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研究課題名（和文）Developing an innovative hydroacoustics system for river discharge monitoring and investigating watershed characteristics during torrential floods

研究課題名（英文）Developing an innovative hydroacoustics system for river discharge monitoring and investigating watershed characteristics during torrential floods

研究代表者

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交付決定額（研究期間全体）：（直接経費）　　3,500,000円

研究成果の概要（和文）：本研究では、西日本の山間部流域における豪雨時の河川流量と流域貯留指標の隠れたパターンを調査・解析しました。主な成果は以下となる。
河川音響トモグラフィシステムの新世代機を改良し、洪水時の河川流動の正確な情報を取得することに成功した。更に、世界初となる、三角形配置の音響断層撮影システムを用いて、流量方向の連続的推定のためのガイドラインを構築した。なお、デープラニング学習モデルやエントロピーモデルなどの手法を用いて、隠された洪水パターンとその類似性を解読した。更に、降雨-濁度と濁度-流出の関係を解析した。

研究成果の学術的意義や社会的意義
The scientific contribution is to clarify accurate dynamics of floods using advanced, automated real-time monitoring system. Besides, to elucidate watershed response during torrential floods. Thus, to create safe environments and communities as an important social objective.

研究成果の概要（英文）：In this project, the PI investigated and examined the hidden patterns of river flow behavior and catchment storage indicators in a mountainous watershed located in west of Japan mainly during torrential floods.In particular, the key achievements can be outlined as follows:
First, a new generation of the Fluvial Acoustic Tomography system was improved and deployed to provide precise information of river dynamics during floods. Second, for the first time, guidelines were developed to continuously estimate flow direction using a triangular arrangement of acoustic tomography system. Third, hidden flood patterns and their similarities were deciphered using different models (e.g., deep learning and entropy models). Last, relationships of rainfall-turbidity and turbidity-runoff were examined and investigated.

研究分野：River Engineering

キーワード：River　Streamflow　Tomography　Watershed　Rainfall

様　式　Ｃ－１９、Ｆ－１９－１（共通）

１．研究開始当初の背景

Torrential floods, particularly in the Chūgoku region of Japan, are hydrological processes resulting from the precipitation of huge amounts of rainfall during the rainy season. Nonetheless, the dynamics of rivers during torrential floods are diverse. Yet, interaction among these hydrological and meteorological controls is imperfectly understood since meteorological conditions are spatially varied and complex.

During a flood event, watershed characteristics influence the shape and peak of the runoff hydrograph. Basically, runoff mean velocity and discharge are the primary elements to estimate these features. In principle, average flow velocity and total runoff are used, but the key challenge is to acquire real-time temporal variations of stream velocity and runoff instead of using average values during floods which was not performed previously.

On the other hand, characterization of real-time dynamics and processes of stream velocity and massive flows had not been investigated precisely since acquisition of river discharge is generally accomplished by the Rating Curves (RCs) approach, which has a number of limitations. Therefore, deep investigations of how a river system behaves during torrential floods using accurate real-time monitoring system with high-resolution is the prime precondition to comprehend these hydrological behaviors.

２．研究の目的

The purpose of this research was to achieve the following key objectives:

(1) To investigate and monitor accurate river dynamics in west of Japan, particularly in Hiroshima, in real-time using an advanced tomographic system namely the Fluvial acoustic tomography (FAT) system.

(2) To characterize the annual and intra annual flood patterns embedded in the Gōno River catchment located in west of Japan using new methods in the field (e.g., deep learning, entropy, etc.).

(3) To elucidate rainfall-runoff and sediment-discharge behaviors during the rainy season and provide valuable insights into river dynamics during this critical period.

３．研究の方法

The following framework was implanted to meet the research goals:

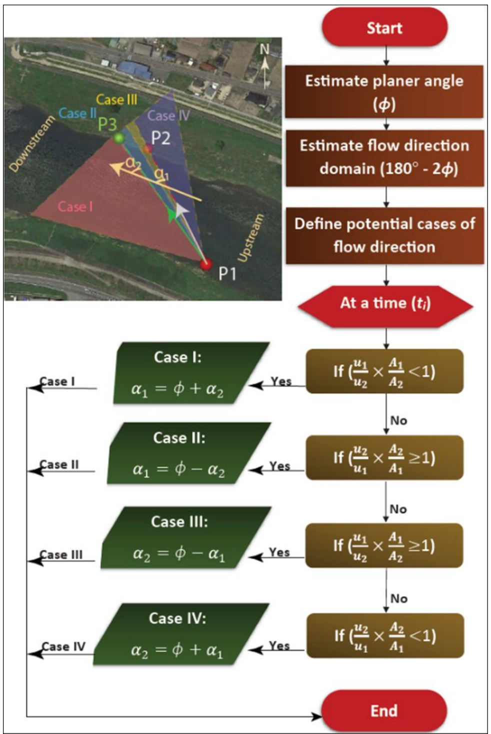

Fig. 1 Deployment of the FAT system at the river site and flowchart of continuous river flow direction estimation.

(1) Accurate real-time monitoring of streamflow dynamics using the FAT system:

First of all, a new version of the FAT system developed by Hiroshima University was improved and deployed to provide accurate and precise measurements of sound speed, cross-sectional average velocity, and streamflow in real-time. To track flow directions variations during flood events. The PI successfully discussed in details the principles of flow direction estimation using cross- pattern deployment of four FAT systems. More importantly, The PI, introduced complete guidelines for continuous flow direction estimation using a triangular deployment of three FAT systems in unidirectional streams as depicted in Fig. 1.

(2) Investigating inter and intra-annual variations of hidden flood patterns in a mountainous watershed:

At this stage, the changeability of 20 years in the annual flood patterns across all river stations located over the Gōno River watershed were examined using information-complexity metrices. First, the river stage data were encoded using Boolean conversion scheme to 0 or 1. Then, the findings were decoded using different information and complexity measures to have comprehensive understanding quantitively and qualitatively regarding the different detected patterns.

(3) Examining rainfall-sediment and sediment-discharge behaviors during the rainy season: To investigate how rainfall events in west Japan have modified due to climate change, a pentad analysis at different levels was conducted. In addition, turbidity records were utilized as a proxy for estimating the suspended sediment concentrations in the Gōno River. In this regard, to gain a holistic understanding of the rainfall–runoff processes in comparison to the turbidity behavior during flood events, a statistical analysis using the rainfall as a forcing factor on suspended sediment dynamics and river discharge was performed. That is to say, the antecedent precipitation index was computed as an indexing measure of the moisture content stored within the watershed prior to a storm event and then compared with the turbidity records to find the lag times between the peak versus turbidity. Accordingly, the generated relationships (i.e., hysteresis) of rainfall-turbidity, turbidity-discharge were examined using hysteresis index to quantify the magnitude and direction of the formed loop per event.

４．研究成果

(1) Performance of streamflow measurement using high-resolution of the utilized acoustic tomography (FAT) system:

Previous works used four acoustic stations or more to continuously measure cross-sectional average velocity, flow direction, and streamflow based on the travel time principles. Of great importance in this research, it was demonstrated that the minimum number of acoustic stations that can be used to determine the river flow in unidirectional streams can be reduced to three stations which can be more practical and easier.

First, three FAT systems were installed in a gravel-bed river forming a triangle shape as shown in Fig. 1. To boost the performance of the recorded acoustic signals from a technical point view, the PI used two different types of acoustic beams, i.e., two cylindrical beams (at P1, P2) and another hemispherical beam pattern of sound rays (at P3). Figure 2a shows the temporal variation in the cross-sectional average velocity along the studied cross-sections. Figure 2b presents the temporal variations in the estimated values of flow angle between P1-P2 and flow direction (i.e., α_1), and P1-P2 and flow angle (i.e., α_2). In addition, Fig. 2 (c &d) compares the discharge measured by the FAT (Q_{FAT}) with the discharge computed using the rating curve (Q_{RC}) approach. Encouragingly, it can be noticed from the error percentage plots (Fig. 2 (c &d)) an acceptable range of variation between Q_{FAT} and Q_{RC} can be noticed during baseflow conditions i.e., steady,

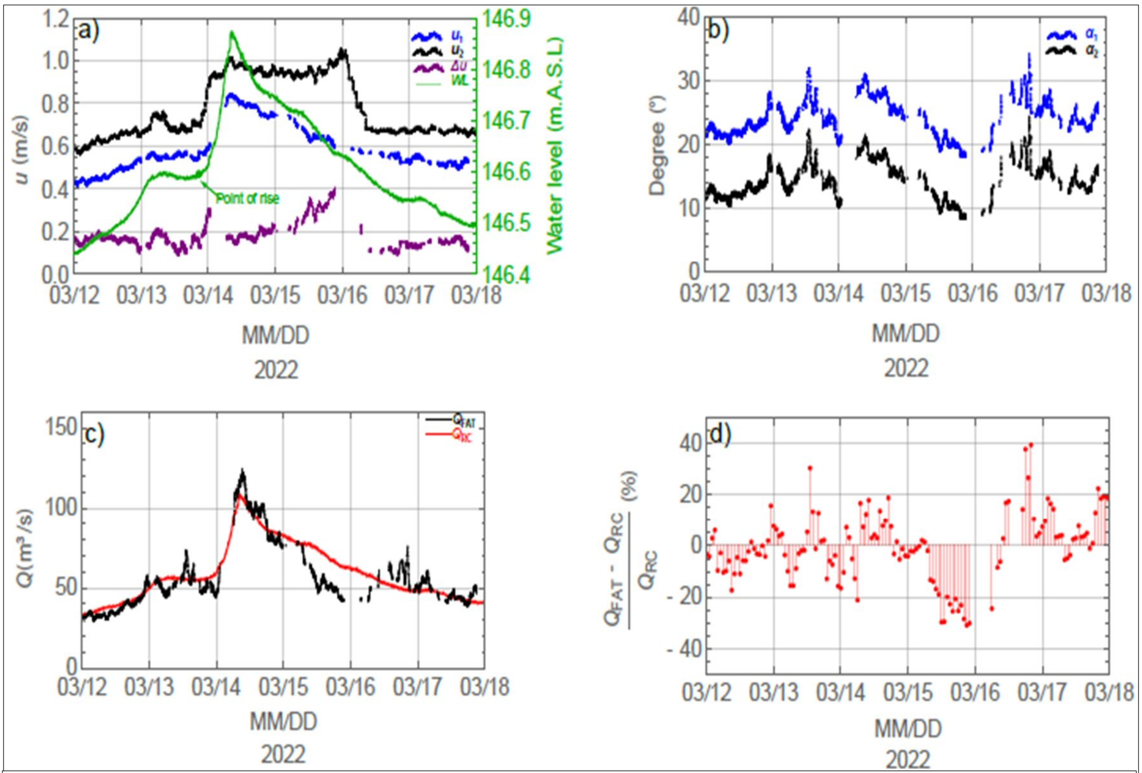

Fig. 2 Temporal variations in the a) cross-sectional average velocity, b) flow direction, c) streamflow, and d) percentage errors.

and quasi steady flow conditions.

(2) <u>New guidelines to estimate continuous direction using a triangle shape deployment of three acoustic tomography systems</u>:

For the first time in the world, the PI successfully proposed new guidelines to continuously estimate flow direction using three tomographic systems placed in triangular plane in unidirectional streams. Figure 3 shows the potential cases that flow can change its direction. Therefore, examining the temporal variations in cross-sectional areas and cross-sectional velocities as depicted in the flowchart of Fig. 1, a specific equation should be used to determine the flow direction angle as follows:

For Case I:

$$\alpha_2 = \cos^{-1}\left(\frac{1}{2}\sqrt{\frac{2\mathrm{Cos}(\phi)^2 A_1 u_1 - 3A_2 u_2 + \mathrm{Cos}(2\phi)A_2 u_2 - 2\mathrm{Cos}(\phi)\sqrt{\mathrm{Cos}(\phi)^2 A_1^2 u_1^2 + \left(-3 + \mathrm{Cos}(2\phi)\right)A_1 A_2 u_1 u_2 + \mathrm{Cos}(\phi)^2 A_2^2 u_2^2}}{A_1 u_1 - A_2 u_2}}\right.$$

For Case II:

$$\alpha_2 = \cos^{-1}\left(\frac{1}{2}\sqrt{\frac{2\mathrm{Cos}(\phi)^2 A_1 u_1 + 3A_2 u_2 - \mathrm{Cos}(2\phi)A_2 u_2 + 2\mathrm{Cos}(\phi)\sqrt{\mathrm{Cos}(\phi)^2 A_1^2 u_1^2 - (-3 + \mathrm{Cos}(2\phi))A_1 A_2 u_1 u_2 + \mathrm{Cos}(\phi)^2 A_2^2 u_2^2}}{A_1 u_1 + A_2 u_2}}\right.$$

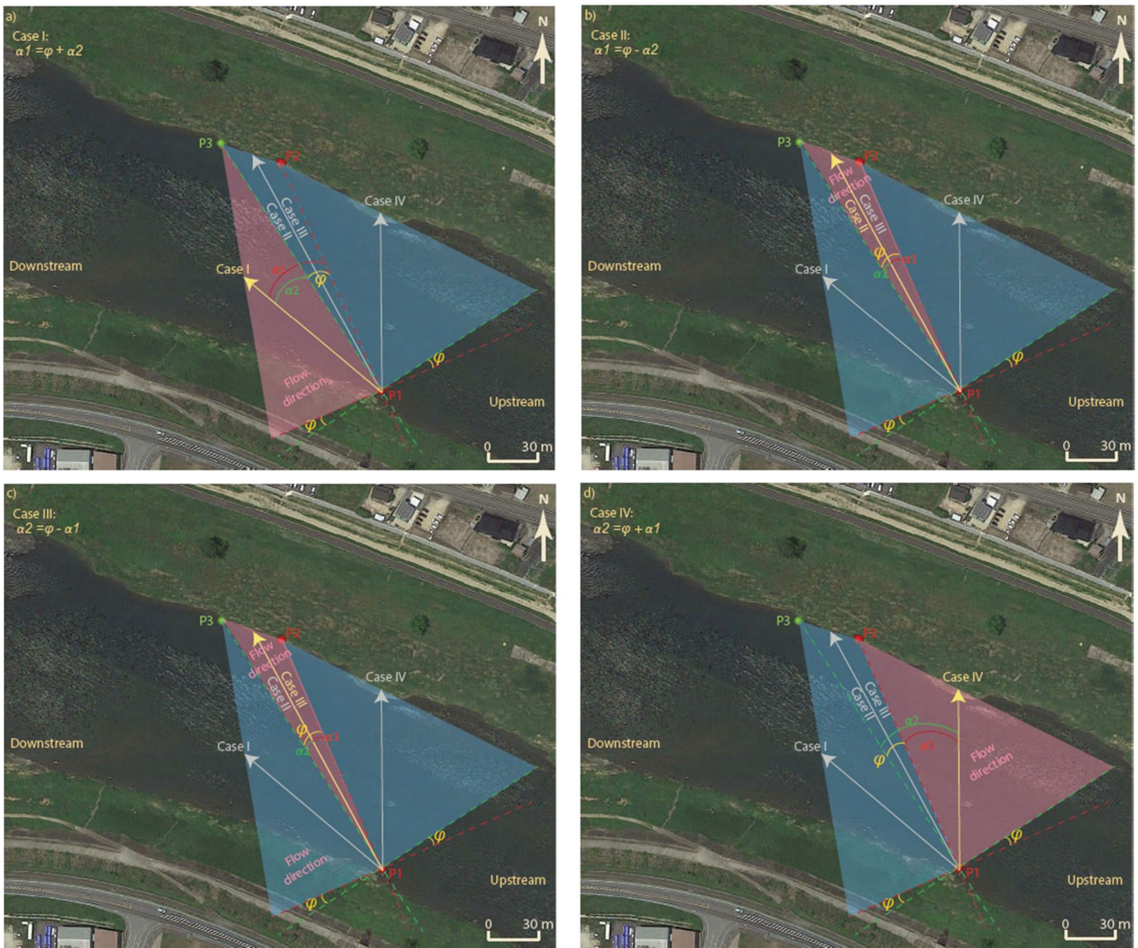

Fig. 3 Flow direction conditions of b) case i; c) case ii; d) case iii; and e) case iv.

For Case III:

$$\alpha_1 = \cos^{-1}\left(\frac{1}{2}\sqrt{\frac{-(-3 + \mathrm{Cos}(2\phi))A_1 u_1 + 2\mathrm{Cos}(\phi)(\mathrm{Cos}(\phi)A_2 u_2 + \sqrt{\mathrm{Cos}(\phi)^2 A_1^2 u_1^2 - (-3 + \mathrm{Cos}(2\phi))A_1 A_2 u_1 u_2 + \mathrm{Cos}(\phi)^2 A_2^2 u_2^2})}{A_1 u_1 + A_2 u_2}}\right.$$

For Case IV:

$$\alpha_1 = \cos^{-1}\left(\frac{1}{2}\sqrt{-\frac{(-3+\mathrm{Cos}(2\phi))A_1u_1 + 2\mathrm{Cos}(\phi)\left(Cos(\phi)A_2u_2 + \sqrt{\mathrm{Cos}(\phi)^2A_1^2u_1^2 + (-3+\mathrm{Cos}(2\phi))A_1A_2u_1u_2 + \mathrm{Cos}(\phi)^2A_2^2u_2^2}\right)}{A_1u_1 - A_2u_2}}\right)$$

(3) <u>Characterizing annual flood patterns variation using information and complexity indices</u>:
A new assessment model based on information and complexity principles was proposed to examine the annual variation of flood patterns embedded in Gōno river system (Fig. 4). The key strength of the proposed model was being established on two fundamental pillars: <u>(i) word pattern</u>; gives an image about the detected flood patterns, i.e., simple flood occurs within one day or severe flood persists for two days or more, and <u>(ii) information-complexity</u> indices that report the frequency and randomness of the detected patterns. The finding showed that the proposed model is very powerful in detecting hidden patterns. Furthermore, the model succeeded in capturing the stations that exhibited the same flood patterns. In addition, this model was a powerful tool in capturing different internal structures of flood patterns including the degree of randomness, the length of flood events, and the number of separated flood events.

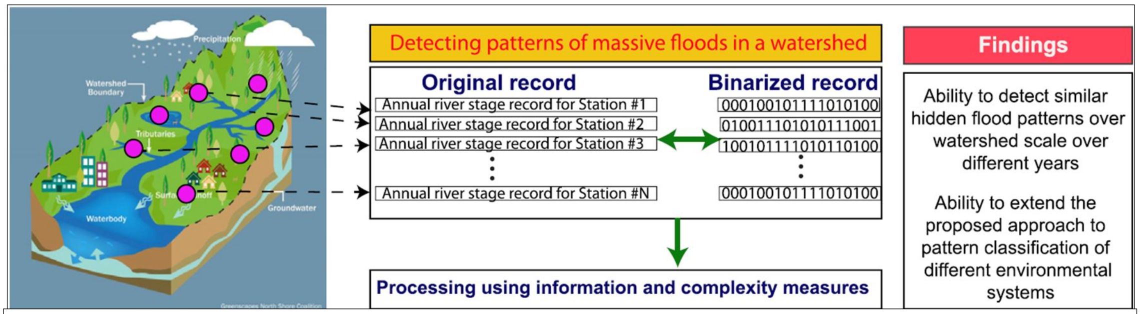

Fig. 4 Summarization of the proposed model and main findings

(4) <u>Precipitation pentad analysis</u>:
Figure 5 shows that two pentads marked the highest values of accumulated precipitation. That is to say, in 2018 and 2010, with 323 and 280 mm/pentad, respectively. Alternatively, the remaining years of the study scored a maximum pentad value roughly equal to 140 mm/pentad, suggesting that the precipitation events that occurred in 2010 and 2018 showed an increasing value that can be estimated as approximately ~200%. Besides, the results showed a kind of intense rainfall event occurs every 3 to 4 years.

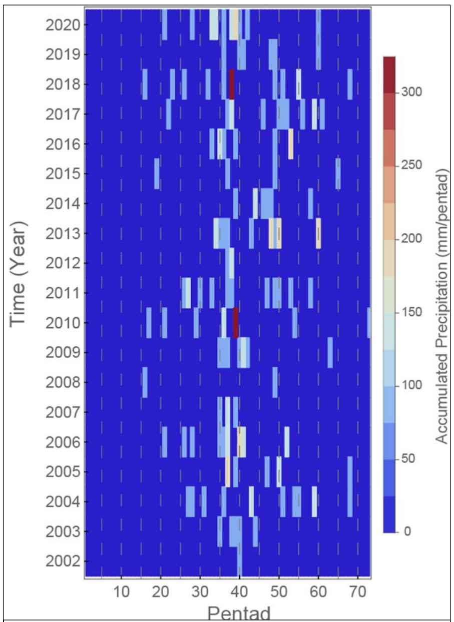

Fig. 5 Annual accumulated precipitation per pentad for the entire watershed of the Gōno River.

(5) <u>Flow–Turbidity Events</u>:
It was found that clockwise hysteresis patterns were caused by sediment sources from near-channel areas, while anticlockwise patterns were caused by soil erosion from nearby areas.
Another notable finding was that turbidity peaks during floods may represent bursts of earlier (or later) arrival of turbid water from distant upstream sources due to intense precipitation.

5．主な発表論文等

〔雑誌論文〕　計6件（うち査読付論文　6件／うち国際共著　6件／うちオープンアクセス　2件）

1．著者名 Al Sawaf Mohamad Basel、Kawanisi Kiyosi、Bahreinimotlagh Masoud	4．巻 5
2．論文標題 Examining the Relationship between Rainfall, Runoff, and Turbidity during the Rainy Season in Western Japan	5．発行年 2024年
3．雑誌名 GeoHazards	6．最初と最後の頁 176～191
掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/geohazards5010009	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Al Sawaf Mohamad Basel、Kawanisi Kiyosi、Gusti Gillang Noor Nugrahaning、Khadami Faruq、Xiao Cong、Bahreinimotlagh Masoud	4．巻 617
2．論文標題 Continuous measurement of flow direction and streamflow based on travel time principles using a triangular distribution of acoustic tomography systems	5．発行年 2023年
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.jhydrol.2022.128917	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Xiao Cong、Kawanisi Kiyosi、Al Sawaf Mohamad Basel、Zhu Xiao Hua	4．巻 37
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3．雑誌名 Hydrological Processes	6．最初と最後の頁 1～15
掲載論文のDOI（デジタルオブジェクト識別子） 10.1002/hyp.14841	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Sawaf Mohamad Basel Al、Kawanisi Kiyosi、Jlilati Mohamad Nazieh、Xiao Cong、Bahreinimotlagh Masoud	4．巻 193
2．論文標題 Extent of detection of hidden relationships among different hydrological variables during floods using data-driven models	5．発行年 2021年
3．雑誌名 Environmental Monitoring and Assessment	6．最初と最後の頁 692 ~ 692
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/s10661-021-09499-9	査読の有無 有
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1．著者名 Al Sawaf Mohamad Basel、Kawanisi Kiyosi、Xiao Cong	4．巻 806
2．論文標題 Characterizing annual flood patterns variation using information and complexity indices	5．発行年 2022年
3．雑誌名 Science of The Total Environment	6．最初と最後の頁 151382～151382
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.scitotenv.2021.151382	査読の有無 有
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1．著者名 Sawaf Mohamad Basel Al、Kawanisi Kiyosi、Xiao Cong	4．巻 2090
2．論文標題 Assessment and ranking flood events in a regulated river using information and complexity measures	5．発行年 2021年
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/1742-6596/2090/1/012169	査読の有無 有
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〔学会発表〕　計5件（うち招待講演　0件／うち国際学会　4件）

1．発表者名 Mohamad Basel AlSawaf
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3．学会等名 Proceedings of the 40th IAHR World Congress 21-25 August 2023 Vienna, Austria（国際学会）
4．発表年 2023年

1．発表者名 Mohamad Basel AlSawaf
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4．発表年 2023年

１．発表者名 Mohamad Basel AL Sawaf
２．発表標題 Applications of Travel Time Principle to Measure River Flow Dynamics Using Underwater Acoustic Tomography System
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１．発表者名 Mohamad Basel Al Sawaf
２．発表標題 Application of the Fluvial Acoustic Tomography to Monitor Dam Lake Hydrodynamics
３．学会等名 6th Underwater Acoustics Conference & Exhibition (UACE2021) Kalamata, Greece&（国際学会）
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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関