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FIELD STUDY ON UNSTEADY SALINITY INTRUSION INTO A SMALL ESTUARY

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SYNOPSIS

Salinity, velocity, and SS were measured at fixed points in the downstream part of Nanakita River Estuary (Miyagi Prefecture). Hourly variation of vertical distribution of salinity and velocity at the river mouth were also observed. There were three types of hourly variation of salinity distributions in the intruding salt water. A submerged weir, a depression, and a hump of the river bottom had observable effects on the behavior of the intrusion. In this estuary, distributions were stratified, partially mixed, or well mixed according to river discharges, or to tidal ranges at the river mouth. At the river mouth, two differrent types of variation were observed for salinity during flood tide. In one case salinity is always stratified during flood tide and in the other case uniform distributions were observed as the surface rose during flood tide. Vertical distributions of velocity at the river mouth were logarithmic except at the beginning of ebb tide and flood tide.

INTRODUCTION

Many researchers (1, 2, 3, and 8) have made field observations on the movement of salt water intruding into an estuary, in order to investigate problems of water quality in water utilization, sedimentation caused by the existence of salt water, and so on. However, there have not been many investigations of unsteady movements, particularly on the behavior of salinity intrusion.

Recently a two-dimensional numerical model of estuary circulation and of the unsteady movements of salt intrusion were presented (4 and 6). However, one of the problems for the application of these numerical models to the field is how we should set appropriate boundary conditions for the river mouth. Thus, actual field observations are most important. This paper summarizes the field observation carried out in the downstream part of Nanakita River Estuary (Miyagi Prefecture, Fig. 1).

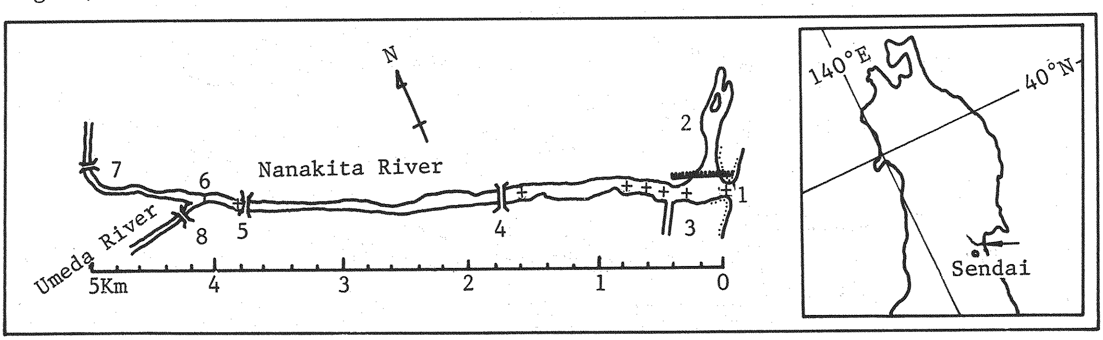

Fig. 1 Nanakita River Estuary, showing main positions of station (+). Mouth - 1, Gamō Lagoon - 2, Teizan Bori Canal - 3, Takasago Bridge - 4, Takasago Ōhashi Bridge - 5, Weir - 6, Fukuda Ōhashi Bridge - 7, Umeda Bridge - 8.

Some studies have been carried out on the intrusion of salt water into Nanakita River Estuary (7), and the effect of boundaries on steady salinity intrusion and that of river discharge on flushing and recovering of salt wedge (5 and 9).

In this study, the unsteady movements of intruding salt water will be examined from the data of field observations, and some typical cases of salinity and velocity at the river mouth will be presented.

SUMMARY OF THE FIELD OBSERVATION

Gamō Lagoon, famous for migratory birds such as snipes and plovers, which is located on the left bank 200m upstream from the mouth of Nanakita River Estuary, exchanges its seawater with the Nanakita River through two Hume pipes in a training jetty of the estuary. In addition, Teizan Bori Canal joins the right bank 500m upstream, and its lock gate is closed during flood tide and discharges the water of Teizan Bori Canal during ebb tide. There is a submerged weir made of steel plates 4150m upstream where the intrusion of salt water is stopped, and slight difference of water surface occurs between upstream and downstream regions at this submerged weir during low water. The Umeda River joins just an upstream reach of the submerged weir. River discharge was observed at Fukuda Ōhashi Bridge and Umeda Bridge during low water. The low water discharge is 2-3m^3/sec. The observation control section was chosen between the river mouth and the submerged weir within the tidal portion (Fig. 1).

Although this section is almost straight, water depth and river width vary as in Table 1.

Table 1 Water depth and river width of Nanakita River Estuary.

At T.P.+0.0m

Section	Width	Depth (center)	Depth (max)	Section	Width	Depth (center)	Depth (max)
0m	34.3m	1.12m	1.40m	500m	73.8m	4.18m	5.28m
50	51.0	1.00	1.74	600	111.0	3.08	3.20
100	102.3	1.50	2.42	1000	152.3	1.39	1.76
150	136.5	1.60	2.55	1600	125.0	1.00	1.13
200	183.5	0.25	3.08	2000	51.5	1.56	2.97
250	145.0	0.68	2.38	2600	56.4	1.87	2.76
300	74.2	1.42	2.55	3000	55.1	1.31	1.45
410	75.3	2.63	2.89	3850	35.7	2.03	2.07

The average water depth is about two or three meters, but in some parts of the river depth is larger than the average because of the traces of gravel picking. Fig. 2 shows contours between the river mouth and the section 700m upstream. The deeper sections of the river bed are along the right bank, and the

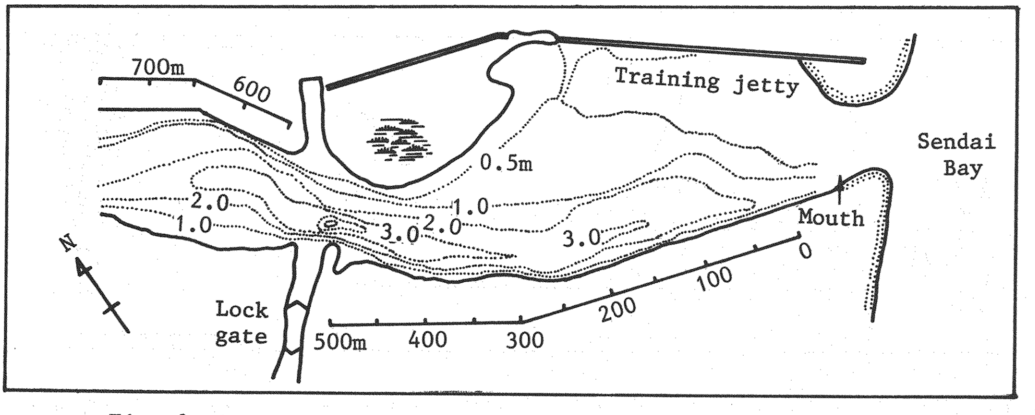

Fig. 2 Contours near the river mouth. T.P.+0.5m, 12/80-2/81.

deepest place of 5m a depression appears at the section of 500m from the mouth of the river.

The flow conditions observed are listed in Table 2. Observation stations

Table 2 List of flow conditions.

Observation number	Date	Tidal range at the river mouth	River discharge	Maximum salinity at the river mouth
1	9/1-9/2/82	0.75m (S.T.)	6.9m³/sec	30.4 ‰
2	9/18/82	1.09 (S.T.)	9.2	27.5
3	9/18/80	0.40 (N.T.)	2.3	28.7
4	9/9/79	—— (S.T.)	2.9	30.0
5	10/11/80	0.61	——	31.8
6	8/4/74	0.80 (S.T.)	8.0	26.0

S.T.: Spring tide, N.T.: Neap tide.

set up at intervals of 100-200m are indicated by the distance from the river mouth shown by crosses in Fig. 1. The observed items are river stage, salinity, velocity, and SS.

Cross sectional measurements were carried out with appropriate intervals from a boat moving along a rope stretched across the river. Traveling observations were also made on an outboard motorboat. For the measurement of flow velocities, propeller current meters of CM2-TYPE, CM1S-TYPE, CM10S-TYPE (produced by Tōho-Dentan), V303-TYPE (by Keisoku- Giken), and UC-3-TYPE (by Tamaya) were used. For the measurement of salinity, Portable S-T meter (by Auto Lab. Model 602), Salino-meter (by EIL, MC5/2), and salinity meter (by Tōho-Dentan, ECT-6) were used, and samples which were gathered with high funnels were analyzed with a conductivity meter (by Keisoku-Giken). Accuracy of these current meters and salinity meters was checked before and after measurements.

RESULTS OF OBSERVATIONS

It was found by the analysis of observed data that the unsteady movements of salt water in Nanakita River Estuary could be classified into the following three types due to the tidal range and the river discharge.

The first type is one with moderate river discharge, when the tip of the salt wedge reaches the upstream section where the submerged weir blocks its upstream movement and the new salt water mass is pushed into it by the following flood. The second case is with rather large river discharge and with spring tide, when salt water is excluded from the estuary during ebb tide, while the salt wedge gets half way between the river mouth and the submerged weir during flood tide. Finally the third case is with small river discharge, when the tip of the salt wedge reaches the submerged weir section and the new salt water mass is pushed into it by the following high tide during neap tide.

The first case is shown in observation number 1 in Table 2, during spring tide. Tidal range at the river mouth was 0.75m. River dischage was 6.9m³/sec which was larger than low water discharge, or 2-3m³/sec. Observations were carried out every two or three hours for 34 hours from 11:00 on Sept. 1st, 1982, at three stations (at the river mouth, 1600m and 3850m). When high waves made it danger-ous to observe, the observation section was shifted upstream from river mouth.

Figs. 3(a), 3(b), and 3(c) represent hourly variation of the heights of salin-ity lines from the bottom at 600m, 1600m, and 3850m, respectively. At 600m, contour lines of salinity showed almost the same variation as water surface curve (Fig. 3(a)). On Sept. 2nd, the line of 30‰ of salinity appeared about 16:00 for the first time in the observation period. Fig. 4 represents the hourly variation of the salinity at the surface in fixed stations. Salinity at the surface of 600m rose during flood tide. This is attributed to the diffusion caused by the intrusion of salt water (1). At 1600m, the 30‰ line did not appear, and the maximum salinity fell to 28‰ (Fig. 3(b)). During the flood tide from 10:00 on

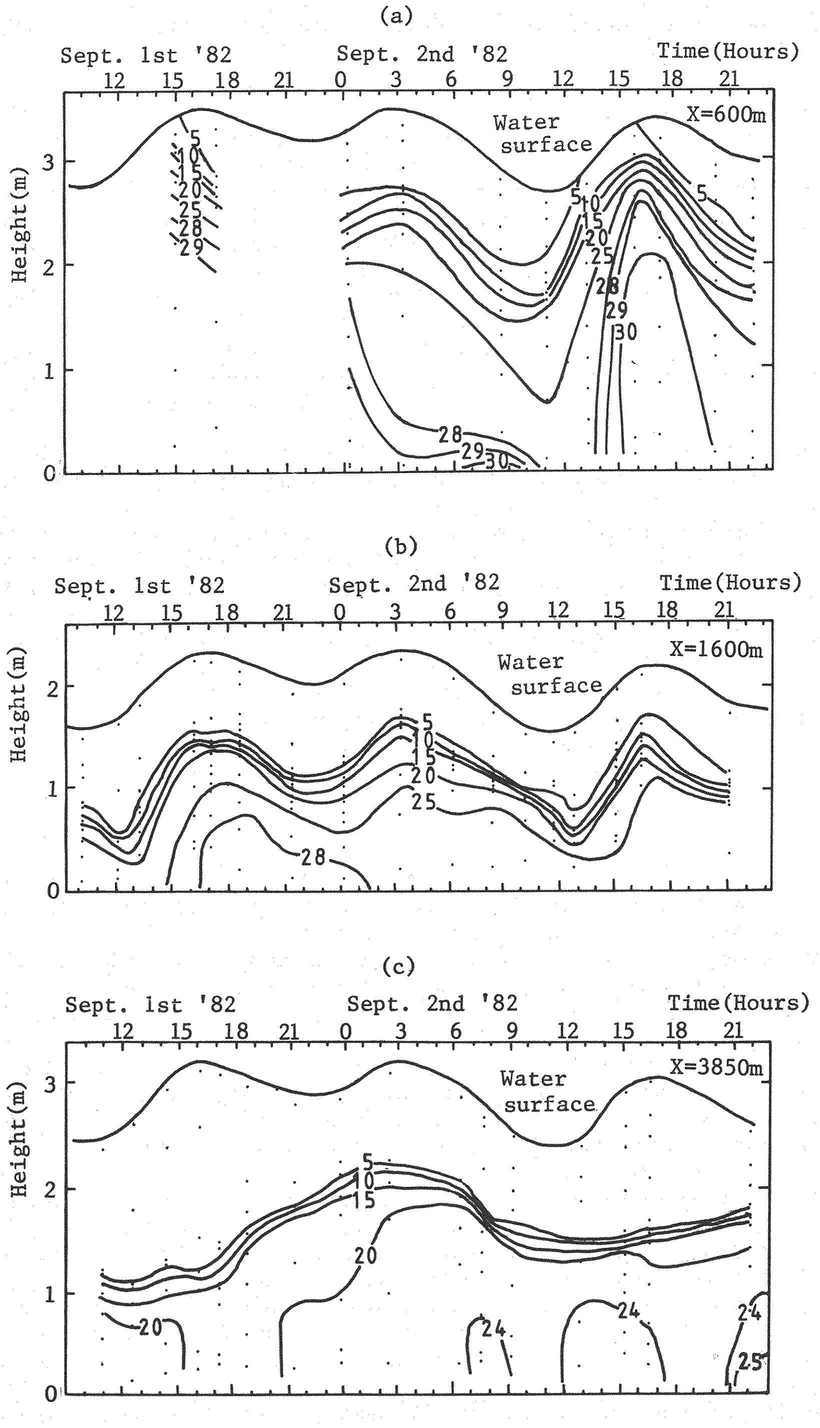

Fig. 3 Variation of longitudinal salinity (‰) Sept. 1st to 2nd, 1982.
River discharge: 6.9m^3/sec ; tidal range at the river mouth: 0.75m
(a) 600m (b) 1600m (c) 3850m.

Sept. 1st, although contour lines of salinity began to rise a little later than the water surface and reached a peak almost at the same time as the latter, again their movement was behind the latter during the following stage. The variation of 25 ‰ line, which was different from those of other lines, was closely tied with the intrusion of salt water. Although the surface salinity of 1600m was similar to that of 600m, it was between 1.68‰ and 2.7‰, and so its variation and numerical values were smaller than those at 600m. At 3850m (Fig. 3(c)) the variation of 5-15‰ lines was small during the flood tide on Sept. 1st and even the line of 20‰ disappeared at the peak of river stage.

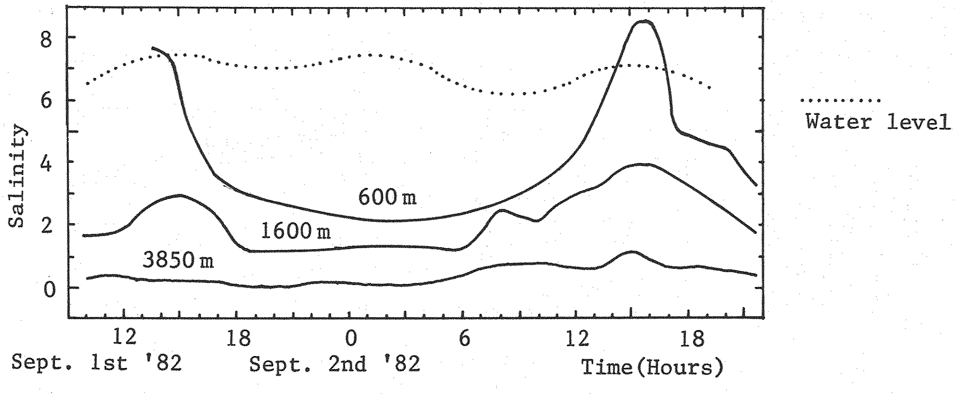

Fig. 4 Variation in surface salinity (‰) Sept. 1st to 2nd, 1982.
River discharge: $6.9m^3/sec$; tidal range at the river mouth: 0.75m.

Hourly variations of the SS at the bottom are represented in Fig. 5, and Fig. 6 shows the longitudinal distributions of the salinity. Topography of the river bottom is shown by the depth at the center of the each section. The movement of the salt water with the passage of the time is descrived as follows according to Figs. 6, 3(a), 3(b), and 3(c).

At 15:00, the salt water intruded into the river mouth had arrived at 1600m, for the 25‰ line, which once disappeared, was observed again at this time. At 17:00, although tidal level at the river mouth showed ebb tide, salt water still continued to intrude in the estuary. In addition, from the rising of 5-15‰ lines and of SS in Fig. 5, it can be said that the salt water which had intruded into the river mouth reached 3850m about 6 hours later, but the 20‰ line did not yet appear, as in Fig. 3(c). This line reached 3850m at 21:00. At 0:00, flood tide was in progress at the river mouth, and at the submerged weir the salt water depth continued to rise, while at 1600m it began to fall. At 3:00, except for the 25 ‰ line, the contour lines of salinity were almost horizontal in the estuary. At 8:30, according to our observations, the average velocity of ebb tide on the water surface went up to 0.35m/sec at 1600m and to 0.3m/sec at 3850m. At 600m, there were depressions on the 5‰ to 25‰ lines. These phenomena were observed also in the other cases. At 15:00, distribution of salinity at the river mouth was almost uniform in the longitudinal direction, while between 300m and 1600m the salt wedge was partially mixed type. The 25‰ line at 1600m went down more slowly, compared with the other lines. It can be said that the outflow of salt water from upstream to the river mouth were hindered on account of the hump near 1400m.

The case illustrated above is influenced by the submerged weir. It was observed that there is a difference between the salinity distribution in the region from the river mouth to 600m and the region more upstream. Thus the former sometimes shows a partially mixed type, while the latter always shows a stratified type. The thickness of salt layer is changed due to the intrusion of salt water, independent of the variation of water surface; moreover, intrusion movements are influenced by the bed topography.

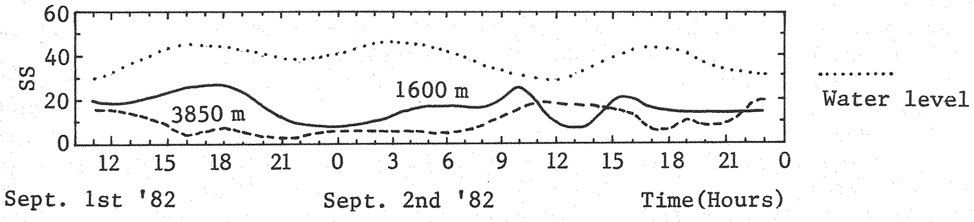

Fig. 5 Variation of the SS (ppm) at the bottom Sept. 1st to 2nd, 1982. River discharge: 6.9m^3/sec; tidal range at the mouth: 0.75m.

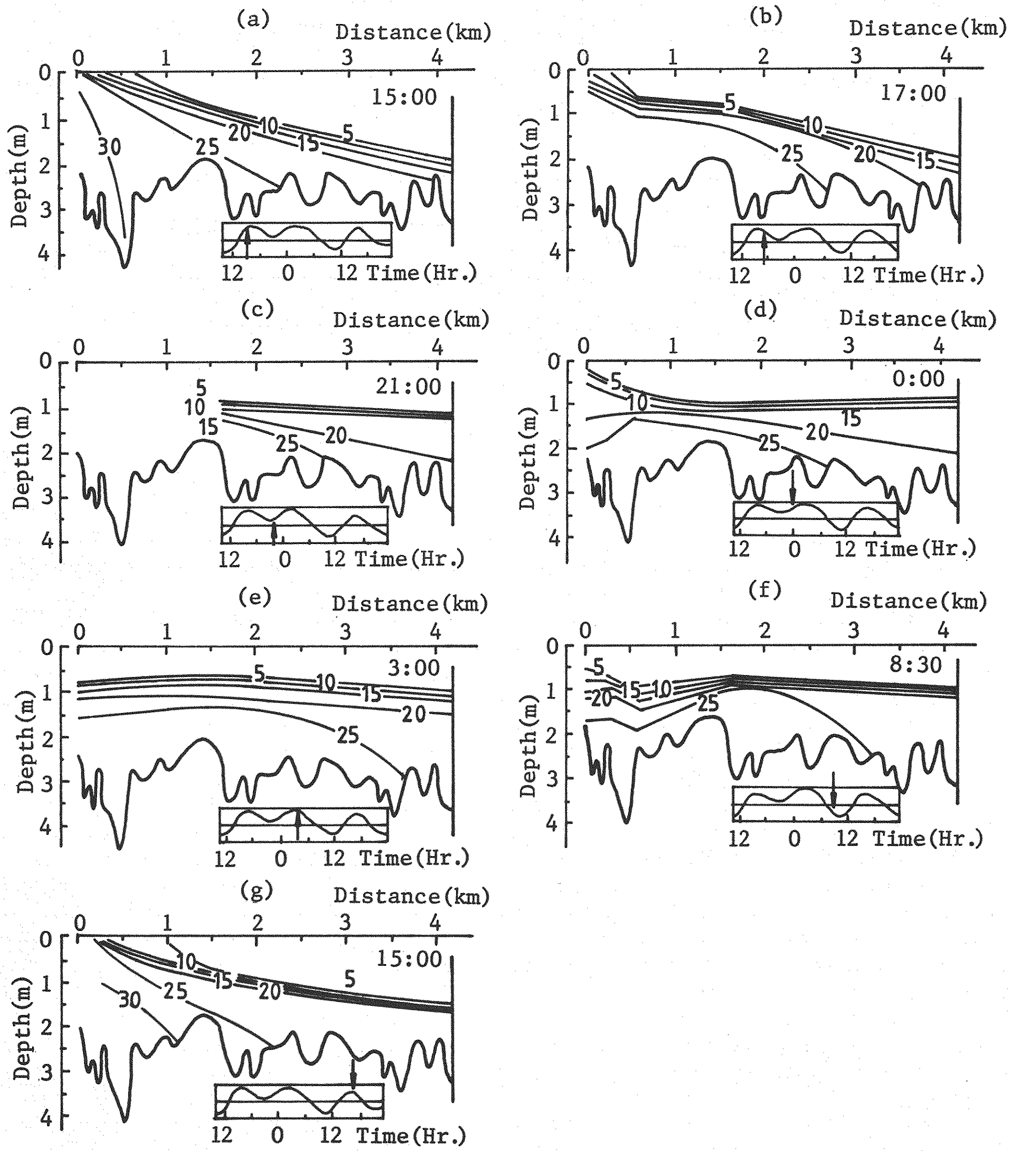

Fig. 6 Longitudinal distribution of salinity (‰) Sept. 1st to 2nd, 1982.
(a) near high water (15:00); (b) just after high water (17:00); (c) higher low water (21:00); (d) just before high water (0:00); (e) just after high water (3:00); (f) just before lower low water (8:30); (g) high water (15:00).

The second case is shown as observation number 2 in Table 2. Tide was also the spring tide. Tidal range at the river mouth was 1.09m. River discharge was increased to $9.2m^3$/sec. Traveling observations were made from an outboard motor-boat for cross sections at the river mouth, 100m, 200m, and 300m from the mouth. Fixed point observations were done at 400m, 500m, 600m, and 800m from the mouth, respectively. Salt water intrusion was pursued as far as 2400m. These observations were carried out every hour from 9:00 to 16:00 on Sept. 18th, 1982. Thus the movements of salt water from around the end of ebb tide through low water to the flood tide are investigated.

Fig. 7(a) and Fig. 7(b) represent hourly variation of velocity of flow and salinity for 400m. During ebb tide, salt water suddenly decreased in thickness and flowed seawards. During low water, only a small part of the 15 ‰ contour line of salinity remained, and velocity of flow also decreased. During ebb tide the velocity was large on the surface and small near the bottom. During flood tide, velocity of the flow became larger first near the bottom and then part of larger velocity moved in to the middle of the depth as time elapsed.

Fig. 7(c) represents the vertical distributions of upstream velocity measured between 11:30 and 11:38, and of salinity sampled at 11:55. The salinity continued to be a small value, or 4.7 ‰ in the bottom layer. Thus at the beginning of flood tide water in the bottom layer was flowing at high velocity while salt water did not yet intrude. When salt water came, the salinity was abruptly increased. Finally, contour lines of salinity intersected with the water surface, and then the salinity was raised more than 20 ‰ in whole water depth. However when the tide turned to flood tide, the salt water mass blocked downstream movement of the fresh water and pushed it back upstream. It took about four hours for salinity to rise to more than 20 ‰, and the salinity on the surface did not reach 25 ‰.

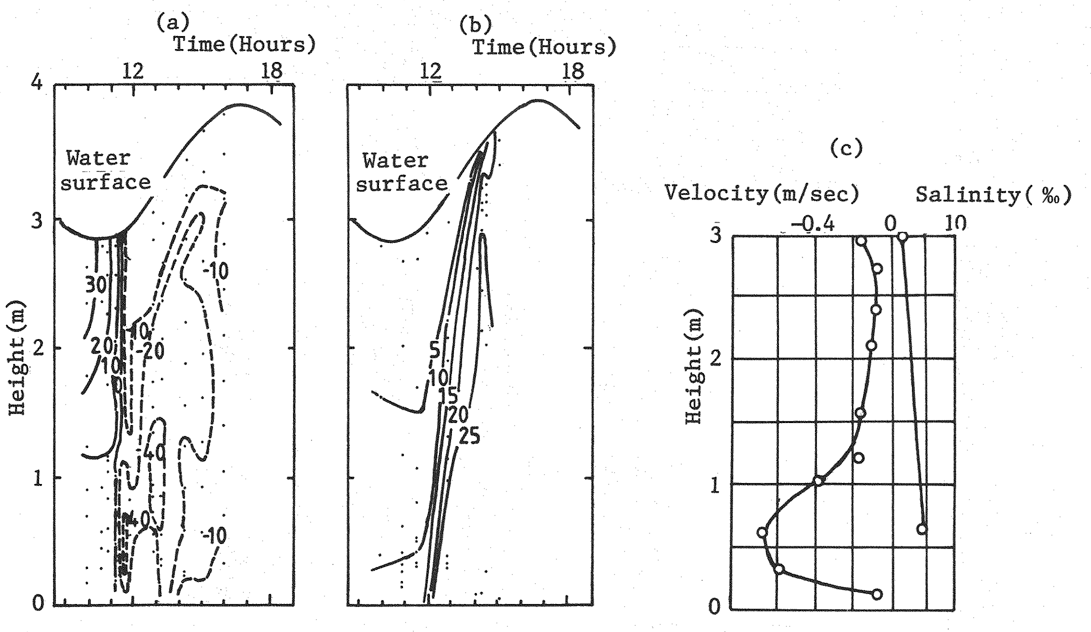

Fig. 7 Variation of (a) longitudinal velocity (cm/sec), (b) salinity (‰) and (c) a vertical distribution at 11:00-11:55 Sept. 18th, 1982.
River discharge: $9.2m^3$/sec; tidal range at the river mouth: 1.09m.
Negative values of velocity of flow denote the upstream flow.

Fig. 8 shows the longitudinal distribution of the salinity. Fig. 8(a) shows an aspect of ebb tide when salt water retreated and the line with high salinity fell down to the edge of the depression near 500m. In Fig. 8(b), where tidal level was the lowest, part of the salt water with high salinity decreased and was driven up from the bottom of the depression, and in Fig. 8(c), the salt water dropped into the depression.

Fig. 8(d) represents an aspect of the start of the flood tide and Fig. 8(e to h) show the movement of salt water during flood tide. The salinity in the bottom part of the depression increased to 25‰, due to the flowing in of the salt water from the sea. Then the salt wedge gradually proceeded upstream and reached to 2000m from the river mouth. Although final distribution showed the typical distribution of the salt wedge, there was a gradual mixing zone during the flooding which was strongly influenced by the depression at 500m and the hump at 1400m from the mouth.

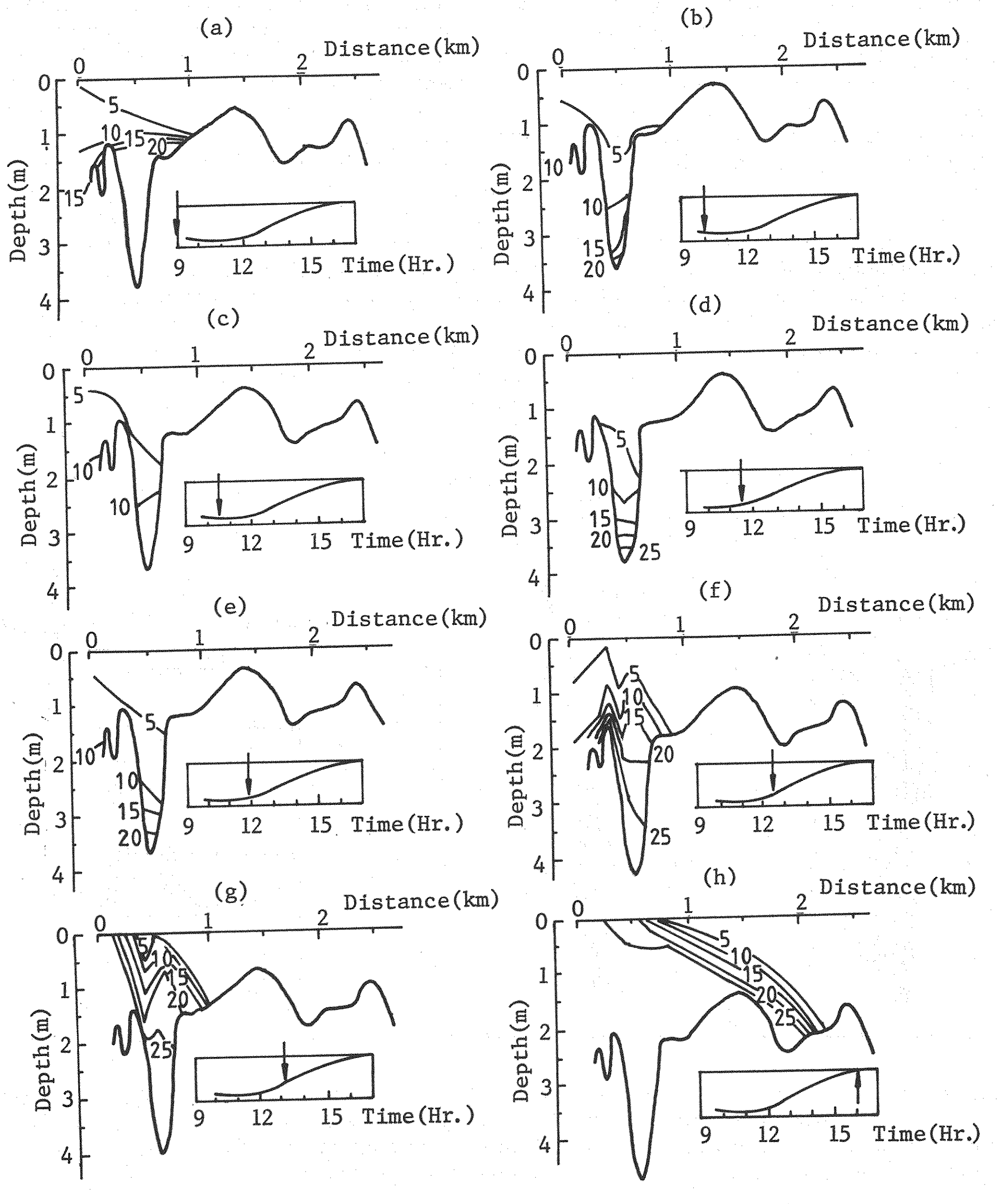

Fig. 8 Longitudinal distribution of salinity (‰) Sept. 18th, 1982.
(a) ebb tide (9:00); (b) near low water (10:00); (c) near low water (10:30); (d) start of flood tide (11:30); (e) flood tide (11:50); (f) flood tide (12:30); (g) middle of flood tide (13:10); (h) high water (16:10).

The third case is shown as observation number 3 in Table 2. Tide was neap tide. Observations were done every hour from 6:00 to 17:00 on Sept. 18th, 1980. Tidal range was 0.4m at the river mouth. River discharge was 0.5m^3/sec in the Nanakita River and 1.8m^3/sec in the Umeda River. Observation focus was set on the section from the river mouth to 800m. Fig. 9 represents hourly variation of salinity at the river mouth. Tidal level rose from lower low water up to lower high water, went down a little, and then went up again. It can be found from Fig. 9 that at the river mouth, where the maximum salinity of the intruding salt water was 25‰ salinity was stratified even during flood tide, and that contour lines of salinity varied widely as time elapsed, compared with the case in which tidal level suddenly went up. We can conjecture that this is because, although salt water begins to flow in, increasing in thickness, at about 7:00, it cannot continue to intrude at one time on account of the small rise of tidal level and it works its way into the estuary against the oncoming current. Such a distribution was also found at the other stations.

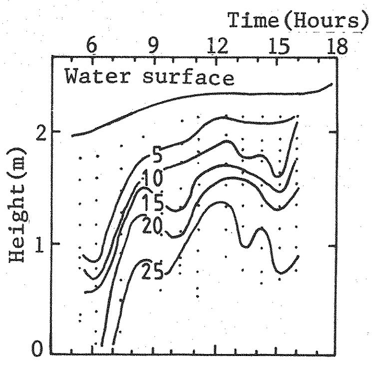

Fig. 9 Hourly variation of salinity (‰) at the mouth Sept. 18th, 1980. River discharge: 2.3m^3/sec; tidal range at the river mouth: 0.4m.

Fig. 10 shows the longitudinal distributions of the salinity. In Fig. 10(a), where tidal level at the river mouth began to go up, salt water flowed into the depression near 500m from both downstream and upstream, because salt water in bottom layer receded from upstream to downstream. In Fig. 10(b), salinity at the bottom including that in the depression became 25‰ because of the intruding salt water, and in Fig. 10(c), since all the contour lines of salinity went up almost in the same way, salt water seemed to immediately intrude upstream. But this was not the case because the hump near 1400m refrained salt water from finding its way further upstream. In Fig. 10(d), the 30‰ line turned up in the bottom layer of the depression at 500m. In Fig. 10(e), the line reached a considerable height, and then fell down at the edge of the depression. Although it is not clear why

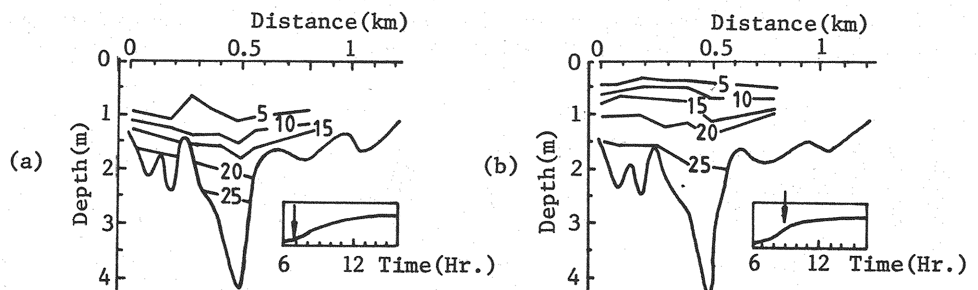

Fig. 10 Longitudinal distribution of salinity (‰) Sept. 18th, 1980.
(a) Start of flood tide (7:00); (b) flood tide (9:00).

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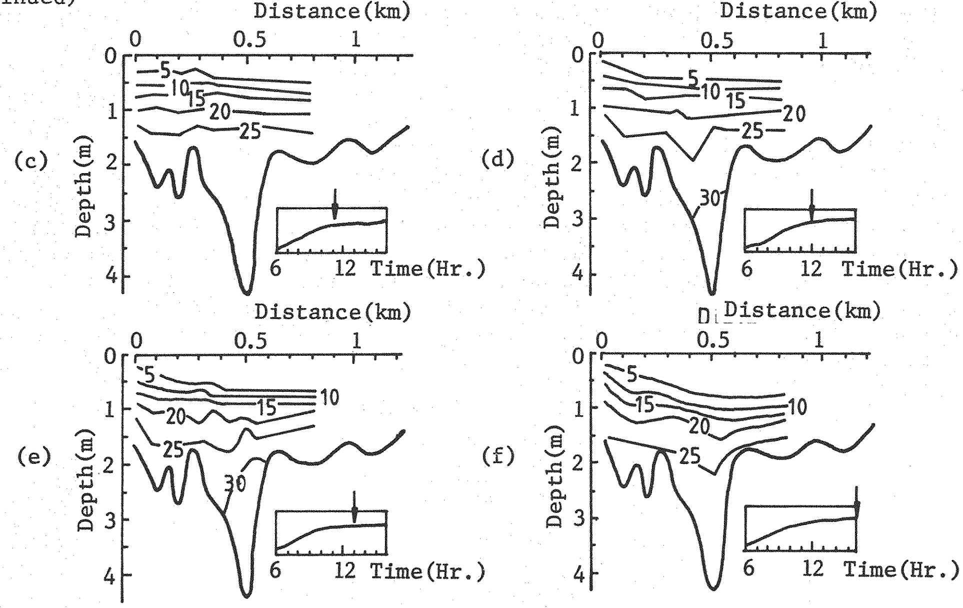

Fig. 10 Longitudinal distribution of salinity (‰) Sept. 18th, 1980.
(c) Lower high water (11:00); (d) start of ebb tide (12:00);
(e) flood tide (13:00); (f) flood tide (16:00).

the 30‰ line came about, an inflow from Teizan Bori Canal seemed the main reason for the higher concentration.

After that, since tidal level at the river mouth once went down, salt water receded as seen in Fig. 10(f). The tide then shifted into flood tide again. The falling of tidal level at this time, which happened in a very small scale of 0.03 m, had an effect on the recession of salt water. Since, in this case, the inflow of salt water from the river mouth is small compared with that of the two cases mensioned above, the new intruding salt water, at least the part with high salinity, could not go beyond the hump near 1400m regardless of the small river discharge.

It turned out from the observations summarized above that, within the tidal portion of the Nanakita River, the submerged weir at 4150m, the hump at 1400m, and the depression at 500m, are topographically important to the intruding salt water, and that partially mixed or stratified type of salinity distribution arises, according to the conditions of tide, or to river discharge.

Fig. 11 represents a typical case of contour lines of velocity at the river mouth; Fig. 12, the distributions of velocity and of salinity at the river mouth. Even if salinity was stratified, vertical distribution of velocity was similar to

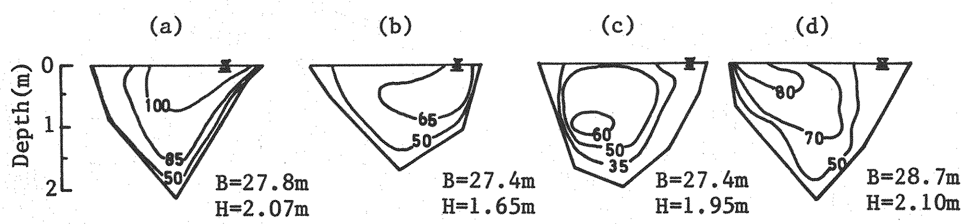

Fig. 11 Variation of velocity (cm/sec) on cross section at the river mouth. Observation number 6, Aug. 4th, 1974. River discharge: 8.0m^3/sec; tidal range at the mouth: 0.8m (spring tide). (a) Middle of ebb tide; (b) ebb tide; (c) start of flood tide; (d) middle of flood tide.

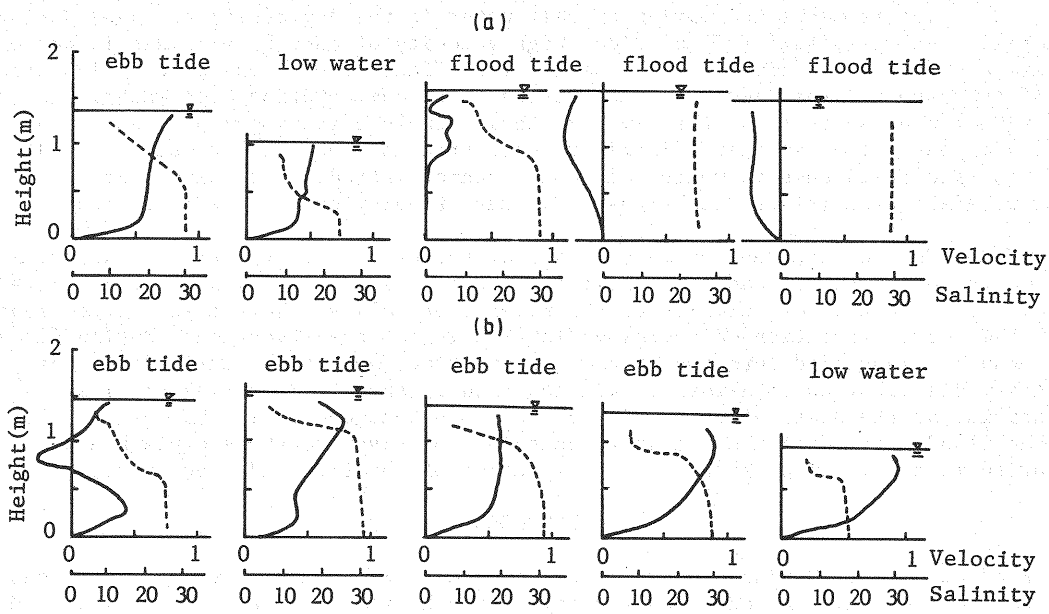

Fig. 12 Variation of salinity (‰) and longitudinal velocity (m/sec) for the river mouth (center of the section). (a) Observation number 4. Sept. 9th, 1979. River discharge: 2.9 m^3/sec (ordinary water discharge); spring tide. (b) Observation number 5. Oct. 12th, 1980. River discharge: ordinary water discharge; tidal range at the river mouth: 0.61 m. ———— velocity; -------- salinity.

that of homogeneous flow and was an almost logarithmic distribution except during the starting period of flood and ebb tides. When tidal level was low and river discharge was normal water, as seen in Fig. 9, the distribution of salinity at the river mouth shoud be regarded as stratified (4). Besides the cases shown in Fig. 12 and in the first case, the distribution of salinity at the river mouth keeps homogeneous for a certain period. Since the movements at the river mouth are attributed to the interaction between coastal water and water within the tidal portion, it is necessary to consider this when computing estuary circulation.

CONCLUSIONS

The phases of unsteady salinity intrusion into an estuary and of its recession were investigated by field observations made between the year of 1974 and 1982. Some typical cases of the distribution of velocity and salinity at the river mouth were studied. The results can be summarized as in the following.

(1) The first case in which the tip of the salt wedge reaches the upstream section where the submerged weir blocks its upstream movement and the new salt water mass is pushed into it by the following flood (river discharge=6.9m^3/sec, tidal range at the river mouth=0.75m) :

Salt water intrudes upstream toward the submerged weir independently of variation of tidal level at the river mouth and arrives at the weir at 4150m about six hours after its intrusion from the river mouth. In the intrusion and the recession of salt water, the depression at 500m and the hump at 1400m have an effect on the movements. The distribution of salinity in the estuary shows a stratified type, or at times a partially mixed one. In the distribution of salinity at the river mouth, a stratified type and a homogeneous one are repeated in turn.

(2) The second case in which salt water is almost completely excluded from the river mouth during low water and intrudes again during flood tide (river discharge=9.2m^3/sec, tidal range at the river mouth=1.09m) :

There are remnants and mixing of salt water in the depression at 500m during ebb tide. At the start of flood tide, high velocity of back flow arises in bottom layer, and the depression at 500m has a large effect, the intensity of which gradually decreases as the wedge intrudes further upstream. During high water, the distribution of salinity at the river mouth is completely homogeneous, and a partially mixed type of salinity distribution is brought about in the estuary.

(3) The third case in which salt water cannot intrude as far upstream because of low tidal level (river discharge= $2.3m^3$/sec, tidal range at the river mouth = 0.4m) :

The effect of the depression at 500m at the beginning of intrusion are similar to those in the 2nd case. Salinity cannot find its way beyond the hump at 1400 m. The distribution of salinity at the river mouth always shows a stratified type.

The hourly variation of salinity distribution at the river mouth during flood tide can be classified into two types. In one type (neap tide, small discharge), salinity distribution is always stratified, and in the other (spring tide) it is stratified at the start of flood tide but becomes homogeneous in the latter half of the flood. The distribution of velocity at the river mouth is explained by a logarithmic type, except at the starting period of ebb tide and flood tide.

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APPENDIX - NOTATION

The following symbols are used in this paper:

B	= top width of the flow;
H	= depth of the flow;
N.T.	= neap tide;
SS	= suspended sediment;
S.T.	= spring tide;
T.P.	= datum level of Tokyo Bay(Tokyo Peil); and
X	= distance from the river mouth.