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SEDIMENT BALANCE FROM MOUNTAINS TO COASTS IN JAPAN: WHAT IS THE CAUSE OF COASTAL EROSION IN THE PERIOD FROM 1950 TO 1990?

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Abstract

Amounts of sediment yield, sediment deposits in dam reservoirs, and sediment digging both in river and the sea were analyzed as well as beach width change from around 1950 to 1990 in Japan, to quantitatively clarify the effect of sediment balance in catchments from mountains, rivers, to the sea. The approximate total national amount of the sediment yield is 5,600 million m^3, sediment deposits 790 million m^3, and river digging 1,600 million m^3 in the period, respectively, and more than half of the sediment yield is estimated to be sediment supply potential from rivers to the sea. On the other hand, the approximate total amount of sand loss in the sea is 2,000 million m^3 and sea digging 700 million m^3, respectively. All these data used in this study cannot fully explain the sediment balance in the catchments; however, they revealed that the river digging could be one of the major factors which affected the beach erosion in the period.

Key words: *sediment yield, dam, sediment supply, coastal erosion, rainfall*

1. Introduction

Beach is valuable space having various functions, such as mitigating disasters by attenuating wave energy during stormy weather and providing precious environment for harboring ecosystem and for tourism and recreation. In post-war Japan, infrastructures including check dams, dam reservoirs, and coastal structures for disaster prevention were rapidly constructed, increasing beach erosion drastically in many places nationwide (Kishida and Shimizu, 2000; Yoshida et al., 2012; Udo et al., 2016). In recent years, the shoreline tends to be stabilized compared to the past; however, the beach width is still narrow at most beaches (Udo and Takeda, in press).

Moreover, there are growing concerns on impacts of sea level rise (SLR) and change of wave characteristics caused by climate change. Regarding these impacts in Japan, Yoshida et al. (2013) shows the impact of SLR projected using the Bruun rule is larger than that of wave, and Mimura et al. (1994) and Udo and Takeda (in press) projected nationwide future beach loss caused by SLR using the Bruun rule. The change of rainfall characteristics is another concern since it would change the amount of sediment supply from rivers to the sea. The significant beach erosion in post-war was considered to be caused by the decrease in sediment supply from mountains, rivers to the sea due to the infrastructure constructions in the catchment; however, very few studies have been conducted on a long-term and nationwide effect of the sediment supply on beach erosion. Yokoo and Udo (2016) have conducted quantitative analyses on the connectivity between sediment storage in dam reservoirs and beach erosion nationwide; however, clear relationship could not be found between them in the past few decades.

In Japan, Muramoto (1974) investigated the relationship between river digging and the river-bed elevation change by using the nationwide data from the 1930s to the 1970s and the data of permissible amount of river digging in the 1960s. Through the detailed analysis of the Sho River, Muramoto (1974) demonstrated river digging is the dominant factor that caused the degradation of river bed. According to a

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report on the Chikugo river catchment (Ministry of the Environment, 2006), river digging is the most affecting factor on the degradation of the Chikugo river bed in the past 50 years. Isobe (2000) also demonstrated the relationship between the river digging and the beach erosion concerning the shoreline change of the Shizuoka-Shimizu coast. In the view of control of the submarine landslides and tsunami-generating mega-earthquakes, Korup et al. (2014) estimated volumes and rates of delivery of terrestrial sediment from Japanese islands to their Pacific subduction zones by widely used predictions (Ohmori, 1978). In a global scale, Syvitski et al. (2005) shows the flux of terrestrial sediment to the coastal ocean and impact of humans on it. These studies explain parts of the sediment transport from mountains to coastal areas; however, there are still many aspects unclarified regarding the dynamics of sediment transport from mountains to coastal areas including the effects of human activities. It is thus necessary to quantify such dynamics so as to find appropriate coastal strategies including adaptation measures for future beach loss.

This study conducts a GIS-based analysis on the amount of sediment deposits in check dams in addition to those of sediment yield, sediment deposits in dam reservoirs, sediment digging in rivers and the sea, as well as river-bed elevation change and relative sea level rise, with the changes of beach widths at 77 costal zones from around 1950 to 1990 in Japan (Udo et al., 2016), aiming to quantitatively evaluate the effect of the sediment balance in catchments from mountains, rivers, to the sea, on beach erosion.

2. Method

2.1. *Beach changes in the past 100 years*

Change of the average beach width for 77 coastal zones was calculated using the spatial shape data (Kishida and Shimizu, 2000) obtained from maps measured by Geospatial Information Authority of Japan around 1900, 1950, and 1990. The average width for each coastal zones was obtained by dividing the beach area of each zone by each beach length. Likewise, the national average beach width was calculated by dividing Japan's entire beach area by its beach length. The sediment balance in the beach area (V_{SB}) was also calculated by multiplying the amount of beach area changes nationwide around 1950 to 1990, by the average sediment transport height 10 m of Japan's beaches facing the open sea (Uda, 1977). Note that the modes of measurement years of the maps were 1903, 1953, and 1991 with the standard deviation of more than 4 years; therefore, the measurement years were indicated as around 1900, 1950, and 1990, respectively. Note also that the beach width change is different from shoreline position change.

2.2. *Amounts of sediment yield, sediment deposits in check dams and dam reservoirs, and sediment digging in each coastal zone catchment*

Catchments of rivers flowing into each coastal zone (hereinafter referred to as coastal zone catchment) were divided by referring to the river data of the National Land Numerical Information provided by the National Spatial Planning and Regional Policy Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Japan (MLIT). For each catchment, the amounts of sediment yield (Y), sediment deposits in check dams (D_C) and dam reservoirs (D_D), and river and sea digging (D_R and D_S, respectively) were calculated.

For the data of Y, we used a 1-km mesh data of annual sediment yield strength nationwide estimated by Okano et al. (2004), converted to those of 40 years. Regarding D_C, capacity of the check dams obtained from Sabo handbook (2016) was used assuming that the check dams were fully filled with sediments during several years. For D_D, we used the actual values of the dams throughout Japan in 2008 provided by MLIT. Regarding the dams constructed as of 1990, the amount of sediment deposits of 2008 was divided by the period from the year of construction to 2008 so as to obtain the annual amount of sediment deposits, and was multiplied by the period from the year of construction to 1990 so as to obtain the converted values of sediment deposits from 1950 to 1990. Negative values exist in the data, but it is physically impossible. We thus regarded them as measurement error and conducted the analysis with the negative values to be zero. Note that the data of the sediment deposits in the check dams and dam reservoirs include only the data of major dams; therefore, the actual amount in each coastal zone catchment would be larger than that in this study.

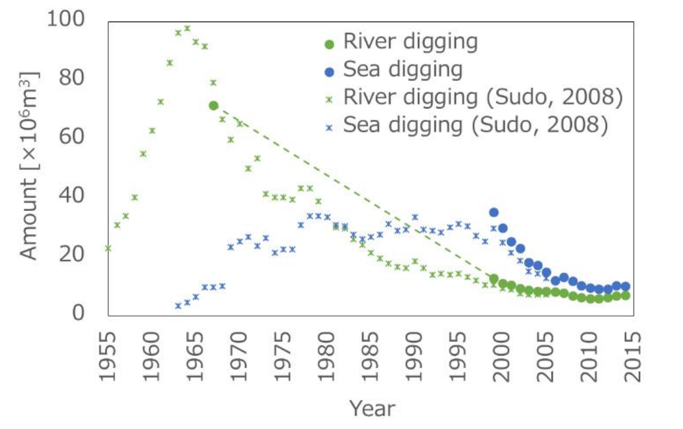

Figure 1. Temporal change of national amounts of river and sea digging

For D_R, we used the amounts at each prefecture of river digging from 1965 to 1969 by Muramoto (1974) and of river and sea digging from 1999 to 2014 by the Manufacturing Industries Bureau, Ministry of Economy, Trade and Industry (METI) and MLIT (2000-2015). The amounts were calculated according to sand (sizes that passes through a 5 mm sieve), gravel (5 mm to 10 cm in size), round stone (10 cm to 30 cm in size), and crushed round stone (Igarashi, 1985). Long-term data of nationwide aggregate demand from 1955 to 2005 by Sudo (2008) was found to be consistent with the permissible values both in the late 1960s of Muramoto (1974) and from 1999 to 2014 of the statistical reports (METI and MLIT, 2000-2015) as shown in Fig. 1 (Udo et al., 2016). Thus, the data by Sudo (2008) was referred as temporal change of the amount of nationwide sediment digging. As shown in the figure, the amount of river digging increased rapidly around the 1950s to the early 1960s because of the post-war constructions of infrastructures; however, it has decreased since 1964 when the Japan's River Act was revised, because of prohibiting or limiting river digging in major rivers (Sudo, 2008). Alternatively, the amounts of land, pit, and sea digging have increased. As of 2015, the amount of river digging is slightly smaller than that of sea digging. Therefore, we interpolated the amount of river digging linearly between in 1967 averaged from 1965 to 1969 (Muramoto, 1974) and in 1999 (METI and MLIT, 2000) (see the broken line in the figure). The value of 1975, which is the average of 1960 (the year when full-scale river digging started) to 1990 (the last year of this analysis), was obtained from the linear interpolation and then multiplied by the years of this period, converting the amount of sediment digging to that of 30 years. The value of each coastal zone was obtained by dividing each value by prefecture, proportionally by area of each coastal zone catchment. This value is referred to as D_R'. Muramoto (1974) noted that the actual amount of river digging D_R around the 1960s was said to be two to three times that of the permissible amount D_R'.

Considering concern that sea digging affects coastal erosion (Isobe, 2000; Ministry of the Environment, 2006), we attempted to obtain D_S in each coastal zone similarly to the case of river-digging. However, the data of each prefecture before 1999 was unavailable; therefore, we used the data of 1999 (METI and MLIT, 2000-2015). According to the data by Sudo (2008) as shown in Fig. 1, the nationwide amount of sea digging increased from 1963, which was around 20 to 30 million m^3 from the 1970s to the 1990s, then the amount has decreased since 2000. Accordingly, we assumed that the amount of sea digging from 1970 to 1990 would be equivalent to that of 1999 at each prefecture, and used the amount of 1999 by adding up 20 years of it as D_S from 1950 to 1990.

2.3 *Sediment supply potential and sediment balance potential*

For analysis of sediment balance in the coastal area, sediment supply potential (P_{SS}) and sediment balance potential (P_{SB}) are defined as indices of sediment supply from rivers to the sea and sediment balance in the coastal areas, respectively. P_{SS} and P_{SB} are obtained by the following equations using the amounts of Y, D_C, D_D, D_R, and D_S.

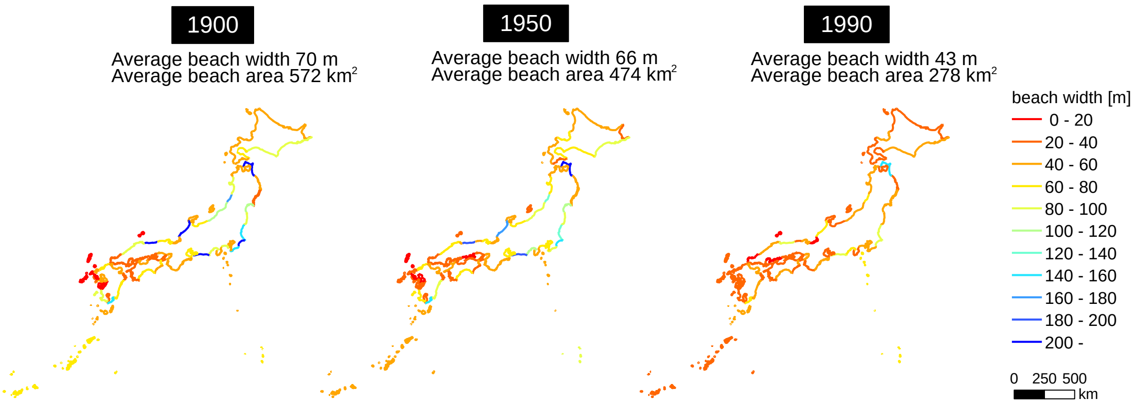

Figure 2. Average beach widths at around 1900, 1950, and 1990 in 77 coastal zones in Japan.

$$P_{SS} = Y - D_C - D_D - D_R. \quad (1)$$

$$P_{SB} = P_{SS} - D_S = Y - D_C - D_D - D_R - D_S. \quad (2)$$

D_C and D_D as well as D_R were subtracted from Y to calculate P_{SS} at each coastal zone catchment, and D_S was further subtracted from P_{SS} to calculate P_{SB}. Negative values in P_{SS} are physically impossible and then we regarded the negative values of P_{SS} as zero.

2.4 *Amount of river channel change and relative sea level change*

The amounts of sediments transported from rivers to beaches are affected by river channel change in addition to Y, D_C, D_D, D_R, and D_S; e.g., the degradation of river bed has a positive effect in terms of the sediment supply potential from rivers to beaches. River channel change data of the 60 first-class rivers throughout Japan by Muramoto (1974) was also referred for the period from 1960 to 1972.

The subsidence of ground in coastal area is a factor of relative sea level rise, which also affects shoreline change. In this study, we investigated the relative sea level changes at the observation points having more than 30 years of data from 1950 to 1989, among the annual average tide level data provided by the Coastal Movements Data Center, Geospatial Information Authority of Japan. Among the data obtained, the average value of the first 5 years from 1950 was deducted from that of the last 5 years until 1989, converting the difference to the change of 40 years.

3. Results and Discussion

3.1. *Beach changes in the past 100 years*

Figure 2 shows the average beach width around 1900, 1950, and 1990 calculated for each coastal zone. The national average around 1900, 1950, and 1990 was 70 m, 66 m, and 43 m respectively, indicating that beaches rapidly eroded from 1950 to 1990. During this period, the area eroded was approximately 200 km^2, which was then multiplied by sediment transport height of 10 m, indicating that V_{SB} for 40 years was –2,000 million m^3 (–50 million m^3/year); in other words, the sediment of 2,000 million m^3 was lost from beaches.

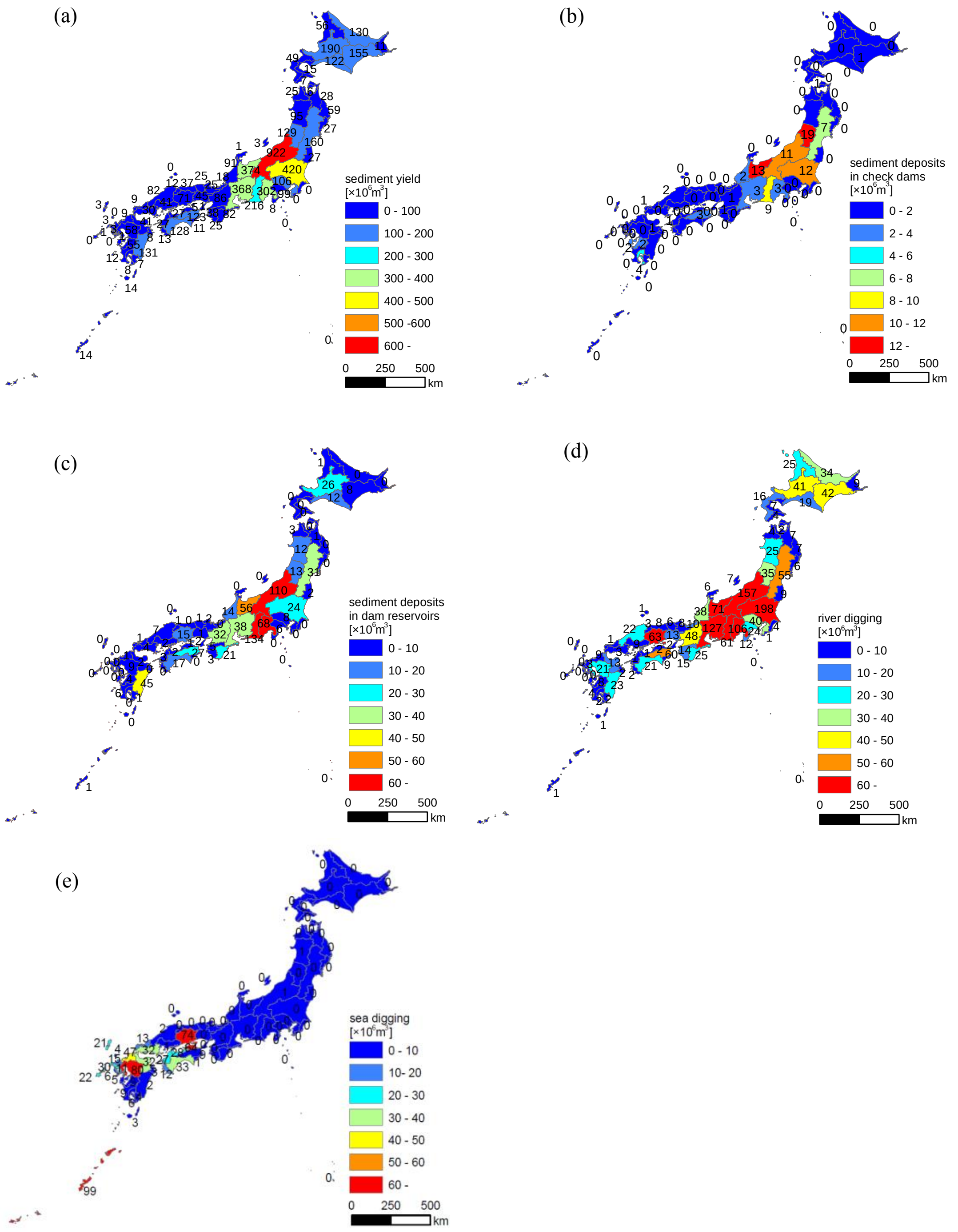

Figure 3. (a) The sediment yield strength (Y), the sediment deposits in (b) check dams (D_C) and (c) dam reservoirs (D_D), (d) river digging (D_R), and (e) sea digging (D_S) in each 77 coastal zone catchment from 1950 to 1990.

Table 1. National sediment amount regarding coastal erosion

Factors	1950-1990 [× 10^6 m^3]	Annual [× 10^6 m^3/year]
Sediment yield (Y)	5,600	140
Check dam (D_C)	98	2.5
Dam reservoir (D_D)	790	20
River digging (D_R)	1,600–4,900	41–120
Sediment supply potential (P_{SS})	**1–3,000**	**0–76**
Sea digging (D_S)	700	18
Sediment balance potential (P_{SB})	**0–3,000**	**0–76**
Beach sediment balance (V_{SB})	**2,000**	**50**

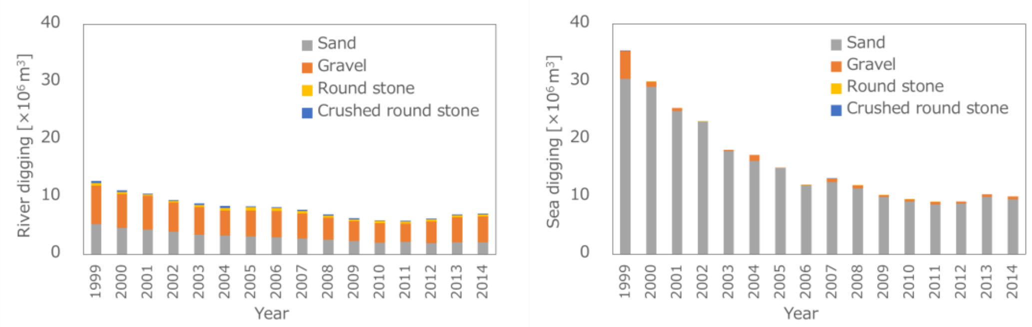

Figure 4. Temporal change of national amounts of river and sea digging according to the types of aggregate.

3.2. *Amounts of sediment yield, sediment deposits in check dams and dam reservoirs, and river digging in each coastal zone catchment*

Figure 3 and Table 1 show the amounts of Y, D_C, D_D, D_R, and D_S in each 77 coastal zone catchment from 1950 to 1990. Y is especially significant in the coastal zone "Northern Niigata" mainly covering Niigata Prefecture where the amount is 922 million m^3 (23.0 million m^3/year; Fig. 3a); on the other hand, it is less than 5 million m^3 (0.1 million m^3/year) in many isolated islands. Its total national value for 40 years is approximately 5,600 million m^3 (140 million m^3/year). D_C is also significant in the northern Niigata where the amount is 19 million m^3 (0.5 million m^3/year; Fig. 3b). Its total national value is approximately 98 million m^3 (2.5 million m^3/year). These amounts are strongly affected by topography (slope) and geology.

The amount of D_D is also significant in the northern Niigata where it is 110 million m^3 (2.8 million m^3/year; Fig. 3c). D_D tends to be larger with Y because the equation used to calculate Y was calibrated using D_D (Okano et al., 2004). It is noted that D_D also depends on dam construction plan for the water management. Its total national amount is approximately 790 million m^3 (20 million m^3/year).

Figure 3d shows D_R in each coastal zone catchment from 1950 to 1990. D_R is significant in the zone "Ibaraki" and 198 million m^3. The value is greater than that of "Northern Niigata" because the Ibaraki zone is closest to the Tokyo metropolitan area. The national value is approximately 1,600 million m^3. Considering the possibility that the actual amount of D_R in the 1960s was a few times greater than the permissible amount (Muramoto, 1974; see also Fig. 1), this must have been a significant impact on the decrease of sediment supply from rivers to the sea. Regarding D_S, it was greater in the catchments of the western Japan where the sediment resources in the land were limited. Its national value is approximately 700 million m^3 and less than half of D_R. Figure 4 shows temporal changes of national amounts of D_R and D_S according to the types of aggregate from 1999 to 2014. The amounts of gravel and sand of D_R are almost equivalent, whereas the amount of sand of D_S is considerably greater than that of gravel.

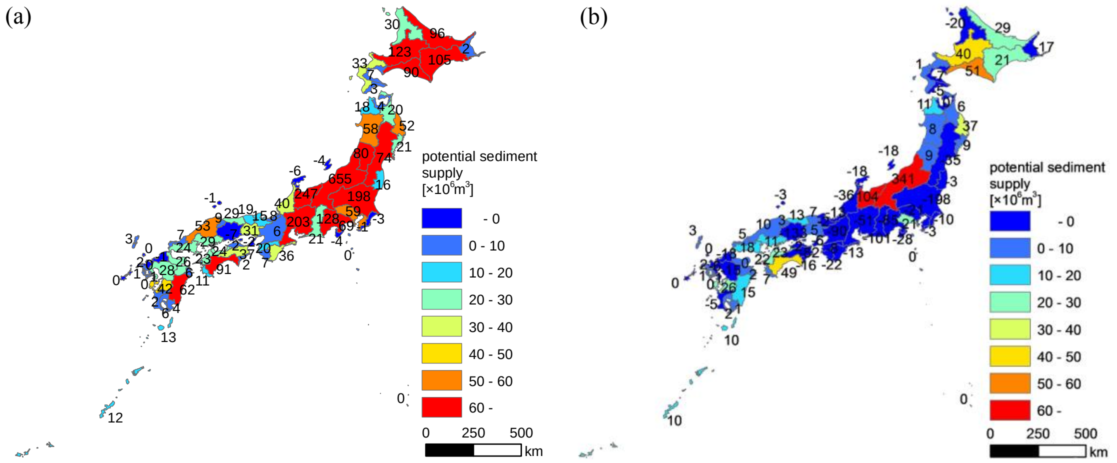

Figure 5. Sediment supply potential from rivers to the sea (P_{SS}) at each 77 coastal zone catchment from 1950 to 1990 for cases (a) D_R was given by D_R' and (b) D_R was given by $3D_R$'.

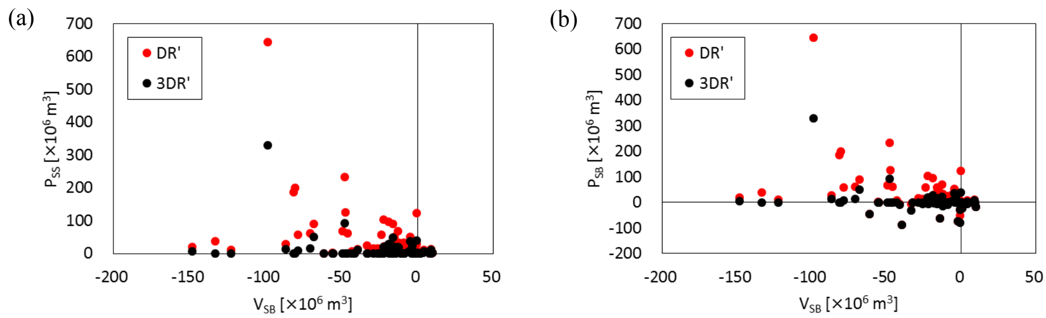

Figure 6. Relationships between sediment balance in the coastal area (V_{SB}) and (a) the sediment supply potential (P_{SS}) as well as (b) the sediment balance potential (P_{SB}) from 1950 to 1990 for cases D_R was given by D_R' and $3D_R$'.

3.3. *Relationships between sediment supply potential from rivers to the sea as well as sediment balance potential and sediment balance in the coastal area*

Figure 5 and Table 1 indicate P_{SS} of each coastal zone catchment from 1950 to 1990 for cases that D_R was given by D_R' and $3D_R$'. The negative values of P_{SS} were shown here without regarded as zero to express the effect of D_R on P_{SS}. For the case of $D_R = D_R$', P_{SS} was negative for several catchments, whereas it was positive for most catchments. On the other hand, for the case of $D_R = 3D_R$', P_{SS} was negative for most catchments. For the former case, the amount of nationwide P_{SS} (negative P_{SS} of each catchment was summed up with regarded as zero as mentioned in section 2.2) was calculated to be 3,000 million m^3, suggesting that more than half of Y became P_{SS}. However, for the latter case considering that the actual amount of river digging in the 1960s is possibly three times greater than D_R' (Muramoto, 1974), P_{SS} would be calculated as approximately 1 million m^3, suggesting that most of Y was possibly lost mainly by river digging.

Figure 6 shows the relationships between sediment balance in the coastal area (V_{SB}) and the sediment supply potential (P_{SS}) as well as the sediment balance potential (P_{SB}) from 1950 to 1990 for cases D_R was given by D_R' and $3D_R$'. Regarding P_{SS}, the figure does not show a clear relationship with V_{SB}; however, large negative V_{SB} tend to appear for large P_{SS}. A similar tendency is found for the relationship between V_{SB} and P_{SB}, indicating that the effect of the river digging was much larger than the sea digging in Japan.

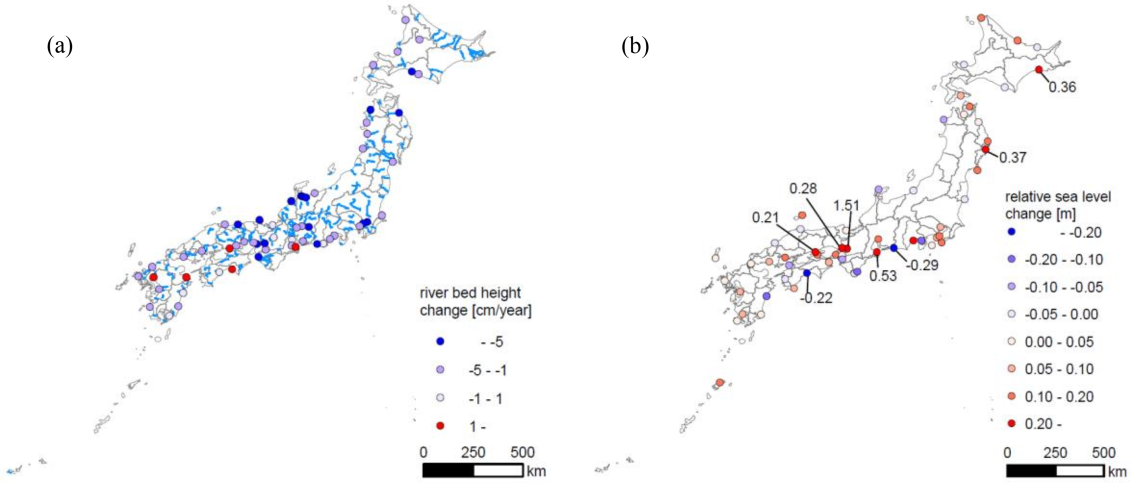

Figure 7. (a) Average speed of river bed height changes in the 1960s (Muramoto, 1974) and (b) relative sea level changes from 1950 to 1990.

3.4. *Other factors which affect sediment balance in the coastal area*

As mentioned above, the sediment balance in the coastal area cannot be explained clearly from Y, D_C, D_D, D_R, and D_S and their resultants P_{SS} and P_{SB}. The data used in this study contains some errors and some elements need further consideration, and there are additional factors to be taken into account. The value of average sediment transport height used for calculation of V_{SB} should be also reconsidered.

In addition to these factors, Muramoto (1974) stated that the degradation of river bed was occurred in many downstream sectors of, at least, 60 first-class rivers throughout Japan in the 1960s (see Fig. 7a). In view of sediment supply balance from rivers to the sea, this has a positive effect. Factors having negative effects on the sediment balance in the coastal zone catchments would be the sediment loss from coastal areas to offshore and inland.

Another important factor is the relative sea level change. Figure 7b shows the changes obtained from the records of 58 tide observation stations. Only values greater than 0.4 m are indicated here. The nationwide distribution of the changes is roughly consist with a nationwide distribution of the vertical crustal movement from 1951 to August 1982 by Kato and Tsumura (1983), in terms of the characteristics of subsidence (positive in sea level change) in the Pacific coast of Tohoku region and the coast of the Seto Inland Sea, and of uplift (negative in sea level change) in the other areas, though the relative sea level change is also affected by the sea level change. Note that the ground subsidence of 1.5 m found at Osaka in the figure is mainly due to ground water extraction (Ministry of the Environment, 2015). Udo and Takeda (2014) predicted that the rate of beach loss would be approximately 20% if a 10 cm sea level rise occurs evenly nationwide. Reversely, beach expansion would be possible in areas where the uplift occurs. Relative sea level changes with only a few tens of centimeters would cause serious impact on the coasts.

This study analyzed available sediment data from mountains to the coasts and the sediment balance in the coastal zone catchment could not be explained clearly because of data availability and quality. However, even from these data, it is quantitatively demonstrated that substantial amounts of the yielded sediment had been lost due to deposition in the dam reservoirs and especially river digging, indicating that this is one of the major factors causing coastal erosion.

4. Conclusion

This study conducts a GIS-based analysis on the amount of sediment deposits in check dams in addition to those of sediment yield, sediment deposits in dam reservoirs, sediment digging in rivers and the sea, as well as river-bed elevation change and relative sea level rise, with the changes of beach widths at the costal zones from around 1950 to 1990 in Japan to evaluate the effect of the sediment balance in catchments from mountains, rivers, to the sea, on beach erosion.

Regarding the sediment amount in rivers, the approximate total national amount of the sediment yield is 5,600 million m^3, sediment deposits 790 million m^3, and river digging 1,600 million m^3, respectively, and in the sea, the sediment digging is 700 million m^3. On the other hand, the approximate total amount of sand loss in the coasts is 2,000 million m^3. Even with data availability and quality taken into account, the results demonstrated that among sediments yielded, considerable amount was lost by the river digging. Furthermore, both the sediment supply potential and the sediment balance potential from the available data was estimated, thereby investigating the sediment balance in the coastal zone catchments. We could not find a clear relationship between the sediment loss in the coastal area and both the potentials, though there was a tendency that the large negative values of the sediment loss in the coastal area appear for the large sediment potentials.

All these data used in this study could not fully explain the sediment balance in the catchments; however, they revealed that the river digging was one of the major factors which affected the beach erosion in the period. Further investigation would be necessary on matters not fully discussed in this study, including such effects as erosion control facilities disturbing sediment transport, river bed height change, crustal movement, and offshore and inland sediment losses in coastal areas.

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