is composed of sand with the median grain diameter of 4mm near the Tenryu River mouth, and 0.3mm 10km or more from the mouth. On the basis of the comparison of past aerial photographs of this coast, the shoreline is found to have retreated by 400m near the Tenryu River mouth, and beach erosion expanded from the river mouth to a location 5km west of the mouth from 1946 to 1995. The fluvial system of the study area has the following grain size characteristics, as shown in Fig. 2:

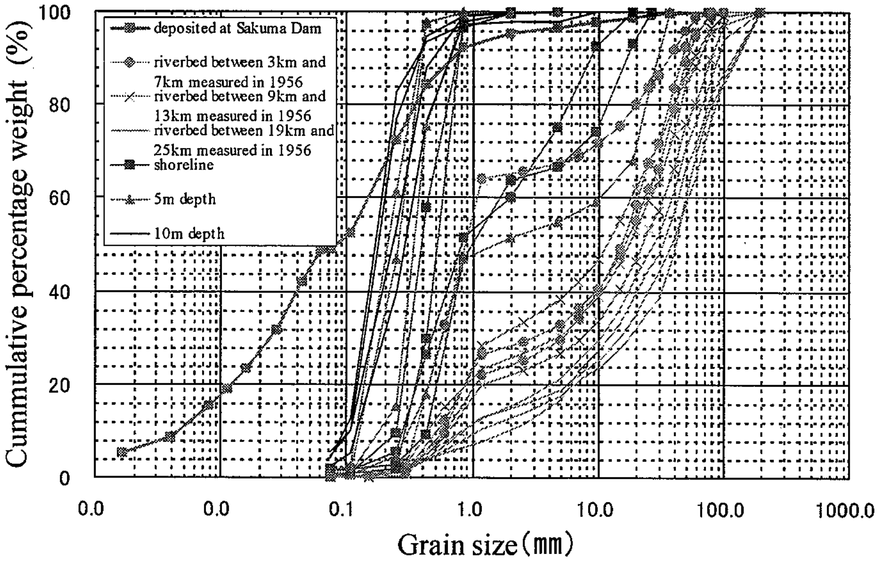

Figure 2. Grain size distribution in the fluvial system of the Tenryu River, including Sakuma Dam reservoir, riverbed and Enshu-nada coast.

1. Since the bed slope of the Tenryu River is as steep as 1/871, bed materials are mainly composed of gravel with grain diameter in the range of $4.8\text{mm} < d \leqq 100\text{mm}$.
2. On the other hand, beach materials, including the river mouth bar, are mainly sand with grain diameter in the range of $0.11\text{mm} < d \leqq 0.85\text{mm}$.
3. Thus, the mean diameter of grain size populations of the sediment making up the riverbed and the coast differs by the order of 10^{2}.

In the lower basin of the Tenryu River, each component of gravel and sand is transported down to the coast along the course of the river in a different sediment transport regime (Matsuo et al., 1999). In applying the one-dimensional model of riverbed change, the change in the sediment transport regime must be taken into account.

3. Investigation of Change in Fluvial System and Predictive Model

3.1. *One-Dimensional Model of Riverbed Change*

In the prediction using the one-dimensional model of riverbed change, it is usually assumed that all the components of grain size are completely mixed in the mixing layer at each step. However, in the lower basin of the Tenryu River, the bed slope is as steep as 1/871 and the mean diameter of the effective grain size population of the bed materials changes by the order of 10^2. The riverbed materials are mainly composed of gravel, and sand is distributed in the gaps between grains of gravel except near the river mouth.

For the above reason, sediment transport regimes of two effective grain size populations are assumed to be wash load for sand and bed load for gravel and their motions are independently determined under the assumption of negligible interaction between the two populations. In other words, if a general one-dimensional model of riverbed change is applied to the prediction of riverbed change of the Tenryu River, the movement of sediment of each grain size may not be appropriately evaluated in the lower basin.

Accordingly, two grain size populations composed of sand and gravel components are assumed not to mix in the exchange layer in the application of the one-dimensional model for the lower basin of the Tenryu River. Based on this concept, it is assumed that tractive force does not reach the gravel layer accumulated under the sand layer when sand is deposited on the riverbed. The sediment discharge rate of the gravel component is set to be zero at the cross section used for the calculation of riverbed change. Furthermore, the sand component can be deposited on the gravel layer when the riverbed rises, whereas it is only transported without mixing with the gravel component when the riverbed degrades. Here, both sand and gravel components are assumed to be mixed in each exchange layer of the components. Measured grain sizes were classified into fourteen ranges in the simulation.

3.2. *Prediction of Beach Changes*

For the prediction of beach changes, Kumada et al.'s (2003) shoreline change model was applied, taking the sorting effect of sand of mixed grain size into account. The initial beach profile is assumed to be a uniform slope of 1/75, the closure depth off the coast, h_c, is 10m, the breaking wave height, H_b is 1.7m and wave period is 6s.

4. Verification of Predictive Model

4.1. *Verification of One-Dimensional Model of Riverbed Change*

The reproduction of the long-term sediment budget in a widespread basin using the numerical model was verified in terms of the changes of riverbed and longitudinal grain size distribution on the riverbed.

Calculated results are shown in Fig. 3. It is confirmed that the numerical model well reproduces measured values in the lower basin, although there are some discrepancies in the fluctuation of the riverbed in the upstream basin, as shown in Fig. 3 for the zones between the 26km and 33km and between 49km and 51km upstream of Akiba Dam. Figure 4 shows the measured and predicted grain size distributions 9km upstream of the river mouth. The predicted distribution corresponds well with measured values.

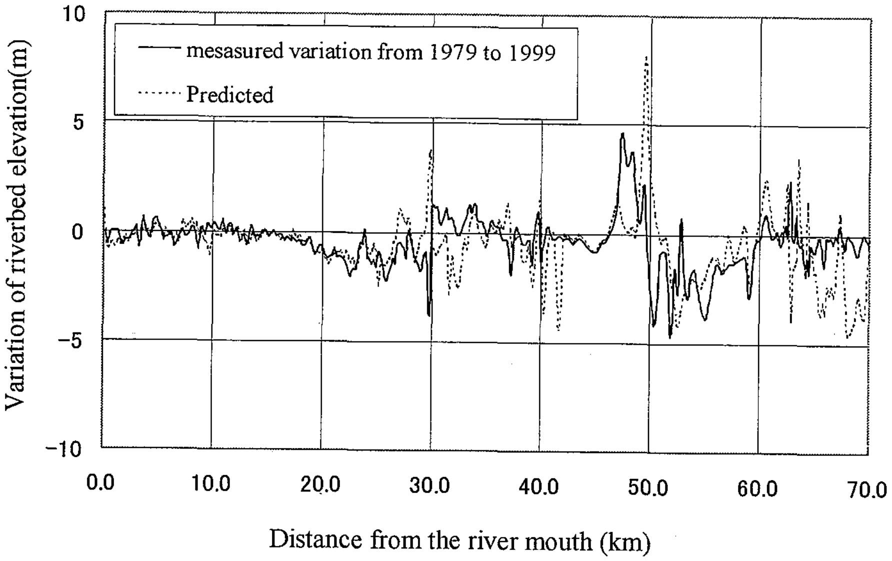

Figure 3. Results of reproduction of variation of riverbed height.

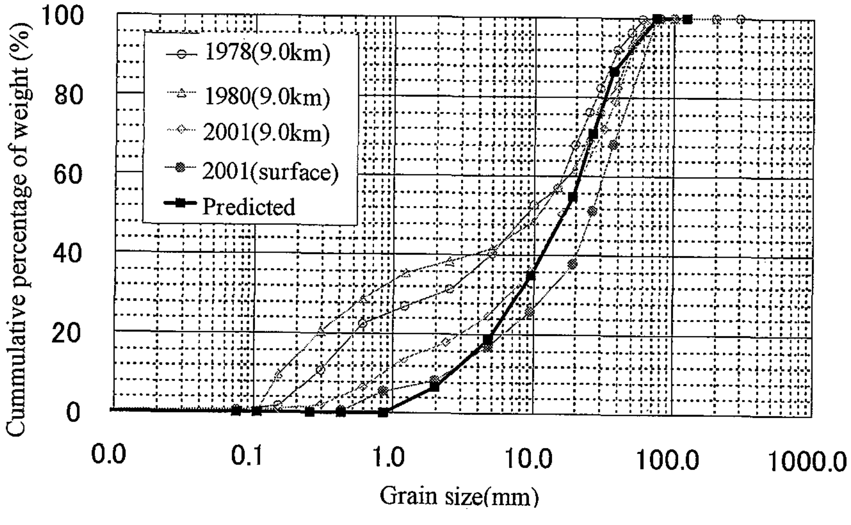

Figure 4. Cummulative weight curves of grain size distribution 9km upstream of the mouth.

In fluvial sediment supply through the river mouth, fine sediment may diffuse offshore due to the action of waves and currents, resulting in no contribution to the beach changes in the vicinity of the shoreline. Uda (1997) showed that the median diameter of grain size takes a maximum value in the vicinity of the shoreline and gradually decreases with depth. Accordingly, the lower limit of grain size is assumed to be 0.2mm in the vicinity of the closure depth, taking the above information into account. Of the fluvial sediment supply, $Q_{in}=131.7\times10^4 m^3/yr$, obtained using the one-dimensional model of riverbed change, sediment discharge of grains with diameter finer that 0.2mm was excluded and the rest, $Q_{in}=83.3\times10^4 m^3/yr$, was given as the effective sediment discharge.

4.2. *Verification of Predictive Model of Beach Change*

The longshore sand transport rate calculated under the condition of no dam construction and no riverbed excavation was compared with the longshore sand transport rates measured at Fukude fishing port, Imakiri-guchi Jetty and Akabane fishing port by Uda (1997). Uda's values were estimated from the temporal change in sand volume accumulated upcoast of the breakwater that obstructs continuous sand movement. Since these values were estimated in the 1960s and 1970s before any significant impacts of these factors on the coast, except at Fukude fishing port, the natural longshore sand transport rate without the influence of artificial modification is considered to have been estimated.

Calculated and estimated results of longshore sand transport show a gradual decline with distance from the river mouth, as shown in Fig. 5. Calculated values fall within one to two times larger ranges of measured values, indicating the appropriateness of the calculation.

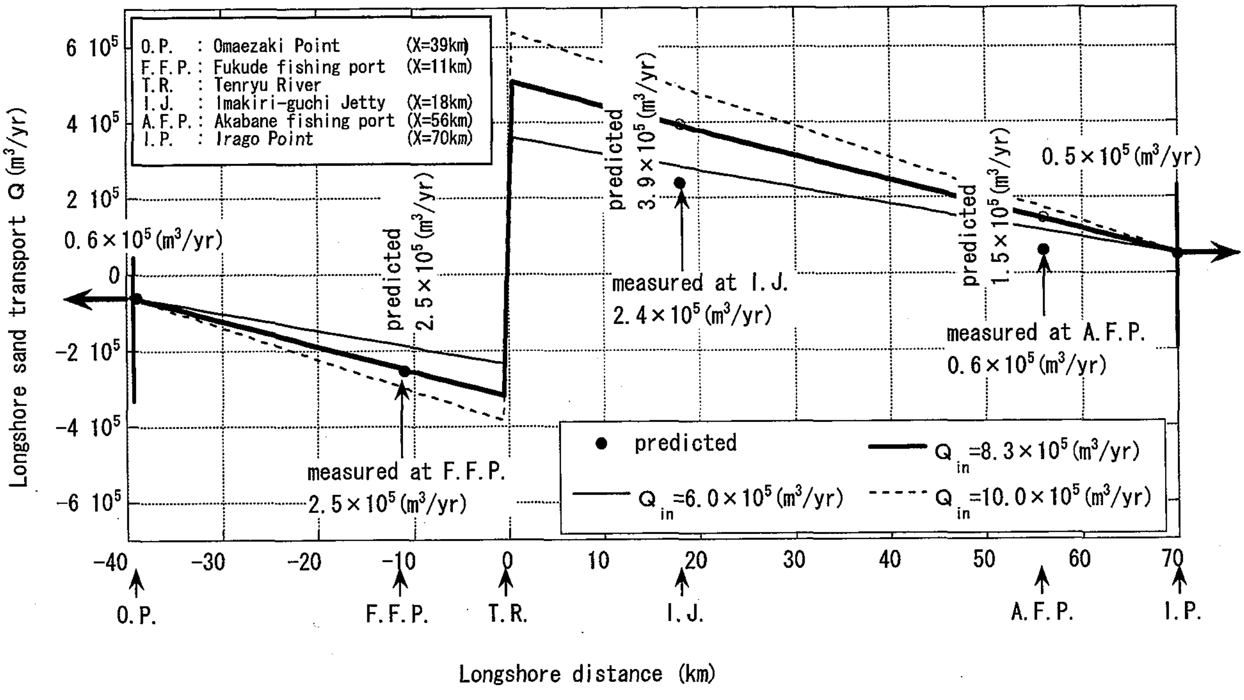

Figure 5. Calculated and estimated results of longshore sand transport.

Calculated and measured shoreline changes around the river mouth delta were compared, taking into account the effects of dam construction and riverbed excavation before 1967. The predicted maximum shoreline recession around the river mouth agrees with the measured one, as shown in Fig. 6, during the period from 1946 to 1962, before any coastal protection facilities such as detached breakwaters and seawalls had been constructed. The predicted and measured shoreline recession around the river mouth are also in agreement, indicating the effectiveness of the predictive model.

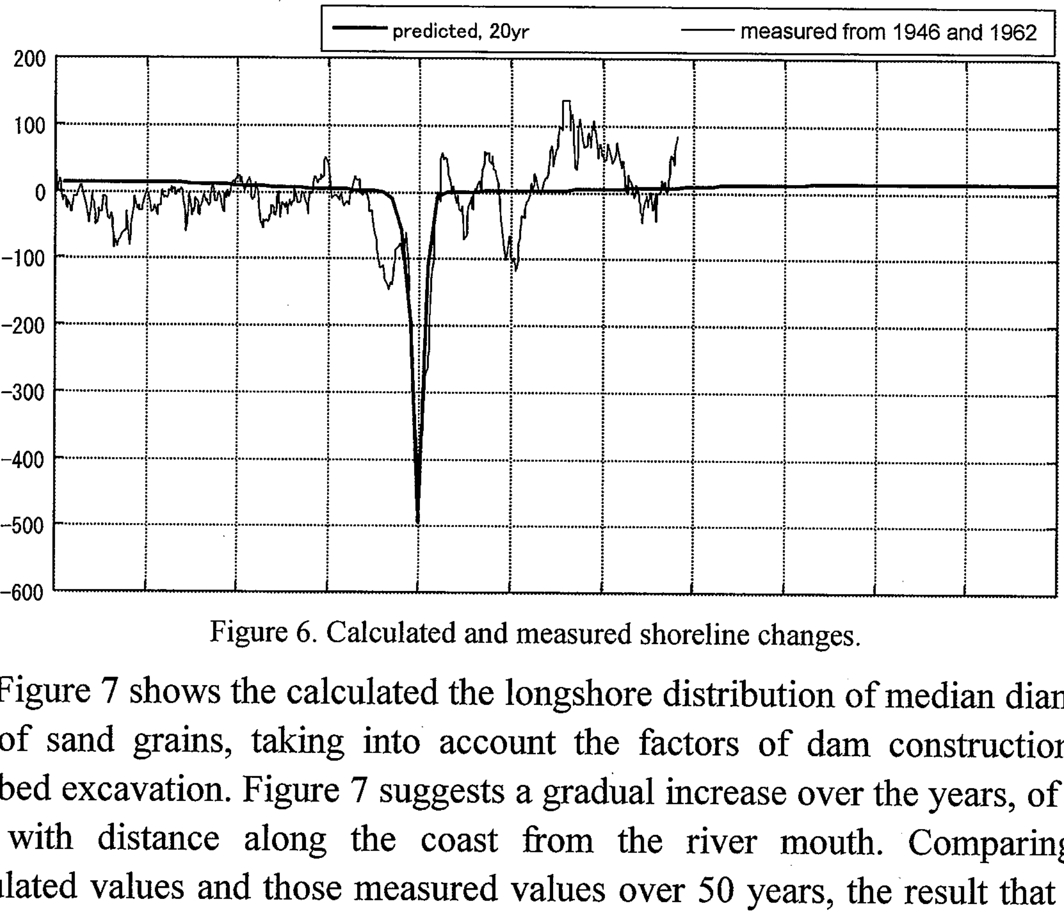

Figure 6. Calculated and measured shoreline changes.

Figure 7 shows the calculated the longshore distribution of median diameter, d_{50}, of sand grains, taking into account the factors of dam construction and riverbed excavation. Figure 7 suggests a gradual increase over the years, of grain size with distance along the coast from the river mouth. Comparing the calculated values and those measured values over 50 years, the result that grain size is the coarsest at the river mouth and that it gradually decreases toward the far end of the coastline from the river mouth agree each other.

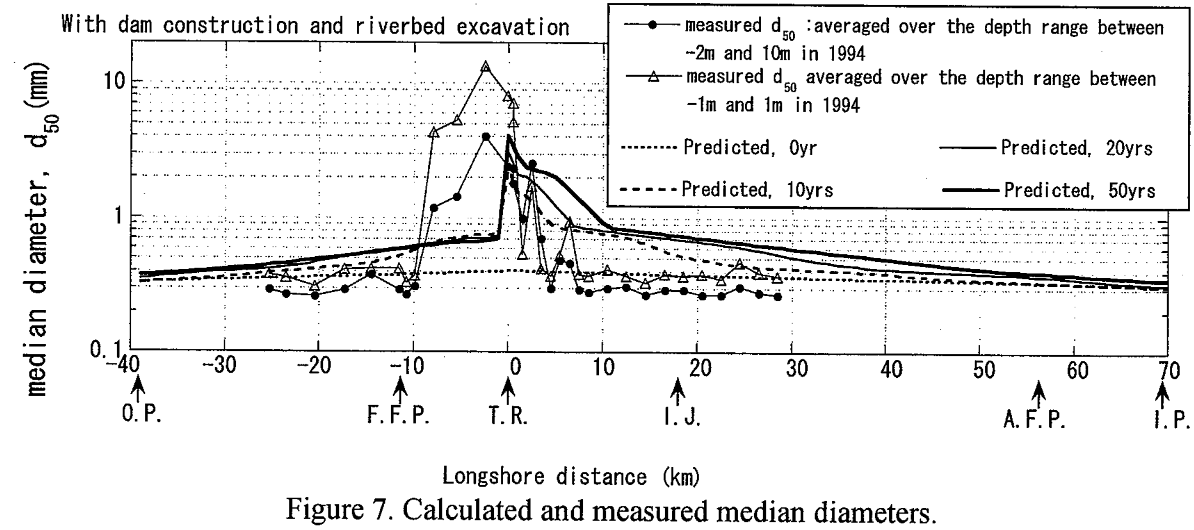

Figure 7. Calculated and measured median diameters.

Rapid accumulation of fine sand around the river mouth, as shown by measured values, is considered to be affected by the construction of detached breakwaters between the river mouth and Fukude fishing port, because such structures obstruct continuous longshore sand transport, resulting in changes in the longshore inclination of the shoreline.

5. Prediction of Riverbed Changes Due to Sand Supply Downstream of Dam

5.1. *Prediction of Riverbed and Longitudinal Distribution of Mean Diameter*

The changes of the riverbed and fluvial sediment supply from the river mouth, and the changes in the longshore distribution of the grain size of beach materials were analyzed for the case of sediment with grain sizes effective for beach formation being supplied, from the sediment deposited upstream of the dam: fine sand ($0.20 < d \leqq 0.25$mm), medium sand ($0.25 < d \leqq 0.425$mm), coarse sand ($0.425 < d \leqq 0.85$mm) and gravel ($4.75 < d \leqq 9.5$mm).

Table 1 shows the total sediment discharge from the river mouth, as shown in the shaded areas, when sand of a specific grain size was additionally supplied at a location 39.25km downstream of Akiba Dam. It is understood from the data in this table that the fine, medium and coarse grains are immediately transported to the river mouth after their supply, unlike the case of gravel.

Table 1. Total sediment discharge from the river mouth, as shown by the shaded areas, when sand of specific grain size is additionally supplied downstream of Akiba Dam.

		Total sediment discharge, Q_t(x10^4m^3/yr)			
		$0.106 < d(mm) \leqq 0.25$	$0.25 < d(mm) \leqq 0.425$	$0.425 < d(mm) \leqq 0.85$	$4.75 < d(mm) \leqq 9.5$
Present sediment discharge, Q_0(x10^4m^3/yr)		5.5	3.3	2.0	0.8
Additional sediment discharge, Q_{add}(x10^4m^3/yr)					
$0.106 < d(mm) \leqq 0.25$	10	15.5	3.3	2.0	0.8
	20	25.4	3.3	2.0	0.8
	40	45.4	3.3	2.0	0.8
	60	65.3	3.3	2.0	0.8
$0.25 < d(mm) \leqq 0.425$	10	5.5	13.3	2.0	0.8
	20	5.5	23.2	2.0	0.8
	40	5.5	43.1	2.0	0.8
	60	5.5	63.0	2.0	0.8
$0.425 < d(mm) \leqq 0.85$	10	5.5	3.3	12.0	0.8
	20	5.5	3.3	21.9	0.8
	40	5.5	3.3	41.7	0.8
	60	5.5	3.3	61.6	0.8
$4.75 < d(mm) \leqq 9.5$	5	5.5	3.3	2.0	0.8
	10	5.5	3.3	2.0	0.8
	20	5.5	3.3	2.0	0.7

Figure 8 shows the longitudinal distribution of the mean diameter of sediment deposited on the riverbed in the case that coarse sand and gravel with grain size in the range of $4.75 < d \leqq 9.5$mm were supplied with changing sediment volume. It is seen that gravel is deposited on the riverbed between 18km and 39.25km without transport to the river mouth. Figure 9 shows the corresponding riverbed change. The riverbed height rises by 3m and 2.5m at maximum at a location 25km and in the area between 32km and 37km downstream of Akiba Dam, respectively.

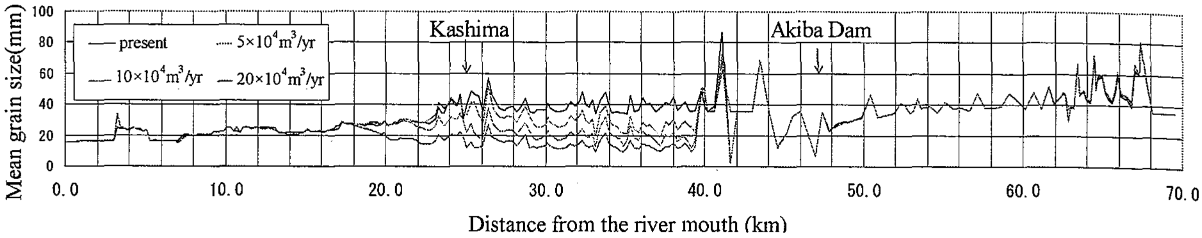

Figure 8. Longitudinal change of mean grain size in the case that gravel with grain size in the range of $4.75 < d \leqq 9.5$mm is supplied 39.25km downstream of Akiba Dam.

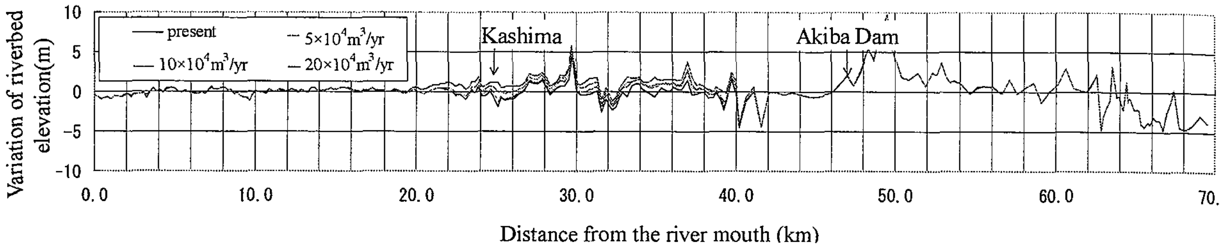

Figure 9. Longitudinal change of riverbed height in the case that gravel with grain size in the range of $4.75 < d \leqq 9.5$mm is supplied 39.25km downstream of Akiba Dam.

5.2. *Prediction of Shoreline Changes Associated with Sand Supply*

The changes in shoreline position and longshore distribution of median diameter, d_{50}, of sand grains were analyzed in order to investigate the impact of sand supply to the river downstream of Akiba Dam.

In the calculation, sand supply at the mouth was carried out in every time step of $\Delta t = 0.1$yr, changing the grain size of the material and the sand volume supplied per year.

Tables 2 through 5 show the shoreline changes, and predicted and measured median diameters in the central part of the river mouth, when an amount of sediment was supplied per year into the river mouth corresponding to each grain size. Sand supply to the river mouth was assumed to be not only 10×10^4 m^3/yr, that is, the present level, but also 20×10^4, 40×10^4 and 60×10^4m^3/yr.

Table 2. Supply of sand of fine grains ($0.2 < d \leqq 0.25$mm, representative grain size: 0.224mm) to the river mouth.

Sand supply $\alpha \times 10^4$ (m^3/yr)	Shoreline changes (m)	Median diameter, d_{50} (mm), at the river mouth	Measured d_{50} (mm)
60	+179	0.24	2.34
40	+4	0.24	
20	-158	0.49	
10	-238	1.19	
0	-317	4.07	

Table 3. Supply of sand medium-sized grains ($0.25<d\leqq 0.425$mm, representative grain size: 0.326mm) to the river mouth.

Sand supply α x10^4 (m^3/yr)	Shoreline changes (m)	Median diameter, d_{50} (mm), at the river mouth	Measured d_{50} (mm)
60	+290	0.35	2.34
40	+73	0.37	
20	-125	0.42	
10	-222	0.82	
0	-317	4.07	

Table 4. Supply of sand of coarse grains ($0.425<d\leqq 0.85$mm, representative grain size: 0.601mm) to the river mouth.

Sand supply α x10^4 (m^3/yr)	Shoreline changes (m)	Median diameter, d_{50} (mm), at the river mouth	Measured d_{50} (mm)
60	+526	0.63	2.34
40	+214	0.65	
20	-56	0.70	
10	-188	0.79	
0	-317	4.07	

Table 5. Supply of gravel component ($4.75<d\leqq 9.5$mm, representative grain size: 6.72mm) to the river mouth.

Sediment supply α x10^4 (m^3/yr)	Shoreline changes (m)	Median diameter, d_{50} (mm), at the river mouth	Measured d_{50} (mm)
20	+394	6.63	2.34
10	+91	6.65	
5	-104	6.45	
0	-317	4.07	

It was found that in order to sustain the shoreline around the river mouth, 40x$10^4$$m^3$/yr of fine sand, 30x$10^4$$m^3$/yr of medium-sized sand, 25x$10^4$$m^3$/yr of coarse-grained sand and 7.5x$10^4$$m^3$/yr of gravel must be supplied. Grain size of the sediment around the river mouth tended to become finer when sand with fine, medium and coarse grains was supplied at 10x$10^4$$m^3$/yr, whereas it tended to become coarser when 5x$10^4$$m^3$/yr of gravel was supplied.

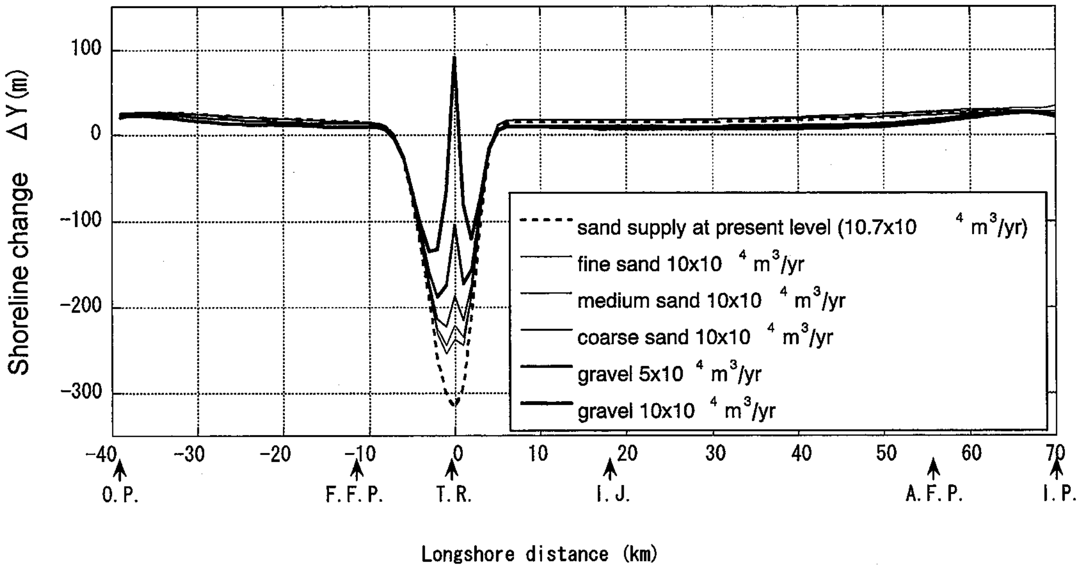

Figure 10. Shoreline changes after 50 years in the case of the supply of 10x$10^4$$m^3$/yr of sand.

Figures 10 and 11 show examples of shoreline changes for the cases described above. When 10×10^4m^3/yr of sand was supplied at the river mouth, the most effective method of recovering the shoreline near the river mouth is to supply gravel. The supply of fine material has minor effect on the recovery of the shoreline near the river mouth, but it is effective for the shoreline far from the river mouth, since fine material is easily transported by longshore drift. When gravel is supplied to the river mouth, the originally deposited fine sand is selectively transported by longshore drift, resulting in shoreline recession near the river mouth.

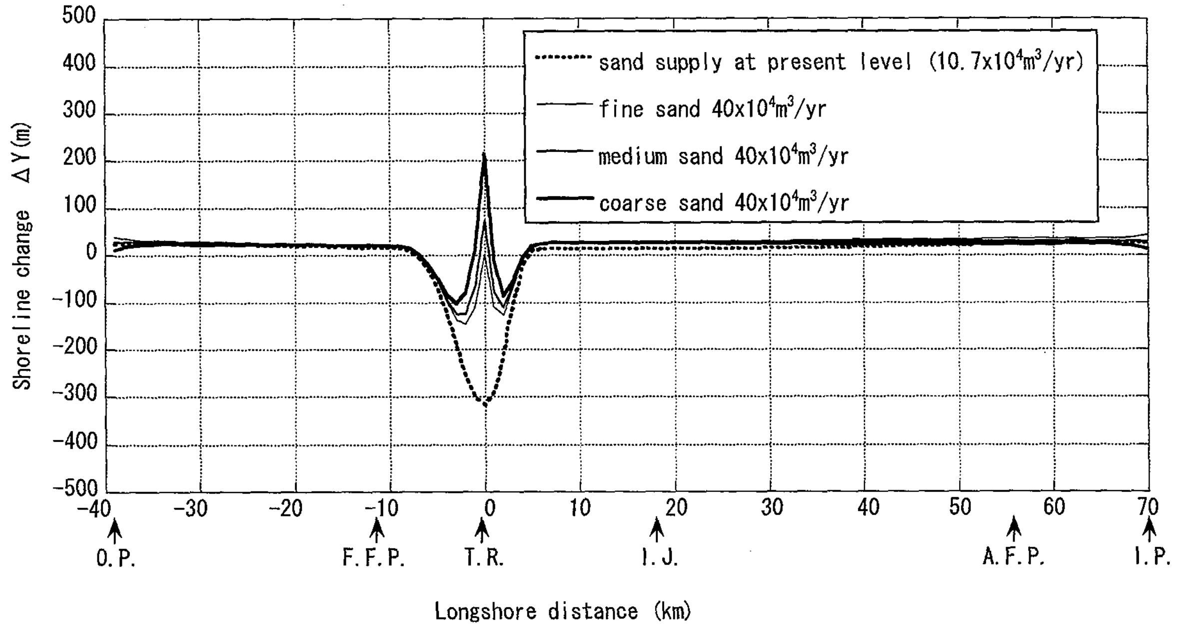

Figure 11. Shoreline changes after 50 years in the case of the supply of 40×10^4m^3/yr of sand.

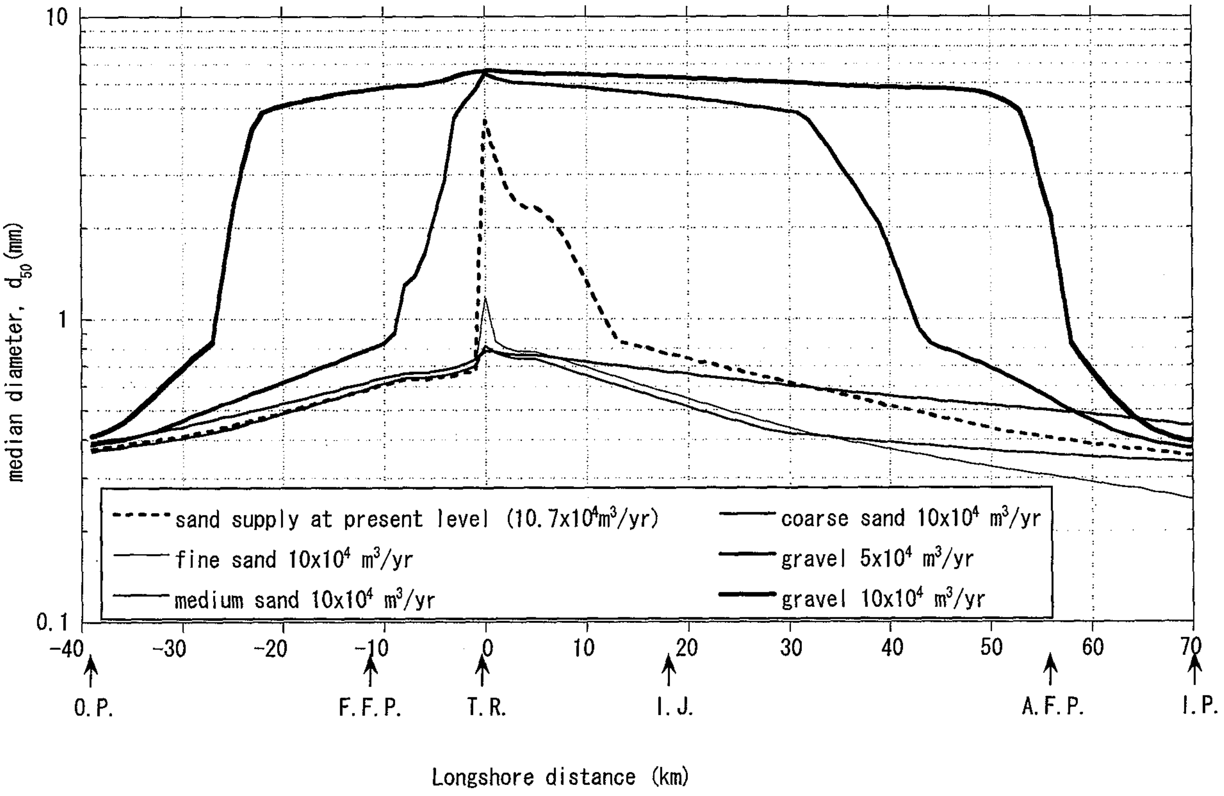

Figure 12. Change in median diameter, d_{50}, after 50 years.

Figure 12 shows the longshore changes in median diameter. When sand of fine and medium grains was supplied to the river, d_{50} became smaller than the present level, and vice versa when coarse material was supplied. Figure 13 shows the temporal change in the longshore distribution of the content of each grain size when $20\text{x}10^4\text{m}^3$ /yr of fine sand with grain size in the range of $0.16 < d \leqq 0.25$mm was supplied. It is seen that the shoreline composed of the finer material spreads far from the river mouth.

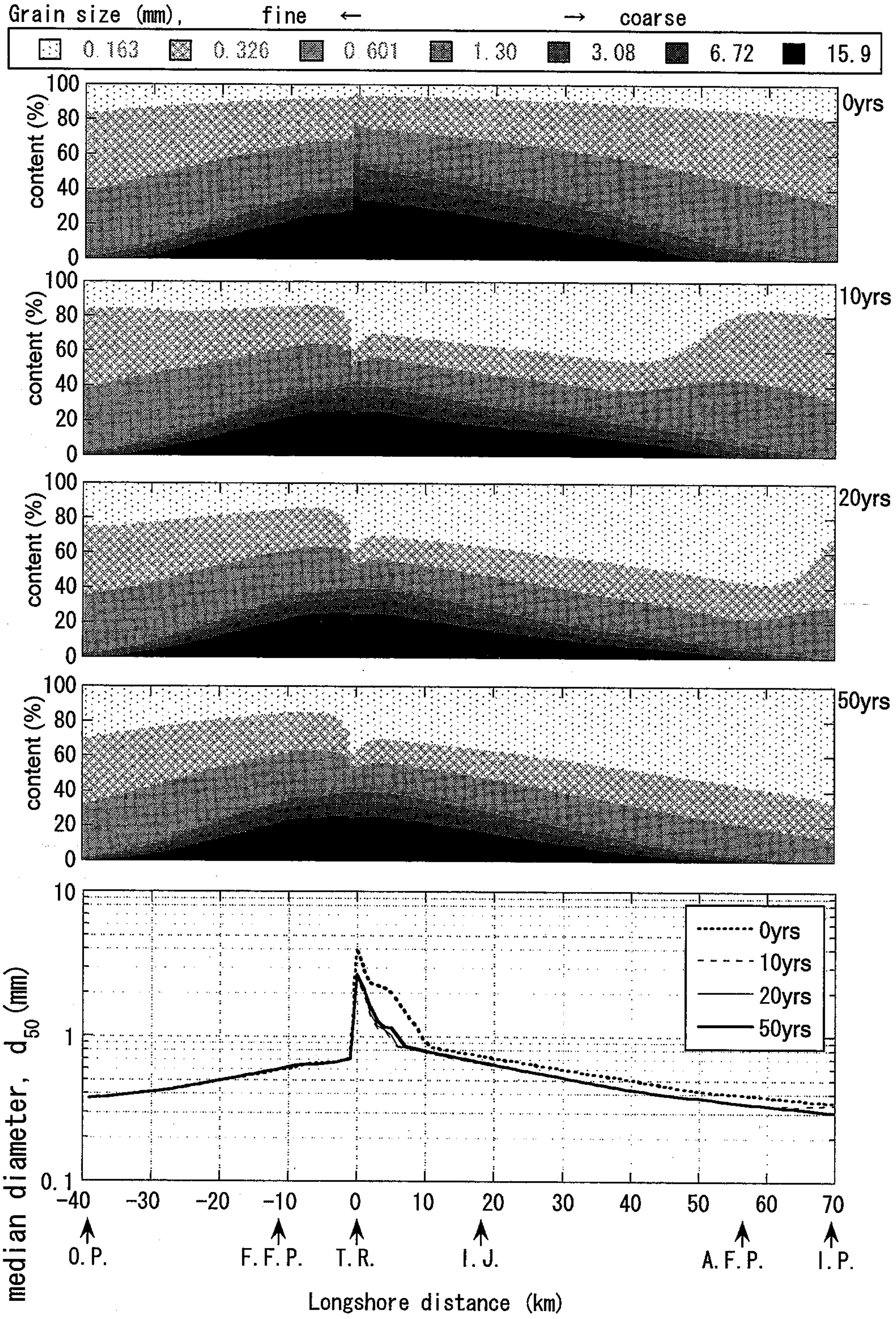

Figure 13. Content of typical grain size and change of d_{50} after 50 years, when fine sand with grain size in the range of $0.16 < d \leqq 0.25$mm is supplied at the rate of $20\text{x}10^4$ m^3/yr.

6. Conclusions

For the planning of comprehensive sediment management of fluvial systems, a one-dimensional model of riverbed change combined with Kumada et al.'s (2003) model for predicting shoreline and grain size changes was applied to a fluvial system composed of the Tenryu River and the Enshu-nada coast. The main conclusions are summarized as follows.

1. Sediment with grain size in the range of $0.85\text{mm} < d$ is easily deposited on the riverbed due to the sorting effect and rarely reaches the river mouth despite the high sedimentation yield in the upstream region. The volume of sediment reaching the river mouth further decreases in the case of dam construction or riverbed excavation. Accordingly, in order to supply sediment with grain size in the range of $0.85\text{mm} < d$ to the coast, the necessary sand volume must be directly transported to the river mouth.
2. Sand with grain size in the range of $0.2 < d \leqq 0.85\text{mm}$ is easily transported to the river mouth with little deposition on the riverbed. Sand supply of this grain size has been greatly reduced by dam construction and riverbed excavation. Accordingly, the supply of sand to the coast becomes insufficient unless the necessary volume of sand is dredged from the reservoirs of dams and supplied to the river course downstream of these dams.
3. The shoreline change of the Enshu-nada coast from 1946 to 1995 was reproduced using Kumada et al.'s (2003) model for predicting shoreline and grain size changes, which can be used to predict not only the shoreline change but also grain size distribution along the coastline. The characteristic grain size distribution was reproduced well. The present method is found to be an effective tool for analyzing the sensitivity of shoreline and grain size changes along the coastline in response to sediment supply from rivers.

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