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Quantitative assessment of the most decisive factors determining river level in an estuary

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Abstract

Generally, the response of the river water level in an estuary to the river flow rate 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 flow rate can be made from the river level. This paper uses data taken in the Ishikari River estuary over the last 5 years to present a quantitative relationship for of the above 4 factors on the level of the Ishikari River. These relationships permit highly precise calculation of the river flow rate, using observed values of the above 4 factors, at any arbitrary location in the estuary.

1 Introduction

It is essential to find the correct relationship between flow rate and river level in order to have information about the flow rate during flood and about uses of the river water like agriculture and hydroelectric generation. Normally, the river flow rate is assumed to be given by the level through the empirical *H-Q* equation,

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where H is the water level (height) and Q is the flowrate[1], but during drought, it becomes extremely more difficult to apply this expression to the estuary than to locations upstream. This is because the river level can take a large range of values under the influence of the four key factors of tide, atmospheric pressure, wind direction and wind speed[2,3]. In the present study, data taken in observations of the Ishikari River estuary over the last 5 years have been used to identify a quantitative relationship between the four factors and the alteration in the water level described above. Also, it will be shown that the obtained relationship and the observed values for the four factors and the water level enable prediction of the river flow at any arbitrary river location or time with dramatically higher precision than conventional methods.

2 Observation methods and results

The portion of the Ishikari River which was the object of this paper is shown in Fig.1. The Ishikari is a river, 268 km long, and its valley covers 14,330 km^2. It enters Japan Sea through the Ishikari Bay from the south-east. Its estuary measures about 44.5 km long. Because ocean water invades the estuary from the mouth about 70% of the year, creating a so-called 'highly stratified' flow[4,5,6,7,8] consisting of two layers, in many cases, the flow structures in the lower reaches of the river are complicated; often, long-term and thorough observations of not only the entire estuary but also background influences like the weather are necessary to understand conditions in the river. This study describes the lower reaches of the Ishikari over the last 5 years. The observed quantities used in this study are the river levels at 8 locations (KP44.5, 26.6, 20.0, 15.0, 10.0, 4.5, 3.0 and 1.6), and the parameters which affect them, including flow rate, length of the salt invasion, level of the ocean (at Otaru Harbor), atmospheric pressure (KP4.5), and wind direction and speed at KP26.6, 15.0, and 4.5.

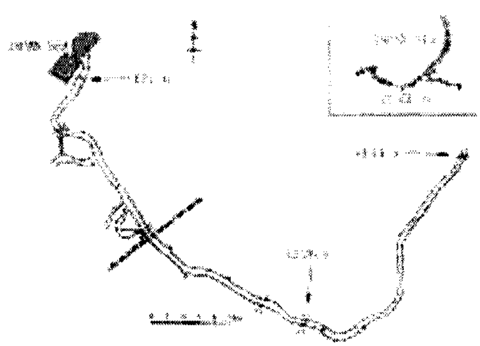

Figure 1: Tidal lower reaches of the Ishikari River

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Fig.2 displays the observed water level (*H*) and flow rate (*Q*) near the uppermost reach of the tidal lower reaches, at KP44.5. This excludes flood conditions; flow rate was below 1,000 m^3/s. The time span was, as mentioned above, the last 5 years. It is plain from the data here that the water level and flow rate show a good correlation, with a one-to-one correspondence between the two. The same information is provided in Fig.3 for the point KP26.6, over the same time period. Here, the relation between *H* and *Q* shows much scatter, and this tendency is stronger at lower flow rates. For example, at H=0.40m, which corresponds to a steady flow rate, the flow rate was $50<Q<400$ m^3/s, a quite high range of scatter. The reasons for this scatter will be explained below. First, some comments should be made about the characteristics of river flow which are obvious from the records of water level. Fig.4 shows time series of the fresh water layer thickness and flow rate per unit width at KP26.6 over the period 30 June – 10 July, 2001, recorded with an ADCP (WH-1200 Hz) placed on the bed at the center of flow. The flow rate per unit width is calculated from the average flow velocity and the depth[8]. According to this figure, height H≒0.7 m functions as a borderline. Below this the water level fluctuates as in a semidiurnal tide, and the flow rate per unit width is seen to increase and decrease in response to them. Those phases are not of equal length, however; they differ by about 3 hours. The reason for this is, the flow speed lags behind water level by $\pi/2$. When *H* is above 0.7, the flow rate remains unaffected by tide, and the flow rate increases

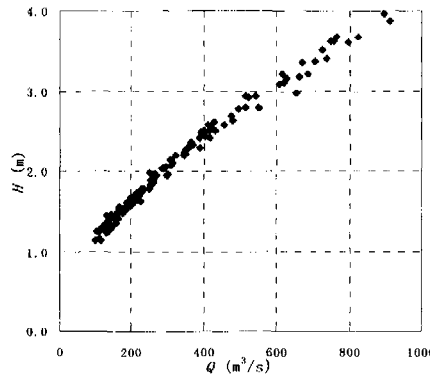

Figure 2: The observed *H* and *Q* at kp44.5

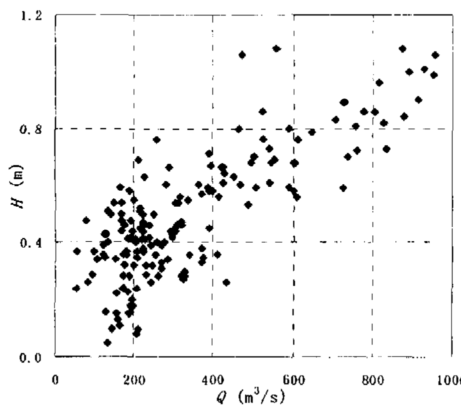

Figure 3: The observed H and Q at kp26.6

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and decreases without phase. Another factor is visible in the rise of the river on 6 and 9 July. Even though the peak flow on the 6 was greater than that on the 9, the flow on the 9 was higher. Furthermore, the peak in water level on the 6 was extremely steep, and could not have been caused by the tide or changes in the river flow rate. This new phenomenon must have been brought about by factors other than the tide or flow rate; it must be assumed that these were the factors of atmospheric pressure or wind.

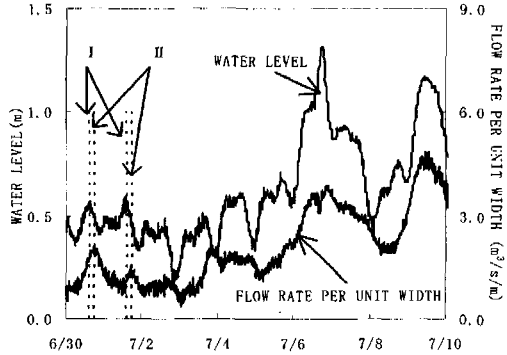

Figure 4: Relation between *H* and Flow rate per unit width

3 Assessments of 4 factors contributing to water level

This chapter provides a quantitative assessment of each of the four main factors in water level fluctuation described above.

3.1 Estimate of influence of tide and atmospheric pressure on water level

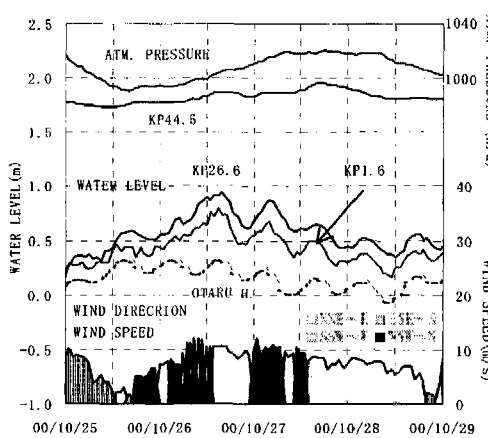

Figure 5: Time series of water level during drought and strong wind.

Fig.5 and 6 present examples of measured data for all four of the above factors, observed 25 – 29 October 2000 and 18 – 22 June 2001, respectively. From the top of the figures down, these data were taken at KP4.5 (atmospheric pressure), KP44.5, 26.6 and 1.6 (water level), Otaru Harbor tidal level, and wind speed and direction at KP4.5. Otaru Harbor is in the western portion of Ishikari Bay and has little effect on the sea level during summer season. The data at KP20.0, 15.0, 10.0, 4.5 and

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3.0, locations between KP26.6 and KP1.6, are omitted from the figure for legibility.

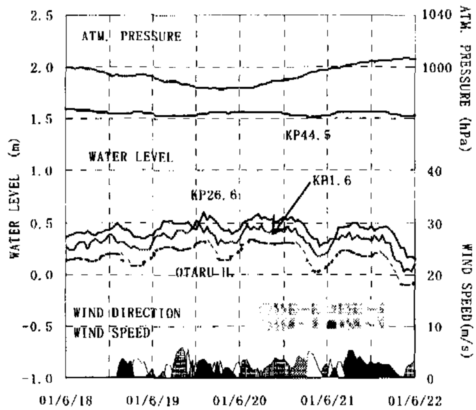

Figure 6: Time series of water level during drought and windless.

The water levels in each record show that at the upstream point of KP44.5, there was no effect from tide; there was little fluctuation in water level, indicating that these were periods of nearly steady flow. However, at both KP26.6 and KP1.6, the water level fluctuated at nearly the same amplitude as the tide. In other words, the degree of fluctuation of the river level due to tide corresponded exactly to the tidal difference, regardless of the location. The fluctuations in sea level also show the same trend when the fluctuations in atmospheric pressure have a longer period than the tide.

A key phenomenon in Fig.5 is the sharp rise in water level which began on 26 October. This does not appear in the other figure. Also, the difference between maximum and minimum levels of river water at KP26.6 are 0.69m in Figure 5 and 0.46 m in Figure 6; the difference are at KP1.6 are 0.63m in Figure 5 and 0.48m in Figure 6.

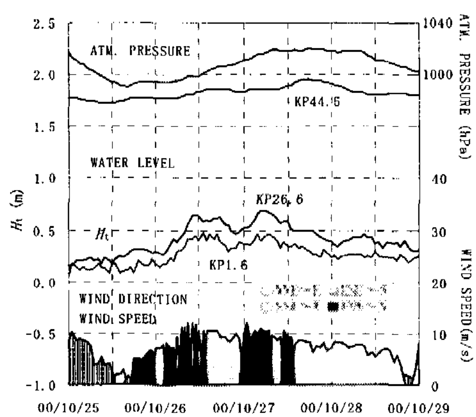

Figure 7: Time series of H_t during drought and strong wind.

Next, the factors which lead to these fluctuations will be explained. In order to obtain river levels relative to sea level, the observed water level in Otaru Harbor was subtracted from the downstream water level in Fig.5 for display in Fig.7 as H_t. Here, it is necessary to bear in mind that the value subtracted, the Otaru Harbor water level, is affected by the combination of tide and atmospheric pressure. To put it another way, the variable H_t is the water level which is

independent of both components, tide and atmospheric pressure.
Turning, then, to Fig.7, we still find that variable H_t climbed abruptly on 26 October even though the flow rate was nearly constant. Actually, the difference between the maximum and minimum levels of H_t were 0.50 m at KP26.6 and 0.41 m at KP1.6. The wind record is notable here. At this time, it changed abruptly from SE to NW (blowing
from the sea into the Ishikari River valley, and briefly reached the high speed of 12.1 m/s. Buffeted by this strong wind, the waves and the sea water transported leeward due to the frictional coefficient at the interface, the water at the river mouth rose and propagated upstream as a surface wave. This explanation seems to account for the occurrence of the large rise in the water level.

However, the analytical results presented so far are not sufficient for quantitative estimates of how the wind affects water level. In order for those, it is necessary to know the relation between the river flow rate and the water level, given in the following chapter.

3.2 Estimate of influence on water level by flow rate

As explained above, the water level in the Ishikari River depends greatly on tide, atmospheric pressure, wind direction and wind speed. However, H_t also fluctuates with flow rate, which may seem obvious. The effect of river flow rate on water level is therefore assessed before the effect of wind is assessed.

First of all, water level data under windless conditions like those in Fig.6 are extracted from past observed data and processed with Otaru Harbor water level data to provide H_{tn}. An example is shown in Fig.8. The water level in this figure is free of the influences of tide, atmospheric pressure or wind. Fig.9 shows results, under differing flow rates, from which these influences were removed in the same way. The data were taken at KP26.6, 1.6, and 15.0, a location

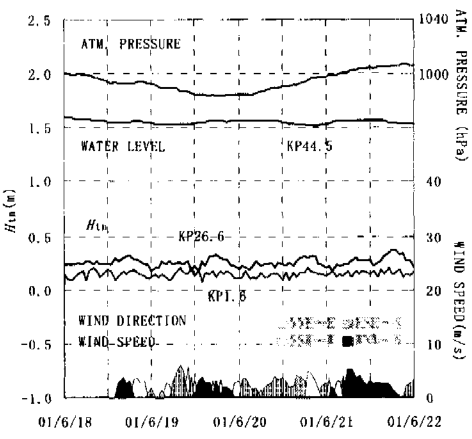

Figure 8: Time series of H_{tn} during drought and windless.

between the first two. H_{tn} was calculated for each location at arbitrary flow rates. For example, at KP26.6, at a flow rate of 200 m^3/s, H_{tn} was 0.26 m; at Q=300 m^3/s, H_{tn} was 0.32 m. Meanwhile, at KP1.6, below flow rates of 300 m^3/s, H_{tn} was nearly constant at 0.14 m. As is plain from the results for H_{tn} at KP15.0, H_{tn} shows a trend to increase with flow rate and with distance upstream from the river mouth.

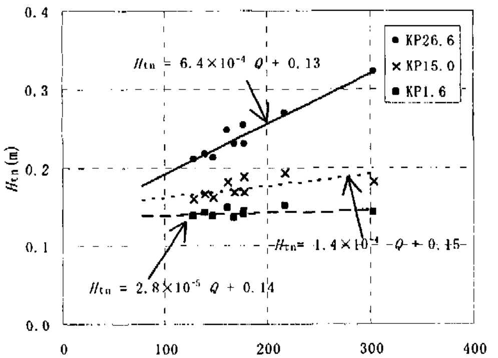

Figure 9: Relation between H_{tn} and flow rate, Q.

3.3 Estimate of influence on water level by wind direction and speed

So far, it has been possible to obtain quantitative assessments of water level fluctuations due to tide, atmospheric pressure and river flow rate. The same can also be done for wind direction and speed.

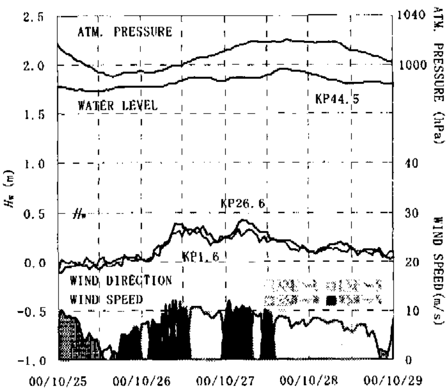

Figure 10: Time series of water level caused by NW wind.

Since the effects of tide and atmospheric pressure were removed to generate H_t, this can be subtracted from H_{tn}, the parameter free of those two plus the effects of wind, to generate H_w, the height of the river due only to the effect of wind. When there is no wind, H_w must be 0 m. The data in Fig.7 were processed by this method to create H_w, graphed in Fig.10. When the data from KP26.6 and 1.6 in Fig.10 are checked, H_w is approximately zero for windless. When there is a prevailing wind from the northwest, however, the water level rises. Conversely, when there was a southeast wind (blowing down the river toward the ocean), as there was on 6 – 10 August 2001, H_w took on the values shown in Fig.11. The maximum SE wind speed in Fig.11 was 15.1 m/s, and examining H_w, there is a small but definite trend to lower negative values with wind speed, in contrast to the previous example.

Quantitative expressions have thus been found for the influences of

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each factor on water level; it remains to examine just how closely the combination of all of these predicts the flow rate of the Ishikari River.

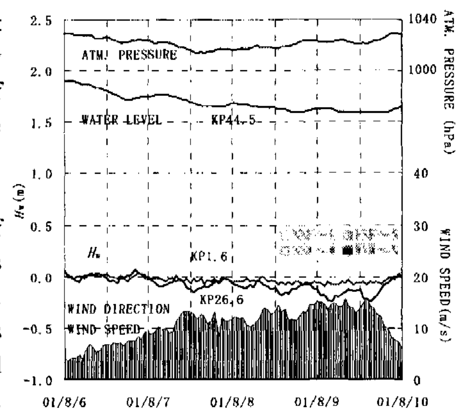

Figure 11: Time series of water level caused by SE wind.

Fig.12 displays the plot of maximum H_w, H_{wmax}, and its corresponding peak wind speed U. The positive and negative portions of the horizontal axis indicate wind directions of NW and SE. According to this figure, when the wind direction is NW (positive), H_w rises with the second power of wind speed. A close examination of the details shows that for a speed of 15 m/s, at KP1.6, H_w is 0.48m, while at KP26.6, water level rise H_w is actually 0.65 m. This rise is greater than that caused by tide, atmospheric pressure or flowrate. When the wind direction is SE(negative), H_w does not vary as dramatically, but for the speed of 15.9 m/s, H_w is –0.06m at KP1.6 and –0.24 m at KP26.6.

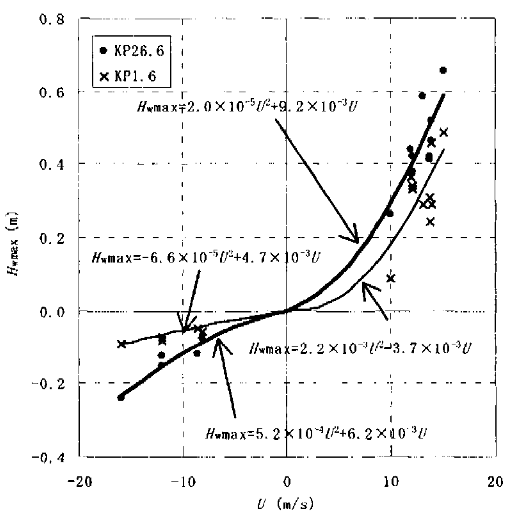

Figure 12: Relation between water level, wind speed, and wind direction.

The results in Fig.12 can also be applied to estimation of the water level for arbitrary wind directions and speeds. First of all, when the effects of tide, atmospheric pressure and wind are removed, the water levels show the results in Fig.13 and 14. The actually observed water levels are shown in these figures with solid lines, and the values calculated for the levels unaffected by the factors, in dashed lines.

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When the obtained water levels at KP26.6 are used to estimate the average flow rate for through 4 days, these are obtained: Fig.13, 218 m^3/s; Fig.14, 270 m^3/s. These results are not far from the values observed at KP44.5, 237 m^3/s and 220 m^3/s, respectively.

Thus, the method of estimation described in this study enables calculation of the river flow rate during drought with acceptable accuracy.

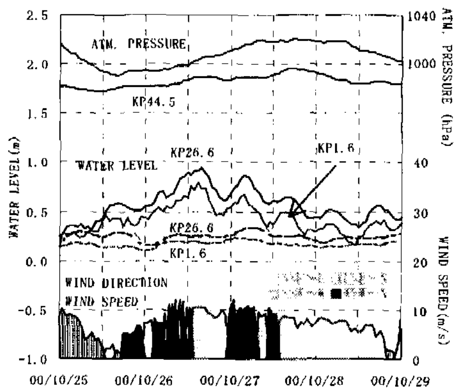

Figure 13: Relation between water level and modified flow rate for NW wind.

4 Conclusions

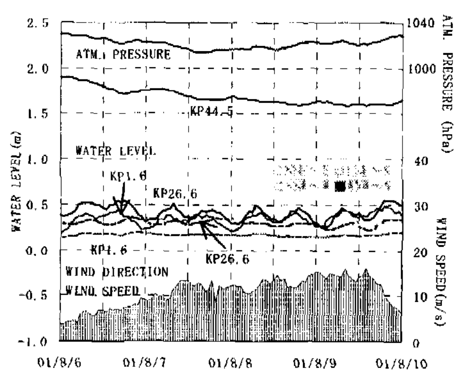

Figure 14: Relation between water level and modified flow rate for SE wind.

In this study, it was attempted to derive a method for quantitative estimation of the effects of tide, atmospheric pressure, wind direction and wind speed on flow rate in the estuary of the Ishikari River, where these four factors dramatically lower the correlation between water level (*H*) and river flow rate (*Q*). It was found that the effect of tide and atmospheric pressure on sea level is almost exactly reflected in the fluctuations of river level. Data from observations of river level under windless conditions and steady river flow rate allowed application of empirical rules for river rise due purely to flow rate, providing a quantitative estimate of the relation between wind and river water level. Next, the flow rate was estimated at a certain location using the obtained quantitative relation between the four factors and river level, and this was found to be nearly identical to the observed flow rate. This confirmed the practical validity of this study.

Acknowledgements

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