様　式　C－１９、F－１９－１、Z－１９　（共通）

科研費
KAKENHI

科学研究費助成事業　　研究成果報告書

令和　６ 年　 ６ 月 ２５ 日現在

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研究種目：基盤研究(B)（一般）
研究期間：2021～2023
課題番号：２１H０１４３４
研究課題名（和文）ダム下流への掃流砂供給を目指した土砂還元の高度化手法の開発

研究課題名（英文）Development of Advanced Sediment Replenishment Methodology for Bedload Continuity below Dams

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交付決定額（研究期間全体）：（直接経費）　　13,500,000円

研究成果の概要（和文）：このプロジェクトは、日本の那珂川における堆積物補充 (SR) のリアルタイム監視システムと評価アプローチを開発することを目的としていました。 私たちは、補給場所の流速と堆積物の浸食速度を検出するための画像ベースのアプローチを作成しました。 那珂川における SR の水理形態変化をシミュレーションするための 2 次元モデルを開発しました。 このプロジェクトの発見は、SR 侵食プロセスと下流の地形学的変化を予測するのに役立ちます。 このプロジェクトはまた、那珂川における SR の将来の最適化に向けたアプローチを開発し、利害関係者に SR 最適化のコストと下流域の修復の利点を評価するよう推奨しました。

研究成果の学術的意義や社会的意義
The project offers valuable suggestions for improving the SR in the Naka River, including increasing the frequency of sediment flushing, improving the materials used in the SR, and building new SR stockpiles to ensure a consistent sediment supply during dry periods.

研究成果の概要（英文）：The project aimed to create a real-time monitoring system and assessment approach for sediment replenishment (SR) in Naka River, Tokushima prefecture, Japan. The main practice involves adding sediment using artificial deposits or injections to restore downstream geomorphic ecology. We developed an image-based approach to detect the replenishment site's flow velocities and sediment erosion rates. We conducted a field visit and collected data from the Buech River in France. We established a two-dimensional model to simulate the hydro-morphological changes of SR in the Naka River. The impacts of flushing flow, replenished sediment, and the SR arrangement were assessed using morphological alterations and two scientific indicators (the transport ratio (TR) and the bed change indicator (BCI)). This project's findings can help predict the SR erosion processes and downstream geomorphological alterations of the SR.

研究分野：Hydraulic Engineering

キーワード：Sediment Replenishment　Morphological changes　Erosion processes　2D numerical modeling　Optimization of SR　Imaged- based-technique　Habitat restoration

１．　　研究開始当初の背景

Humans intervene in river basins by constructing hydraulic infrastructures like dams to control water and climate variabilities. However, these dams interrupt the connectivity of rivers from the mountains to the sea by trapping sediment in reservoirs and reducing flood peaks. This significantly decreases the quantity and quality of released sediments, which are mostly very fine grain sizes. Also, the flow transport capacity is significantly reduced. To address this issue, innovative sediment management options are needed to restore sediment connectivity below dams. One such technique is sediment reclamation (SR), which can be implemented in over 27 Japanese dams without requiring additional installations along the river. However, extensive efforts are required to dredge the sediment from the reservoir, transport it by trucks, and place it on the riverbanks using external machines. The SR technique involves three phases:

1. Dredging the sediment from the reservoir.
2. Transporting it by trucks to the dams below.
3. Injecting it into the rivers by placing it on the riverbanks.

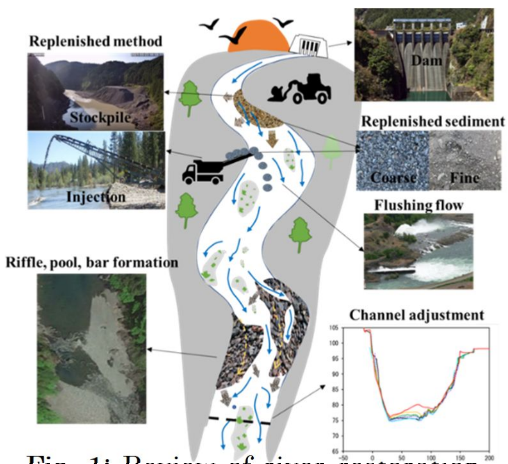


Fig. 1: Review of river restoration projects and its potential responses

Fig. 2: Examples of SR stockpiles in Japan, including the target study area in Naka River, Tokushima.

Figure 1 illustrates the state of the art of SR and its potential responses to downstream reaches using various injection methods. Specifically, SR is a method that utilizes trapped sediment from upstream to replenish downstream reaches artificially. Different characteristics of replenishment projects can be investigated, including different replenishment methods (stockpile or injection), different grain sizes of replenished sediment (fine or coarse), different locations and shapes of the replenished stockpile, and different flushing flow (magnitude and frequency). The additional sediment supply will directly lead to geomorphological changes, such as riffle, pool, bar formation, and channel adjustment, which may further influence habitat quality and diversity. These characteristics are the current research gaps in investigating and understanding SR implementation and its corresponding responses to downstream hydro-geomorphic ecology. Therefore, it is important to understand the relationships between each characteristic better to conduct an efficient and sustainable SR project. Typically, a large amount of sediment (approximately 1.7 million m^3) is replenished using a high-flow stockpile, with flushing flow rates ranging from 500 m^3/s to 5000 m^3/s. The project aims to dispose of the accumulated sediment upstream and restore the geomorpho-ecology downstream.

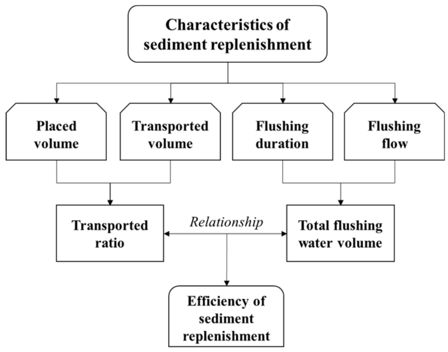


Fig. 3: Studied variables in the field and numerically for designing optimum SR options.

This project aims to develop a comprehensive tool for assessing the variables related to sediment removal (SR), as illustrated in Figure 3. The effectiveness of SR in transporting scouring sediment under various flushing flows was discussed based on two new parameters: the transported ratio (TR) and the total flushing water volume (TFWV). Additionally, several indicators from existing literature were used to intuitively present the downstream responses of SR, such as the Geomorphic Units Survey (GUS), the Hydro-geomorphological Index of Diversity (HMID), and Fish Diversity Index (H value).

The study assessed the impacts of flushing flow, replenished sediment, and the arrangement of SR through morphological alterations and two scientific indicators: the transport ratio (TR) and the bed change indicator (BCI). The results revealed that a higher magnitude of flushing flow does not significantly promote the erosion of SR sediment, with an optimal value of approximately 40% of the original discharge. Introducing an additional flood pulse can enhance SR erosion, increasing the eroded volume and TR by approximately 1.5% compared to a single flood pulse. Furthermore, adding a percentage of fine sediment to the composition of the SR material can significantly enhance SR erosion and promote the formation of riffles and bars near the SR site. Additionally, arranging double stockpiles at the SR site can increase the TR by 3% and the downstream BCI by 0.01 m.

The findings of this study can help predict the stockpile erosion process and downstream geomorphological alterations of the SR. Moreover, the study provides valuable recommendations for the future optimization of SR in the Naka River. These recommendations include increasing the flushing frequency, refining the SR material, and constructing new SR stockpiles to maintain sediment supply during drought. Stakeholders should evaluate the cost of SR optimization and the benefits of downstream restoration.

２．　研究の目的

SR is being implemented to restore the continuity of sediment transport blocked by the dam. The main question is how to recover the sediment balance volume, grain sizes, and flow regime in a form close to the original state. For such alterations of sediment and flow values below dams, the following questions were answered during this project:

1. How to design the timing of sediment supply in different sediment volumes, GSD, and placement conditions under different flood wave magnitudes.
2. How to naturally erode and accelerate the SR stockpile of continuous and variable flushing flows.
3. How can we optimize future SR implementation projects for hydro-geomorphic-ecological recovery?
4. How do we assess the SR projects under different flow and sediment characteristics?

３．研究の方法

Figure 4 provides a summary of the project's research methodologies. Initially, we conducted literature reviews on sustainable replenishment (SR) concepts, implemented projects, and riverine hydro-geomorphic ecology to identify research gaps. We then collected the necessary data on the replenishment site and downstream reaches from previous research and reports. Additional data needed to be collected, so we conducted image-based velocimetry to measure flow patterns and performed an on-site field survey to measure gravel bars.

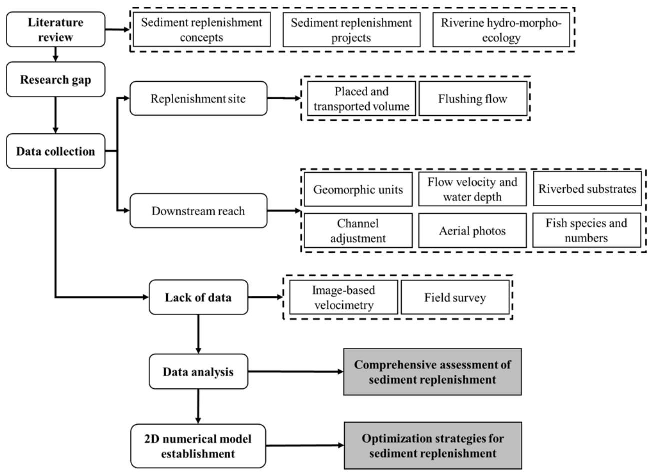


Fig. 4: Project research methodologies

Subsequently, we developed a comprehensive assessment approach to evaluate the erosion process and downstream impacts of SR, establishing several assessment indicators based on the available data. Finally, we developed a 2D numerical model (TELEMAC-2D coupled with Gaia) to comprehend the erosion process of replenishment and downstream geomorphological changes. We designed several scenarios to analyze the influence of different flushing flows, replenished material, placed volume, and locations based on the previous assessment approaches, aiming to investigate countermeasures for the optimization of SR

４．研究成果

（１） Design of SR:

The proposed optimization for the sediment replenishment SR works in the Naka River is summarized in Figure 5. When considering the downstream flood risks and the limitation of releasing flow during dry seasons, increasing the frequency of the released flushing flow from the dam is more effective than increasing the flood peaks of shorter duration for promoting sediment removal erosion and downstream hydro-geomorphic ecology. As for the sediment in the SR material, increasing the percentage of finer sediment can significantly enhance sediment erosive from the stockpile. However, determining the optimal composition of SR sediment requires considering the long-term downstream responses and the available sediment sources, which will be investigated in the future. Implementing double stockpiles is more efficient in increasing the sediment supply from the SR site and is beneficial for downstream restoration. Nevertheless, this countermeasure needs further evaluation of its feasibility since it requires higher funds and technical support.

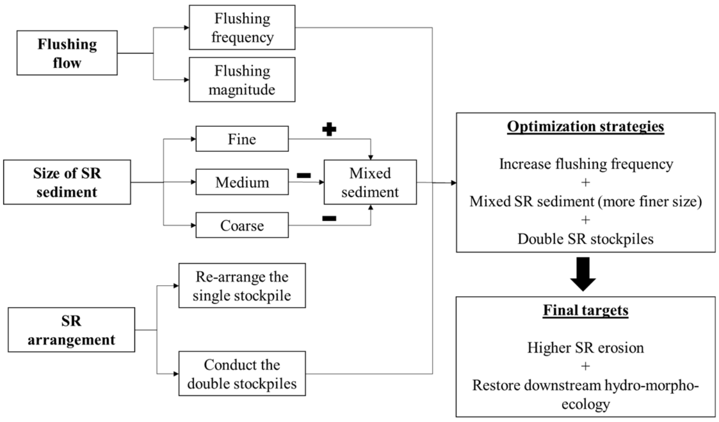
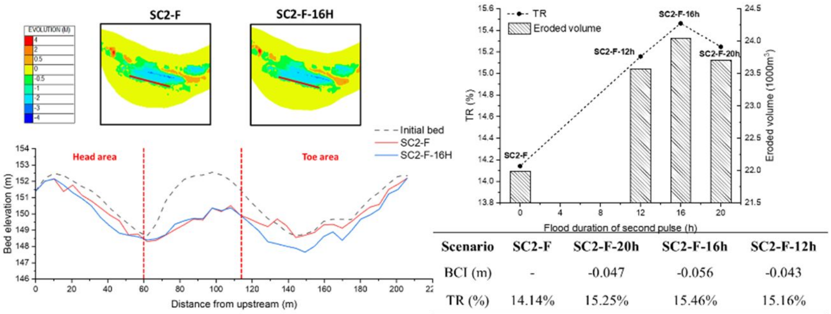


Fig. 5: Proposed optimization for SR method

(2) Erosion of SR:

The erosion results for the SR stockpile during different flood pulses are illustrated in Figure 6. Implementing a second flood pulse promotes the erosion process, particularly at the head and tail areas of the SR stockpile. The cross-sectional bed elevation from the stockpile head to the stockpile tail is presented at the bottom of Figure 6. It is evident that the depth of erosion increases by approximately 1 meter at the head area and by 0.5-2 meters at the tail area during 16-hour flushing flows. The velocity magnitude near the SR site remains similar between 12-hour and 16-hour flushing periods at the first flood peak, indicating that the flow magnitude does not significantly influence. The second flood pulse contributes to an additional flushing process, facilitating SR erosion. However, the erosion in the middle area remains similar, with no significant promotion. The flow velocity in the middle area is higher, and the erosion is mostly completed after the first flood pulse. During the second pulse, erosion is more likely to occur at the head and tail areas due to the greater sediment accumulation in these locations. The TR and eroded volume assessment between single and double flood pulses is examined. Across all scenarios of double flood pulses, the TR increases by approximately 1%, and the eroded volume increases by about 2000 m^3, primarily due to the additional erosion at the head and tail areas.



Scenario	SC2-F	SC2-F-20h	SC2-F-16h	SC2-F-12h
BCI (m)	-	-0.047	-0.056	-0.043
TR (%)	14.14%	15.25%	15.46%	15.16%

Fig. 6: How to naturally erode and accelerate the SR stockpile of continuous and variable flushing flows.

Furthermore, higher TR is observed compared to the flushing duration and magnitude of the second pulse. It is important to consider the pros and cons of the flushing magnitude and duration. A higher magnitude can promote erosion with higher flow velocity (middle area). At the same time, a longer duration can facilitate erosion in the area with lower flow velocity (head and tail areas). Therefore, a medium magnitude and duration scenario is efficient for SR erosion.

(3) Unified SR assessment:

In the framework of the research project for the target study area, the reach divided the downstream area of the Naka River into 12 sections, each 1 km apart. The GUS indicators were calculated for each section based on the geomorphic units survey shown in Figure 7. The results for two indicators, GUSI-R and GUSI-D, from 2015 to 2018 for each section are also displayed in Figure 7. A significant change in both indices is noticeable between 2015 and 2016 in the middle of the reach (3 km to 8 km), with a difference of around 30%. Specifically, GUSI-R decreased, indicating that the types of units remained stable, while GUSI-D increased, suggesting that the number of units was rising.

Additionally, the average value of both GUSI indicators is closely linked to the variation in transported sediment from the replenishment site. GUSI-R decreased after the 2015 replenishment, while GUSI-D showed the opposite trend. The significant amount of sediment transported in 2015 (300,000 m^3) may be the main reason for such substantial changes. The flushing flow carried sediment from the replenishment site and accumulated in the middle reach after two years of flushing. The deposition of this sediment significantly altered the formation and distribution of habitat structures, such as creating new bars and riffles. Furthermore, GUSI-R and GUSI-D remained stable in the following years, likely due to the reduced transported sediment from the SR site (70,000 m^3 in 2017).

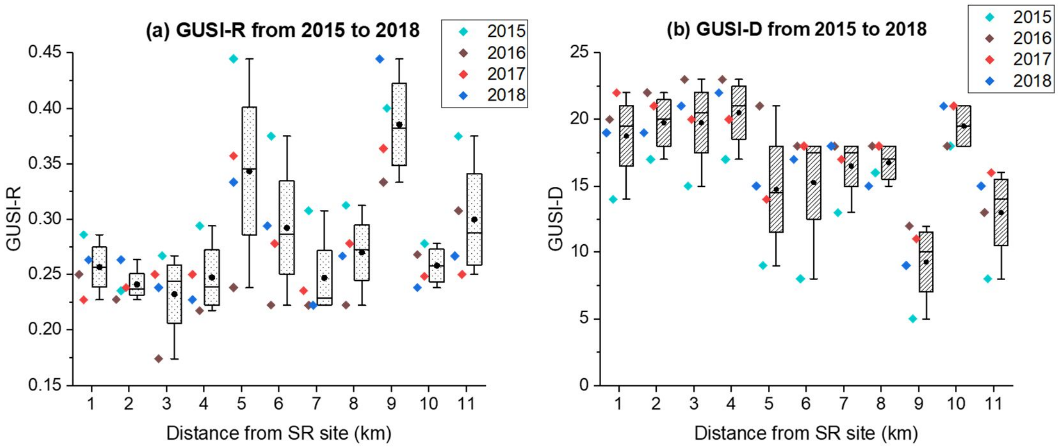


Fig. 7: The GUSI-R and GUSI-D at 12 km downstream of the replenishment site in the Naka River from 2015 to 2018

Summary of the research findings and recommendations for

- Sediment release (SR) combined with flushing flow can improve the downstream environment by increasing gravel units (GU), enriching substrates, and adjusting the channel.
- It's important to maintain an adaptable annual value of transported sediment downstream (e.g. 100,000 m^3 for the Naka River) to avoid harming habitat quality or GU maintenance.
- Adding fine sediment to SR material can significantly enhance SR erosion, requiring long-term simulation to assess the impacts.
- An additional flood pulse can facilitate SR erosion but may limit downstream morpho-ecology improvement due to varied sediment movements.
- Rearranging the current stockpile is not recommended for promoting SR erosion while adding an extra stockpile at the left bank is preferable for enhancing SR efficiency.

Please take note of the following recommendations for the Naka River and Buëch River:

1. Conduct field surveys such as bathymetric, drone, and fish surveys to assess the impacts of continuous sediment removal (SR) in the Naka River. Additionally, conduct a survey related to aquatic habitats in the Buëch River.
2. Implement additional calibration by collecting field measurement data of bathymetry, flow velocity, water depth, and Ground Control Points (GCPs) to improve the quality of image-based results. In the future, this approach can be expanded to use the Structure from Motion (SFM) approach to study the erosion process of SR.
3. Provide more Digital Elevation Model (DEM) and hydrological data for calibration and validation to enhance the reliability of the numerical model. To improve the model, consider constructing monitoring gauges for measuring water depth, flow velocity, or Suspended Sediment Concentration (SSC).
4. To optimize sediment removal in the Naka River, consider dividing the current single sediment removal site into multiple sites to increase efficiency and maintain the adaptable volume of sediment supply. If a suitable sediment source can be found, SR material that facilitates erosion is also recommended.
5. For optimizing sediment removal in the Buëch River, continuous sediment removal work is recommended to maintain positive responses in the downstream area, especially if the stakeholders aim to restore the long-term effects of dam construction.

５．主な発表論文等

〔雑誌論文〕　計9件（うち査読付論文　9件／うち国際共著　9件／うちオープンアクセス　6件）

１．著者名 Al-Mamari, M., Kantoush, S.A., Al-Harrasi, T., Al-Maktoumi, A., Abdrabo, K., Saber, M. and T., Sumi	４．巻 617
２．論文標題 Assessment of sediment yield and deposition in a dry reservoir using field observations, RUSLE and remote sensing: Wadi Assarin, Oman	５．発行年 2022年
３．雑誌名 Journal of Hydrology	６．最初と最後の頁 128-892
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.jhydrol.2022.128982	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 Binh, D.V., Kantoush, S.A., Ata, R., Tassi, P., Nguyen, T.V., Lepesqueur, J., Aberrezzak, K.E., Bourban, S.E., Nguyen, Q.H., Phuong, D. N., Trung, L.V., An, T.D., Letrung, and T., Sumi	４．巻 413(15)
２．論文標題 Hydrodynamics, sediment transport, and morphodynamics in the Vietnamese Mekong Delta: Field study and numerical modelling	５．発行年 2022年
３．雑誌名 Geomorphology	６．最初と最後の頁 108-368
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.geomorph.2022.108368	査読の有無 有
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１．著者名 Nguyen, B. Q., Kantoush, S. A., Saber, M., Binh, D. V., Vo, N. D., & Sumi, T.	４．巻 37(3)
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1002/hyp.14834	査読の有無 有
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１．著者名 Haghjouei H., Kantoush, S.A., S Beiramipour, Rahimpour M., Qaderi K.	４．巻 14
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３．雑誌名 Water	６．最初と最後の頁 15-88
掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/w14101588	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 Lin J. Q., Kantoush, S. A., Sumi, T., and Takemon, Y.	4．巻 66
2．論文標題 Comprehensive assessment of sediment replenishment in Naka River: Hydrological, morphological, and ecological perspectives	5．発行年 2021年
3．雑誌名 Journal of Japan Society of Civil Engineers (JSCE), Hydraulic Engineering	6．最初と最後の頁 256-262
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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

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2．論文標題 Experimental investigation of the diameter and length effects of the dendritic, bottomless, extended structure on reservoir sediment removal efficiency by flushing	5．発行年 2022年
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3．雑誌名 Science of The Total Environment	6．最初と最後の頁 152-992
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.scitotenv.2022.152992	査読の有無 有
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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

〔学会発表〕　計7件（うち招待講演　5件／うち国際学会　5件）

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4．発表年 2021年

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１．発表者名 Kantoush, S. A., Al Mamari, M. M., Kobayashi, S., Takemon, Y., Saber, M., Habiba, O., Sumi, T., Tazumi, M.
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２．発表標題 Eliminating Fixation of Alternate Bars by Using Impermeable Groynes
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１．発表者名 宮本理希・武藤裕則・田村隆雄
２．発表標題 長安口ダム下流域における長期河床変動予測について
３．学会等名 令和4年度土木学会四国支部技術研究発表会
４．発表年 2022年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

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
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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