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SHORE PROTECTION OF NOTSUKEZAKI SAND SPIT

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Abstract

Notsukezaki is a hook-shaped spit and the longest sand spit in Japan. In 1990's, severe erosion of the sand spit had started around the down-drift side of a fishing port. As a result, overwash and breaching risk had increased rapidly. Due to this, construction of groins have been conducted since 1990's. In this paper, we analyze response of shoreline to these shore protection projects (combination of groins and beach nourishment). Additionally, we suggest a numerical model for shoreline changes along the entire long curved spit. The agreement between measured and computed shoreline changes is good because all important factors are taken into account. Wave forecasting and hindcasting data is applied, so that we can predict shoreline change under climate change scenarios by the verified one-line model.

Key words: sand spit, shoreline change, groin, beach nourishment, numerical modelling, wave forecasting and hindcasting data

1. Introduction

Formation of a sand spit depends on dominant littoral drift by waves and wave-induced current in coastal zone. Notuskezaki is located in Nemuro Straight in Japan. Figure1 shows that there are two sand spit at least. Notsukezaki sand spit was formed by continuous sediment transport for the last 6,000 years, and the complicated inner bay pattern indicates the step-by-step growth history of the sand spit(Uda and Yamamoto,1992).There are wetlands, tidal flats and extensive seaweed bed in the bay of Notsuke. These are registered on Ramsar Convention in 2005. Tourists have visited this site for the sake of watching a great variety of rare species. In addition, fishermen have been traditionally catching salmon on foreshore (approximately 20km), and shrimp and clam in bay area with sustainability for a long time. It must have been protected because Notsukezaki is special infrastructure for many lives. The main purpose of this paper is analysis about shoreline-change under construction of several groins and several artificial beach nourishment against severe beach erosion (reaching to overwash and breaching) and suggestion of a numerical model for shoreline changes along the entire long curved spit. There are many data such as aerial photographs, surveyed profiles, time series of shape of shore line and boundary of coastal vegetation, beach materials, habitat of wild birds and natural marine lives at this site.

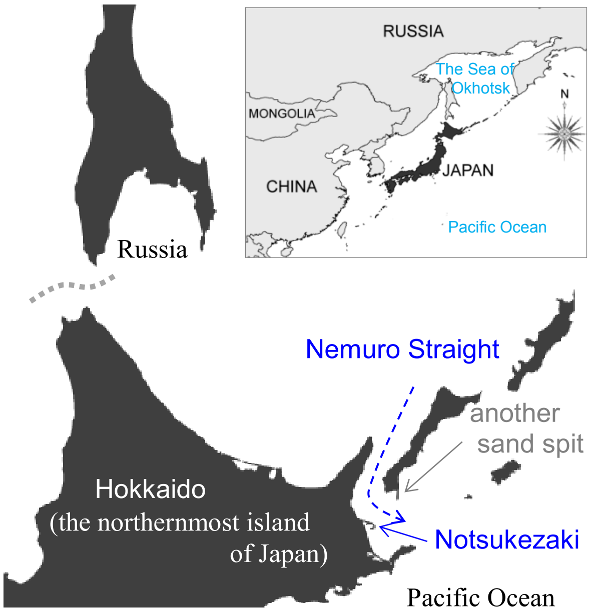

Figure 1. Location of Notsukezaki Sand Spit.

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2. Field Observation

2.1. *Shoreline Changes*

Figure2 and 3 shows the study site in this paper. Longshore sediment transport rate at the north side of Shibestu fishing port is estimated as 27,000~86,000m^3/year by survey data in 1980's (Uda et al, 1991). On the assumption that sediment transport must be 0m^3/year in the near future, combination of groins for shore protection is suggested for each respective section (I ,II and III) with order of priority (Uda et al,1994).In each section of coast, several short groins of 35m length have been constructed since 1995. The number of designed groins is 51 (in 2016). In contrast, the number of constructed short groins is getting to 39 (=76% of whole designed position) in 2015.

Figure 2. Bird's-eye view of Notsukezaki sand spit

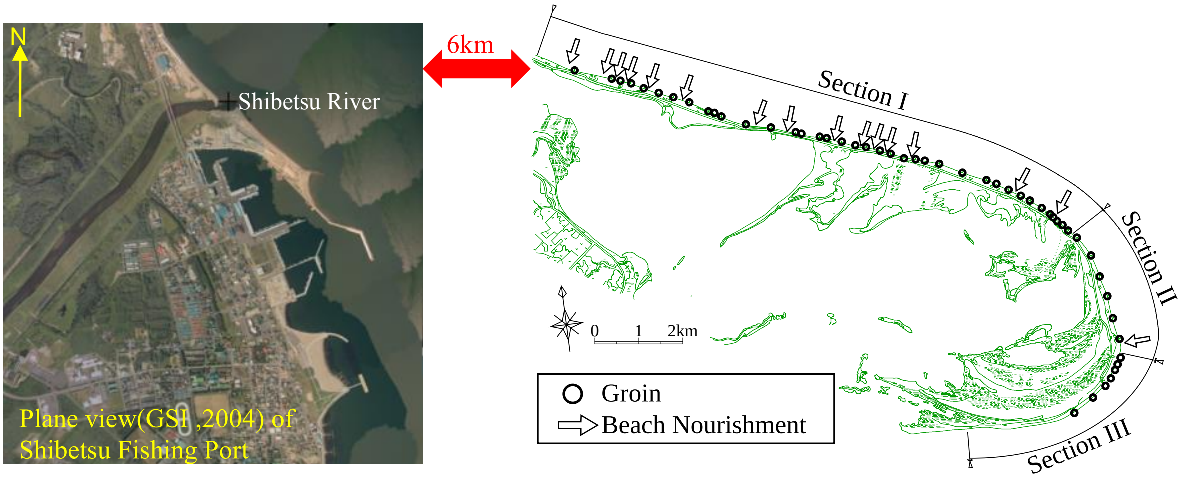

Figure 3. Shore protection of Notsukezaki sand spit

Figure 4 shows that the changes of the shoreline protected by groins and beach nourishment using the field data in Table1. In section I from 1990 to 1999, severe erosion had occurred at down-drift zone (south-east side) of coastal revetment with several jetty or detached breakwater that had been previously constructed at the area (from -2.5 to 0km). This protected area continues from Shibetsu fishing port. Meanwhile, there are many saw-toothed patterns related to left hand side accretion and right hand side erosion at new groin. Specifically, shoreline change from 1995 to 2005, from 2005 to 2015 is respectively -0.6m/year,-0.2m/year. Hence, the rate of erosion along overall sand spit has decreased.

Table 1. Overview of field data (No subscript number means data by Hokkaido Government)

Category	Year	Additional Information
Aerial Photograph	1947[1] ,1990[2], 1995[2], 1999[2], 2000[2], 2004, 2009, 2015	[1] U.S. Armed Forces [2] Geographical Survey Institute
Shoreline position and Boundary of vegetation	2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015	By a man with Real Time Kinematic-GPS(GNSS)
Beach Profile	1992*, 1999*, 2003, 2004, 2007*, 2009, 2010, 2011, 2012, 2013*, 2014, 2015	* Wide range from coastline
Beach Materials	2008, 2013	Sieve analysis

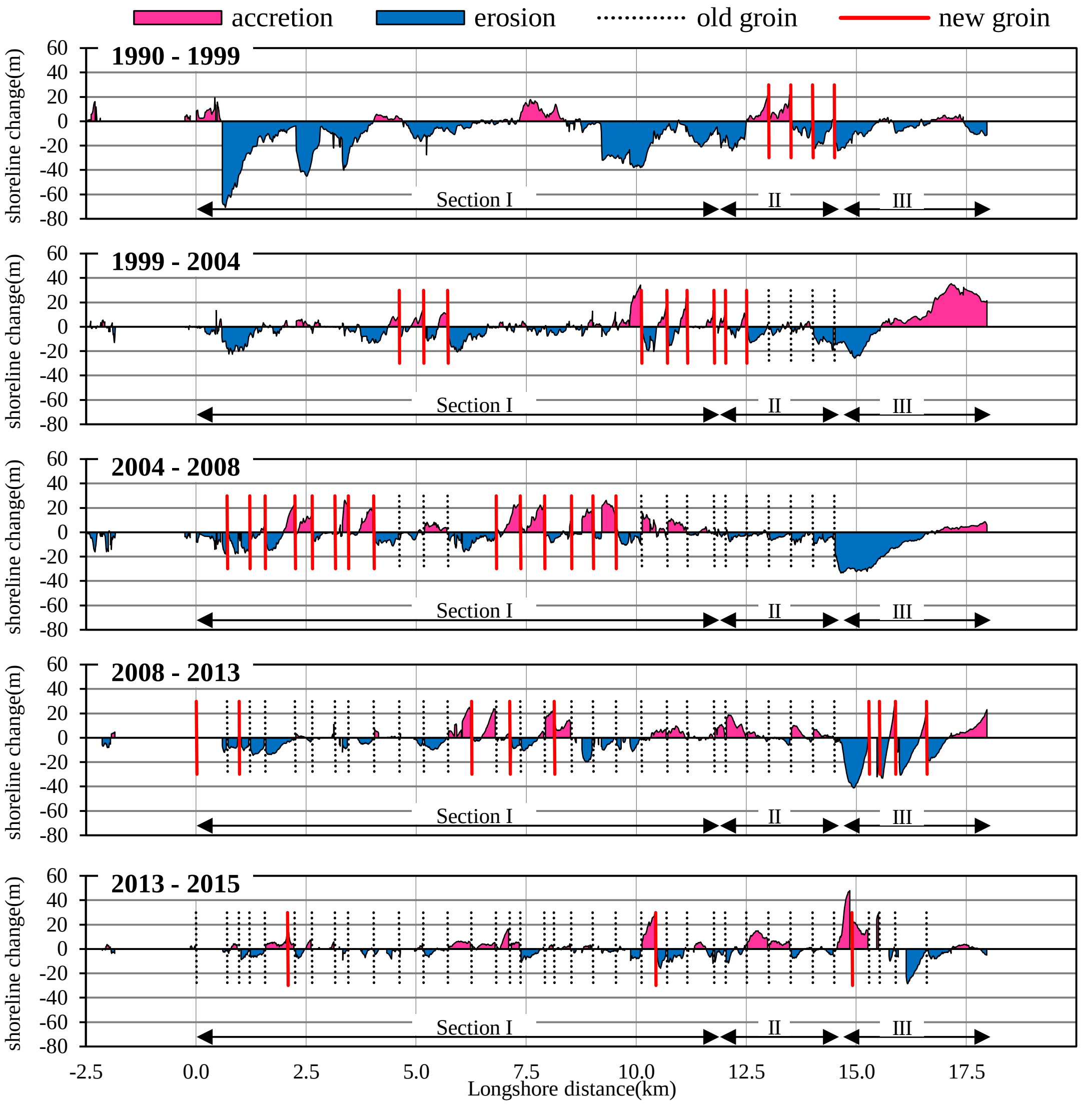

Figure 4. Shoreline change of Notsukezaki sand spit

On the other hand, figure 5 shows that the horizontal spreading of the sand spit distal end. Net longshore sediment transport is continuous toward to the sand spit distal end. Besides, the orientation of sediment transport is different from Section I and II. In addition, it is revealed that shoreline retreat has uniformly occurred at south side of sand spit distal end. This is because uniform sediment transport must have been reduced in up-drift zone of coastline and the source of sediment is erosion of the sand spit itself.

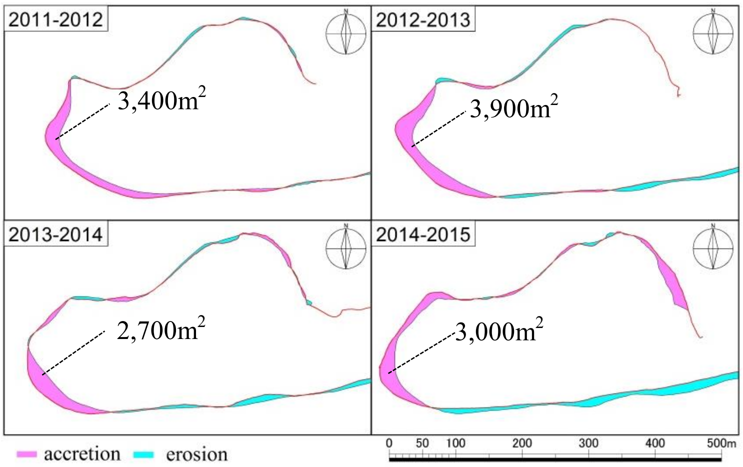

Figure 5. Measured shoreline of distal end at sand spit

2.2. ***Wave Climates***

There is no long-term wave observation station in Nemuro Straight. Short-term wave observation was conducted in 1992 (Uda et al,1994) and in 2003 (Hayashi et al,2010) The GPV-data(the coastal wave spectral model : CWM) which can be obtained from JMA wave forecasting model MRI-III was verified by wave gauges which were installed at 2 sites in the Nemuro Straight (fig. 6). Spatial resolution of the CWM is 0.05 degrees in longitude and latitude and wave spectral resolutions of CWM is 36 azimuthal directions since 2007. Figure7 compares the GPV-data with the measured significant wave heights to indicate the utility and limitation of the GPV-data.

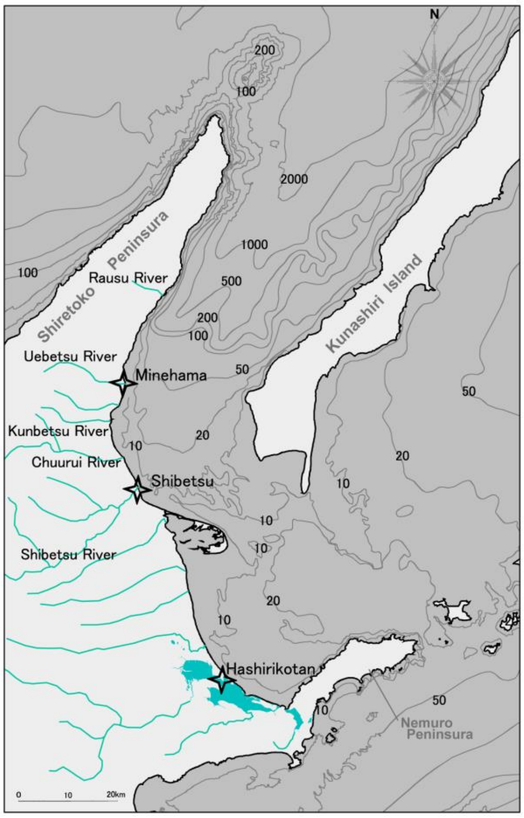

Figure 6. Wave observation at Nemuro Straight.

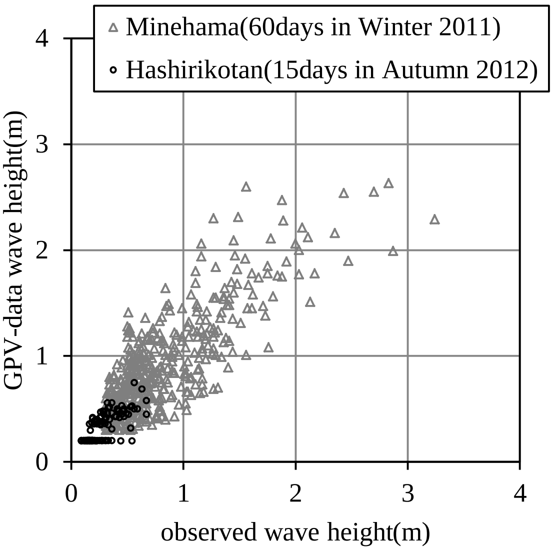

Figure 7. Correlation of significant wave height

According to this GPV-data(fig. 8), annual wave characteristics at offshore of each section is different , because Shiretoko Peninsula and Kunasiri island blocks the waves from northern directions and Nemuro Peninsura blocks the waves from southern directions. In section I, wave energy from north is dominant and wave energy from east increase during spring and autumn. In section III, wave energy from east is dominant for all seasons. Severe storm waves (maximum significant wave height 4.6m and significant wave period 9.4s) were detected at grid B on 9th October 2009. Meanwhile, drift ice arrives from the Sea of Okhotsk in winter. Drift ice movement on sea surface in Nemuro Straight also depends on this wave climates. As a result, drift ice moves away in March at Notsukezaki.

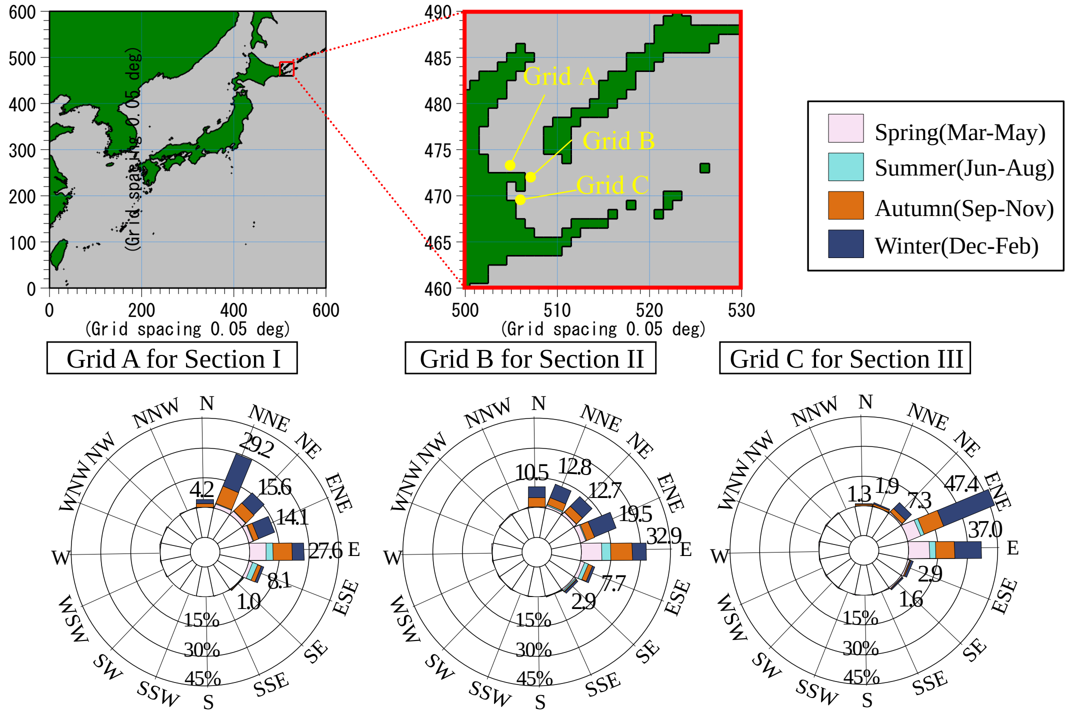

Figure 8. Summation of wave energy flux for each direction(2009-2012,GPV-data).

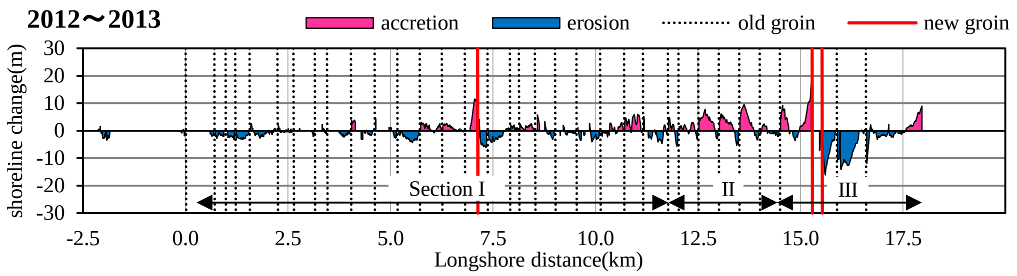

Figure 9. Annual shoreline change (2012 – 2013)

Southward sediment transport is dominant but Northward sediment transport was also detected by observed shoreline changes at several groins (near 12.5km) in section II (fig.9). Figure10 shows that the southward and northward sediment transport directions are related to the dominant wave energy flux directions

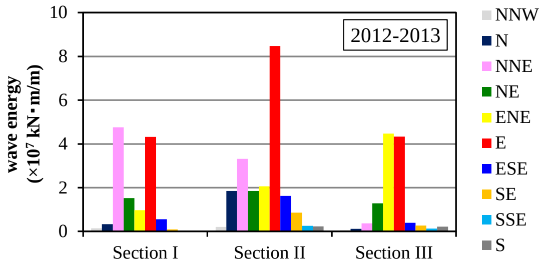

Figure 10. dominat wave of each section(2012-2013,GPV-data).

during the shoreline change measurement interval. Furthermore, the volume change at section III and the growth of distal end of sand spit depend on the cumulative wave energy flux at section III (fig.11).

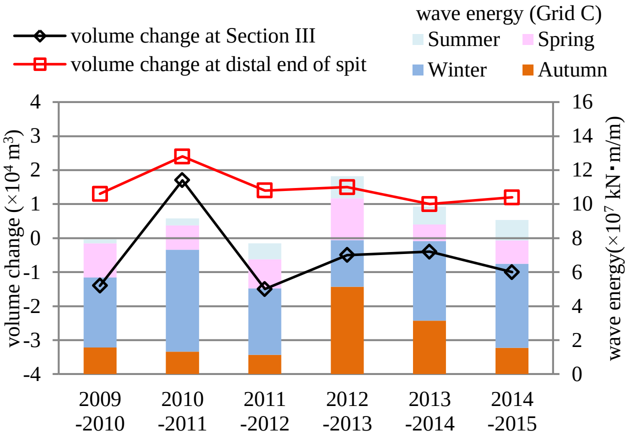

Figure 11. wave energy and accretion area of distal end of spit

2.3. *Sediments*

Figure12 shows that beach material of each depth in 2008 and 2013. It had been showed that a depth which mean diameter decrease drastically will agree with a closure depth of beach profile change and the closure depth at Notsukezaki is about 4m (Uda et al,1994). By contrast, the depth at main breakwater head of Shibetsu Fishing Port was above 4m in 1987 and it had been extended toward offshore since 1987. It is appears that the closure depth at Notsukezaki is stable for a long time. These beach sediment consists of coarse sand and gravel that can be transported by breaking waves and longshore currents.

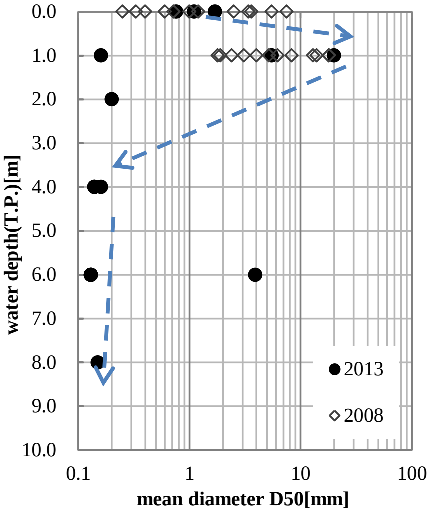

Figure 12. Beach material of Notsukezaki sand spit

2.4. *Beach Profiles*

There have been fixed 12 surveying post in Notsukezaki sand spit (fig.13). The sand spit is hook-shaped, so that direction of survey lines on Notsukezaki sand spit by bottom profiler is very important in case of wide range survey from coastline. In addition, surveyor is not same in each year. Designed crown height of groins is +2m. Designed crown height of beach nourishment is also +2m. The road height through section I and II in 2005 spit is from +1.6 to +5.8m. These are taken into account.

Offshore beach profile is quite different in each section. This may have caused by the formative process of Notsukezaki sand spit. Most of profile shows that significant closure depth in last 2 decades was about 4m and natural berm height was from +1 to +2m in last 2 decades. There are no artificial structure at profile no.9 and no.10. There is groin at down-drift side of profile No.3, No.4 and No.7. There are wave absorbing breakwater along the coastline at profile No.3 and No.4. There is groin at up-drift side of profile No.12. At profile No.3, No.4 and No.12, stability after construction of shore protection against erosion is detected. Profile no.3 shows that width of land is about 50m under astronomical high tide and overwash in storm surge would increase the risk of breaching. At profile no.7, typical accretion in up-drift of groins is detected in 2015.In addition, effect of beach nourishment in 2014 is included at profile no.7 in 2015. At profile no.9 and No.10, profile change depends on natural sediment transport. On the other hand, profile no.10 at the distal end of sand spit shows that drastic change in last 2 decades. At first, retreat of the position of berm is detected and height of berm is stable. Secondary, The width of land is decrease and tidal flat in inner bay is stable. At last, a bar have been grown to above 1m and bottom slope of the bar is stable. According to characteristics of these profiles, the concave shape of profile near shoreline shows that record of erosion. At profile No.7 and No.9, remarkable accretion (convex or trapezium shape of profile near shoreline) also detected.

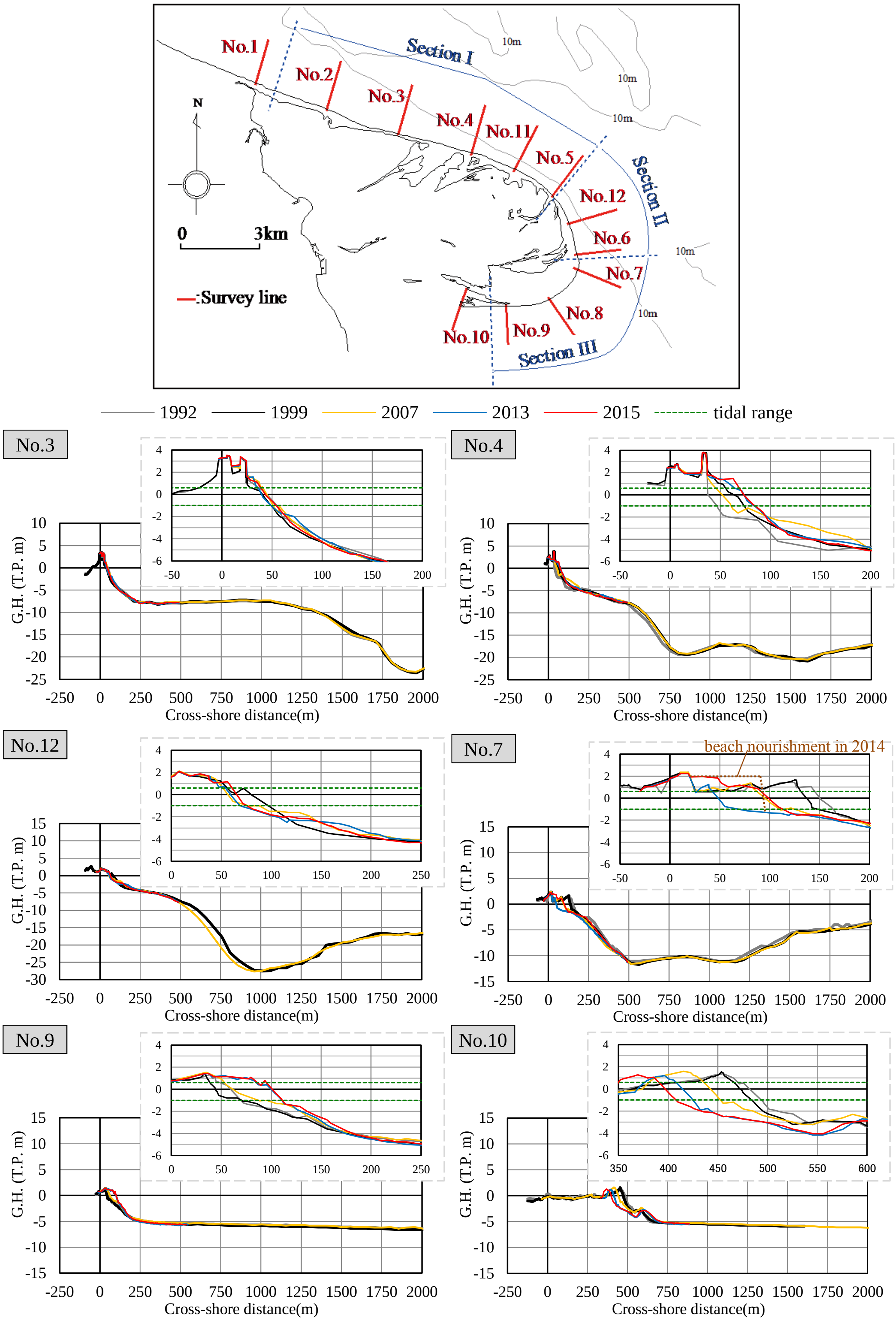

Figure 13. Typical beach profile at Notsukezaki sand spit

2.5. *Regional Sediments Budget*

Figure14 shows that sediment budget along coastline including Notsukezaki sand spit in Nemuro Straight. The main breakwater at Shibetsu fishing port had been preventing longshore sediment transport. The material of beach nourishment at Notsukezaki sand spit is sand which has been deposited at Shibetsu fishing port. Some of them were dredged at shoreline between the mouth of Shibetsu River and Shibetsu fishing port and had been stocked at the fishing port. But the most important issue at the port is safe navigation for fishermen. The main material for nourishment is mostly very fine sand in channels and basins of the fishing port.

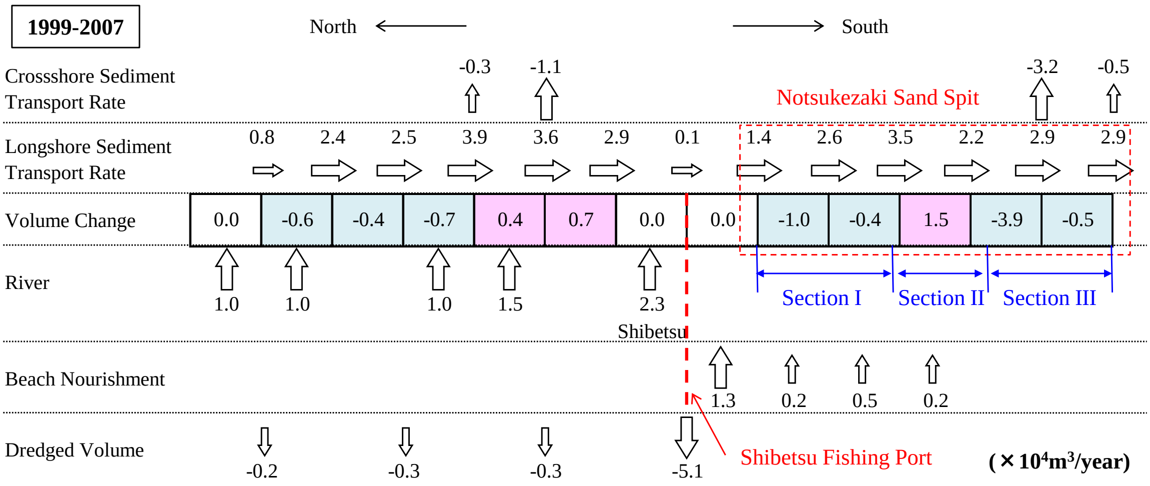

Figure 14. Regional sediment budget at Nemuro Straight

3. Numerical modeling for shoreline changes

3.1. *Theory*

One-line models are widely used to predict the shoreline change in the presence of shoreline protection structures. The continuity of sediment transport is expressed as

$$\frac{\partial \mathrm{x_s}}{\partial t}+\frac{1}{D_s}\left(\frac{\partial Q}{\partial y}-q\right)=0 \tag{1}$$

where $\mathrm{x_s}$ is the cross-shore position of the shoreline, D_s is the maximum depth to which sediment can be transported, Q is longshore sediment transport including porosity, and q is the cross-shore sediment transport volume, such as the sand supply from a river or the seaward loss of sediment to the sea. The longshore sediment transport (JSCE, 2004) is expressed as

$$\mathrm{Q}=\frac{(E\cdot C_g)_b}{(\rho_s-\rho)g(1-\lambda)}\cdot\left[K_1\sin\alpha_b\cdot cos\alpha_b-K_2 cos\alpha_b\cdot\cot\beta\frac{\partial H_b}{\partial y}\right] \tag{2}$$

where ρ_s and ρ are the densities of sand and sea water, respectively, λ is the porosity, E is the wave energy,C_g is the group velocity of the wave, α_b is the angle between the shoreline and the wave crest line, tan β is the bottom slope, and the subscript b indicates values at the breaking point.The first term in equation (2) is equivalent to the CERC formula. The second term express longshore sediment transport due to changes in breaking wave heights in the longshore direction. This model requires input of the longshore distribution of wave heights and wave angles along the breaking points. The energy balance equation (e.g.,JSCE) is applied for estimating wave height and wave period in breaking zone at each grid along coastline.

3.2. *Settings*

3.2.1. *Waves*

The observed wave climate along the 20-km curved spit by Hayashi et al (2010) varied alongshore noticeably. For this reason, wave climate at each section should be taken into account. We suggest to input the time-series of wave condition to numerical wave field model which treats wave breaking at several offshore points along the entire spit every 6-hours.Time-series data of wave specification in breaking zone at each grid was obtained at each time step using look-up tables (495 patterns) obtained previously for each class (wave height and wave period and wave direction) of wave climate in each section(GPV-data) by 2D simulation of wave propagation from offshore to breaking zone.

3.2.2. *Closure depth*

Closure depth of beach profile change is known to be very important for longshore sediment transport over groins. Furthermore, measured data shows that bottom slope of each section is distinctly different. Therefore, we suggest to input the closure depth at each shoreline grid by experimental formula with the combination of mean diameter of sediments in each section and time-series of wave conditions.

The relation for the initiation of general sand movement is expressed as

$$\frac{\mathrm{H}_0}{\mathrm{L}_0} = 1.35\left(\frac{d}{L_0}\right)^{1/3} \cdot \frac{H_0}{H} \cdot \left(\sinh\frac{2\pi h}{L}\right) \tag{3}$$

where d is the diameter of sand grains, H_0 and L_0 are the offshore wave height and wavelength respectively, H and L are the wave height and wavelength at the water depth ,h,which is a critical depth of sand movement. This equation corresponds to the state where all sand particles on the surface layer of the sea bed move collectively in the direction of wave propagation (Sato and Isobe, 2015).

3.2.3. *Shore protection works*

All the groins and beach nourishment (fig.3) in simulation period are included in the time-series simulation.

Table 2. Conditions of numerical simulation for each section

	Sediment transport coefficient		mean diameter	Closure depth	Berm height (m)
	K_1	K_2	d (mm)	h(m)	
Section I	0.18	0.08	1.1	time-series data	+1.0
Section II	0.13	0.05	1.7	time-series data	
Section III	0.20	0.07	0.8	time-series data	

3.3. *Results*

Table2 summarizes the input used in the numerical simulation.Figure15 shows that the agreement between measured and computed shoreline changes is good because all important factors are taken into account. Relations between the closure depth and the depth at top of groins in every wave field is most important factor.

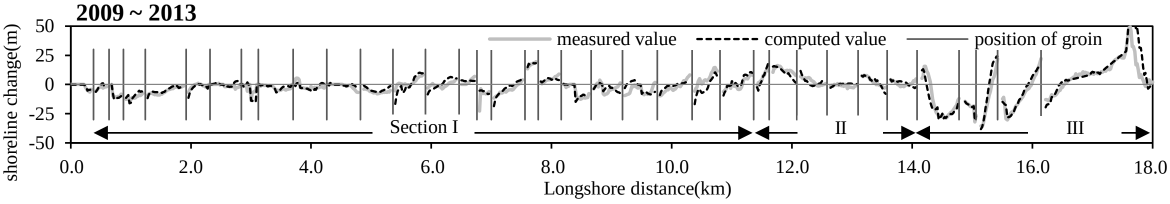

Figure 15. Measured and computed shoreline by one-line model

4. Conclusions

Monitoring and assessment of sediment transport patterns are necessary to design shore protection. Down-drift erosion and up-drift accretion of each groin must be carefully monitored. Local erosion may make direct and severe influences for the house or warehouse of fishermen and for safety of many tourists. Furthermore, sand management at deposit areas such as river mouths, fishing port navigation channels, the sand spit distal end is an important element of the shoreline protection of Notsukezaki sand spit. It must be carefully tested about for physical, chemical and biological characteristics in fishing port navigation channels before construction of beach nourishment. The management of beach material is specifically difficult because of environmental, social and economic points of view in Japan. Meanwhile, wave forecasting and hindcasting data is applied, so that we can predict shoreline change under climate change scenarios by the verified one-line model. In future, the one-line model will need to be extended to include sea level rise and land subsidence. Sand exchanges between the longshore sediment transport zone and the overwash zone will need to be included to predict the longer-term shoreline change.

Acknowledgements

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