LONG-TERM SEDIMENT TRANSPORT IN KUZURYU RIVER AND KAETSU COAST UNDER HOLOCENE SEA LEVEL VARIATION

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The Kaetsu Coast has been facing problems of coastal erosion and accumulation of sediments in dams and harbors. This study aims to investigate sediment transport and its long-term changes considering sea level variation in the Holocene. Numerical calculation of waves and nearshore currents, together with analysis of physical properties of sand particles such as diameter, color and thermo-luminescence were conducted to estimate the source and transport direction of sediment over geological time scale. It is found that the changes in the nearshore currents around the Kuzuryu River mouth and sediment supply from old dunes onto the coast north of the Kuzuryu River mouth are essential in understanding the sediment movement in the watershed scale.

Keywords: Regional sediment transport; sea level variation; coastal erosion

INTRODUCTION

Kaestu Coast is located in the middle of Japan, facing the Sea of Japan (Fig. 1). The coastal area extends about 120 km and most of the coast is covered by fine sand occasionally mixed with gravels. The dominant sources of sediment supply to the coast are the Kuzuryu River and the Tedori River. A relatively small river, the Daishoji River, flows between the Kuzuryu River and the Tedori River. Two rocky capes appear to separate nearshore sediment cells; the Cape Anto is located on the north of the Kuzuryu River mouth and the Cape Kasano-misaki is located between the Daishoji River and the Tedori River.

In this region, construction of dams and excavation of river channel have been introduced and consequently the region has been facing problems of coastal erosion and accumulation of sediments in reservoirs and harbors in recent years. The coastal erosion is especially significant on both sides of the Kuzuryu River mouth as well as on both sides of the Tedori River mouth. Harbor sedimentation is significant in the Fukui Harbor constructed in the period from 1971 to 1978 on the west side of the river mouth of the Kuzuryu River. In Figure 1, it is confirmed that five large dams were constructed about 30 to 40 years ago in the watersheds of the three rivers. The total catchment areas for dams in the Kuzuryu River and the Tedori River exceed 400 km^2 while the catchment area by two dams in the Daishoji River is about 150 km^2. As for the Tedori River and the Daishoji River, the catchment areas for dams reach half of their whole river basins. Various countermeasures against coastal erosion and harbor sedimentation have been introduced, such as construction of a series of detached breakwaters, groins and dredging navigation channels. However, the sedimentary problems are not resolved yet although the countermeasures appear to be effective in decelerating the speed of the erosion and the sedimentation. Figure 2 illustrates significant erosion on the south of the Daishoji River mouth in which seawalls are constructed along the foot of an old sand dune. In order to develop a long-term conclusive resolution, a comprehensive study is required for regional sediment movement since nearshore sediment transport appear to be complicated owing to the presence of an offshore shoal (Gentatsu-se) as well as an old sand dune on the north of the Cape Anto as shown in Figure 1. This study aims to investigate the formation mechanism of coastal topography and sediment transport over geological time scale considering sea level variation in the Holocene.

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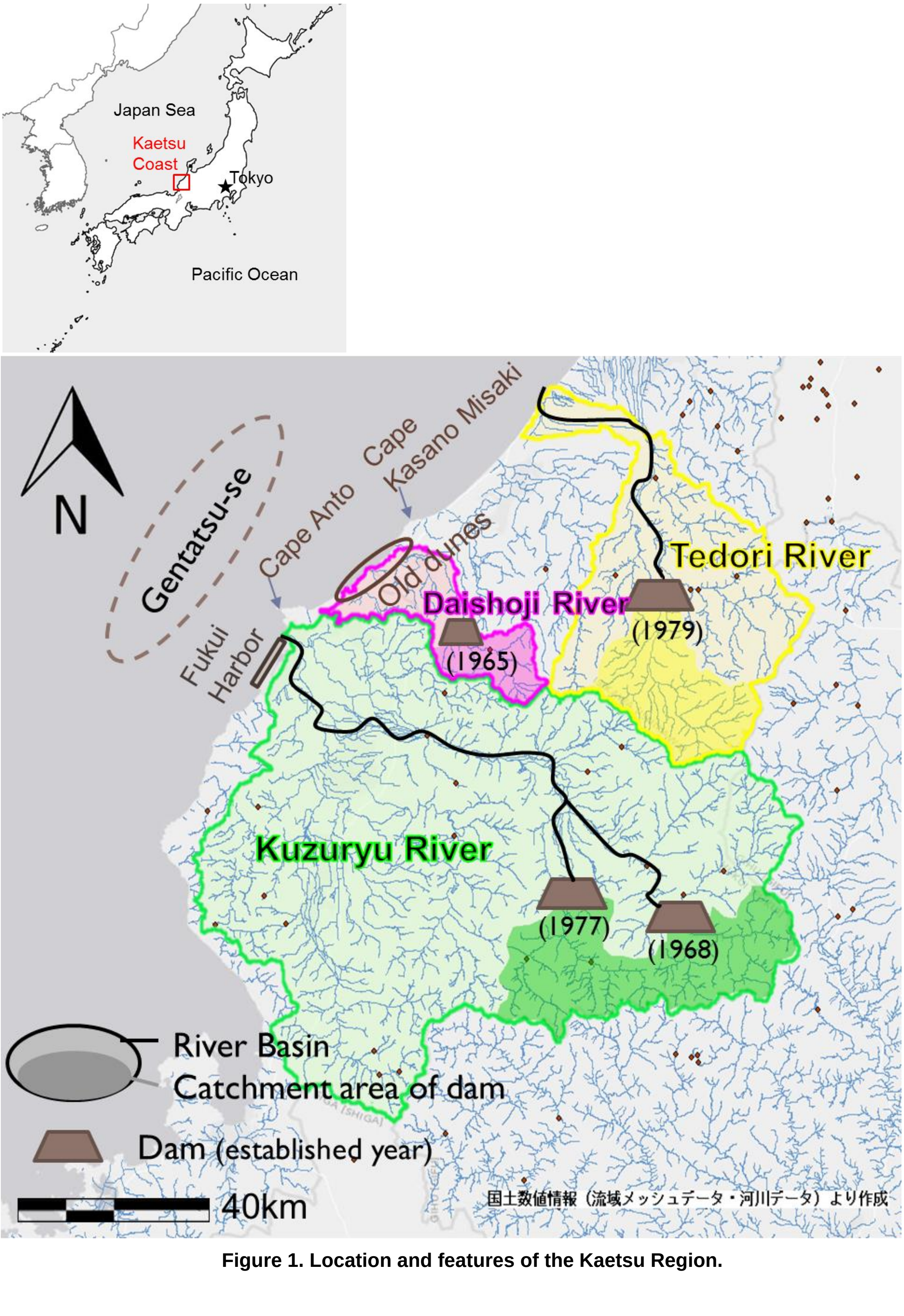


Figure 1. Location and features of the Kaetsu Region.

Figure 2. Eroding coast in front of the old dune on the south of the Daishoji River mouth. Seawalls are installed to decelerate erosion.

SEDIMENT RETENTION IN RESERVOIRS AND REDUCTION OF SEDIMENT SUPPLY

Figure 3 shows the annual changes in sediment retention in reservoirs of each river. The total amount of sediment retention reaches 6 million m^3 for the Kuzuryu River, 8 million m^3 for the Tedori River and 1.4 million m^3 for the Daishoji River. The speed of the total sediment retention in reservoirs in the Kuzuryu watershed is 160 thousand m^3/year and that in the Tedori watershed is 270 thousand m^3/year.

Figure 4 shows the relationship between the specific sediment discharge and the catchment area, plotted with five trend lines (1) to (5) proposed by Ashida and Okumura (1974). The specific sediment discharge is calculated by dividing the annual rate of sediment retention in reservoirs with the catchment area of the reservoir.

The line (1) represents rivers with large sediment yield (*i.e.* Kurobe, Oi, Tenryu). The lines (2) and (3) represent rivers with relatively large sediment yield (*i.e.* Kiso, Yoshino). The lines (4) and (5) represent rivers with small sediment yield which are mostly located in the Chugoku District. Most rivers in Japan are likely to be in between line (3) and (4). The Kuzuryu River and the Tedori River are plotted between line (2) and (3), which indicates that the two rivers produce relatively large amount of sediment among rivers in Japan. The Kuzuryu River and the Tedori River are considered to be main sources of sand supply to the coast as they potentially produce large amount of sand. However, based on the large catchment area of the dams and increasing sediment retention in reservoirs, sediment supply to the coast must have significantly decreased after the construction of dams.

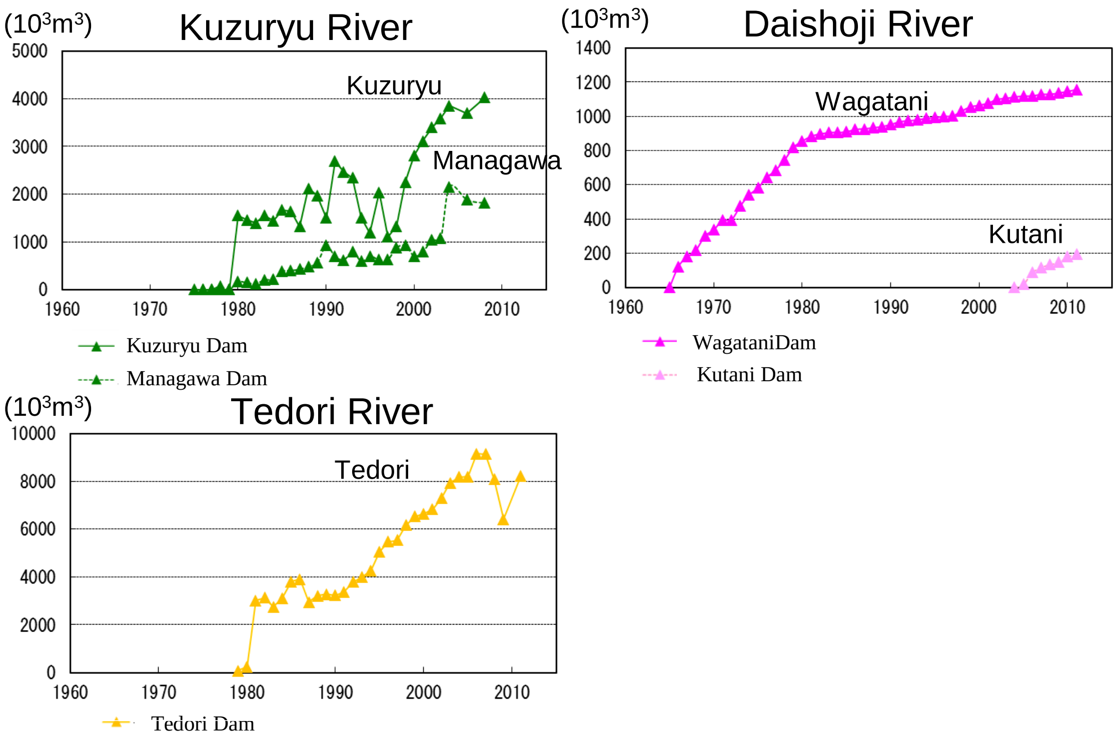


Figure 3. Sand retention in reservoirs. Note that the vertical axis is in different scales. The largest retention is in the reservoir of the Tedori Dam and the second largest is in the

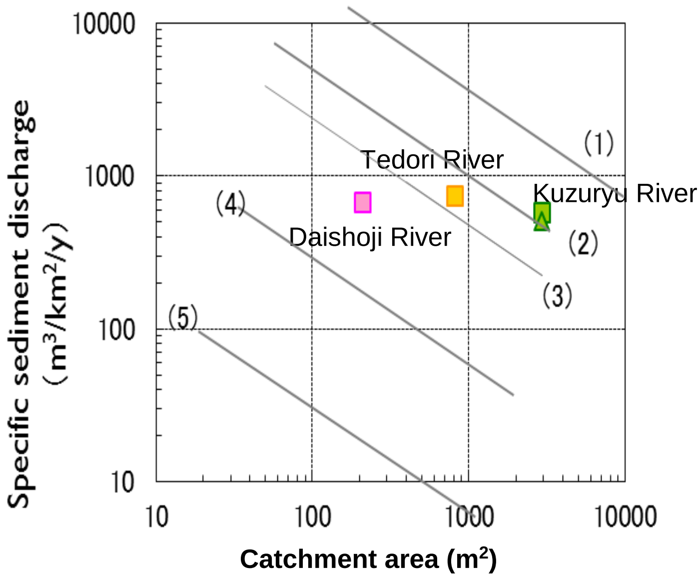


Figure 4. Sediment yield of the Tedori River, the Kuzuryu River and the Daishoji River. Lines (1) to (5) are trend lines proposed by Ashida and Okumura (1974).

COASTAL TOPOGRAPHY FORMATION IN THE HOLOCENE

Target Area and Sea Level Variation

It is known that the sea level 20,000 years ago in the last glacial period was 100-120 meters lower than that of the present sea level (Kaseno et al., 1992). The shoreline then was estimated to be 20 km farther offshore in our target area. The sea level rose to -40m relative to the current sea level 10,000 years ago and reached the current sea level about 2,000 years ago.

We considered that this sea level variation must have exerted an essential impact on the sediment movement along the coast due to its unique topography as well as large sediment supply from two major rivers. As shown in Figure 5, there is a shallow area called Gentatsu-se 20 km offshore from the mouth of the Kuzuryu River. The Gentatsu-se is 18 km wide and 10 m deep at its shallowest area. Since the sea level varied about 100 m, the Gentatsu-se must have been an island in the last glacial period. Therefore waves and currents are considered to have changed by the unique topography/bathymetry. In this study, we investigated changes in waves and nearshore currents under the sea level variation by using numerical models.

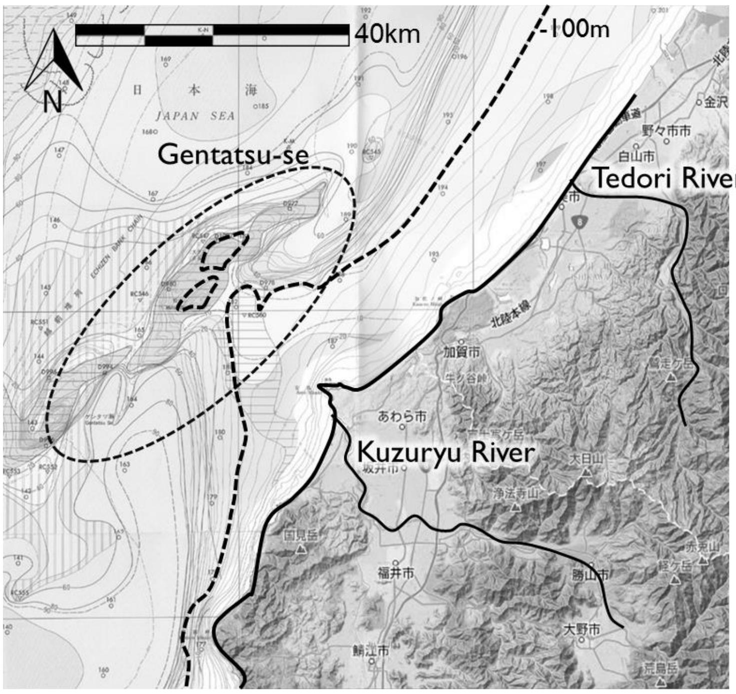


Figure 5. Topography of the Kaetsu Region. A shallow shoal, Gentatsu-se, is considered to be an island in the last glacial period.

Numerical Model

First, wave height distribution was estimated by using the following energy-balance equation:

$$\frac{\partial}{\partial x}(Dv_x)+\frac{\partial}{\partial y}(Dv_y)+\frac{\partial}{\partial \theta}(D_\theta v_\theta)=-D_B \qquad (1)$$

$$v_x = C_g \cos\theta \qquad (2)$$

$$v_y = C_g \sin\theta \qquad (3)$$

$$v_\theta = \left(\frac{C}{C_g}\right)\left(\frac{\partial C}{\partial x}\sin\theta - \frac{\partial C}{\partial y}\cos\theta\right) \qquad (4)$$

where $D(x,y,\theta)$ is the directional spectrum, C_g is group velocity, C is wave velocity and D_B is the dissipation rate of the breaking wave energy (Tajima and Madsen, 2006). The energy balance equation can simulate wave refraction without using much computer resources. Using radiation stress estimated by energy balance equation, nearshore currents were then calculated on the basis of shallow water equation with forcing terms.

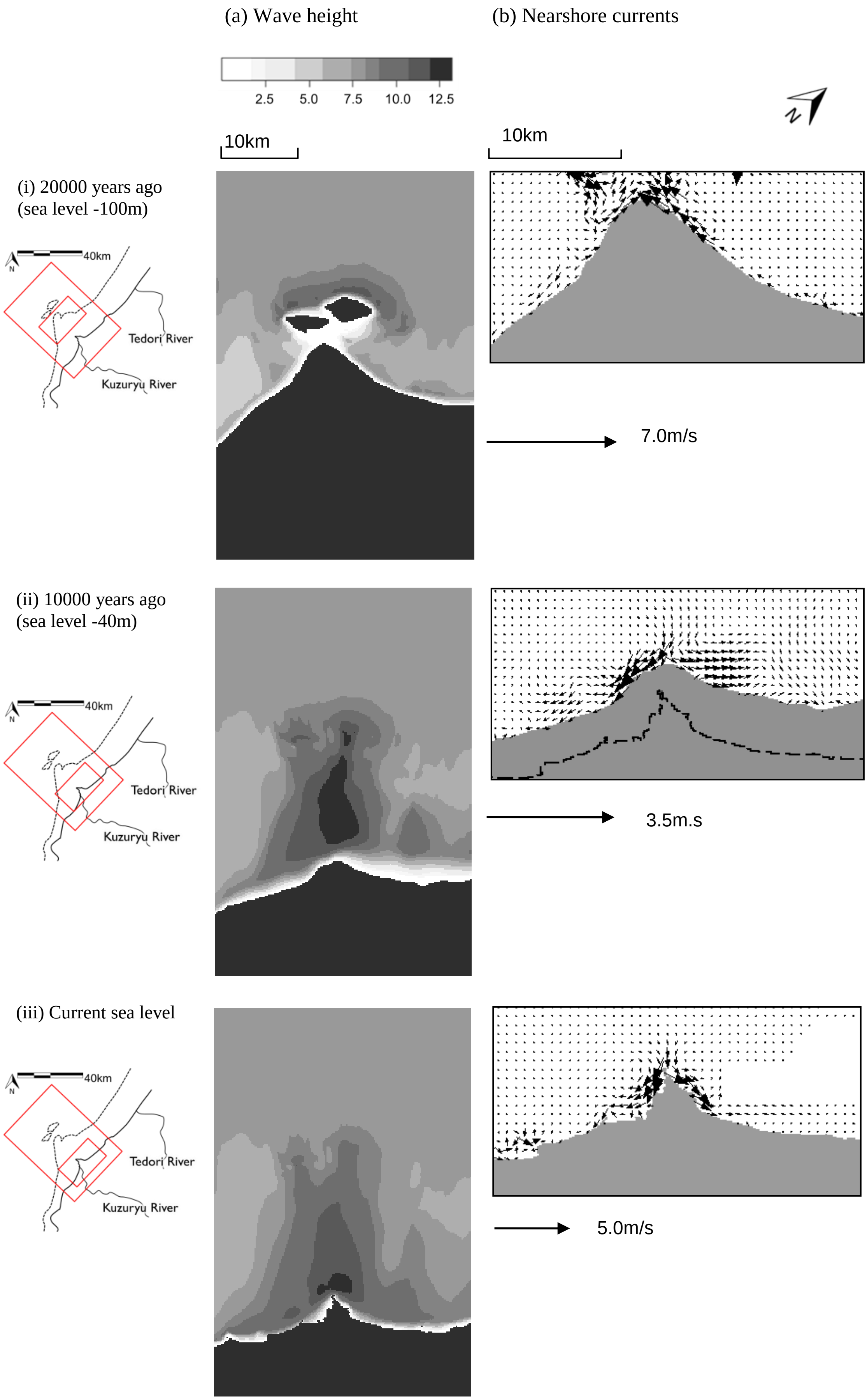


Figure 6. Changes in wave height and nearshore current around the Gentatsu-se and the mouth of Kuzuryu River.

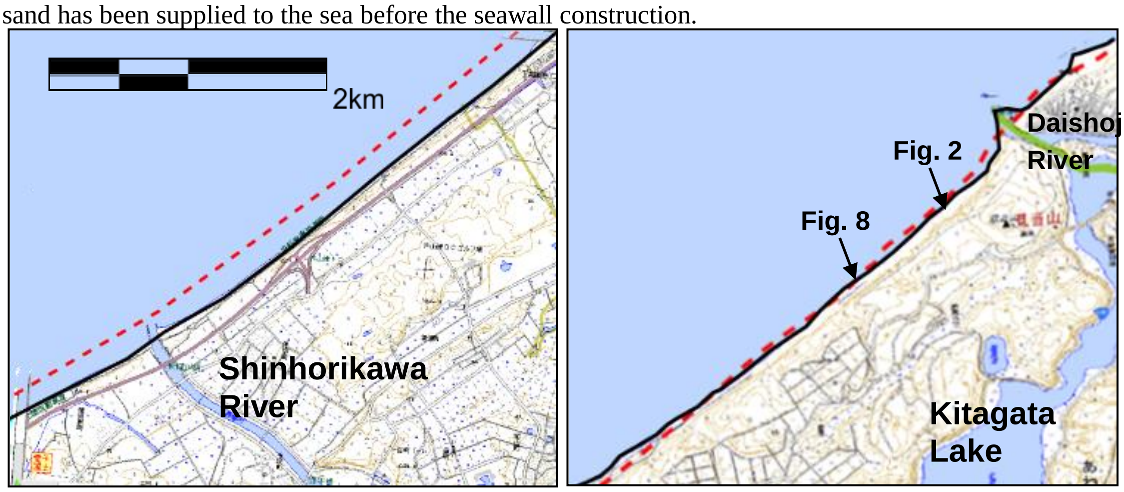
In the calculation, we used incident wave from NNW since the prevailing wave in this area is known to be from NW to NNW. The incident wave height and period are decided to be of the largest waves observed in the area, 8 m and 10 s respectively, since large sediment movement develops under large waves. The calculation was carried out for three cases with different sea levels: the present sea level, -40 m ($10x10^3$ years ago) and -100 m ($20x10^3$ years ago). We assumed tectonic uplift/subsidence is negligible compared to the sea level change.

Result

Figure 6(a) shows the result of wave height distribution. When the sea level is low, the area between Gentatsu-se and the mouth of the Kuzuryu River becomes a sheltered area by Gentatsu-se emerged above the sea. As the sea level rises, Gentatsu-se becomes submerged and starts acting as a shoal. Consequently, the wave height appears to be higher around the river mouth located behind Gentatsu-se owing to refraction and shoaling.

As shown in Figure 6(b), nearshore currents develop from the both side of the river mouth converging to the river mouth at low sea level. On the other hand, the direction of the nearshore currents becomes opposite when the sea level rises, which shows the currents diverging from the river mouth. Based on this result, we conjecture that sufficient sediment supply from the Kuzuryu River and the current towards the river mouth could have caused deposition of sand around the river mouth but with the sea level rise the coast started to be eroded and sediment from the river started to be transported to both side of the coast due to the diverging currents from the river mouth.

The large sediment delivery from the Kuzuryu River to the sea can also be supported by the presence of old sand dunes with height over 30 m on the coast south of the Daishoji River mouth (Figure 2). The Cape Anto is located between the Kuzuryu River mouth and the old sand dunes, which is considered to be remained during the eroding process caused by sea level rise because it is composed of rock. It is reasonable to consider that the formation of the cape decreased sediment supply from the Kuzuryu River to the northern coast backed by the old sand dune and thus caused coastal erosion. However, comparing geographical map of about 200 years ago and of the present, coastal erosion was found insignificant as shown in Figure 7. In Figure 7, more than 200 m shoreline retreat is observed for the coast south of the Tedori River mouth while the deformation is small for the coast south of the Daishoji River mouth. This contrast in changes of coastline can be explained by the existence of another source of sediment to the coast north of the Kuzuryu River. Possible source of sediment is the old high dune. Although the coast is protected by seawalls located at the foot of the old dune, we found several land slide locations where the steep seaside slope of the old dune was slid to produce sand debris over the seawalls (Figure 8). It is therefore straightforward to consider that a large amount of sand has been supplied to the sea before the seawall construction.



Coastline in Inou map (200 years ago)

Current coastline

(left:Komatsu Coast, right:north of the Kuzuryu river)

Figure 7. Changes in coastline in 200 years.

(a) Land slide on the steep seaside slope

(b)Land slide sand piled up on the top of seawall

Figure 8. Land slide on steep seaside slope of the old sand dune. The location is 500 m south of the Daishoji River mouth and close to the sampling point C4.

FIELD SURVEY

Field surveys were conducted on September 11-13 and December 3-4, 2012 to collect sand samples from 50 sites including coast, rivers and dunes in the target area. The collected sample was analyzed in terms of their color, grain size, and thermo-luminescence (TL) intensity in order to determine the source and its supplying area, and transport direction. The sand samples for color and grain size analysis were collected from the ground surface and the samples for TL analysis were collected from 10 cm beneath the surface. TL samples were collected by opaque black film cases in order to avoid exposure to the sunlight during sampling as shown in Figure 9.

Figure 9. Beach sand sampling for TL analysis. Opaque black film cases are used to minimize exposure to light during the sampling.

Color Ratio Analysis

Methodology. Analysis of mineral composition is widely used for the estimation of the source of sediment supply. In this study, in order to simplify the process, we analyzed color of sand grains quantitatively instead of identifying mineral of each grain. About two hundred sand particles were randomly extracted from each sample and taken in digital images by a digital microscope. The digital images were taken in two ways, one of which is with front light and the other is with back light (Figure 10). Following Yoshii and Sato (2010), each grain in the image was detected and identified. For each grain, the average value of the CIE 'xyY' color space components was calculated from the front light image to detect its color and 'Red' value in the 'RGB' color space was used from the back light image to detect its transparency. Based on the calculated values, each grain was classified into five color categories following the criterion shown in Figure 11; white/transparent, gray, yellow, brown and black. The ratio of color category in one sample is then calculated. In the following, this ratio is referred to as "color ratio."

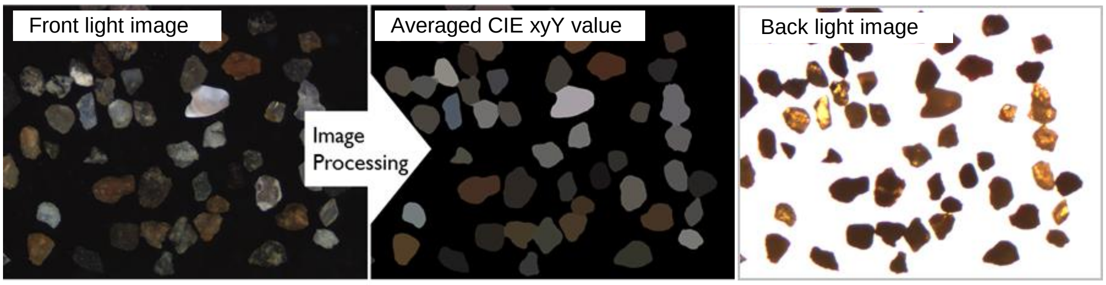


Figure 10. Front light and backlight Images used for color ratio analysis.

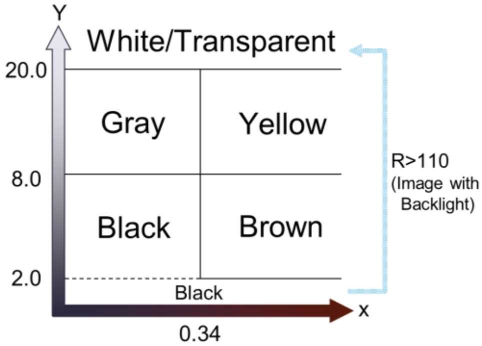


Figure 11. Criteria of grain color classification. Transparency was judged from the backlight image by using 'Red' values in the 'RGB' color space. For non-transparent particles, front light image was used to categorize color. Values of x and Y in the 'xyY' color space were used.

Result. Color ratio variation along the coast is shown in Figure 12(d). It is clear that the color ratio changes at the mouth of the Kuzuryu River. The coast north of the river mouth has higher percentage of black grains which is similar to the color ratio of Kuzuryu River. On the other hand the percentage of black grains is low in the north area. This implicates that the sediments supplied from the Kuzuryu River has been transported mainly to the south due to the protruding cape existing north of the river mouth. In contrast, samples collected in front of the old dunes, located north of the Cape Anto, exhibit higher percentage of yellow colored grains compared to nearby samples. This is similar to that of the old dunes, indicating the possibility of sediment supply from the dunes as well.

Around the Tedori River mouth, the percentage of black colored grains has a trend to decrease with its distance from the river mouth. This continuous trend changes at the Cape Kasano-misaki. This leads to an assumption that the boundary of sediment supply from the Tedori River and Kuzuryu River is located at the Cape Kasano-misaki.

In addition, the same analysis was applied to samples collected from the sea bed at depth of 10 m as shown in Figure 12(c). The difference between the north and south of the Kuzuryu River was not obvious in these marine samples. The color ratio is almost uniform along the coast. This result supports our estimation that the sediments supplied from the Kuzuryu River had been distributed on the both side of the river mouth before the Cape Anto was formed on its north side

Grain Size Analysis

Methodology. Grain size was measured with a laser diffraction particle size analyzer (Shimadzu SALD-3100). Each sample was washed and dried before the measurement. Grains with diameter larger than 2 mm were removed from the sample as a measuring range of the analyzer is below 2 mm.

Result. Figure 12(b) illustrates the grain size distribution along the coast. There is a decreasing trend towards north both on the north and south coast around the Kuzuryu River mouth. Generally, grain size tends to decrease in the direction of prevailing sediment transport. Therefore the dominant sediment transport in this area is estimated to be in northward direction. As for the north side coast, this estimation is consistent with the calculation of the nearshore currents described in the preceding chapter. However in the south side coast, the sediment transport is opposite to the calculation. This is considered to be due to the Fukui Port breakwaters constructed between the south side coast and the Kuzuryu River mouth, which was not taken into account in the numerical model.

The grain size varies only slightly on the coast north of the Cape Kasano-misaki. Relatively large grains are found on severely eroding beaches.

Thermoluminescence Analysis

Thermoluminescence. In a sedimentary environment, quartz and feldspar particles undergo natural radioactive process. Through the process, the natural radiation causes the electron in the grain crystal lattice to be trapped in excited states, building up the latent luminescence signals in constituent mineral grains. Heating or exposure to the light enables excited states to decay into lower-energy states. During this energy transition, luminescence signal is released as luminescence light. The magnitude of total luminescence signals in a grain is proportional to the accumulated energy. The emission of light in the heating process is termed thermoluminessence (e.g., Aitken, 1998). In the fluvial environment, the luminescence signal is accumulated during the stage buried underground and starts to decrease during movement in the watershed and in the nearshore zone with occasional light exposure. Thermoluminessence of a feldspar particle takes a few days to reduce to zero, therefore travel distance of a particle can be estimated from thermoluminessence signal. According to previous studies conducted by Rink (1999) and Kishimoto (2008), the luminescence signal of a feldspar grain decreases as it is transported far from the river mouth.

Methodology. Luminescence was measured with a Risø 48-sample automated TL/OSL Reader (model DA-20) with an internal 90Sr/90Y β irradiation source. TL measurements were carried out based on the TL test protocol proposed by Kishimoto (2008). Feldspar particles were extracted from sand sample. Preheat temperature to eliminate any unstable signals was determined as 200 ^{o}C/10s by preheat test. Sample TL signals were measured up to 500 ^{o}C with a heating ramp rate of 50 ^{o}C/s. A natural TL glow curve is then obtained by plotting the measured TL signals against heating temperature. Then normalization on the TL glow curve is achieved by dividing the measured TL signals by the averaged value of 10.8 Gy test dose induced TL signals. In this study, the TL intensity is defined as the average value of the normalized TL signals over the temperature range of 200-500 ^{o}C.

Result. Figure 12(a) demonstrates the TL intensity distribution along the coast. The TL intensity decreases in northward direction on both north and south coast of the Kuzuryu River mouth. This implies the northward direction of prevailing sediment transport, which is consistent with the result of grain size analysis. Looking at the sample C4 which is collected on the coast near the landslide of the old dune (Figure 8), the TL signal at C4 is larger than that of the sample at the Kuzuryu River mouth. In addition, as illustrated in Figure 13, the glow curve of C4 sample is similar to samples collected from the old dunes (S1-S3). This leads to the presumption that sand in this area is mainly supplied from the old dunes. The result of the color analysis also supports this presumption. The north coast of the mouth of the Kuzuryu River could have been developed with sand by erosion of the old sand dunes even after the supply of sand from the Kuzuryu River had decreased. This also could be the reason for the relatively small amount of shoreline retreat in this area as confirmed in Figure 7.

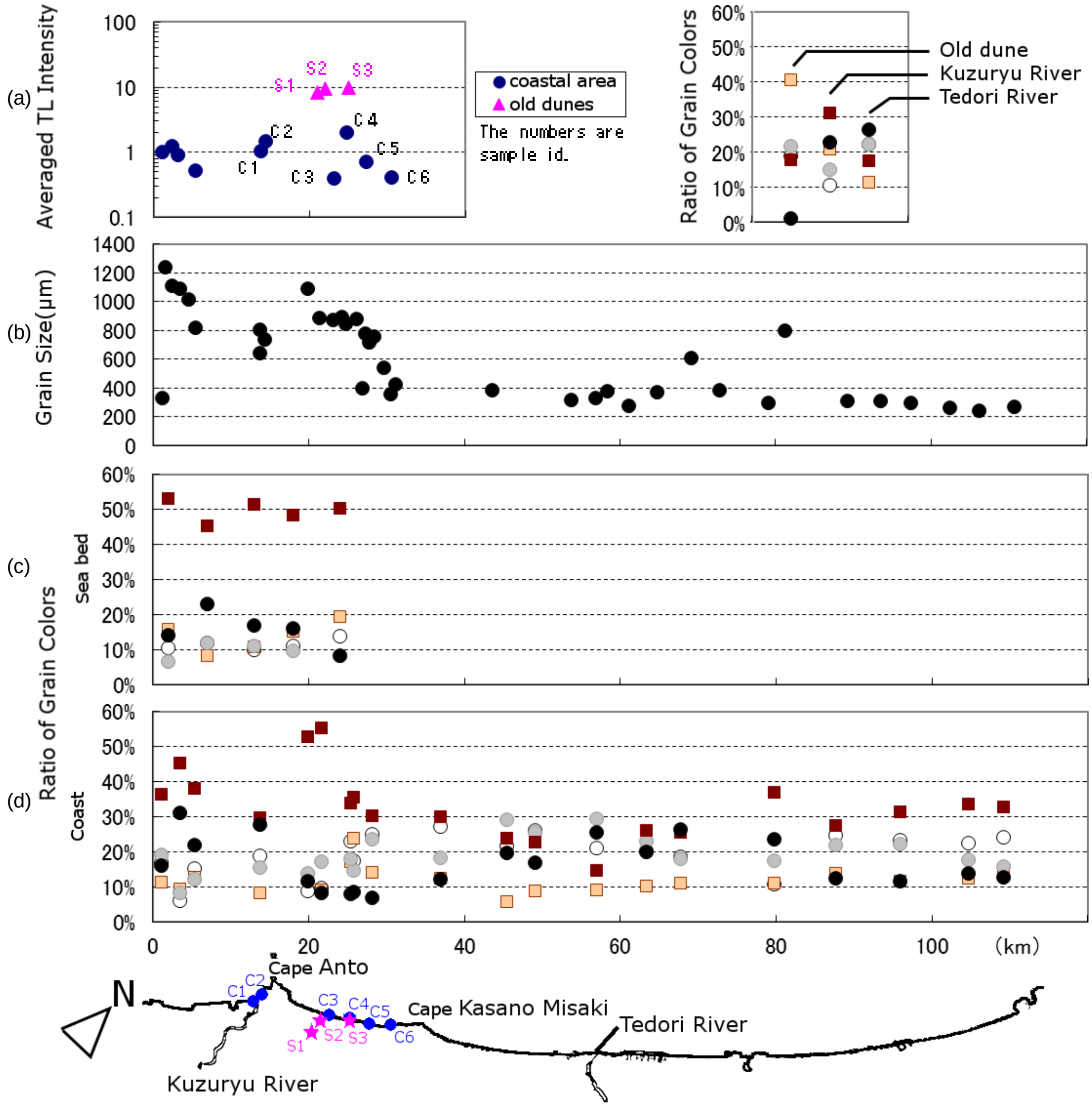


Figure 12. Results of grain analysis.

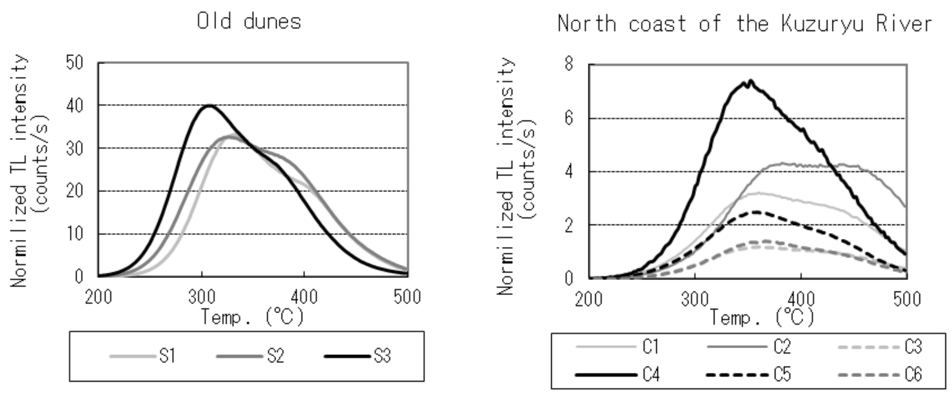


Figure 13. Thermoluminescence glow curve of the samples of old dunes and on the coast in front of the old dunes.

SUMARY OF SEDIMENT TRANSPORT IN THE STUDY AREA IN THE HOLOCENE

Figure 14 illustrates a schematic diagram about the changes in sediment transport under sea level variation conjectured by numerical simulation and analysis of sand samples. When the sea level was low, nearshore currents converging toward the Kuzuryu River mouth behind Gentatsu-se caused sediment accumulation around the river mouth forming protruding coastal topography. As the sea level rose, the direction of the nearshore currents changed to the diverging direction as illustrated in Figure 6. Then the accumulated sediments started to be eroded and transported to the both side of the coast. The old dunes are considered to have been formed by sediment blown up onto the land at this time. Further sea level rise formed the Cape Anto on the north of the Kuzuryu River mouth, which blocked sediment movement from the Kuzuryu River to the northern beach. However, the northern beach was still supplied with sand by erosion of the old dunes. In recent years, the construction of dams in the watershed has reduced total amount of sediment supply to the coast. The sediment supply from the Kuzuryu River to the southern coast of the river mouth was further decreased by the construction of breakwaters of the Fukui Port. The breakwaters presumably changed the nearshore currents causing more complex changes in beach deformation. For example, the direction of sediment transport on the coast south of the Kuzuryu River mouth is currently northward.

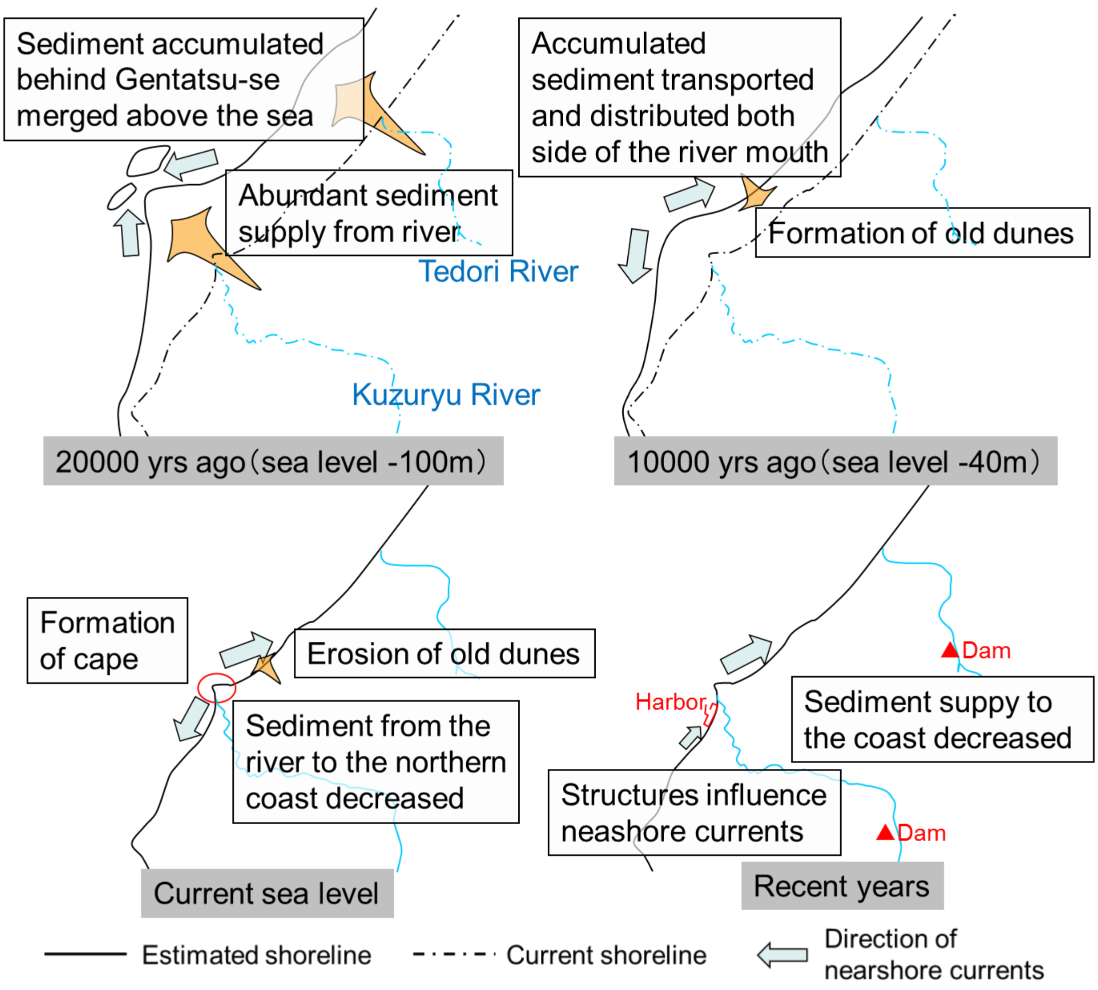


Figure 14. Summary of sediment transport in the Kaetsu Region in the Holocene.

CONCLUSIONS

In this study, sediment transport and its long-term changes in the Kuzuryu River and the Kaetsu Coast was investigated on the basis of luminescence, size and color analysis of sediment and numerical simulation of wave and currents. The main conclusion are summarized as follows:

1. The Kuzuryu River and Tedori River are categorized as river with large sediment yield in Japan. The interruption of sediment flow by dam construction must have decreased sediment supply to the coast significantly.
2. Direction of the nearshore currents around the mouth of the Kuzuryu River changed from the converging direction towards the Kuzuryu River mouth to the diverging direction to the both side of the river mouth with sea level rise in the Holocene.
3. The TL and color analysis of sand grains revealed that the erosion of old dunes located north of the Cape Anto and south of the Daishoji River mouth is another source of nearshore sediments.
4. The boundary of sediment supplied by the Tedori River and the Kuzuryu River is found at the Cape Kasano-misaki.
5. The dominant direction of sediment transport around the Kuzuryu River mouth is estimated to be northward in the present situation although sediment supply from the river has been decreased significantly.

ACKNOWLEDGMENTS

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