河口域における浮泥輸送の潮時による非対称性と河口堰の影響

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著者	杉本, 隆成 伊藤, 喜代志 佐藤, 英夫
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Tidal Asymmetry of the Sediment Transport in Estuaries and its Amplification by the Weir

Takashige Sugimoto,*[1] Kiyoshi Itoh,*[1] and Hideo Sato*[2]

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Vertical profiles of the velocity, turbidity and salinity were observed over one tidal cycle in the Hattae estuary in the inner part of Ariake Bay which contains wide tidal flat. The vertical profiles are more uniform in the flood stage than those in the ebb stage. This tidal asymmetry causes net upstream transport of the suspended sediment.

Closing the gate of the weir weakens the ebb currents but not the early flood current, thus will intensify the tidal asymmetry further.

In the Rokkaku-river estuaries in the inner part of Ariake Bay, it is planned to close the gate of the weir near the river mouth to store the fresh water for irrigation during summer. However, once the gates of the weir are closed, tidal currents in the downstream of the weir may become weak, which might accelerate sedimentation rate.

If the sedimentation rate of the suspended sediment is too large, some kinds of algae on the bottom surface and larvae of bivalves such as clams might be buried under the sediment. To evaluate the effect of such environmental changes and damages on the fisheries around the river mouth, it is necessary to make clear the spatial structures and their temporal variations of the tidal currents as well as the processes of the sediment transport and sedimentation.

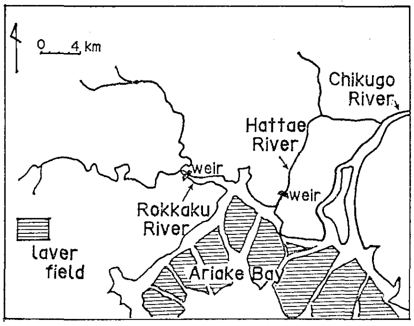

Fig. 1(a). The rivers of Rokkaku, Hattae and Chikugo which flow into the inner part of Ariake Bay. Closed trapezoids and shadowed portions indicate the weirs and the laver fields, respectively.

Shirota and Tanaka[1] described the vertical and longitudinal variations of the suspended sediment as well as their tidal variations in the Chikugo-river estuary in the inner part of Ariake bay. Tanaka and Hamada[2] discussed on the transport of nutrients absorbed in or released from the suspended sediments. Shiroishi and Ohnishi[3] investigated the effect of the deposition and the resuspension of the suspended sediments on the

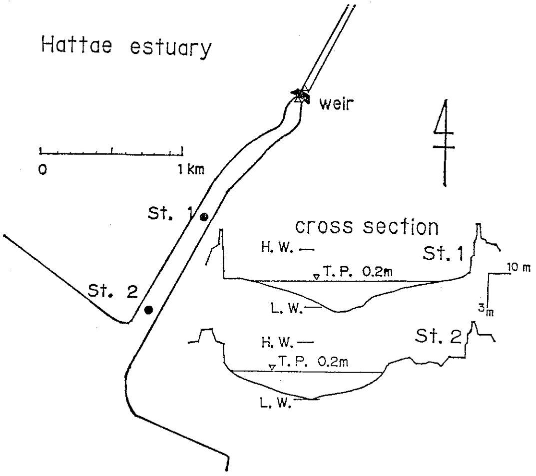

Fig. 1(b). A schematic view of the Hattae estuary. Closed circles indicate observation stations and open triangles tidal stations at upstream and downstream of the weir, respectively. High and low waters in the spring tide as well as mean-sea level (T. P. 0.2 m here) are shown in the cross sections of the channel looking downstream.

[*1] Ocean Research Institute, University of Tokyo, 1–15–1, Minamidai, Nakano, Tokyo 164, Japan (杉本隆成，伊藤喜代志：東京大学海洋研究所).

[*2] Co. Phi-Lambda, 402 Saikachizaka Buld., 2–11–16 Surugadai, Kanda, Chiyoda, Tokyo 100, Japan (佐藤英夫：株式会社ファイラムダ).

vertical distribution and its temporal variations based on the numerical model experiments.

It is well known that turbidity maximum in the longitudinal distribution is formed in the upstream regions of the salt-water intrusion into the river. This is due to the upstream transport of the suspended sediment, which is mainly caused by the gravitational circulations in partially mixed estuaries.[4-6] However asymmetry of the tidal current, which may also affect the formation of the turbidity maximum, is not well understood yet.

Hence vertical and temporal variations of the sediment transport were observed in the Hattae estuary during 30 and 31 July, 1985. To investigate the effect of the weir on the tidal-current asymmetry, the gate of the weir was closed on the 31st. Variations of the value of the current, turbidity and sediment transport between both days were compared in order to evaluate the effect of the weir on these variations.

Observation site and methods

Vertical profiles of the current velocity, turbidity, salinity, temperature and the bottom materials were observed in the Hattae estuary in the inner part of Ariake Bay (Fig. 1 (a)) on 30–31 July, 1985, over one tidal cycle. Fig. 1 (b) shows the site and the observation stations. At 2 km upstream of the Hattae estuary, there is a weir to prevent the intrusion of the salt water. The river width in the downstream of the weir is about 110 m and the water depth changed from about 0–0.5 m at low water to 4.5–5 m at high water in the midst of the channel. The weir has two gates, which are closed usually during high water. During the high water of 4–10 o'clock and 16–23 o'clock on the 30th, one of the gates was closed and the other was opened only 10 cm hight from the bottom. On the 31st, both gates were com-

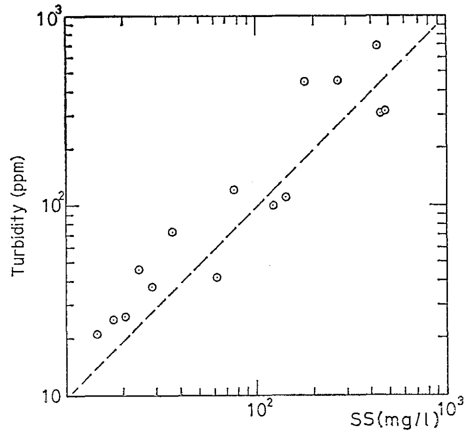

Fig. 2. Relations between observed turbidity and suspended sediment concentration.

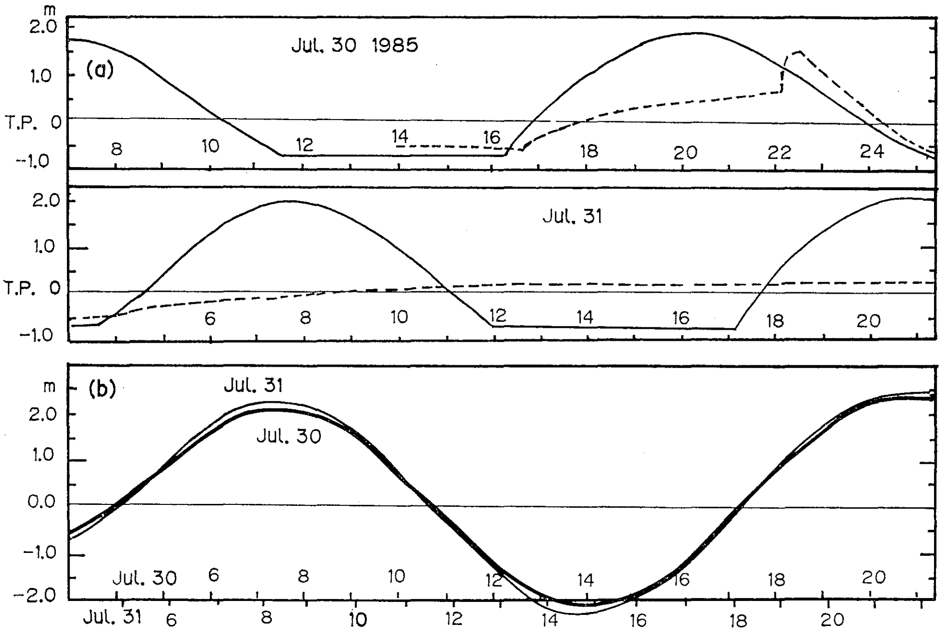

Fig. 3. Temporal variations of the sea level at upstream (dashed line) and downstream (solid line) of the weir (a), and at Marine tower station of Saga University (b).

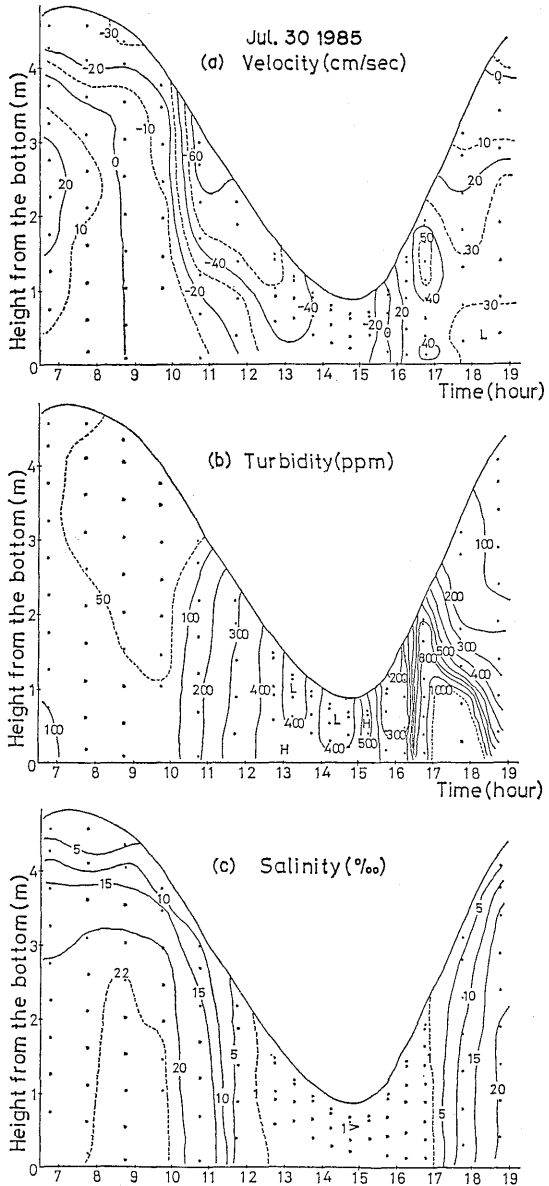

Fig. 4. Tidal variations of the vertical profiles of the current velocity (a), turbidity (b) and salinity (c) at St. 1 on 30th July.

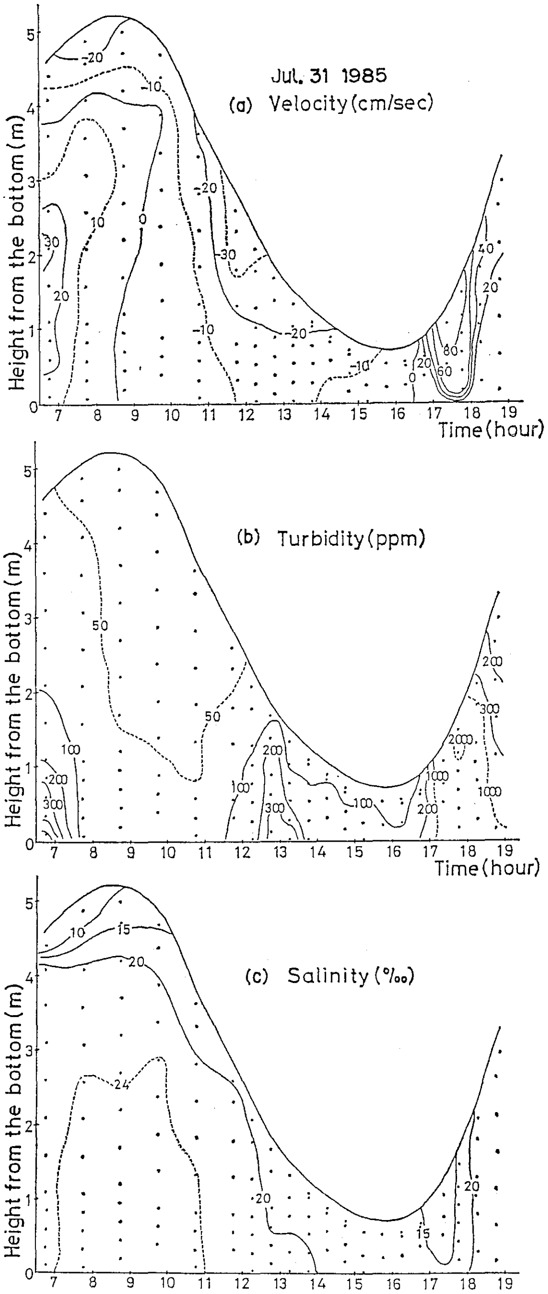

Fig. 5. The same with Fig. 4 except on 31st July.

pletely closed from 3 o'clock till midnight.

The velocity, turbidity, salinity and temperature were measured by every 50 cm and every one hour around high water and by every 25 cm and every half an hour around low water. Propeller typed current meter CM-2S of Toho-Dentan Co., turbidity meter MA-921W made of Hokuto-Riken Co. which measures the intensity of back-scattering light and a potable salinometer of Electronic Switchgear LTD. were used for the measurement. Water samples were obtained every 2 hours with 1 *l* sampler for suspended sediment. Fig. 2 showed fairly good correlation between the turbidity and SS weight.

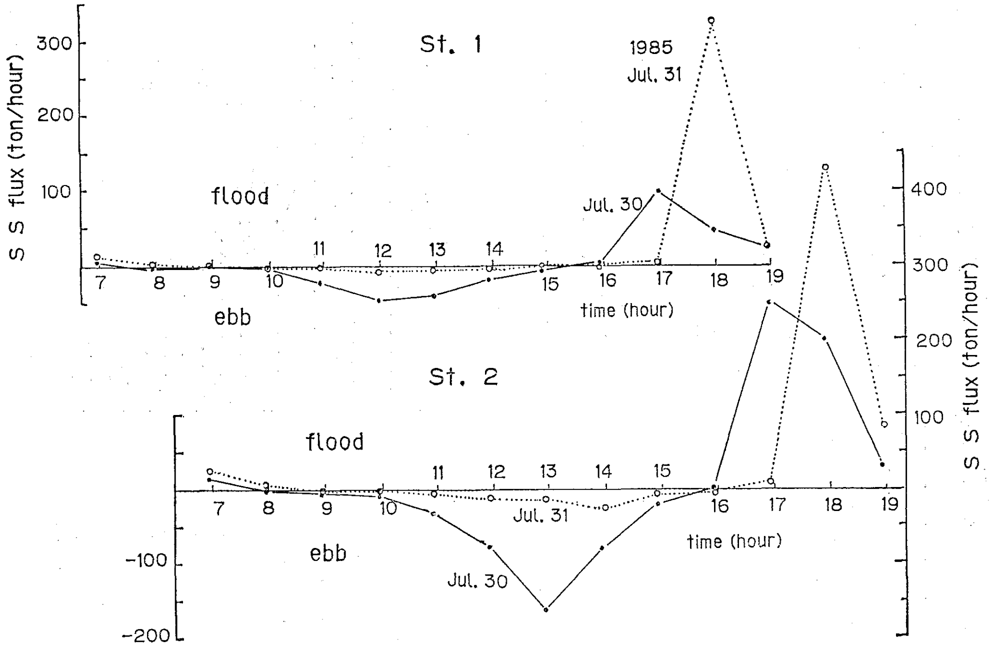

Fig. 6. Temporal variations of the transport of the suspended sediment at St. 1 and St. 2. Solid and dashed lines indicate the values on 30 and 31 July, respectively.

Results of the observation

Fig. 3 shows sea-level records just upstream and downstream of the weir and at the Marine tower station of Saga University which stands about 5 km offshore from the mouth of the Hattae river. Water level at upstream of the weir, shown by a broken line, rose up gradually by 0.75 m during one tidal cycle (3–15 o'clock) on 31 July due to the complete closing of the gate. This rising rate of the water level corresponds to the river discharge rate of 5.3 m^3 s^{-1}, using the tidal area in the upstream of the weir of 30×10^4 km^2 which was estimated from the tidal records and tidal current observations. Temporal variations of the vertical profiles of the current velocity, turbidity and salinity on 30 and 31 July at St. 1 are shown in Fig. 4 (a)–(c) and Fig. 5 (a)–(c), respectively.

In Fig. 4 (a), the minus sign indicates downstream velocity. The slack stage appears about one hour later than the high and low water. The maximum velocity of the ebb current becomes up to 60 cm s^{-1}, although it is limited in the surface layer. Vertical profiles of the current in the flood stage are more uniform and the bottom currents are almost the same with those in the ebb stage, as are seen in partially mixed estuaries.

Difference of turbidity between the flood stage and the ebb stage is more conspicuous than the current speed. In the tidal change of the turbidity, the maximum values appear about one hour later than the time of the maximum velocity in the ebb and about half an hour later in the flood.

Fig. 4 (c) shows that the fresh water (less than 1 % of salinity) covers the observation area.

Comparing Fig. 5 (a) with Fig. 4 (a), the maximum current velocity in the ebb decreased to 30 cm s^{-1}, although the tidal range on 31st (spring tide) was larger than that on the 30th by about 0.6 m (about 10% of the tidal range). However, the current velocity in the early flood stage on the 31st increased to 80 cm s^{-1} that was about 160% of that on the 30th. It might be caused by the increase of the rising rate of the water level and by the cease of flushing of the river water.

Fig. 4 (b) and Fig. 5 (b) show that the value of the turbidity decreased to less than 50 ppm in the early ebb, but it increased rapidly when the bottom currents exceeded 25 cm s^{-1} and increased to greater than 200 ppm during the later ebb on the 30th and 31st. However variations of the turbidity in the flood between the 30th and the 31st was conspicuous. It was about 1000 ppm on the 30th but increased to 1000–2000 ppm on the 31st.

Temporal variations of the current velocity,

Table 1. Transport of mass Q_m, salinity Q_s and suspended sediment Q_{ss} during the flood, ebb and one tidal cycle at St. 1 and St. 2 on 30th and 31st July, 1985

	Date	30 July			31 July		
	Flux	Flood	Ebb	Total	Flood	Ebb	Total
Stn. 1	$Q_m \times 10^{-4}$ m^3	32	− 68	−36	35	− 37	− 2
	$Q_s \times 10^{-2}$ ton	45	− 52	− 7	68	− 60	8
	$Q_{ss} \times 10^{-2}$ ton	1.2	−1.1	0.1	2.4	−0.2	2.2
		(1.2)	(−0.9)	(0.3)	(3.5)	(−0.2)	(3.3)
Stn. 2	$Q_m \times 10^{-4}$ m^3	81	−118	−37	58	− 67	− 9
	$Q_s \times 10^{-2}$ ton	118	−126	− 8	122	−126	− 4
	$Q_{ss} \times 10^{-2}$ ton	4.3	−2.8	1.5	4.3	−0.9	3.4
		(4.3)	(−2.3)	(2.0)	(6.3)	(−1.0)	(5.3)
Stn. 1– Stn. 2	$\Delta Q_m \times 10^{-4}$ m^3	49	− 50	− 1	23	− 30	− 7
	$\Delta Q_s \times 10^{-2}$ ton	73	− 74	− 1	54	− 66	−12
	$\Delta Q_{ss} \times 10^{-2}$ ton	3.1	−1.7	1.4	1.9	−0.7	1.2
		(3.1)	(−1.4)	(1.7)	(2.8)	(−0.8)	(2.0)

turbidity and salinity at St. 2 showed similar manner of behaviour to those at St. 1, although their values were larger.

Discussion

Tidal Asymmetry of the Concentration and the Transport of the Suspended Sediment

In Fig. 4 and Fig. 5, maximum turbidity appears about one hour and half an hour later than the time of maximum velocity in the ebb and the flood, respectively. Because the turbidity is almost uniform vertically at each moment, this delay of turbidity maximum should be analized taking the effect of the deceleration rate on the turbulence and resuspention rate into consideration. Values of deceleration rate in the midst of the flood is larger than those in the later ebb, which also corresponds to the larger turbidity in the flood.

Fig. 6 shows temporal variations of the transport of suspended sediment on 30th and 31st July at St. 1 and St. 2, where transports of suspended sediment Q_{ss} were calculated by integrating the multiples of the concentration $c(z)$, the velocity $u(z)$ and the river width $b(z)$ at each hight vertically from the bottom ($z=0$) to the sea surface ($z=h$).

$$Q_{ss}=\int_0^h c(z)u(z)b(z)dz$$

Table 1 shows the transports of mass Q_m, salinity Q_s and suspended sediment Q_{ss} integrated during the flood, ebb and over one tidal cycle at St. 1 and St. 2 on the 30th and the 31st.

As the current was observed near the center of the lateral section, values of the volume transport might be overestimated. Hence these values were corrected, using the tidal records of the sea levels in the upstream and downstream of the weir. The volume of the tidal prisms between the weir and St. 1 and between the weir and St. 2 are estimated to be 37×10^4 m^3 and 67×10^4 m^3, if we use the tidal area between the weir and St. 1 ($A_1=11\times10^4$ m^2), the one between St. 1 and St. 2 ($A_2=8.8\times10^4$ m^2) and the tidal range in the downstream of the weir on 31 July (=3.4 m). Corresponding volumes obtained from the current observation at St. 1 and St. 2 are 58×10^4 m^3 and 85×10^4 m^3, meaning that the correction coefficient of the volume transport is 64% at St. 1 and 79% at St. 2. Values in the parentheses in Table 1 are corrected ones using above-mentioned correction coefficients for the volume transport.

As shown in Table 1, the mass transport reduced to 50–60% of that on the 30th, because the gate of the weir was completely closed and the current speed decreased. The net mass transport (difference of the mass transport between the flood and the ebb stages) on the 30th were 0.8 and 2.4 m^3 s^{-1} on the 31st, which must be equal to the river discharge on each day. Difference of the net mass transport between St. 1 and St. 2 is small enough. Salinity fluxes in the ebb and the flood stages at St. 1 and St. 2 are almost balanced.

The transport of suspended sediment in the flood is more than 2 times larger than that in the ebb, causing the tidal asymmetry.

Effect Vertical Shear on the Sediment Transport

Fig. 7 shows temporal variations of the transport of the suspended sediment per unit width (1 m)

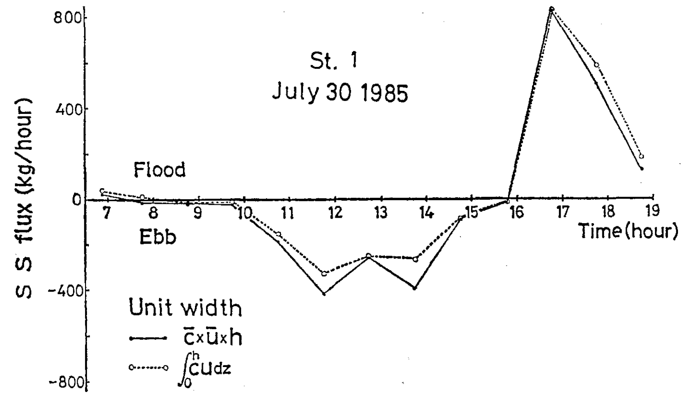

Fig. 7. Temporal variations of vertically integrated transport of suspended sediment and $\bar{c}\bar{u}h$.

and those computed from a formula $\bar{u}\bar{c}$, where $\bar{u}$ and $\bar{c}$ mean the vertically averaged velocity and turbidity, respectively. Their difference $\left(\int_0^h ucdz-\bar{u}\bar{c}\right)$ means the vertical shear effect (V. S. E. here after) on the sediment transport.

Effect of the vertical shear of the current on the sediment transport V. S. E. is nearly zero or small positive in the flood stage. In the ebb stage, however, it becomes about 10% of the vertically integrated sediment-transport $\left(\int_0^h ucdz\right)$ towards upstream. Hence, if it is intergrated over one tidal cycle, the net value of the V. S. E. becomes positive and as much as 30 to 40% of the net upstream transport of the suspended sediment.

In this observation the current and other parameters were measured at only one station for each cross sections, hence analysis of the lateral shear effect is beyond the scope of this paper.

Effects of the Weir on the Tidal Current and the Net Transport of the Suspended Sediment

As shown in Fig. 3 (b) the tidal range on the 31st increased by about 10% of that on the 30th. However, Table 1 show that the values of the volume transport in the flood and the ebb on the 31st were reduced by about $-10\sim30\%$ (St. 1) and 55% (St. 2) on the 30th due to closing of the gate.

Fig. 6 shows clearly the difference of the transport of suspended sediment between the 30th and the 31st. Solid and dotted lines indicate the tidal variations of the SS fluxes on the 30th and the 31st, respectively. The figure shows that transport of the suspended sediment in the flood on the 31st were greater than those on the 30th because of the increase of the tidal range on the 31st. However, its transports in the flood on the 31st decreased to 1/3 at St. 1 and 1/6 at St. 2 of those on the 30th. Hence the volume of the net upstream transport of the suspended sediment at St. 1 and St. 2 on the 31st become more than that on the previous day, as shown in Table 1. Numerals in the parentheses at the bottom of the table show that the differences between the sediment transport at St. 2 and St. 1 are 1.4×10^2 ton on 30th and 1.3×10^2 ton on 31st. This means that the volume of the deposited sediment in one tidal cycle did not decrease between St. 1 and St. 2 but increased between the weir and St. 1 by closing the gate.

To prevent this kind of increase of sedimentation due to the weir, it is necessary to investigate a suitable handling of the gate to make the downstream sediment transport increase and the upstream transport decrease during spring tide.

Acknowledgement

This study was done partially in the consulting work in the specialists' committee to assess the effect of the weir in the mouth of Rokkaku river on the fisheries. The authors would like to express sincere thanks to Dr. Toshizo Suto of former professor of Tohoku University and the staff in the Planning and Development Section of Saga Prefectural Office who organized and helped the observation as well as permitted us using the data. Thanks are extended to Prof. Kiyoshi Watanabe in the Department of Agriculture of Saga University for his valuable comments and help.

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