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CURRENT RESERVOIR SEDIMENT COUNTERMEASURES AND SYSTEMATIC METHODOLOGY TO SELECT APPROPRIATE COUNTERMEASURES

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1. INTRODUCTION

Due to the mountainous geography and weak soil structures, many areas in

Japan produce vast quantities of sediment. Although some dams have already implemented countermeasures against sedimentation, numerous dams may face sediment issues in the future. Currently each dam individually considers the applicability of sediment control method and decides the appropriate countermeasure; a systematic methodology for planning countermeasures against sedimentation has yet to be established. However, some advanced dams in Japan are taking advantage of sediment treatment technologies such as flushing, sluicing, and tunnel bypassing, indicating that the accumulation of experiences for systematic counter-sediment technologies has started.

In this paper, first, the current status of countermeasures and our survey results on countermeasures against sediment in reservoirs at 20 dams in Japan are examined. Then to achieve sustainable sediment management and to contribute to a more advanced sediment management, we discuss our efforts to systematize procedures that are considered effective. Herein technologies for countermeasures against sedimentation, which are primarily applicable to existing dams, are discussed.

2. CURRENT STATE OF RESERVOIR SEDIMENTATION COUNTERMEASURES

In Japan, the primary countermeasure for sedimentation in dam reservoirs is mechanical sediment removal, including excavation and dredging. Excavation is typically done with backhoes and dump trucks to remove sediment from the reservoir, whereas dredging involves pumps, grab bucket dredgers and/or sand carriers to move sediment with water (transportation within the reservoir). For example, the Miwa Dam (multipurpose dam in the Tenryu River System) has excavated and dredged 7.5 million m^3 of sediment (mainly gravel, the cumulative amount from 1966 through 2008), and the Sakuma Dam (hydroelectric dam in the Tenryu River System) removes 200,000 to 400,000 m^3/year. Since 1970, the following projects have been carried out by the Ministry of Land, Infrastructure, Transport and Tourism:

- 1979 – The Reservoir Maintenance Project implemented infrastructures such as check dams and sediment transportation routes.
- 1987 – The Sediment Removal Project for Specified Dams (dam refreshing project) installed sediment excavation facilities and permanent sediment removal facilities.
- 1992 – The Disaster Relief Project removed sediment within the flood control capacity for specified flood control dams when sediment reached a certain level due to flooding of a certain magnitude or greater.

On the individual dam level, sediment flushing began in 1991 at the

Dashidaira Dam (hydroelectric dam in the Kurobe River System), and coordinated flushing commenced between the Dashidaira Dam and the Unazuki Dam (multipurpose dam in the Kurobe River System) in 2001. Additionally, sediment bypass operations were initiated at the Asahi Dam (hydroelectric dam in the Shingu River System) in 1998 and at the Miwa Dam in 2005.

3. SURVEY ON RESERVOIR SEDIMENTATION COUNTERMEASURES

3.1 SURVEY OF THE CURRENT STATE

The amount and shape of sediment are occasionally defined by the inflow of sediment associated with major events such as a large amount of water flow. We collected information on the actual countermeasures against sedimentation across Japan, and summarized the appropriateness of selected methods, restrictions when projects were implemented, and the tasks when evaluating actual countermeasures implemented at dams (removal of sediment using excavation and dredging). Our survey included dams that collected 800,000 m^3 or more of sediment annually in some year. Additionally, we collected information about dams that removed sediment with their water level lowered. Consequently, we identified 80 dams with annual sediment of 800,000 m^3 or more, and of these, we selected 20 dams that appeared to have experience with sediment removal via questionnaires (Table 1). Furthermore, we selected eight dams that are expected to show detailed information and effective responses, and conducted interviews on sediment removal methods and restrictions. Figure 1 shows the locations of dams we surveyed.

Table 1
Surveyed Dams

Dam	Maximum Annual Sedimentation (10^3 m^3)	Administered by	Interview
Sakuma	8,750	J-POWER	○
First Hatanagi	4,542	CHUBU Electric Power Co., Inc	○
Ikawa	2,517	CHUBU Electric Power Co., Inc	○
Takase	2,400	Tokyo Electric Power Company	○
Sagami	2,403	Kanagawa Prefectural Public Enterprises Agency	○
Yahagi	2,800	Chubu Regional Bureau, Ministry of Land, Infrastructure and Transport and Tourism (hereinafter called “MLIT”)	
Koshibu	2,404	Chubu Regional Bureau, MLIT	○
Nagayasuguchi	2,083	Dept. of Infrastructure and Dept of Enterprises, Tokushima Prefectural Government	
Miwa	4,241	Chubu Regional Bureau, MLIT	○
Tedorigawa	2,772	Hokuriku Regional Bureau, MLIT	

Dam	Maximum Annual Sedimentation (10^3 m^3)	Administered by	Interview
Makio	2,342	Japan Water Agency (Min. of Agriculture, Forestry and Fisheries)	○
Kawaji	1,491	Kanto Regional Bureau, MLIT	
Iwaya	1,656	Japan Water Agency	
Kuzuryu	1,300	Kinki Regional Bureau, MLIT	
Nagashima	801	Chubu Regional Bureau, MLIT	
Agigawa	1,315	Japan Water Agency	
Shintoyone	511	Chubu Regional Bureau, MLIT	
Kazeya	882	J-POWER	
Sameura	2,946	Japan Water Agency	
Taki	872	J-POWER	

Fig.1
Locations of surveyed dams

3.2 Sedimentation Countermeasures at Surveyed Dams

Table 2 summarizes sedimentation countermeasures at eight of the dams we surveyed.

Table 2
Sedimentation countermeasures and use of sediment at each dam

Dam	Mean Annual Sedimentation (10^3 m^3)	Quantity of removed sediment per year (1,000 m^3)	Method of sediment removal	Use of removed sediment
Sakuma	1,509.7	① Removal from reservoir: 400 ②Intra-reservoir transportation: 700 ③Intra-reservoir flushing: 1,000 - 2,000	Removal from reservoir; Sand pump barge & dump trucks Intra-reservoir transportation: Pump barge & sand carrier Intra-reservoir flushing: Force of natural flow	Aggregate, 400,000m^3/year
First Hatanagi	758.2	9	Barge with crane & bagging	Dead water zone in reservoir
Ikawa	468.0	42	Barge with crane & solidifying	Inside reservoir
Takase	713.1	350	Backhoe & dump trucks	Aggregate, 150,000 m^3
Sagami	298.5	①Dredging: 250 ②Excavation at check dam: 50 ③Commercial contractor: 50	①Backhoe dredger & sand carrier ②Backhoes	Aggregate,10,000 m^3/year Land fill,80,000 m^3/year Land development, 100,000 - 120,000 m^3/year Beach nourishment, 300,000 m^3/year
Koshibu	318.6	160	Backhoes & dump trucks	Aggregate, 141,000 m^3
Miwa	437.0	300 - 500	Backhoes & dump trucks Pump dredger & dump trucks	Agricultural field development Aggregate, 100,000 m^3
Makio	181.5	300 - 1,000	Backhoes & dump trucks	Total of 5,140,000 m^3 is transported to a disposal site. Part of removed sediment is used to construct parks.

3.2.1 Sakuma Dam

The Sakuma Dam accumulated sediment that amounted to more than 100 million m^3, which is more than 1/3 of the total reservoir capacity. Accumulation was due mainly to floods in 1961 and 1982. The sediment removal began in 1971 (full-fledged operation began in 1978), and excavation and dredging have been removing about 200,000 to 400,000 m^3 of sediment annually since 1985. Beginning in 1990, the sediment has been moved within the reservoir (Intra-reservoir sediment transportation), and sediment sluicing within the reservoir has been conducted since 1991 (See Fig. 2).

・Sediment removal out of the reservoir: Since 1995, gravel extraction contractors have been extracting 400,000 m^3 of sand (mostly coarse sand) annually using sand pump vessels. This sand has been used as construction materials and as additional soil in land development. Additionally, sediment, which has been excavated on land at the end of the reservoir, is hauled away by dump trucks.

- Intra-reservoir sediment transportation: Dredgers have been collecting 700,000 m^3 of sediment annually from locations higher than the planned level of the river bed (300,000 m^3 from the upper stream and 400,000 m^3 from the mid-stream), and sand carriers have transported and dropped this sediment into the dead water zone. Two pump purge vessels (400 kVA) have been used for intra-reservoir transportation from mid-stream of the reservoir. Although intra-reservoir transportation increases the effective capacity of the dam, the total amount of sediment remains the same.
- Sediment sluicing within the reservoir: The water level is lowered in February and March due to sediment sluicing (25 to 30 m lower than normal level) in order to move the sediment to the dead water zone by water flow. Like intra-reservoir transportation, this does not decrease the total amount of sediment in the reservoir. The amount of sediment moved in this manner is as much as 1 to 2 million m^3 annually. This operation has been recently called sediment flow promotion.

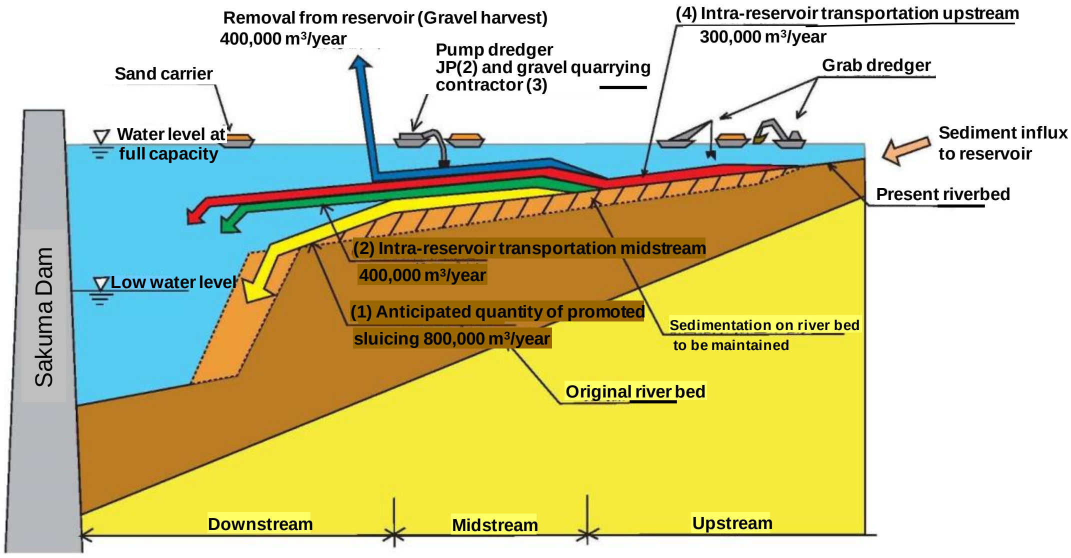


Fig.2
Overview of sediment countermeasures at Sakuma dam

3.2.2 First Hatanagi Dam and Ikawa Dam

The areas in front of the intake gates of the First Hatanagi Dam and Ikawa Dam are dredged to remove obstacles to maintain flushing gates. Because the roads leading to either dam are narrow, bringing in grab ships and pump ships is difficult. Thus, crawler cranes are setup on an assembly ship to perform dredging. Because the First Hatanagi Dam lacks a dump site, dredged sediment is bagged up and immersed where it is not affected much by water flow (bagging and dehydrating method) (See Fig. 3). This point is 200m upstream from dam. The advantages of the bagging and dehydrating method are: (1) sediment does not flow because it is kept in bags and (2) lessen the volume of sediment because the pressure in the bags reduces the water content. However, the Ikawa Dam has a dump site on the reservoir and thus, sediment is solidified.

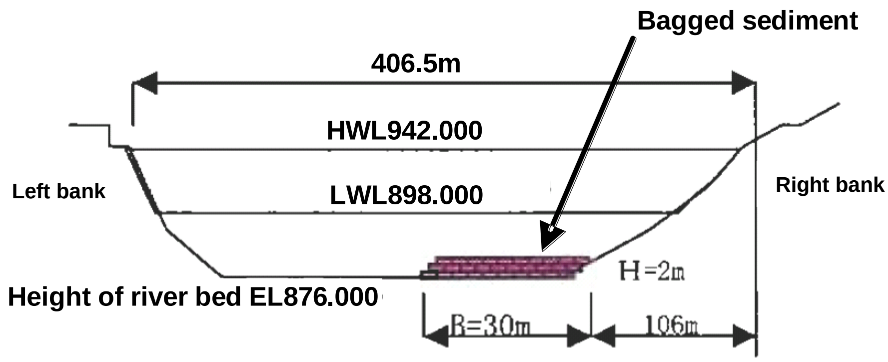


Fig. 3
Bagging and dehydration method

3.2.3 Takase Dam

Sediment at the Takase Dam is fed from the Hudouzawa River and Nigorizawa River, which are immediately upstream on the left bank of the dam. Currently the average annual sediment inflow is 700,000 m^3 of which 30% is from the main river, 55% is from where the Hudouzawa River and Nigorizawa River combined, and the remaining15% is from other tributaries. Countermeasures target where the Nigorizawa River and Hudouzawa River meet because this is the largest source of sediment (on average, 350,000 m^3 of sediment is produced annually). 10-Ton dump trucks haul away sediment from the Hudouzawa River (200,000 m^3 annually) and the sediment flow direction is controlled by digging and open channels at the Nigorizawa River (150,000 m^3 annually).

3.2.4 Sagami Dam

In addition to excavation, backhoe dredgers have been dredging 100,000 to 150,000 m^3 of sediment annually since 1987. As part of the Sagami Reservoir Large-Scale Construction and Improvement Project, the scale of the operation has been expanded to include two backhoe dredgers, and dredged sediment is discharged onto a temporary sediment dump site on the lakeshore. The planned amount of sediment to be removed is 350,000 m^3 per year: 250,000 m^3 per year by dredging, 50,000 m^3 per year removed from check dams, and 50,000 m^3 per year of aggregates excavated by commercial contractors. The dredged sediment has been used as aggregate for construction (10,000 m^3 per year), banking (80,000 m^3 per year), land development (100,000 to 120,000 m^3 per year), artificial beach nourishment (30,000 m^3 per year), etc.

3.2.5 Koshibu Dam

The first check dam was completed in 1977, and the second one was completed in 1989. Almost every year, 160,000 m^3 of sediment in the reservoir is excavated. Future plans include implementing sediment bypass system with a flow capacity of 500 m^3/sec to reduce the annual sediment accumulation in the dam reservoir from 554,000 m^3 to 200,000 m^3 (a 36% reduction).

3.2.6 Miwa Dam

In the last 40 years, about 7.5 million m^3 of sediment has been removed. This represents over 30% of the total amount of sediment, and about 2 million m^3 of this was removed in the redevelopment project. Methods of sediment removal include excavation, which began in 1961, and pump dredging since 1973. Since the 1970s, these operations removed about 200,000 to 400,000 m^3 of sediment per year. Additionally, excavation and dredging have removed about 100,000 m^3 of sediment per year since 1982, and have been removing 300,000 to 500,000 m^3 of sediment per year since 2000. Permanent measures include a check dam (completed in 1994) and the commencement of test operation of sediment bypass system in 2005. The sediment bypass system has flushed wash load downstream during four floods. For example, during floods in July 2006 and September 2007, about 310,000 m^3 of wash load was flushed downstream. Excavated sediment from the reservoir has been used in road construction and agricultural fields.

3.2.7 Makio Dam

A countermeasure against large-scale sedimentation was conducted on an emergency basis when the West Nagano Prefecture Earthquake (M6.8 in September 1984) produced a large amount of sediment: 2.34 million m^3 per year of sediment flowed into the dam reservoir, and by 1992 the total accumulation amounted to 10.8 million m^3. The Makio Dam Sedimentation Countermeasure Project, which began in 1998 (full-fledged operation started in 1999), excavated 0.3 to 1 million m^3 of sediment per year on land at locations higher than the operating water level of the dam using backhoes (1.4 m^3 bucket) during the winter. The excavated earth was hauled to two dump sites upstream the dam reservoir and then transported by dump trucks. When the project ended in 2007, 5.14 million m^3 of sediment was removed.

3.3 RESTRICTIONS SURROUNDING SEDIMENTATION COUNTERMEASURES

Our surveys on 20 dams revealed that there are various restrictions surrounding the removal of sediment such as use and disposal of removed sediment. The top five types of issues are (the numbers in parentheses indicate the number of dams that are facing such issues):

① Securing places to use and/or dispose of removed sediment (14)
② Issues in transporting removed sediment (10)
③ Obstacles (such as drift woods, debris) (5)
④ Treatment of excess water and securing locations for temporary sediment disposal (3)
⑤ Generation of muddy water associated with sediment removal (3)

The majority of dams face issues with ① Securing places to use and/or dispose of removed sediment followed by ② Sediment transportation. Intra-reservoir transportation of sediment occurs mainly through pipelines (Ikawa Dam and First Hatanagi Dam) or sand carriers (Sakuma Dam and Sagami Dam), whereas transportation away from a reservoir is typically performed by dump trucks. The transport distance is typically 4 to 15 km. The Makio Dam uses the most dump trucks (daily maximum of 800 dump trucks) followed by the Kawaji Dam (daily maximum of 300 dump trucks).

3.4 Summary of Our Survey Results

The following summarizes what points were considered and how methods were selected for sediment removal from dams. The flowchart below depicts the basic procedure to select sedimentation countermeasures:

(1) Removal of sediment

Numerous methods exist to remove sediment, and each dam selected a method based on their unique operational situations. Below are the factors considered when selecting the appropriate method.

① Factors to consider for excavation or dredging

Sediment removal can be performed either by excavation or dredging. Although many factors affect the selection of methods, all the dams that we surveyed employed one of these methods. For example, dams capable of lowering the water level due to their operational requirements typically employed excavation, which is more economical and produces less harmful effects due to muddy water.

② Factors to consider for machines for sediment removal

Field conditions (geography, season, and environment) should be thoroughly researched prior to selecting machines to remove sediment, and the machines should meet these specific conditions.

Excavation machinery: Various specifications of backhoes were determined after considering factors such as the length of work, cost, and ease of work.

Dredging: Machines were selected based on the depth and amount of sediment to be dredged.

(2) Transportation of removed sediment

① On-land transportation (dump track transportation)

Noise (introduction of low-noise vehicles), dust (spraying water), and speed limit for vehicles must be considered prior to implementing land transportation to haul away sediment. Additionally, a consensus with neighboring residents on the appropriate countermeasure is necessary.

② On-water transportation

The locations of sand carriers should be considered in on-water transportation to effectively move the desired amount of sediment as well as the formation of sand carriers for the specific shape of the reservoir. It is also important to consider whether structures span the reservoir in pressurized transportation by using pipes.

(3) Effective use of removed sediment

The biggest issue in conducting a countermeasure against sedimentation is what to do with the removed sediment.

① Disposal

Disposal can be divided into two methods: intra-reservoir transportation and flushing. For intra-reservoir transportation, among other factors, effective use of the capacity of the dead water zone should be considered.

② Effective use

Effective use of removed sediment can be classified into aggregate for construction, banking, land development, and replenishment of sand to downstream rivers. It is extremely important to investigate the demand for each type of use. The use of removed sediment may be limited due to its characteristics (particularly its diameter). Therefore, it is important to allocate an appropriate use depending on the sediment characteristics. Additionally, a temporary dump site for sediment excavated and dredged must be secured.

Dam reservoirs not only function to store water, but also end up storing earth and sand. Floods, typhoons, and earthquakes can cause a large inflow of sediment into a dam reservoir. When this happens, it is important to provide a countermeasure without delay to maintain the functions of the dam in accordance with countermeasure manuals previously prepared based on past experiences.

4. CHARACTERISTICS AND APPLICABILITY OF RESERVOIR SEDIMENTATION COUNTERMEASURES

4.1 Characteristics of Sedimentation Countermeasures

Figure 4 classifies sedimentation countermeasures in accordance to policies for reservoir sediment management and the location where countermeasures are applied. Herein reservoir sediment management policies refer to policies on how sediment in a reservoir is to be controlled in the future, and can be classified into three categories: (1) Reduction of sediment inflow into a reservoir, (2) Pass-through of sediment inflow into a reservoir, and (3) Removal of sediment accumulated in a reservoir.

Major sedimentation countermeasures considered often include excavation and dredging, sediment replenishment to downstream rivers, hydrosuction method, sediment bypass, and flushing. Table 3 shows an overview of each of these countermeasures, which can be classified according to characteristics of each method into the following four categories: (1) Mechanical countermeasures, including excavation, dredging, and hydrosuction method, (2) Bypass type countermeasures, (3) Reservoir water-assisted countermeasures such as flushing and sediment sluicing (hereinafter called "sluicing"), and (4) Fine particle countermeasures such as density current venting.

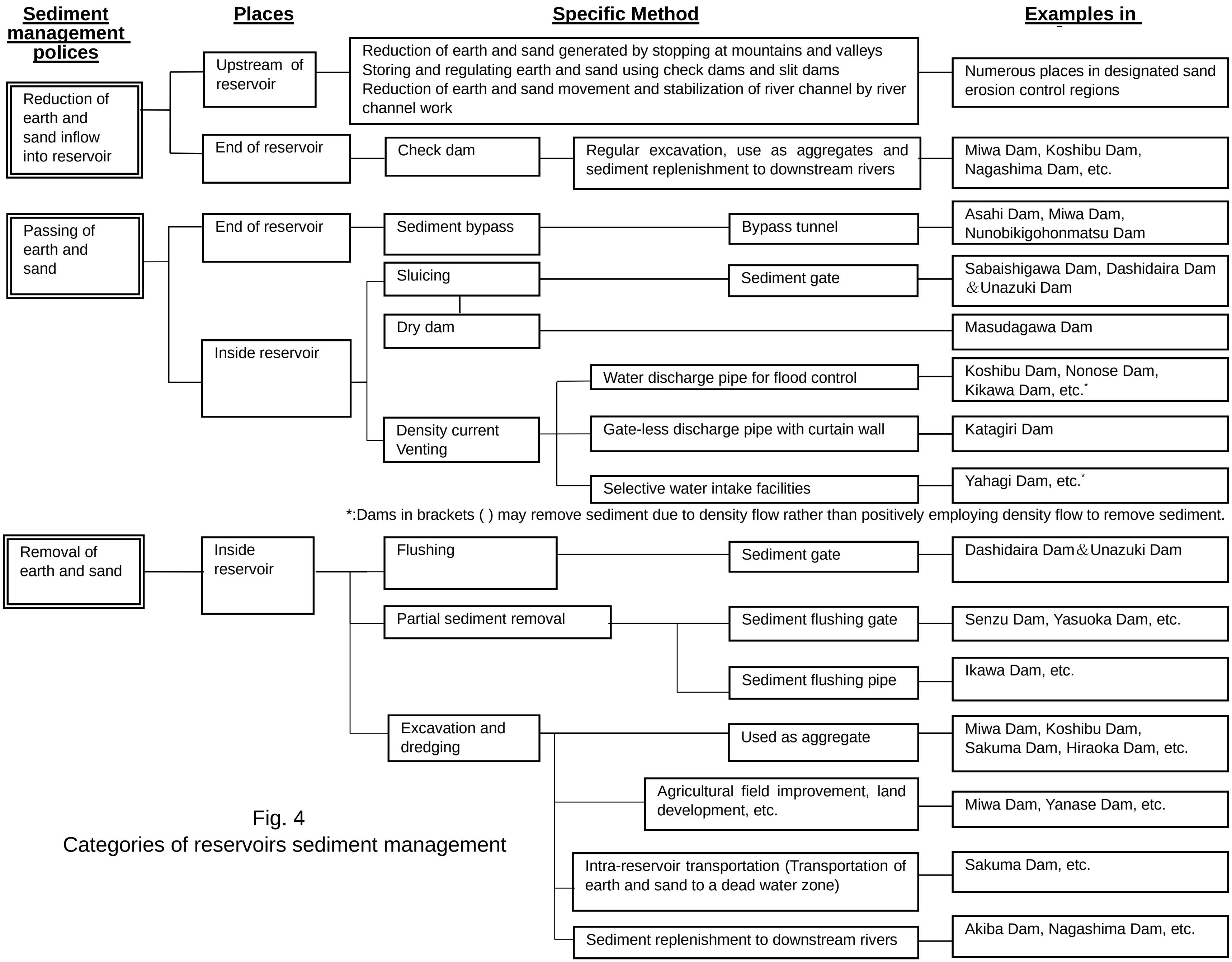


Fig. 4
Categories of reservoirs sediment management

Table 3
Overview of major sedimentation countermeasures

Sedimentation countermeasures	Category	Overview of countermeasure
Excavation and dredging	Mechanical method	Sediment is removed using backhoes and grab dredgers, and dredged sediment is transported using dump trucks and pumps. <Merit> Sediment can be removed without specialized equipment <Demerit> Quantity of removed sediment is low, requires space to temporarily store removed sediment, and restrictions in transporting earth and sand
Sediment replenishment to downstream rivers		Excavated sediment from dam is placed on flood river banks and is flushed downstream by flood water <Merit> Sediment can replenish downstream without specialized equipment <Demerit> Quantity of removed sediment is low, requires space to place removed sediment, and flushing of removed sediment depends on the occurrence of floods
Hydrosuction method		Siphon action due to the water level difference sucks sediment to discharge downstream. The stationary type has a suction pipe underneath the sediment, while the mobile type uses a ship equipped with a suction pipe. <Merit> Energy-efficient, sediment concentration can be adjusted. <Demerit> Sediment removal performance has not been well established. Suction pipe may clog due to driftwood, etc.
Sediment bypass	Bypass method	Earth and sand are carried with flood water diverted by a diversion weir through a tunnel downstream <Merit> Sediment quantity removed is proportional to the amount of water used. <Demerit> Tunnel construction is expensive. Requires a diversion weir. Requires a repair due to wear.
Flushing	Intra-reservoir tractive force method	Sediment in a reservoir is flushed from a gate using the force of flood water. <Merit> Gate operation removes sediment. <Demerit> Requires the reservoir water level to be lowered. Requires flushing gate. Requires repair due to wear.
Sluicing		Earth and sand flowing into the reservoir is flushed from a gate using the force of flood water. <Merit> Gate operation removes sediment. <Demerit> Requires the reservoir water level to be lowered. Requires flushing gate. Requires repair due to wear.
Density current venting	Fine particle method	Muddy water and fine particles accumulated at the bottom of the reservoir are discharged from a facility like a gate with the occurrence of a density current. <Merit> If the timing is right, fine particles can be efficiently removed. <Demerit> Requires density current to occur. Requires a discharge pipe (gate) at a low position. Discharge timing is difficult to judge.

4.2 APPLICABILITY OF SEDIMENTATION COUNTERMEASURES

The applicability of each sedimentation countermeasure depends on the characteristics of the reservoir, sediment accumulation, river channels, and flow. Therefore, a countermeasure should be chosen considering these characteristics. Table 4 summarizes the applicability of a sediment removal method for each of these characteristics. Excavation and sediment replenishment to downstream rivers require space where earth and sand associated with the work can be moved and temporarily stored. The flushing requires the reservoir water level to be lowered and a sufficient water flow to quickly recover the normal water level. Sediment bypass system requires a sufficient amount of removed sediment to justify the cost of constructing a tunnel.

The characteristics of a reservoir with respect to sediment removal can be described using the lifespan of reservoir in terms of inflow (CAP/MAS, where CAP is the total reservoir capacity and MAS is the mean annual sediment inflow) and the reservoir turnover rate with regard to the amount of water inflow (MAR/CAP, where MAR is mean annual water inflow). As shown in Fig. 5, each sediment removal method is closely related to these parameters. Furthermore, the applicability of removal methods can be categorized using the sediment diameters to be removed. Figure 6 is a guide to select an appropriate method. The sediment bypass method can remove a large amount of sediment with a wide range of diameters. Although the flushing can remove a large amount of sediment, the diameter is typically limited to the 1 to 10 mm range. In contrast, the density current venting deals exclusively with fine particles, which arrive at a dam with the density current. Sediment replenishment to downstream rivers is for particle diameters suitable for civil works using machinery. The hydrosuction method can handle a wide range of particle diameters, albeit with a limited maximum diameter, and the quantity of removable sediment is relatively large. Thus, each method has its own target sediment particle diameters and annual sediment removal capacity.

Table 4
Applicability of sedimentation countermeasures

	Characteristics of reservoir and sediment	Characteristics of river channels and water flow	Other characteristics
Excavation and dredging	・Reservoir water level is low (excavation) ・Barge and/or other vessels may be used on the reservoir (dredging) ・Space is available to temporarily store removed sediment ・Muddy water generated due to the operation is at such a level that its spread is prevented using a contamination prevention membrane.	・Quantity of sediment inflow is not large	・Does not require specialized equipment ・Excavated and dredged sediment can be used or disposed of ・Transportation to a disposal site is readily available
Sediment replenishment to downstream rivers	・Quantity of sediment to be used for replenishment is not very large ・Toxic substances are not present in the sediment	・Space is available to place removed sediment on a river channel ・Removed sediment can be placed at a higher altitude than the muddy water level during flood ・Carrying power can be expected during flood	・Does not require specialized equipment
Hydrosuction method	・Reservoir water level can be maintained at a level that does not decrease sediment suction efficiency ・Sediment height does not fluctuate much during a normal flood ・Need to remove coarse particles is low ・Small accumulation of clay and	・Not much debris like driftwood to clog discharge pipes and suction pipes ・Not used often when flow rate is low and SS concentration becomes high in downstream river channels due to this sediment removal operation	・Discharge sediment concentration can be adjusted by introducing clear water

	Characteristics of reservoir and sediment	Characteristics of river channels and water flow	Other characteristics
	solidified earth	・Construction of a tunnel is not difficult	
Sediment bypass	・Reservoir water level can be maintained at a level that does not decrease the sediment suction efficiency ・Facilities, such as diversion weir, can be constructed to direct flood water to a bypass tunnel ・Vast quantities of sediment can be removed ・Coarse particles from sediment should be removed	・Only one major river flows into the reservoir ・Gradient of the tunnel can be made sufficiently steep to prevent sediment from accumulating in the bypass ・Construction of a tunnel is not difficult	・Quantity of sediment is sufficient to justify the high cost of constructing a tunnel
Flushing Sluicing	・Relatively easy to lower the water level of the reservoir operation ・Frequency of sediment removal operations can be set so that SS concentration in downstream river channels is not elevated ・Gradient is sufficient for water current to carry sediment away ・Sediment discharge gate is located at a low position on a dam	・Flow rate is high enough to recover the reservoir water level after a sediment removal operation ・Sediment inflow to a reservoir is sufficiently low that continued sediment management is not difficult	・Remedies can be applied to wear
Density current venting	・Density current occurs readily: Reservoir turnover rate is low and sediment gradient is large ・Sediment delta is not far from a dam ・Water discharge pipe (gate) is located at a low position on a dam ・Fine particles among sediment is to be removed		・Approach of a density current to the vicinity of dam is predictable ・Timing of discharge can be well-coordinated with the arrival of density flow

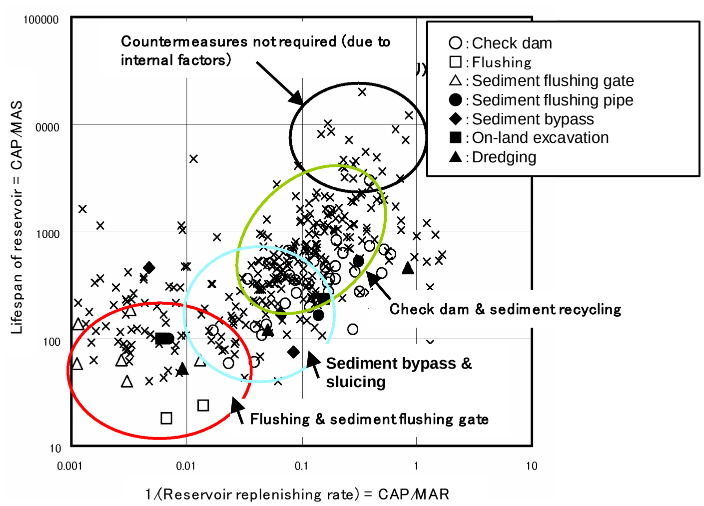


Fig. 5

Characteristics of reservoir and sediment removal method

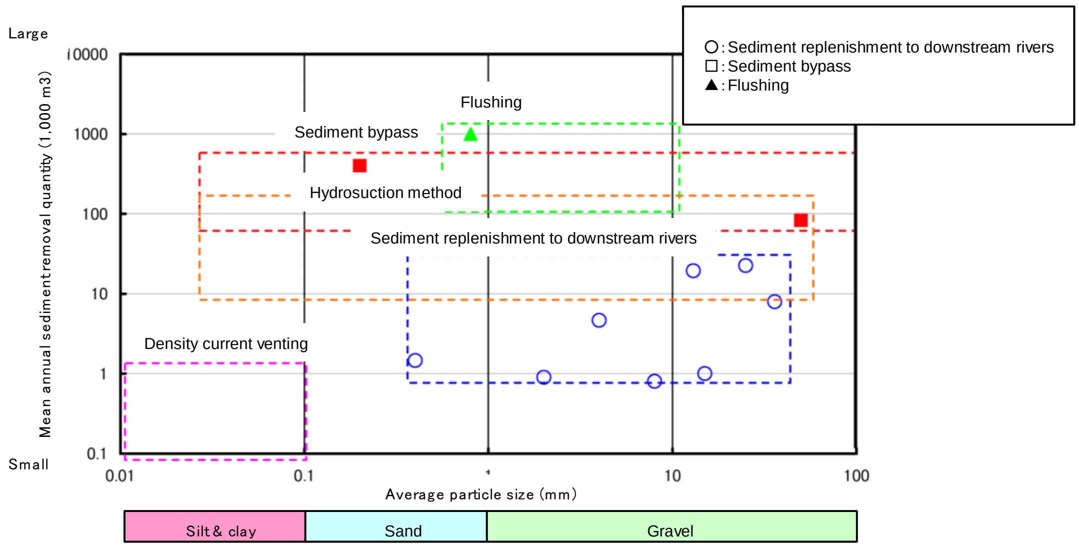


Fig. 6
Distribution of quantities and particle sizes of sediment to be removed

5. SELECTION OF RESERVOIR SEDIMENTATION COUNTERMEASURES

5.1 PROCEDURES TO DETERMINE APPROPRIATE SEDIMENTATION COUNTERMEASURES

To determine an appropriate countermeasure against sediment accumulation, first the necessity of a sedimentation countermeasure is examined. Then an appropriate countermeasure is determined based on factors specific to the dam such as the characteristics of the reservoir. Parameters employed to categorize the characteristics of a reservoir include the ability to lower the reservoir water level, lifespan and turnover rate of reservoir water, quantity and particle size of sediment, gradient of the river bed, and altitude of water discharge pipes.

Figure 7 shows the four step procedure to determine a sedimentation countermeasure: (1) Evaluate the necessity for sedimentation countermeasures, (2) Draft a sediment removal scenario, (3) Create a list of potential sediment removal methods, and (4) Select the most appropriate sedimentation countermeasure. If an appropriate method is not found in the countermeasure selection procedure, then the examination results are used to alter the parameters, such as the sediment removal scenario and preliminary selection conditions, for further review. To verify the effectiveness, the chosen sedimentation countermeasures should be reevaluated via an appropriate monitoring method.

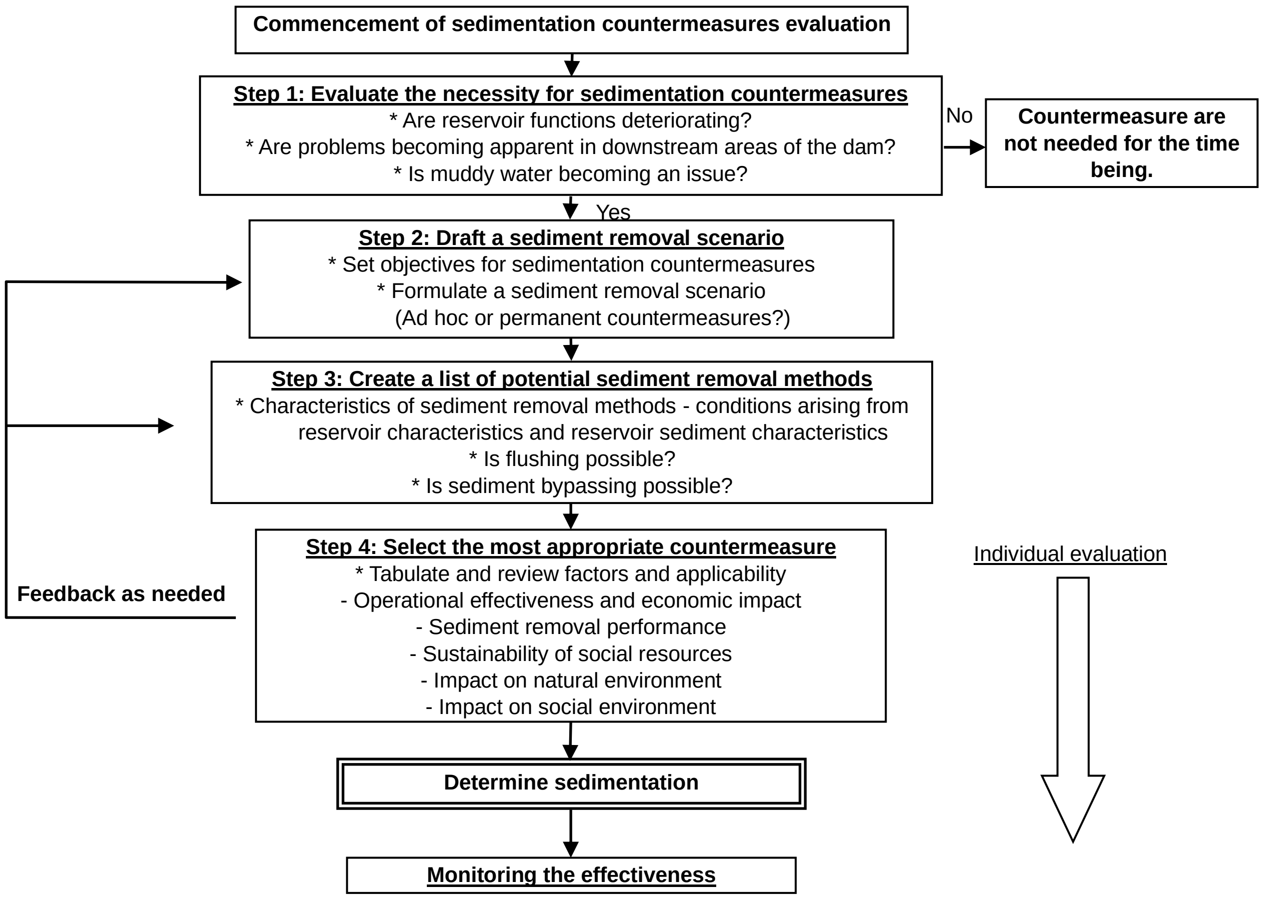


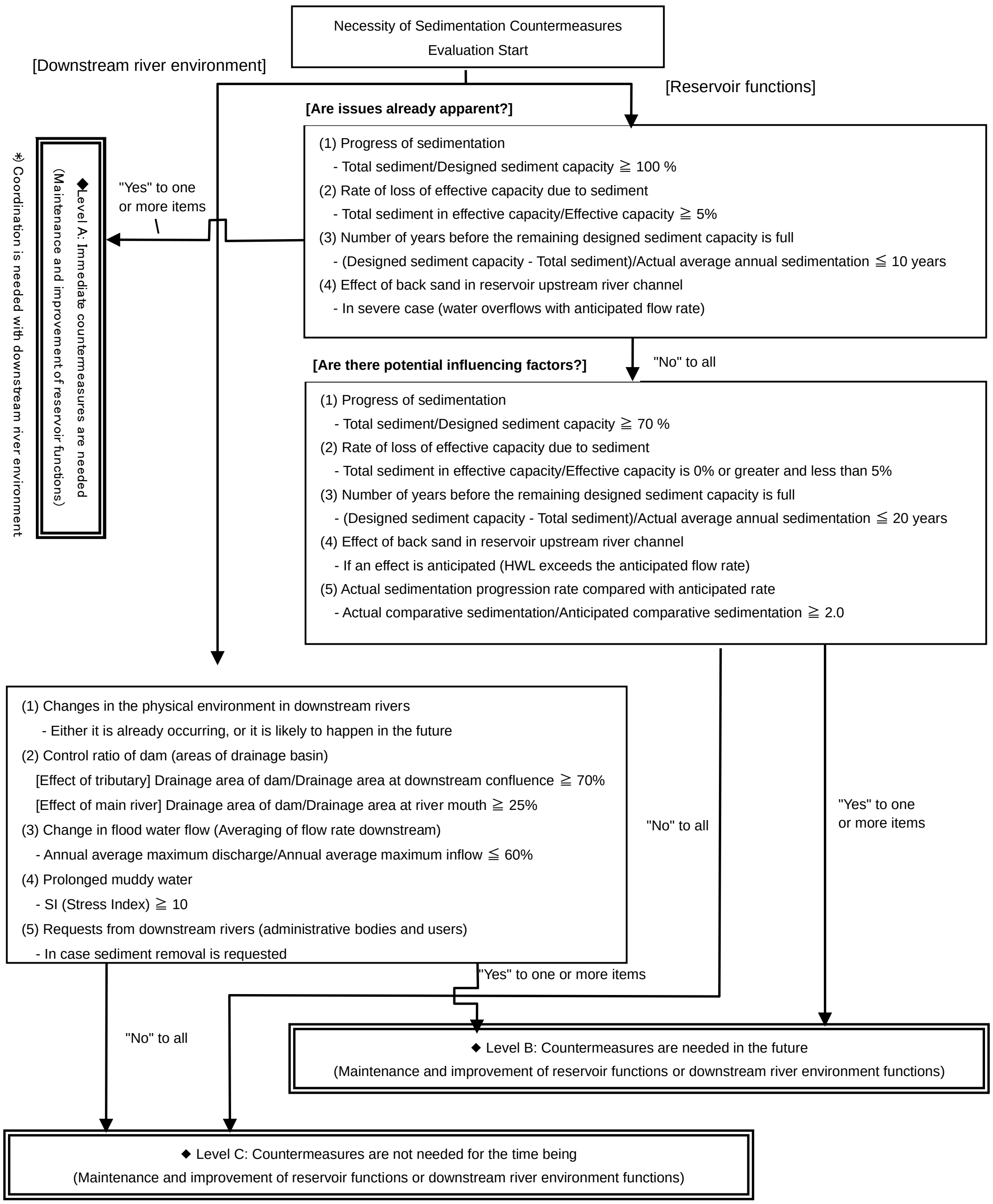
Fig. 7
Flowchart to determine appropriate sedimentation countermeasure

5.2 Evaluating the Necessity for Sedimentation Countermeasures

As shown in Fig. 8, we set several criteria, including reservoir functions and effects on the downstream environment, to evaluate the necessity for countermeasures. The necessity for sedimentation countermeasures is graded into three levels: Level A: Countermeasures are urgently needed, Level B: Countermeasures will be needed in the future, and Level C: No countermeasures are needed. Dams that currently have issues such as a severe sediment accumulation in their dam reservoir are categorized as Level A. Dams are assessed from the viewpoints of maintaining reservoir functions and environmental changes downstream. Factors include the potential effect of sediment such as the rate of sediment accumulation as well as requests for sediment removal from river management bodies and users. If any of the factors are applicable, then the dam is classified as Level B. If a dam does not have influencing factors, then it is classified as Level C.

When an effect upon reservoir functions is evaluated, the necessity for countermeasures is determined not only by the current state of reservoir capacity inhibition due to sediment, but also by the designed amount of sediment capacity as well as the forecasted vs. actual quantity of sediment accumulation because sediment accumulation may be an issue in the future.

On the other hand, the effects of sediment on the downstream environment are judged to have an impact if the dam is making a significant contribution. Such cases include foreseen changes in the physical environment, including lowering of river bed and the particle size becoming larger as less earth and sand are fed downstream, as well as cases where changes happen in terms of the percentage of water a dam carries in a particular river basin and flow changes due to a dam. The threshold is determined by a detailed analysis of the quantity and rate of sediment accumulation, the percentage of water a dam controls in a river basin, changes the flood water quantity, and other factors in dam reservoirs.



Note) "SI" means Stress Index, which indicates effects of muddy flow on organism, especially fishes, by muddy intensity and its duration.

Figures given in the above flowchart should be used to evaluate each item in principle. However, they should be adjusted according to the characteristics of each dam.

Figure 8

Flowchart to evaluate the necessity for sedimentation countermeasures (Step-1)

5.3 DRAFTING A SEDIMENT REMOVAL SCENARIO

Formulating a sediment removal scenario for a dam that requires countermeasures is a multistep process. First, the lifecycle of dams, their sediment removal facilities, and requisite functions (reservoir capacity to be maintained, earth and sand to be fed downstream, etc.) must be evaluated. Second, the objectives of the sedimentation countermeasures (such as maintenance, improvement, or both, of reservoir functions and downstream environment) must be clarified. Third, the goals of sediment removal, such as the quantity and location of sediment to be removed are set to meet these objectives. This step determines whether a temporary measure is sufficient or a permanent measure is needed by considering the economic impact, balance of the overall project, and priority in the project. Finally, to meet the sediment removal objectives and to formulate a sediment removal scenario, the quantity and frequency of removed sediment for each removal operation are considered. Figure 9 shows a flow chart for formulating a sediment removal scenario. It should be noted that a comprehensive earth and sand management program, which includes future rivers and seashores to be achieved by sediment removal, the dam reservoir capacity, and coordination with other dams, must be assessed in the sediment removal scenario.

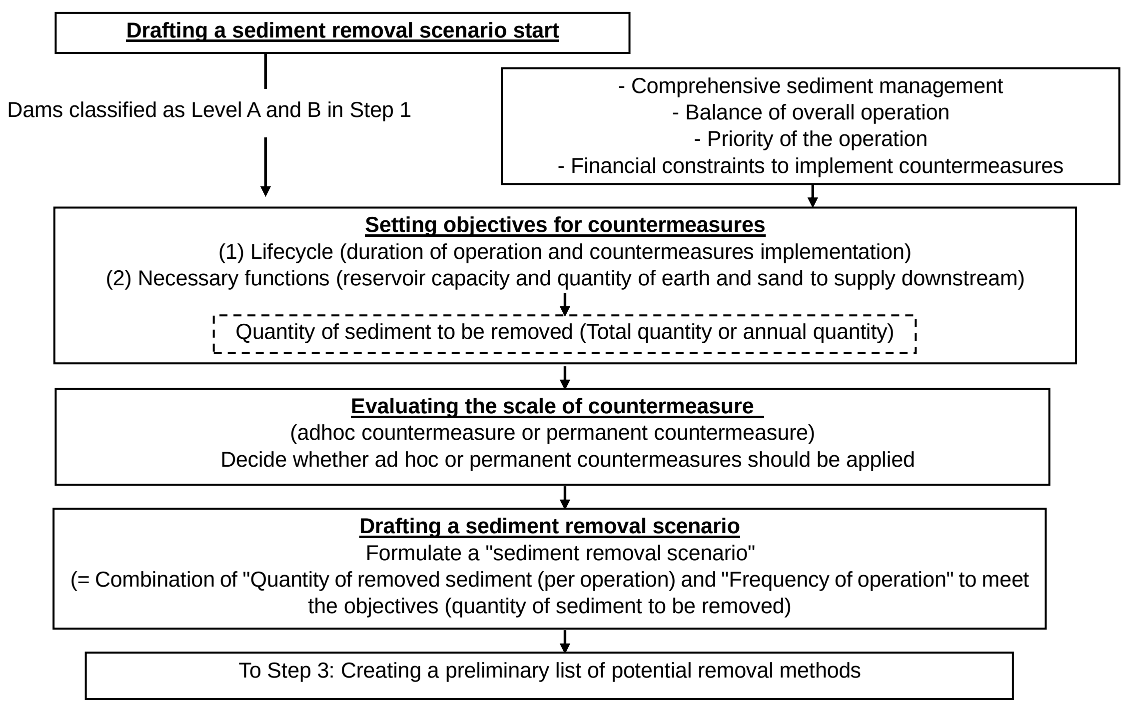


Figure 9
Drafting a sediment removal scenario (Step-2)

5.4 Creating a List of Potential Sediment Removal Methods

Preliminary sediment removal methods are determined in accordance with the flowchart in Fig. 10, which indicates the sedimentation countermeasures applicable to each dam. This chart is based on various conditions set by the sediment removal scenario using parameters regarding reservoir characteristics and reservoir sediment characteristics, which pertain to the applicability of each sedimentation countermeasure shown in Table 5. Changes in the reservoir water level and the gate height are often dominant parameters in flushing and sluicing sediment removal. On the other hand, the shape of reservoir is the main parameter in the sediment bypass method, while the gate height and particle sizes of target earth and sand are predominant in density current venting.

5.5 Selecting the Most Appropriate Sedimentation Countermeasure

The preliminary sediment removal methods are compared in terms of operational effectiveness and economic impact, sediment removal capacity, sustainability of social capital, availability of remedies against impact on society and the river environment, and other evaluation indices. The best countermeasure for a given dam is then selected. Table 6 shows an example of items to be considered in order to select the best sedimentation countermeasure. Evaluation items and criteria should be individually set by each dam.

＊1 CAP: Total capacity of reservoir
＊2 MAR: Mean annual rainfall
＊3 H_D : Depth of water down to where a sediment removal gate can lower (= Height of sediment removal gate)
H_{max}: Depth of water during surcharge water level
＊4 Classification of reservoir shapes
Type A: Reservoir is made on one river channel
Type B: Reservoir is made on two river channels
Type C: Reservoir is made on three or more river channels
＊5 Water pressure suction method need to maintain reservoir water level so that sediment removal efficiency is not degraded during floods
＊6 Countermeasure that can be applicable in combination with another one
(For example, Sediment bypass [main method] + Excavation and dredging [auxiliary method])

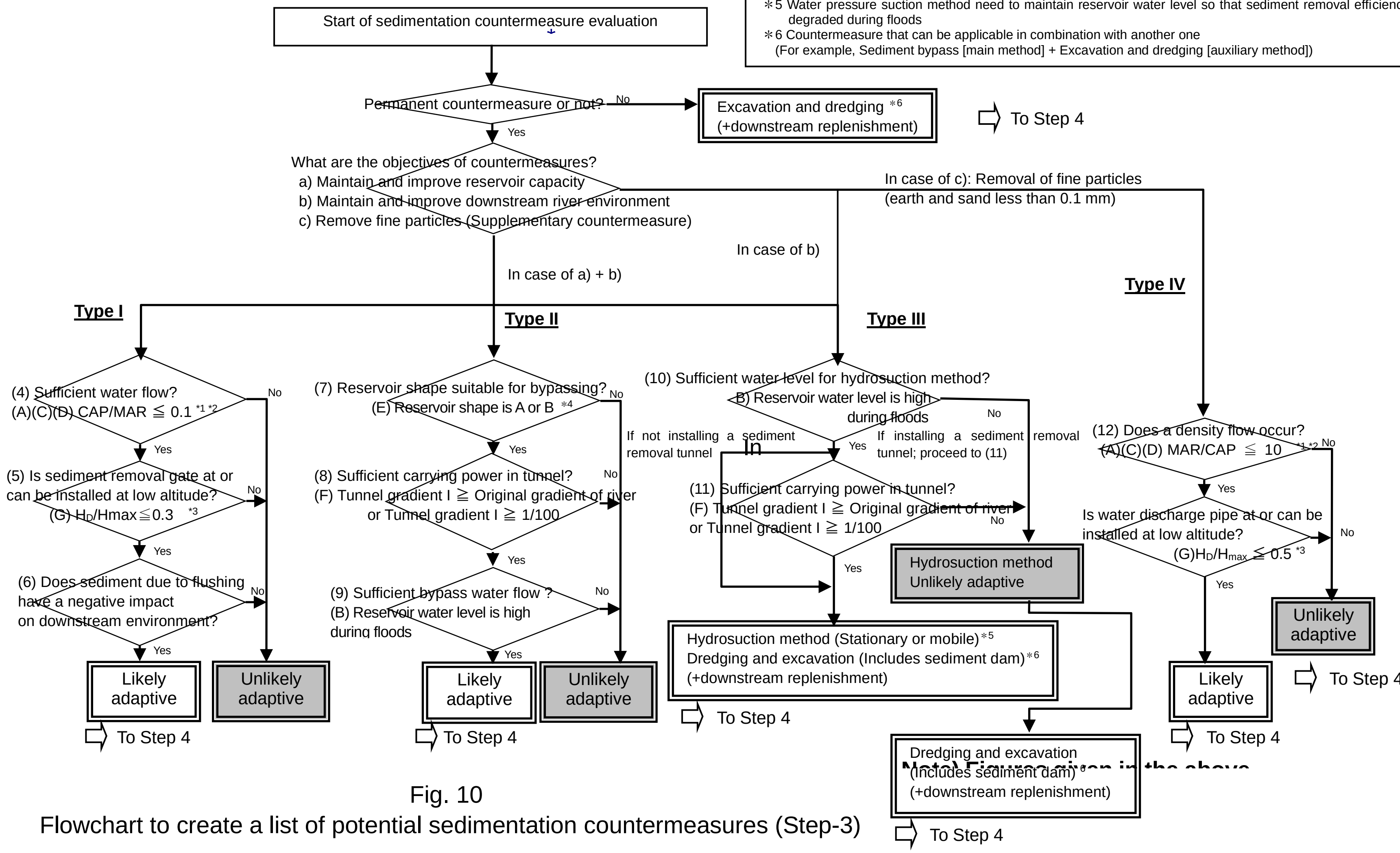


Fig. 10

Flowchart to create a list of potential sedimentation countermeasures (Step-3)

Note) Figures given in the above flowchart should be used in evaluating each item in principle. However, adjust items as needed.

Table 5
Reservoir characteristics to consider
when applying sedimentation countermeasures

Characteristics \ Type of sedimentation countermeasure, Sediment removal method			**Type I:** Intra-reservoir tractive force method	**Type II:** Bypass method	**Type III:** Mechanical method	**Type IV :** (auxiliary method) Fine particle method
			Flushing Sluicing	Sediment bypass	Excavation Dredging Hydrosuction	Density current venting
Water flow characteristics	Inflow water Quantity	A	○	—	△	○
	Changes in reservoir water level	B	(◎)	○	○	—
	CAP/MAR	C	○	—	—	○
Physical characteristics	Capacity of reservoir	D	○	—	—	○
	Shape of reservoir	E	—	◎	△	—
	Gradient of river bed (Gradient of tunnel)	F	△	○	○	—
	Gate height	G	◎	—	—	◎
Sediment characteristics	Inflow sediment quantity	H	△	△	△	—
	Particle size of sediment to be removed	I	△	△	△	◎
	CAP/MAS	J	—	△	—	—

[Legend]
○: Parameter may be a dominant factor in evaluating applicability of a sedimentation countermeasure,
(◎ indicates imperative condition)
△: Although not a predominant factor, parameter must be fully considered when evaluating a sedimentation countermeasure

Table 6

Considerations for determining the most appropriate sedimentation countermeasure (Step-4, example)

Evaluation criteria				TypeII		TypeIII	
				PlanA	PlanB	PlanA	PlanB
[Viewpoint 1] Operational effectiveness and economic impact	Economic impact		- Lifecycle cost				
	Effectiveness (Unit cost for sediment removal)		◎ : Y5,000 m^3or less ○ : Y7,000 m^3or less △ : Y7,000 m^3or more				
	Duration of operation		◎: 10 years or less ○: 15 years or less △: More than 15 years				
[Viewpoint 2] Sediment removal performance	Sediment removal performance		- Is expected sediment removal performance sustainable?				
	Range of removable particle size		◎: Can remove silt, clay, sand and gravel ○: Can remove silt, clay, and sand △: Can remove only silt and clay				
	Ease of sediment removal operation		◎ No foreseen difficulties △: Operation is difficult				
	Control over sediment quantity removed		◎: Can control sediment removal quantity △: Difficult to control sediment removal quantity				
	Certainty		◎: Many similar operations have been conducted ○: Some similar operations have been conducted △: Similar operations have yet to be conducted				
[Viewpoint 3] Sustainability of social resources	Maintenance	Ease of routine maintenance	◎: Routine inspections and maintenance are easy △: Routine inspections and maintenance are difficult				
		Frequency of facilities repair	◎: High frequency of facilities repair △: Low frequency of facilities repair				
		Ease of updating facilities	◎: Facilities can be updated while maintaining their functions △: Facilities cannot be updated while maintaining their functions				
	Crisis management		◎: Easy to resume operation after a disaster △: Difficult to resume operation after a disaster				
[Viewpoint 4] Social and river* environment impact	Quantity of earth and sand supplied downstream		◎: 30% or more of inflow earth and sand ○: 10% or more of inflow earth and sand △: Less than 10% of inflow earth and sand				
	Impact on downstream physical environment		◎: Elevation does not occur in downstream river bed △: Elevation occurs in downstream river bed				
	Impact on downstream biological environment		◎: Small impact on downstream biological environment △: Large impact on downstream biological environment				
	Impact on social environment	Impact due to sediment removal operation	◎: Small impact on downstream users △: Large impact on downstream users				
		Impact due to reservoir operation	◎: Small impact on downstream users △: Large impact on downstream users				
Overall evaluation							

6. CONCLUSIONS

This paper examines sedimentation countermeasures in Japan and proposes a method to systematically select the appropriate countermeasure. Initially reservoir sedimentation countermeasures in Japan are briefly overviewed. Our survey results on reservoir sedimentation countermeasures at 20 dams across Japan revealed that almost all are resorting to ad-hoc measures such as mechanical excavation and dredging using backhoes and grab dredgers. We also found special countermeasures such as the bagging method and intra-reservoir transportation. Then to achieve a sustainable sediment management program and to realize a more advanced sediment management in the future, we systematized the procedures to consider effective countermeasures against sedimentation. We reviewed the methods used to examine the necessity and applicability of countermeasures against reservoir sediment, which ranged from sediment accumulation processes to characteristics of such items as reservoirs, river channels, and floods. Then we made specific proposals using select indices to determine the necessity for a countermeasure. Furthermore, we discussed the importance of drafting an appropriate scenario to meet the sediment removal objectives by clarifying the objectives of countermeasures against sedimentation based on a quantitative evaluation of necessary functions using various constraints. Finally, we proposed specific indices with their thresholds in a preliminary determination of sediment removal methods.

The next step in evaluating the methodology for determining sedimentation countermeasures will be to apply the procedures herein to select dams that are likely to require sedimentation countermeasures as models. Based on the evaluation results, it may be necessary to refine the procedures to select and apply countermeasures in terms of applicable conditions, threshold, etc. Additionally, we need to further study issues of reservoir water allocation with respect to the inclined sediment as well as a large-scale earth and sand inflow to reservoirs.

This paper has been prepared based on our research results at the WEC (Water Resources Environment Technology Center) along with the newly reviewed committee discussion materials at the Comprehensive Dam Sedimentation Countermeasures Committee (Masanori Michiue, Chair, also serving as Chairperson of the Tottori Regional Cooperation & Research Center). We would like to take this opportunity to express our gratitude towards the committee members who have provided valuable advice and guidance.

REFERENCES

[1] Water Resources Environment Technology Center. Note of technologies for dam sediment countermeasures, 2008
[2] Hiroyuki IWAMOTO, Tadashi SUETSUGI, Hidekazu TAHARA, Takaharu NOMURA, Katsuhide SATO. Study on removal method of reservoir sedimentation and restrictions on implementation, 2009
[3] Takaharu NOMURA, Tadashi SUETSUGI. Study on application of sediment flushing method at dam reservoir from viewpoint of various characteristics of reservoir and so on, 2008
[4] Tetsuya SUMI. To realize one-thousand-year-old dam by sediment management, 2005

SUMMARY

Because Japan has steep topography and weak geology, numerous regions produce a lot of sediment. Thus, Japan's dams are likely to face sediment problems in the near future, although some dams have already taken action.

Our field survey, which includes 20 domestic dams suffering from sediment problems, indicates that almost all dams employ mechanical excavation/dredging methods using backhoes or grab dredgers as a tentative solution for sediment problems and that some sites even take distinct countermeasures such as the sand package method and in-reservoir sediment transportation in cooperation with mechanical excavation/dredging. The field survey also reveals that several dams are subjected to various restrictions in transportation and utilization of carried sand in implementing countermeasures.

Currently many Japan's dams evaluate the applicability of sediment control methods and determine countermeasures on a case-by-case basis without a systematic methodology for selecting countermeasures for reservoir sedimentation. On the other hand, some pioneering dams have been employing practical sediment control techniques such as flushing/sluicing and tunnel bypassing, and their experiences have encouraged the development of a systematic methodology for selecting sediment countermeasures.

Implementing the methodology proposed below could improve the sophistication of reservoir management and aid in realizing sustainable reservoir management: (1) Categorize the characteristics of and clarify the applicability of individual sediment countermeasures, (2) Evaluate the necessity for countermeasures, (3) Develop a scenario of sediment elimination based on the target and quantity of sediment control, (4) Screen applicable sediment control methods via the reservoir and sediment characteristics, and (5) Select the appropriate sediment control methods from comprehensive viewpoints of project effects, economy, continuity of sediment transportation, and environmental impact on downstream rivers.

Keywords: Reservoir sediment countermeasure, Reservoir sediment management, Field survey, Systematic methodology for selecting sediment countermeasures, Scenario of sediment elimination, Sediment control method, In-reservoir sediment transportation