Coastal Dynamics 2017
Paper No. 132

MULTIDECADAL SHORELINE EVOLUTION DUE TO LARGE-SCALE BEACH NOURISHMENT −JAPANESE SAND ENGINE?−

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Abstract

Beach nourishment is one of the countermeasures against erosion. Large-scale beach nourishment was conducted with 50 million m^3 of dredged sediment on the Hasaki coast of Japan from 1965 to 1977. Here, using aerial photographs, we found that the nourishment caused an increase in the sediment budgets that led to significant long-term shoreline advance. The mean shoreline position in 2013 was located approximately 70 meters seaward compared with the position in 1961. The shoreline in the northern part of the coast advanced soon after the nourishment; however, the shoreline in the south began to advance approximately 10 years after the advance of the northern section. The shoreline advance amounted to approximately a third of the total sediment supplied by the nourishment. This shows that beach nourishment is good solution to counteract beach erosion and also achieves the beneficial use of dredged sediment, both on the large- and small-scale.

Key words: beach nourishment, shoreline change, coastal morphodynamics, dredged sediment, Sand Engine, EOF analysis

1. Introduction

Under the current global climate change, sea level rise and wave climate change are predicted to cause severe beach erosion. To manage this coastal response to the climate change along with multi-decadal coastal changes, unprecedented adaptation methods will be required. Beach nourishment is one of the countermeasures against erosion. A mega beach nourishment project in the Netherlands, called the Sand Engine, has received attention as a new type of nourishment (e.g., Stive et al., 2013). As an example of a similar case in Japan, from 1965 to 1977, approximately 50 million m^3 of sand was nourished into the nearshore zone of the Hasaki coast. The large-scale beach nourishment was conducted for the disposal of dredged sediment during the construction of the Kashima Port, which is an artificially excavated port. Therefore, this served the dual purpose of environmental preservation and the beneficial use of dredged sediment that had to be disposed of. Here, to assess the impact of the beach nourishment on morphological changes, we investigated the shoreline changes from 1961 to 2013 on the Hasaki coast.

2. Japanese Sand Engine?

The Kashima Port, which is located in eastern Japan facing the Pacific Ocean (Figure 1), is one of the world's largest excavated ports (Figure 2). The Y-shaped channel was excavated up to approximately 20 m. The length of the breakwater is approximately 4 km, which is one of the largest breakwater in Japan. The Hasaki coast on the southern side of the Kashima Port has a 16 km-long sandy beach (Figure 3).

Construction of the port began in 1963. The excavated and dredged sediment was used for beach nourishment of the Hasaki coast from 1965 to 1977, and the total amount of added sediment was approximately 50 million m^3 (Figure 4). The sediment was spread adjacent to the southern end of the port (Figure 1), within 500 m of the shoreline. The median grain size of the dredged sediment ranged from 0.13 mm to 0.17 mm, depending on the excavation depth of the port channel. The median grain size of the present coast is approximately 0.18 mm. A section of the area that received sediment was reclaimed for land use in the 1970s after the shoreline here had advanced sufficiently far, concurrently with the beach nourishment. The reclaimed volume was estimated as 23 million m^3 according to the reclaimed area and the height of the land. Therefore, approximately 27 million m^3 of total added sediment contributed to the beach morphological changes. This volume is comparable to the nourishment of the Sand Engine, which had a volume of 21.5 million m^3 (Stive et al., 2013). In the case of Kashima, because the nourishment lasted over ten years, the nourished sediment was transported offshore and spread over a wide area in the sea after the nourishment was completed. Conversely, in the case of the Sand Engine, a large new beach was constructed in one place and at one time in 2011 (Figure 5). Therefore, the influence of the nourished sediment will be different between these two cases.

Figure 1. Satellite image of the Kashima Port from Google Earth.

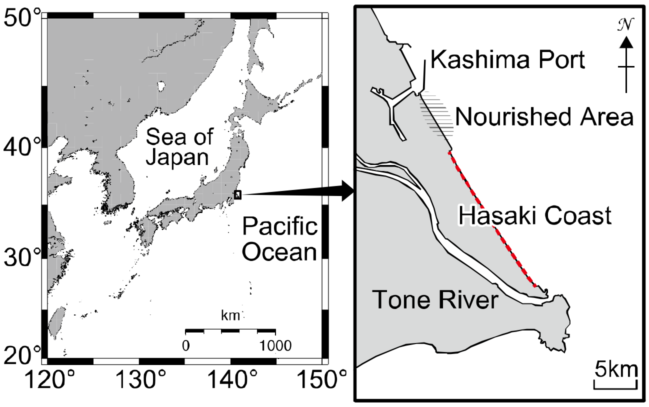

Figure 2. Locations of the Kashima Port, the Hasaki coast, and the nourished beach area.

Figure 3. View of the southern section of the Hasaki coast.

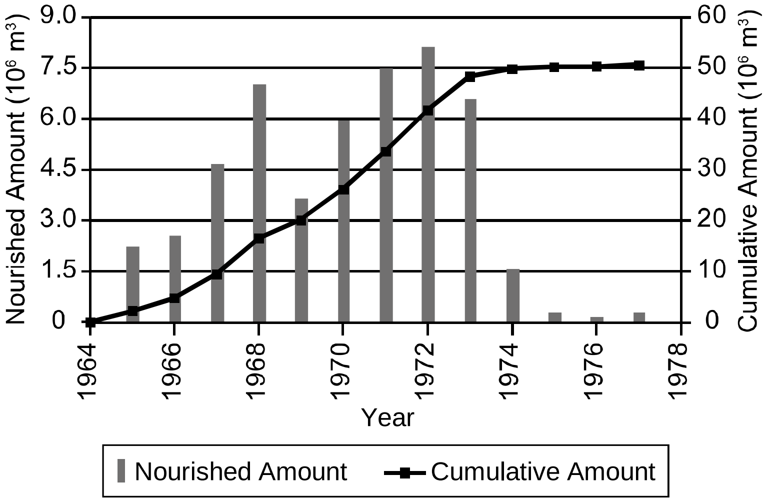

Figure 4. Time-line of the beach nourishment.

Figure 5. Satellite image of the Sand Engine in the Netherlands from Google Earth.

3. Hydrographic Condition

The tidal levels at low, mean, and high tide are −0.2, 0.65 and 1.25 m from the datum line (D.L. = Tokyo Peil − 0.69 m), respectively. The principal natural source of sediment is Tone River, which is located on the southern side of the coast. The annual amount of sedimentation near the coast due to the fluvial transport and deposition has been estimated at approximately 50 thousand m^3 (Uda et al., 2007).

Deepwater waves were measured at a water depth of 24 m every 2 hours offshore of the Kashima Port with an ultrasonic wave gage. The seasonal mean significant deepwater wave height and the period from 1986 to 2013 are shown in Figure 6. The wave height was relatively small from May to August (spring/summer), but relatively large from September to April (autumn/winter) because of typhoons and extratropical cyclones. The waves came mainly from the south from spring to summer, and from the north from autumn to winter. In response to this, the longshore current was northward from spring to summer, and southward from autumn to winter. The long-term predominant direction of the longshore current was northward on the shoreside, but southward farther approximately 150 m offshore (Kuriyama et al., 2008).

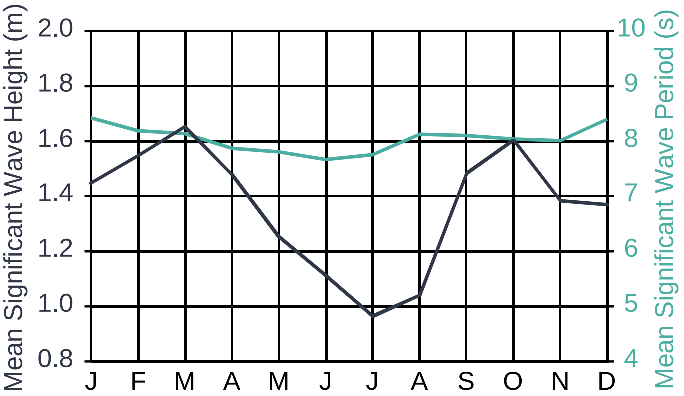

Figure 6. Seasonal mean significant wave height and period.

4. Construction History of the Coastal and Port Structures

Beach morphological change on the Hasaki coast was influenced by the nourishment, and by the coastal and port structures (Figure 7). During the construction of the Kashima Port, construction also began in 1964 on a breakwater called the “Kashima southern breakwater” at approximately 7 km north of the present coast. It was over 3000 m in length in 1972 and 3875 m in 2004. The water depth at the tip of the breakwater is approximately 20 m. The beach reclamation at the northern edge of the coast was completed for a 6.4-kilometer-long section in 1975.

On the southern edge of the coast, extension of a breakwater at the Hasaki Fishery Port began in 1989. The length of the breakwater reached 1170 m in 2006. The water depth at the tip of the breakwater is approximately 6 m. On the southern part of the coast, five artificial headlands (T-shaped groins) were also constructed sequentially from 1968 to 2000. The length of the headland across the shore is 150 m and the length of the tip is also 150 m.

HORS (Hazaki Oceanographical Research Station), which is a research station with a research pier, was constructed in 1986. The location is 4 km south from the northern edge of the coast. The influence of the pier on the morphological changes is relatively small, thus the bathymetry around HORS is almost uniform alongshore. In this study, we used the coordinate system based on the location of the pier. The longshore coordinate axis was orthogonally crossed to the pier (Figure 8).

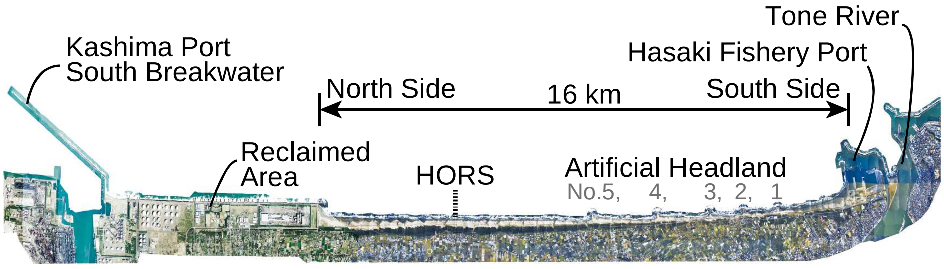

Figure 7. Locations of the coastal and port structures on the Hasaki coast.

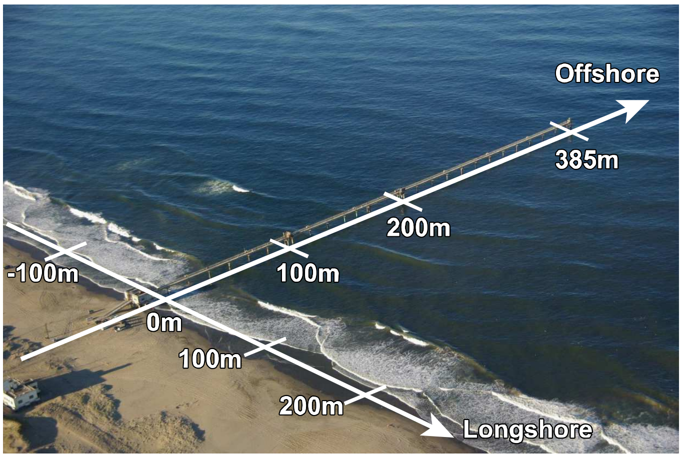

Figure 8. Coordinate system used for the definitions of the shoreline positions.

5. Shoreline Evolution After Beach Nourishment

The shoreline position from 1961 to 2013 was extracted from aerial photographs. The photographs were taken every 3 to 5 years (1961, 1965, 1969, 1974/1975, 1979, 1984, 1987,1990, 1993, 1996, 1999, 2002, 2005, 2009, and 2013) by the Japanese government or a local government. An aerial photograph was also taken by the U.S. Army in 1947, but it was not used in this paper to focus the impact of the beach nourishment. As a reference, the shoreline change between 1947 and 1961 was small relative to the one after the nourishment (Sato et al., 2002). The temporal and spatial data on the extracted shoreline positions were corrected for the influence of tidal variation with reference to M.W.L. based on the deviation of sea levels when the photographs were taken. The foreshore slope used to calculate the correction amount for the shoreline position was based on the bathymetry obtained by an airborne laser in 2006. Figure 9 shows the spatial shoreline change from 1961.

An increase in the sediment budgets due to the nourishment resulted in an advance of the mean shoreline by approximately 40 meters from 1969 to 1984 (Figure 10). Although the nourishment began in 1965 and was completed for the most part in 1974, the response of the shoreline did not appear to match this. In addition, although the advance lessened from 1984 to 1993, the shoreline began to advance again from 1993 (Figure 10). As a result, the mean shoreline position in 2013 was located approximately 70 meters seaward compared with the position in 1961. However, the changes in the shoreline position based on the aerial photographs included short-term and seasonal variations because the photographs only provided instantaneous values at the time they were taken. According to beach profiles measured at HORS (e.g., Kuriyama et al., 2012), the daily variation of the shoreline position over one year at the Hasaki coast had a standard deviation (S.D.) of approximately 10 m (Figure 11). Therefore, the long-term shoreline change was sufficiently large compared with the variation, showing that the nourishment led to a significant advance in the shoreline.

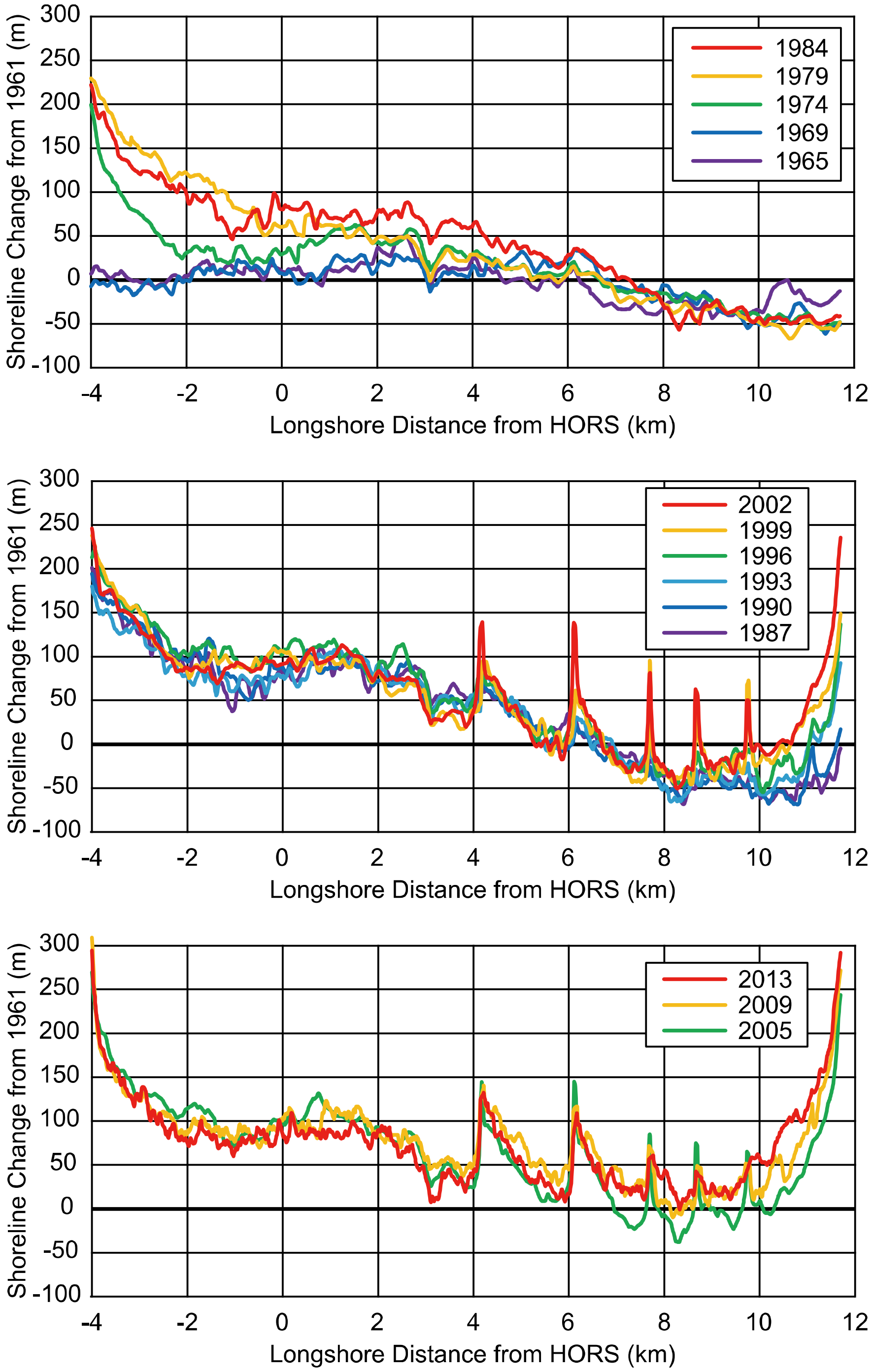

Figure 9. Spatial shoreline change from 1961 onwards.

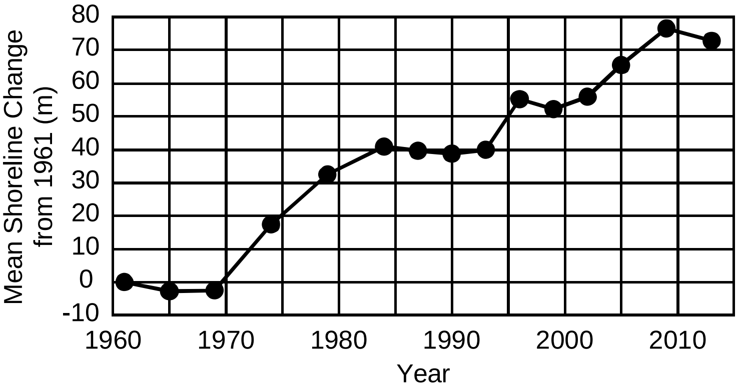

Figure 10. Mean shoreline change from 1961 to 2013.

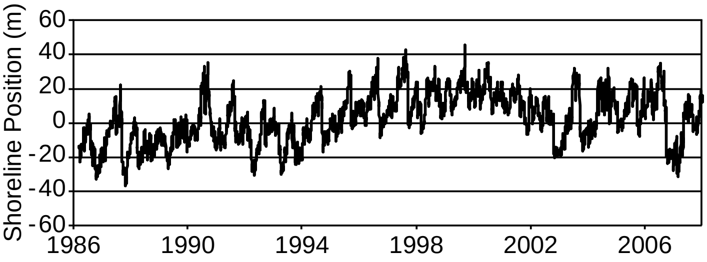

Figure 11. Shoreline change at HORS from 1986 to 2007.

6. Efficiency of Nourishment

Based on the mean shoreline advance of approximately 70 meters from 1961 to 2013, the sediment amount deposited nearshore was estimated at approximately 8 million m^3, assuming that the height between the upper and lower limit of the beach profile change was 7 meters. This amount was much greater than the one supplied from Tone River (total amount of 2.5 million m^3), showing that the notable shoreline advance was clearly caused by the mega beach nourishment.

In terms of long-term beach stability, approximately a third of the total sediment supply of 27 million m^3 supplied by the nourishment influenced the beach morphology. The rest of the sediment would be lost through offshore transport. The efficiency of small-scale nourishment is difficult to estimate quantitatively because the shoreline is influenced to a greater extent by other factors, such as, external forces. However, the large-scale beach nourishment clearly indicates that it will have a beneficial impact on coastal protection against erosions.

7. Shoreline Evolution Process

Regarding the spatial distribution of the shoreline change (Figure 9), the shoreline positions around the northern and southern edges of the coast had notably advanced by over 100 meters by 2013. These shoreline advances were caused by the increase in the sediment budget due to the nourishment and the sediment trapping due to the coastal structures perpendicular to the shoreline. The beach reclamation structure on the northern edge and the breakwater on the southern edge prevented part of the longshore sediment transport and accumulated sediment. The spatially heterogeneous shoreline evolution on the southern section of the coast (longshore coordinate values from 4,000 m to 10,000 m) was due to artificial headlands.

Empirical orthogonal function (EOF) analysis was used for the temporal and spatial data of the shoreline positions. EOF analysis can extract the principal component of the shoreline change (e.g., Miller and Dean, 2007). The shoreline positions are expressed by Equation (1) as a sum of the product of the temporal and spatial components.

$$y_s\left(x,t\right)=\sum_n C_n\left(t\right)\cdot e_n\left(x\right) \tag{1}$$

where y_s (x,t) = shoreline position; x = longshore coordinate; t = time; $C_n(t)$ = temporal coefficient on mode n, and $e_n(x)$ = spatial function on mode n.

The spatial domain was split between the northern and southern parts in the analysis to clarify the local variation pattern. In the northern section, the large shoreline advance from 1969 to 1979 after the nourishment was the dominant pattern (Figure 12). Conversely, the consecutive shoreline advance from 1990 was the dominant pattern in the southern part (Figure 12). The southern shoreline advance, which followed the northern one, may have been induced by the construction of the breakwater on the southern edge of the coast. After the construction of the artificial headland, the shoreline between the artificial headlands also recovered from 2002, as shown in mode 2 of Figure 12.

According to the bathymetry change (Figure 13), the sediment was transported onshore when the southern shoreline advanced, in parallel with the deposition at the southern edge as described above. This contributed to the large shoreline advance from 1993. However, the reason why the sediment was transported onshore from a depth greater than 4 meters is still unknown.

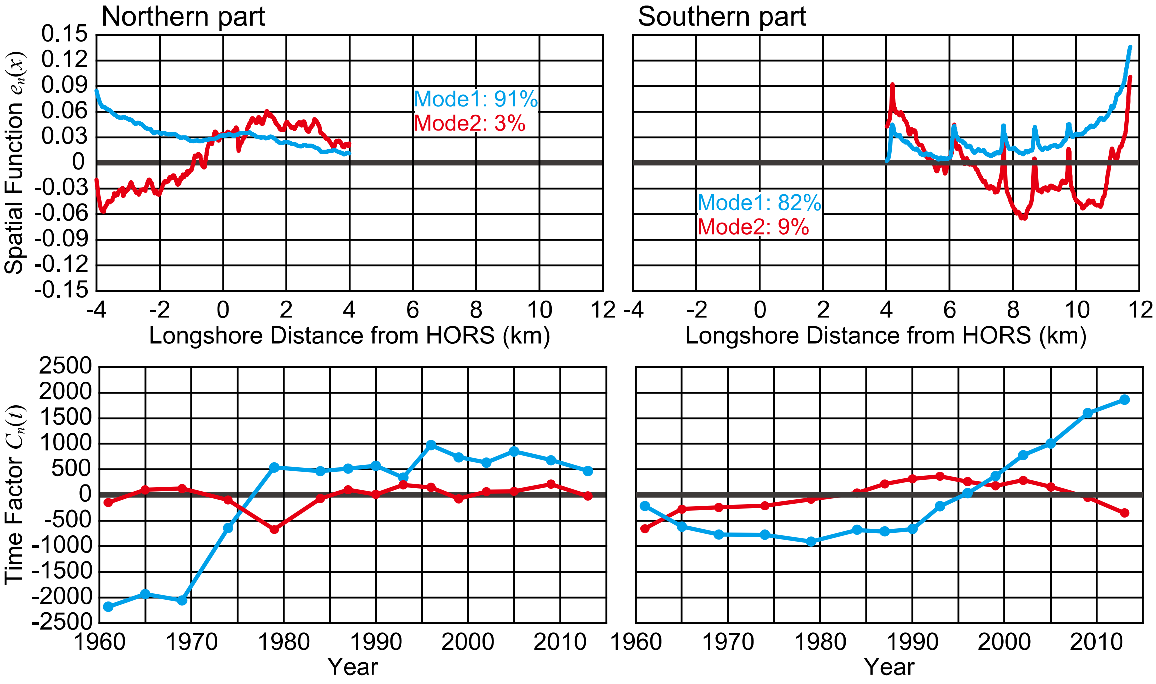

Figure 12. EOF analysis of the temporal and spatial data of the shoreline positions.

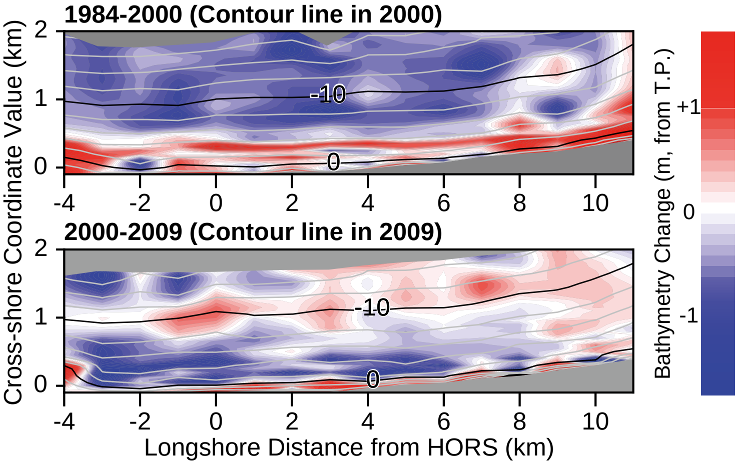

Figure 13. Bathymetry change on the Hasaki coast.

8. Conclusions

We investigated the multi-decadal shoreline evolution due to large-scale beach nourishment using aerial photographs. The mean shoreline advance at the Hasaki coast exceeded 70 meters caused by the increase in the sediment budgets following the beach nourishment that provided approximately 50 million m^3 of sediments. The shoreline in the northern part of the coast advanced soon after the nourishment; however, the shoreline in the southern part advanced approximately 10 years after the advance in the north. As a result of the onshore sediment transport, the construction of the breakwater and the artificial headlands likely caused the large shoreline advance on the southern section of the coast.

The shoreline advance was equivalent to approximately a third of the volume of the total sediment supply of 27 million m^3 supplied by the nourishment. Although such large-scale beach nourishment is expensive, it will be a highly effective method for beach management, simultaneously achieving the beneficial use of dredged sediment.

Acknowledgements

The authors would like to acknowledge the significant contributions of Dr. Yasuyuki Nakagawa in writing this paper. Some of the aerial photographs in this study were used with courtesy of the Ibaraki Prefecture Government. The construction histories were provided by the Ministry of Land, Infrastructure, Transport and Tourism, and the Ibaraki Prefecture Government. A part of this work was conducted within the framework of the "Social Implementation Program on Climate Change Adaptation Technology (SI-CAT)" supported by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT).

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