ASSESSMENT OF PROPAGATION CHARACTERISTICS FOR TSUNAMI WAVE ASCENDING RIVER

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Tsunami wave ascending rivers is one of the important phenomena in river and coastal engineering. It is regarded as a potential disaster due to the tsunami propagation. The features of the tsunami wave in the river can be explained by physical parameters. This study focuses on the verification of an estimation method for the tsunami parameters. A numerical experiment was used to evaluate the suggested method using measured water level data. The method applied to real observation data during the 2011 Tohoku Tsunami. The tsunami characteristics along the river were confirmed by the calculated river discharge and flow velocity induced by the tsunami.

Keywords: The 2011Tohoku Tsunami; river discharge; tsunami flow velocity

INTRODUCTION

On March 11th, the 2011 off the Pacific Coast of Tohoku Earthquake generated devastating tsunami waves, particularly in the Tohoku District, Japan. In this area tsunami caused severe damaged in many structures and infrastructures and so on. One of them is the hydrological measurement stations where water level, tidal or sea level was observed. There are lots of problems in analyzing the measurement data that are crucial parameter to obtain the physical characteristics in understanding the tsunami wave propagation into rivers.

Many studies have been carried out by researchers in order to understand the characteristics of tsunami waves ascending rivers. Abe (1986) analyzed the measurement water level data in rivers to assess the propagation features when the tsunami wave propagates into rivers. Tsuji (1991) studied the behaviors of an undular bore related to the tsunami ascending rivers. Yasuda (2010) carried out a numerical simulation for the tsunami wave ascending the river using several numerical models. Yeh et al. (2012) simulated the effects of the Colombia River due to the 2011 Tohoku Tsunami. Indeed, many natural factors influence the tsunami propagation in rivers. However, there are limited studies on tsunami propagation into rivers by means of numerical simulation, theoretical analysis, and laboratory experiments. Tanaka et al. (2011) suggested that the propagation characteristics in Japan due to the 2010 Chilean Tsunami were classified into the river mouth morphological features. Adityawan et al. (2012a) and Tanaka et al. (2013) studied the impacts due to the different river bed slopes on the tsunami propagation into rivers. Furthermore, Adityawan et al. (2012b) applied long wave theory to obtain the tsunami physical parameters such as tsunami speed, river discharge and flow velocity induced by the tsunami wave. Based on the past studies, it can be concluded that tsunami wave propagation into the river is an important research topic. In order to achieve a detail analysis of tsunami impact in the river, tsunami physical characteristics such as tsunami speed, flow velocity and river discharge variation will be very crucial parameters.

In this study, the physical parameters of the tsunami wave ascending river will be assessed using measured water level along the river. Relation of arrival time and distance between the measurement stations will be used to estimate the tsunami speed. Furthermore, flow velocity and river discharge variation induced by the tsunami wave will be calculated by using the available water level data based on conservation equation.

STUDY AREA

The Kitakami River is one of the main rivers in Japan. The river is located in the north-eastern part of Miyagi Prefecture as shown in Fig. 1. The Kitakami River mouth is facing the Pacific Ocean, and the distance from the epicenter is only approximately 90 km. There is one of the most severe damage area attacked by the 2011 Tohoku Tsunami. The general information of this river is classified as the Class A that is managed by the central government. As a main river in Japan, the catchment area is attained as 10,150 km^2, and river length is 249 km. Hydraulics measurement stations have been utilized to control the extreme natural events such as heavy flood and so on by the regional river authority. Three measurement data were available to obtain the tsunami physical parameters. In Table 1, the locations of the measurement stations indicate the distance from the river mouth. P1 is located at 8.57 km from the river mouth. P2 and P3 are located at 14.94 km and 17.20 km from the river mouth, respectively.

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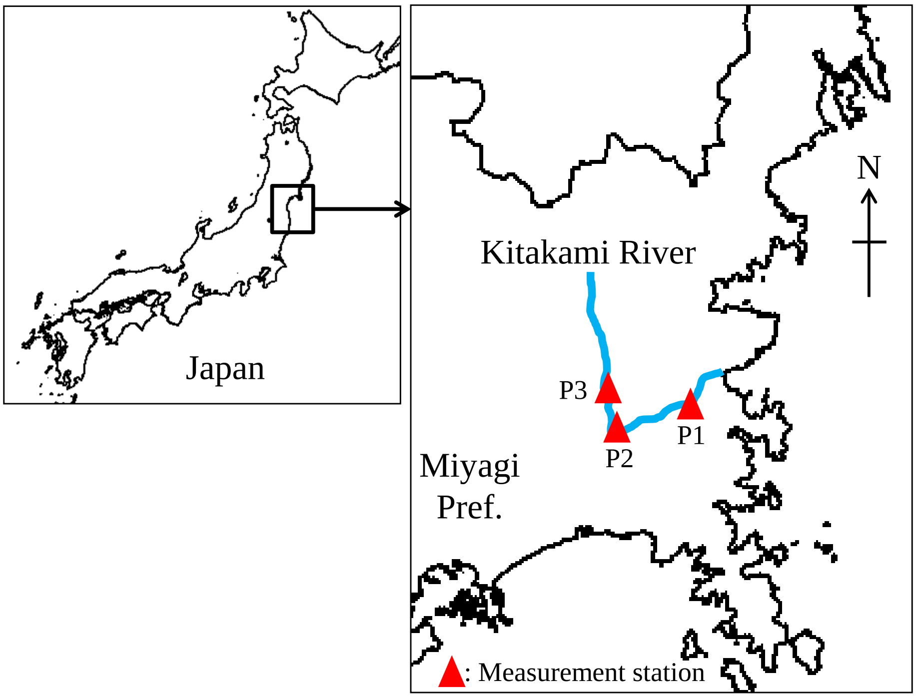

Figure 1. Location of study area.

The detail water level data and information of the measurement stations were provided by the Tohoku Regional Bureau of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). They also provide several video data recording by CCTV located along the river. Unfortunately, it was difficult to decide the real time of recording video data. The recoding devices might be caused by the powerful earthquake. Therefore, this study concentrated the available water level data on the three measurement stations.

Table 1. Information of measurement stations.

	Distance from river mouth (km)
P1	8.57
P2	14.94
P3	17.20

DATA COLLECTION

Available water level data at the measurement stations are used to obtain the tsunami impacts in the river as seen in Fig. 2. It was observed every 1 min at the measurement stations. Especially, a floodgate is located in P3 is at 17.20 km from the river mouth. The water levels of upstream and downstream at 17.20 km from the river mouth show big difference because the tsunami propagation up to the river upstream was reduced due to the floodgate. Moreover, the observed water level of P3 was higher than P2 water level. It might be affected by the tsunami reflection due to the hard structure in the river. The various impacts of the river structures are also one of the important parameters in assessing the tsunami propagation characteristics in the river.

Above all, data availability and collection were recognized the significant process in this study. The quality of measured data is the key to assessing the tsunami physical parameters. However, water level data near the Kitakami River mouth would not be observed unfortunately because the hydraulics measurement stations near coastal areas and river mouths were totally destroyed and washed away by the powerful tsunami propagation and inundation. If water level data at the river mouth was available, the tsunami propagation mechanism along the river could have obtained. Furthermore, the series of the tsunami propagation process due to the river characteristics can be described obviously.

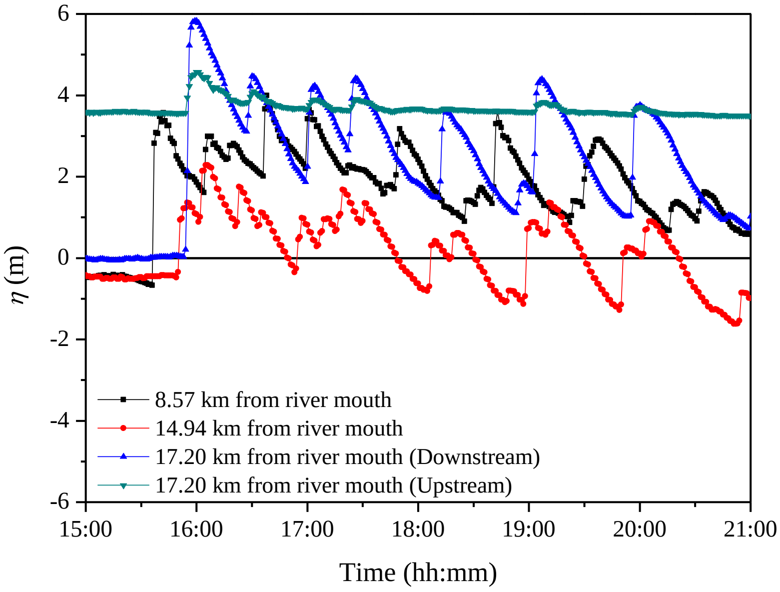

Figure 2. Available water level data of the Kitakami River.

METHOD

Water level data is crucial source to obtain the tsunami physical characteristics. Tsunami speed in the river can be calculated briefly by using tsunami travel time and travel distance between the measurement stations whereas the estimation of river discharge and flow velocity induced by the tsunami was very difficult compared to the tsunami speed calculation. Therefore, an estimation method was needed to obtain the tsunami flow velocity and discharge. Herein, the method using observed water level data based on the conservation equation was suggested in this study. It can be assessed briefly the physical characteristics. Furthermore, the applicability and the accuracy of the conservation equation model were verified by a numerical experiment based on hypothetical case. The details of the conservation equation method and the numerical model are described below.

- Conservation equation model

Tsunami flow velocity and tsunami induced river discharge can be calculated by the conservation equation as shown in Eq. 1(Adityawan et al. 2012b):

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \tag{1}$$

where A is river cross-section area, Q is river discharge, t is time, and x is an arbitrary point along river based on the location of measurement stations.

Eq. 1 is integrated between two points from x_1 to x_2. Then, it can be rewritten as follows:

$$\int_{x_1}^{x_2}\frac{\partial A}{\partial t}dx+Q_{x_2}=Q_{x_1} \tag{2}$$

The term of integration on the left-hand side is calculated by using the simplified differential equation and the formula of a trapezoid area. And then, Eq. 3 can be suggested for the solution of the river discharge variation induced by using water level data at the arbitrary point.

$$\frac{1}{2}\left(B_{x_1}\frac{\Delta\eta_{x_1}}{\Delta t}+B_{x_2}\frac{\Delta\eta_{x_2}}{\Delta t}\right)\Delta x+Q_{x_2}=Q_{x_1} \tag{3}$$

where B is river width, η is water level.

If the water level data at the two points and upstream end discharge are given, downstream end discharge can be calculated by using Eq. 3. It can be extended to several points or segments along the river based on the measurement stations. The extended equation is written in Eq. 4. Herein, flow velocity at the each station can be obtained from the calculated river discharge from Eq. 4 by using the continuity equation:

$$Q_i^t = \sum_{j=i}^{2} \frac{B_{j+1}\left(\eta_{j+1}^t - \eta_{j+1}^{t-\Delta t}\right) + B_j\left(\eta_j^t - \eta_j^{t-\Delta t}\right)}{2\Delta t}\left(x_{j+1} - x_j\right) + Q_3 \tag{4}$$

where j is the index of summation operator which corresponds to the location of the cross area i. The upstream end discharge Q_3 is assumed as zero for the condition of the tsunami induced river discharge.

- Numerical experiment model

For the verification of the conservation equation model, 1-D shallow water equations have been solved by using Finite Volume Method (FVM). The governing equations are written as below:

Continuity equation

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} = 0 \tag{5}$$

Momentum equation

$$\frac{\partial (hu)}{\partial t} + \frac{\partial (hu^2)}{\partial x} + \frac{\partial}{\partial x}\left(\frac{1}{2} g h^2\right) = gh\left(S_o - S_f\right) \tag{6}$$

where t is time, h is total water depth, u is depth averaged velocity, S_o is bed slope, S_f is friction slope, and g is gravity acceleration.

The Manning coefficient is employed in order to calculate the bottom friction term as seen in Eq. 7:

$$S_f = \frac{n^2 u \sqrt{u^2}}{h^{4/3}} \tag{7}$$

where n is Manning coefficient.

FORCE-MUSCL scheme is used to solve the shallow water equations as one of the FVM solutions (Mahdavi and Talebbeydokhti 2009). The numerical model calibration has been conducted through many researches and test cases. This solution is widely used in various engineering fields.

To achieve the purposes of the conservation equation model verification and the sensitivity analysis, the hypothesis domains was created as seen in Fig. 3 that is based on the Kitakami River elevation data. The hypothetical domain is used to verify the sensitivity and the accuracy due to time and spatial variables in the conservation equation model. The computational domain is shown that the total length of the river channel is 40 km. It is assumed that the river width and bed slope are constant, respectively. The value of Manning's roughness coefficient is 0.025. The observed data of the first measurement station from the river mouth is used as the inlet wave condition at the generating wave zone, and the measured water level at P1 station was interpolated by the spline function. The right-hand side is open boundary condition which allows freely moving inflow and outflow at the boundary. The numerical model was set up to consider the effect of the tsunami propagation into a river. In this simulation, the time interval is 1.0 s, and the space difference is 100 m, respectively.

The computed water level data from the numerical experiment model can be extracted into several cases. The extracted water level is able to apply to the Eq. 4 as the conservation equation model using water level data. Then, the accuracy and sensitivity can be confirmed by the comparison between the computed velocity from the numerical experiment model and the estimated velocity using the conservation equation model.

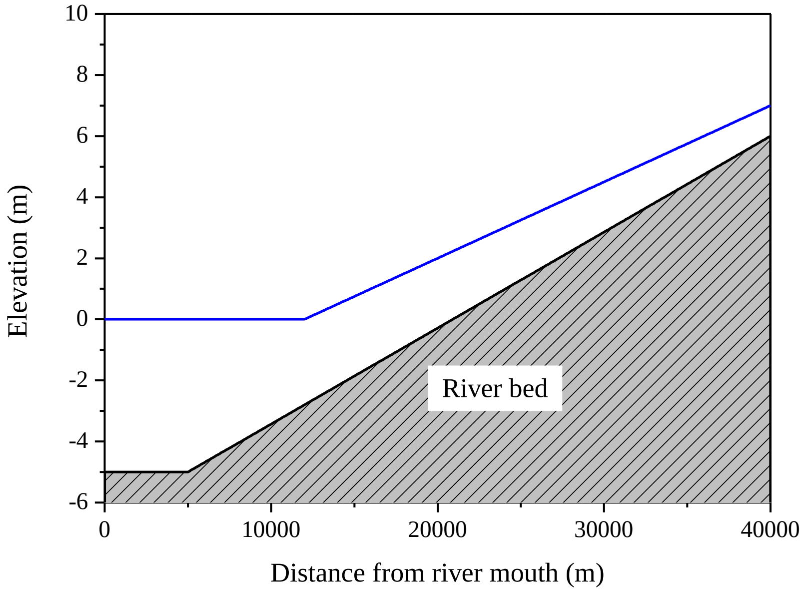

Figure 3. Hypothetical calculation domain.

ANALYSIS RESULTS

The analysis results are described that first is the validation result of the conservation equation model using useful index numbers, second is the application result for the Kitakami River. Finally, it shows the tsunami speed in the river estimated by using measured water levels.

- Validation of conservation equation method

Test cases were determined to confirm the effects of the time interval and space difference as seen in Table 2. The important point is how to determine the most suitable conditions of time and distance. It needs a criterion to indicate the difference between each test case. For this reason, the numerical simulation result of hypothetical case is considered as the exact solution to assess the accuracy and the sensitivity of the conservation equation model. These variables impacts are presented by using Nash-Sutcliffe model efficiency coefficient which are widely used to verify the model accuracy compared with the observed data (Nash and Sutcliffe 1970). The Nash-Sutcliffe coefficient (*E*) is calculated as follows:

$$E = 1 - \frac{\sum_{t=1}^{T}\left(Y_o^t - Y_m^t\right)^2}{\sum_{t=1}^{T}\left(Y_o^t - \overline{Y}_o\right)^2} \tag{8}$$

where Y_o is observation data, Y_m is simulated value, and $\bar{Y}_o$ is mean value of the observation data.

The *E* value has a range of from -∞ to 1.0. This is 1.0 that means the simulated value and observed value is perfectly matched. The coefficient is zero indicates the model calculation is as accurate as the mean value of the observation. If *E* is less than zero, the mean value is a better than the model simulation. In case of over value 0.5, it is considered as the satisfactory result (Moriasi et al. 2007).

According to the all test cases, the calculated Nash-Sutcliffe model efficiency coefficients are presented in Fig. 4. It is found that the conservation equation model is significantly influenced by the variables of time and space. The high accuracy was calculated in the small time interval and the space. The large time interval cases can be obtained as the satisfying result up to the space interval 5.0 km. However, most results of large space intervals showed very low accuracy and applicability. The lower accuracy in cases of 60 s and 600 s started approximately over 1.5 km and 5.0 km, respectively. As the result, the accuracy of the estimated flow velocity using the conservation equation model is higher with a higher resolution data in time and space. Unfortunately, the availability of observation data in a real case is normally limited. In case of the Kitakami River, space intervals are 6.37 km and 2.26 km, respectively. If measured water level data of 60 s is used to obtain the river discharge and flow velocity induced by the tsunami, it may calculate a low accuracy result. Therefore, the extracted 600 s water level data from 60 s measured data is also used in the same condition on the conservation equation model as seen in Fig. 5.

Table 2. Test cases for time and space variables for conservation equation validation.

No.	*dt (s)*	*dx (km)*	*E*	*No.*	*dt (s)*	*dx (km)*	*E*
Case 1	60	10.0	-11.019	Case 21	300	3.0	0.639
Case 2	60	8.0	-8.560	Case 22	300	2.0	0.783
Case 3	60	5.0	-4.026	Case 23	300	1.0	0.795
Case 4	60	4.0	-2.889	Case 24	300	0.5	0.810
Case 5	60	3.0	-1.518	Case 25	420	10.0	-2.265
Case 6	60	2.0	-0.179	Case 26	420	8.0	-1.526
Case 7	60	1.0	0.847	Case 27	420	5.0	0.270
Case 8	60	0.5	0.957	Case 28	420	4.0	0.523
Case 9	180	10.0	-5.500	Case 29	420	3.0	0.806
Case 10	180	8.0	-4.646	Case 30	420	2.0	0.752
Case 11	180	5.0	-1.457	Case 31	420	1.0	0.807
Case 12	180	4.0	-0.925	Case 32	420	0.5	0.804
Case 13	180	3.0	0.014	Case 33	600	10.0	-0.849
Case 14	180	2.0	0.733	Case 34	600	8.0	-0.348
Case 15	180	1.0	0.886	Case 35	600	5.0	0.593
Case 16	180	0.5	0.884	Case 36	600	4.0	0.641
Case 17	300	10.0	-3.586	Case 37	600	3.0	0.644
Case 18	300	8.0	-2.334	Case 38	600	2.0	0.605
Case 19	300	5.0	-0.467	Case 39	600	1.0	0.579
Case 20	300	4.0	0.059	Case 40	600	0.5	0.592

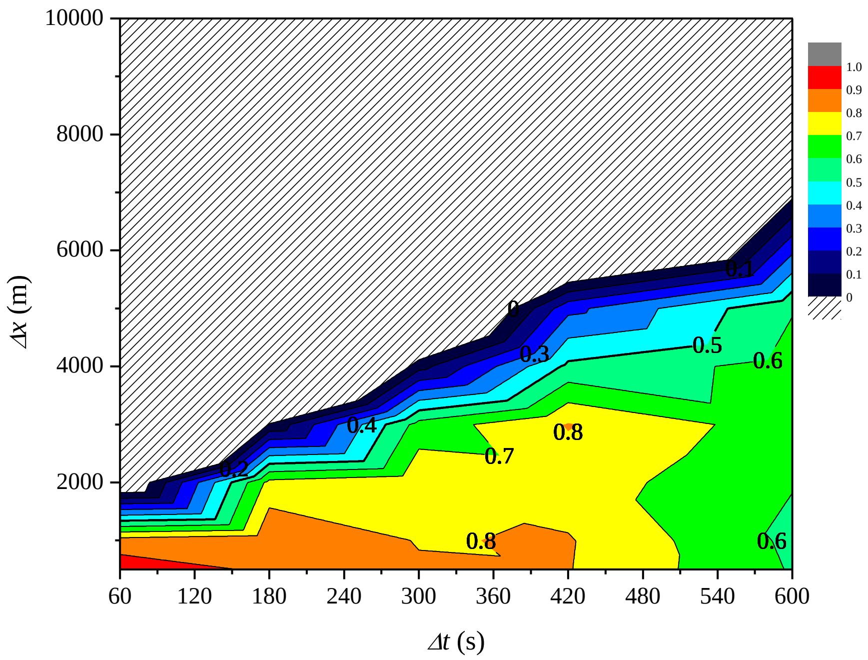

Figure 4. Comparison result between hypothetical simulation model and conservation equation model.

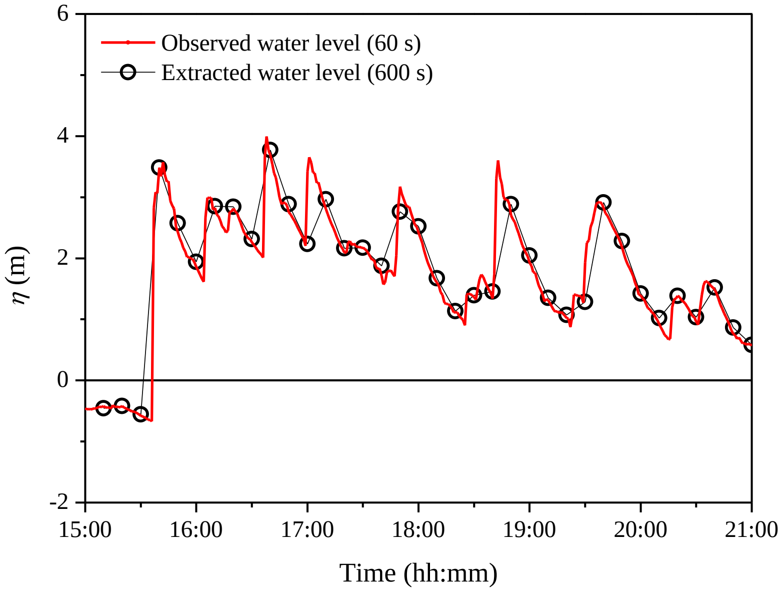

Figure 5. Observed water level and extracted water level at P1 of the Kitakami River.

- River discharge and flow velocity induced by tsunami

  The conservation equation model was applied to the real case of the Kitakami River. The river discharge variation induced by the tsunami wave was assessed by using Eq. 4. Fig. 6 shows the temporal variation of the river discharge and flow velocity induced by the tsunami according to the time interval. In case of 600 s, the results were found that the numerical oscillation and fluctuation occurred during the calculation in the conservation equation model.

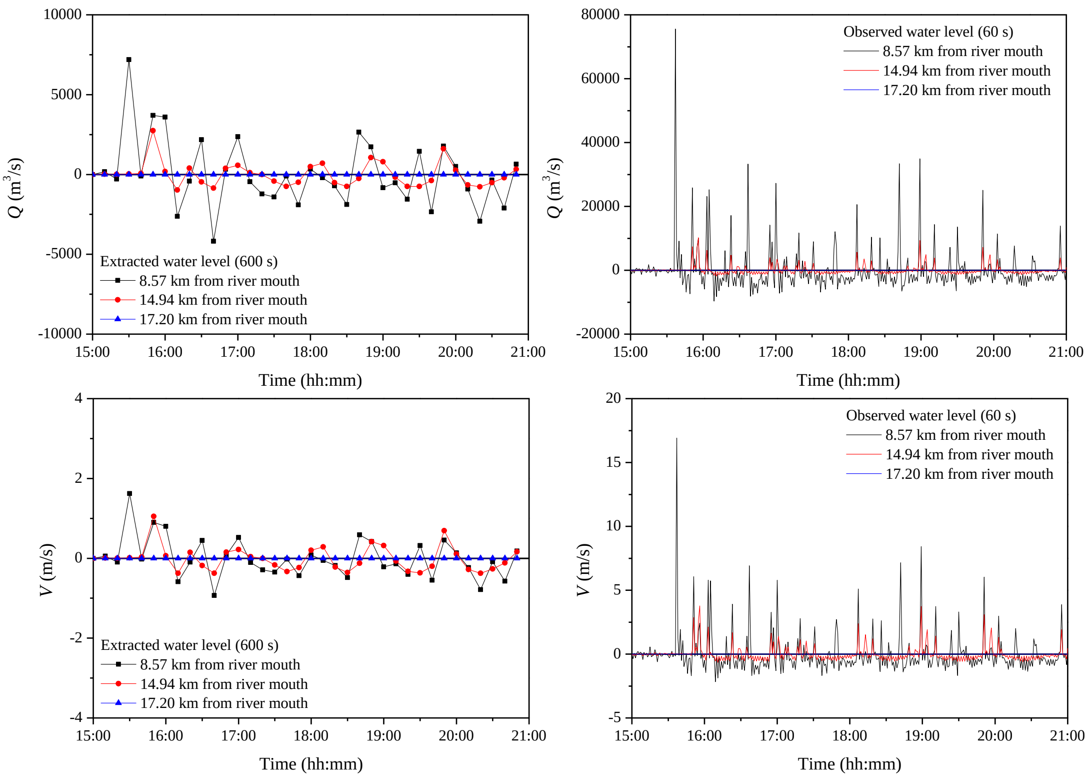

Figure 6. Calculated river discharge and flow velocity using extracted water level data and observed water level data of the Kitakami River.

As the result, the calculated river discharge and flow velocity showed quite a big difference between two different conditions using 60 s water levels and 600 s water levels. It is confirmed that the measured water level data conditions affect the calculation results on the conservation equation model. This model has still limitations in applying the real observation data and measurement conditions. Nevertheless, the validation process of the conservation equation model was successful and the index number showed a valid value. It is found that the influences due to the variables of time and space have clarified obviously in this study. For the future, it is strongly required the detail research for the good applicability and high accuracy according to the conservation model.

- Tsunami speed

The arrival times of peak tsunami wave and the travel distances at the three stations are summarized in Table 3. The tsunami speed was obtained as approximately 8.0 ~ 9.0 m/s based on the information of travel distance and arrival time at the measurement stations.

Table 3. Tsunami travel distances and arrival times.

	Distance from river mouth (km)	Arrival time (hh:mm)
P_1	8.57	15:42
P_2	14.94	15:55
P_3	17.20	15:59

CONCLUSIONS

This study concentrated the estimation method of the tsunami propagation characteristic physically. The validation of the conservation equation method was described mainly, further the applicability and accuracy. It can be concluded several important points as below.

- The assessment of the tsunami physical parameters has been carried out successfully by using the measured water level data.
- The proposed estimation method using available water level data based on the conservation equation has been confirmed by the reasonable validation result.
- The conservation equation model applied to the real observation data of the Kitakami River to obtain river discharge and flow velocity induced by the tsunami wave. It was found that the calculation results were significantly influenced by time and space intervals. The real observation data conditions affected the limited applicability in determining the tsunami induced river discharge and flow velocity.
- It is hoped that the present study will be able to help engineers and researchers better understand the real problems in the fields of coastal and river engineering.

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