Estimation of freshwater discharge by using freshwater fraction and tidal prism in a river estuary

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1. INTRODUCTION

Freshwater discharge is one of the most important factors used to evaluate the ecological and environmental conditions in estuaries. Quantifying freshwater discharge is an ongoing problem that is yet to be overcome due to the tidal effects as well as the inherent difficulty of observing system. In a tidal region, the freshwater flow can be determined directly by averaging the measurements over a tidal cycle or indirectly through numerical studies. These time-consuming methods are highly expensive as they require a large number of equipment and laborers as well as measurable input data.

In this study, we propose a simple method to estimate the freshwater discharge in tidal estuaries. The method was first introduced by Sheldon and Alber[1] for the discharge rate averaged throughout a tidal cycle. By considering a simple tidal prism approach with complete tidal exchange and using the measured salinity data, we can determine the freshwater discharge at both rising phase and falling phase of the tide, and hence the daily freshwater discharge. The method was applied to the Abashiri River estuary (ARE) in Northeast Hokkaido (**Fig. 1**). Measured data of river discharge at the upstream end of the ARE were compared with computed results of the method for both validation and efficiency.

2. MEHODS

Sheldon and Alber[1] estimated the flushing time (T_{FW}) for an estuary. They treated the estuary as a single box. The flushing time is determined by dividing the freshwater volume (V_{FW}) of the estuary by the freshwater inflow rate (Q_{FW}) averaged over a given period of time, i.e.: a tidal cycle.

$$T_{FW} = V_{FW}/Q_{FW} \tag{1}$$

where freshwater volume is calculated by multiplying the estuary volume (V) by the freshwater fraction (f_{FW}), which is calculated by comparing the average estuarine salinity (S_{AVG}) to the salinity of seawater[2].

$$f_{FW} = (S_0 - S_{AVG})/S_0 \tag{2}$$

where S_0 is the salinity at the estuary mouth. Thus,

$$T_{FW} = (V * f_{FW}) / Q_{FW} \tag{3}$$

Q_{FW} is the tidally averaged freshwater discharge or the daily discharge. However, it can also be defined for the flood- or ebb-phase duration as follows:

$$T_{FW\_flood} = (V_{flood} * f_{FW\_flood}) / Q_{FW\_flood} \tag{4}$$

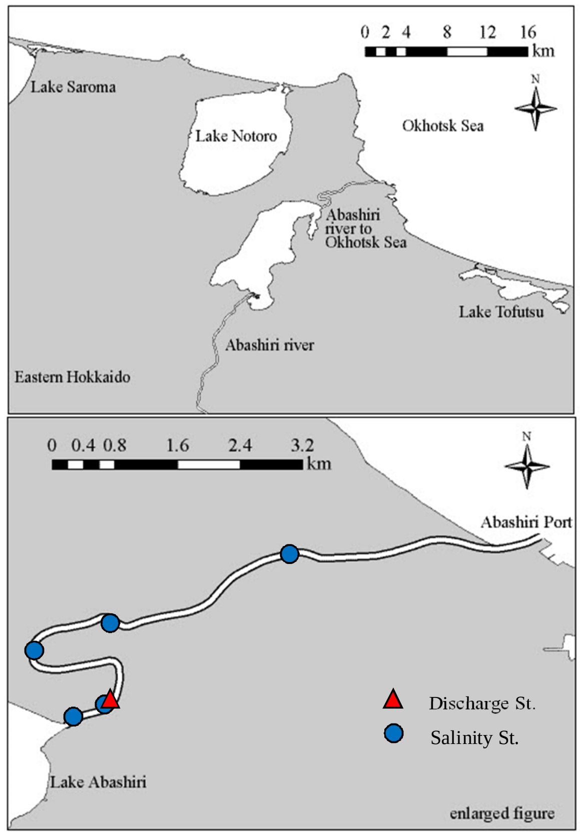

Fig. 1　Map of the study area.

and,

$$T_{FW\_ebb} = (V_{ebb} * f_{FW\_ebb}) / Q_{FW\_ebb} \tag{5}$$

From Eqs. (4) and (5), we can estimate the freshwater discharge if the estuary volume and flushing time are known.

Let us start with the flood volume P_T, which is the integral of the tidal discharge between low water slack (LWS) and high water slack (HWS) at the estuary mouth (x=0). Definition of the water levels, including LWS and HWS is depicted in **Fig. 2**.

$$P_T = \int_{LWS}^{HWS} Q(0,t)dt \tag{6}$$

where $Q(0,t)$ is the discharge at the estuary mouth. Since this integral is difficult to determine through direct measurement, it can be approximated by computing the flood volume as the tidal prism enclosed between the envelopes of HWS and LWS and by equating it to the product of the tidal excursion with the cross-sectional area of the estuary mouth[3] (see **Fig. 3**).

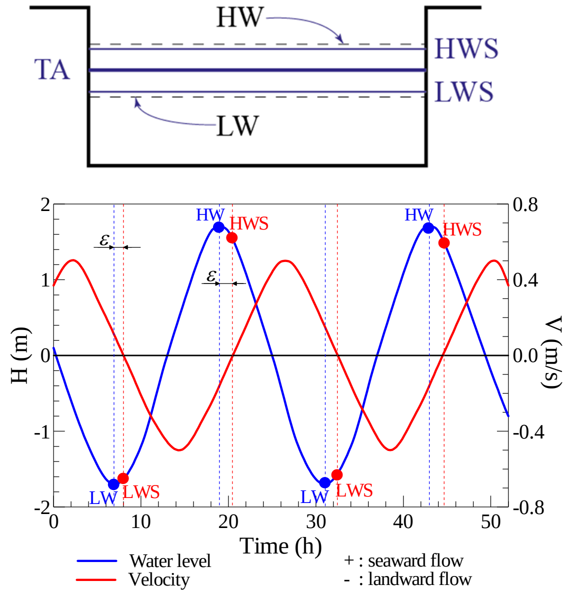

Fig. 2. Variations in water level in a channel. Slack waters occur at time tidal velocity equals zero. ε is the phase lag between high water (HW) and high water slack (HWS) or between low water (LW) and low water slack (LWS).

The first approach yields:

$$P_T = \int_{LWS}^{HWS} A_0 U(0,t)dt \approx A_0 E \qquad (7)$$

where A_0 is the cross-sectional area at the estuary mouth and E is the tidal excursion. Here, we assumed that the cross-sectional area acquired at the tidal average (TA) can be representative for the variation of the channel size between LWS and HWS. In addition, the integral over time of the Eulerian velocity U was assumed to be approximately equal to the tidal excursion E, which is the net horizontal distance traveled by a water particle from LWS to HWS or vice versa. E can be obtained by integrating a sinusoidal tidal velocity over a tidal cycle ($E=\upsilon_0 T/\pi$, in which υ_0 is the tidal velocity amplitude and T is the tidal period). We also assumed that the tidal volume is conserved throughout a tidal cycle ($V_{flood}=V_{ebb}$).

The second approach yields:

$$P_T \approx \int_0^\infty HBdx \qquad (8)$$

where H is the range between HWS and LWS, and B is the channel width. Here it is assumed that these levels are reached almost instantaneously along the estuary.

In the present study, we used the first approach to estimate the estuary volume, and hence the freshwater discharge.

3. STUDY SITE AND DATASETS

3.1 SITE DESCRIPTION

The ARE connects the lake of Abashiri to the Okhotsk Sea in Northeast Hokkaido. The river plays a vital role to the ecological system of the lake because of its high primary productivity. The total length of the river is 7.2 km, and the annual discharge is about 23 m^3/s. The river water is almost fresh during neap tide. During spring tide, salinity from the Okhotsk Sea can intrude into the lake and perennial well-mixed condition develops[4]. The tide of the Okhotsk Sea is predominantly a diurnal type during spring tide and semi-diurnal type during neap tide. The tidal range at river mouth varies from 0.6 m during neap tide to 1.1 m during spring tide.

3.2 DATASETS

Data used in this study are salinity, water level, and river discharge. A series of field measurements for salinity, water

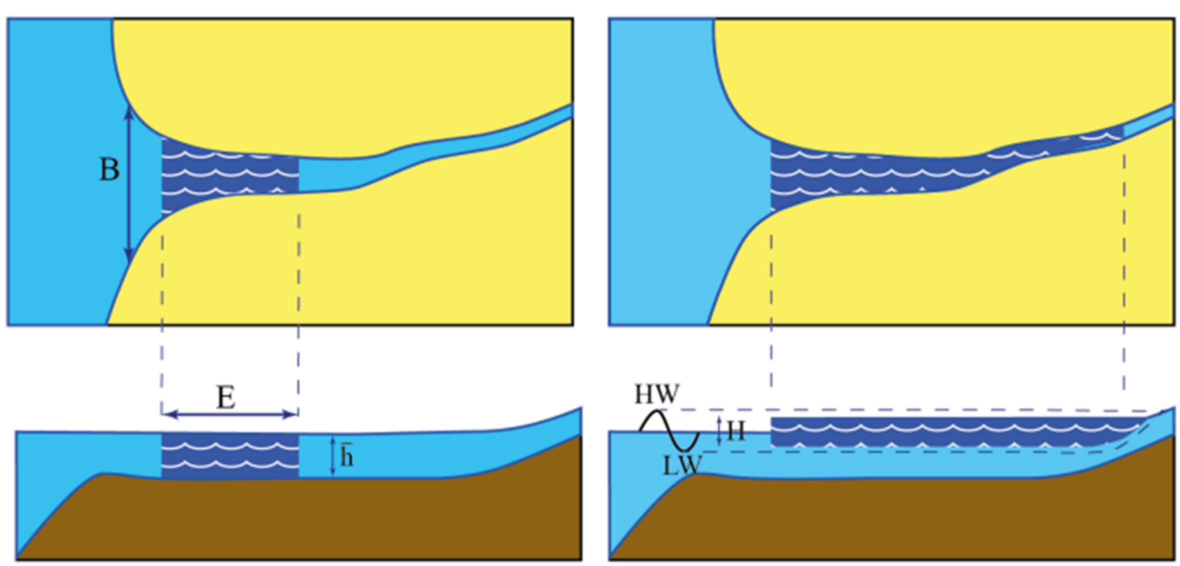

Fig. 3 Definition sketch for the tidal volume as the product of cross-sectional area and tidal excursion (*left*) and as the product of the surface area and tidal range (*right*).

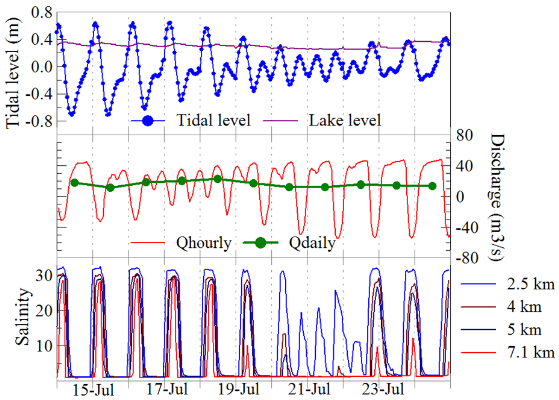

Fig. 4 Collected data during a spring-neap tidal variation in the Abashiri River estuary in 2007.

level, and river discharge were conducted by the Hokkaido Development Bureau (HDB), Ministry of Land, Infrastructure, Transport and Tourism. The salinity measurements were carried out at five locations along the ARE (i.e., 2.5 km, 4.0 km, 5.0 km, 6.9 km, and 7.1 km) from March to December during period of 2005-2009 (see **Fig. 1**). At each location, the salinity was determined simultaneously at three different depths: near the surface, mid-depth, and near the bottom. The measuring interval was 10 minutes. Salinity data at the estuary mouth was obtained from numerical results conducted by Shintani and Nakayama[4]. In addition to salinity data, water level was also acquired at these locations. In addition, tidal velocity was also observed at the Abashiri Port and near the upstream end of the ARE. The discharge measurements were conducted at location of 6.9 km from the estuary mouth during the period of 2005-2009. During this period, the maximum and minimum daily discharges were 98 m^3/s and 6 m^3/s, respectively. The maximum monthly discharge was found to occur in April and May as a result of the snow melting, while the minimum discharge was observed in July during the summer.

In this study, data obtained during a period from July 14 to July 24, 2007 were used to validate the proposed method. Collected data were shown in **Fig. 4**.

4. RESULTS

In order to estimate the freshwater discharge by using Eqs. (4), and (5), information on the estuary volume, salinity, and flushing time should be determined beforehand. The tidal volume (V_{flood} or V_{ebb}) was calculated based on values of the velocity amplitude, which was obtained from the salinity measurements at HWS or LWS and at two locations along the estuary length, i.e.: 2.5 km and 4.0 km. The flushing time at both flood and ebb tidal phases was determined from the maximum and minimum salinity occurred at HWS and LWS, respectively.

The daily freshwater discharge is determined by averaging the obtained values of the flood and ebb tide as follows:

$$Q_{FW\_daily} = (Q_{FW\_flood} + Q_{FW\_ebb})/2 \qquad (9)$$

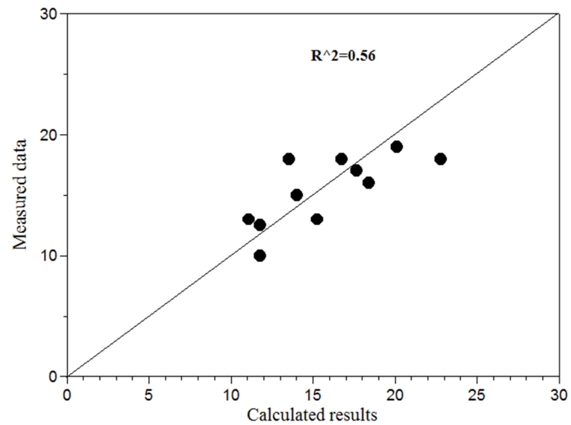

Fig. 5 Comparison of calculated results against measured data for the freshwater discharge.

Figure 5 shows the comparison between computed results of the freshwater discharge and the observed data. It can be seen that the correspondence with observations is good (R^2=0.56), which suggest that the proposed method can be useful tool to have a first order estimation of freshwater discharge in the tidal region.

5. CONCLUSIONS

A simple method was developed to estimate the freshwater discharge in tidal estuary by considering a simple tidal prism approach with complete tidal exchange and using the measured salinity data along the estuary length. The method was applied to the ARE in Hokkaido. The computed results show a good agreement with observed data, which suggest that the present method can be a powerful instrument for estimating the freshwater discharge in tidal estuaries.

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