Title	A Salt Wedge at the Estuary of the Ishikari River in Hokkaido
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Citation	北海道大學工學部研究報告, 130, 1-15
Issue Date	1986-03-25
Doc URL	https://hdl.handle.net/2115/41979
Type	departmental bulletin paper
File Information	130_1-16.pdf

北海道大学工学部研究報告
第130号（昭和61年）

Bulletin of the Faculty of Engineering,
Hokkaido University. No. 130 (1986)

A Salt Wedge at the Estuary of the Ishikari River in Hokkaido

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(Received November 20, 1985)

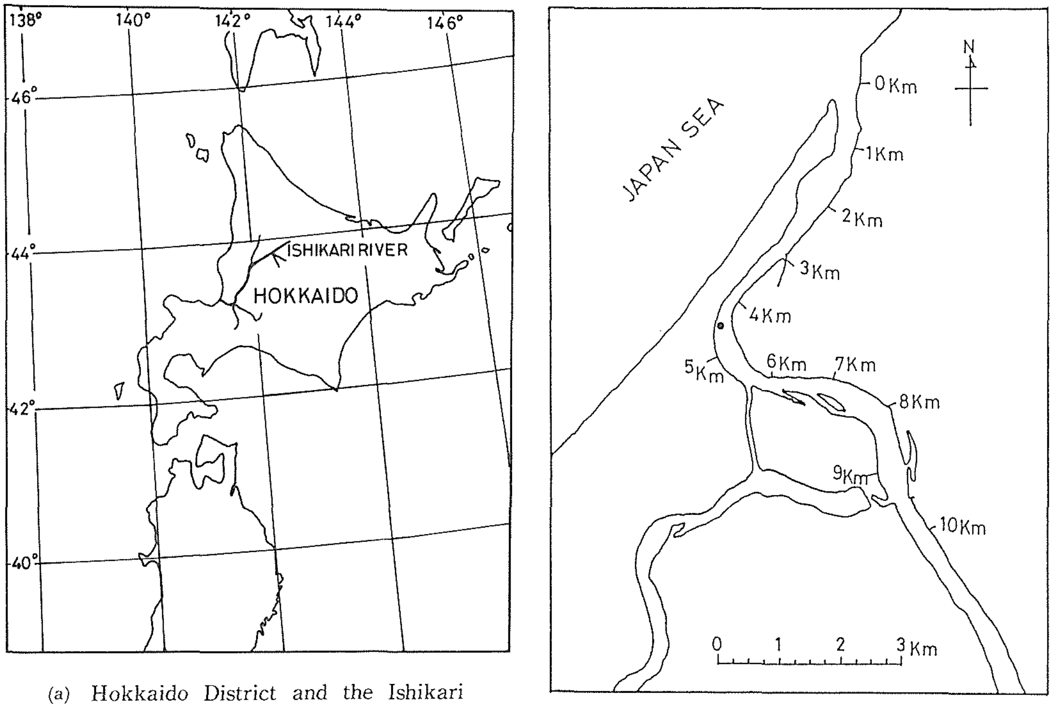
Abstract

Many observations of a salt wedge has been carried out by the use of the ultrasonic method at the estuary of the Ishikari River since 1961. The behavior of the salt wedge is much influenced by the shape of the river bed at the estuary. The critical discharge at which the salt wedge begins to penetrate into the river mouth was estimated as 550～600 m^3/s. When the discharge increases, the mixing of the fresh and salt water grows along the interface and the salt wedge begins to decay. In the steady state of the salt wedge, the amplitude of the internal tide was intensified 5.2 times as large as the tidal motion of the surface. An abrupt change of the level of the interface, influenced by a storm surge, was observed when the atmospheric depression passed through the sea area near the river mouth.

1. Introduction

The authors and other workers have performed many observations of salt wedges and salinity diffusion at the interface of the fresh and salt water at the estuary of the Ishikari River in Hokkaido, Japan[1)2)]. The Ishikari River, which has a length of about 270 km and an amount of normal discharge of 300～500 m^3/s, flows through the Ishikari Plain and pours into the Japan Sea (Fig. 1). Because the Japan Sea has a small tidal range of about 30cm at its maximum throughout the year, the salt water penetrates into the river mouth taking the form of wedge when the discharge decreases below a critical value. The front of the salt wedge reaches a point about 15km or more upstream from the mouth at the discharge of about 200m^3/s in the low water season of summer. As long as the state of the salt wedge is steady, a remarkable stratification is usually observed. When the discharge increases because of a rainfall, however, the salt wedge changes to an unsteady state and begins to decay. In such a case violent mixing of the fresh and salt water can be found everywhere along the interface.

The authors have developed an ultrasonic method to observe the profile of the salt wedge. Since an ultrasonic wave is reflected at the interface and also at the river bed, a profile of the salt wedge, as well as the shape of the bed, can be recorded by means of echo-sounding.



(a) Hokkaido District and the Ishikari River.

(b) Observational station near the river mouth.

Fig. 1 Location map.

2. Behavior of the salt wedge

Among the records of the longitudinal profile of the salt wedge observed by the ultrasonic method, an example of 24 July 1964 when the river discharge was 380m^3/s is shown in Fig. 2. The record was obtained by echo-sounding from the river mouth to a distance of 9km upstream. At the same time, vertical distributions of velocity and salinity were measured at the river mouth and at stations 2.0, 3.7 and 4.5km upstream respectively from the mouth. The results of the observation are shown in Fig. 3. From the record (Fig. 2), it is found that there are many rises and depressions along the river bed, consequently the behavior of the salt wedge is somewhat different from that of an ideal river with a flat bed. According to Figs. 2 and 3, a discontinuity in salinity is remarkably sharp at the interface. Particularly at the station 4.5km, the interface is very clear. At the station 3.7km, however, mixing of the fresh and salt water is considerably strong and a clear stratification can no longer be seen. Such a transition of the interface is believed to be the result of an internal jump which is caused by a big projection on the river bed. The water in the mixing layer gradually diffuses into the fresh water layer while it flows downstream, and the interface recovers its clearness at the station 2.0km. At the river mouth, as the water depth decreases, flow-out velocity of the fresh water and flow-in velocity of the salt water are both large. Therefore, mixing is strong there and salinity of the surface layer rapidly increases outside the mouth.

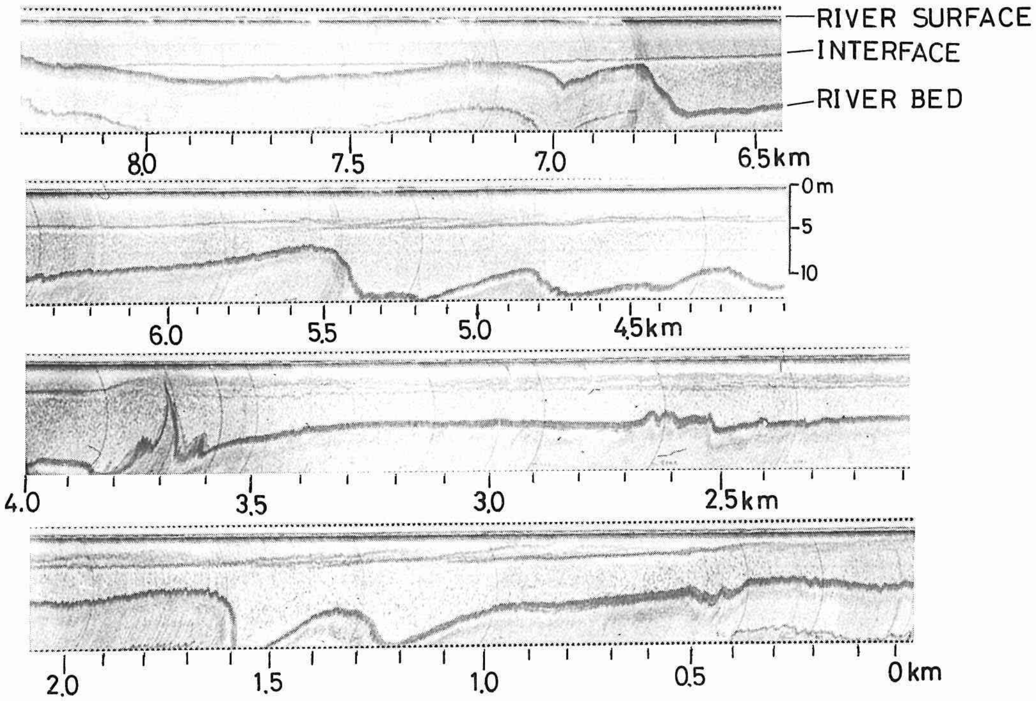
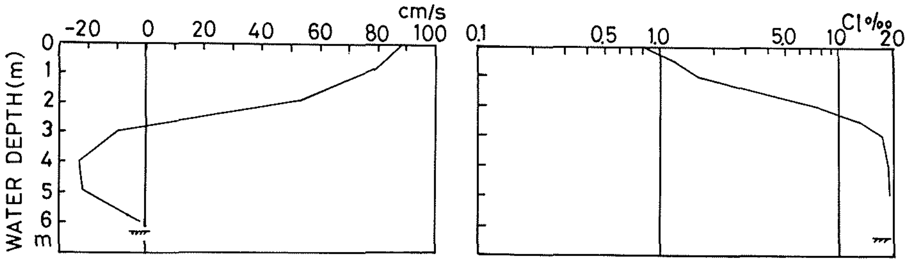


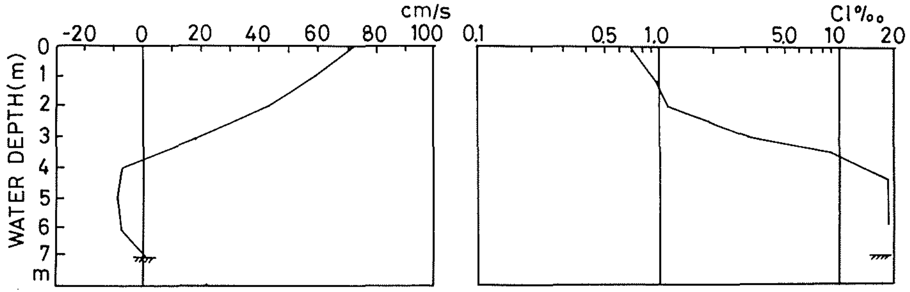
Fig. 2 A longitudinal profile of the salt wedge (24 July 1964).

When the discharge of the fresh water increases, the front of the salt wedge begins to recede. At times, however, the salt water is found to be left in hollows on the river bed even when the front has been driven downstream. Figure 4 shows a record, observed on 11 August 1965, in which the salt water remains in the bed hollow located at a distance of 9.4km upstream from the mouth. The critical discharge Q_{out} at which the salt water is completely washed away from the deepest hollow near the river mouth, namely when the salt water cannot be found inside the mouth, seems to reach a considerably large value which is more than 1400m^3/s at the lshikari River.

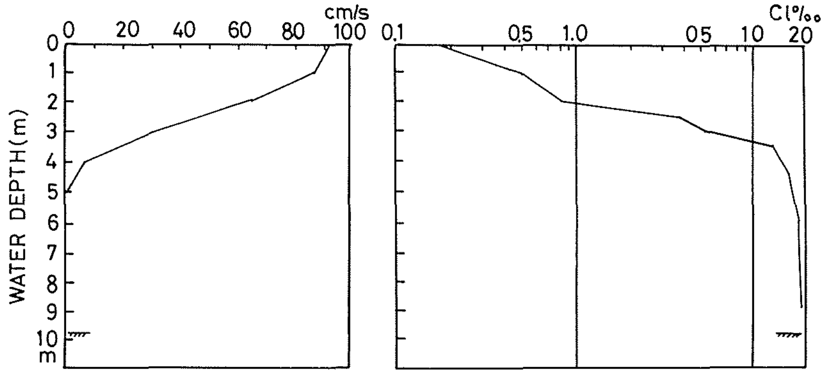
When the discharge decreases again below a certain critical value Q_{in}, which was estimated as 550～600m^3/s at the lshikari River, the salt wedge begins to penetrate into the mouth. The salt water progresses upstream along the bed after filling up the bed hollows successively. For instance, Fig. 5 shows the picture in which the salt water is flowing into the bed hollow about 9.5km upstream from the mouth (on 20 July 1961). Figure 6 is an interesting record, observed on 25 April 1964, where the salt water is trapped in the hollow (left side of the picture) and a new front of the salt wedge is progressing toward the hollow (right side of the picture). The salt water left in the hollow is diffusing into the upper fresh water layer across the interface. The front of the salt wedge is wedge-shaped and the internal wave can be recognized at the interface. Figure 7 shows a profile near the front of the salt wedge progressing along the river bed of inverse gradient at 3.0km upstream from the mouth (on 13 October 1983). In a record observed on 25 July 1968, the big projection on



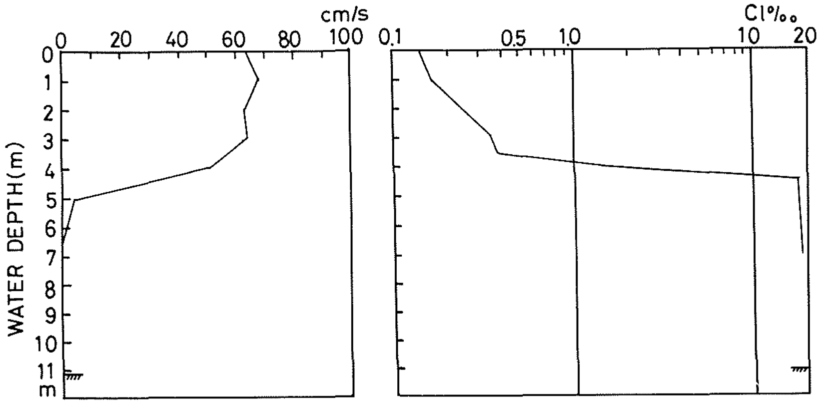
THE RIVER MOUTH



2.0km UPSTREAM



3.7 km UPSTREAM



4.5 km UPSTREAM FROM THE RIVER MOUTH

Fig. 3 Vertical distributions of velocity and salinity (24 July 1964).

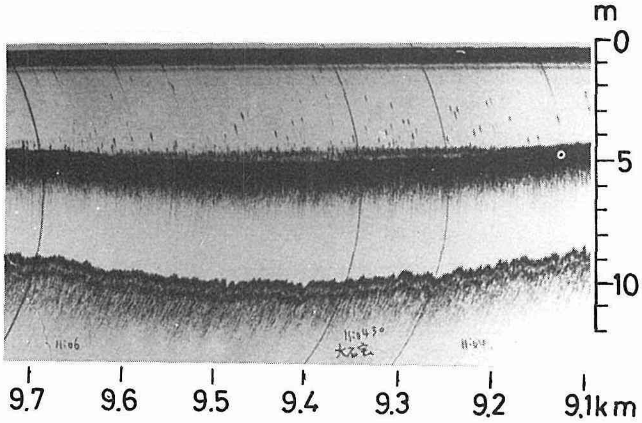


Fig. 4 The salt water left in the bed hollow (11 August 1965).

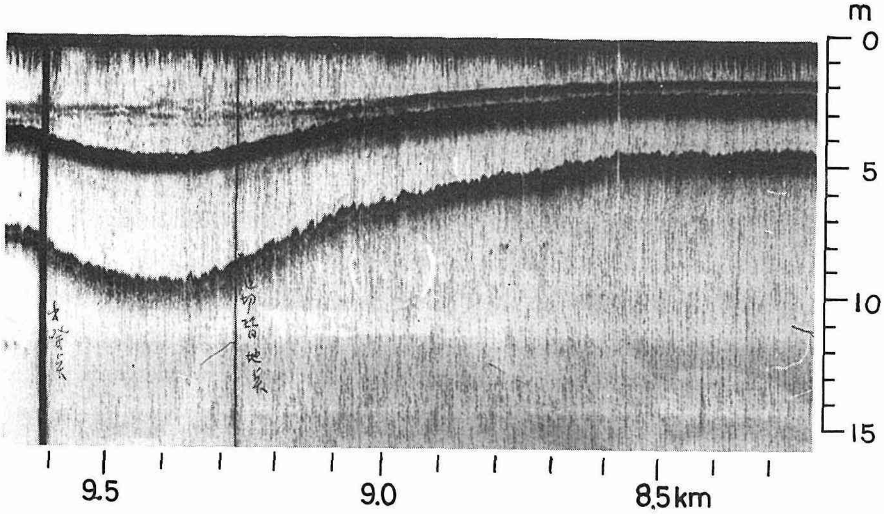


Fig. 5 The salt water flowing into the bed hollow (20 July 1961).

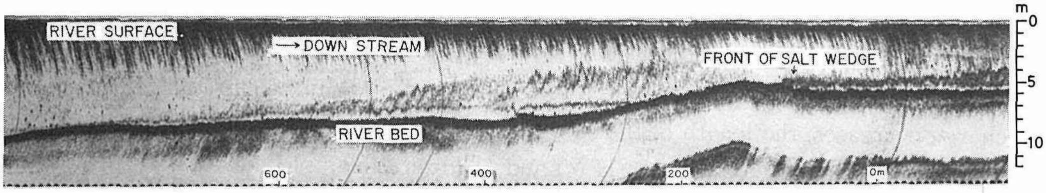


Fig. 6 Diffusion of the salt water and a front of the salt wedge (25 April 1964).

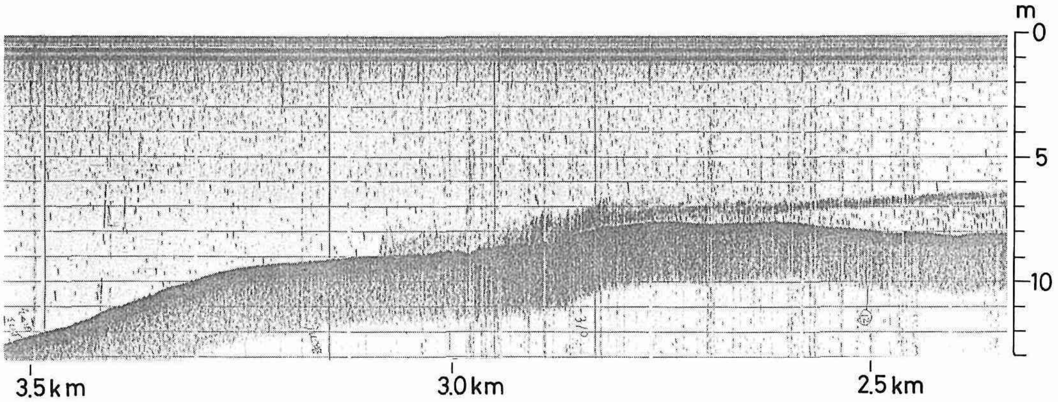


Fig. 7 A longitudinal profile near the front of the salt wedge (13 October 1983).

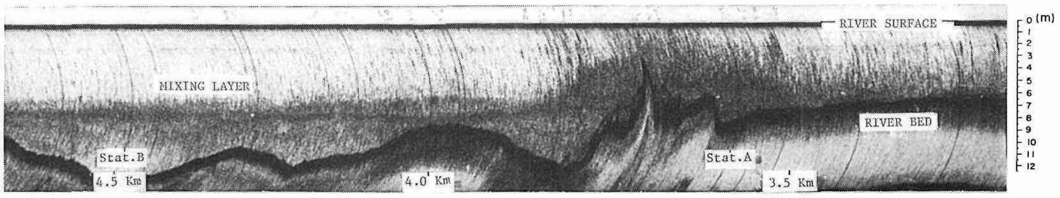


Fig. 8 Mixing of the fresh and salt water near the big projection on the river bed (25 July 1968).

the bed located 3.7km upstream facilitates the mixing of the fresh and salt water and the thickness of the mixing layer becomes remarkably large there (Fig. 8).

It is found that the big rises on the river bed sometimes prevent the salt water from penetrating upstream. On 7 October 1961, the progression of the front of the salt wedge was stopped by the projection at 5.8km upstream (Fig. 9). Figure 10 shows a profile near the front of the salt wedge observed on 17 July 1968 about 12.5km far from the mouth. In this picture, the wedge-shaped front cannot be recognized clearly because the progression of the salt water is partially arrested by the projection on the bed at the shallow part in the cross section.

Figures 11 and 12 show typical longitudinal profiles of the interface and the river bed in various stages of the river discharge. Figure 11 shows profiles when the salt wedge is progressing or it is in the steady state. As shown in Fig. 11 (a), the salt water could not flow into the river mouth at the discharge of 720m^3/s (on 4 June 1965), which is larger than the value of Q_{in}. At the discharge of 550m^3/s, however, the front was seen penetrating into the mouth beyond the depression, forming a tongue pattern on 5 June 1965 (Fig. 11 (b)). As the discharge decreases, the length of the salt wedge increases and thickness of the fresh water layer gradually decreases. Figures 11 (c) and 11 (d) are examples at a period of low river discharge ; 270m^3/s on 21 August and 190m^3/s on 3 August, 1967. On 3 August, the front of the salt wedge reached a point 13km upstream from the mouth.

When the discharge increases, the interface changes to an unstable state and the salt

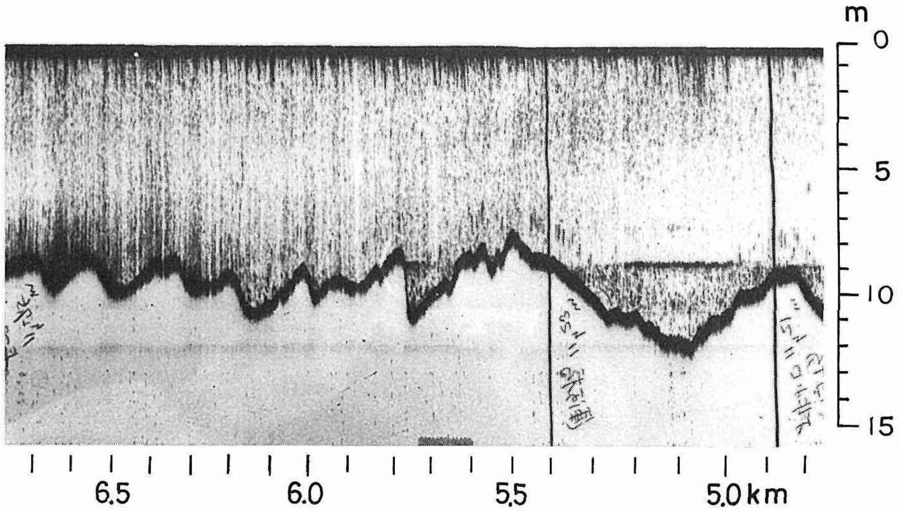


Fig. 9 A profile near the front of the salt wedge (7 October 1961).

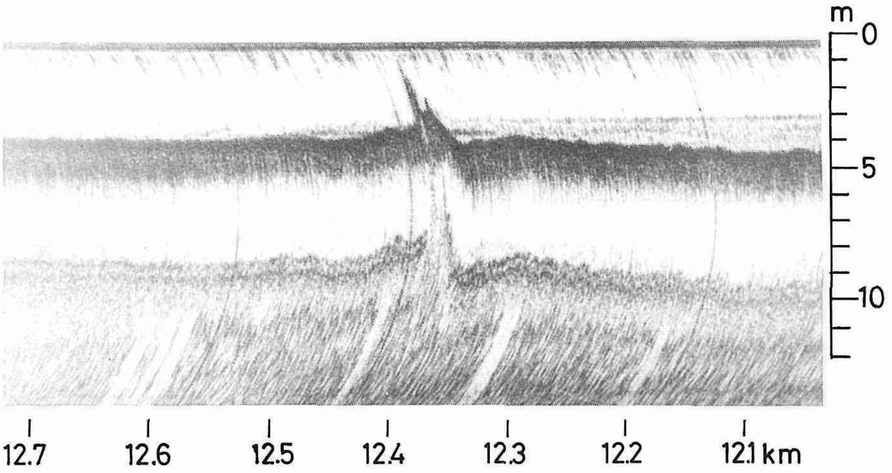
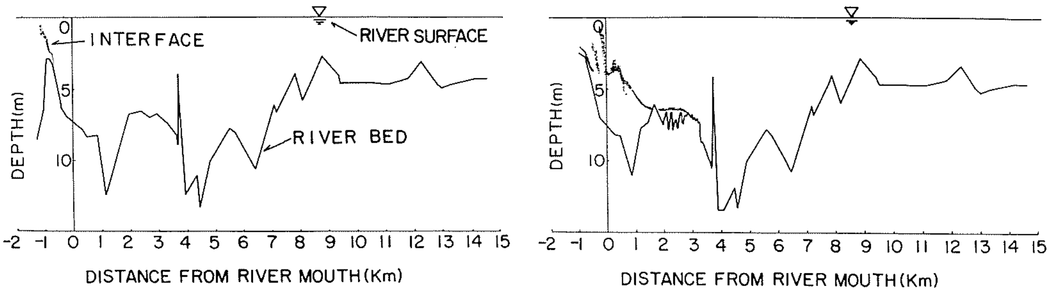


Fig. 10 A profile near the front of the salt wedge (17 July 1968).

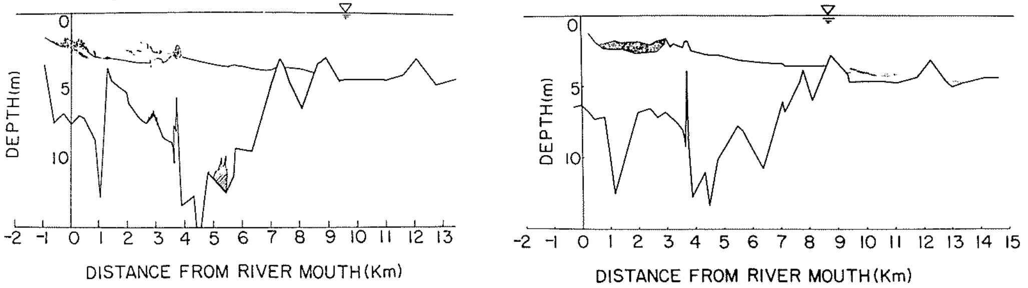
wedge begins to decay. Figure 12 shows examples of this case. As compared with Fig. 11 of the same discharge, the interface is very unstable and a violent mixing of the fresh and salt water is found everywhere along the interface.

Figure 13 shows the relation between the river discharge and the length of the salt wedge in the steady state. In this figure, the closed circle ● and the open circle ○ indicate the data observed by authors and by members of the Hokkaido Development Bureau respectively. It is found that the relation is greatly influenced by the shape of the river bed at the estuary. As seen in Figs. 11 and 12, at the section from the river mouth to 8.5km upstream, the water depth is deep and a big hollow is formed along the bed. When the discharge decreases, the salt water penetrates upstream after filling this big hollow. Consequently, the rate of intrusion for a change of the discharge is small. On the other hand, at the section upstream



(a) 4 June 1965, Q=720m³/s (Q : River discharge)

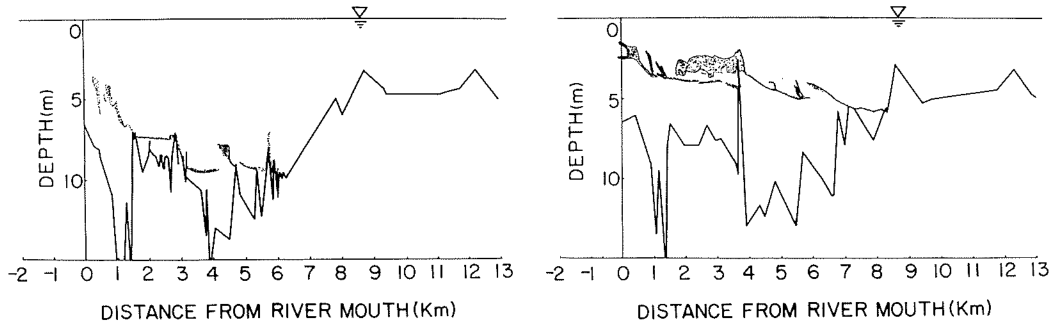
(b) 5 June 1965, Q=550m³/s



(c) 21 August 1967, Q=270m³/s

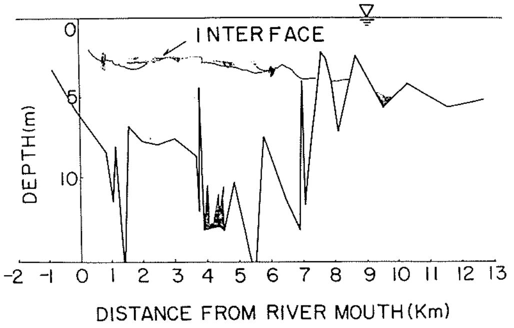
(d) 3 August 1967, Q=190m³/s

Fig. 11 Longitudinal profiles of the interface and the river bed in the steady state.



(a) 7 October 1961, Q=500m³/s

(b) 24 July 1964, Q=380m³/s



(c) 22 July 1964, Q=200m³/s

Fig. 12 Longitudinal profiles of the interface and the river bed in the unsteady state.

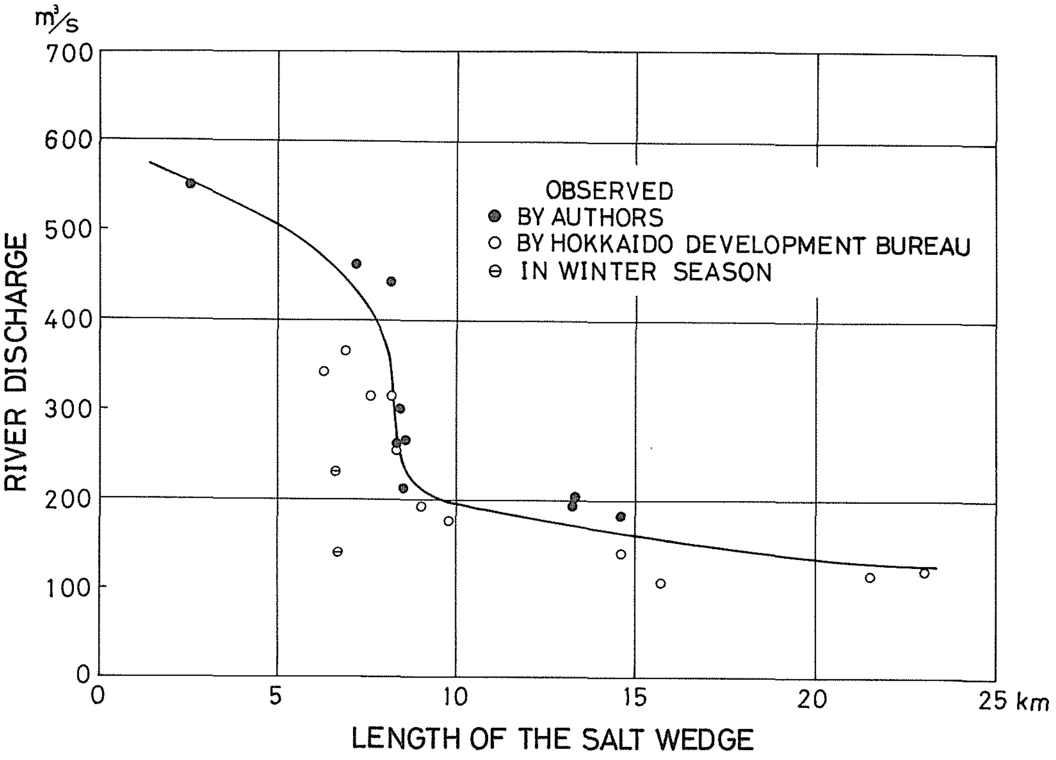


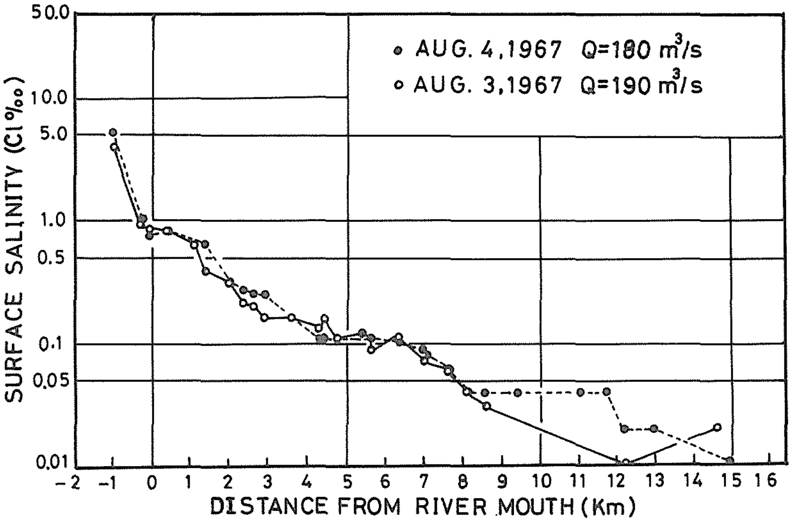
Fig. 13 Relation between the river discharge and the length of the salt wedge.

from the point 8.5km, the water depth becomes shallow and the shape of the bed is nearly flat. Therefore, the progression of the front is sensitively influenced by the change of the discharge. As a result, the relation can be represented by a curve upward convex at the former section, and conversely upward concave at the latter section. At the low water period in summer, the front is found to be 23km upstream far from the river mouth for the discharge of 120m^3/s. In the winter season, however, the salt water cannot penetrate upstream as easily as in summer, because the river mouth is narrowed on account of the sand drift caused by the northwesterly monsoon. The data observed on 12 January and 28 February 1968, shown by the circle ⊖ in Fig. 13, are examples of this case. The distance of intrusion is somewhat short compared with other data for the same discharge.

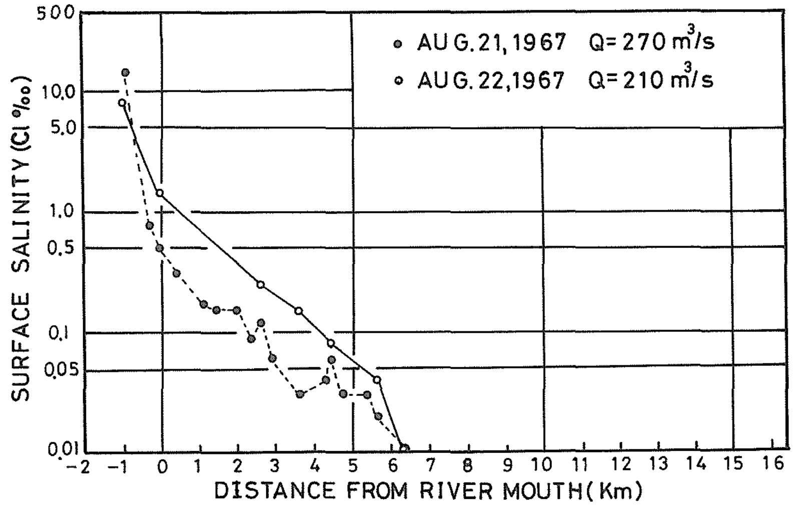
3. Salinity diffusion at the interface

The degree of mixing of the fresh and salt water at the interface of the salt wedge is influenced by the river discharge and varies with a distance from the mouth.[3][4][5] In order to grasp the phenomenon of mixing, it is necessary to obtain a longitudinal distribution of salinity in the surface layer. Therefore, the authors sampled 300cc of surface water every 30s during the sail for echo-sounding and measured the quantity of chlorinity in the water.

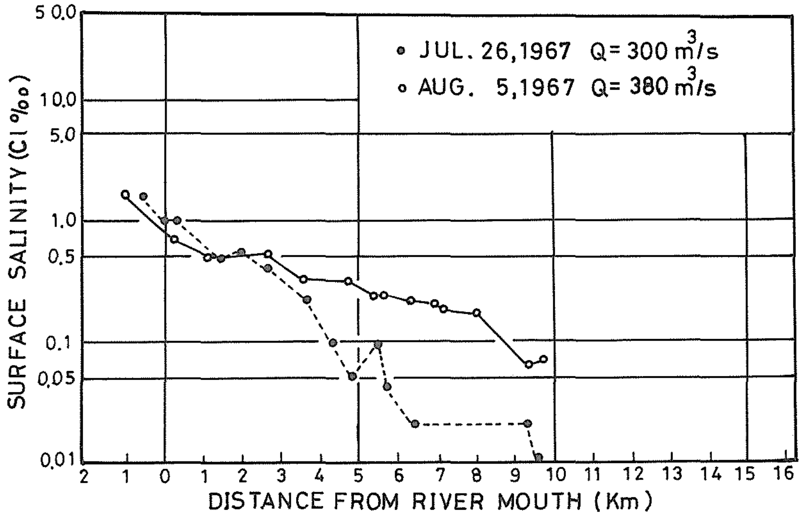
Figure 14 shows longitudinal distributions of chlorinity in the surface water in cases of different discharges. The chlorinity increases downstream and the gradient of chlorinity



(a) 3 and 4 August 1967



(b) 21 and 22 August 1967



(c) 26 July and 5 August 1967

Fig. 14 Longitudinal distributions of surface salinity.

increase becomes steep near the mouth, showing that the mixing is violent there. Figure 14 (a) shows two examples (on 3 and 4 August 1967) observed in the low water season of summer. According to the observation by the ultrasonic method the salt water penetrated as far as 15km from the mouth and the salt wedge was very stable. Two distribution curves shown in the figure are almost the same. When the river discharge increases, however, the gradients of chlorinity-distance curves become steep especially near the mouth, as seen in Fig. 14 (b) and (c). Figure 14 (b) shows observational results on 21 and 22 August 1967, with discharges of 270 and 210m^3/s respectively. Although the salt wedge was stable on both days, the chlorinity on 22nd was more than that of 21st. Such a result is caused by the wind stress. Namely on 22 August, the mixing of two layers were developed by a southerly wind of velocity 10m/s. In Fig. 14 (c), the curves obtained on 26 July and 5 August 1967 are compared. In the case of 5 August, the river discharge was large and the value of chlorinity was high near the front of the salt wedge. On the other hand, the curve of 26 July shows a type of ordinary stable one. Because both curves are controlled so that the chlorinity at the mouth is about the same value, the curve of 5 August has a rather gentle gradient along the salt wedge compared with that of 26 July, showing a remarkable difference between the stable and unstable cases.

4. Influence of the tide

On the boundary of the fresh and salt water at the salt wedge, the internal wave is caused by the tidal motion which propagates along the river surface. To study the relation between the internal wave and the tide, the authors observed the change of the level of the interface by the use of a Step-type Interface Meter[6] during the periods from September to October, 1982 and from June to November, 1983 at the station located 4.4km upstream from the river mouth (shown by the closed circle in Fig. 1 (b)). The Interface Meter was set with two sensors of salinity meter at the site 15m off the left bank of the river, where the water depth was about 11m. The salinity of the two points, 1m and 10m down from the river surface, was continuously recorded with the level of the interface by a six channel recorder.

Figure 15 gives an example of the record of the internal tide observed at the period 21～22 August, 1983. The amplitude ratios of the internal to surface tide in the steady state of the salt wedge observed in 1983 are shown in Fig. 16 for the amplitude of the surface tide. In this figure the amplitude of the internal tide is found to be 5.2 times as large as the tidal motion of the surface on an average.

On the basis of the observational results during the period 24～27 October, 1982 we consider the change of the water level in the lower region of the Ishikari River and its influence to the internal wave in an unsteady state. Daily changes of the water level observed at the stations given by closed circles in Fig. 17 are shown in Fig. 18. The distance from the river mouth to each station is respectively as follows ; ① Ino 150km, ② Osamunai 130km, ③ Hashimotocho 94km, ④ Naie 77km, ⑤ Tsukigata 58km, ⑥ Iwamizawa 44.5km, ⑦ Ishikari Ohashi 26.5km, ⑧ Shinoro 15km and ⑨ Bunchujo 4.4km. The lowest picture of this figure shows the observed (solid line) and estimated (dotted line) sea levels at Otaru Harbor,

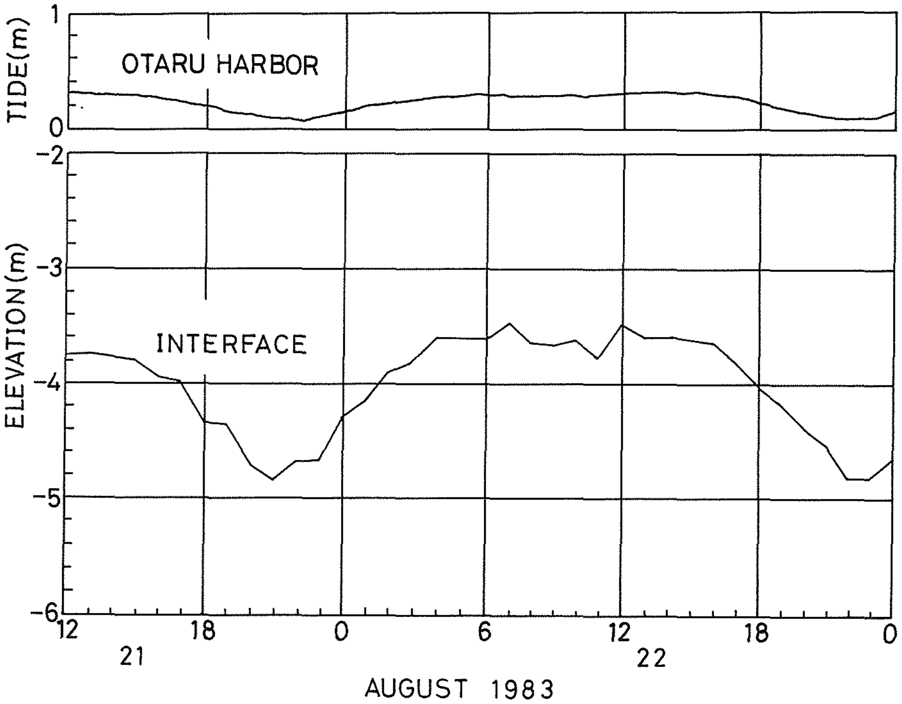


Fig. 15 An example of the internal tide observed at the station 4.4km upstream from the river mouth (21～22 August 1983).

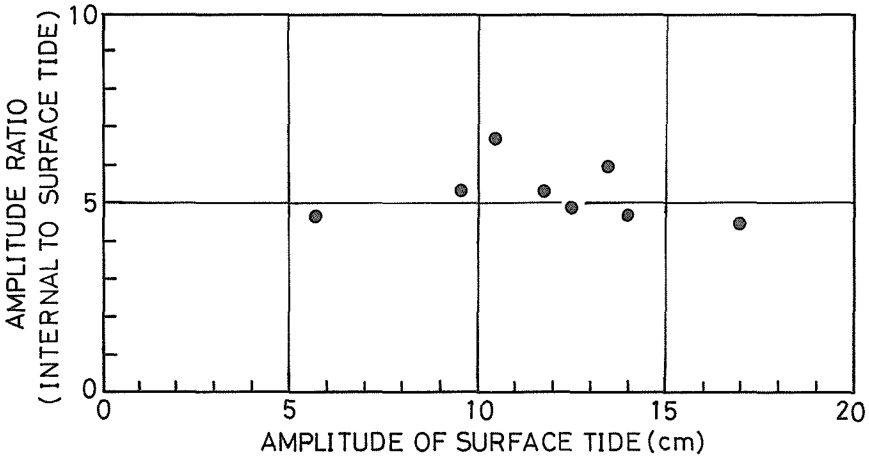


Fig. 16 The amplitude ratio of the internal to surface tide at the station 4.4km.

located about 33km west from the river mouth. On 25 October, the observed level was at its maximum 30cm larger than the estimated value showing that the sea level had risen in a peculiar fashion. An atmospheric depression had passed through the Japan Sea from SW to NE direction near the river mouth on the morning of 25th, and the rise of the sea level was caused by the storm surge. As seen in Fig. 18, the tidal motion of the water level can be recognized at stations located at the section from the river mouth to Ishikari Ohashi but not

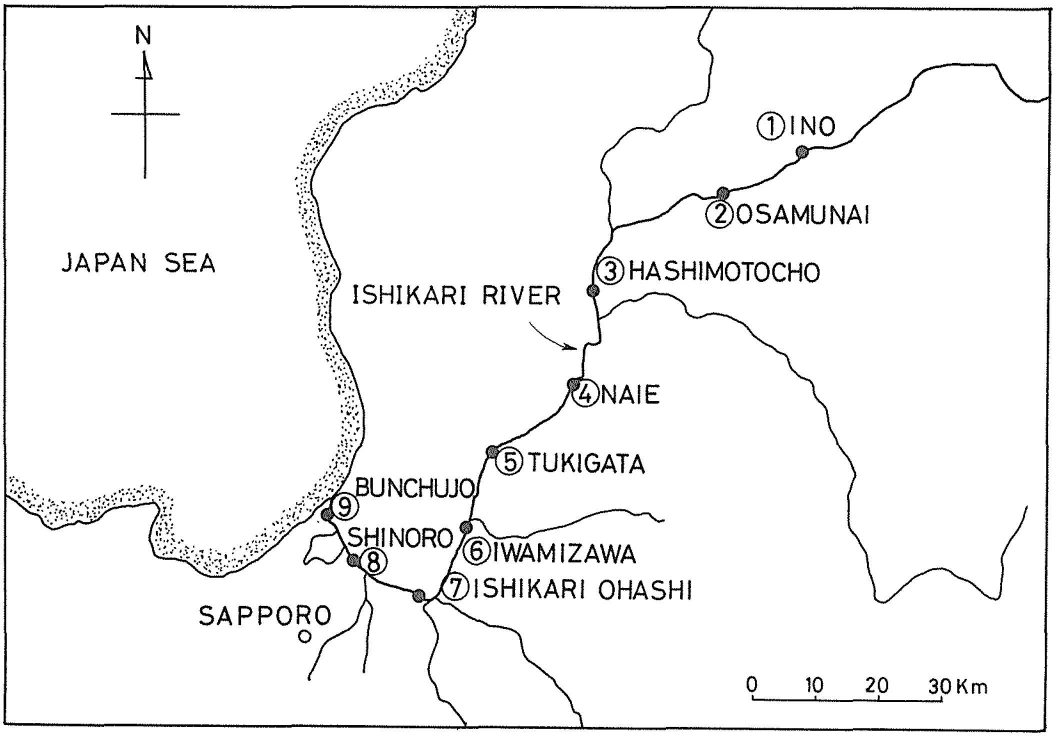


Fig. 17 The lower region of the Ishikari River.

at Iwamizawa. This fact shows that the limit of the ordinary tidal propagation is located near a point where the mean sea level intersects with the river bed.[7] This point is estimated as 34.5km upstream from the mouth in the case of the Ishikari River.

At this observational period, the river discharge increased (from 130m^3/s to 560m^3/s at Iwamizawa) and a peak of the water level was propagated downstream. It grew at the section from Ino to Iwamizawa and decayed from Iwamizawa to the river mouth. On the other hand, the peculiar rise of the sea level was propagated upstream from the mouth to Iwamizawa. Figure 19 shows the change of the interface (dotted line) and salinity (solid line) at the station 4.4km upstream from the mouth. The interface rose at maximum 1.05m at 12 : 00 of 25th, 2.4 times as large as the rise of the surface caused by the storm surge. Thereafter, the interface descended below the limit of measurement at 16 : 00. At the same time that the peak of the interface was recorded, salinity of the upper point abruptly increased from 0.5 Cl‰ to 15.2 Cl‰ showing that mixing of the fresh and salt water was violent. According to the observation of wind at Otaru Harbor, a westerly wind of a velocity over 10m/s continued for about four hours on the morning of 25th and the maximum velocity 16m/s was recorded at 10 : 00. The mixing seems to be caused by the continuous blow of a strong wind. Salinity of the lower point, on the other hand, decreased gradually from 19.1 Cl‰ (at 16 : 00 of 24th) to a minimum value of 6.4 Cl‰ (at 10 : 00 of 26th), and recovered to a value of 14.3 Cl‰ at 7 : 00 of 27th. It seems that this fall of salinity in the lower layer was caused by the decay of the salt wedge.

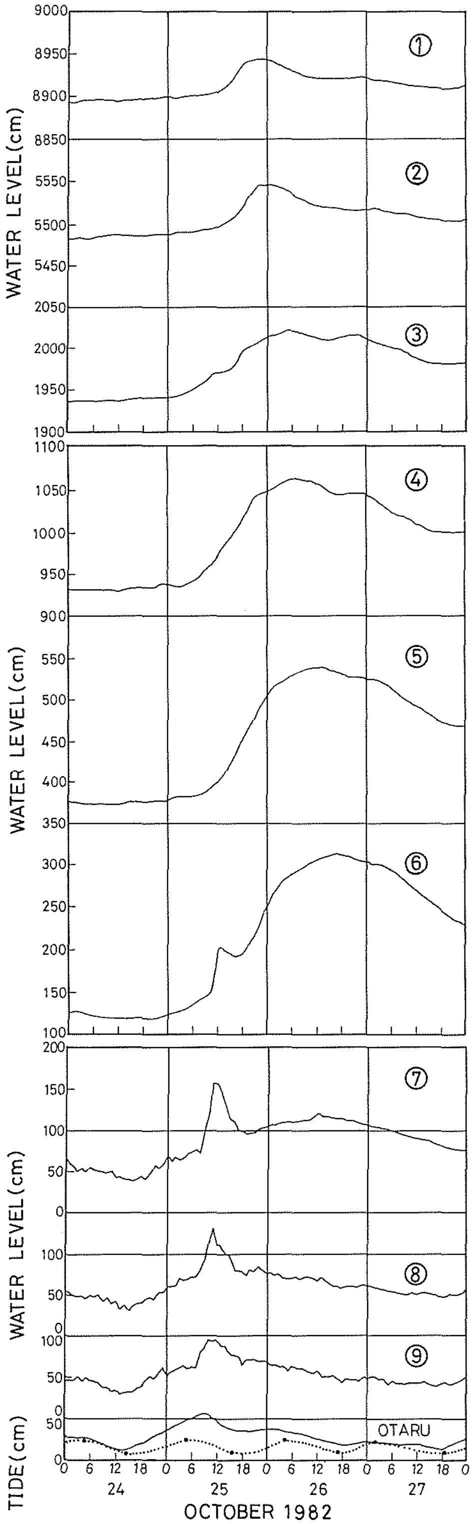


Fig. 18 Changes of the water level at the lower region (24～27 October 1982).

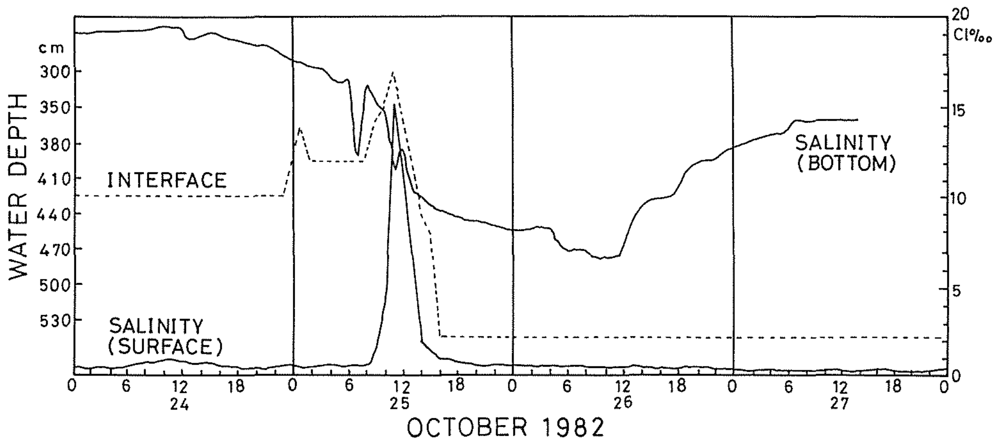


Fig. 19 Changes of the interface level and salinity observed at the station 4.4km (24～27 October 1982).

5. Conclusion

On the basis of the observational results of the salt wedge at the estuary of the Ishikari River, the behavior of the salt wedge and diffusion of the salt water at the interface were studied at various stages of the river discharge.

The gradients of the interface and degrees of diffusion in steady and unsteady states of the salt wedge are different even though they correspond to the same discharge amount.

In the steady state, the relation between the discharge and the length of the salt wedge is represented by a curve whose shape is strongly influenced by the longitudinal profile of the river bed. From this relation, the critical discharge at which the salt wedge begins to penetrate into the river mouth was estimated as 550～600m^3/s.

According to the observational results at the station 4.4km upstream from the river mouth, the amplitude of the internal tide was intensified 5.2 times as large as the tidal motion of the surface. The change of the interface level was also influenced by a storm surge.

Acknowledgment

The authors would like to express their sincere thanks to the Hokkaido Development Bureau for supplying data of the river discharge of the Ishikari River.

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