Effect of wind on highly stratified flow

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Abstract

Generally, the response of the river water level in an estuary to the river flowrate is far from simple. The main reasons for this are the four competing factors of tide, atmospheric pressure, wind direction and wind speed, whose effects drive the river level to a variety of elevations. The error represented by the average of that dispersed group can at times be over 200%. No matter what statistical analysis is applied, no plausible estimate of the flowrate can be made from the river level alone. This paper uses data taken in the Ishikari River estuary over the last 5 years to present a quantitative relationship of the above 4 factors on the level of the Ishikari River. These relationships permit highly precise calculation of the river flowrate, using observed values of the above 4 factors, at any arbitrary location in the estuary.
Keywords: estuary, river mouth, two-layer flow, river level, tidal river, flowrate, H-Q curve.

1 Introduction

It has been over 60 years since the inaugural research into highly stratified rivers in Japan with observations of the salt wedge in the Ishikari Estuary in 1939 (Fukushima [2]). Stratified flow problems are far better known now, and a large number of researchers have provided a generous fund of data on stratified flows in estuaries and the littoral zone (Dyer [1]; Officer [5]; Manual of Hydraulic Engineering [4]; Yoshida [8]). However, some reflection on the currently available results will show that even though it has become possible to predict the shape of the salt wedge in quasi-steady flow, nearly all real estuarine flows are *not* quasi-steady, because of the various factors influencing real rivers. It is difficult to say that previous research has been that helpful for practical river management. The main reason for this impasse is the great expense of field

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observations. Most studies in highly stratified flows are theoretical or laboratory-based, rather than observations of actual estuarine phenomena. Of course, there have been a few observations of actual estuarine flows, but the number of factors controlling these natural phenomena is huge, and it is extremely difficult to infer empirical laws which point to essential properties of estuarine flows from the available results.

With the goal of breaking past the impasse, several years ago, the authors installed water level stations and constructed three river-sea water interface observation stations at strategic locations on the Ishikari Estuary. We have conducted several thorough field studies of that estuary. These include 24-hour observations of salinity at certain locations during drought, longitudinal section sonar surveys of the salt wedge during various hydraulic conditions, and simultaneous automatic continuous surveys of surface salinity at multiple locations. These have allowed assessment of many factors controlling these flows: flow rate, atmospheric pressure, tide, wind direction, and wind speed (Yoshida et al. [7, 8, 9]). This study presents some quantitative assessments of those results, with emphasis on the great effect of the wind on estuarine flows.

2 Observation methods

Figure 1 is a diagram of the geography of the Ishikari Estuary, which was the object of the observations for this report. The total length of the Ishikari River is 268 km, and its valley covers 14, 330 km^2. The estuary is about 45 km in length. Sea water invades the river mouth and estuary for about seven-tenths of the year, forming a so-called “highly stratified flow” or “two layered flow” system. Since this structure is mainly complicated by meteorological factors, it has taken long-term, thorough observations including meteorological observations of the entire estuary to gather the long-term background data necessary to understand events in this river. This research has examined a large number of parameters. Water levels were recorded at 12 locations in the estuary (KP44.5, 38.5, 35.0, 30.0, 26.6, 20.0, 15.0, 10.0, 4.5, 3.0, 1.6, 0.1; nomenclature corresponds to km upstream of the river mouth). The flow rate was recorded at KP44.5, where no tidal effect is observed, and the salt-fresh water interface levels, which affect water levels, were recorded at KP26.6, 15, 0 and 4.5. Longitudinal sections of the salt wedge were scanned 5 times each summer. Surface (1 m depth) salinity measurements were taken at 6 locations (KP20.0, 14.0, 11.7, 9.0, 4.5, 3.0), the ocean water level was measured in Otaru Harbor, in the west of Ishikari Bay, the atmospheric pressure was measured at KP4.5, and the wind direction and speed were recorded at 3 locations (KP26.6, 15.0, 4.5). Other data were also taken in 24-hour observations.

3 Results and analysis of observations

3.1 Effect on river water level of wind direction and speed

First, the effects of atmospheric pressure and tide were eliminated from the data by subtracting the measured value of water level in Otaru Harbor from the

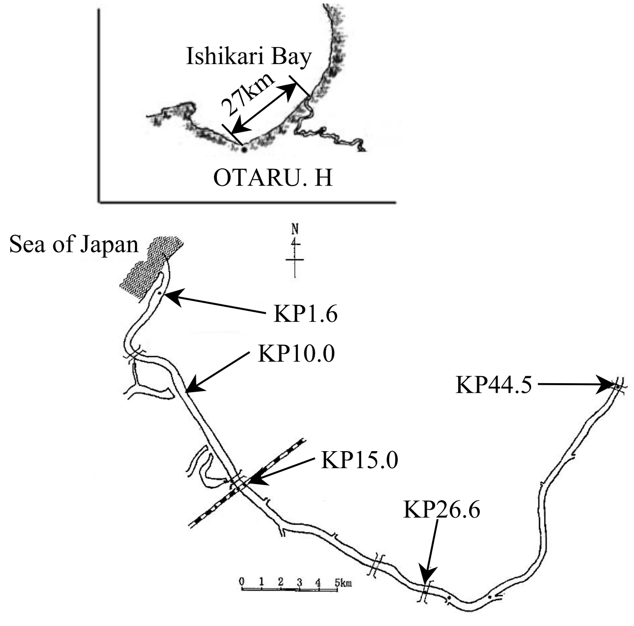

Figure 1: Geography of Ishikari Estuary.

measured water level at the river mouth under the condition of a constant river flowrate (the water level at Otaru Harbor shows almost no rise due to wind, because of the seawall, but since there is no seawall at the river mouth, the water level is dramatically raised by WNW–NW winds). The reason for this was to look for a relation between wind parameters and water level at the river mouth. Figure 2 was obtained after examining for various relations between wind direction and speed and water level at KP26.6 and KP1.6. For the sake of clarity, the figure only shows results from two locations, but the water level data from all 12 locations were consistent with the results shown. The results are also limited to those wind directions paralleling the main orientation of the flow in the estuary, namely WNW–NW and ESE–SE. The solid lines approximate the empirically observed relation between the variations in wind speed and in water level fluctuations. The moving average (10-minute averages) values for maximum wind speed U and water level H_{wmax} were plotted (instantaneous values at 30-minute intervals). The positive and negative portions of the horizontal axis represent WNW–NW (blowing upstream) and ESE – SE wind directions, respectively. Figure 2 indicates that H_{wmax} rose quadratically fashion with increase in wind speed in the positive direction. For example, when wind speed was 15 m/s, the rise in water level at KP1.6 was 0.48 m, and at KP26.6, it was 0.60. These magnitudes were considerably larger than the rises attributable to tide or atmospheric pressure. When the wind was blowing in the negative direction, the closer the direction to NW, the less effect there was, but the water level change under a 15 m/s at KP1.6 wind was –0.10 m, and at KP26.6, it was –0.30 m. The relation between wind speed and water level was examined in the same way for speeds at or below 3.0 m/s; the results are shown in Fig.3. This figure shows the water level H_{tn} with the river flow rate Q, which itself is unaffected by wind speed. The two empirical relations obtained at this stage provide a relation between water level and flow rate for any arbitrary point in the estuary; the reader is invited to examine this further in one of the authors' previous papers (Yoshida et al. [9]).

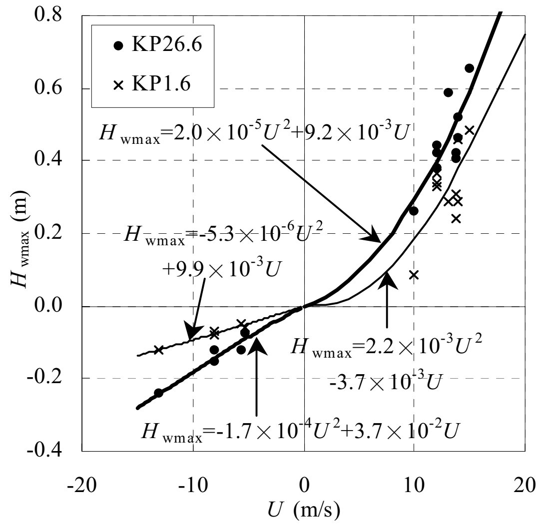

Figure 2: Relation of wind direction and speed with rise and fall of water level.

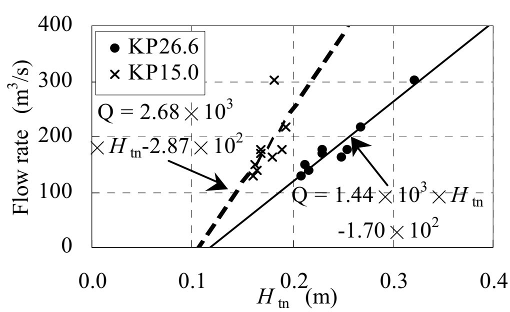

Figure 3: Relation between water level and flow rate under windless conditions.

A very important phenomenon was identified which occurs because of the effect of the wind on river water level. It seems at first glance to be an unlikely event, but in fact, it is not that rare during drought. During June–July, 2003, the flow rate of the Ishikari River reached the lowest volumes ever recorded. Because of this, the salt wedge reached the greatest length ever seen, extending to KP29.5. During this time, an ESE–S wind blew continuously at speeds of 5–9 m/s. The river water salinity increased to an extreme level. Figure 4 shows the surface salinity (depth 1 m) measured on July 5–10 at 3 representative points of 6 points between KP3.0 and KP 20.0, for comparison with the wind parameters from KP15.0. This shows that the sharp increases in the surface salinity was not merely due to the great length of the salt wedge extending upstream, but rather, to the continuous wind blowing ESE – S down the river valley. Well, then, what causes this rise? Details of this will be described in the following section; first, let us examine the mechanisms at work, as this will illuminate the findings described later.

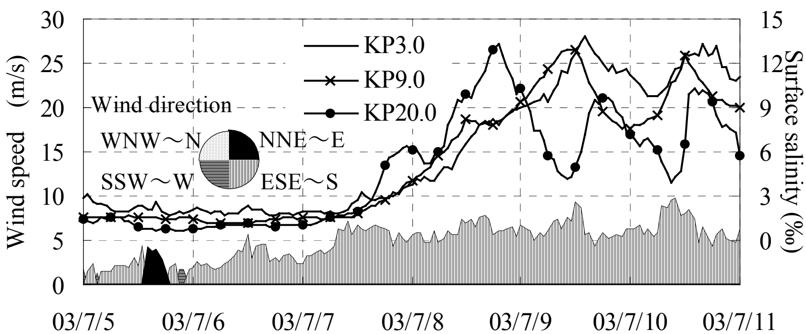

Figure 4: Time series of wind surface salinity data.

First of all, as shown in Fig.1, the river curves sharply near KP30.0, then remains nearly straight until the vicinity of KP5.0. It is notable that most of the salt wedge remains within this straight section. Figure 5 shows the actually measured shape of the water surface under a continual ESE–S wind. This indicates that the water level drops by 0.15–0.20 m between KP30.0 and KP5.0 under higher wind speeds; it can even take a "bowl" shape. This is caused by surface frictional stress imposed by the wind. The fall in level is not large in comparison to the total river depth, and the acceleration of the upper layer is also small; however, in response to the thinning of the upper layer, there was a quite marked upwelling of the lower, sea-water layer. This will be described later. In fact, the salt wedge rose to about 1 m below the river surface during the period when there was a local minimum water level around KP15.0–26.6. The interface did not remain flat under these conditions. It developed the instability waves shown in Fig.6, greatly accelerating the diffusion of salinity into the upper layer.

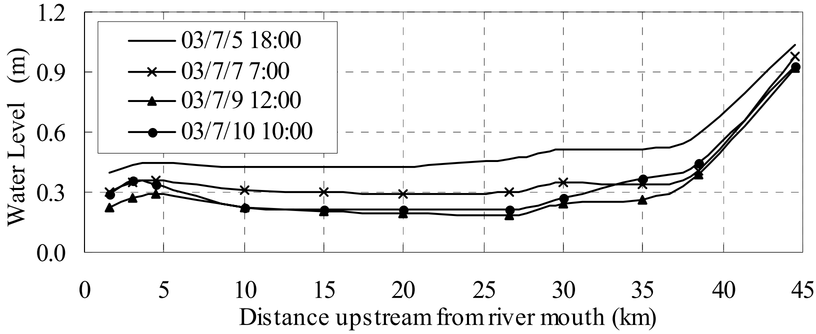

Figure 5: Longitudinal cross section of water level.

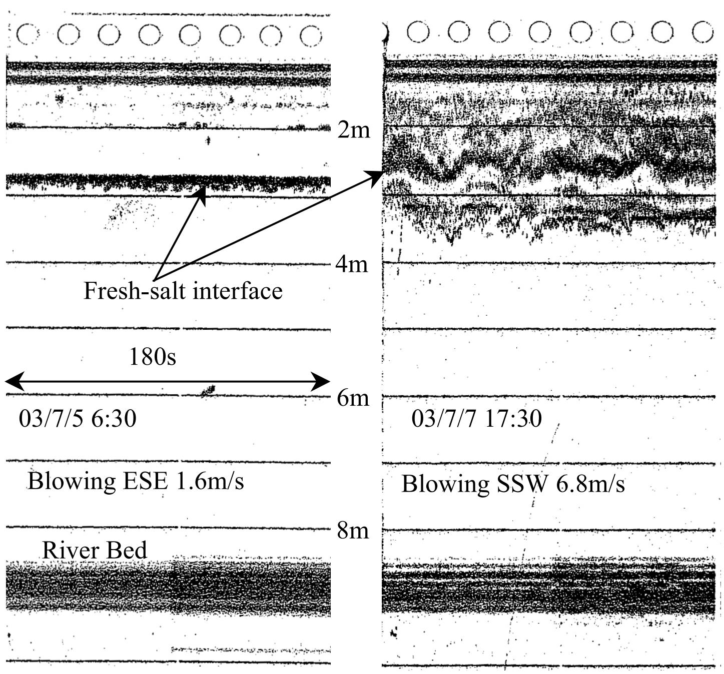

Figure 6: Sonar observations of fresh-salt interface.

In contrast, when the wind was blowing in the opposite direction, the wind stress decelerated the downstream flow of the upper layer, thickening the upper layer and increasing the pressure exerted by it, so that the interface dropped until a new equilibrium was reached. Even when the rise in level due to wind transport is subtracted, there is no significant fall in water surface level. It is speculated that this is because there is a rise in water level approximately equal to that caused by wind transport.

Extreme water level rises sometimes occur due to wind transport, causing flood damage. An example of this occurred on 26 December 2003, during a winter low-pressure system, giving rise to high winds, which is typical for Hokkaido. On that date, high winds blew from the SE, then SW, then N, at a maximum recorded speed of 20 m/s. An abrupt rise occurred in the sea surface, causing flooding of residences near tributaries of the Ishikari River. There have been such strong winds before; it is not yet understood why this is the only recorded time such severe flooding followed them. This unusual rise in the sea water surface caused a historic rise in the upstream water level. Figure 7 shows the record of the propagation of the water level rise. According to this record, there was even a 0.7 m rise in water level at KP45.5, the innermost tip of the estuary. It will be necessary to elucidate the mechanisms for the occurrence of this event; this will probably require consideration of the topography of the Ishikari Bay.

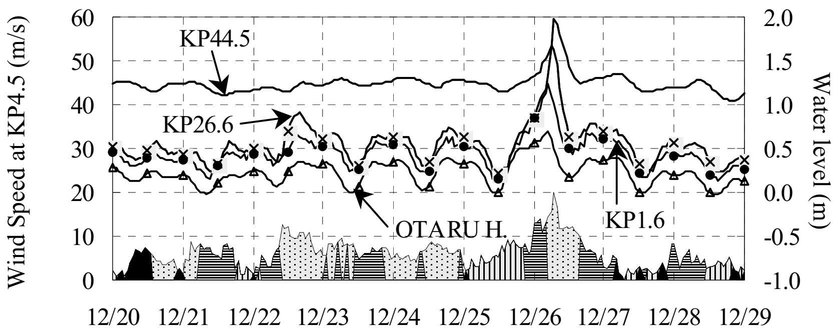

Figure 7: Time series of wind and water level (example of unusual water level).

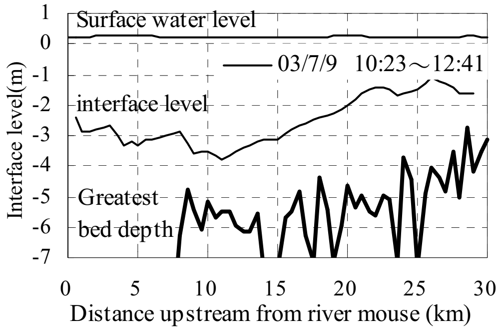

Figure 8: Observed interface shape for wind blowing in the ESE-S directions.

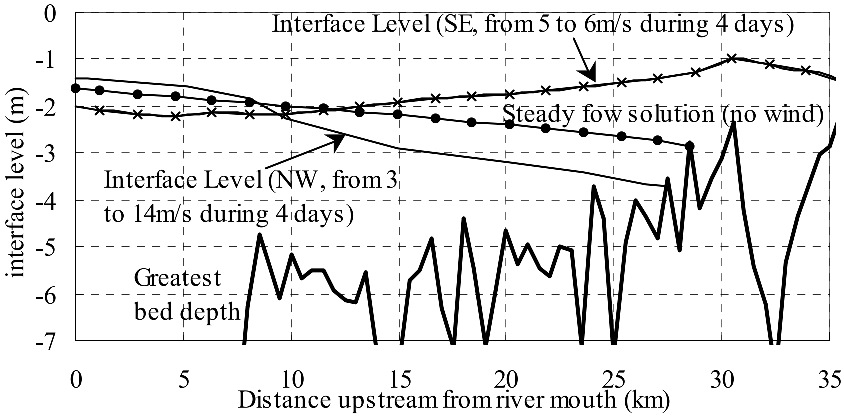

Figure 9: Calculated shapes of interface for f_a=4.0x10^{-6}.

3.2 Effect on salt wedge of wind direction and speed

Figure 8 shows a longitudinal section sonar survey of the salt wedge during drought on 9 July 2003. The figure shows the physically contradictory finding of an increasingly high interface with increasing distance from the river mouth. This represents the upwelling of the tip of the salt wedge mentioned earlier. It was caused by continuous wind blowing in the ESE–S directions. Thus, the wind exerts a powerful effect not only on the water surface but also on the level of the interface.

3.3 Numerical calculations for highly stratified flow including wind direction and speed

The aforementioned dynamic mechanisms for the fluctuations of water level appearing in the water surface and interface were touched upon in §1; this section will provide some numerical results which help explain them. To save space, the reader is referred to an earlier work (Yoshida et al., 2000, see eq. (1) ~eq.(4) for an explanation of the equations for layer mean values. It must be noted that the following correction must be added to the right side of the equation of motion for the upper layer.

$$-\frac{f_a}{2gh_1}\left(U_a - U_1\right)\left|U_a - U_1\right|$$

The results of the calculations are shown in Fig.9. A river flowrate of the observed 110 m^3/s and the wind conditions shown in Fig.4 are also provided for comparison with the results in Fig.8. A value slightly higher than the mean value of that proposed by many researchers (Manual of Hydraulic Engineering 1963) was used for wind stress coefficient on the water surface. In addition, a value was used for interfacial coefficient of friction which well accounts for the interface shape during windless conditions. The interfacial coefficient of friction is an essential factor in the general theory of highly stratified estuarine flow and is discussed in the following section.

The results shown in Fig.9 clearly show that the salt wedge extends further upstream under wind blowing downstream than it does during a windless period, and that the tip rises very close to the surface. Thus, the dynamic model confirms the explanation of wind stress as the cause for this actual phenomenon. Space considerations preclude further discussion here, but the model also predicted quite well the lowering of the interface beneath the level observed during windless periods which was observed under downstream winds.

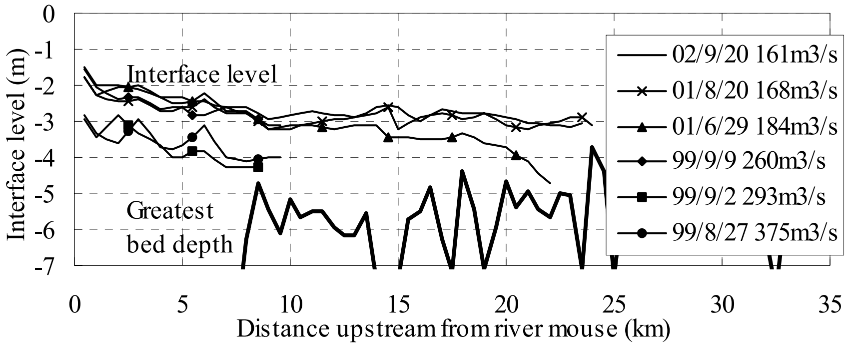

Figure 10: Observed longitudinasl sectioons of salt wedge (no wind).

3.4 Interfacial friction coefficient

The conventional method for estimating the interfacial friction coefficient has been to solve for it from known quantities in the interface shape, since it has been impossible to predict it. That method has led to the following formula for the interfacial friction coefficient f_i :

$$f_i = C\Psi^{-0.5} \tag{1}$$

where Ψ is the Iwasaki number equal to the reciprocal of the cube of Keulegan number and C is any of several proposed values, all of which have been less than 1 (Manual of Hydraulic Engineering [4]).

In order to verify whether C actually a constant, sequences of data were extracted from the present large data base for periods when the flow rate of the Ishikari was constant and there was no wind. The interface shapes during these flows were examined. The results of this analysis are shown in Fig.10. To the authors' knowledge, this is the first available analysis based on observational data, so the expression given below is a particularly valuable finding of this report. As for river bottom topology, the densimetric Froude number at the point considered the river mouth was much smaller than 1 for all cases considered; therefore, the observed densimetric Froude numbers were employed.

These results were solved to back-calculate C, yielding Fig.11. There is not enough data and the inconsistencies cannot be ignored, but it appears that C can be approximated by the following:

$$C = 0.0094Q^{0.352} \tag{2}$$

Equation (2) is operative under the following flow rates:

$$150\mathrm{m}^3/s < Q < 400\,\mathrm{m}^3/s \tag{3}$$

The above result was used for the calculations in the previous section. Result (2) actually presents a very important point. Formerly, C was believed to be a constant. This result, in combination with the steady-state salt wedge shape provided in Fig.10, may open the way to a much better understanding of the interfacial friction coefficient.

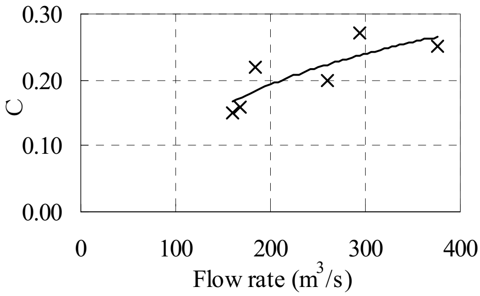

Figure 11: Relations between flow and *C*.

4 Conclusions

The following summarizes the conclusions drawn from this research.

(1) It was possible to find a function for sea level at a river mouth in terms of wind direction and speed.

(2) There is a straight section of the Ishikari River where wind transport under upstream winds causes a rise in the river level relative to the level during windless periods while the interface level falls below the ordinary level during windless periods. Correspondingly, when the wind blows downstream in this section, the river surface falls below its normal level and the interface rises above its normal level during windless periods.

(3) A dynamic analysis showed that the above phenomena of the water surface and the interface are caused by wind stress.

(4) The interfacial friction coefficient was found to be independent of any factor affecting water level except flowrate.

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