CHAPTER 80

STUDIES ON SALT WEDGE BY ULTRASONIC METHOD

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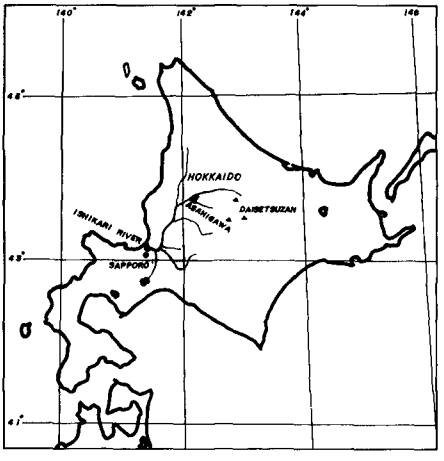
ABSTRACT

This paper presents some observational results on salt wedges obtained by the ultrasonic method at the mouth of the Ishikari River, with a description of some studies on the two-layer flow developed by the authors.

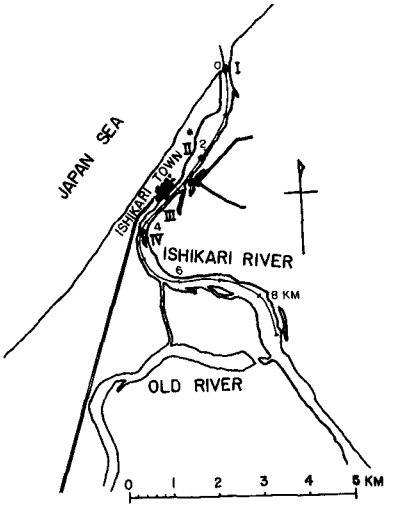
INTRODUCTION

The authors have been interested in the problem of water stratification at a river mouth, and have made a series of observations at the mouth of the Ishikari River in Hokkaido for many years.

The Ishikari River, which has a length of about 300 km, flows through the Ishikari Plane and pours into the Japan Sea, as shown in Fig. 1. The amount of normal discharge is $300 \sim 500$ m^3/sec. At the river mouth, a longitudinal and a sectional profile of salinity distribution can frequently be observed by a measurement of electric conductivity of water or by a chemical analysis of chlorinity contained in water.



(a) Hokkaido District and the Ishikari River.



(b) The mouth of the Ishikari River.

Fig. 1.

Several techniques, which were used by the authors in field observations, were a measurement of salinity by a chemical or elctrical analysis and somewhat indirect methods by a currentmeter, a thermometer, a turbidimeter, etc. Those techniques, however, were not sufficiently effective to perform an observation over a great distance in a short time.

Fukushima proposed an ultrasonic method which was essentially the same with an echo-sounder of high sensitivity. For example, when the salt wedge is in a state of weak mixing, an interface or an intermediate layer formed between the fresh water and the salt water can easily be recorded as shown in Fig. 9.

This paper describes this useful method and also presents some results obtained at the mouth of the Ishikari River.

SALT WEDGE AT THE ISHIKARI RIVER

The Ishikari River has a salt wedge which lies beneath the river water for a distance of more than 10 km under a normal river discharge. As the Japan Sea, to which the Ishikari River opens, has a small tidal range of about 30 cm at the maximum throughout a year, the salt wedge is formed very distinctly.

FUKUSHIMA (1942) observed a two-layer flow at the Ishikari River for the first time, with a currentmeter and a turbidimeter, and he detected a periodically moving two-layer which responds sensitively to a small tidal change.

FUKUSHIMA (1955) also devised a chemically recording tube, which drew a vertical figure of the two-layer in colour on a piece of chemical test-paper. The piece was fixed in the tube which was closed at one end, and was changed in colour by salinity contained in the water which invaded into the tube by pressure. He also investigated a vertical eddy diffusion by chemical analysis of chlorinity in sampled water. He found that coefficients of the vertical diffusion lay within a limit of $0 \sim 80$ c.g.s. He also found that the coefficient was extremely small at an interface of the two layers.

FUKUSHIMA et al. (1960) observed a growth of the salt wedge, which penetrates into the Ishikari River after a flood. The process is shown in Fig. 2. The distance of the wedge front from the river mouth increases gradually with time by drawing two steps. Fukushima et al. tried to explain the reason for the two steps by taking account of the bed configuration which has two large hollows along the river, and calculated the progressive velocity of the wedge front after a theoretical treatment. The result was in good agreement with the observation as shown in Fig. 2.

OTSUBO & KISHI (1959) and OTSUBO & FUKUSHIMA (1960) calculated shear stresses at the interface of the two layers. They obtained

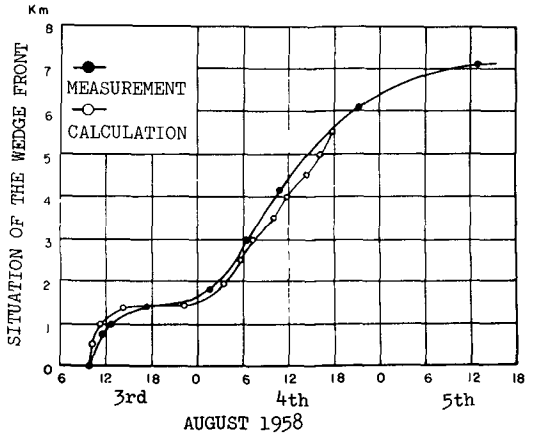


Fig. 2. Growth of the salt wedge.

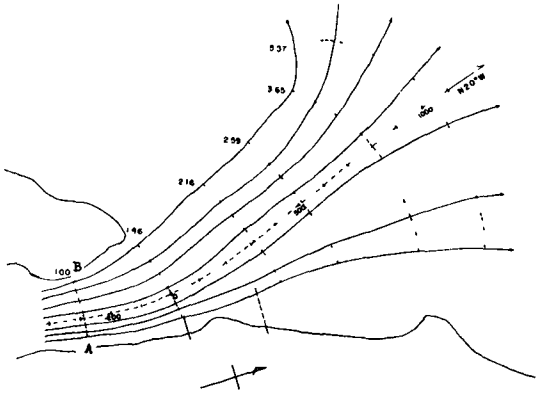


Fig. 3. Stream-lines of the outflow

the values of 0.16 ~ 1.22 dyne/cm^2 at the Ishikari River in a normal discharge of 283 m^3/sec. They also found that the salinity contained in the surface layer decreased exponentially with the distance upstream from the mouth, and explained it under assumptions of salinity balance and water mass conservation.

FUKUSHIMA et al. (1961, 1963) conducted precise observations on the two layers in the vicinity of the mouth of the Ishikari River. They observed a stream-line form of the fresh water outside the mouth for several times, and revealed that the interval of any two stream-lines increased exponentially with the distance from the mouth. The following is an example of the observation in July, 1960. The observation was made by using a dynamo current meter which was applicable to a quick measurement. By tracing the stream line from the distribution of the stream directions at about 60 spots on the sea surface, Fig. 3 was obtained. Broken lines correspond to velocity potentials, and every length of them may be a measure of the spread of the surface stream. By putting the breadth AB as unity, the relationship between the intervals and the distance along the middle stream-line was obtained as shown in Fig. 4. This shows that the stream has an exponential spread. Almost all examples for several years presented the same character with this example. The outflow from a river mouth has frequently been discussed by a turbulent jet theory without a consideration of a density difference of fresh and salt water. However, such a stream of this exponential type, cannot be explained solely by the jet theory, but it must be treated in taking account of the density

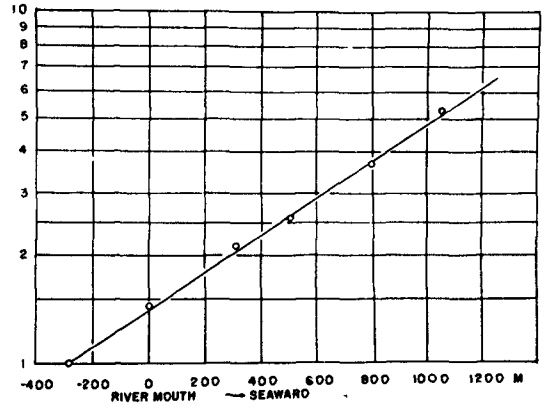


Fig. 4. Exponential spread of the outflow.

difference. The hydraulic condition of a transition from the exponential type into the jet type is now under study.

Besides those observations, the authors made precise measurements on the velocity and the thickness of the fresh water in the vicinity of the mouth. The stream was accelerated and the thickness was rapidly decreased at the mouth.

KASHIWAMURA (1963) studied a periodical motion of the salt wedge of the Teshio River, which also

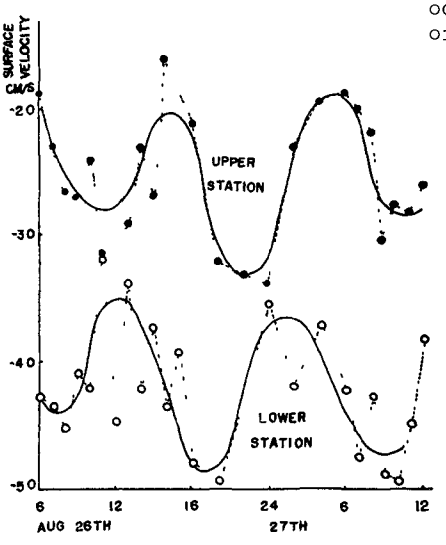


Fig. 5. Variation of the surface-velocity along the Teshio River.

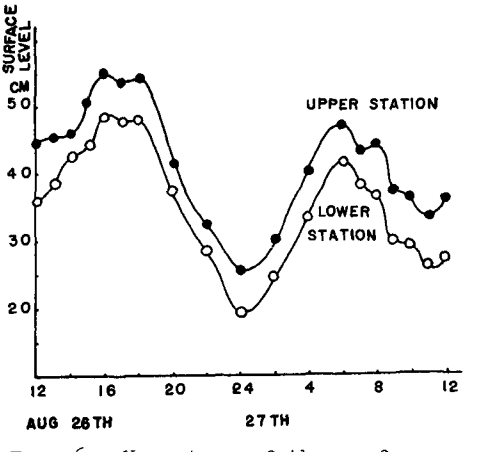


Fig. 6. Variation of the surface-level along the Teshio River.

opens to the Japan Sea. He observed periodical changes of the surface level and the surface velocity of the river in response to a tide. He found that the surface level shows a great difference in propagation celerity from the surface velocity. The change of the surface level propagates upstream in a few minutes for a distance of 5 km, in contrast with the surface velocity which takes

3 hours for the same distance. The difference between them is shown in Figs. 5 and 6. He explained the difference by a theory of internal wave. According to his theory, the propagation of the surface level was dominated mainly by an external wave, while the surface velocity was by an internal wave. As a result of calculation, the good agreement with the observation was obtained.

All the observations, which were carried out with the instruments already stated, generally needed many hours and many days. However, the ultrasonic method, which was proposed by Fukushima, brought a great advance in technique for a study on the salt wedge (FUKUSHIMA et al., 1963, 1964, and 1965). The method can draw a longitudinal figure of the salt wedge vividly on a recording chart and does it in a short time.

MEASUREMENTS AND RESULTS

Since ultrasonic wave is reflected at an interface between salt and fresh water and also at a river bed, a longitudinal profile of

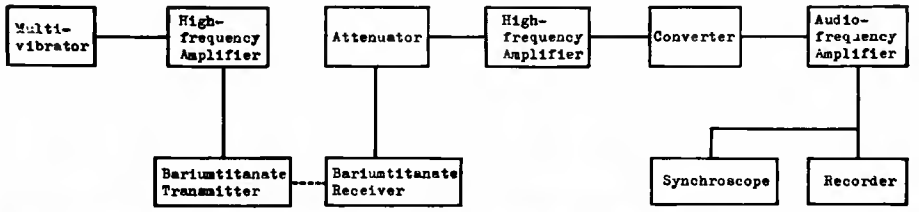


Fig. 7. Block diagram of the echo-sounder.

Fig. 8. Apparatus of the echo-sounder.

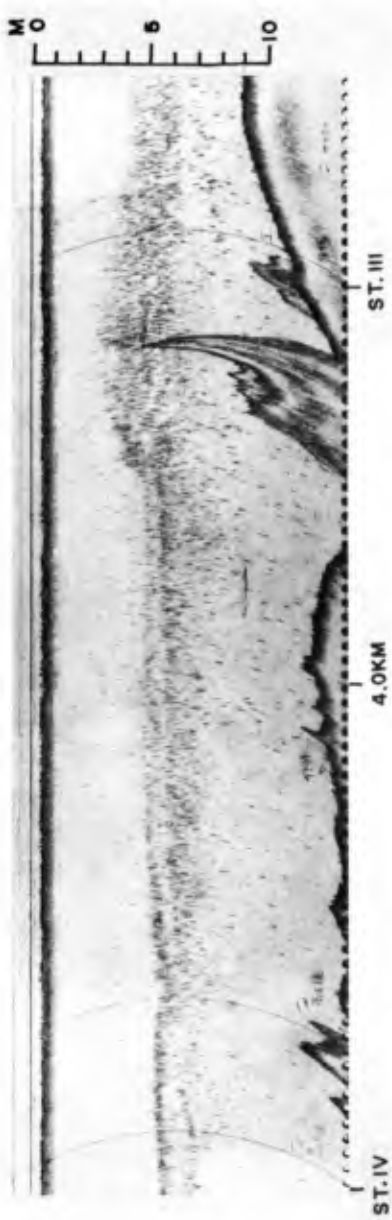


Fig. 9. A longitudinal profile of a salt wedge in the mouth of the Ishikari River (August 9,1963).

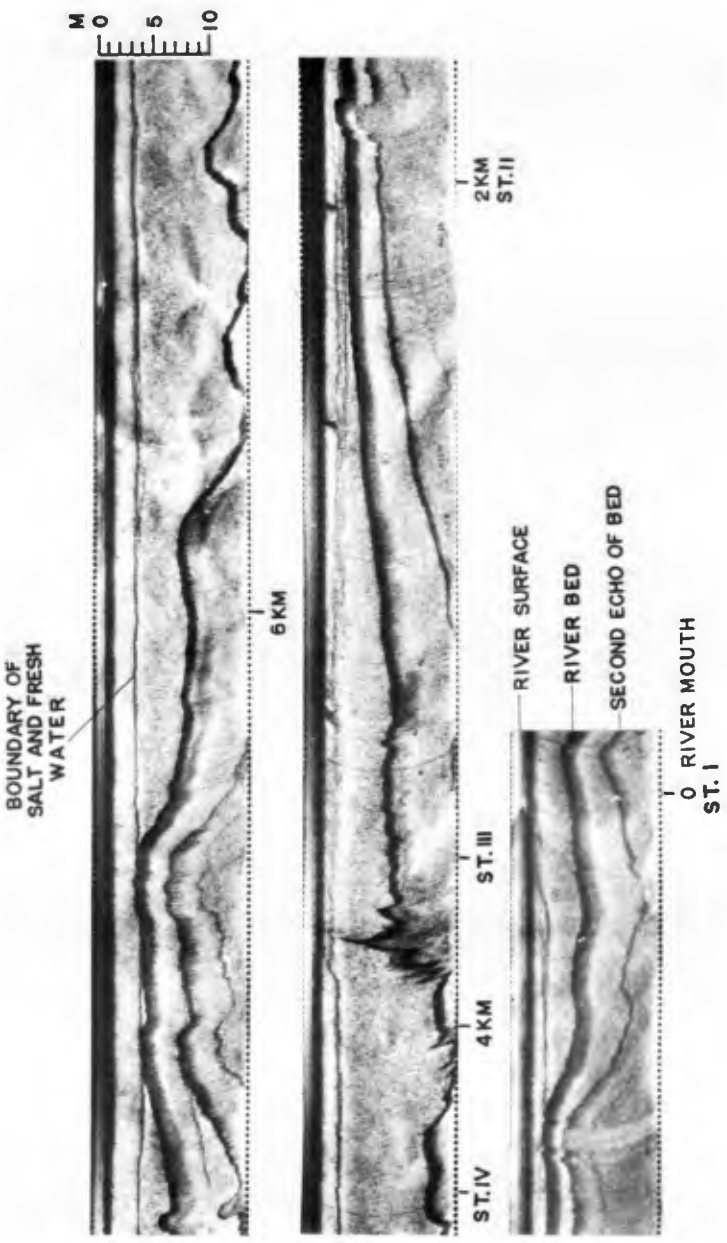


Fig. 10. A longitudinal profile of a salt wedge in the mouth of the Ishikari River (July 22, 1964).

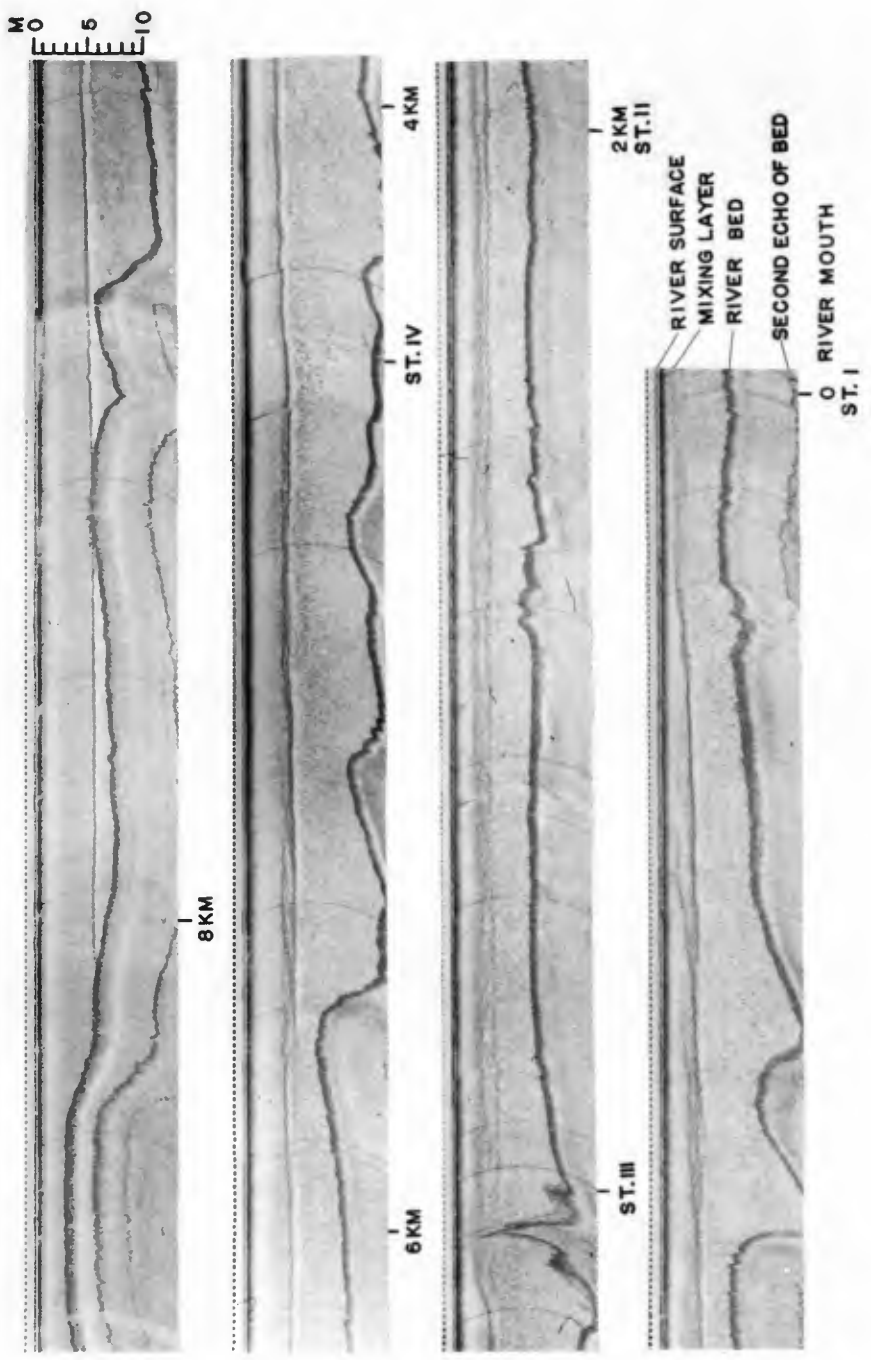
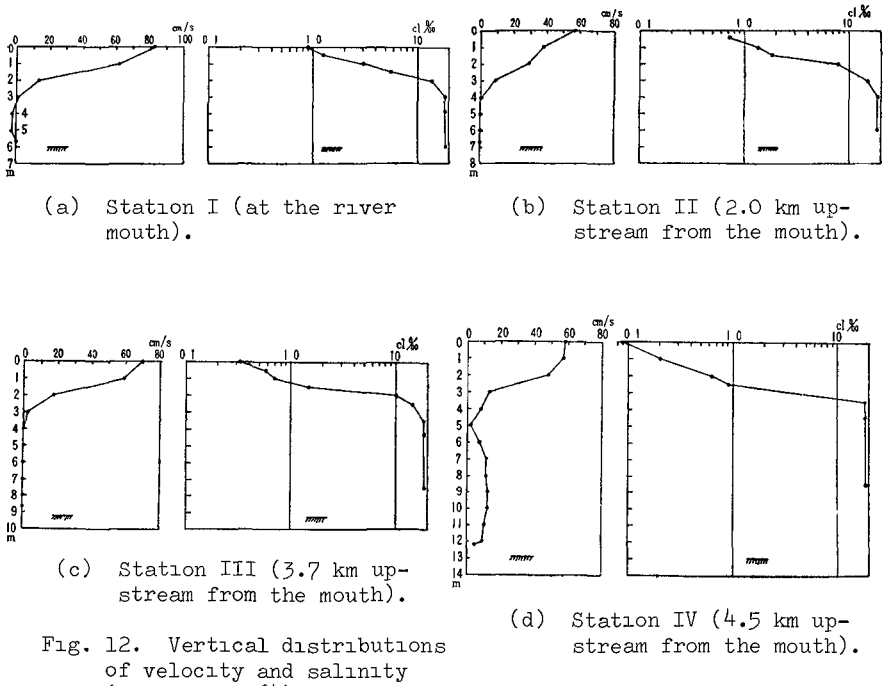


Fig. 11. A longitudinal profile of a salt wedge in the mouth of the Ishikari River (July 24, 1964).

a salt wedge as well as a river bed can be recorded by means of echo-sounding. The echo-sounder which the authors emplyed was of 200 KC in frequency and was specially designed for the use in shallow water of 0 ~ 12.5 m in depth. A block diagram of its electric system and a photograph of the apparatus are shown in Figs. 7 and 8.

A series of observations on the salt wedge have been conducted by using this method at the mouth of the Ishikari River during the period from 1961 to 1965. One of the typical records is shown in Fig. 9.



(a) Station I (at the river mouth).

(b) Station II (2.0 km upstream from the mouth).

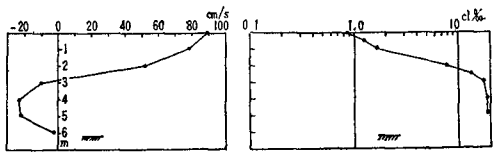
(c) Station III (3.7 km upstream from the mouth).

(d) Station IV (4.5 km upstream from the mouth).

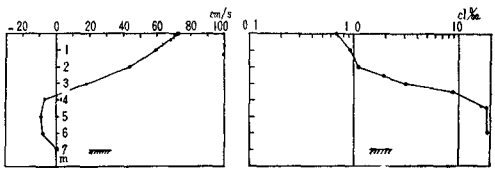
Fig. 12. Vertical distributions of velocity and salinity (July 22, 1964).

Vertical distributions of velocity and salinity were measured together at several stations at the same time with echo-sounding. According to the record, it is found that there are rises and depressions along the river bed. The behavior of the salt wedge, therefore, is somewhat different with that of an ideal river with a flat bed. Outside the mouth the depth of water is gradually decreased owing to sediments issued from the river.

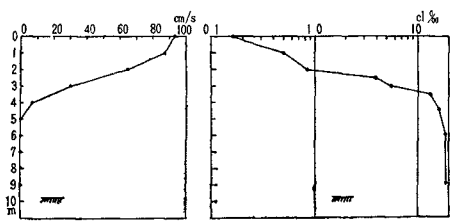
Among the records of the salt wedge at the Ishikari River, two examples are shown in Figs. 10 and 11. Both records were obtained over a distance of 9 km that stretches upstream from a station located about 1 km outside the mouth. The vertical distributions of velocity



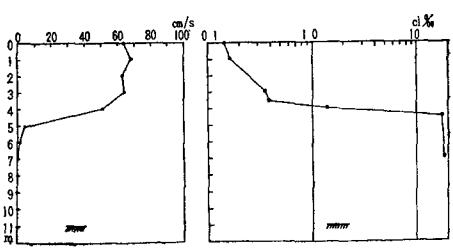
(a) Station I (at the river mouth).



(b) Station II (2.0 km upstream from the mouth).



(c) Station III (3.7 km upstream from the mouth).



(d) Station IV (4.5 km upstream from the mouth).

Fig. 13. Vertical distributions of velocity and salinity (July 24, 1964).

and salinity at stations I, II, III and IV in Fig. 1(b) are shown in Figs. 12 and 13.

According to Figs. 10, 11, 12 and 13, a discontinuity in salinity is remarkably sharp at the interface of salt and fresh water, and particularly at the station IV, the interface is very clear. At the station III, however, mixing of the fresh water and the salt water is considerably strong and a clear stratification can no longer be seen. Such a transition of the interface is believed to be resulted by a stationary internal jump which is caused by a big projection on the river bed. The water thus once mixed at the station III gradually diffuses into the fresh water layer while it flows downstream, and the interface recovers its clearness at the station II. At the river mouth (station I), flow-out velocity of the fresh water and flow-in velocity of the salt water are both large because of a vertical circulation of water due to the conservation law of water mass and salinity. Therefore, mixing of both the layers is strong at the river mouth and the salinity of the surface layer

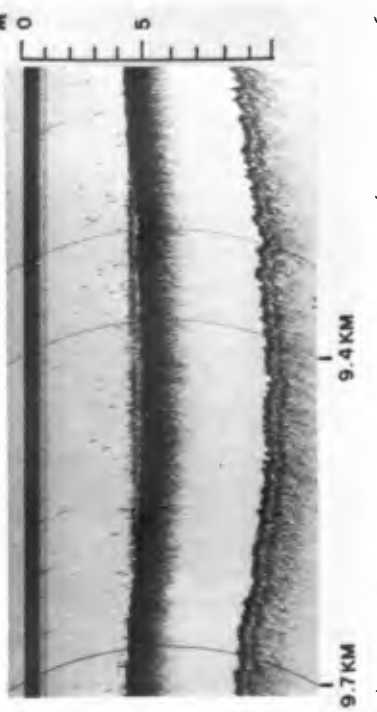


Fig. 14. Salt water remained in a depression (August 11, 1965).

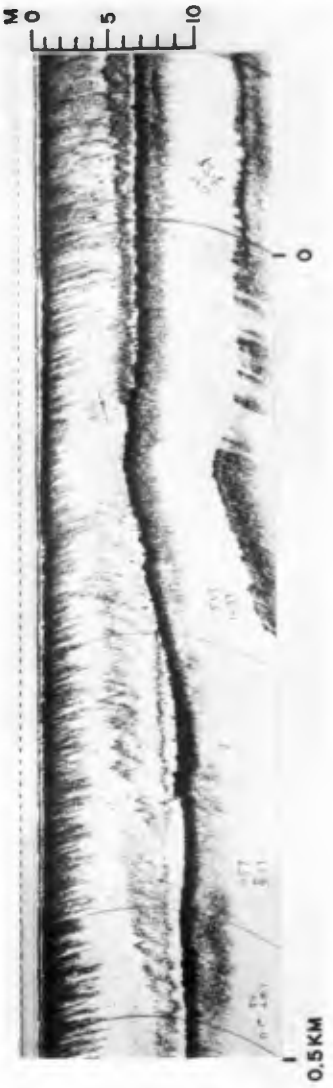


Fig. 15. A longitudinal profile of a salt wedge in the mouth of the Ishikari River (April 25, 1964).

rapidly increases outside the mouth.

When the record in Fig. 10 was obtained (on July 22, 1964), a discharge of the fresh water was observed as 190 m^3/sec which was in a state of low-water that is frequently experienced in summer. In this case, the interface was stable and the front of the salt wedge reached a point about 8.9 km upstream from the mouth.

On the other hand, in a case of Fig. 11 (on July 24, 1964), the discharge was larger than the former case as 380 m^3/sec due to a rainfall, and the interface was no longer so clear except at the upper part of the salt wedge. Mixing of the salt water and the fresh water can be found everywhere along the interface.

When the discharge of the fresh water increases, the front of the salt wedge recedes. Sometimes, however, the salt water can be detected on the river bed even at a station further upstream from the wedge front. This suggests that the salt water is sometimes left in hollows on the river bed even when the wedge front has been driven down by an increase of the fresh water. Fig. 14 shows a record of the salt water left in a bed hollow which is located at a distance of 9.4 km upstream from the river mouth.

The critical discharge of the fresh water Q_{out}, at which the salt water is completely washed away from the deepest hollow near the river mouth, namely the salt water cannot be found inside the mouth, seems to reach a considerably large value which is at least more than 1400 m^3/sec at the Ishikari River.

When the discharge of the fresh water decreases again below a certain critical value Q_{in}, which is estimated as $550 \sim 600$ m^3/sec at the Ishikari River, the salt wedge begins to invade into the mouth. The salt wedge grows by filling up the bed hollows successively with the salt water.

Fig. 15 is an interesting record that the salt water is left 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 front of the salt water is wedge-shaped. Internal waves can be recognized at the interface. The salt water in the hollow is diffusing into the upper fresh water.

The peak value of the discharge during the observation that is shown in Fig. 15, was measured as about 1400 m^3/sec. Therefore, the critical discharge Q_{out} at which the salt water completely disappears inside the river mouth can be estimated to reach a value of more than 1400 m^3/sec.

CONCLUSION

A series of observations and studies have been made on the

salt wedge at the Ishikari River. As a new technique of detecting a salt wedge, the authors employed the ultrasonic method, which is the same with an eco-sounder in principle but of particularly high sensitivity.

The record presents a detailed profile of a salt wedge as well as some dynamical behaviors, namely, a stability or a mixing process of the interface of salt water and fresh water, a slope of the interface, a longitudinal change of a thickness of the fresh water, an internal jump or an internal wave, etc. The ultrasonic method is very useful for a study of the salt wedge and even a common stratified flow.

REFERENCES

FUKUSHIMA, H. (1942): Observations at the mouth of the Ishikari River. Journal of the Oceanographical Society of Japan, Vol. 1, No. 1, (in Japanese).

FUKUSHIMA, H. (1955): On the eddy diffusion in water layer of estuary. Bulletin of the Faculty of Engineering, Hokkaido University, Vol. 12, (in Japanese).

FUKUSHIMA, H., M. KASHIWAMURA, I. YAKUWA and S. TAKAHASHI (1960): On the growth of a salt wedge in the Ishikari River. Geophysical Bulletin of the Hokkaido University, Vol. 7, (in Japanese).

OTSUBO, K. and T. KISHI (1959): Invasion of salt water at a rivermouth. Technical Report of Civil Engineers in Hokkaido, Vol. 15, (in Japanese).

OTSUBO, K. and H. FUKUSHIMA (1959): Density currents in a river mouth with a small tidal range. International Association for Hydraulic Research, 8th Congress.

FUKUSHIMA, H., M. KASHIWAMURA, I. YAKUWA and S. TAKAHASHI (1961): Water stratification at the mouth of the Ishikari River. 8th Meeting of Coastal Engineering in Japan, (in Japanese).

FUKUSHIMA, H. and M. KASHIWAMURA (1963): On the dynamical problems at the mouth of the Ishikari River. Coastal Engineering in Japan, Vol. 6.

KASHIWAMURA, M. (1963): Variation of surface velocity in a tidal river. Journal of the Oceanographical Society of Japan, Vol. 19, No. 1.

FUKUSHIMA, H., M. KASHIWAMURA, I. YAKUWA and S. TAKAHASHI (1964): A study on the salt water wedge at a river mouth by the ultrasonic method. Coastal Engineering in Japan, Vol. 7.

FUKUSHIMA, H., M. KASHIWAMURA, I. YAKUWA and S. TAKAHASHI (1964): Studies on the mouth of the Ishikari River - 1. 11th Meeting of Coastal Engineering in Japan, (in Japanese).

FUKUSHIMA, H., M. KASHIWAMURA, I. YAKUWA, S. TAKAHASHI and M. OTANI (1965): Studies on the mouth of the Ishikari River - 2. 12th Meeting of Coastal Engineering in Japan, (in Japanese).