ANALYZING HYDROACOUSTIC SIGNALS TO MEASURE THE STREAMFLOW OF A SHALLOW MOUNTAINOUS RIVER

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ABSTRACT

In this work, a new generation of hydroacoustic tomography system operated by high-frequency 53-KHz underwater acoustic transducers was used to measure discharge in a shallow mountainous river. The system was placed in very stringent site conditions which imposed a challenge to improve discharge estimates. To overcome this challenge, authors applied a practical method to tune the hydroacoustic data, this method depends on graph theory applications to analysis arrival times. The results showed that discharge estimated by FAT is in perfect agreement with discharge estimated by the RC method.

Keywords: FAT, river discharge, shallow river, hydroacoustic, distance function

1. INTRODUCTION

Continuous streamflow records are of paramount to gain information about the underlying hydrological processes that take place within a catchment and a sub catchment scales. Indeed, long-term endeavors to explore the potential opportunities for improving the discharge computation by means of the RC-based methods had increased up the precision and quality of discharge measurements. Nonetheless, one of the important challenges linked to flow measurements by the RC approach for all water resources experts is that the empirical stage–discharge equations naturally change over time as the stream exposes to fluctuating flow, erosion, and deposition resulting in frequent geomorphological modifications. Hence, maintaining the quality state of RC equations being precise depends on the consistency of performing direct streamflow measurements to calibrate RC equations repeatedly (Jalbert et al., 2011).

It is known that streamflow in an open channel (Q) is calculated by multiplying the cross-sectional average velocity (V) by the cross-sectional area (A). Temporal variations in cross-sectional area can be measured automatically by water loggers, however, obtaining long-term velocity measurement perfectly and continuously, typically, is expensive and entails highly skilled personnel. On the other hand, recent advancement in several underwater acoustic sensors has led to measure different river parameters accurately, especially for discharge and velocity. Among the developed instruments, the Fluvial Acoustic Tomography (FAT) system had been proven to be a competitive hydroacoustic instrument that can manage numerous hydrological applications. The progressively improved 30-KHz FAT system, have documented various advantageous applications demonstrated in many works such as; estimating continuous long-term river discharge and streamflow direction (Bahreinimotlagh et al., 2016; Kawanisi et al., 2018, 2016, 2013), reconstructing horizontal flow velocity and visualizing current field in a shallow river (Razaz et al., 2015), and detecting high-frequency scaling characteristics of river discharge (Al Sawaf et al., 2017).

To extent the applications of the FAT system to be utilized for more shallower and narrower rivers, a new version of FAT system with higher frequency (i.e. 53 kHz) had been recently developed and tested in some river and estuary locations in Hiroshima for very short observation periods (i.e. few hours). However, it was found that long-term records revealed some periods of multivariate arrival time signals recorded by the FAT system due to imperfect sound transmission, which in turn resulted in very poor estimates for stream velocity and hence for streamflow as well. In a practical manner, dealing with sub-millisecond timing accuracy is critical because very small differential arrival travel time mistakes will generate enormous errors in acoustic analysis (Razaz et al., 2015).

Therefore, the purpose of this work is to present a straightforward approach to tune the arrival times obtained by the new high frequency 53-KHz FAT underwater acoustic transducers based on graph theory method namely the shortest path graph approach and thus to retrieve river discharge in case of receiving unclear acoustic signal data.

2. OBSERVATION SITE AND MEASUREMENT PRINCIPLES

2.1 Observation Site

Field observations were carried out in the Basen River, which is a gravel-bed river located in Hiroshima prefecture, west of Japan. The 50 m width river flows over 39.2 km, with a watershed area estimated by 680 km^2. The water depth at the observation site becomes significantly shallow under low flow situations. The locations of the underwater acoustic transducers are shown in figure 1.

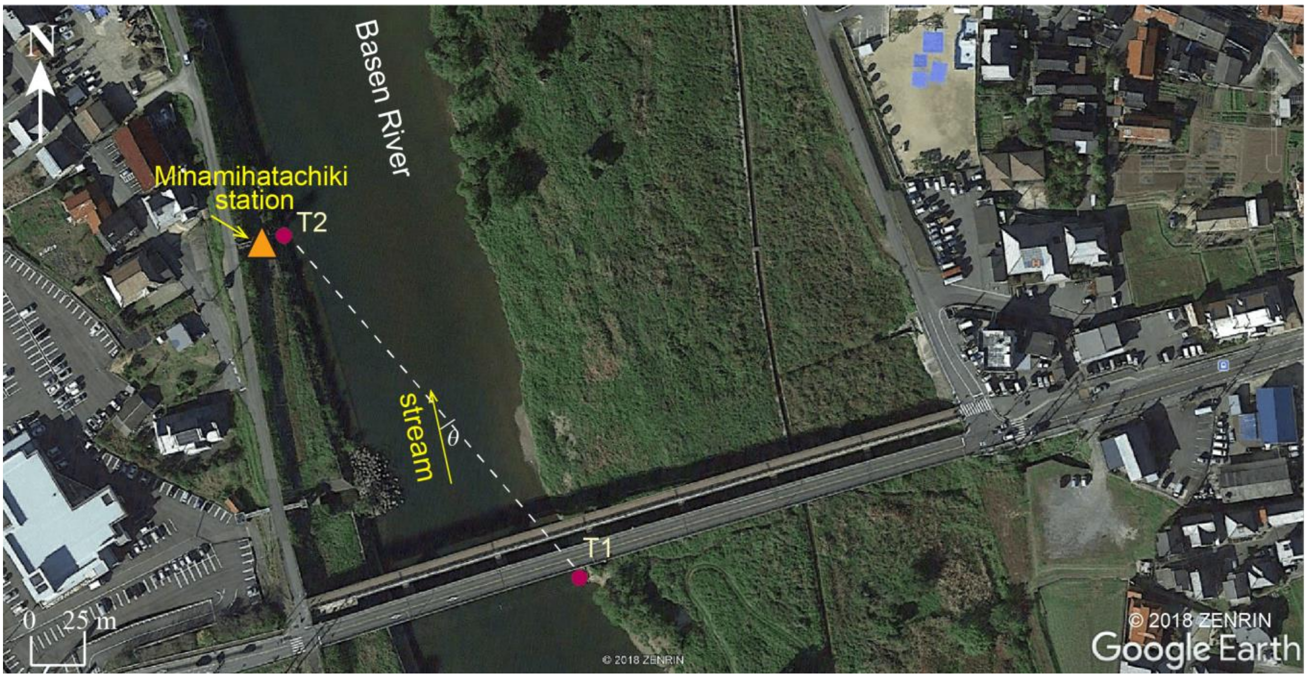

Figure 1. The location of field measurement site and positions of the deployed FAT system and the Minamihatchiki station.

As can be seen in figure 1, the Minamihatashiki gauging station, which was established by the Ministry of Land Infrastructure and Tourism (MLIT) Japan, measures water level H and estimates discharge Q_{RC} indirectly by means of RC equation. The bed topography survey was accomplished using unmanned autonomous boat with a single-beam echo sounder and a GPS. Water level data were acquired every 30 s by submersible level transmitters. The water loggers were placed near the two transducers. The total error band is ±0.1% of the measurement range.

2.2 The Fluvial Acoustic Tomography System Overview

The Fluvial Acoustic Tomography (FAT) system is a hydroacoustic system that was produced by Hiroshima University for utilizing the applications of underwater acoustics to monitor streamflow properties in very shallow streams ranging from 0.5 m deep (such as mountainous streams) up to 10 m deep (such as some coastal estuaries) (Razaz et al., 2015). The "time-of-travel" method is the backbone principle of the FAT system, similar to the acoustic velocity meters to some extent, nevertheless, the key advantage of the FAT system is that the average cross-sectional velocity can be measured with no complex post-processing steps (Kawanisi et al., 2012).

The FAT system can be installed and operated in any river within complex geometries and landscapes, regardless the distance between the river banks (i.e. short or long), and within stringent observation sites, thus it overcomes many drawbacks and provides numerous advantages comprising: (i) preserving the diversity of riverine aquaculture, (ii) avoiding disturbance of fishermen activities, (iii) empowering the functionality of river site for boat navigation, also, (iv) providing a practical solution for measuring streamflow within complex bathymetries and very shallow rivers.

Since the FAT utilizes travel-time tomography approach, the arrival time of acoustic signals at the upstream (T1 or t_{up}) and downstream (T2 or t_{down}) (figure 1) are transmitted and received by both transducers, the range-averaged sound speed (c) and stream velocity along the sound ray path (u) are determinable according to the following equations:

$$c = \frac{L}{2}(\frac{1}{t_{up}} + \frac{1}{t_{down}}) \quad (1)$$

$$u = \frac{L}{2}(\frac{1}{t_{up}} - \frac{1}{t_{down}}) \quad (2)$$

where L is the oblique distance between the upstream and downstream transducers. Discharge by FAT, Q_{FAT}, can be estimated as:

$$Q_{FAT} = u \times A \times \tan\theta \quad (3)$$

where A is oblique cross-sectional area along transmission line and θ is the flow angle. The streamflow angle θ of FAT was determined using regression analysis for reference discharge records (Kawanisi et al., 2016). In this observation, the transmission line length between the transducers was 149 m, and 53 kHz transducers were used in velocity measurements.

2.3 The Challenge of Imperfect Detection of Acoustic Arrival Times

The expected arrival time between the two acoustic stations (T1&T2) considering that sound speed for fresh water ≈ 1425 m/s and the water temperature was roughly 5.6℃ during the observation days is estimated as 105 milliseconds (ms). Hence, the expected domain was determined using data obtained in the range from 10 milliseconds before and after the expected arrival time.

As a general rule, to determine the arrival times for both upstream and downstream transducers (T1, T2), the largest arrival peak is selected with maximum peak that satisfies SNR ≥ 10 dB in the whole of each correlation pattern (Chen et al., 2018). The corresponding time series for the arrival times for downstream and upstream transducers is plotted in figure 2, however, the acquired arrival time records by means of FAT system show inconsistent signals from the main trend, i.e. the arrival time data obtained by both upstream and downstream transducers were scattered as revealed in figure 2.

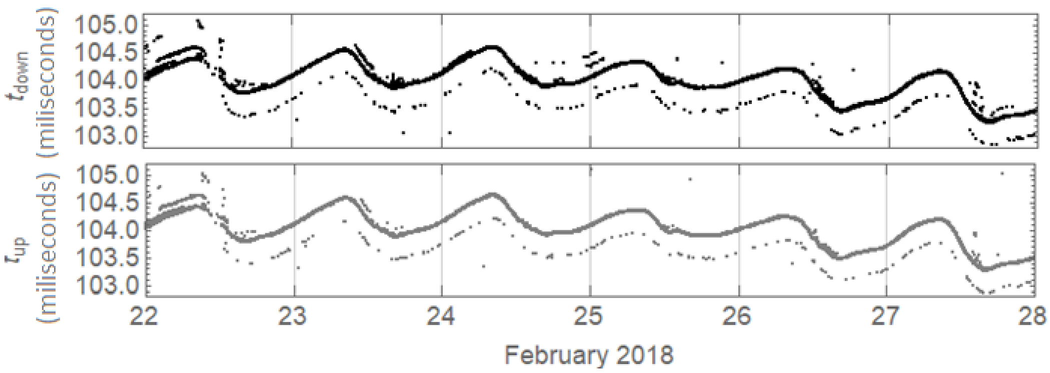

Figure 2. Arrival times (milliseconds) recorded by downstream (black) and upstream (gray) transducers during the observation period.

It was expected to have one arrival time group, nonetheless, the recorded arrival time-series from both transducers showed multivariate datasets. This is because the largest peak that satisfies SNR ≥ 10 dB of each correlation pattern was significantly scattered inconsistently over the whole receiving period, resulting in different multi arrival time groups as can be seen in figure 2. Apparently, it is clear that there is a group of data shown in figure 2 exhibits a continuous behavior (inlier data), other recorded arrival times are scattered up and down suggesting that those readings are not desired data and thus should be rejected. In the case of a handful number of outliers or scattered data, it is easy to eliminate any non-desired readings. However, if numerous readings are scattered as figure 2, it will be a convoluted task to pick up the desired points. Averaging methods, on the other hand, will not be useful because dealing with sub milliseconds accuracy entails very sensitive analyses. Without removing those undesirable readings, velocity and streamflow estimates will be incorrect. Hence to overcome this challenge, the arrival peaks were analyzed using the shortest path method as a proposed solution.

2.4 Analysis by Shortest Path Graph

In order to evaluate the river velocity and discharge, first it is required to find the appropriate arrival peak data and then compare discharge estimates with another independent measurement method. To detect the appropriate arrival time peak data the implemented analysis herein is to find a graph that passes through the nearest neighbor points "inliers" and declines the farther ones "undesired outliers" in figure 3. Once the graph defined, velocity and discharge by means of FAT can be evaluated as formerly described in section 2 using equations (1 to 3).

To obtain the desired graph, the shortest path method was applied in this work. The shortest path method is one of the common approaches that is widely used in pattern recognition problems. The fundamental concept of the shortest path method is to find a path in a set of points starts from a given origin point to a fixed end point where the sum of the weights of its elements edges is minimized. The computation of the shortest path analysis was accomplished following the main assumptions of (De Berg et al., 2011). It is assumed that the inputs (i.e. arrival time records from upstream and downstream stations in figure 2), are a set S of positive samples in $\mathbb{R}^2$. The goal is to find the interpolated shortest graph that capture most of inliers. To accomplish the highest resolution for the conducted analyses, the shortest path was estimated for each day separately and after that interpolated for the entire observation time. First of all, for each single day (window), the arrival time data $S_{d,i}$ (d is day index and i refer to the time index (hour: minute: second) starting from i= 00:00:00 to i= 23:59:30), acoustic arrival times were normalized using the well-known rescaling approach (min-max normalization), because the arrival peak data fluctuated significantly. This process is crucial to get rid of any potential mistakes in some machine learning algorithms. The next step is to assign each edge (p, q) a weight (i.e. distance function), which is the square of the Euclidean distance between p and q. Then, the shortest path graph Gs was plotted for each input daily data $S_{d,\mathrm{i}}$ and then interpolated for the entire study period as presented in figure 3.

3. RESULTS AND DISCUSSION

3.1 The shortest path analysis

The shortest path graph seemed to be superior. Figure 3 obviously illustrates the performance of the shortest path graph for capturing the desired arrival times at downstream and upstream transducers during the monitoring time. Indeed, utilizing the squared Euclidean distance as a distance function for edge weight, the shortest path neatly detected the required inliers.

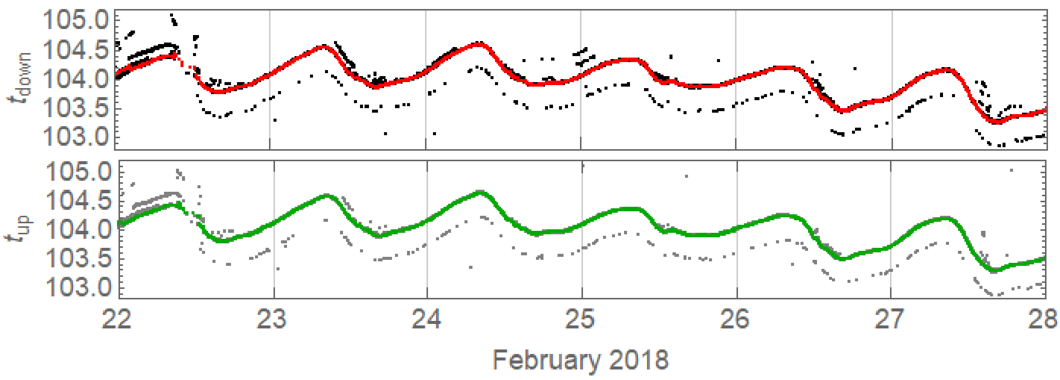

Figure 3. Arrival time (milliseconds) recorded by downstream and upstream transducers (black, and gray) and the detected inliers (red, green) by the shortest-path graph.

To the best of our knowledge, this is the first study that incorporates the applications of the shortest path graphs to analyze hydroacoustics multipeak arrival time shortcomings in riverine areas. Although there are no direct rules to suggest the perfect distance function that ensure the best results in graph theories, however, it should be emphasized that it is important to understand the nature of the observed data (i.e. real or synthetic), and thus the suitable distance function may differ depend on different scenarios. accordingly, one can realize the reality that some distance functions in machine learning may act perfectly with particular dataset, or extremely poor with other cases, and therefore there is a need to consider a number of distance functions prior to the final judgement. Certainly, analyzing the accuracy of sub-millisecond timing in hydroacoustic data is extremely sensitive issue because even with extremely small differential arrival travel times will cause enormous errors and mistakes (as can be seen in figure. 5a).

3.2 Temporal variations in stage, velocity and streamflow

To estimate streamflow by means of FAT, initially, the stream velocity was calculated by substituting the new arrival time data detected from the previous section analyses in Eq (2). On the other hand, the oblique cross-sectional area along transmission line was estimated by finding the integration between the river-bed and the temporal variation of mean water depth measured from the water level loggers placed on both river banks (the loggers were placed side by side to T1 &T2, respectively). In addition, the flow angle θ were determined by performing a nonlinear regression as described by (Kawanisi et al., 2016) to the RC discharge records obtained from the Minamihatashiki gauging station (figure 1). The regression analysis for the studied period resulted in θ=19.5° during the baseflow and 22.2° due to the last rainy event day. Flow angle estimates by this method is expected to be accurate because there was almost no rainfall event detected during the observation period. Lastly, the river discharge Q_{FAT} was computed by substituting in Eq (3).

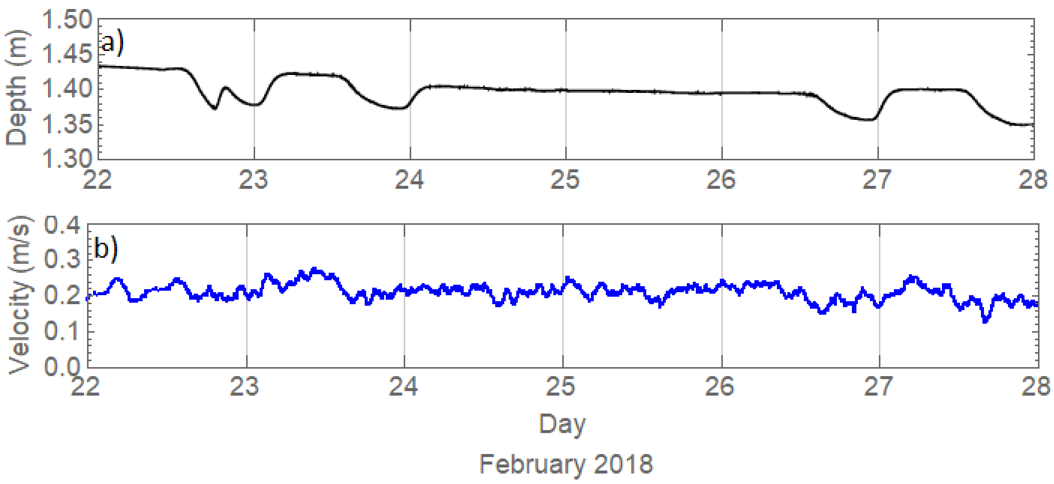

Figure 4. Temporal variations in a) average water depth (black), and b) stream velocity (blue dots).

The temporal variations in the mean water depth and velocity are depicted in figure 4 (a & b). The average water depth during the observation period was 1.4 m, whereas the minimum and maximum water depth varied between 1.35 and 1.45 m, respectively. Minimum and mean velocity during the observation period on the other hand were 0.13 and 0.26 m/s, respectively, and the maximum value was observed at 0.28 m/s.

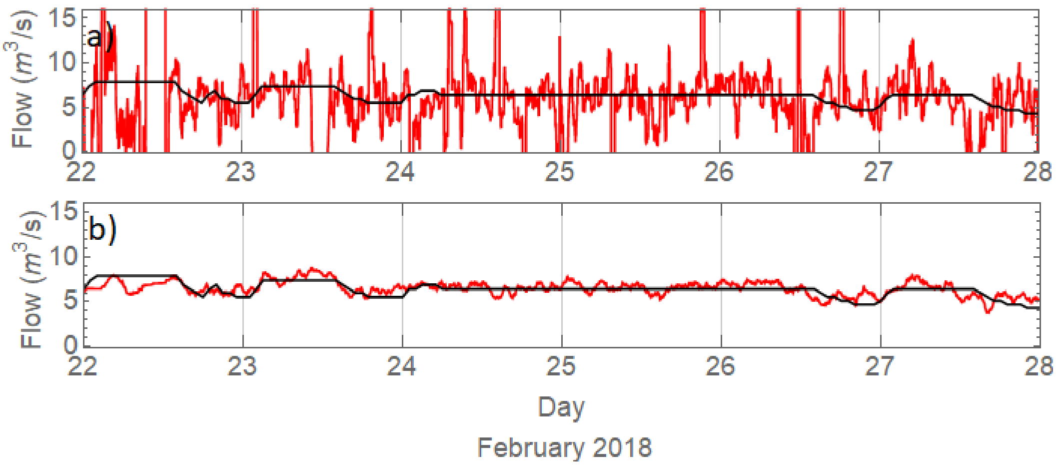

Figure 5. Discharge time series observed by FAT (red) and RC (black) during the study period a) comparison before correcting the arrival times of the acoustic transducers, and b) comparison after correcting the arrival times of the acoustic transducers using the shortest path graph.

Discharge measurements for both Q_{FAT} and Q_{RC} are presented in figure 5. Figure 5a shows the discharge time-series estimated by means of FAT without using the shortest path graph. Interestingly, the temporal variations in the discharge evaluated by FAT (Q_{FAT}) as improved by the shortest path graph seem to be in very good agreement with the discharge estimated by RC method (Q_{RC}) revealed in figure 5(b). These analyses reflect the importance of considering the highest quality of acoustic arrival time data. In this work, the author did not aim to investigate the potential variations between Q_{RC} and Q_{FAT} since it was discussed in other previous works (Kawanisi et al., 2018, 2016), rather to use the records of Q_{RC} as a reference for general comparison. To make further assessment for discharge estimated by means of Q_{FAT} compared to streamflow measured by RC (reference discharge record), a graphical demonstration presented in figure 6 shows the comparison between the Q_{RC} and Q_{FAT} estimates, the determination coefficient $R^2 = 0.95$ which is very good.

A noteworthy question that can be raised is about the reason for receiving scattered arrival times. In fact, the authors believe that the existence of outliers in the arrival times from upstream and downstream transducers (figure 2), does not mean that those readings are wrong measurements. However, this phenomenon (i.e. multipeak arrival times) was observed during extremely shallow periods, where the water depth near banks (similarly for the submerged underwater acoustic transducers) is low.

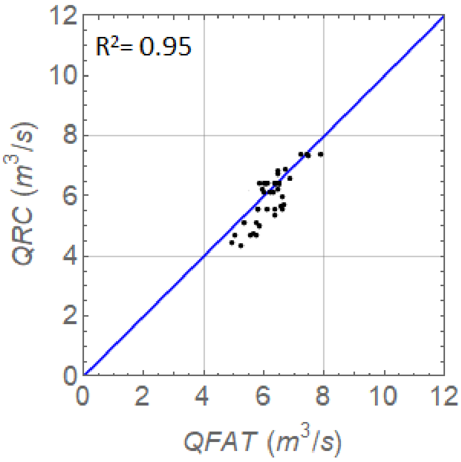

Figure 6 Association between the Q_{RC} and Q_{FAT} estimates.

4. CONCLUSIONS

This work presents the performance of a promising hydroacoustic system in measuring a mountainous shallow-water river discharge within very constrained monitoring site conditions. Generally, most of common continuous discharge measurement methods have a set of guidelines for selecting the optimum monitoring site, nevertheless, practically, it is not quite easy possible to find a stream that meets all the proposed site criteria. In contrast, the FAT system does not require a set of rules for site selection. The most important point in selecting measurement location is to ensure that underwater acoustic transducers are diagonally placed on both riverbanks with adequate depth.

The new FAT system was deployed in the Basen River, Japan, equipped with 53-KHz underwater acoustic transducers to enhance the resolution of flow measurements within narrower rivers. The stringent site conditions produced multivariate arrival times and hence impaired the quality of hydroacoustic data. To overcome this challenge, authors utilized the shortest path method for analyzing the acoustic arrival times. This approach depends finding the shortest path that covers the desired inliers data. Although this study focused on the Basen River as a case study, the findings can be extended to be utilized by several works concern about measuring streamflow in shallow, narrow, and even within limited or minimum degree of flexibility.

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REFERENCES

Al Sawaf, M.B., Kawanisi, K., Kagami, J., Bahreinimotlagh, M., Danial, M.M., 2017. Scaling characteristics of mountainous river flow fluctuations determined using a shallow-water acoustic tomography system. P*hys. A Stat. Mech. its Appl*. 484.

Bahreinimotlagh, M., Kawanisi, K., Danial, M.M., Al Sawaf, M.B., Kagami, J., 2016. Application of shallow-water acoustic tomography to measure flow direction and river discharge. *Flow Mea*s. Instrum. 51.

Chen, M., Syamsudin, F., Kaneko, A., Gohda, N., Howe, B.M., Mutsuda, H., Dinan, A.H., Zheng, H., Huang, C.F., Taniguchi, N., Zhu, X., Adityawarman, Y., Zhang, C., Lin, J., 2018. Real-Time Offshore Coastal Acoustic Tomography Enabled With Mirror-Transpond Functionality. *IEEE J. Ocean. Eng*.

De Berg, M., Meulemans, W., Speckmann, B., 2011. Delineating imprecise regions via shortest-path graphs, in: GIS: Proceedings of the ACM International Symposium on Advances in Geographic Information Systems.

Jalbert, J., Mathevet, T., Favre, A.C., 2011. Temporal uncertainty estimation of discharges from rating curves using a variographic analysis. *J. Hydrol*. doi:10.1016/j.jhydrol.2010.11.031

Kawanisi, K., Al Sawaf, M.B., Danial, M.M., 2018. Automated Real-Time Streamflow Acquisition in a Mountainous River Using Acoustic Tomography. *J. Hydrol. Eng*. 23, 04017059.

Kawanisi, K., Bahrainimotlagh, M., Al Sawaf, M.B., Razaz, M., M.B., M.B., Razaz, M., 2016. High-frequency streamflow acquisition and bed level/flow angle estimates in a mountainous river using shallow-water acoustic tomography. *Hydrol. Proces*s. 30, 2247–2254.

Kawanisi, K., Razaz, M., Ishikawa, K., Yano, J., Soltaniasl, M., 2012. Continuous measurements of flow rate in a shallow gravel-bed river by a new acoustic system. *Water Resour. Res*. 48, 1–10.

Kawanisi, K., Razaz, M., Yano, J., Ishikawa, K., 2013. Continuous monitoring of a dam flush in a shallow river using two crossing ultrasonic transmission lines. *Meas. Sci. Technol*. 24, 055303.

Razaz, M., Kawanisi, K., Kaneko, A., Nistor, I., 2015. Application of acoustic tomography to reconstruct the horizontal flow velocity field in a shallow river. *Water Resour. Res.* 51, 9665–9678.