TEMPORAL VARIABILITY OF DISCHARGE RATING CURVE INVESTIGATED USING SHALLOW-WATER ACOUSTIC TOMOGRAPHY

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ABSTRACT

Acquiring continuous streamflow estimates is paramount in hydrological studies, extreme event analyses, and water resources management. The discharge uncertainty caused by temporal variability of stage–discharge relationships is significant. The short-term changes of the discharge rating curve (HQRC) caused by flood events are undetectable by traditional rating techniques. This paper investigates the temporal variability in HQRC from unique high-frequency (every 10 minutes) streamflow time series. The time series data have been obtained using a novel acoustic method: fluvial acoustic tomography (FAT). In contrast to the traditional point/transect measurements of discharge, the FAT system enables us to continuously measure the depth- and range-averaged flow velocity along the ray path. A 115-m wide straight reach of the Gono River, Miyoshi City, Japan was selected as the survey site. The riverbed consisted of gravel (d_{50}=27 mm). The bed slope around the observation site was approximately 0.11%, and the Manning roughness was approximately 0.03. For falling limbs of 16 hydrological events, the discharge rating curves were analyzed. Temporal variations in hydraulic parameters of the rating curve were examined in addition to the variability of HQRC. The rapid changes of HQRC occurred owing to flood events.

Keywords: Streamflow, Continuous discharge measurement, Stage–discharge relationship, Shallow-water acoustic tomography, Gravel-bed river

1. INTRODUCTION

Acquiring continuous streamflow estimates is paramount in hydrological studies, extreme event analyses, and water resources management. The streamflow is commonly estimated using stage-discharge relations because it hard to do direct continuous flow measurements for years. The relation is called rating curve (RC). It is believed that the RCs are liable to change depending on channel conditions such as cross-sectional shape, vegetation, and so on (Guerrero et al. 2012). However, a hydrological dataset sparse in time is insufficient to shed light on the temporal variability in the stage–discharge relation. This paper examines the temporal variability in RC from streamflow time series with uniquely high temporal density (every 10 minutes). The streamflow time series are obtained using a novel acoustic method: fluvial acoustic tomography (FAT) developed by Hiroshima University. In this study, 16 hydrological events in a gravel-bed river for 2016-2018 were analyzed, and the variable rating curves were assessed.

2. OVERVIEW OF THE FLUVIAL ACOUSTIC TOMOGRAPHY SYSTEM

The shallow-water acoustic tomography technique has been under development for a number of years at Hiroshima University (Kawanisi et al. 2018; Kawanisi et al. 2012; Razaz et al. 2013). A new travel-time tomography technique/system makes it possible to accurately measure the sound arrival times in shallow waters. The new system is called Fluvial Acoustic Tomography (FAT) system and is designed for continuous measurement of the cross-sectional average velocities in rivers.

2.1 Basic theory of the FAT measurement

Although the range averaged velocity is measured using the "time-of-travel method", FAT system can gauge the instantaneous section-average-velocity using multi-rays that cover the entire flow cross section unlike conventional acoustic velocity meters. The travel time for each ray path Γ_i is given by

$$t_i^{\pm} = \int_{\Gamma_i} \frac{ds}{c(x,y,z) \pm u(x,y,z)} \tag{1}$$

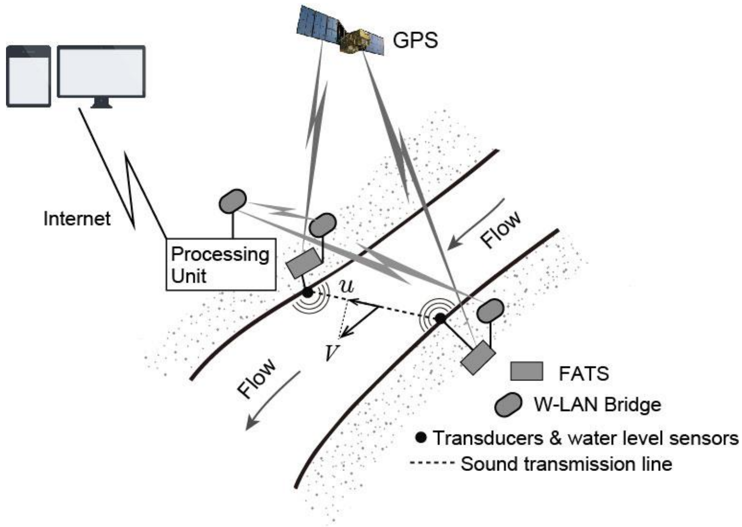

Figure 1. Schematic representation of the FAT system: Streamflow measurement and data transfer.

where +/- present the positive/negative direction from one transceiver to another. ds and c are the increment of length and sound-speed field, respectively. u is the velocity component along the ray path. Because usually $c(x,y,z) \approx c_{mi}$, $u(x,y,z) \ll c(x,y,z)$, Eq. (1) gives the following formulae:

$$t_i^- - t_i^+ (\equiv \Delta t_i) = \frac{2}{c_{mi}^2} \int_{\Gamma_i} u(x,y,z)\, ds = \frac{2}{c_{mi}^2} R_i\, u_{mi} \tag{2}$$

$$\frac{1}{2}\left(t_i^+ + t_i^-\right)(\equiv t_{mi}) = \int_{\Gamma_i} \frac{c(x,y,z)}{c(x,y,z)^2 - u(x,y,z)^2}\, ds \approx \int_{\Gamma_i} \frac{1}{c(x,y,z)}\, ds \tag{3}$$

$$u_{mi} = \frac{c_{mi}^2}{2R_i} \Delta t_i = \frac{R_i}{2t_{mi}^2} \Delta t_i \tag{4}$$

where c_{mi} and u_{mi} are range averaged sound speed and water velocity, respectively. The ray length R_i is roughly equal to the horizontal distance between the source and receiver, L, regarding the shallowness of the river.

Assuming that the water surface profile between both transducers is linear, streamflow Q is given by the following formula:

$$Q = \left(H_m - z_{Bm}\right) L \tan\theta \times u_m \tag{5}$$

where L is the horizontal distance between the both transducers and H_m and z_{Bm} are the mean values of the both water levels and the mean bed level, respectively. θ is the angle between the transmission line and the stream axis, and u_m is the cross-sectional-average velocity component along the transmission line. The average velocity u_m is estimated from the primary rays' group. The flow angle θ is deduced from moving-boat ADCP campaigns.

2.2 Automated flow data acquisition

An automatic data transfer function and Internet connection are added to provide real-time monitoring of river flow (Kawanisi et al. 2018). As shown in figure 1, the received acoustic data at both riversides are transferred to the processing unit using the wireless LAN bridge. The GPS receivers provide two accurate timing signals. One timing pulse (1 Hz) is used to ensure that both systems run synchronously. Another signal of 10 MHz is used as the base clock of FAT system for high-precision transmitting and receiving signal processing. The acoustical signal phase-modulated by M-sequence (pseudo random number) of 9-order is reciprocally transmitted every 30 seconds. The central frequency of the sound is 30 kHz.

The measured data by the water level sensors (Acculevel ACL-10-A, Keller America Inc.), which are located near the transducers, are also transferred to the processing unit of FAT system to estimate the cross-sectional area of stream. The time between each two successive measurements is 30 seconds. The total error band is ±0.1% FS.

3. SURVEY SITE

A 115-m wide straight reach of the Gono River, Miyoshi City, Japan was selected as the survey site (figure 2). The details of the study area are shown in (Kawanisi et al. 2012). The riverbed was consist of gravel (d50=27

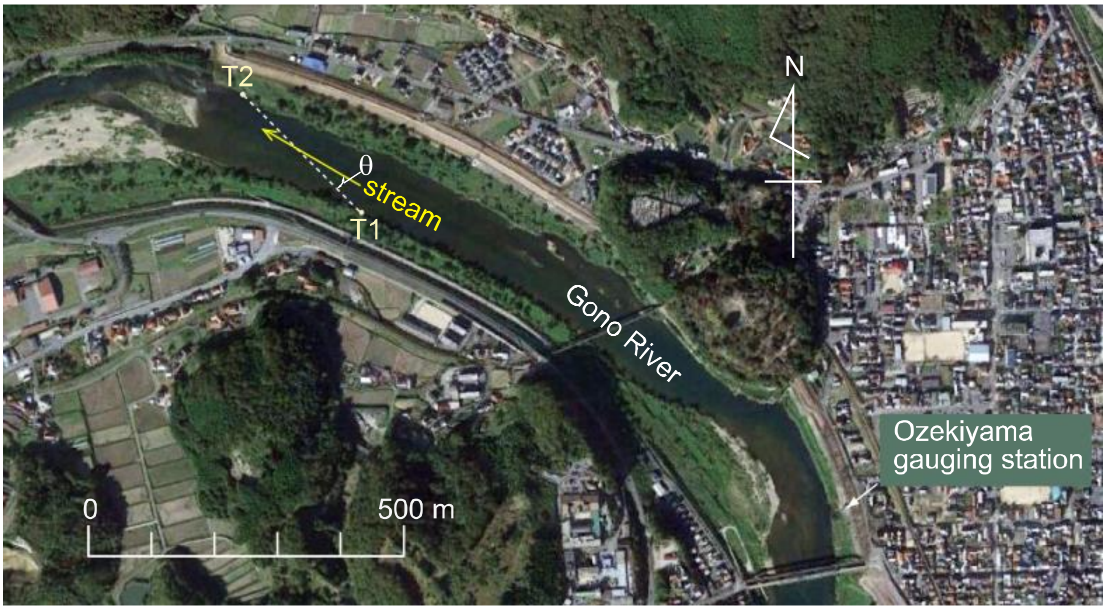

Figure 2. Study area: installation points of transducers (30 kHz) and location of Ozekiyama gauging station.

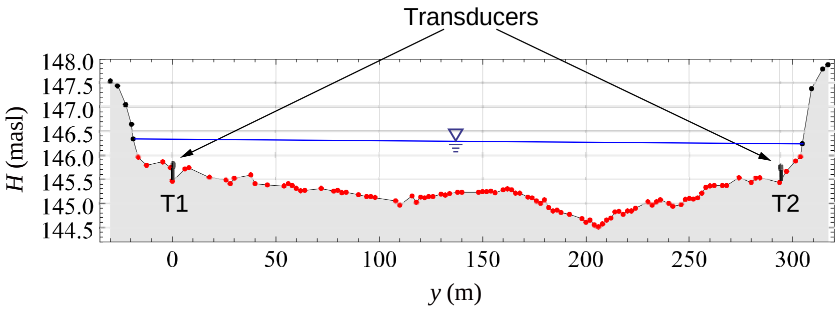

Figure 3. Oblique cross section along the transmission line and the locations of transducers.

mm). The bed slope around the observation site was approximately 0.11%, and the Manning roughness estimated from the stream velocity and the water surface slope was approximately 0.03. As shown in figure 2, a couple of transducers (T1 and T2) were diagonally installed in the straight reach. The Ozekiyama gauging station of the Ministry of Land, Infrastructure, Transport and Tourism, Japan (MLIT), is located ~1.1 km upstream of the survey site.

Figure 3 shows the oblique cross section along the transmission line. The red dots denote the bathymetry points measured by an unmanned autonomous boat with a single-beam echo-sounder and a GPS on December 25, 2015. The vertical resolution of the echo-sounder was 0.01 m. The horizontal interval changed between 0.9 and 10 m along the transmission line; 68% of the interval was less than or equal to 2 m

4. RATING-CURVE METHOD

Streamflow estimates are commonly extrapolated from water level measurements because direct streamflow measurements are labor-intensive. The discharge rating curve is usually modelled hydraulically as a power law:

$$Q = a\left(H - H_0\right)^b, \tag{6}$$

where Q is streamflow, H water stage, and a, b and H_0 are semi-empirical hydraulic parameters. Given steady and uniform conditions and ' water depth $\ll$ river width ', the exponent b has the theoretical value of 5/3 (Manning formula). The parameter a could be expressed as a function of friction coefficient and energy slope. The parameter H_0 represents the reference level for zero flow.

For practical purposes, the hydraulic parameters are estimated using the least squares method based on direct streamflow and water level measurements. However, it is time-consuming to measure streamflows using velocity-area method (ISO 2007). Thus, the frequency of streamflow measurements is insufficient. In the case of MLIT, only three direct streamflow measurements per month are carried out.

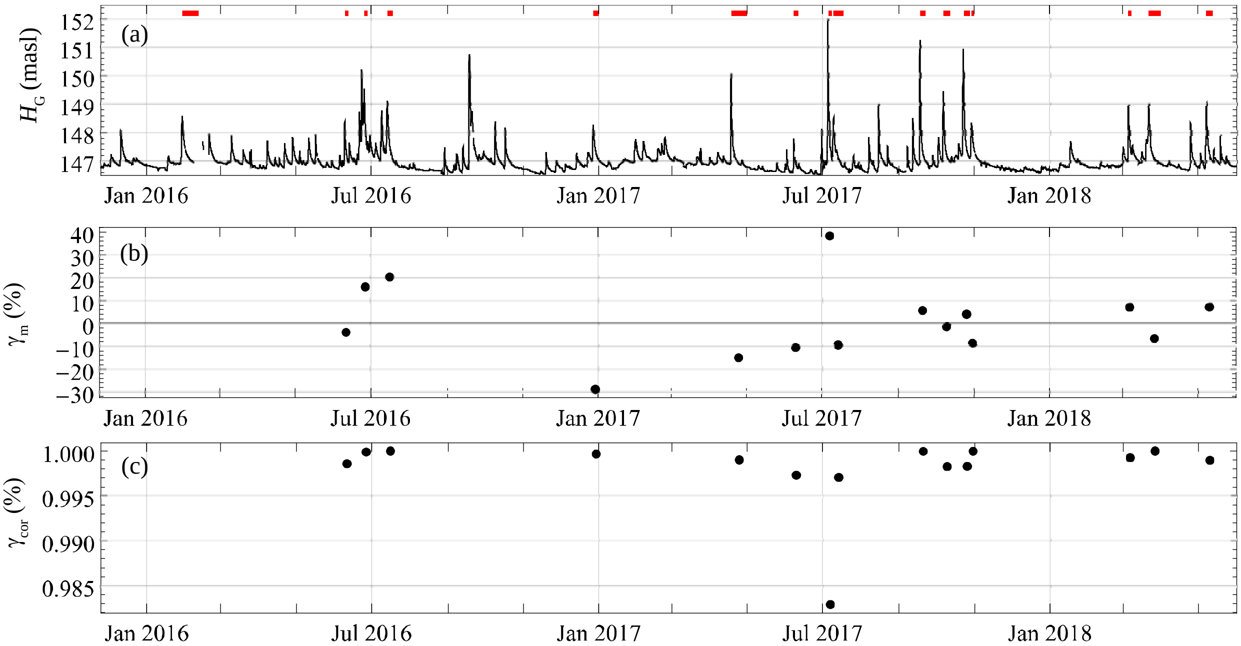

Figure 4. (a) Time series of the water level at the Ozekiyama gauging station (masl: m above mean sea level). Red marks denotes the analyzed periods. (b) Temporal variation in the relative difference of between successive RCs (8). (c) Temporal variation in the correlation coefficient between successive RCs (9).

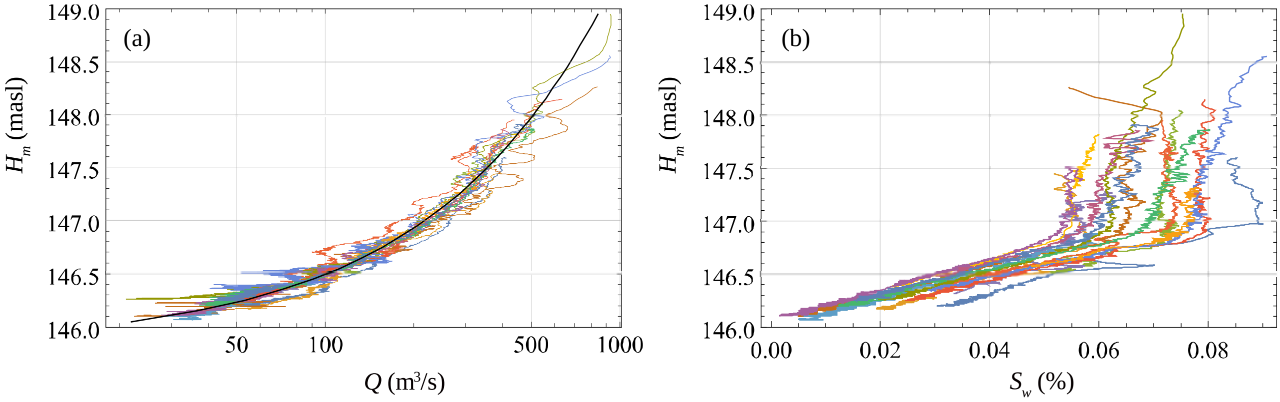

Figure 5. (a) Stage–discharge relations; black line denotes fitting curve (6); (b) Stage–water-slope relations.

5. RESULTS

5.1 Stage–discharge and stage–water-slope relationship

Figure 4(a) shows the time history of water level at the Ozekiyama gauging station from November 2015 to May 2018. The rating curves were established from streamflow time series with high temporal density using FAT system. The average of water level at both acoustic stations, H_m , were used as the water stage in rating curves. For falling limbs of 16 hydrological events, which are shown by the red marks in figure 4(a), the rating curves were analyzed. The stage–discharge and stage–water-slope relations did not show significant hysteresis loops at the survey site because of the steep bed slope. The three parameters of discharge rating curve, estimated from the 16 hydrological events, ranged $a = 65.9 \sim 262.3$, $b = 0.911 \sim 2.486$, $H_0 = 145.3 \sim 146.2$.

Figures 5(a) and (b) present the stage–discharge and stage–water-slope relations, respectively. The slope of water surface S_w is evaluated from the water levels at the both acoustic stations (T1, T2). The water slopes S_w linearly increase with increasing stage by $H_m \approx 147$ masl (masl: m above mean sea level). The increases of S_w are insignificant while $H_m > \sim 147$ masl . Because the water slope is milder than the bed slope of 0.11%, the survey site is located in backwater. The backwater is caused by the downstream sand banks (Figure 2). It appears to induce the behavior of water slope that the most of downstream sand banks submerge when the stage is higher than 147 msal (Figure 6).

The mean rating curve denoted by a black line in figure 5(a) is defined by fitting a power function to data of 16 events:

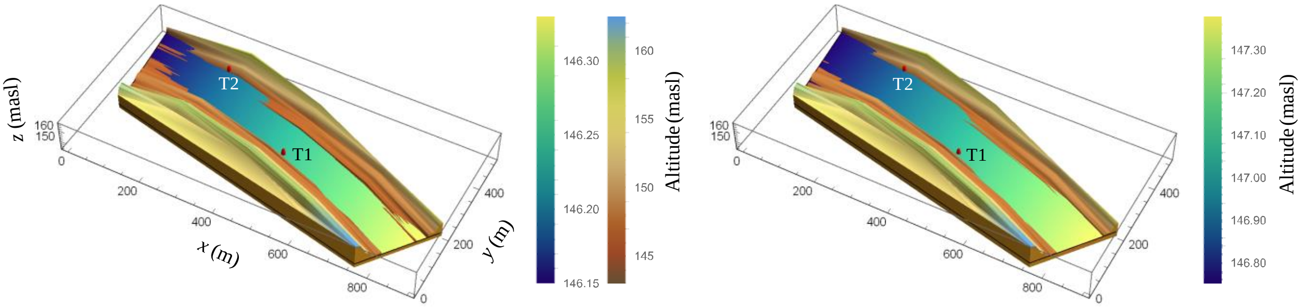

Figure 6. Typical water surfaces in the survey site.

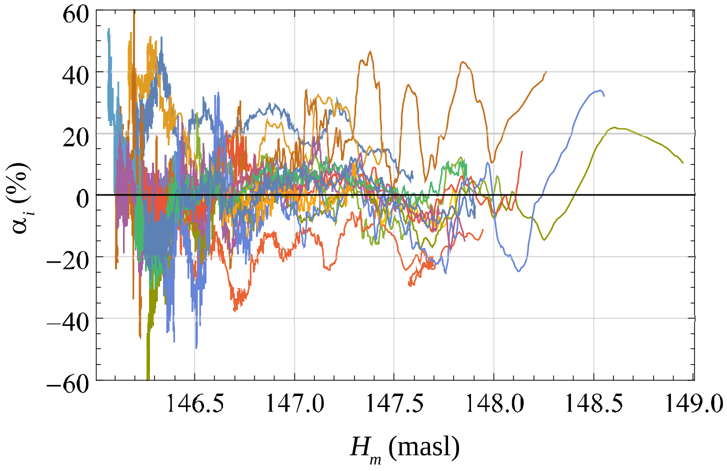

Figure 7. Relative residuals in stage–discharge relations (7).

$$Q_M\left(H_m\right)=175.07\left(H_m-145.83\right)^{1.38}. \tag{7}$$

The determination coefficient was 0.9842. The stage–discharge relations have the fine structures, i.e., it seems that the real rating curves are not smooth and undulate. The relative residual α is defined as:

$$\alpha_i\left(H_m\right)=\frac{Q_i\left(H_m\right)-Q_M\left(H_m\right)}{Q_M\left(H_m\right)} \tag{8}$$

where i is the hydrological event number. The relative residuals in % are shown in figure 7. The large residuals of ~ ±40% can be seen.

5.2 Temporal variability in discharge rating curve

The fallowing quantities $\left(\gamma_m, \gamma_{cor}\right)$ are estimated to examine the short-term variation in the rating curve (RC).

$$\gamma_m=\frac{\overline{Q_{RC,i-1}-Q_{RC,i}}}{\left(\overline{Q}_{RC,i-1}+\overline{Q}_{RC,i}\right)/2} \quad \text{for} \quad i=2,\ldots,16 \tag{9}$$

$$\gamma_{cor}=\frac{\overline{Q_{RC,i-1}Q_{RC,i}}-\overline{Q}_{RC,i-1}\overline{Q}_{RC,i}}{\sqrt{\left(\overline{Q^2}_{RC,i-1}-\overline{Q}^2_{RC,i-1}\right)\left(\overline{Q^2}_{RC,i}-\overline{Q}^2_{RC,i}\right)}} \quad \text{for} \quad i=2,\ldots,16 \tag{10}$$

where $\overline{}$ denotes stage averaging and i is the hydrological event number. The determination coefficient for each fitting of the power function ranged from 0.9809 to 0.9986. γ_m and γ_{cor} indicate the relative variation and the correlation coefficient between the successive rating curves (RCs), respectively.

Figures 4(b) and 4(c) show the time histories of γ_m in % and γ_{cor}, respectively. It is found that the rapid changes of the rating curve occurs owing to large flood events from γ_m and γ_{cor}. The largest flood in July

2017 especially leads to a significant change of RC. Thus, it is significant to consider the intra-year change of RC.

6. CONCLUSIONS

The discharge uncertainty caused by temporal variability of the rating curve (RC) is significant. The short-term changes of RC caused by flood events are undetectable by traditional rating techniques. A RC established from the sparse gauging in a hydrological year can result in large errors in the streamflow estimation.

The novel FAT system allowed the unique high-frequency (every 10 minutes) streamflow gauging. The uncertainty of RC reached around ±40% in the mountainous river. The streamflow records with uniquely high temporal density shed light on the irregularity in stage–discharge relations. It shows that the power function is too simple as a real rating curve.

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