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Novel high-frequency acoustic monitoring of streamflow-turbidity dynamics in a gravel-bed river during artificial dam flush

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ABSTRACT

To assess the dynamics of rivers, a reliable characterization of river streamflow during unsteady flow regimes is of paramount importance. In this work, we aimed at investigating the characteristics of turbidity–discharge (T–Q) dynamics corresponding to annual artificial dam flush release in a mountainous stream. Two methods for evaluating discharge were used in this study: the classical rating curve and the fluvial acoustic tomography (FAT) system that was developed by Hiroshima University. Interestingly, during dam flush, the discharge records obtained by FAT showed striking features of unsteady streamflow behavior, such as discharge shoulders and, in some events, secondary discharge peaks. According to the T–Q hysteresis loops, the common type of T–Q observed patterns were anticlockwise loops. During the studied DF events, sediment was supplied by river banks located at different sites along the river channel.

1. Introduction

Investigating the temporal variability in the dynamics of suspended sediment (SS) is vital to further our knowledge about and comprehensive understanding of the drainage basin processes. Properties of a catchment such as its geology, drainage, slope, and land use, are all factors governing the quantity and form of sediment transported into rivers (Kang et al., 2009; Miller et al., 2003; Peraza-Castro et al., 2016). However, locating the sources of sediment and where in a watershed erosion and sediment storage are occurring is a challenge. Furthermore, computation and determination of the contribution of streambank erosion to a basin budget is very important in controlling soil erosion and introducing suitable mitigation practices to decrease stream SS and associated pollutant load (Gellis et al., 2017; Marttila and Kløve, 2010) and thus improving downstream surface water quality.

Sediment transport during a dam flush (DF) event or due to scouring may have negative effects on the ecosystem in the downstream river reaches (Kondolf, 1997). Bilotta and Brazier (2008) stated that the effects of SS on fish rely on various key factors such as the SS concentration and the duration of exposure to it, and the chemical composition and particle-size distribution of the SS. An understanding of the sublethal effects of augmented sedimentation and turbidity dynamics is crucial to enhance our knowledge of the potential impacts of increased sediment loading on stream fish production and how these effects vary among species living in sympatry (Sweka and Hartman, 2001).

During a single hydrological event, analyzing the relationship between suspended sediment concentration (SSC) and discharge (Q) hysteresis is a good method to reveal the characteristics of sediment dynamics and obtain information about the underlying geomorphic processes taking place at the basin scale (Asselman, 1999; Fan et al., 2013; Hudson, 2003). The suspended sediment concentration and discharge (SSC–Q) hysteresis behaviors (either clockwise or counterclockwise loops) have been attributed to diverse phenomena according to the properties of the watershed area (Aich et al., 2014; Smith and Dragovich, 2009). The complex behavior of SSC–Q hysteresis patterns is assessed based on different hysteresis-index approaches (Aich et al., 2014; Langlois et al., 2005; Lawler et al., 2006). However, interpreting SSC–Q hysteresis events remains problematic; hence, additional investigations are required to extend our knowledge about the hidden ecological aspects that are subjected to SS transport.

Turbidity is commonly viewed as a proxy for determining the suspended sediment concentration (SSC) in rivers by calibrating site-specific empirical relationships between turbidity and in-situ measured SSC (Göransson et al., 2013). In addition, turbidity observation is widely used to investigate sediment-related hydrological issues. Turbidity measurement can be considered an alternative to estimating sediment concentration using direct sampling and subsequent laboratory analysis: in-situ turbidity monitoring techniques tend to be cheaper and simpler (Diodato, 2006; Lewis, 1996; Pavanelli and Bigi, 2005;

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Pavanelli and Pagliarani, 2002). Moreover, many studies have monitored the dynamics and characteristics of turbidity–discharge (T–Q) and turbidity–rainfall, and have found very close relationships between turbidity and SSC (Chanson et al., 2008; Ochiai and Kashiwaya, 2010; Pavanelli and Bigi, 2005; Ram and Terry, 2016; Tananaev and Debolskiy, 2014; Ziegler et al., 2014).

Accurate estimation of the direct and continuous discharge passing through a river cross-section remains a fundamental problem in the field of water-resources engineering. Currently, the approach used most to estimate river discharge is the classical rating curve (RC) method. Uncertainty estimation in the RC approach has been studied by (Di Baldassarre and Montanari, 2009; Kawanisi et al., 2016; McMillan et al., 2010). However, to the best of our knowledge, there is currently no accepted approach for estimating discharge uncertainties. An empirical one-to-one relationship between water level and discharge: rating curves (RCs) can be determined under the important assumption that streamflow is steady; however, this method may not be precise in the case of streams that are subjected to unsteady flows.

The development of various techniques and instruments has led to improved streamflow measurements; Kawanisi et al. (2016) have recently demonstrated that the streamflow measured by the FAT system changes at very short time scales (i.e., daily and sub-daily scales). In other words, they demonstrated the presence of discharge fluctuations detected by FAT rather than RC discharges that took place over very short time periods. This feature motivated us to observe the variations in streamflow behavior over high-frequency scales (i.e., short time periods of several hours) especially within artificial DF events, and also the scattered turbidity (T) and discharge (Q) (T–Q) hysteretic behavior related to lag time between peaks of discharge and turbidity.

Therefore, the main aims of this work are (i) to shed light on the characteristics of T–Q dynamics resulting from artificially operated DF events in a mountain river, and (ii) to investigate what information can be realized and observed from streamflow records obtained by FAT compared with discharges measured by means of classic approaches such as the RC method.

2. State-of-the-art, study site and artificial dam flush operation

2.1. State-of-the-art; the fluvial acoustic tomography (FAT) system

The shallow acoustic tomography system is the result of the progressive studies by Kaneko et al. (1994), Park and Kaneko (2000), Kawanisi et al. (2012, 2010), and Razaz et al. (2013). The FAT system is developed to improve the applications of the acoustic system first developed by Kaneko et al. (1994) to even shallower waters. However, Razaz et al. (2015) examined shallower flows, from mountainous streams (0.5 m deep) to flows at the mouth of estuaries in coastal areas (maximum 10 m deep).

The fundamental principle of FAT is based on the “time-of-travel” approach, such as using acoustic velocity meters (Laenen and Smith, 1983). However, the acoustic signals of a FAT system are emitted from omnidirectional transducers in the range of 10–55 kHz. Unlike other approaches, cross-sectional average velocity can be measured by FAT with no additional for any complicated post-processing steps (Kawanisi et al., 2012). FAT is supported by Global Positioning System (GPS) receivers (u-blox LEA-6T). The satellite information from the receivers enables a high-precision standard frequency (10 MHz) and precise timing pulse (1 Hz), which is necessary to guarantee and maintain that both upstream and downstream systems run exactly concurrently. The 10-MHz signal is used as the base clock of the FAT system for high-precision processing of the transmitting/receiving signal. Every 30 s, acoustic beats are triggered by a GPS clock and are transmitted simultaneously from two transducers installed across the river banks diagonally. Fig. 1 illustrates the installation and operation process for the FAT system in river.

2.2. Study site

Field observations were conducted in the Gono River, which is a shallow gravel-bed river located in the city of Miyoshi, Japan. The general climate of Miyoshi is temperate, with annual average temperatures varying from 8.5 °C to 19.4 °C, with a mean annual precipitation of 1492 mm. The basin area is 3900 km^2. The river is 115 m wide with a Manning roughness of roughly 0.03 estimated from the water surface profile and a bed slope of 0.11% around the observation area. The water depth at the observation site becomes considerably shallow under conditions of low flow. The Saijo River and the Basen River are the main tributaries of the Gono River, unite 2.7 km upstream of the observation site, and the confluent rivers meet the Gono River 0.9 km downstream of the junction (Fig. 2). The annual mean flowrate at the Ozekiyama gauging station (the nearest station to our experiment site), located approximately 1.1 km upstream of the study site, is estimated to be approximately 75 m^3/s (see Fig. 2(a)). The grain-size distribution at the monitoring location reveals an average median size (d_{50}) of 27 mm and an average d_{90} of 115 mm. The grain-size distribution shows a lack of silt, fine sand, and clay (Kawanisi et al., 2012). The locations of the experiment site and the FAT transducers (T1 & T2) are shown in Fig. 2.

2.3. Annual artificial dam-flush events

The Gono River is the habitat of the Ayu and Yamame sweetfish, which feed on sphagnum growing on bedrock in the Gono River streams. Hence, in the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) of Japan framework, to protect and promote fishery resources in the Gono River, water from both Haji and Haizuka dams is scheduled for flushing ordinarily once a year at the end of March. However, MLIT used several patterns of artificial DF to meet the optimum ecological factors that enhance the growth of new sphagnum (Kawanisi et al., 2013).

The Haizuka dam, which is located around 26 km upstream from the study area, was flushed once a year individually in 2007, 2010, and 2011 (Fig. 3). In contrast, the Haji dam, which is located around 40.2 km upstream from the monitoring site, was operated once a year in 2008, and 2009, 2012, and 2014 in completely concurrent coupling with the operation of the Haizuka dam; however, since 2015, it has been operated in non-concurrent coupling with the Haizuka dam. The discharge patterns from the Haji and Haizuka dams within the studied events are depicted in Fig. 3.

Upstream of our observation location and the Ozekiyama gauging station, there are four gauging stations that measure hourly water level alongside the river branch that receives water from the Haji dam. This allows us to estimate the flow rate using the RC method based on their specific site conditions. In contrast, only three gauging stations are distributed alongside the river branch that receives the water released from the Haizuka dam (Fig. 2(a)).

3. Methodology, materials, and data description

The observations presented herein were performed using several methods and techniques; thus, we summarized them in the Table 1. Nonetheless, our main interest in this work was to investigate river dynamics within artificial DF events; in particular, our goal was to investigate the characteristics of streamflow using a novel acoustic system and the corresponding turbidity dynamics resulting from the DF.

3.1. FAT principle and measurement campaigns

As the FAT utilizes the travel-time tomography approach, the arrival time of acoustic signals at the upstream (t_{up}) and downstream stations (t_{down}) (see Fig. 1), the sound speed (c) and streamflow velocity along the sound ray path (u) were determinable according to the following