14

Reservoir Sediment Flushing and Replenishment Below Dams: Insights from Japanese Case Studies

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14.1 Introduction

Dam construction disrupts the longitudinal continuity of the river system and interrupts the action of the belt conveyor of sediment transport (Kondolf 1997). Reservoirs can trap and permanently store virtually the entire sediment load delivered from the upstream basin (Petts 1979; Williams and Wolman 1984). Upstream of the dam, all bedload sediment and all or part of the suspended load are deposited in the stagnant water of the reservoir that results in reduction of reservoir capacity and its upstream reaches influenced by backwater. Current gross storage capacity in the world is 6000 km^3 with 45 000 large dams, and total storage loss and annual sedimentation rate are about 570 km^3 (12%) and 31 km^3/yr (0.52%/yr), respectively. If additional new development projects are not considered, total capacity will be decreased to less than half by 2100.

The rapid reservoir sedimentation not only decreases the storage capacity, but also increases the probability of flood inundation due to heightening of the bed elevations at the upstream end of the reservoir and the confluences of the tributaries (Liu *et al.* 2004b). Immediately downstream sediment load is greatly reduced. In addition, typical downstream changes in the flow regime include a reduction in the magnitude of peak flows and a possible increase in the magnitude of low flows (Williams and Wolman 1984). As a result, the downstream river may adjust in an attempt to re-establish an asymptotic equilibrium between the channel and the discharge with sediment load being transported. Possible adjustments include channel-bed erosion or deposition, channel widening or narrowing, and changes in channel pattern. Downstream impacts develop through discontinuity in downstream gradients, e.g., sediment supply, water quality, temperature, flow, and sediment regimes. Morphological effects on the river channel (e.g., Kondolf and Matthews 1993; Kantoush, Sumi, and Kubota 2010) include riverbed incision, riverbank instability, groundwater overdrafting, damage to bridges, embankments, and levees (e.g., Kondolf 1997; Batalla 2003), and changes in channel width. In order to solve these problems, an integrated approach is necessary for sediment management through flow and sediment regimes (Sumi and Kantoush 2010).

In many countries, various countermeasures have been implemented to decrease sediment accumulation and loss of storage capacity. These are: (i) reducing the sediment inflow by erosion control and upstream sediment trapping; (ii) routing sediments by sediment bypass facilities, off stream reservoirs,

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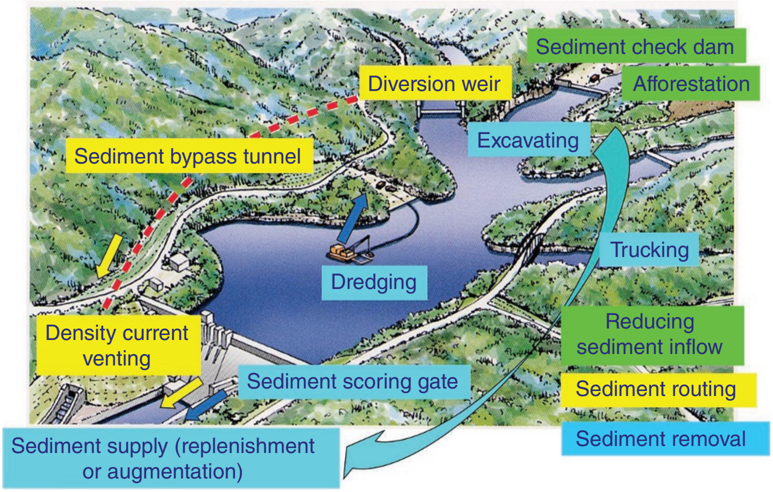

Figure 14.1 Reservoir sediment management measures in Japan.

sediment sluicing (drawdown routing), and venting of turbid density currents; and (iii) removing sediment by mechanical dry excavation, dredging, drawdown/pressure flushing and Hydrosuction Sediment Removal System (i.e., HSRS). Kantoush, Sumi, and Takemon (2011) reviewed several case studies in Japan and Kondolf *et al.* (2014) collected experiences from five continents. Current reservoir sediment management measures in Japan are illustrated in Figure 14.1. Among these methodologies, sediment bypass (Sumi *et al.* 2005) and drawdown flushing are considered to be permanent remedial measures for Japanese reservoirs. Feasibility conditions on drawdown flushing have been discussed by Atkinson (1996), White (2001), and Palmieri *et al.* (2003). Sumi (2008) reviewed sediment-flushing efficiency in the Kurobe River, Japan. In addition, sediment replenishment or augmentation after mechanical excavation has been intensively implemented in order to mitigate the adverse effects below dams by supplying mainly coarse sediments. Gaeuman (2014) reported coarse sediment augmentation on the Trinity River, and Bunte (2004) summarized gravel mitigation and augmentation below hydroelectric dams in salmon-bearing Pacific Coast gravel-bed rivers in the United States from a geomorphological perspective. Sakurai and Hakoishi (2013) have Japanese case studies and a numerical model to formulate the erosion and transport process of sediment replenishment.

In this chapter, current overviews of the mentioned measures regarding the reservoir sediment management as well as detailed planning and operational procedures associated with drawdown flushing and sediment replenishment are presented.

14.2 Present State of Reservoir Sedimentation in Japan

14.2.1 Reservoir Storage Loss

As of 2013, from 971 dams accounting for approximately one third of 3000 Japanese dams with height over 15 m, annual changes in sedimentation volume and the shape of accumulated sediment were reported (Sumi 2013). Probably, only Japan has established such a nationwide survey system, and has accumulated such amount of data as a considerably valuable record on a global basis.

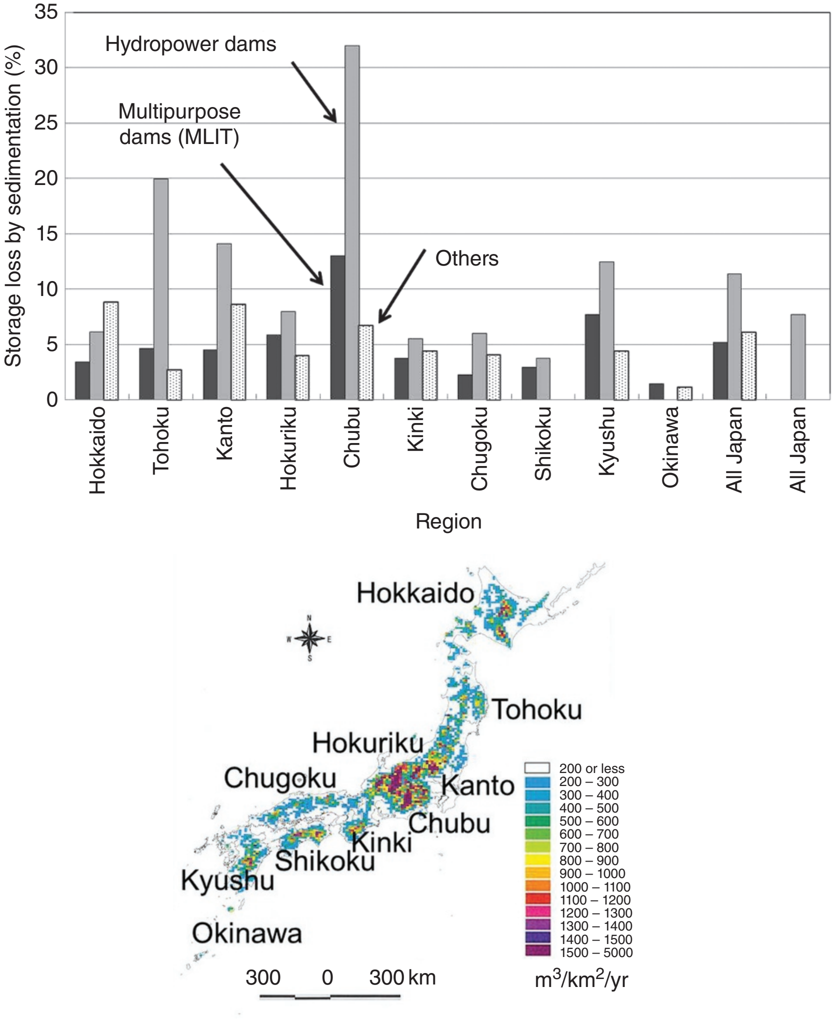

Figure 14.2 Reservoir storage loss by sedimentation and sediment yield potential map in Japan (After Sumi (2013) and Okano *et al.* (2004)).

Figure 14.2 shows reservoir storage losses by sedimentation depending on regions and categories based on purpose: three columns show multipurpose, hydropower, and other-purpose dams. Figure 14.2 also shows a "Sediment yield potential map of Japan" that has been extracted utilizing the GIS technique, which employs input data such as reservoir sedimentation records, existing geographical features, and geological data. (Okano *et al.* 2004). This map is currently used to check sedimentation planning for newly constructed dams and to estimate future sedimentation amount for existing dams.

14.2.2 Comprehensive Sediment Management in the Sediment Routing System

Nowadays, a new concept of sediment management is considered in Japan. River fluvial systems are composed of six segments: headwater, mountain, valley, alluvial fan, floodplain, and delta. The amount

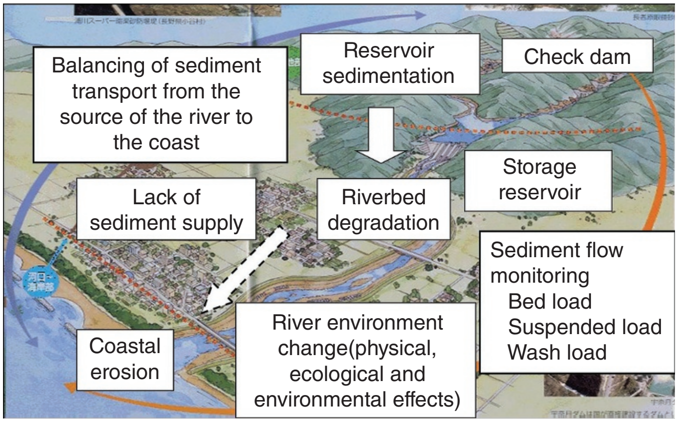

Figure 14.3 Comprehensive sediment management in the sediment routing system (Kantoush, Sumi, and Takemon 2011).

of sediment supplied from rivers to coasts was drastically reduced due to the construction of many check dams and storage reservoirs in mountainous areas and also because of the growth in gravel mining from riverbeds in Japan after World War II. As a result, various problems emerged such as riverbed degradation at downstream channel locations, fixing of river channels, erosion of coastal areas, and severe environmental changes along rivers and coastal areas. Environmental changes are largely dependent on armoring of the riverbed and lack of sediment transport (Williams and Wolman 1984). Such changes cause too much vegetation growth in the river channel and loss of suitable habitats for native aquatic species (Sumi and Kantoush 2010). Following a recommendation by the River Council of Japan in 1997, comprehensive sediment management has been proposed in order to recover sound sediment transport with regard to quantity and quality in the sediment routing system, as shown in Figure 14.3 (Japanese Ministry of Land, Infrastructure, Transport and Tourism 2005). The sediment routing system includes six segments and a coastal segment to which sediment has been transported there. For storage dams, sediment supply to the downstream river is strongly required in order to reduce the storage loss for reservoir sustainability and to mitigate adverse environmental impacts as much as possible for river restoration purposes.

14.3 Selecting Suitable Sediment Management Options

14.3.1 Classification of Sediment Management Measures

Sediment management in reservoirs is generally classified into the three approaches: (i) to reduce sediment inflow to reservoirs; (ii) to route sediment inflow to prevent accumulation in reservoirs; and (iii) to remove sediment accumulated in reservoirs. Sumi and Kantoush (2011) have classified selected examples in Japan and Europe according to these methodologies (Figure 14.4).

14.3.2 Promotion Strategy of Reservoir Sedimentation Management

In order to increase the number of good examples for reservoir sediment management, it is important to establish a guideline to select appropriate sediment management measures. ICOLD (2009) released

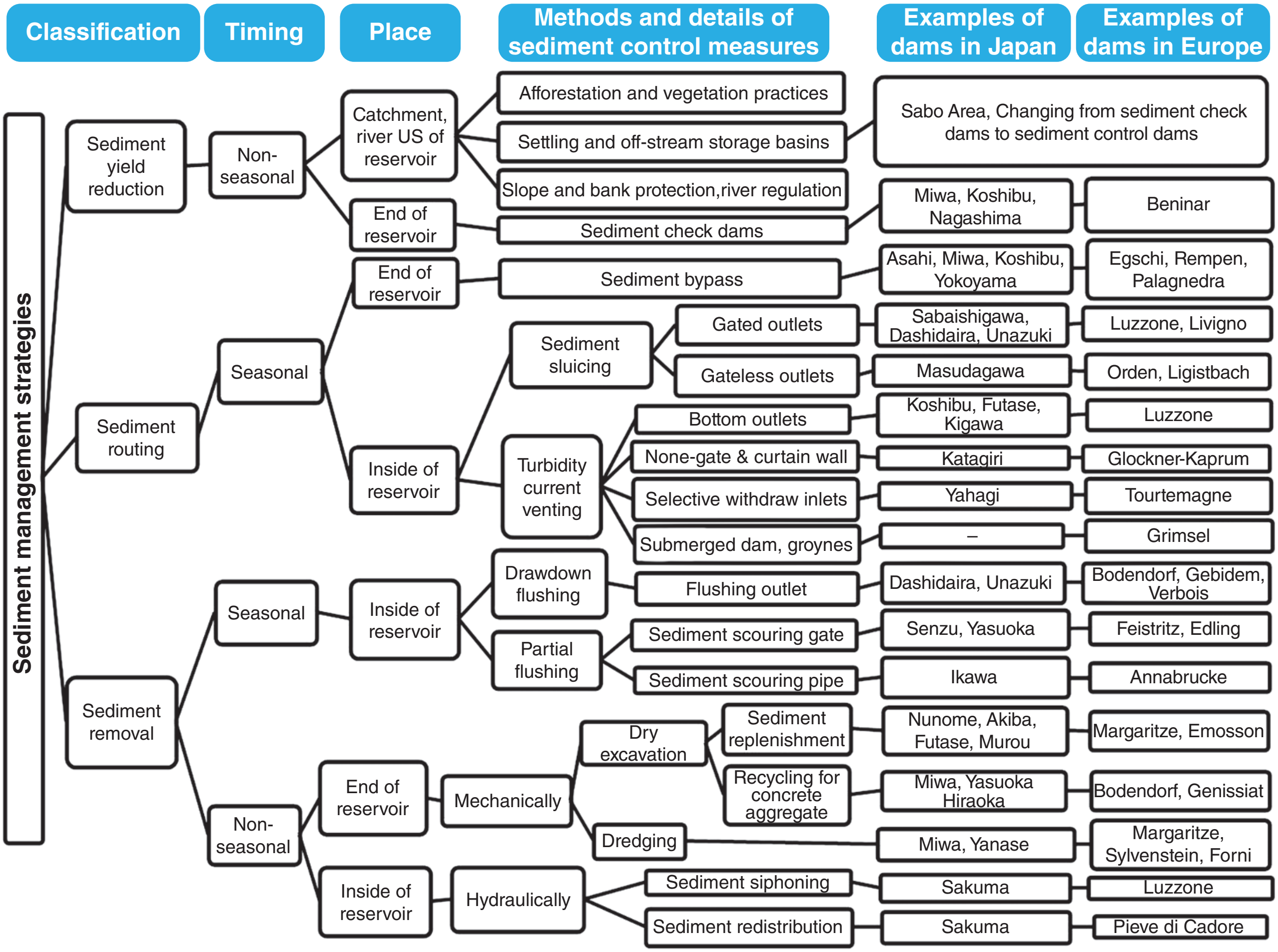

Figure 14.4 Classification of sediment control measures (Sumi and Kantoush 2011).

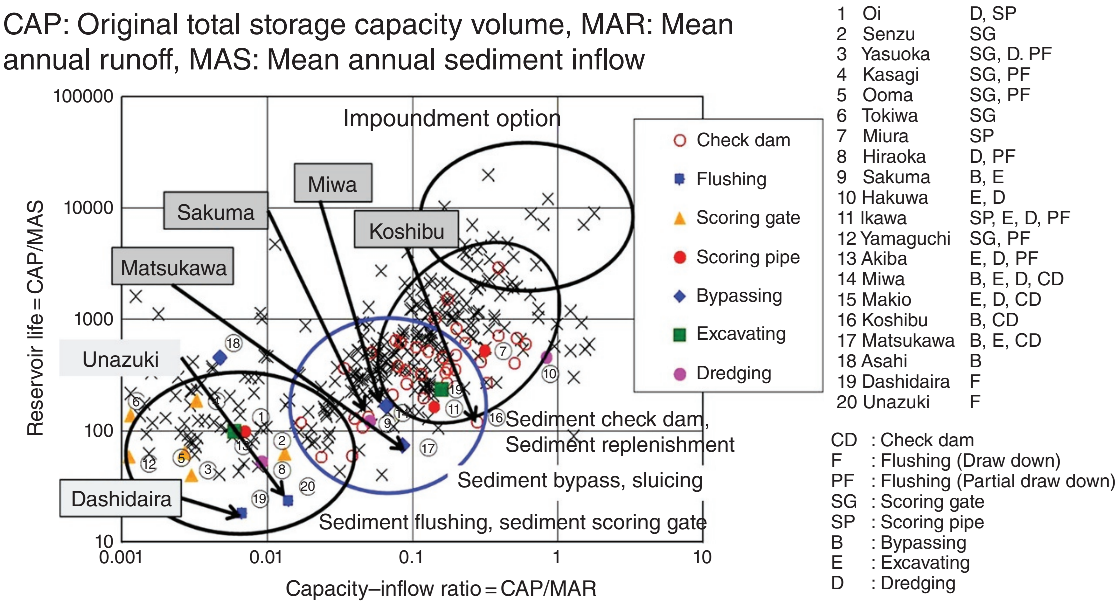

Figure 14.5 Representative sediment management measures in Japanese reservoirs (Sumi 2008).

Bulletin 147 entitled "Sedimentation and Sustainable Use of Reservoirs and River Systems." This bulletin discusses the upstream and downstream fluvial and morphological impacts of reservoir sedimentation and possible mitigation measures. In this bulletin, the current state and possible future sediment deposition in reservoirs have been investigated globally with the aid of the ICOLD Register on Dams. This bulletin also investigates the impacts of dams on the ecological features related to fluvial and morphological changes, and guidelines are proposed to try and mitigate the impacts on the downstream river morphology. Finally, the RESCON model (REServoir CONservation; Palmieri *et al.* 2003), which considers the life-cycle approach and reservoir conservation, is presented. This model, developed by the World Bank, is a prototype model to guide suitable options based on the conditions of the reservoirs. Sumi (2008) has analyzed Japanese dams based on the parameter of the turnover rate of water (CAP/MAR = total capacity/mean annual runoff) and sediment (CAP/MAS = total capacity/mean annual inflow sediment), as shown in Figure 14.5. It is thought that the selected sediment management measures can be classified by these two parameters. It is understood that selected measures actually change in the order of the sediment flushing, sediment bypass, sediment check dam, and excavating and dredging, as CAP/MAR increases (decrease in the turnover rate). This occurs owing to the considerable dependence of a selected sediment management measure on the amount of available water.

14.4 Sediment Flushing

14.4.1 Classification of Sediment Flushing

Among these approaches, flushing is considered as an economic approach to restore the storage capacity of reservoirs with severe deposition. "Sediment flushing" refers to an operation which

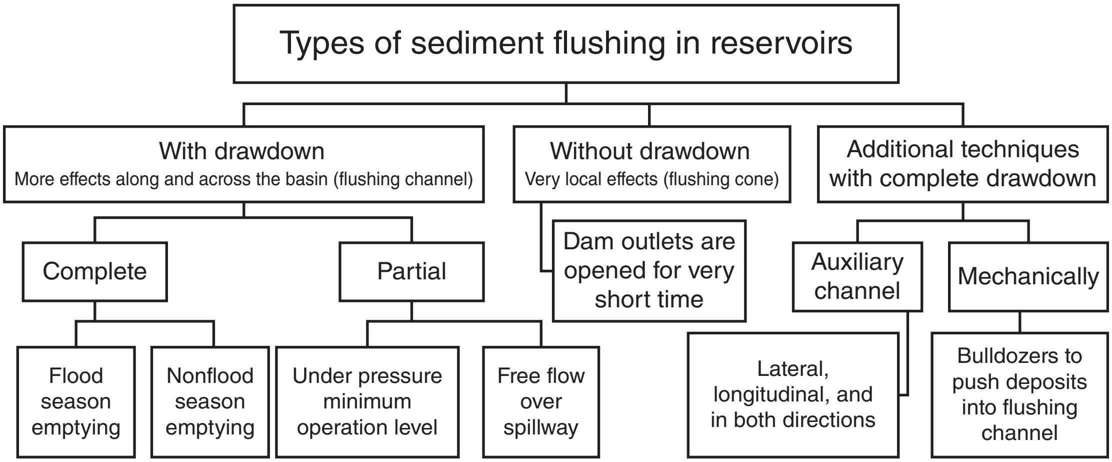

Figure 14.6 Classification of sediment flushing techniques (Kantoush *et al*. 2010a).

flushes sediment accumulated in the reservoir downstream through sediment flushing facilities using the tractive forces of the accelerated river flow. Basically, there are two types of flushing operations, with and without drawdown, and optional techniques can be also used with the complete drawdown flushing as shown in Figure 14.6 (Kantoush *et al*. 2010). Sediment flushing is performed at many dams all over the world, as shown in Table 14.1 (Sumi 2008). The necessary conditions for adopting sediment flushing in dam reservoirs are: 1-they are equipped with bottom outlets (sediment flushing outlets) through which the reservoir level is drawndown and flowing water can be discharged in an open channel during sediment flushing: 2-sufficient amount of water is secured for a series of operations of reservoir level drawdown, open channel discharge, and reservoir refill. Reservoir drawdown by opening the bottom outlet generates and accelerates unsteady flow towards the outlet (Morris and Fan 1998). This accelerated flow possesses an increased stream power, which consequently erodes a channel through the deposits and flushes the fine and coarse sediments through the outlet (Lai and Shen 1995, 1996; Shen 1999). During this process a progressive and a retrogressive erosion pattern can occur in the tail and delta reaches of the reservoir, respectively (Batuca and Jordaan 2000).

Sediment flushing is considered to be an extremely effective technique for discharging out sediment in terms of harnessing the tractive force in a natural river channel. However, when this technique is introduced, an extensive study is required in the planning stages, considering such conditions as inflow, sediment inflow, storage capacity, grain-size distribution, and reservoir operation. It should be also considered that information about flushing experience in the real scaled reservoirs with respect to flushing channel formation is scarce. One of the phenomena in reservoirs that is not well investigated and theoretically explained is the formation of flushing channels in the delta of the reservoir (Sloff, Jagers, and Kitamura 2004). These channels can be found in the deltaic deposition mainly in wide reservoirs. Another important aspect is to consider measures concerning environmental impacts under sediment flushing processes. In Japan, intensive studies on sediment flushing operations have been implemented in the Dashidaira and the Unazuki reservoirs in the Kurobe River.

Table 14.1 Global distribution of sediment-flushing in dam reservoirs.

Name of dam	Country	Year dam completed	Dam height (m)	Initial storage capacity (*CAP*) (million m^3)	Mean annual sediment inflow (*MAS*) (million m^3)[*]	1/(mean turnover ratio) (= *CAP*/*MAR*)	Reservoir life (= *CAP*/*MAS*)	Average flushing discharge (m^3/s)	Flushing duration (hours)	Flushing frequency (per year)
Dashidaira	Japan	1985	76.7	9.01	0.62	0.00674	14.5	200	12	1
Unazuki	Japan	2001	97	24.7	0.96	0.014	25.7	300	12	1
Gebidem	Switzerland	1968	113	9	0.5	0.021	18.0	15	70	1
Verbois	Switzerland	1943	32	15	0.33	0.00144	45.5	600	30	3
Barenburg	Switzerland	1960	64	1.7	0.02	0.000473	85.0	90	20	5
Innerferrera	Switzerland	1961	28	0.23	0.008	0.00018	28.8	80	12	5
Genissiat	France	1948	104	53	0.73	0.00467	72.6	600	36	3
Baira	India	1981	51	9.6	0.3	0.00489	32.0	90	40	1
Gmund	Austria	1945	37	0.93	0.07	0.00465	13.3	6	168	NA
Hengshan[†]	China	1966	65	13.3	1.18	0.842	11.3	2	672	2–3
Santo Domingo	Venezuela	1974	47	3	0.08	0.00667	37.5	5	72	NA
Jen-shan-pei[†]	Taiwan	1938	30	7	0.23	NA	30.4	12.2	1272	1
Guanting	China	1953	43	2270	60	1.5	37.8	80	120	NA
Guernsey	United States	1927	28.6	91	1.7	0.0433	53.5	125	120	NA
Heisonglin	China	1959	30	8.6	0.7	0.6	12.3	0.8	72	NA
Ichari	India	1975	36.8	11.6	5.7	0.00218	2.0	2.16	24	NA
Ouchi-Kurgan[†]	Former USSR	1961	35	56	13	0.00376	4.3	1000	2400	NA
Sanmenxia[†]	China	1960	45	9640	1600	0.224	6.0	2000	2900	NA
Sefid-Rud[†]	Iran	1962	82	1760	50	0.352	35.2	100	2900	NA
Shuicaozi	China	1958	28	9.6	0.63	0.0186	15.2	50	36	NA

[*] Average after dam completion.

[†] Sluicing dams.

14.4.2 Case Study in the Kurobe River, Japan

14.4.2.1 Outline of the Kurobe River and Planning of Coordinated Sediment Flushing

The Kurobe River in the eastern region of Toyama Prefecture is a representative steep river in Japan that stretches over 85 km in a 682 km^2 drainage basin (Figure 14.7). The Unazuki Dam (completed in 2001, height 97 m, gross capacity of reservoir 24 700 000 m^3), which is under the control of Ministry of Land, Infrastructure, Transport and Tourism, is located at the farthest point downstream of the Kurobe River. The Dashidaira Dam (completed in 1985, height 76.7 m, gross capacity of reservoir 9 010 000 m^3) owned by Kansai Electric Power Co. Ltd., is located upstream of the Unazuki Dam. These two dams have an extremely large amounts of sediment inflow compared to their gross storage capacity; therefore, they were the first cases in Japan that were built with full-scale sediment flushing facilities (sediment flushing gates). Sediment flushing has been conducted in the Dashidaira reservoir since 1991. Since 2001, when the Unazuki Dam was completed, *sediment flushing* and *sediment sluicing* have been conducted coordinately for the two dams (Figure 14.7). Here, *sediment flushing* refers to a drawing down operation just after the peak water flow in the first flood event of the year. *Sediment*

(a)

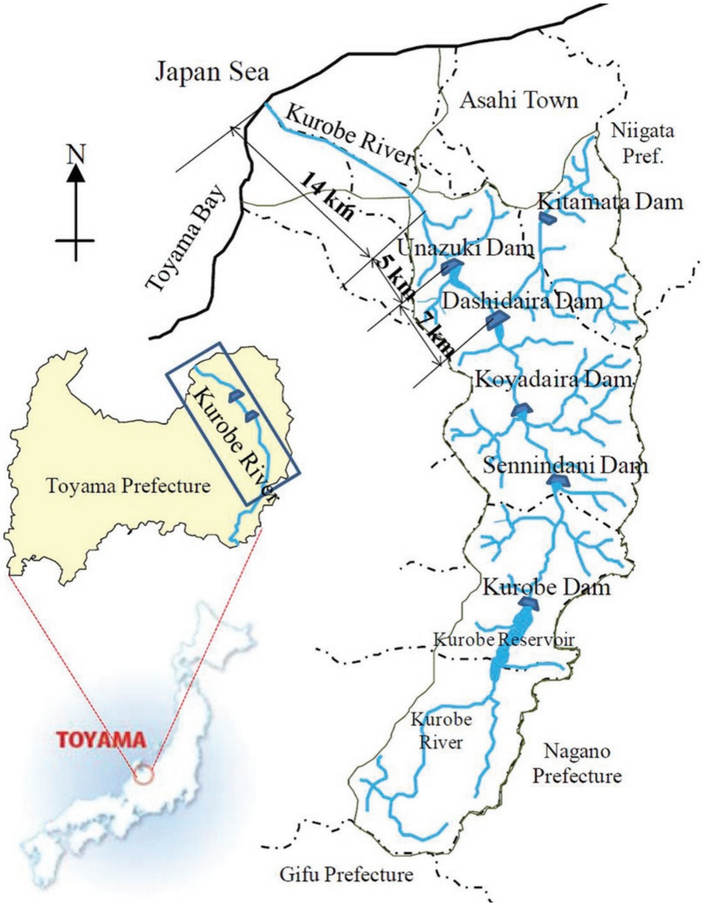

Figure 14.7 (a) Outline of the Kurobe river basin and (b) coordinated sediment flushing of Dashidaira and Unazuki dams. (After Kantoush *et al.* (2010) and Minami *et al.* (2012)).

(b)

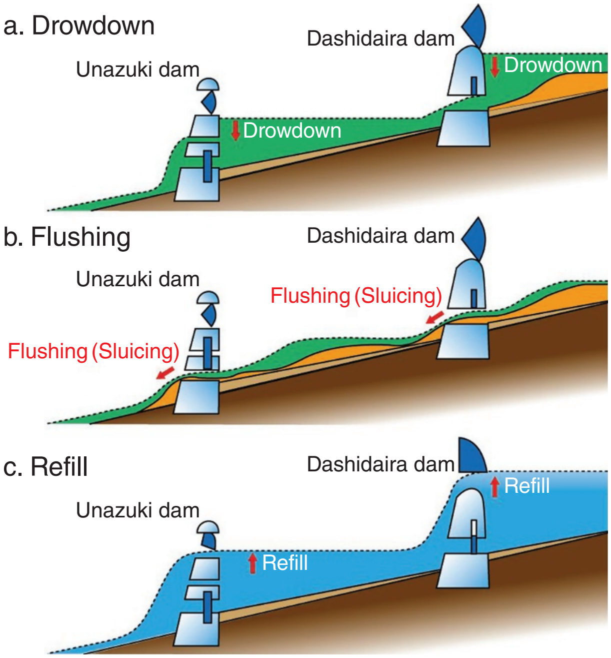

Figure 14.7 (*Continued*)

sluicing refers to an operation to sluice the additional sediment flowing into a reservoir after sediment flushing, using an operation similar to the sediment flushing.

Kokubo, Itakura, and Harada (1997), Liu *et al.* (2004a, b), Sumi and Kanazawa (2006), Sumi (2008), Sumi, Nakamura, and Hayashi (2009) and Minami *et al.* (2012) presented an overview of coordinated sediment flushing operations at the Dashidaira and the Unazuki Dams, which are typical sediment flushing sites in Japan. While it is important to maintain high sediment flushing efficiency in a sediment flushing operation, it is also necessary to minimize the environmental impacts of flushed out sediment in downstream areas. For this reason, the recent sediment flushing results from the Dashidaira Dam have been analyzed to evaluate the sediment flushing efficiency and the quality of flushed out water using discharged suspended sediment concentrations (i.e., SS).

14.4.2.2 Results of Coordinated Sediment Flushing

Since the completion of the Unazuki Dam in 2001, sediment flushing and sediment sluicing operations have been conducted almost annually (Figure 14.8). When a flood inflow discharge exceeds 300 m^3/s (250 m^3/s in some special cases) at the Dashidaira Dam for the first time of the year between June and July, a coordinated sediment flushing is performed. When a flood inflow discharge exceeds 480 m^3/s at the Dashidaira Dam after sediment flushing, a sediment sluicing is performed. These sediment flushing and sluicing practices have been conducting in coordination with the Kurobe River Sediment Flushing Evaluation Committee and the Kurobe River Sediment Management Council, monitoring the natural flow regime in the Kurobe River as well as the impacts of sediment discharge downstream.

Figure 14.8 Photographs of (a) Unazuki and (b) Dashidaira dams during coordinated sediment flushing operation (Sumi *et al*. 2009).

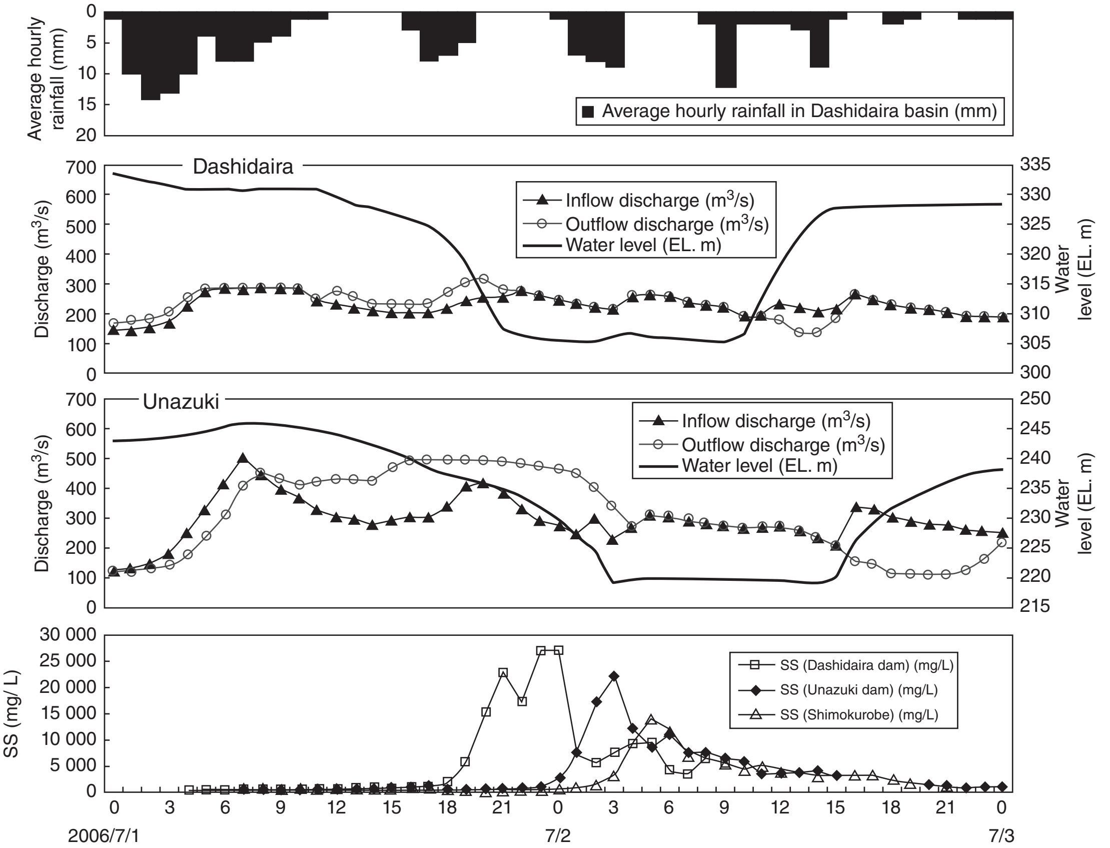

Figure 14.9 Recorded available data during the coordinated sediment flushing operation in 2006 (Sumi *et al*. 2009).

Sediment flushing operation includes the following procedures: drawing down the reservoir water level, keeping free-flow state for several hours, and recovering water level. The amount of time for the free-flow sediment flushing operation depends largely on the target amount of sediment to be flushed out, which is planned before the sediment flushing operation. Figure 14.9 exemplifies a sediment flushing operation performed in July 2006. A free-flow state was continued for 12 h to flush 240 000 m^3 of deposited sediment.

Table 14.2 shows the amount of sediment flushed out of Dashidaira Dam from 2001 to 2007. Sediment flushing is performed during the first big flood in the rainy season (i.e., between June and July) with a peak discharge about 500 m^3/s and sediment sluicing is conducted with a peak discharge about 700 m^3/s. The average drawdown period is 12 h for both operations. The flushing volume data was obtained by measuring the cumulative amount of sediment in the dam reservoir after the previous year's sediment flushing operation till end of May. This quantity fluctuates depending on flooding events outside the sediment-flushing season from autumn to spring.

The major outcomes of sediment flushing operations up to now are as follows.

1) At the Kurobe River, both sediment flushing and sluicing are performed approximately once a year without major environmental impacts (Sumi and Kanazawa 2006) by restricting sediment flushing operations to appropriate sediment-flushing seasons (June to August), and times when the natural

Table 14.2 Sediment flushing and sluicing operations at the Dashidaira Dam (Sumi, Nakamura, and Hayashi 2009).

Year and operation	Maximum discharge inflow (m^3/s)	Average discharge inflow (m^3/s)	Flushing volume (10^3 m^3)	Maximum SS (mg/L)	Average SS (mg/L)
2001 Flushing	333	277	590	90 000	15 000
2001 Sluicing	491	273		29 000	6700
2002 Flushing	362	215	60	22 000	4500
2003 Flushing	777	217	90	69 000	7100
2004 Flushing	356	229	280	42 000	10 000
2004 Sluicing	1152	281		16 000	7300
2005 Flushing	958	290	510	47 000	17 000
2005 Sluicing 1	835	275		90 000	16 000
2005 Sluicing 2	790	250		40 000	7300
2006 Flushing	308	246	240	27 000	6500
2006 Sluicing 1	378	203		12 000	2500
2006 Sluicing 2	685	264		27 000	5200
2006 Sluicing 3	529	196		7400	1800
2007 Flushing	418	245	120	25 000	3500
Average of flushing	502	246	270	46 000	9100
Average of sluicing	694	249		31 600	6700
Average of all data	598	247	270	38 800	7900

water flow rate exceeds a certain level, 300 m^3/s (250 m^3/s in some special cases) or more for sediment flushing, and 480 m^3/s or more for sediment sluicing.

2) The sediment-flushing efficiency at the Dashidaira Dam, which is calculated by using the quantity of flushed sediment and the quantity of water used during the free-flow phase, was about 0.01–0.03.
3) Discharged SS at the Dashidaira Dam during a sediment flushing operation was 8000 mg/L on average (40 000 mg/L at the peak), averaged over 14 sediment flushing operations. The average SS values are closely related to the quantity of flushed sediment as well as the quantity of water used during a flushing operation. Furthermore, peak SS depended on the rate of water level drawdown in the reservoir.
4) The Dashidaira Dam is currently at an equilibrium state in terms of its sediment, and the quantity of sediment passing through is approximately one million cubic meters annually. In contrast, sediment is still being accumulated at the Unazuki Dam since it is not in a conditions of equilibrium. While the majority of sediments of grain sizes larger than 2 mm are trapped in the reservoir, about 70% of the sediment, which is mostly of grain size smaller than 2 mm, is sluiced.
5) Active sand bars are observed in the river channels downstream, which are considered as a positive effect of sediment transport process during a coordinated sediment flushing operation in two successive dams. In particular, the supply of sandy materials has caused riverbed aggradation in some sections and has reversed armoring at all sections.

6) Sediment flushing operations ensure that the surface layer of accumulated sediment on the bottom of the reservoir is continually replaced with fresh sediments, decreasing the organic materials and the eutrophication indices.
7) In order to prevent accumulation of fine sediment on the sand bars in the downstream river channel after sediment flushing operations, a rinsing discharge from both dams is practiced. This is particularly effective to reduce the environmental impact after sediment flushing operations when a large volume of fine sediments has been discharged.
8) Evacuation channels have been prepared as shelters for many species of fish, such as Ayu (*Plecoglossus altivelis*), during the high turbidity in the main river due to a sediment flushing operation. They are showing a high performance by securing clear water sources to these channels during the flushing operation.

14.4.3 Improvement of Sediment Flushing

14.4.3.1 Relevant Key Factors for Sediment Flushing

In order to improve the sediment flushing operation, the following three relevant key factors should be studied.

1) Flushing efficiency: scoured sediment volume/water used.
2) Flushing effect: scoured sediment volume/total deposited sediment volume before flushing.
3) Environmental impacts: dissolved oxygen (DO) decreases rapidly with increase in SS concentration and fine sediment deposition on the downstream riverbed

14.4.3.2 Flushing Efficiency

There is a high interest to measure the efficiency of sediment flushing operations. There is a limited number of dams, shown in Table 14.1, surveyed in detail for collecting the sediment flushing data. Sumi (2008) evaluated efficiency of reservoir sediment flushing in the Kurobe River and compared the results with other dams in the world, such as the Gebidem and the Verbois dams in Switzerland, and the Baira dam in India, where the flushing data were recorded. In this case, the water consumption for sediment flushing has been calculated only during the full drawdown period, although discharge of fine sediment may start during the reservoir drawdown period.

Figure 14.10 shows sediment flushing efficiency ($F_e = S/W$) calculated by flushed out sediment volume (S) and the water consumption volume (W). Among these, the sediment flushing efficiency in the Gebidem dam is comparatively high since sediment flushing is performed with a low flow discharge for a long time. Moreover, in the Baira dam, flushing efficiency is also comparatively high although there is some variation. On the other hand, since the Verbois dam is located at the mainstream of the Rhone River and the sediment flushing is executed with a large amount of water from Lac Leman, the sediment flushing efficiency is not high. In the Dashidaira dam, the sediment flushing efficiency is also not so high similar to the Verbois dam.

In these four dams, sediment flushing is strictly managed in the Dashidaira and the Verbois dams through preventing any remarkable water quality change to the downstream river by maintaining a sufficient amount of water relative to sediment. Considering the downstream river environment implies the application of sufficient volume of water that suppresses the flushing efficiency. In the Kurobe River, the sediment flushing is executed by securing enough river discharge just after the natural floods. Also, the additional discharge has been recently introduced to wash out the fine sediment silted in the downstream river channel after sediment flushing operations; thus sediment flushing is using a larger volume of water.

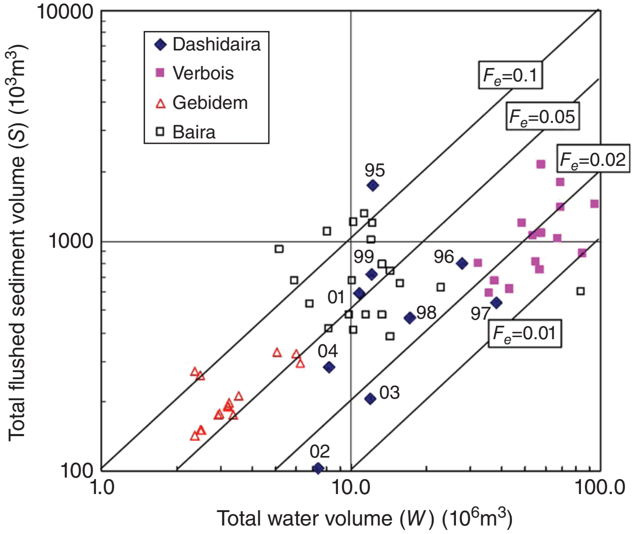

Figure 14.10 Total used water volume and flushed out sediment volume in sediment flushing (Sumi 2008).

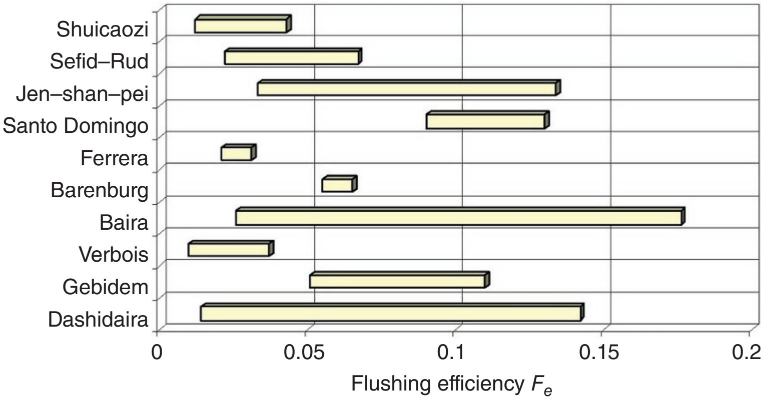

Figure 14.11 Variation range of sediment flushing efficiency in dams with sediment flushing operation (Sumi 2008).

The sediment flushing efficiency F_e of other dams is shown in Figure 14.11. The variation range of flushing efficiency is between 0.01 and 0.15 for most of the cases. There are also some cases with the flushing efficiency less than 0.05, which relates to flushing operations with less harmful environmental impacts. According to research on the feasibility evaluation of the sediment flushing, a feasible range of the sediment flushing can be obtained by the following equation using the parameter shown in Figure 14.5 (Sumi 2008). Here, the sediment flushing efficiency and the proportion of water consumption by the sediment flushing to the mean annual runoff (*MAR*) volume are shown by F_e and β, respectively. Here, *CAP* and *MAS* are the total capacity and the mean annual inflow sediment, respectively

$$\frac{CAP}{MAS} > \frac{\frac{CAP}{MAR}}{F_e\left(\beta - \frac{CAP}{MAR}\right)} \tag{14.1}$$

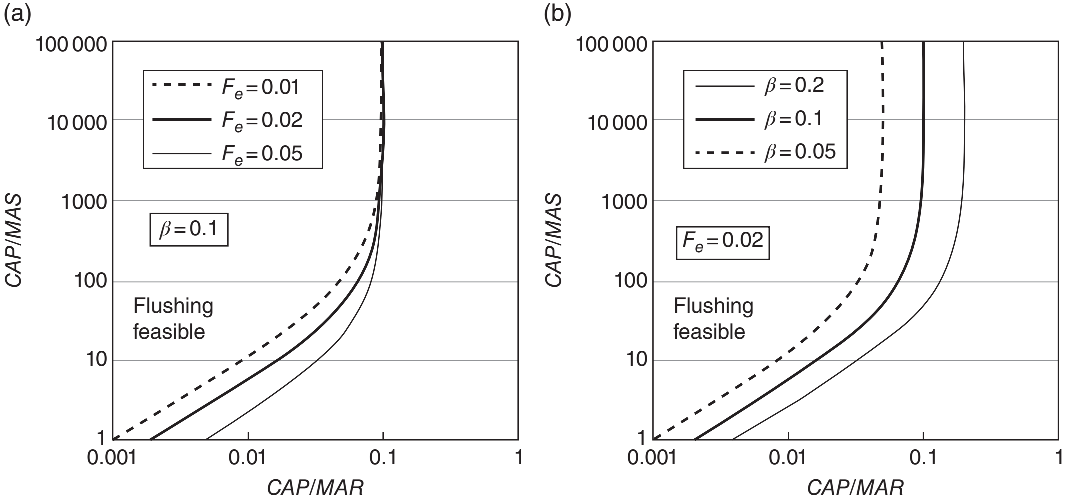

Figure 14.12 Extracted diagrams using equation 14.1 when (a) the proportion of water consumption to the mean annual runoff volume β is fixed; (b) sediment flushing efficiency F_e is fixed.

In Figure 14.12(a) and (b), a feasible range of the sediment flushing in the case that F_e changes to 0.01, 0.02, and 0.05 under fixed $\beta = 0.1$, and also in the case that β changes to 0.05, 0.1, and 0.2 under fixed $F_e = 0.2$ are shown, respectively. Feasible ranges are shown on the left-hand side of each line. According to which, change in F_e mainly influences within a small range of *CAP*/*MAS* and even a small turnover rate of the reservoir, e.g. large *CAP*/*MAR* introduces a possible rise of F_e under constant β. If river environmental conservation is considered, the possible range of the sediment flushing becomes narrower because it should estimate a low F_e. However, if β can be increased, the possibility of sediment flushing will increase under the same F_e since the water volume ratio that can be used for sediment flushing increases.

14.4.3.3 Flushing Channel Formation in the Deposited Reservoir Sediment

Kantoush and Schleiss (2009) conducted an experimental study on channel formation during the flushing of shallow reservoirs with different geometries. The flushing efficiency changes widely by various factors such as reservoir configuration, elevation of sediment flushing gates, volume and grain size of deposited sediment, discharge rate during a sediment flushing, and duration from the start of drawdown flushing. During the flushing processes two types of erosion patterns can occur; a progressive erosion in the tail reach of the reservoir, and a retrogressive erosion in the delta reach of the reservoirs. In order to predict the flushing channel width and location, it is important to understand the erosion process of sediment inside reservoirs.

Figure 14.13 shows erosion processes of deposited sediment in the Dashidaira reservoir in 2004. Longitudinal and lateral erosion were formed by riverbed degradation and side-bank erosion. A meandering flushing channel in the accumulated sediment was also formed. Not all the sediment is flushed out during the free flow duration. However, the sediment on both banks gradually falls by stream bank erosion. During very high discharges in 2004 the channel was able to break through the sand bar with bend cut-off and forming a wide channel section. Nevertheless, these cut-off events can occur only when water level at the dam in not completely drawn down. Simultaneously, the flow

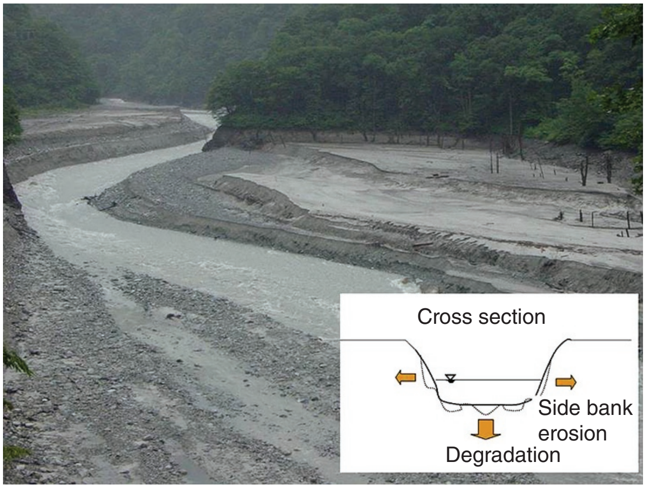

Figure 14.13 Flushing channel formed in the Dashidaira reservoir. This photograph was taken when the water level had completely drawn down (Kantoush *et al.* 2010).

becomes concentrated in the existing deep channel. The flushing operation has a significant contribution to maintain the storage capacity, which extends reservoir lifetime.

The key parameters of the flushing channel when the reservoir is fully drawn down are location, width, side and longitudinal slopes, as well as shape. Some of them have been investigated experimentally in shallow reservoir geometries with different shapes (Kantoush and Schleiss 2009). The width of the flushing channel W_f is estimated as proposed by the RESCON model (Palmieri *et al.* 2003) and Atkinson (1996). To predict W_f, Atkinson (1996) suggests the empirical relationship ($W_f = KQ_f^{0.5}$) based on prototype measurements in four reservoirs of China, United States and India. In this equation, W_f is the flushing-channel width, K is a coefficient dependent on bed material type (in this case K is 12.8) and Q_f is the discharge that will contribute to flushing channel formation.

Figure 14.14 shows the relationship and a comparison of observed flushing-channel widths in the Dashidaira reservoir with four other reservoirs. The measured flushing-channel width in the Dashidaira reservoir was about 170 m at a distance of 640 m from the dam under a discharge of 250 m^3/s. Therefore, Kantoush *et al.* (2010a) suggested that value of K should be reduced to half for Japanese reservoirs (i.e., 6.4 for K).

14.4.3.4 Modelling of Sediment Flushing

There are studies on sediment flushing simulation using one-, and two-dimensional models. One-dimensional numerical modeling usually uses some assumptions and simplifications that could not represent the real nature of the complex interacting flow–sediment field during the flushing process. More advanced two-dimensional numerical models were used by Olsen (1999) and Badura, Knoblauch, and Schneider (2008) for simulating the flushing in both a physical model and prototype scale studies. Two-dimensional depth-averaged numerical models can not directly simulate a complex three-dimensional flow field, including secondary flows in channel bends, although they have made a strong contribution in natural sediment transportation processes.

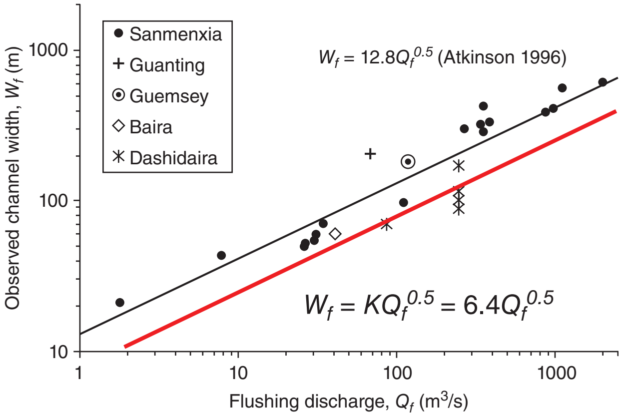

Figure 14.14 Comparison of Dashidaira dam's flushing-channel width with Atkinson's (1996) relationship (Kantoush *et al.* 2010).

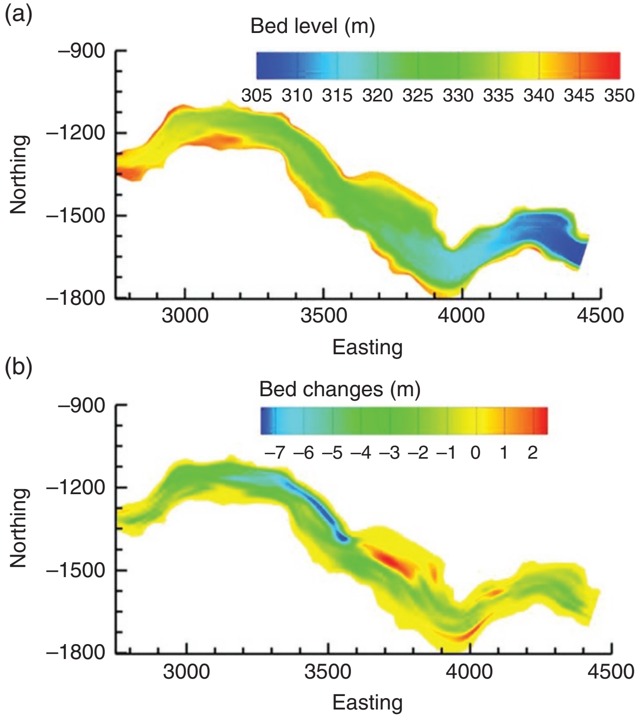

Figure 14.15 (a) Measured bed topography of Dashidaira reservoir after the flushing operation in June 2012; (b) corresponding measured bed changes after the flushing operation (Esmaeili *et al.* 2015).

Three-dimensional numerical models are still under development for application in this field. Khosronejad *et al.* (2008) and Haun and Olsen (2012a,b) used three-dimensional models for simulating the flushing process in the physical model and prototype scale, respectively. The complexity of three-dimensional flow patterns is better highlighted over the existing bedforms, on the deformed bed, during the free-flow state (Haun and Olsen 2012a; Esmaeili *et al.* 2014). Thus, application of three-dimensional numerical models is essential when the velocity variation over the flow depth plays a major role (e.g. in channel bends). Recently, application of three-dimensional numerical models became feasible for simulating the sediment transport process owing to the increase in calculation power of computers. Examples are the sediment transport simulation in Three Gorges project (Fang and Rodi 2003), simulation of the flushing process in rectangular reservoirs (Esmaeili, Sumi, and Kantoush 2014), Bodendorf reservoir (Haun *et al.* 2012), Angostura reservoir (Haun and Olsen 2012b; Haun *et al.* 2013), and also in an Alpine reservoir (Harb *et al.* 2014).

In order to develop structural or nonstructural methodologies to increase the flushing effect by controlling flushing channel formation, Esmaeili *et al.* (2015) studied sediment flushing processes in the Dashidaira reservoir during 2012. In the study, a computational fluid dynamic (CFD) code, SSIIM 2, developed by Olsen (2014) was used to perform the numerical simulations. The measured bed levels before and after the flushing operation were used to set up and validate the calculated morphological bed changes. Figure 14.15 demonstrates the measured bed levels after the flushing operation, together with the bed changes that were extracted by comparing the measured

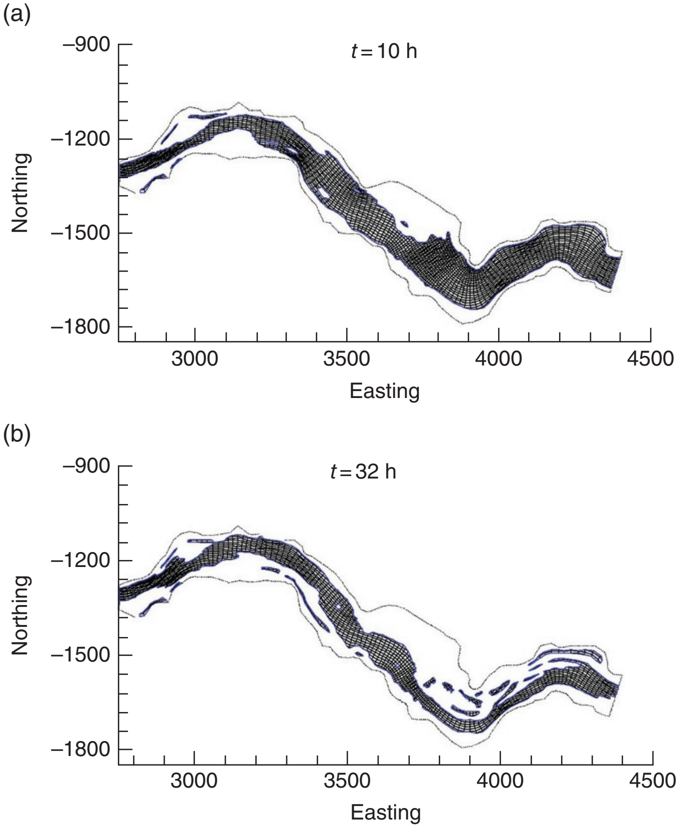

Figure 14.16 Computational grid at (a) the beginning of preliminary drawdown stage ($t = 10$ h) and (b) during the free-flow condition ($t = 32$ h) (Esmaeili *et al.* 2015).

bed levels before and after flushing. As can be seen, there is a significant bed erosion along the left embankment of lower area in the upstream half of the reservoir. Similar to the observations in the prototype, a distinctive flushing channel appeared in the numerical simulations during the free-flow condition. Figure 14.16 shows the computational grid adjustment at the beginning of preliminary drawdown stage, and also within the free-flow condition with a low water head in the reservoir. Cells with a lower water head than a specified value are removed from the computational domain due to the employed wetting/drying algorithm. Outputs reveal that flow deflects to the right-hand side in the middle part of the reservoir during the free-flow condition and, therefore, the flushing channel location is close to the right bank. Using this model, the effect of additional artificial discharge that can be supplied from upstream reservoirs during the free flow state was tested. It showed considerable effects on the bed changes and flushed-out sediment volume by increasing the flushing efficiency.

14.4.4 Environmental Impacts

Historically, adverse effects of the fine sediment on aquatic ecosystems have been largely reviewed (e.g. Newcombe and MacDonald 1991; Newcombe and Jensen 1996; Bilotta and Brazier 2008). Particularly, environmental impacts of sediment flushing have been studied in terms of water quality, benthic communities, fish mortality, and the modification of riverbed substrate (e.g., Gray and Ward 1982; Rambaud *et al.* 1988; Garric, Migeon, and Vindimian 1990; Wohl and Cenderelli 2000; Crosa *et al.* 2010). Adverse environmental impacts by sediment flushing can be summarized as rapid DO decrease with the increase in SS concentration during the free-flow discharge. Fine sediment deposition on the downstream riverbed has been recognized as one of the major environmental impacts.

The fine sediment can jam fish gills, thus greatly degrade their capability to absorb oxygen from water. Effects of the sediment flow on fish generally depend on comprehensive factors such as SS, DO, sediment particle grading, exposure duration, and fish category. Garric, Migeon, and Vindimian (1990) reported lethal effects of water quality degradation on brown trout caused by dam sediment flushing. Gerster and Rey (1994) proposed some implementing guidelines based on experiences of sediment flushing in Switzerland and France, and Staub (2000) pointed out that hypoxia would immediately become a critical factor for living fish when DO was below 2 mg/L or the SS exceeded 30 000 mg/L. Merle (2000) concluded that hypoxia (DO < 2 mg/L) showed more significant effects than high SS (> 30 000 mg/L) on the ecosystem. Crosa *et al.* (2010) proposed that the highest SS level should be controlled below 10 000 mg/L during sediment flushing periods in order to prevent significant negative impacts on the ecosystem of an alpine stream.

Bouchard (2000) proposed a one-dimensional sediment transport model (COURLIS) to predict the impact of SS during a reservoir emptying and flushing considering erosion of deposited cohesive sediment in reservoirs. Valette and Jodeau (2012) illustrated case studies of emptying and flushing of reservoirs using this model. Sumi and Kanazawa (2006) assessed environmental influences of the SS based on observations during sediment flushing periods in the Kurobe River, Japan with the stress index method (Newcombe and MacDonald 1991; Newcombe and Jensen 1996). In order to minimize environmental impacts, Sumi, Nakamura, and Hayashi (2009) discussed possible mitigation measures that provide evacuation channels for fish during the sediment flushing operation near downstream riverbanks, and also proposed rinsing discharge with clear water to minimize the long-term effect of fine sediment deposition on the riverbed after sediment flushing.

14.5 Sediment Replenishment

14.5.1 Definition and Objectives

Sediment replenishment basically consists of dredging or excavating the sediments accumulated in reservoirs, transporting them to the reaches just below the dam, and distributing the sediments along downstream channels by the following natural or artificial peak flows. The sediment sorting process occurs within a reservoir according to particle size. Coarse particles mainly deposit in the upstream area and finer particles can reach the hydraulic structure (Okano 2004; Knoblauch 2006). This size distribution process within a reservoir can be applicable to prepare selectively for downstream replenishment, optimal material, because coarser sediments (gravel and sand) are more beneficial for river systems than silt, which makes substratum clogging and causes high turbidity (Hartmann 2009). Check-dams, built upstream of main dams, can trap coarser sediments before entering a reservoir and facilitate their removal by land-based excavation. Thus, it does not require any water-level modification in the larger reservoir (Okano 2004). Currently, Japan is a leading country in the field of sediment replenishment application, with nearly 25% of dams resorting to sediment excavation for downstream replenishment.

Bunte (2004) reviewed gravel augmentation projects which have been conducted below hydroelectric dams in salmon-bearing Pacific Coast gravel-bed rivers in the United States from a geomorphological perspective. Because in the region, salmon habitats became severely degraded since large dams were constructed, resulting in the dramatic decline of salmon populations over the past several decades. In order to mitigate the poor quantity and quality of spawning habitat, spawning-sized gravels are artificially added to channels downstream of dams.

Gravel augmentation for enhancing spawning riffles has been undertaken downstream from at least 18 dams in California (Kondolf and Matthews, 1993; Bunte, 2004; Kondolf *et al.*, 2014). Among them, the Trinity River in Northern California is the focus of one of the most comprehensive programs to restore salmonid habitat by a combination of ecological flow and coarse sediment augmentation which began in 1976 and continues to date. By virtue of the combination approaches, the Trinity River Restoration Program (TRRP) has been at the forefront of efforts to restore bedload supply and transport in the regulated reaches below dams in the United States (Gaeuman 2012), developing systematic sediment management techniques and accumulating empirical data that cover various aspects of physical and ecological researches.

Ock, Sumi, and Takemon (2013) compiled sediment replenishment activities comparing cases of Japan and the United States. Though they share a similar concept, the implementation techniques have been developed based on both site-specific requirements and restrictions, for instances, mainly for reservoir sedimentation management or more for focusing on downstream river restoration. Compared with other sediment management strategies in reservoirs such as sediment flushing, bypassing, and sluicing options, sediment volume for downstream replenishment is very limited and insufficient to make up for the sediment deficit in rivers caused by dams. This is because of many restrictions in trapping volume in the upstream of reservoirs, trucking capacity, acceptable dumping sites, and transport capacity in the downstream river channel. Nevertheless, this approach has been widely applied in Japanese and US rivers because of immediate benefits, particularly to restore the downstream habitat primarily with regards to improved fish spawning habitat (Wheaton, Pasternack, and Merz 2004).

14.5.2 Implementation of Sediment Replenishment

Regarding implementation techniques of sediment replenishment, a number of restoration projects described the difficulty of implementation activity (Harvey *et al.* 2005). Several implementation techniques have evolved in response to available spaces, release flow regimes, costs and accessibility as well as primary objectives.

However, these applications still require a systematic development in the stages of planning and implementation, both of which are in concert with specific objectives and local hydrophysical restrictions in the basin, reservoir, and river. In particular, incorporating with flushing flows (magnitude, frequency, and timing), determining quantity (amount added) and quality (grain size and source materials) of coarse sediment, and selecting an effective implementation technique for adding and transporting sediment in the field are key factors in achieving a successful result in ecological river management and restoration.

14.5.2.1 Scale of Sediment Replenishment

Bunte (2004) classified the sediment augmentation approach into three spatial scales: local, multireach, and river-segment wide. Based on these scales, target sediment volume and expected effects will differ considerably:

- direct creation of spawning habitat by one-time gravel additions in stream areas with low erosion potential;
- passive gravel augmentation at a logistically convenient location to create spawning habitat where the added gravel deposits naturally;
- intensive multireach stream restoration (covering several reaches, perhaps 20–50 stream widths long);
- river segment-wide gravel augmentation and sediment management plan to restore geomorphological and biological functioning of the stream (10–100 km).

14.5.2.2 Types of Sediment Input

Regarding sediment input methodologies, Ock, Sumi, and Takemon (2013) summarized these types as shown in Figure 14.17.

In-channel bed stockpile is a relatively old method that started from 1970, but even now it is widely used for supplementation of riffles or pool tails. This approach places directly spawning gravels within the low-flow channel to provide immediate usable habitat features. This method, however, involves in-channel work at low flows, which may increase turbidity downstream. Sediment that is largely immobile under low flow would start to transport downstream when the flow exceeds the bed-mobility threshold.

High-flow stockpile method places gravel along the channel bank margin to be distributed downstream by high flows. This method assumes that the river will transport sediment and reshape the channel during high-flow events. Where peak flows in stream channel have a short duration and high magnitude, it would be applicable as an efficient method. It is a common method currently applied in Japan. This approach can add relatively large amounts of gravel at relatively low cost, but is limited to the volume piled and the number of suitable sites.

Point-bar stockpile method introduces coarse sediment to augment or create a point bar. The augmentation is accomplished using site-specific low-flow and bankfull channel dimensions of the reaches. The volume of coarse sediment introduced can be exaggerated because some of it may be routed downstream during high-flow events. However, the coarse sediment stockpiled at the inside bend in a meandering channel would be limited to erosion and transport downstream during high flows.

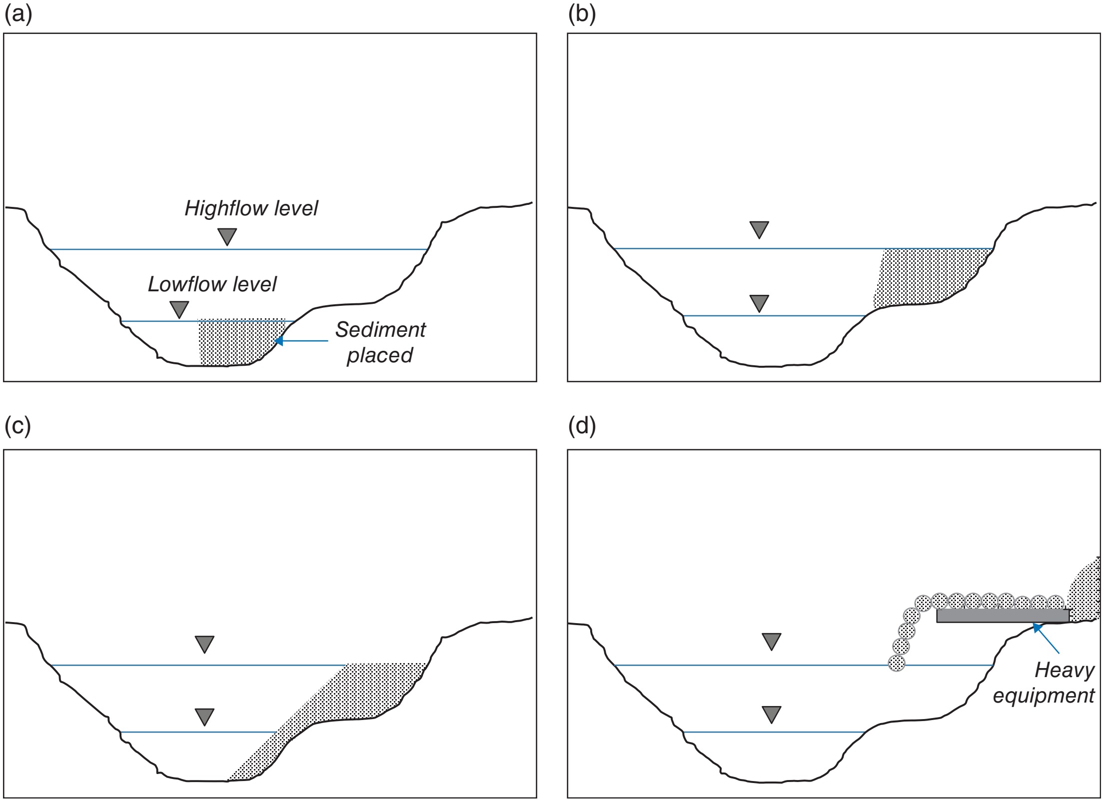

Figure 14.17 Sediment replenishment methods according to sediment placement or injection types: (a) in-channel bed stockpile, (b) high-flow stockpile, (c) point-bar stockpile, and (d) high-flow direct injection (Ock *et al.* 2013).

Gaeuman (2012) proposed the process of *high-flow direct injection*, which directly introduces gravel to the river channel during a high flow event using heavy equipment such as a conveyor belt. While the high-flow stockpile can be quickly exhausted in a large flow, this approach can allow new sediment to replace the material already transported. Also, an advantage of this method over a high-flow stockpile is that a larger volume and coarser gravel can be introduced during the course of a flood.

14.5.3 Environmental Effects and Monitoring

14.5.3.1 Creating Habitat for Spawning and Other Salmon Life-Stages

Bunte (2004) summarized environmental effects of gravel augmentation mainly on creating habitat for spawning and other salmon life-stages. Kondolf and Wolman (1993) reported that suitable spawning gravel must be well-rounded, the right size distribution for spawning fish, which means D_{50} particle size should be between 1 and 10% of the fish length, and without containing fine sediments (very fine gravel smaller than approximately 6.3 mm, sand, silt, and clay), which reduces intragravel flow and the dissolved oxygen content. Based on this information, spawning gravel quality should be carefully designed and monitored in the field after implementation, such as size distribution of bed material on spawning riffles, amount of fine sediment in spawning areas, and intragravel flows and dissolved oxygen content.

14.5.3.2 Suspended POM Retention Capacity and Hyporheric Flow Effect

Ock *et al.* (2013) showed that geomorphological changes in downstream reaches (e.g. lengthened riffles and restored bars) increased particulate organic matter (POM) retention, which is an ability of the channel to reduce the POM concentration and provide aquatic ecosystems with a primary energy resource (Tockner *et al.* 1999). However, in regulated rivers below dams, input of large amount of plankton from dam outflows influences POM quantity and quality, and subsequently could disturb the downstream ecosystem foodweb (Akopian *et al.* 1999). Thus, the retention efficiency of reservoir-derived plankton can be important component for recovering a normal state of trophic structure. In this sense, this "natural filtering" function, is significant for enhancing self-purification along channels and restoring the downstream ecosystem foodweb.

Ock *et al.* (2015) investigated water temperature alongside a gravel bar created by sediment augmentation and demonstrated that hyporheic flow between mainstream and subsurface waters beneath the bar provides thermal heterogeneity along the perimeter of gravel bars by cooling, buffering and lagging temperatures. For maximum hyporheic cooling benefit in summer, it is a strategy to increase the hyporheic flow rate, which is a function of hydraulic gradient and substrate permeability (Tonina and Buffington 2007). Coarse-sized gravels from gravel augmentation, allow a high permeability and increase hydraulic gradients within a gravel bar (Boulton 2007).

14.5.4 Case Studies in Japan

In order to reduce the sediment inflow, sediment trapping with check dams above reservoirs has been commonly implemented in Japan. In this technique, a low check dam is constructed at the end of a reservoir and regularly excavated mechanically to remove the trapped sediment, which mainly consists of coarse bedload sediments. (Figures 14.1, 14.4, and 14.5). Traditionally, the trapped coarse sediments have been used for construction materials. Recently, sediment replenishment has been carried out at least in 15 dams in Japan (Okano *et al.* 2004) including the Kizu River basin system (Kantoush, Sumi, and Kubota 2010; Kantoush and Sumi 2011).

In Japan, a high-flow stockpile is commonly used in order to avoid artificial turbid flow that is released through the side bank erosion at low flows. Sakurai and Hakoishi (2013) showed the location of typical case studies in (Figure 14.18). In the sediment replenishment measure, sediment replenishment volume and grain size are recognized as key factors for a successful management in the river basin to create and maintain physical habitats, and aquatic and riparian ecosystems. Figure 14.19 illustrates the relationship between the annual excavated sediment volumes from reservoirs and annual reservoir sedimentation volumes within reservoirs (Sumi and Kantoush 2011). Although sediment replenishment can be considered as a sediment management approach in reservoirs, its quantity compared to annual reservoir sedimentation is still very small (i.e., between 0.1% to 10%). Figure 14.20 shows the grain size distributions of replenished sediment, which are very different for each case because of difference in the available location to take the sediment out from each reservoir. In most cases in Japan, sediment replenishment is focusing both on reducing the reservoir sedimentation and on enhancing the river channel improvement, such as by detaching algae on the riverbed material (Okano *et al.* 2004). Creating new habitats for spawning and other fish life-stages is a new challenging topic in Japan. Further studies, and sharing the outcomes obtained from advanced case studies, are necessary when the scale and volume of sediment replenishment increases.

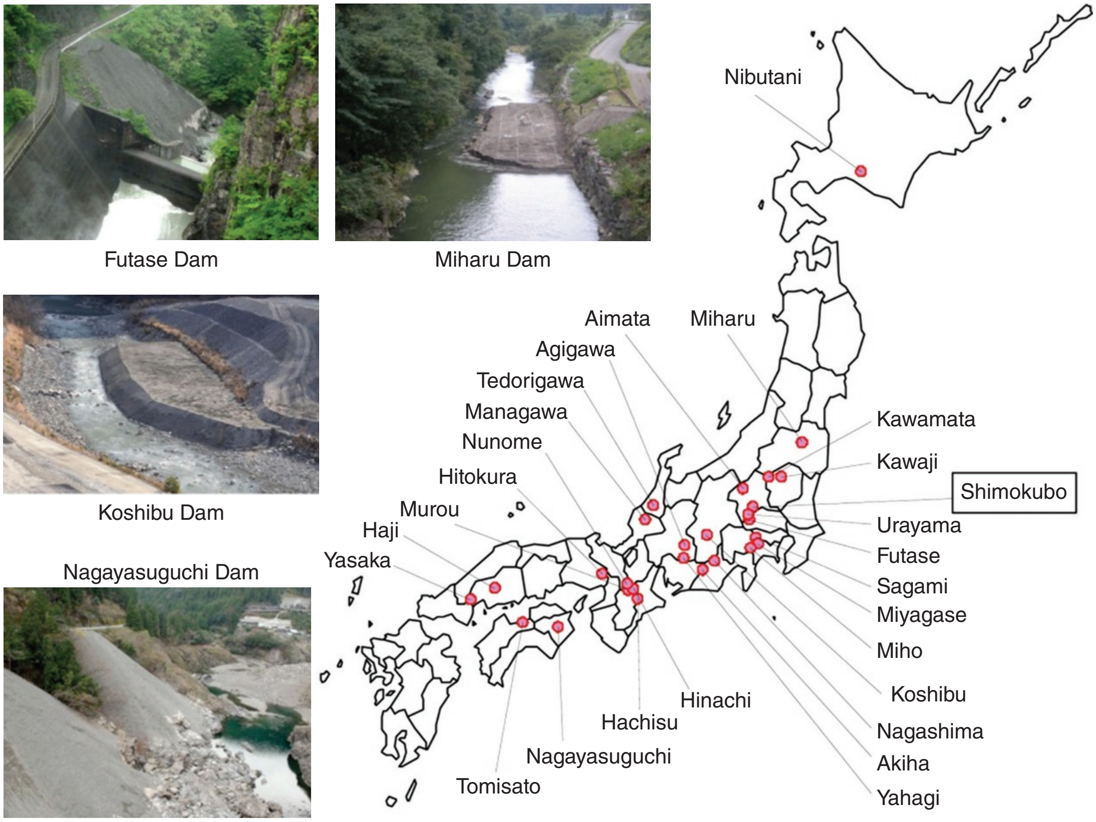

Figure 14.18 Location map of dams with sediment replenishment in Japan (Sakurai and Hakoishi 2013).

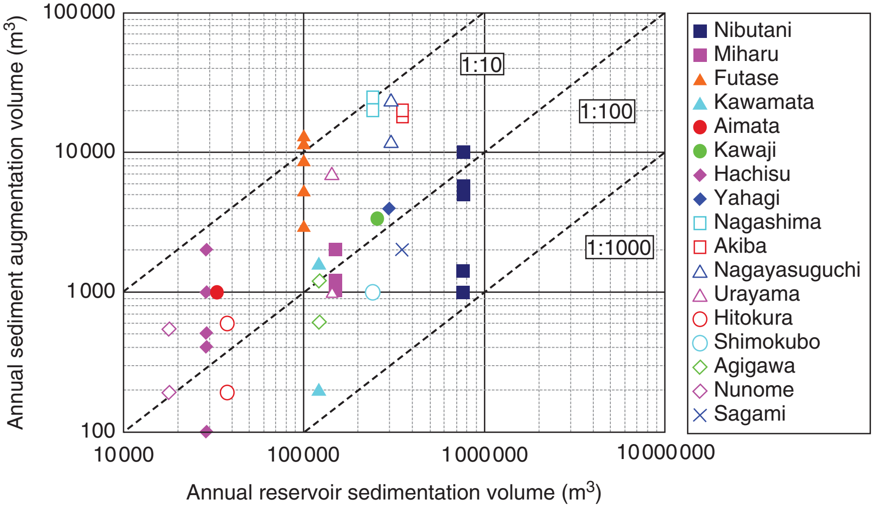

Figure 14.19 Relationship between annual reservoir sedimentation and replenishment volumes (Sumi and Kantoush 2011).

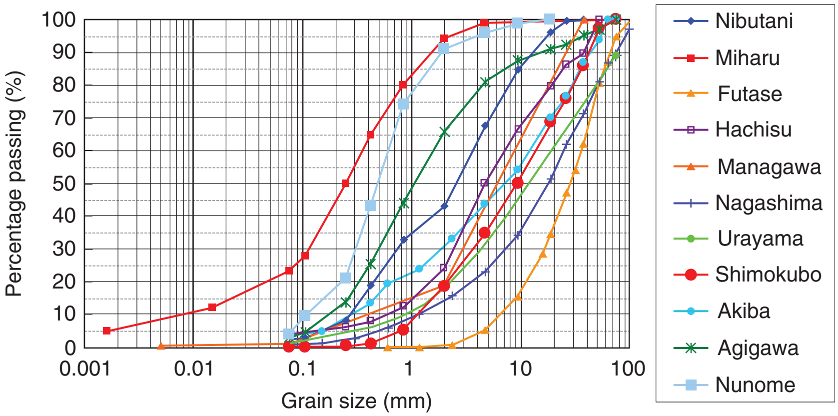

Figure 14.20 Grain-size distributions of sediment replenishment (Sumi and Kantoush 2011).

14.6 Conclusions

In the case of reservoir sediment management, it is necessary to assess the current situation and possible future scenarios from a reservoir sustainability point of view. In order to increase the number of best practices for reservoir sediment management, it is important to establish a suitable guideline to select appropriate sediment management measures based on both river basin and reservoir conditions. On this point, the turnover rate of water (*CAP*/*MAR*) and sediment (*CAP*/*MAS*) can be the key parameters to design reservoir sediment management strategy. For the sediment management plan, a combination of flow and sediment release should be appropriately designed to meet the demands of various functions based on hydrology, water quality, river morphology, and ecosystem data, etc. Furthermore, the integrated sediment management approach should be considered in sediment routing systems that cover not only the river basin but also coastal areas. Among several updated methodologies, effective and eco-friendly sediment flushing and replenishment techniques have been intensively applied in Japan. Even though the target volume of sediment is very different between these approaches, positive influences should be clarified from the point of view of both reservoir sustainability and downstream environmental improvement. Sediment flushing is now a common approach worldwide but problems still exist, such as how to increase flushing efficiency by minimizing environmentally adverse impacts. Sediment replenishment or augmentation can be more easily applied as a start-up option without installation of any large facilities, both for reducing reservoir sedimentation and for improving the downstream river environment. In order to maximize the benefit, incorporating flushing flows (magnitude, frequency, and timing), determining quantity (amount added) and quality (grain size and source materials) of coarse sediment, and selecting an effective implementation technique for adding and transporting sediment in the fields, are key factors in achieving a successful result in ecological river management and restoration. For the future, it is important to increase the scale and volume of sediment replenishment, and to establish sustainable management in order to maintain long-term benefits.

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