Monitoring Inflow Dynamics in a Multipurpose Dam Based on Travel-time Principle

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Abstract
Understanding inflow dynamics in a dam lake forms the basis for optimal dam operation and management practices. However, methods pertaining to adequately determining negative inflows and addressing them, as well as quantifying uncertainties in dam inflow, have been scarcely investigated. In this study, the inflow was observed using two pairs of fluvial acoustic tomography (FAT) systems placed diagonally in a dam lake, forming a crossed-shaped pattern. The “travel-time” principle is the primary approach for measuring the inflow by FAT. The novelty of this study is in discussing the inflow characteristics within a slow water-flow environment monitored by FAT. Based on the reciprocal sound transmission, we upgraded an equation to estimate the flow direction; this newly proposed generalized equation can be used in a fluctuating flow environment. We also discussed the sound propagation characteristics for slow flow velocities. Finally, we demonstrated that a small inaccuracy in the acoustic signal, even by a sub-millisecond, can cause significant errors in measurements. One of the novel findings of this study is the detection of internal waves using the improved flow direction equation and acoustic travel-time records. Overall, this study presents a promising approach for inflow measurements under extremely slow flow conditions.

Keywords Dam lake · Inflow · Hydroacoustics · Slow inflow velocities · Travel-time · Flow direction

1 Introduction

Dams are important hydraulic structures because they have various positive impacts on the environment (Hariri-Ardebili 2018) through single or multi-purpose functions, including flood control, water supply, and hydroelectric power generation. However, dam construction is accompanied by the transformation of a wide range of aquatic ecosystems and alteration of river flow dynamics. Among the most prominent effects of dam construction are...
variations in sediment transport conditions, alteration of river thermal regime, obstruction of fish migratory patterns, and destabilization of riverine biodiversity (Nazeer et al. 2016; Stähly et al. 2019). These effects may continue for many years, even decades, or constitute a permanent ecohydrological change that may or may not reach a new equilibrium. Hence, understanding the effects of a dam on upstream and downstream sites is a key challenge in ecohydrology.

Accurate measurement of dam inflow is critical because it allows for optimal planning and management practices with respect to water resources, particularly for flood control and power generation (Rahimi et al. 2020). Control strategies for power generation vary for low and high inflow rates. Similarly, dam flush patterns are scheduled and calibrated based on the recorded amount of inflow, which differs during dry and rainy days (Ahmad and Hossain 2019). Accurate dam inflow forecasting has been a focal point in recent research studies (Ahmad and Hossain 2019; Noorbeh et al. 2020). The selection of suitable methods for accurate inflow forecasting and modeling considerably depends on watershed characteristics and available data. In this regard, accurate real-time and/or quasi real-time quantification of stream dynamics is a severe challenge encountered while improving the performance of reservoir inflow forecasting, creating physical models of dam inflow, and, more importantly, regulating the outflow quantities.

Typically, dam inflow is computed using the main water balance method represented by the following equation:

$$Q_I = Q_O + \frac{\Delta S}{\Delta T} + Q_L$$

(1)

where \(Q_I\) and \(Q_O\) are the reservoir inflow and outflow, respectively; \(\Delta S (\Delta S = S_{i+1} - S_i)\) is the difference between the final and initial water storage for the time period \(\Delta T (\Delta T = T_{i+1} - T_i)\); and \(Q_L\) is the amount of water loss from the reservoir, including that from evaporation and seepage (Deng et al. 2015). The temporal variation in the reservoir storage, \(S_i\), can be expressed as \(S_i = f(H_i)\). Nonetheless, uncertainties exist in the reservoir inflow derived by the main water balance method as a result of errors in the reservoir stage-storage relationships and water level measurements (Tao 1999). Stage-storage errors are generated by continuous alteration in the topography of the reservoir lake due to continuous sediment deposition mobilized from upstream regions and as a consequence of poor surveying of lakebed bathymetry and terrain surveying techniques. The limitations of water level monitoring techniques, along with certain natural influencing factors, such as reservoir waves, induce errors in the water level records (Deng et al. 2015).

Previous studies aimed to improve reservoir inflow measurements and minimize potential errors in the inflow estimates using various approaches, such as the ensemble Kalman filter (EnKF) (Deng et al. 2015), applying the moving average of mean water balance equation (Budu 2014), and employing remote sensing information for reservoir slope storage computation (Suzuki et al. 2008). These studies have led to improvements in the accuracy of dam inflow quantification; however, additional efforts should be directed toward improving the precision of reservoir inflow measurement techniques. Likewise, certain issues related to dam inflow estimation, such as adopting methods to accurately address and determine the negative inflows and quantify the uncertainties in dam inflow, have received little attention.

In cases of considerably slow flow environments, such as inflow to a dam lake, measuring variations in water stage and storage does not reflect sufficient precise information on real-time inflow dynamics. Alternatively, to acquire an average stream cross-sectional velocity and the corresponding flowrate, a set of one-point current meters can be installed. However, this
approach cannot be considered practical for long-term measurement in sites such as dam lakes and may even be obstructed in certain locations due to site utilization by fisheries or shipping traffic (Zhu et al. 2012).

This study presents findings from a site-based observation of the inflow to a dam lake obtained using an advanced underwater acoustic tomography system, namely the fluvial acoustic tomography (FAT) system. This study is based on travel-time principles and discusses the prominent issues observed during our monitoring program. We aim to answer the following research questions: 1) What kind of information and knowledge can be derived using underwater acoustic tomography during the slow flow of controlled reservoir releases? 2) What kind of hydrological processes can be identified to improve and correct the analytical models for inflow estimation? Our main objective was to identify the hydrological features that can be deduced from sound transmission in water within slow flows, rather than developing advanced analytical models to calculate the accurate inflow values.

This study is novel in both scientific and technical aspects. First, to the best of our knowledge, in a scientific sense, cross-sectional average velocity and inflow measurements in a shallow dam lake (by means of reciprocal sound transmission) have not been investigated previously. In this study, we observed the temporal variations of inflow dynamics using crossed acoustic path configurations executed by two pairs of underwater acoustic tomographic systems with two distinct transmission frequencies, which also offers a technical novelty to our study. Moreover, we upgraded the determination of flow direction proposed in a previous study by improving it to determine fluctuating flow direction.

2 Materials and Methods

2.1 Study Area

Field observations were conducted in Haji Dam, a concrete gravity dam located in Akitakata City, Hiroshima, Japan (Fig. 1). Haji Dam was built on the upstream region of the Gōno River. The mainstream rises from the mountain region of the Kitahiroshima city, runs through Hiroshima and Shimane prefectures, and finally, discharges into the Sea of Japan near Götsu town in Shimane prefecture (Fig. 1a). The climate of the dam region is generally warm and temperate. The mean annual temperature is 11.7 °C, and the annual precipitation is approximately 1,800 mm.

Table 1 lists the main characteristics of Haji Dam. The dam serves multiple purposes, including flood control, power generation, water supply, and irrigation. The lake formed by Haji Dam is called Yachiyo Lake. As seen in Fig. 1b, tomographic measurements were conducted in the dam lake nearby to the gate to monitor slow inflow dynamics and study several hydrological characteristics, moreover, to provide further insights to the dam management office to improve gate release plans. Interestingly, the dam lake is stomach-shaped, thus being an interesting and challenging monitoring location.

2.2 Methods

2.2.1 Inflow Measurements Using Fluvial Acoustic Tomography (FAT) System

In this study, tomographic measurements of inflow at Yachiyo Lake were performed using the fluvial acoustic tomography (FAT) system developed by our research group at Hiroshima University. Based on the travel-time approach, the FAT system is capable of
Fig. 1  (a) Location of the observation site; (b) map showing Gōno River, Haji Dam, and Yachiyo Lake; and (c) study area map with inflow measurement zone and instrument positions
computing the cross-sectional average sound speed in water \((c)\) and flow velocity along the sound ray path \((u)\). Travel time is the time it takes to transmit an acoustic pulse from one transducer to the target transducer. Hence, for a pair of transducers (such as \(S_1\) and \(S_2\); Fig. 1c), the recorded travel times, \(t_{S_1}\) (i.e., the transmitted acoustic signal from upstream transducer \(S_1\) to the corresponding downstream transducer \(S_2\)) and \(t_{S_2}\) (i.e., the transmitted acoustic signal from the downstream transducer \(S_2\) to the corresponding upstream transducer \(S_1\)), are used to estimate the cross-sectional average sound speed \((c)\) and velocity \((u_s)\) along the transmission line \((S_1-S_2)\) as follows:

\[
c = \frac{D_S}{2} \left( \frac{1}{t_{S_1}} + \frac{1}{t_{S_2}} \right)
\]

\[
u_s = \frac{D_S}{2} \left( \frac{1}{t_{S_1}} - \frac{1}{t_{S_2}} \right)
\]

where \(D_S\) is the oblique distance between transducers \(S_1\) and \(S_2\). Accordingly, the inflow using FAT can be estimated as:

\[
Q_{FAT} = u_s \times A_S \times \tan \theta_1
\]

Table 1 Main specifications of Haji dam and its storage lake (Yachiyo Lake)

| Specification                  | Value     |
|-------------------------------|-----------|
| Dam wall height               | 50 m      |
| Dam wall top length           | 300 m     |
| Dam mass                      | 210,000 m³|
| Catchment area                | 307.5 km² |
| Yachiyo Lake area             | 2.8 km²   |
| Full reservoir storage capacity| 47,300,000 m³|
| Effective water storage capacity| 41,100,000 m³|

\(A_S\) is the cross-sectional area along transmission line \(S_1-S_2\), and \(\theta_1\) is the angle between transmission line \(S_1-S_2\) and the inflow direction. Although several approaches can be used to estimate the flow direction of the FAT system (Al Sawaf et al. 2020), we used two crossed-path configuration approaches to estimate the flow direction.

It should be noted that power shortage due to battery failure is the basic limitation of the FAT system. Additional technical specifications of the FAT system can be found in the supplementary materials.

A dam lake is an ideal area for analyzing sound transmission; however, to overcome obstacles encountered with sound propagation in water and attain precise data recording, the acoustic carrier signal is modulated using a maximum-length sequence (M-sequence), and the received signal is considered to be a set of multipath signals with the same arrival time. Hence, selecting the cross-correlation of the received signal with a replica of the transmitted signal is similar to sending a single strong pulse. The M-sequence is a type of pseudorandom signal, by which the phase shift of \(\pi\) in the carrier is produced at varying time intervals (Simon and Omura 1985).

The FAT system consists of a pair of processing units connected to underwater acoustic transducers. The main operation settings of the FAT systems used in this experiment
are summarized in Table 2. In this study, two pairs of FAT systems were placed diagonally on the lake banks, forming a cross-shaped pattern, as shown in Fig. 1c. Figure 1c also shows the placements of the FAT transducers during the observation period. In this study, two different transmission frequencies were used to monitor the inflow dynamics, with different transmission rates. Along S1_S2, the transmission frequency was 53 kHz with a transmission rate of 10 s, whereas T1_T2 was accomplished using a 30 kHz transmission frequency at a transmission rate of 30 s, and both transducers served the dual function of transmitting and receiving acoustic signals.

At the beginning of the observation period, the water in the dam lake was deep; thus, all transducers were installed approximately 1.5 m below the water surface and suspended on floating boats. The floating boats were poised using nearby trees and/or rocks. At the end of each transducer, a counterweight was fixed to prevent the transducer from drifting in the event of unexpectedly high inflow velocities.

There are several reasons for using two distinctive frequencies. First, a new generation of the FAT system was developed in our laboratory; therefore, to assess the performance of this version within slow inflow velocities, two central frequencies were tested. Second, higher transmission frequency can perform outstandingly in cases of slow water velocity (Kawanisi et al. 2012). In addition, shorter acoustic paths (e.g., S1_S2) entail higher frequencies and vice versa. Furthermore, we used a cross-shaped acoustic path to determine the continuous measurements of the inflow direction (\(\theta_1\) and \(\theta_2\)), as depicted in Fig. 2. This monitoring pattern would be beneficial for tracking slow and fluctuating inflow directions and detecting any period of negative inflows that could be encountered during the discrete opening and closing of the dam gate. Additional details regarding the flow angle estimation are provided in Sect. 2.2.2.

### 2.2.2 Determination of the Inflow Direction Acquired Using Cross-shaped Acoustic Path Configuration

Bahreinimotlagh et al. (2016) proposed the following equation (Eq. (8)) for determining flow direction:

\[
Q_{S1S2} = Q_{T1T2}
\]

\(u_1 \times A_1 \times \tan \theta_1 = u_2 \times A_2 \times \tan \theta_2\)

#### Table 2  Main operation settings of fluvial acoustic tomography systems

| Station | Transmission frequency | Transducer type | Signal transmission rate | Length between stations | Expected arrival time* (milliseconds) |
|---------|------------------------|----------------|-------------------------|------------------------|--------------------------------------|
| S1_S2   | 53 kHz                 | Omnidirectional broadband transducers (T226, Neptune Sonar Ltd) | Each 10 s | 253.04 m | 174.5 ms |
| T1_T2   | 30 kHz                 | Omnidirectional broadband transducers (T257, Neptune Sonar Ltd) | Each 30 s | 287.50 m | 198.2 ms |

*Assuming that the sound speed in freshwater environment is 1,450 m/s.
where $Q_S$, $u_1$, and $A_1$ are the discharge, velocity, and cross-sectional area along $S_1$-$S_2$, respectively; $Q_T$, $u_2$, and $A_2$ are the discharge, velocity, and cross-sectional area along $T_1$-$T_2$, respectively; and $\theta_2$ is the angle between the transmission line $T_1$-$T_2$ and the inflow direction. As illustrated in Fig. 1c, $\Phi_1 = \theta_1 + \theta_2$ is the angle formed by the transection of the two acoustic paths; therefore, it is substituted in Eq. (6) as follows:

$$\theta_1 = \cos^{-1} \left( \frac{u_1 A_1}{u_2 A_2} \right)$$

In essence, $\theta_1$ requires an iteration-solving approach; therefore, using trigonometric expansion, Eq. (7) can be explicitly expressed as follows:

$$\theta_1 = \tan^{-1} \left( \frac{u_1 A_1}{u_2 A_2} \tan(\Phi_1 - \theta_1) \right)$$

$$\theta_1 = \cos^{-1} \left( \frac{u_1 A_1}{u_2 A_2} \right)$$
Equation (8) is limited to unidirectional flow from upstream to downstream. Consequently, to improve the equation representability, $\emptyset_1$ or $\emptyset_2$ must be carefully selected based on the flow direction. This can be accomplished by considering the difference between the arrival times of each pair of transducers and selecting proper geometrical axes, as illustrated in Fig. 2. In the case of Fig. 2d, both velocities along S1_S2 and T1_T2 were positive; therefore, according to Eq. (3), in this case $t_{S1} < t_{S2}$, $t_{T1} < t_{T2}$ and $\emptyset_1 = \theta_1 + \theta_2$. Thus, the current direction can be inferred to be in the 4th quadrant (Q4) of the $x$ shape. Likewise, if $t_{S1} > t_{S2}$ and $t_{T1} > t_{T2}$, $\emptyset_1 = \theta_1 + \theta_2$, but in this case, both velocities were negative (Fig. 2b), and the direction was in the 2nd quadrant (Q2). However, if $t_{S1} > t_{S2}$ and $t_{T1} < t_{T2}$ (i.e., Q1) or $t_{S1} < t_{S2}$ and $t_{T1} > t_{T2}$ (Q3), then $\emptyset_2 = \theta_1 + \theta_2$ (Fig. 2a, c). As a result, if the flow is either in the direction of Q2 or Q4, Eq. (8) can be used in this case. On the other hand, if the flow direction according to the abovementioned assumptions was either in Q1 or Q3 direction, then Eq. (9) should be used in these cases:

$$\theta_i = \cos^{-1} \left( \frac{\sqrt{2\cos(\emptyset_2)} \sqrt{u_1^2 A_1^2 + \cos(2\emptyset_2)(u_1 A_1 - u_2 A_2)^2 + 6A_1 A_2 u_1 u_2 + u_2^2 A_2^2 + \cos(2\emptyset_2)(u_2 A_2 - u_1 A_1) + 3u_1 A_1 + u_2 A_2}}{u_1 A_1 + u_2 A_2} \right)$$

according to recorded arrival times.

2.3 Auxiliary Measurements

The temporal variations in the mean water level and water temperature were acquired every 5 min using a HOBO®_U20 level-temperature logger attached to the bridge column (see “WL” Fig. 1c). The bed topography survey along the two cross-sections (S1_S2 and T1_T2) was conducted using an autonomous boat equipped with GPS and a single-beam echo sounder at a frequency of 200 kHz (resolution of 0.01 m). The time series of the cross-sectional area along S1_S2 and T1_T2 were evaluated by computing the integration between the riverbed and the time series of the average water level observed by the water level logger.

Water temperature profiles were collected using CastAway™ [a conductivity-temperature-depth (CTD) logger] at different locations in the lake (P1, P2, P3, and P4 in Fig. 1c) on October 19, 2020 (fall) and December 2, 2020 (early winter).

Finally, the records of water level, storage, inflow, and outflow were provided by the Haji Dam Monitoring Office (HDMO) and used for further analyses and comparisons. The inflow at Haji Dam was measured using the main water balance approach, where the water level was measured continuously every 10 min using a quartz-type water-level gauge monitoring unit.

Our observation started on November 18, 2020 and ended on December 5, 2020. Owing to certain difficulties related to site accessibility due to severe climate and the restrictions influenced by the COVID-19 pandemic, certain tomographic records could not be obtained before November 30, 2020. No rainfall was observed during the study period.
3 Results

3.1 Time Series of Water Level, Storage, and Water Temperature During the Observation Period

The temporal variation at the water stage, as measured by the HDMO, is plotted in Fig. 3a and was consistent with the readings obtained by the water level-temperature logger. In general, both water level records are highly comparable to each other, even though the HDMO dataset resolution was 10 min, while the water level logger was set to 5 min. Figure 3a shows that the water stage at the dam lake exhibited a daily steady increment estimated at 8 cm. Nonetheless, HDMO performs a scheduled water release for 5 h every afternoon, resulting in approximately 0.5% storage reduction per day (Fig. 3b).

The water temperature recorded by the water level temperature logger is presented in Fig. 3c. Notably, water temperature was almost constant during the study period. As seen in Fig. 3c, the water temperature during the observation period was ~12 °C; however, on the last day, the water temperature dropped drastically because water storage near the sensor was low.

3.2 Hydroacoustic Measurements

3.2.1 Arrival Time Records

As depicted in Figs. 4a, b and 5a, b, samples of the stack plots for the cross-correlation pattern signals were transmitted from the downstream transducer to the upstream transducer and vice versa for S1_S2 and T1_T2, respectively. The diagrams are shown at 5 min intervals and two main groups of arrival times, with a difference of approximately 0.35 ms for the 53-kHz system. However, in the case of the 30-kHz system, only one primary arrival group is observed, whereas multiple arrival peaks are evident in Fig. 5b, with an approximate difference of 1 ms.
In this study, the first arrival peak from each cross-correlation signal was selected, and the corresponding arrival times for the downstream (i.e., $t_{S2}$ and $t_{T2}$) and upstream transducers (i.e., $t_{S1}$ and $t_{T1}$) are identified in Figs. 4c, d and 5c, d, respectively, to compute the velocity and water inflow. The discontinuities in the arrival time series data indicate that these readings could not be selected because the recorded signal was extremely weak. In other words, either the largest peak of each correlated signal did not satisfy an acceptable signal-to-noise-ratio (SNR) threshold (10 dB), or it was considerably scattered, and therefore, the arrival peak could not be defined accurately.

Remarkably, the recorded arrival times in Figs. 4c–d and 5c–d ranged within the expected values presented in Table 2. The arrival times fluctuated during the day and night because of daily temperature variations. Once the arrival time records were defined, the water velocity, flow direction, and inflow by FAT were calculated using Eqs. (2) and (8).

3.2.2 Inflow Velocity

The velocity resolution ($u_r$) of the FAT can be estimated using Eq. (10) (Kawanisi et al. 2012) (also see Fig. 6):

$$u_r = \frac{c_m^2}{4 \times R \times f}$$  \hspace{1cm} (10)

where $f$ is the transducer frequency, $R$ is the ray length (m), and $c_m = 1,450$ m/s. Figure 6 demonstrates that the velocity resolution obtained by 53 kHz is 1.5 times greater than the velocity obtained by the 30-kHz transducer (in the case of our transmission lengths). In
the present study, the velocity resolution acquired by $f=53$ kHz (approximate ray length along $S_1 \_S_2 = 253.04$ m) and $f=30$ kHz (approximate ray length along $T_1 \_T_2 = 287.5$ m) is 0.039 m/s and 0.06 m/s, respectively.

Kawanisi et al. (2012) revealed that the reliability of the FAT records increases as the square root of the number of samples per ensemble increases. Hence, to decrease the uncertainty of the FAT records, 60 samples in the case of 53 kHz (owing to the high transmission rate, i.e., 10 s individually) and 30 samples in the case of 30 kHz were averaged in

Fig. 5 Arrival time records of 30-kHz system: sample of stack diagram of correlated signals recorded on December 1, 2020, with a 5-min interval, a blue dots represent selected peaks of arrival times downstream, and b red dots represent selected peaks of arrival times upstream. Time series plots of arrival times (in ms) obtained by c downstream (black) and d upstream (gray) transducers

Fig. 6 Velocity resolution of fluvial acoustic tomography (FAT) as a function of acoustic ray length and transducer frequency; green and red dots denote velocity resolution in accordance with distance and frequency for $S_1 \_S_2$ and $T_1 \_T_2$, respectively
this study. Consequently, the uncertainty caused by the low velocity resolution could be reduced to $\frac{0.04}{\sqrt{60}} = 0.5 \text{ cm/s}$ and $\frac{0.06}{\sqrt{30}} = 1 \text{ cm/s}$ for 53 kHz and 30 kHz, respectively.

Figure 7a, b show the temporal variations in the cross-sectional mean velocities along S1_S2 and T1_T2, respectively. The cross-sectional average velocity along S1_S2 was evidently very slow during the investigation period, with apparent positive and negative fluctuations. Gaps in the velocity time series were generated because the original arrival times were not recorded due to battery shortage or recorded signals were unreliable.

Similarly, the cross-sectional average velocity along T1_T2 was nearly constant, with positive and negative fluctuations observed until the late morning of December 2, 2020. However, the velocity became completely positive from the afternoon of the same day along T1_T2 and nearly positive along S1_S2, with some periods of negative records which was expected because of the continuous water release compared to the lower inflow rate. Moreover, it should be noted that inflow fluctuated between Q4 (velocity along both axes were positive) and Q1 (velocity along T1T2 positive and negative along S1S2) as can be seen in Figs. 2a, d and 1 due to the opening and closing phases of the dam gate. In fact, post December 4, 2020, the water level at the dam lake had declined significantly near the left bank, particularly at T2, as illustrated in the cross-sectional profile shown in Fig. 10b; therefore, the transducer and floating boat remained almost dried on the bank, and consequently, reliable reciprocal sound transmission along T1_T2 could not be accomplished afterwards. At midday on December 2, 2020, the velocity was not determined because the battery voltages at T1 and S2 dropped and were replaced. The velocity data were processed using the mean filter technique. This technique involves removing local variations caused by rough readings and minimizing noise levels. To evaluate the mean filter of a dataset, every point is replaced by the mean value in its range ($r$) neighborhood. Hence, in the case of the velocity obtained by the 53 and 30-kHz datasets, 60 and 30 points were used during the filtering process, respectively.

![Fig. 7](image-url) Mean average velocity along transmission lines: a S1_S2 (black), and b T1_T2 (red). Releasing periods are highlighted in blue.
3.3 Detection of Flow Direction and Inflow Estimation by Fluvial Acoustic Tomography (FAT)

Owing to the difference in the velocity resolutions, only the computed flow direction and inflow of optimal data records are shown. The water flow direction was computed according to the main assumptions proposed in Sect. 3.2 and illustrated in Fig. 2.

Figure 8a presents the temporal variations in the ensemble-averaged inflow direction between November 30, 2020 and December 1, 2020. In this figure, the flow direction across S1_S2 is marked with four colors. These colors indicate the water direction over a corresponding quadrant, according to the assumptions given in Sect. 2.2.2. Overall, the absolute mean flow direction was 21.47°, and this value varied in different directions. The findings in Fig. 8a reveal that the water direction mainly varied between Q1 and Q2.

Figure 8b shows the temporal variations in the inflow acquired by FAT estimated from Eq. (4) compared to those estimated by the HDMO. The inflow estimated by FAT and that recorded by the HDMO on December 30, 2020 during release and very low release conditions are moderately comparable with each other, with considerable variations in a few periods. The large inconsistencies between FAT and HDMO estimates can be attributed to the low resolution of velocity estimates by FAT (specifically for 30 kHz), which decreased the accuracy of angle determination, or due to uncertainties in the stage-storage term in the main water balance method for inflow calculation. Another possible reason is the limitation of acoustic records in accurately determining the flow direction under slow flow conditions, particularly during the transition of the water direction from one quadrant to another.

Alternatively, considering the absolute mean value of the inflow direction as a fixed value for inflow estimation using FAT (i.e., θ₁ = 21.47°), the inflow rate estimated by FAT is highly comparable to that reported by the HDMO, as depicted in Fig. 8c.

3.4 Lake Thermal Stratification

Thermal stratification is among the most important hydrological processes in lake hydrodynamics. Figure 9a, b show the temperature along the water columns measured
at P1 to P4 (Fig. 1c) during fall and early winter, respectively. The seasonal conditions are evidently influential. In other words, thermal stratification was observed to be strong during the fall. The vertical temperature difference in the water surface within a depth of 3 m was approximately 1.5 °C. However, the temperature dropped drastically beyond 3 m (ΔT ≈ 4.5 °C) compared to the epilimnion temperature and averaged 18.25 °C. However, during early winter, the vertical difference between the temperature of the epilimnion and hypolimnion was approximately (ΔT ≈ 2.5 °C) and generally at an average of 11.5 °C.

Given that the mean air temperatures near the lake area (recorded on the same days when the lake temperature measurements were taken) were 18.86 °C and 9.9 °C, and the diurnal fluctuations of air temperature can also be considered as another controlling factor.

The strong thermal stratification in the fall compared to that in winter can be attributed to the strong solar radiation in the fall and the continuous exchange of heat flux on the water surface, enabling continuous energy accumulation in the lake (Yang et al. 2018). However, overcast weather coupled with strong winds that occur during winter creates some stirring and partial homogenization of the water in the lake. Moreover, penetrative convection occurs more easily at night, resulting in a decrease in the lake water temperature and an additional degree of vertical mixing (Fig. 9b).

Fig. 9 Temperature profiles along water columns measured at P1, P2, P3, and P4, during a fall and b early winter.
4 Discussion

4.1 Hydrodynamics in Light of Hydroacoustics Measurements

The fundamental difference between a river and a lake is that the flow velocity of a lake is far weaker and is not driven by gravity. In addition, the dynamic processes in a dam lake are diverse and differ from those in rivers.

As demonstrated in this study, the travel-time principle is the backbone of the tomographic measurements obtained using the FAT system. Reciprocal acoustic pulses were triggered from both transducers concurrently, and the arrival times were determined from the cross-correlation patterns. Accordingly, the velocity and discharge were estimated using Eqs. (3) and (4), respectively.

The basic approach toward selecting the arrival times for upstream and downstream stations is to select the greatest arrival peak for each correlation pattern (Chen et al. 2018). However, Al Sawaf et al. (2020) found that implementing this approach is imprecise. In this study, we observed certain periods of single arrival peaks and others of double or multiple arrival peaks, where the largest arrival peak was observed in the second group, as demonstrated in Figs. 4a, b and 5a, b.

Two interesting concerns emerged from these results. The first concern is regarding the certain periods showing only a single arrival peak, while other periods showing double or multiple arrival peaks. The second concern is with respect to determining the arrival peak to be selected for calculating the mean cross-sectional velocity when multiple arrival peaks instead of a single peak, is encountered. With respect to the first concern, the sound propagation of acoustic signals in shallow water environments is affected by several factors, including bed material, bathymetry shape, presence of composite layer stratifications of salinity, and different temperature layers (Thorne 1998). The main hindrance for hydroacoustics experts is determining the exact path of each triggered signal from a transmitter to receiver along the acoustic path because of the above-mentioned features that control sound propagation in water. However, a simulation for sound ray propagation along the transmission line can illustrate the behavior of a transmitted acoustic ray in water. To accomplish this task, we used the method proposed by Dushaw and Colosi (1998) for acoustic ray simulation:

\[
\frac{d\beta}{dr} = \frac{\partial c}{\partial r} \frac{1}{c} \tan \beta - \frac{\partial c}{\partial z} \frac{1}{c}
\]

(11)

\[
\frac{dz}{dr} = \tan \beta
\]

(12)

\[
\frac{dt}{dr} = \frac{1}{c} \sec \beta
\]

(13)

where \(\beta\) is the angle of the sound ray estimated from the horizontal and vertical axes, i.e., \(r\) and \(z\), respectively; \(c\) is sound speed; and \(t\) is the time.

Ray simulations were performed for water temperature measurements collected during early winter, as depicted in Fig. 9b. Figure 9b reveals that the temperature difference between the epilimnion and hypolimnion can be estimated as 2.5 °C. In other words, the sound speed at the bottom levels dropped by at least 10 m/s from the upper layers, as shown in Fig. 10. The speed of sound in the water was computed using Eq. (14) proposed...
by (Medwin 1975) as a function of water depth $D$ (m) and temperature $T$ (°C), whereas in fresh water, the salinity ($S$) term was insignificant.

$$c = 1449.2 + 4.6T - 0.055T^2 + 2.9 \times 10^{-4}T^3 + (1.34 - 0.01T)(S - 35) + 0.016D$$ (14)

Figure 10 and Table 3 present some interesting results. Along the transmission line S1\_S2, two arrival groups can be identified; the difference between the first arrival peak and the second arrival peak was 0.27 ms, which is consistent with our observations. Likewise, three arrival groups can be observed along T1\_T2. The time difference between the first arrival peak and the second arrival peak was 0.78 ms, which is also consistent with our recorded signals.

The thermal stratification of the lake indicates that even in the case of relatively low temperature differences between the epilimnion and hypolimnion during winter, as shown in Fig. 9b, the cold temperature of the hypolimnion acts as a shield that obstructs and weaken sound from reaching the warmer layers of the epilimnion for obtaining the largest peak clearly as shown in Fig. 10. Figure 3b also shows that, remarkably, when water release reached 15 m$^3$/s, the water temperature in the lake did not decrease rapidly. This suggests that water release at this rate neither yields a notable feature nor causes apparent thermal mixing.

Table 3  Results of ray simulation along S1\_S2 and T1\_T2

| Transmission line: S1\_S2 | Group number | Ray length (m) | Arrival time (ms) | Difference with the first arrival time (ms) |
|---------------------------|--------------|----------------|-------------------|--------------------------------------------|
| Group I (Black)           | 253.82       | 173.74         | 0                 |
| Group II (Red)            | 254.18       | 174.03         | 0.29              |

| Transmission line: T1\_T2 |
|---------------------------|
| Group I (Black)            | 288.42       | 197.65         | 0                 |
| Group II (Red)             | 289.80       | 198.43         | 0.78              |
To holistically elucidate the observed arrival groups along the two transmission lines with respect to different water temperatures, the arrival times were estimated using the sound speed values. The corresponding arrival times can be calculated by substituting the water temperature readings obtained by the CTD (Fig. 9b) into Eq. (14). Hence, sound speeds at −1 m and −3.8 m were 1456.35 m/s and 1448.90 m/s, respectively; the arrival times are presented in Table 4. Notably, the calculated arrival times are comparable to the simulated values listed in Table 3. Hence, the effect of different temperature layers on generating multi-arrival peaks is elucidated.

The second concern emerges from these findings: which arrival peak should be selected for the estimation of water velocity and discharge when multiple (instead of single) arrival peaks are encountered (the first or delayed arrival peak)? Initially, various arrival time groups were observed along S1_S2 and T1_T2. Nevertheless, in most cases, the received signals from the cross-correlation patterns only showed one apparent single peak located within the range of the first group, and some of the recorded signals showed double or multiple peaks, where one peak appeared within the range of the first group (i.e., peaks located along the red and blue peaks shown in Figs. 4a, b and 5a, b), and the largest peak arrived later. Therefore, we presumed the first peak to be desirable and not necessarily the largest one. However, for a concrete demonstration, we estimated the mean cross-sectional water temperature using the FAT system along T1_T2. In this scenario, we used the arrival times of the first and delayed arrival peaks to estimate the mean water temperature and then, compared the results to the temperature records obtained by the water level-temperature logger, as shown in Fig. 11.

The different arrival time groups observed along T1_T2 in Fig. 11a were used to estimate the sound speed using Eq. (15), and the mean water temperature along the transmission line was determined by substituting the sound speed obtained by the FAT in Eq. (14).

\[
c = \frac{R_i}{2} \times \left( \frac{1}{t_{T1}} + \frac{1}{t_{T2}} \right)
\]

where \( R_i \) is the ray length obtained from the ray simulation in Table 3 (i.e., \( R_1 = 288.42 \) m and \( R_2 = 288.9 \) m) because ray length is a function of water temperature and bathymetry shape.

The trivial difference (i.e., 1 ms) between the first and delayed arrivals, as shown in Fig. 11a, resulted in a temperature difference estimated to be approximately 0.5 °C, which is sizeable (see Fig. 11b); therefore, our assumption with respect to using the first arrival peak appears to be valid.

### 4.2 Internal Waves

One of the novel findings of this monitoring program was the ability to detect internal seiches using a crossed acoustic path scheme (Fig. 8a). To illustrate this, Fig. 8a shows the temporal

| Depth (m) | Temperature (°C) | Sound speed (m/s) | Arrival time (ms) | Transmission Length (m) |
|-----------|------------------|-------------------|-------------------|-------------------------|
| S1_S2     |                  |                   |                   |                         |
| −1.00     | 12.57            | 1456.42           | 173.7             | 197.40                  |
| −3.80     | 10.63            | 1449.11           | 174.6             | 198.4                   |
variations in the flow direction; however, the flow mainly fluctuated between the first and second quadrants (Q1 and Q2) over a period of approximately 3 h. This phenomenon can be attributed to internal seiches in the lake and may have caused the difference between the densities of the epilimnion and hypolimnion as a result of inflow pulses into the lake. Mortimer (1952) stated that if exposing a stratified lake with different densities at the epilimnion, $\rho_e$, and hypolimnion, $\rho_h$, to a steady wind, the surface water moves toward the leeward bank due to frictional drag and wave action. The wind generates a slope on the lake surface uphill in the same direction as the wind, causing a return flow in the lower part of the epilimnion. Simultaneously, a sizable tilt forms at the interface opposite to the surface tilt; this is accompanied by a thermocline slope. In a two-layer stratified lake, the period ($P$) of the seiche can be estimated as follows:

$$P = \frac{2 \times L}{\sqrt{g \times \left( \frac{(\rho_h - \rho_e)}{(h_h + h_e)} \right)}}$$

(16)

where $L$ is the length of the water body; $g$ is the acceleration of gravity; and $h_e$ and $h_h$ are the average thicknesses of the epilimnion and hypolimnion layers, respectively. Upon substituting the average density values of the epilimnion and hypolimnion obtained from the CTD, the internal wave period was calculated to be 3 h, which confirms our assumptions.
4.3 Performance of Inflow Acquired by Fluvial Acoustic Tomography (FAT) System

To verify the performance of the inflow acquired by FAT ($Q_{FAT}$), four transects were conducted as another independent technique along the direct line between the right and left banks at points (R) and (L) using a Teledyne RDI Workhorse Monitor ADCP ($Q_{ADCP}$) operating at 1228.8 kHz, as shown in Fig. 1c. The data obtained via the $Q_{ADCP}$ appear to be comparable to those obtained via $Q_{FAT}$ and $Q_{HDMO}$, as shown in Fig. 12a. The difference among the three methods ($Q_{FAT}$, $Q_{HDMO}$, and $Q_{ADCP}$) is not very significant, considering we worked with considerably slow velocities. Hence, the velocity, to the best of our knowledge, was within the limit of most velocity-measuring instruments. The velocity resolution of the acoustic doppler current profiler (ADCP) can be made reliable by averaging a large set of ping data. Unfortunately, we were unable to use a bottom-fixed ADCP because the dam lake was utilized by certain local fishermen. In addition, deploying a fixed ADCP above the accumulated sediments in the center of the lake was unsafe.

In the absence of a reliable inflow monitoring method, we cannot accurately verify the ultimate performance of the FAT system. Figure 12b reveals a type of low resolution associated with dam inflow records obtained by the HDMO, compared with the measured stage. Therefore, the monotonous inflow behavior can be understood by observations made using the HDMO.

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Fig. 12  a Comparison between inflow acquired by fluvial acoustic tomography (FAT; black), Haji Dam Monitoring Office (HDMO; red), acoustic doppler current profiler (ADCP; green), and outflow by HDMO (blue), and b association between stage and inflow as recorded by HDMO
4.4 Comparison with Previous Studies and Scope for Future Research

Most of the previous monitoring applications via the FAT system were accomplished using a 30 kHz transmission frequency. However, the 30-kHz system has a certain range of transmission length between a pair of transducers, and the minimum water depth must exceed ~0.5 m for effective use (Razaz et al. 2015). Consequently, in 2016, the first version of the FAT system that can be operated using 53 kHz frequency was developed for use in relatively shallower and narrower streams, with higher velocity resolution. Bahreinimotlagh et al. (2016) performed the first discharge monitoring via a cross-transmission configuration using one pair of 30-kHz systems and another of 53-kHz systems in a mountainous river. Their findings confirmed that the velocity resolution was augmented twice when using 53 kHz, with a minimum recorded value of 0.2 m/s. Recently, (Al Sawaf et al. 2020) successfully acquired accurate river velocity for very shallow conditions using a 53-kHz system. The minimum acquired velocity was 0.1 m/s (obtained for a cross-section), with a minimum depth of 28 cm.

In the current observation, two different frequencies were used in a very slow flow condition. Figures 6 and 7 demonstrate that the current velocities captured at 53 kHz seem to be more precise than those obtained at 30 kHz, with a mean absolute cross-sectional velocity of 1.5 cm/s, which is a significant accomplishment.

The precision of the hydroacoustic measurements depends substantially on determining the exact arrival time, and even a mistake as tiny as a sub-millisecond can generate enormous errors. Hence, the FAT system can provide reliable measurements even in extremely slow water-velocity environments. As seen in Fig. 11, the delayed arrival times resulted in increased temperatures compared to the first arrival times.

Another interesting feature in this study is that we improved the flow direction approach proposed by Bahreinimotlagh et al. (2016) for use in different situations. Our improved approach is flexible and appropriate for determining the flow direction not only in cases of dam inflow but also in various circumstances, such as tidal rivers (wherein the flow shifts from landward to seaward and vice versa), and can clarify the occurrence of negative inflow periods. However, we used the temporal variations of the ensemble inflow direction because we assumed that the reservoir inflow direction would not vary significantly over a short period.

Although some of our findings are preliminary, our results are encouraging. The FAT system is capable of capturing flow direction and water velocity; therefore, future studies should consider longer periods to determine the linkage between a fluctuating inflow, while maximizing power generation capacity. In addition, considering measuring streams during fast flows.

Moreover, future studies should examine the hysteresis relationship of the variation in the water flow direction during the opening and closing of the dam gate. Additionally, the relationship between flow direction and inflow velocity can be used to propose another superior equation to supplement the traditional water balance equation because this information captures the velocity along the flow direction in the entire cross-section rather than in a small portion (H-ADCP).

Finally, future research should utilize the findings of this study to improve existing analytical models and seek the most accurate inflow quantities using the travel-time principle of underwater acoustics.
5 Conclusions

The ability to acquire reliable real-time and continuous records of flow data can facilitate optimal utilization of water resources, elucidate hydrologic information, and allow for optimal ecological and societal outcomes. In this study, we observed the water inflow to a dam lake using the FAT system, based on the travel-time approach. The main goal of this study is to offer a practical and reliable monitoring approach for understanding the inflow to a lake, investigating the behavior of underwater acoustic communications within very slow flow environments, and analyzing the related hydrological processes. Two pairs of FAT systems were placed diagonally upstream of a dam lake at two different frequencies. We upgraded the flow direction estimation based on travel-time behavior. Additionally, we discussed the importance of using accurate tomographic data in inflow monitoring and demonstrated that a small mistake in tomographic records (even by a sub-millisecond) could generate substantial errors.

Generally, inflow monitoring based on the travel-time approach appears to be practical and can be considered as a promising and competitive application. In this study, the flow direction was continuously deduced via reciprocal sound transmission using a cross-configuration transmission, and the flow direction equation was improved for applicability to a fluctuating water flow environment. However, the precision of the values is a function of velocity resolution. Our findings reveal that the smallest mistake in selecting the exact arrival times (even by a sub-millisecond) can generate a substantial error. Hence, the FAT system can yield reliable measurements. An interesting study finding is the ability of the FAT system to detect the presence of internal waves (i.e., seiches) based on the travel-time approach and upgraded flow direction equation.

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Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

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References

Ahmad SK, Hossain F (2019) A generic data-driven technique for forecasting of reservoir inflow: Application for hydropower maximization. Environ Model Softw 119:147–165. https://doi.org/10.1016/j.envsoft.2019.06.008

Al Sawaf MB, Kawanisi K, Xiao C (2020) Measuring low flowrates of a shallow mountainous river within restricted site conditions and the characteristics of acoustic arrival times within low flows. Water Resour Manag 34:3059–3078. https://doi.org/10.1007/s11269-020-02557-w

Bahreinimotlagh M, Kawanisi K, Danial MM et al (2016) Application of shallow-water acoustic tomography to measure flow direction and river discharge. Flow Meas Instrum 51:30–39. https://doi.org/10.1016/j.flowmeasinst.2016.08.010

Budu K (2014) Comparison of wavelet-based ANN and regression models for reservoir inflow forecasting. J Hydrol Eng 19:1385–1400. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000892

Chen M, Syamsudin F, Kaneko A et al (2018) Real-time offshore coastal acoustic tomography enabled with mirror-transpond functionality. IEEE J Ocean Eng. https://doi.org/10.1109/JOE.2018.2878260

Deng C, Liu P, Guo S et al (2015) Estimation of nonfluctuating reservoir inflow from water level observations using methods based on flow continuity. J Hydrol 529:1198–1210. https://doi.org/10.1016/j.jhydrol.2015.09.037

Dushaw BD, Colosi JA (1998) Ray tracing for ocean acoustic tomography

Hariri-Ardebili MA (2018) Risk, reliability, resilience (R3) and beyond in dam engineering: A state-of-the-art review. Int J Disaster Risk Reduct. https://doi.org/10.1016/jijdrr.2018.07.024

Kawanisi K, Razaz M, Ishikawa K et al (2012) Continuous measurements of flow rate in a shallow gravel-bed river by a new acoustic system. Water Resour Res 48:1–10. https://doi.org/10.1029/2012WR012064

Medwin H (1975) Speed of sound in water: A simple equation for realistic parameters. J Acoust Soc Am 58:1318–1319. https://doi.org/10.1121/1.380790

Mortimer CH (1952) Water movements in lakes during summer stratification; evidence from the distribution of temperature in Windermere. Philos Trans R Soc Lond B Biol Sci. https://doi.org/10.1098/rstb.1952.0005

Nazeer S, Hashmi MZ, Malik RN (2016) Spatial and seasonal dynamics of fish assemblage along river Soan, Pakistan and its relationship with environmental conditions. Ecol Indic 69:780–791. https://doi.org/10.1016/j.ecolind.2016.05.034

Noorbek P, Roozbahan A, Kardan Moghaddam H (2020) Annual and monthly dam inflow prediction using bayesian networks. Water Resour Manag 34:2933–2951. https://doi.org/10.1007/s11269-020-02591-8

Rahimi H, Ardakani MK, Ahmadian M, Tang X (2020) Multi-reservoir utilization planning to optimize hydropower energy and flood control simultaneously. Environ Process 7:41–52. https://doi.org/10.1007/s40710-019-00404-8

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. https://doi.org/10.1002/2015WR017102

Simon MK, Omura JKL (1985) Spread spectrum communications handbook. McGraw-Hill, New York, p 423

Stähly S, Franca MJ, Robinson CT, Schleiss AJ (2019) Sediment replenishment combined with an artificial flood improves river habitats downstream of a dam. Sci Rep 9:5176. https://doi.org/10.1038/s41598-019-41575-6

Suzuki H, Ochiai A, Kuda M, Mizoguchi A (2008) Investigation about accuracy of discharge data controlled by multi-reservoir system on jinzu river using inflow estimation method based on digital filter. J Japan Soc Hydr WATER Resour 21:285–295. https://doi.org/10.3178/jjshwr.21.285

Tao T (1999) Local inflow calculator for reservoirs. Can Water Resour J. https://doi.org/10.4296/cwrj2401053

Thorne RE (1998) Review: Experiences with shallow water acoustics. Fish Res. https://doi.org/10.1016/S0165-7836(98)00068-X

Yang Y et al (2018) Diurnal and seasonal variations of thermal stratification and vertical mixing in a shallow fresh water lake. J Meteor Res 32(2):219–232. https://doi.org/10.1007/s13351-018-7099-5

Zhu X-H, Zhang C, Wu Q et al (2012) Measuring discharge in a river with tidal bores by use of the coastal acoustic tomography system. Estuar Coast Shelf Sci 104–105:54–65. https://doi.org/10.1016/j.ecss.2012.03.022

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