Chapter 6

Sediment Management of Reservoirs in Volcanic Area: Case of Wlingi and Lodoyo Reservoirs in Indonesia

Fahmi Hidayat, Pitojo T. Juwono, Agus Suharyanto,
Alwafi Pujiraharjo, Djoko Legono,
Dian Sisinggih and David Neil

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.75034

Abstract

Volcanoes erupt in many parts of the world, producing abundant sediment that is rapidly delivered to deposition sites. Where a reservoir is located near an active volcano, the sedimentation will be very severe. Wlingi and Lodoyo reservoirs are severely affected by eruptions of Kelud volcano, one of the most active volcanoes in Indonesia. After the February 2014 eruption, the capacity of Wlingi and Lodoyo reservoirs decreased dramatically to 2.20 million cubic meter (Mm^3) and 1.33 Mm^3, respectively, just 46 and 49% of their pre-eruption capacities and 19.42 and 26.60% of their initial capacities. To cope with the extreme sedimentation problems in Wlingi and Lodoyo reservoirs, diverse sediment management strategies have been applied in these reservoirs and their catchments. Construction of many on-stream sediment control facilities (sabo works) and a sediment bypass channel has reduced sediment inflow to the reservoirs. Removal of deposited sediment by dredging and hydraulic flushing in Wlingi and Lodoyo reservoirs has also resulted in storage capacity recovery. These measures are an integral part of the Mt. Kelud Volcanic Disaster Mitigation Plan.

Keywords: reservoir, sediment management, volcanic area, Wlingi and Lodoyo

1. Introduction

Volcanoes erupt in many parts of the world, from ocean ridges to the center of continents, producing tremendous sediment that is rapidly delivered to sites of deposition. Yearly sediment fluxes from basins affected by volcanic eruptions commonly range from 10^3 to 10^6

mega-grams (Mg)/km^2 that can be considered as the greatest sediment producer on Earth [1]. Prolonged tremendous sediment transport after a volcanic eruption can cause environmental and socioeconomic damage equaling or exceeding that caused directly by an eruption [2]. If volcanic sediment fluxes are ultimately trapped by dams in a river system, severe sedimentation may take place in its reservoir.

Reservoir sedimentation occurs when sediment carried by a river flowing into a reservoir is trapped by a dam and deposited in the reservoir upstream of the dam. The sediment carried by the inflowing river is deposited in a reservoir because the water slows after entering it, reducing its capacity to transport the sediment. Such deposits consume reservoir storage space that was originally intended for water storage, thereby impeding the intended function of the dam and reservoir, i.e., adversely affecting hydropower generation and reducing the reliability of domestic and irrigation water supplies and flood management systems.

Where the reservoir is located near an active volcano, the sedimentation will be very severe. Effective measures to mitigate reservoir sedimentation in a volcanic area include measures to manage sediment inflows during periods of high sediment yield to minimize trapping in reservoirs, removal of sediment already deposited in reservoirs using a variety of techniques, and measures to reduce sediment yield from the area affected by the eruption of the volcano upstream of reservoir. These measures should be an integral part of the volcanic disaster mitigation plan. This chapter discusses the importance of reservoir sediment management in a volcanic area by examining the case of Wlingi and Lodoyo reservoirs which are located near Kelud Volcano, one of the most active volcanoes in Indonesia.

2. Reservoir sedimentation management

Sustainable reservoir sedimentation management is vitally important for preserving reservoir storage space and minimizing long-term maintenance costs. There are three main strategies for reservoir sedimentation management as follows: (1) strategy to reduce sediment inflow from upstream area, (2) strategy to pass sediment through or around the impoundment to minimize sediment trapping effect, and (3) strategy to recover, increase, or reallocate storage or to modify intake or other structures, after sediment has been deposited in the reservoir [3], as summarized in **Table 1**.

3. The eruptions of Kelud volcano in the Brantas River basin, Indonesia

Across Indonesia's 13,677 islands, there has been a volcanic eruption, on average, every year for the past 1000 years. These eruptions have resulted in more than 175,000 deaths and also caused numerous debris flows [4] with significant implications for landscape characteristics, soils, hydrological processes, and human societies. Kelud volcano (1724 m), located in the

Strategy	Description
Reduce sediment inflow from upstream	1. Erosion control to reduce sediment yield
	2. Upstream trapping by check dams, etc.
Route sediment around or through reservoir	3. Bypass sediment to pass sediment around the storage zone by constructing sediment bypass tunnel or channel, etc.
	4. Sediment pass-through to route sediment through the impounded reach by venting turbidity currents or reservoir drawdown
Recover, increase, or reallocate reservoir volume	5. Flushing to scour out deposited sediment in reservoir
	6. Dredging to remove sediment by mechanical means
	7. Dry excavation to remove sediment by earthmoving equipment
	8. Increase storage by raising the dam or constructing additional storage reservoirs
	9. Modify structures to avoid areas of sediment deposition by modifying intakes or other structures
	10. Redistribute sediments to manipulate water levels to deposit sediment in areas of the pool where impacts are reduced
	11. Reallocate available storage to distribute sedimentation impacts among the beneficial uses to maximize the utility of the remaining volume

Table 1. Classification of reservoir sediment management strategies [3].

center of the Brantas River basin at $112^0 18.5'$E and $7^0 56'$S, about 38 km west of Malang City, 35 km east of Kediri City, and 24 km north of Blitar City, is portion of the Sunda volcanic arc system that is linked to the subduction of the Australian plate. Kelud volcano is an andesitic stratovolcano with a complex structure which primarily includes two avalanche calderas, of which one is exposed to the south and the other to the west [5]. **Figure 1** depicts the location of Kelud volcano, Wlingi and Lodoyo reservoirs in the Brantas River basin, East Java, Indonesia.

The morphology of Kelud volcano includes the formation of a deep crater lake, which stores up to 10 million cubic meters (Mm^3) of rainwater. Stored water in the crater of Kelud volcano (see **Figure 2** showing Kelud volcano's crater with the lake in 2005) was the main mover at each eruption, water mixing with the ejecta to produce hazardous hot debris flows. The primary lahars generally flow down the slopes of the western half of the Kelud volcanic area through dissected torrents discharging from the crater area and afterward form abundant deposits on the lower slopes. Those erupted materials deposited on Kelud volcano's slopes are the major source of the hazardous secondary lahars which are usually mobilized by subsequent heavy rains after the eruptions. The eruptions of Kelud volcano affect large area of about 2003 km^2 and cover the catchment area of the Konto, Serinjing, Ngobo, Sukorejo, Petungkobong, Badak, Abab, Putih, Jari, and Lekso Rivers, entirely tributaries of the Brantas River, the longest river in east part of Java.

Historical eruptions of Kelud volcano are well known because they have caused catastrophic outpouring of the crater lake and formation of "primary" (eruption-triggered) lahars. Kelud volcano's 1000 AD eruption is the oldest in the historical record of eruptions for the entire

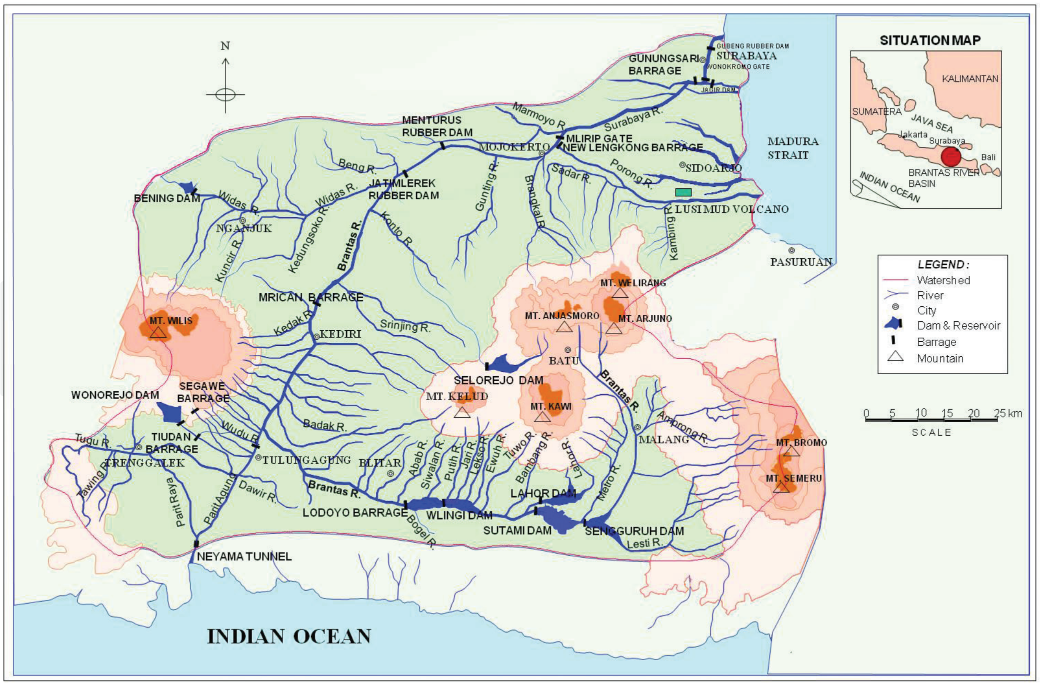

Figure 1. Location of Kelud volcano, Wlingi and Lodoyo reservoirs in the Brantas River Basin, East Java, Indonesia.

Indonesian archipelago. In the recent past, eruptions occurred in 1901, 1919, 1951, 1966, 1990, 2007, and 2014. **Table 2** summarizes the chronology of Kelud volcano's activities in historical time. These eruptions were generally similar, characterized by very short durations. Explosive activity typically started with a phreatomagmatic outburst followed by a short plinian eruption with convective columns reaching an altitude of more than 10 km. These eruptions produced devastating lahars, pyroclastic surges and flows, as well as ash fall deposits.

In May 1919, Kelud volcano erupted, ejected 38.5 Mm^3 of hot lahar, and claimed 5110 lives. After this eruption, a series of drainage tunnels were constructed during the period 1923–1927 through the west rim of the crater lake to decrease the lake water to 1.8 Mm^3, lowering the lake water level by 50 m. The August 1951 eruption produced only minor destruction with total volcanic product estimated at 192 Mm^3 based on point depth surveys of the ash deposits. Kelud volcano erupted again in April 1966, producing an estimated 90 Mm^3 of volcanic materials [6].

The 10 February 1990 eruption began at 11:41 local time (GMT + 7 hours) with a series of phreatic explosions [5]. The eruption resulted in large volumes of volcanic ash spreading over the south to west slopes of Kelud volcano, with deposition in villages, paddy fields, and plantations within a 20–30 km radius. The 1990 eruption produced about 125 Mm^3 of tephra as a combination of fall, flow, and surge and devastated the summit area within 1–5 km from the crater rim. Subsequently, the potential lahar yield (the ash deposits which could form lahar flows) was estimated through field investigation as 57.3 Mm^3. The 2007 eruption of Kelud volcano produced no significant volume of ejecta but created a lava dome which rose through the center of the crater lake atop the volcano. The lava dome expanded to 250 m diameter and

Figure 2. The evolution of Kelud volcano's crater with the lake in 2005 (top, left), the formation of lava dome in 2007 (top-right), the crater before eruption in 2013 (middle- left), the crater after eruption in 2014 (middle-right), and the eruption of Kelud volcano in February 2014 (bottom). Historical eruptions of Kelud volcano are well known, because they have caused catastrophic outpouring of the crater lake and formation of "primary" (eruption-triggered) lahars. Kelud volcano's 1000 AD eruption is the oldest in the historical record of eruptions for the entire Indonesian archipelago. In the recent past, eruptions occurred in 1901, 1919, 1951, 1966, 1990, 2007, and 2014. These eruptions were generally similar, characterized by very short durations. Explosive activity typically started with a phreatomagmatic outburst followed by a short plinian eruption with convective columns reaching an altitude of more than 10 km. These eruptions produced devastating lahars, pyroclastic surges and flows, as well as ash fall deposits.

120 m high and cracked open, and lava began oozing into the surrounding water. **Figure 2** depicts the evolution of Kelud Volcano's crater with the lake in 2005 until the eruption in February 2014 which destroyed the lava dome inside the crater.

Date	Year	Comments
	1000	Reported ash falls
	1311	Reported casualties
	1334	Reported ash falls and lahars
	1376	Explosive, lava dome formed,; reported casualties
	1385	
	1395	
	1411	
	1451	
	1462	
	1481	
	1548	
	1586	About 10,000 casualties
	1641	
Jul-20	1716	Reported casualties
May-01	1752	
Jan-10	1771	Reported ash falls
	1776	
	1785	
Jun-05	1811	Reported ash falls
	1825	Reported casualties
October 11, 14, 18, 25	1826	Strong detonations: glowing avalanche, summit area destroyed; post-eruption lahar
	1835	Reported casualties
	1848	
May-16	1851	
Jan-24	1864	
January 3-4	1901	
May 22-23	1919	Reported casualties
May-20	1920	5110 casualties
Dec 6-12	1951	Formation of lava dome
Aug-31	1966	Destruction of the 1920 lava dome; seven casualties
Apr-24	1990	211 casualties
Feb-10	2007	32 casualties, post-eruption lahar; embryonic lava dome
November 3-4	2014	Formation of lava dome
Feb-13		Destruction of the 2007 lava dome

Table 2. The chronology of Kelud volcano's activities in historical time, based on Bourdier et al. [12] and Hidayat et al. [13].

The most current eruption of Kelud volcano occurred on 13 February 2014. Satellites detected the eruption plume at 11:09 p.m. local time (16,09 UTC). At 12:30 a.m. (17.30 UTC), an image from the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi NPP satellite indicated an ash plume reaching above a lighter-colored cloud deck [7]. CALIPSO satellite data revealed that a rapidly rising portion of the plume ejected material up to an altitude exceeding 26 km, well into the tropical stratosphere [8]. The eruption sent an enormous plume of ash drifting west across Java island and over the Indian Ocean. By 9 hours after the initial eruption, the center of the plume top had drifted 600 km westward [9]. Ash plumes rose to an altitude of 17 km and caused ash fall in areas to the NE, NW, W, and elsewhere as far as Pacitan, East Java (133 km WSW); Kulon Progo, Yogyakarta (236 km W); Temanggung, Central Java (240 km WNW); and Banyuwangi, East Java (228 km E) [8]. A 18 February 2014 satellite image shows that the lava dome was destroyed during the February 2014 eruption and significant ash was deposited on the slopes and in the river channels around Kelud volcano. The lava dome with estimated volume of about 20 Mm^3 was extruded into the crater lake at the summit during the eruption in November 2007 [10], continuing to extrude through the crater lake until growth ceased in March 2008. During the 2007 eruption, nearly all the lake water was vaporized as the lava dome grew to a diameter of 400 m, a height of 260 m, and a volume of 35 Mm^3 [11].

4. Sedimentation problem in Wlingi and Lodoyo reservoirs

Wlingi dam and Lodoyo barrage are located in the Brantas River basin, in the east of Java Island, Indonesia. Wlingi dam, with a catchment area of 2890 km^2, is located on the southern slope of Kelud volcano in the upstream reach of the Brantas River basin and approximately 30 km downstream of Sutami dam. Lodoyo barrage is located approximately 7 km downstream of Wlingi dam. Wlingi dam was completed in 1979 for the purpose of peak demand hydropower generation (54 MW), irrigation water supply (12,687 ha irrigation area), and flood control. Lodoyo barrage is located 7.9 km downstream of Wlingi dam. Construction of Lodoyo barrage, the second stage of the Wlingi Raya Project, started in 1978 and was completed in 1980. The function of Lodoyo barrage is for hydropower generation (4.7 MW) and flood control.

Wlingi and Lodoyo reservoirs are very small with capacity to inflow (C/I) ratios of about 0.007 and 0.001, respectively. Following its completion in November 1979, the gross storage volume of Wlingi reservoir was 24.00 Mm^3, and the effective storage volume was 5.20 Mm^3 between the high-water level (HWL) of 163.50 m and the low-water level (LWL) of 162.00 m, while the gross storage volume of Lodoyo reservoir at the time of its completion in December 1980 was 5.20 Mm^3, and the effective storage volume was 5.00 Mm^3 between the HWL of 136.00 m and the LWL of 125.50 m.

The sedimentation in Wlingi and Lodoyo reservoirs is mainly caused by sediment inflow from the areas most affected by ejecta from eruptions of Kelud volcano, one of the most active volcanoes in Indonesia. Sedimentation in Wlingi reservoir is affected by sediment-laden floods from the major tributaries to the Brantas River, i.e., the Putih, Jari, and Lekso Rivers, which drain the southern slopes of Kelud volcano. **Figure 3** depicts sediment deposits on the southern slopes of Kelud volcano and the upstream of the Lekso River just after the eruption in February 2014. Sedimentation in Lodoyo reservoir is caused by sediment outflow from Wlingi reservoir (66%), and the rest is largely from tributary streams draining the slopes of Kelud volcano and the southern catchment area. Longitudinal bed profile changes of Wlingi and Lodoyo reservoirs and aerial views of both reservoirs taken by a drone showing sediment deposition in the reservoirs during sediment flushing on 25–26 March 2016 can be seen in **Figures 4** and **5**, respectively.

Figure 3. Sediment deposits on the southern slopes of Kelud volcano on 23 April 2014 (top), sediment deposition in the upstream of the Lekso River on 23 April 2014 (middle), and debris flow in the Lekso River on 22 April 2014 (bottom).

http://dx.doi.org/10.5772/intechopen.75034

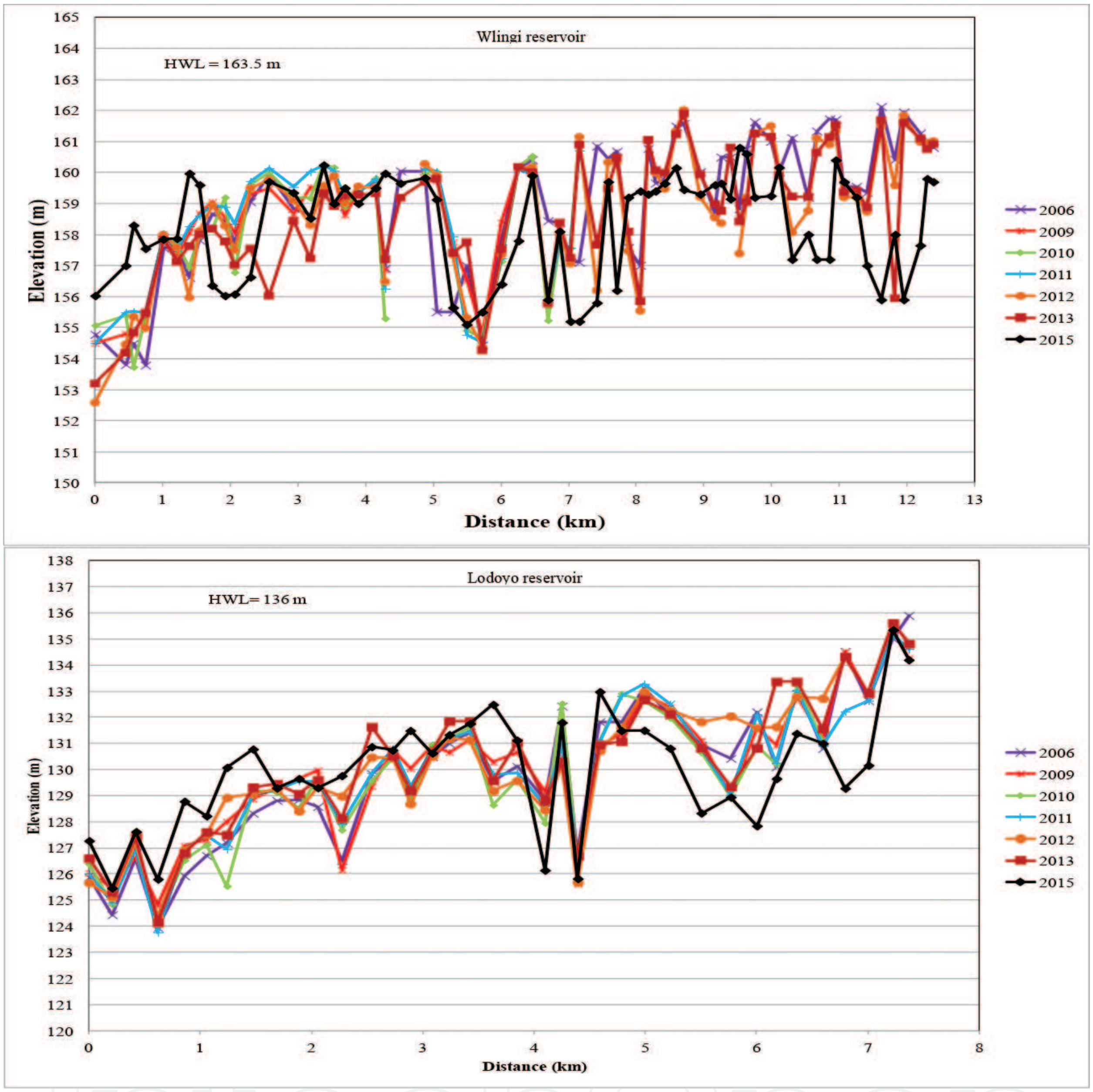

Figure 4. Longitudinal bed profile changes of Wlingi (top) and Lodoyo (bottom) reservoirs.

The sedimentation rate in Wlingi reservoir has been very rapid, with annual average sediment deposition from its completion in 1979 to January 1990 (before the eruption on 10 February 1990) of about 1.49 Mm^3. The sedimentation rate increased over the 1977–1988 period, from 1.14 Mm^3/year in 1977–1982 to 1.29 Mm^3/year in 1982–1985 and 1.65 Mm^3/year for the 1985–1988 period. This increase in yield rate is attributed to sediment outflow from lahar pockets and sabo check dams, which had mostly filled to capacity by the 1990 eruption of Kelud volcano. In the period of 1977 to January 1990, shortly before the February

Figure 5. Aerial views of Wlingi (left) and Lodoyo (right) reservoirs taken by a drone showing sediment deposition in the reservoirs during sediment flushing on 25–26 March 2016.

1990 eruption of Kelud volcano, the gross capacity had decreased to 4.6 Mm^3 (19.16% of the initial volume), and the effective storage decreased to 2.20 Mm^3, 42.31% of the initial volume [14].

The total sediment deposited in Wlingi reservoir from its construction in 1977 to immediately prior to the 1990 eruption is estimated at 19.40 Mm^3. Sediment inflow from the area between Sutami dam and Wlingi dam (catchment area, 430 km^2) which was not affected by Kelud volcano during the survey period is estimated at 0.43 Mm^3/year, 5.59 Mm^3 over the 13-year

Survey years	**Gross storage**		**Effective storage**		**Dead storage**	
	Volume (Mm^3)	**Percentage (%)**	**Volume (Mm^3)**	**Percentage (%)**	**Volume (Mm^3)**	**Percentage (%)**
1977	24.00	100.00	5.20	100.00	18.80	100.00
1982	18.32	76.33	NA	NA	NA	NA
1985	14.44	60.17	NA	NA	NA	NA
1988	9.50	39.58	NA	NA	NA	NA
Jan 1990	4.60	19.16	2.20	42.31	2.40	12.77
Eruption of Kelud volcano in February 1990						
March 1990	1.60	6.67	NA	NA	NA	NA
1995	4.94	20.58	1.59	30.58	3.35	17.82
2004	4.41	18.38	2.01	38.65	2.41	12.82
2009	4.38	18.25	2.01	38.65	2.37	12.61
2013	4.83	20.13	2.01	38.65	2.82	15.00
Eruption of Kelud volcano in February 2014						
2015	2.20	9.17	1.01	19.42	1.19	6.33

Note: NA = not available.

Table 3. Storage capacity change in Wlingi reservoir.

http://dx.doi.org/10.5772/intechopen.75034

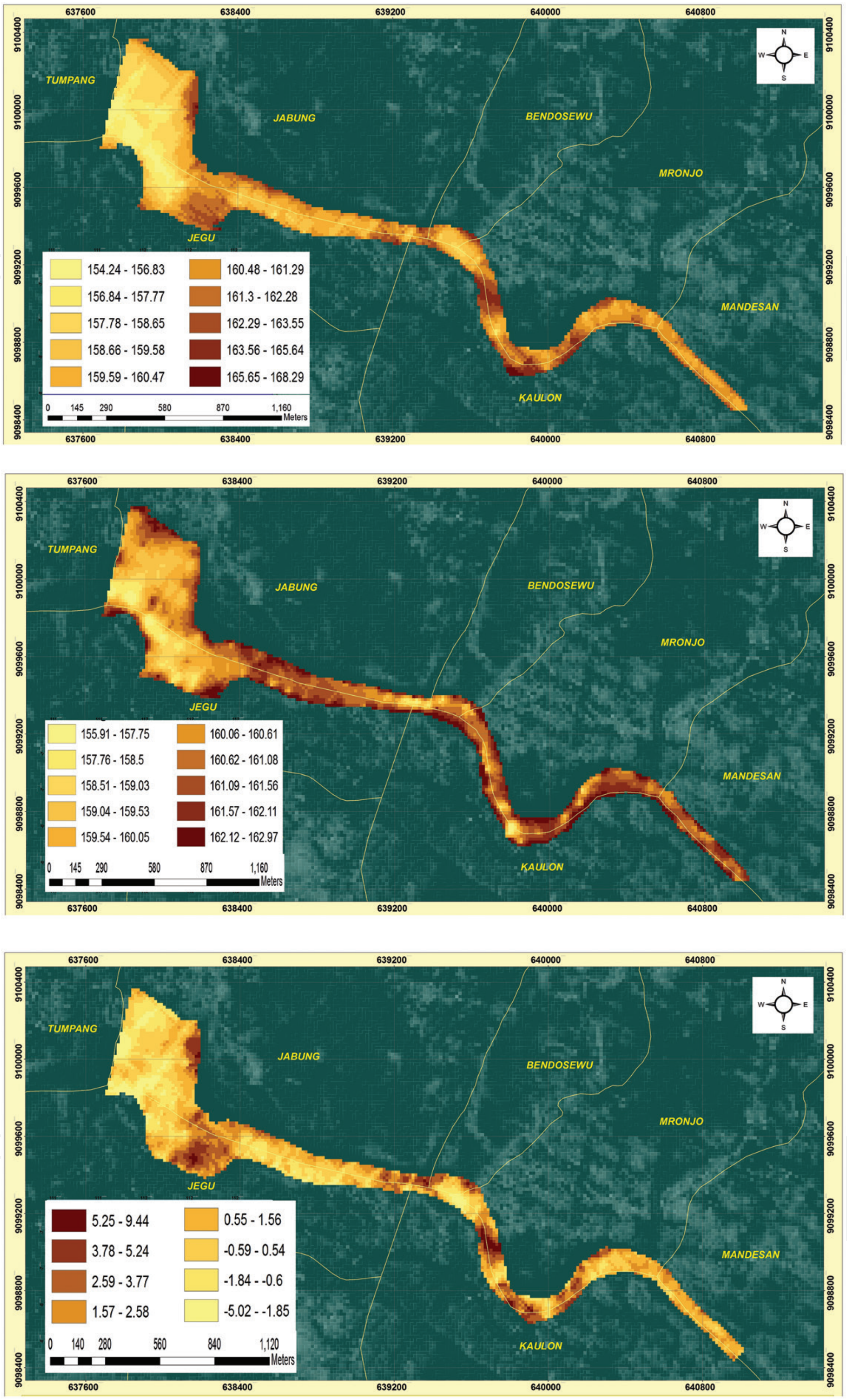

Figure 6. Bed elevation from March 2013 bathymetric survey in Wlingi reservoir (top), May 2015 bathymetric survey in Wlingi reservoir (middle), and measurement of bed evolution in Wlingi reservoir: difference between March 2013 and May 2015 bathymetries (bottom).

period. Thus, net sediment inflow from the tributaries (Putih, Jari, and Lekso) carrying ejecta from Kelud volcano over that period is estimated at 13.81 Mm^3, which corresponds to an average sediment inflow rate of 1.06 Mm^3/year.

After the eruption of Kelud volcano on 10 February 1990, Wlingi reservoir completely filled with sediment. According to the 1995 survey by Jasa Tirta I Public Corporation (PJT-1), the River Basin Management Agency of Brantas River basin, the gross storage and effective storage of Wlingi reservoir were then 4.94 and 1.59 Mm^3, respectively [13]. As a result of the continuous removal works, the effective storage capacity of Wlingi reservoir in 2013 recovered to 2.01 Mm^3, which corresponds to 38.65% of the designed effective storage capacity of 5.2 Mm^3. Changes in surveyed storage capacity since 1990 are significantly affected by the sediment removal works. Kelud volcano erupted again on 13 February 2014. The reservoir capacity survey in May 2015 indicates that the gross storage and effective storage capacities of Wlingi reservoir were decreased to 2.20 and 1.01 Mm^3, respectively [14]. **Table 3** summarizes storage capacity change in Wlingi reservoir from 1977 to 2015. Bed elevations from March 2013 and May 2015 bathymetric survey in Wlingi reservoir can be seen in **Figure 6**.

The rate of storage capacity decline in Lodoyo reservoir is, like Wlingi reservoir, very high. After the eruption of Kelud volcano in February 1990, when Wlingi reservoir completely filled with sediment and the trapping efficiency of Wlingi dam was very low, sediment outflow from Wlingi reservoir deposited in Lodoyo reservoir. According to the 1996 survey by PJT-1, the gross storage capacity of Lodoyo reservoir was 2.35 Mm^3, 45.19% of the initial volume. In 2013, the effective storage capacity of Lodoyo reservoir was reduced to 2.72 Mm^3, despite the implementation of flushing activities from 1999 and dredging from 2003. This represents 52.31% of the designed effective storage capacity of 5.20 Mm^3. Largely as a result of the 2014 eruption, storage capacity in Lodoyo reservoir decreased by about 50% between the surveys of 2013 and 2015. The reservoir capacity survey in May 2015 indicates that the

Survey years	Gross storage		Effective storage		Dead storage	
	Volume (Mm^3)	Percentage (%)	Volume (Mm^3)	Percentage (%)	Volume (Mm^3)	Percentage (%)
1980	5.20	100.00	5.00	100.00	0.20	100.00
Eruption of Kelud volcano in February 1990						
1990	3.69	70.96	3.69	73.80	0.00	0.00
1993	2.84	54.62	2.84	56.80	0.00	0.00
1996	2.35	45.19	2.35	47.00	0.00	0.00
2003	2.03	39.04	1.86	37.20	0.17	85.00
2006	2.73	52.50	2.73	54.60	0.00	0.00
2009	2.67	51.35	2.67	53.40	0.00	0.00
2011	2.65	50.96	2.65	53.00	0.00	0.00
2013	2.72	52.31	2.72	54.40	0.00	0.00
Eruption of Kelud volcano in February 2014						
2015	1.33	25.78	1.33	26.60	0.00	0.00

Table 4. Storage capacity change in Lodoyo reservoir.

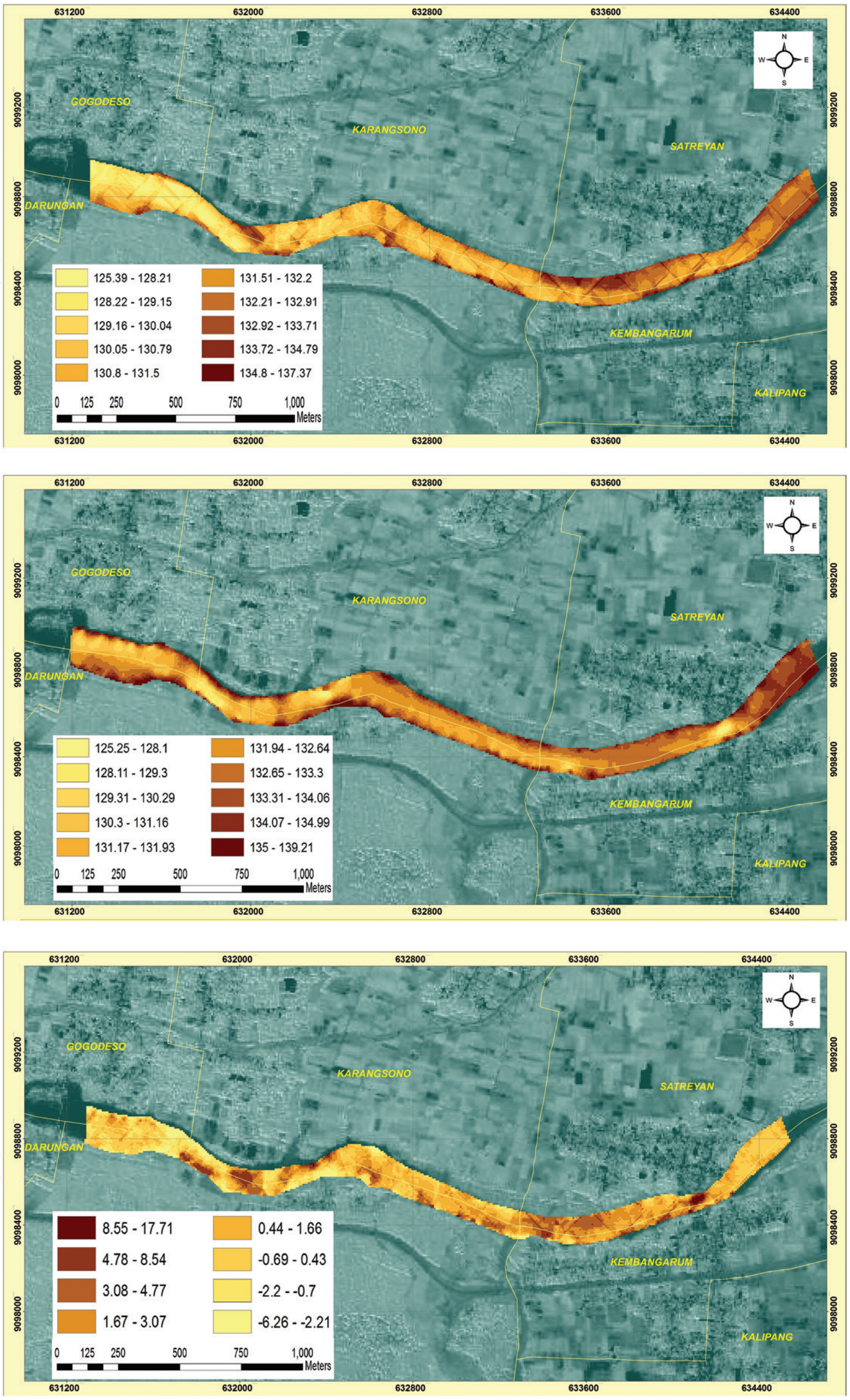

Figure 7. Bed elevation from March 2013 bathymetric survey in Lodoyo reservoir (top), May 2015 bathymetric survey in Lodoyo reservoir (middle), and measurement of bed evolution in Lodoyo reservoir: difference between March 2013 and May 2015 bathymetries (bottom).

effective storage capacity of Lodoyo reservoir was decreased to 1.33 Mm^3 [14]. **Table 4** summarizes storage capacity change in Lodoyo reservoir from 1980 to 2015. Bed elevations from March 2013 and May 2015 bathymetric survey in Wlingi reservoir can be seen in **Figure 7**.

5. Sedimentation management in Wlingi and Lodoyo reservoirs

5.1. Sabo works

Sabo is a Japanese term referring to intensive erosion and sediment control works, particularly in mountainous landscapes. The Sabo Plan in the Brantas River basin was formulated to control sediment and debris flows caused by mobilization of volcanic ash and mud by intensive rains in order to prevent and mitigate disasters [14]. The Sabo Plan targets mountain slope and river channel areas at high risk of debris flows and volcanic hazards. It was formulated by assessing both natural phenomena and socioeconomic conditions in order to ensure safety, quality of life, and socioeconomic development. The Sabo Plan in the Brantas River basin consists of two parts, i.e., the Sediment Control Plan and the Mt. Kelud Volcanic Disaster Mitigation Plan.

The Sediment Control Plan for control of debris flows was formulated using a combination of structural measures and nonstructural measures. The structural measures proposed included construction of 142 sediment control facilities consisting of 134 check dams (61 open-type check dams and 73 closed-type check dams) and 8 closed-type consolidation dams. The urgent works, including construction of five check dams on the upper reach of the Brantas River, one sediment settlement pond upstream of Sengguruh reservoir, one check dam, and two consolidation dams on the Lesti River, were completed in 2008 [15].

The second part of the Sabo Plan in the Brantas River basin is the Mt. Kelud Volcanic Disaster Mitigation Plan comprising: (1) volcanic sediment control plan against rainfall, secondary lahar (debris flow and mudflow), and (2) volcanic sediment control plan against volcanic eruption, primary lahar (nuee ardente, pyroclastic flow, volcanic ash fall, primary lahar with crater water). The Mt. Kelud Volcanic Disaster Mitigation Plan proposes construction of 145 sediment control facilities consisting of 49 check dams (11 open-type check dams and 38 closed-type check dams), 76 consolidation dams (16 open-type consolidation dams and 60 closed-type consolidation dams), and 20 sand pockets. Urgent works included the rehabilitation of one consolidation dam on the Semut River and two check dams on the Badak River, the construction of three check dams and two consolidation dams on the Lekso River, and the construction of a bypass channel. These urgent works were completed in 2011 under the support of the government of Japan [15]. **Figure 8** depicts the check dams in the Lekso River in Kelud volcanic area.

5.2. Bypass channels

The other countermeasure to control debris flow in the area affected by Kelud volcano is the construction of sediment bypass channels. To prevent the Putih River's lahar sediments from entering Wlingi reservoir, the sediment-laden flow of the Putih River was diverted to the Siwalan River by a bypass channel of about 3.32 km length. This first part of sediment bypass channel in Kelud volcanic area was completed in 1991. The bypass channel reduced sedimentation in Wlingi reservoir but shifted it downstream to Lodoyo reservoir. An extension of the bypass channel from the Siwalan River to the Brantas downstream of Lodoyo barrage was completed in 2008 (**Figure 9**). This is the second part of bypass channel development in Kelud

http://dx.doi.org/10.5772/intechopen.75034

Figure 8. Check dams in Kelud volcanic area.

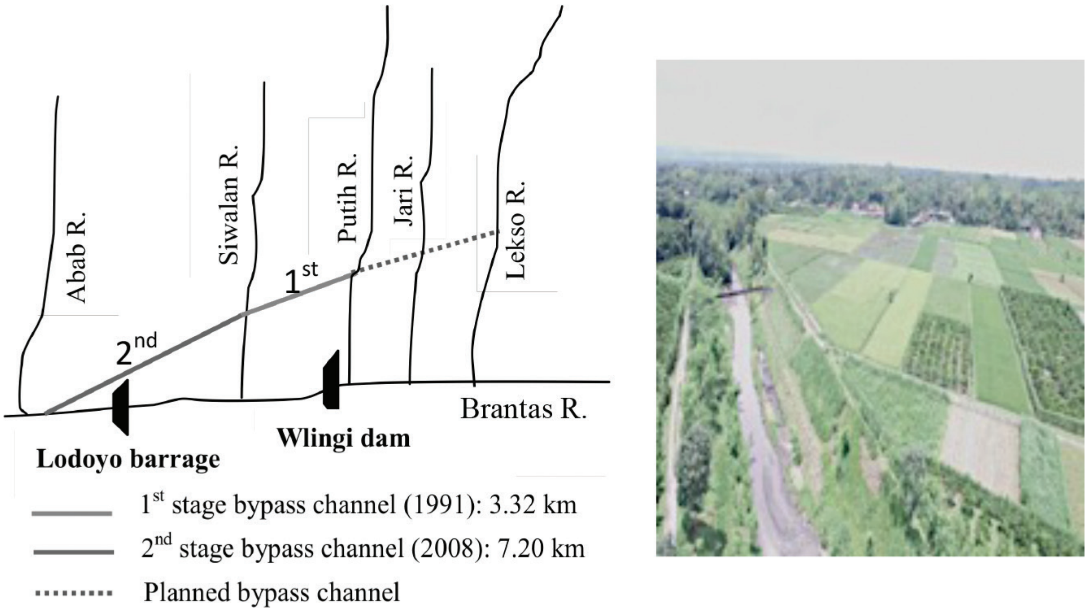

Figure 9. The bypass channel scheme in Kelud volcanic area (left) and photograph showing the bypass channel next to agriculture field.

volcanic area. The completed bypass channel and lower extension is 7.2 km long and 20 m wide, with an average flow depth of 3 m, and includes a side spillway in the Gondang River, 9 drain outlets, and 20 groundsills. The bypass channel extension was also conducted under the support of the government of Japan [15].

Diversion of sediment inflows from the Wlingi and Lodoyo reservoirs by sediment bypass channels is a part of long-term countermeasure program of the Mt. Kelud Volcanic Disaster Mitigation Plan that needs further development by constructing full diversions of both the lower and the upper parts of relevant lahar streams such as the Jari and Lekso Rivers. Sediment flows from the Putih River and the other rivers that drain from Kelud volcanic area to Lodoyo reservoir are diverted to below the reservoir by the existing bypass channel. At the moment, this channel does not divert sediment from the Lekso and Jari Rivers which flow into Wlingi reservoir. Full diversion of the lower parts of these lahar streams by construction of a bypass channel to connect with the existing channel from the Putih River to the Siwalan

River warrants urgent consideration. In addition, full diversion of the upper parts of the lahar streams with a second bypass channel obviously would further reduce reservoir sedimentation in Wlingi and Lodoyo reservoirs drastically. The design criteria for the proposed full diversion of lower and upper lahar streams, such as hydrology, sediment characteristics, and channel hydraulics, require careful survey, investigation, and design. A monitoring program to obtain baseline hydrological and water quality data for these streams should be developed and implemented as soon as possible. The potential problem for the development of the inclusive sediment bypass channel in Kelud volcanic area is primarily related to land acquisition.

5.3. Dredging, dry excavation, and flushing

While sabo facilities and sediment bypass channels are important measures to reduce sediment input from the slopes and channels of Kelud volcano, other measures are required to manage the sediment not trapped or bypassed by these facilities, as well as the 2.52 Mm^3 annual average (1996–2015) sediment inflow to Wlingi reservoir from the upper Brantas River catchment. To that end, sediment deposited in Wlingi and Lodoyo reservoirs is continuously removed by dredging, dry excavation, and flushing in order to recover their storage volume. About 12.52 Mm^3 of sediment have been removed from Wlingi and Lodoyo reservoirs by dredging operations since 1988. Currently, due to limited availability of disposal sites adjacent to Wlingi dam, dredged sediment is also discharged to the river downstream of the dam. **Figure 10** depicts sediment dredging works in Wlingi and Lodoyo reservoirs.

The other measure used to recover the storage volume of Wlingi and Lodoyo reservoirs is flushing operation. The sediment flushing operation in Wlingi and Lodoyo reservoirs is generally conducted during the rainy season by fully opening the spillway gates to empty both reservoirs. Flushing operations commenced in August 1990, 6 months after the 1990 eruption, and have been conducted occasionally since then when there is sufficient water. **Figure 11** depicts the high-flow velocities that entrain and transport large volumes of sediment from the reservoirs to the river downstream during sediment flushing in the Wlingi and Lodoyo reservoirs. About 15.11 Mm^3 of sediment has been removed from both reservoirs by flushing since August 1990. Sediment flushing has proven to be an effective and economical measure to recover the

Figure 10. Sediment dredging works in Wlingi reservoir (left) and Lodoyo reservoir (right).

http://dx.doi.org/10.5772/intechopen.75034

Figure 11. Sediment flushing through spillway gates in Wlingi reservoir (left) and Lodoyo reservoir (right) on 29–31 March 2013.

reservoirs' storage capacity. **Figure 12** shows ratio of total water volume and flushed sediment volume of sediment flushing operations in Wlingi and Lodoyo reservoirs from 1990 to 2016.

The sediment flushing in Wlingi and Lodoyo reservoirs is very effective to remove deposited sediment, same as sediment flushing operations in other cascade reservoirs in the world such as in Verbois and Chancy-Pougny reservoirs on the Rhone River in Europe [16] and Dashidaira and Unazuki reservoirs on the Kurobe River in Japan [17, 18]. The efficiency of sediment flushing operation in Wlingi and Lodoyo cascade reservoirs in 2016 was 0.042, almost three times the efficiency of sediment flushing operation in 2009 [19]. This improved flushing efficiency is largely a result of the very large volume of deposited sediment in both reservoirs after the eruption of Kelud volcano in February 2014. The efficiency of sediment flushing operation in Wlingi and Lodoyo reservoirs in 2016 is higher than reported for cascade reservoirs elsewhere

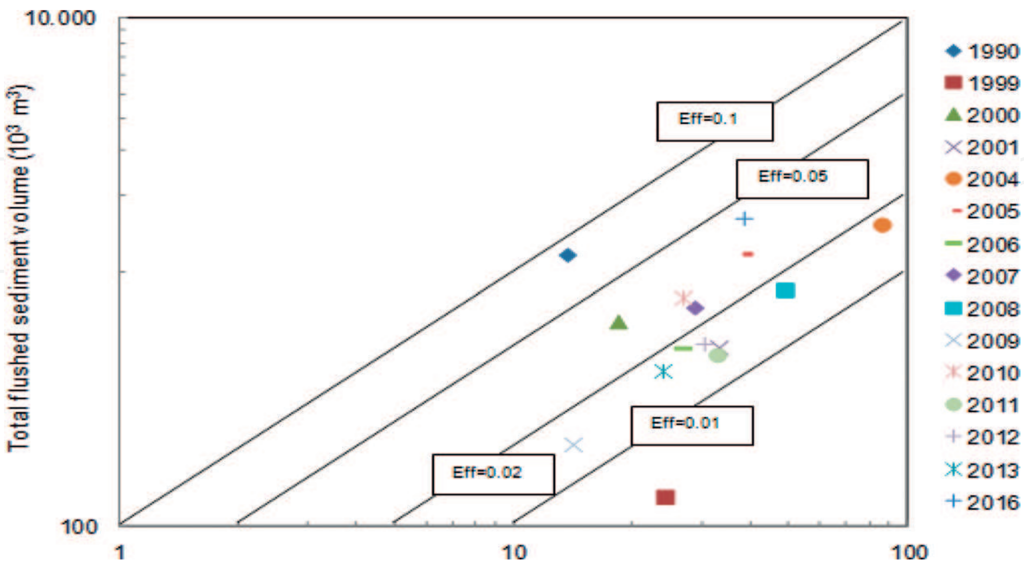

Figure 12. Total water volume and flushed sediment volume of sediment flushing operations in Wlingi and Lodoyo reservoirs (1990–2016).

in the world. In Dashidaira and Unazuki reservoirs, the flushing efficiency calculated from the water consumption including the discharge during drawdown and the sediment volume flushed out is about 0.02 [20]. In four hydropower reservoirs in the Italian central Alps, i.e., Cancano, Valgrosina, Sernio, and Madesimo, sediment flushing efficiency varied between 0.001 and 0.006. This parameter was also calculated as the ratio between the volume of evacuated sediment and the corresponding volume of water employed in the controlled sediment flushing operations (CSFO) including water for dilution [21].

Flushing discharges extreme sediment loads with very limited volumes of water, commonly producing aquatic environmental impacts in downstream area including very low dissolved oxygen (DO) and very high sediment concentrations that interfere with the function of gills in fish, smother stream benthos, reduce visibility and light penetration, and have channel morphological impacts such as infilling of pools and clogging of river gravels with fine sediment, thereby eliminating spawning sites and destroying habitat of vulnerable species [22]. In Wlingi and Lodoyo reservoirs, sediment flushing has caused impacts to river environment and water quality downstream of the reservoirs mainly due to very high concentrations of suspended solids. Currently this impact is not considered adequately, because it is only significant for several days during the flushing operation. However, sediment flushing from reservoirs is not so feasible at many sites worldwide because there have caused severe impacts on the downstream aquatic environment, principally where heavy deposition or high concentration of suspended solids affects the habitat and survival of fish and other wildlife species. In this respect, short periods of high-intensity, high sediment concentration flushing are particularly problematic. Therefore time of flushing operation should be long enough to mitigate the extreme adverse influences of sediment flushing if the higher volume of water needed is available [23]. By adding more clear water to have dilution effect during flushing operation, high peak suspended sediment concentrations may be reduced, diminishing negative ecological impacts [24]. Sediment flushing operation in Wlingi and Lodoyo reservoirs should be supported by additional water available from Sutami and Wonorejo reservoirs upstream to provide the dilution effect and should be timed to coincide with natural high-flow events.

Greater attention has been paid to the environmental effects of sediment flushing in Europe since the flushing of Genissiat reservoir on the Rhone River in France produced severe damage to the downstream fishery due to insufficient water being available from the upstream reservoirs in Switzerland in 1965 and 1978 [23]. Since then, reservoir operations for flushing have been subject to regulatory limits on downstream sediment loads or concentrations, which have to be taken into account in the detailed planning of every flushing operation. For example, in Switzerland, it is stipulated that the mean suspended sediment concentration (SSC) during flushing operation should not exceed 10 mg/L at the reservoirs in crystalline areas and 70 mg/L at the reservoirs in noncrystalline areas and the peak SSC should be in the range 1–10 g/L except one river with 70 g/L [25]. While in France, it is specified that maximum SSC should not exceed 10 g/L during flushing operation [25]. In order to fulfill the environmental regulations, the flushing operation at Genissiat reservoir has been performed in concert with Verbois and Chancy-Pougny dams in Switzerland since 1978 [26]. Thus to control the environmental effects of sediment flushing operations in Wlingi and Lodoyo reservoirs, it is necessary to regulate and monitor the SSC during flushing and take it into account in the detailed planning of the flushing operations.

http://dx.doi.org/10.5772/intechopen.75034

6. Conclusion

Wlingi and Lodoyo reservoirs are severely affected by eruptions of Kelud volcano, one of the most active volcanoes in Indonesia. Before the February 2014 eruption of Kelud volcano, following the eruptions in 1990 and 2007, the capacity of Wlingi reservoir was, by 2013, restored to 4.83 Mm^3, which corresponds to 20.1% of the initial capacity of 24.00 Mm^3. Similarly, the capacity of Lodoyo reservoir was restored to 2.72 Mm^3, which corresponds to 52.3% of the initial capacity of 5.20 Mm^3. However, after the February 2014 eruption, the capacity of Wlingi and Lodoyo reservoirs decreased dramatically to 2.20 and 1.33 Mm^3, respectively, just 46% and 49% of their pre-eruption capacities and 19.42 and 26.60% of their initial capacities. To cope with the extreme sedimentation problems in Wlingi and Lodoyo reservoirs, diverse sediment management strategies have been applied in these reservoirs and their catchments. Construction of many on-stream sediment control facilities (sabo works) and a sediment bypass channel has reduced sediment inflow to the reservoirs. Removal of deposited sediment by dredging and hydraulic flushing in Wlingi and Lodoyo reservoirs has also resulted in storage capacity recovery. The sedimentation problems in Wlingi and Lodoyo reservoirs are affected by recurrent volcanic activity of Kelud volcano. Consequently, sediment management strategies for both reservoirs require constant maintenance and recurrent operations, evaluation, and improvement in order to achieve sustainable use of the reservoirs for their diverse design purposes, while minimizing downstream environmental and economic effects of the management interventions.

Acknowledgements

The material of this chapter is part of the first author’s dissertation research. The authors would like to acknowledge the financial support for the research and this publication from Jasa Tirta I Public Corporation (PJT-I), Indonesia and the Indonesia Endowment Fund for Education (LPDP), the Ministry of Finance, the Government of the Republic of Indonesia.

Author details

Fahmi Hidayat[1,2]*, Pitojo T. Juwono[3], Agus Suharyanto[1], Alwafi Pujiraharjo[1], Djoko Legono[4], Dian Sisinggih[3] and David Neil[5]

*Address all correspondence to: hidayat.f@jasatirta1.net

1 Civil Engineering Department, Brawijaya University, Malang, Indonesia

2 Jasa Tirta I Public Corporation, Indonesia

3 Water Resources Engineering Department, Brawijaya University, Malang, Indonesia

4 Department of Civil and Environmental Engineering, Universitas Gadjah Mada, Indonesia

5 Centre for Advanced Research on Global Change, Hanoi University of Natural Resources and Environment (HUNRE), Vietnam

References

[1] Milliman JD, Syvitski JPM. Geomorphic/tectonic control of sediment discharge to the ocean; the importance of small mountainous rivers. Journal of Geology. 1992;**100**:525-525

[2] Mercado RA, Bertram J, Lacsamana T, Pineda GL. Socioeconomic impacts of the mount Pinatubo eruption. In: Newhall CG, Punonbayan RS, editors. Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines. Quezon City: Philippine Institute of Volcanology and Seismology/Seattle: University of Washington Press; 1996. pp. 1063-1070

[3] Morris L, G. Sediment management and sustainable use of reservoirs. In: Wang LK, Yang CT, editors. Modern Water Resources Engineering. New York, USA: Humana Press; 2014

[4] Jakob M, Hungr O. Debris-Flow Hazard and Related Phenomena. Chichester, UK: Praxis Publishing Ltd; 2005

[5] Lesage P, Surono. Seismic precursors of the February 10, 1990 eruption of Kelut volcano, Jawa. Journal of Volcanology and Geothermal Research. 1995;**65**:135-146

[6] Soetojo et al. Kelut Volcano Volcanic Debris Control Project. Government of Indonesia: Directorate General of Water Resources Development, Ministry of Public Works and Power; 1969

[7] NASA. Indonesia's Mount Kelud Erupts. 2014. Available from: http://earthobservatory.nasa.gov/IOTD/view.php?id=83144 [Accessed: August 27, 2016]

[8] Global Volcanism Program. Report on Kelud (Indonesia). 2014. In: Wunderman R, editor. Bulletin of the Global Volcanism Network, 39:2. Smithsonian Institution. Available from: 10.5479/si.GVP.BGVN201402-263280

[9] Tanaka LH, Iguchi M, Nakada S. Numerical solutions of volcanic ash plume dispersal from Mt. Kelud in Indonesia on February 13, 2014. Journal of Disaster Research. 2016;**11**(1):31-42

[10] Iguchi M, Surono, Nishimura T, Hendrasto M, Rosadi U, Ohkura T, Triastuty H, Basuki A, Loeqman A, Maryanto S, Ishihara M, Yoshimoto K, Nakada S, Hokanishi N. Methods for eruption prediction and hazard evaluation at Indonesian volcanoes. Journal of Disaster Research. 2012;**7**(1):26-36

[11] Bélizal ED, Lavigne F, Gaillard JC, Grancher D, Pratomo I, Komorowski I. The 2007 eruption of Kelut volcano (East Java, Indonesia): Phenomenology, crisis management and social response. Geomorphology. 2010;**136**:165-175

[12] Bourdier JL, Pratomo I, Thouret JC, Boudon G, Vincen PM. Observations, stratigraphy and eruptive processes of the 1990 eruption of Kelut volcano, Indonesia. Journal of Volcanology and Geothermal Research. 1997;**79**:181-203

[13] Hidayat F, Juwono PT, Suharyanto A, Pujiraharjo A, Sisinggih D, Legono D. Sedimentation in rivers and reservoirs following the eruptions of Kelut volcano, Indonesia. In: Wieprecht S, Haun S, Weber K, Noack M, Terheiden K, editors. River Sedimentation. Leiden, the Netherlands: CRC Press/Balkema; 2017

[14] Hidayat F, Juwono PT, Suharyanto A, Pujiraharjo A, Legono D, Sisinggih D, Neil D, Fujita M, Sumi T. Assessment of sedimentation in Wlingi and Lodoyo reservoirs: A secondary

disaster following the 2014 eruption of Mt. Kelud, Indonesia. Journal of Disaster Research. 2017;**12**(3):617-630

[15] Nippon Koei Co., Ltd. and Associates. Completion Report on Overall Consulting Services for Water Resources Existing Facilities Rehabilitation and Capacity Improvement Project. Government of Indonesia: Directorate General of Water Resources Development, Ministry of Public Works; 2012

[16] Bollaert EFR, Diouf S, Zanasco JL, Barras J. Sequential flushing of Verbois and Chancy-Pougny reservoirs (Geneva, Switzerland). In: Schleiss AJ, De Cesare G, Franca MJ, Pfister M, editors. Reservoir Sedimentation. Leiden, the Netherlands: CRC Press/Balkema; 2014

[17] Sumi T. Sediment flushing efficiency and selection of environmentally compatible reservoir sediment management measures. In: International Symposium on Sediment Management and Dams, 2nd EADC Symposium; Yokohama, Japan; 2005

[18] Sumi T. Evaluation of efficiency of reservoir sediment flushing in Kurobe River. In Fourth International Conference on Scour and Erosion; Tokyo, Japan. 2008. pp. 5-7

[19] Hidayat F, Juwono PT, Suharyanto A, Pujiraharjo A, Sisinggih D, Legono D. 2017. Assessment of efficiency and environmental impact of sediment flushing from Wlingi and Lodoyo cascade reservoirs, Indonesia. In: E-proceedings of the 37th IAHR World Congress, August 13-18, 2017; Kuala Lumpur, Malaysia

[20] Kantoush SA, Sumi T, Suzuki M, Murasaki M. Impacts of sediment flushing on channel evolution and morphological processes: Case study of the Kurobe River, Japan. In: Dittrich, Koll, Aberle, Geisenhainer, editors. River Flow 2010. Bundesanstalt für Wasserbau 2010. ISBN 978-3-939230-00-7

[21] Brignoli ML, Quadroni S, Crosa G, Gentili G, Batalla RJ. Experiences of controlled sediment flushing from four alpine reservoirs. In: Wieprecht S, Haun S, Weber K, Noack M, Terheiden K, editors. River Sedimentation. Leiden, the Netherlands: CRC Press/Balkema; 2017

[22] Annandale GW, Gregory LM, Pravin Karki. Extending the Life of Reservoirs: Sustainable Sediment Management for Dams and Run-of-River Hydropower. Directions in Development. Washington, DC: World Bank; 2016. DOI: 10.1596/978-1-4648-0838-8. License: Creative Commons Attribution CC BY 3.0 IGO

[23] Liu J, Minami S, Otsuki H, Liu B, Ashida K. Environmental impacts of coordinated sediment flushing. Journal of Hydraulic Research. 2004;**42**(5):461-472. DOI: 10.1080/00221686.2004.9641216

[24] Sumi T, Nakamura SY, Hayashi K. The Effect of Sediment Flushing and Environmental Mitigation Measures in the Kurobe River. In: 23rd ICOLD Congress; 2009

[25] Staub E. Effects of sediment flashing on fish and invertebrates in Swiss Alpine rivers. In: International Workshop and Symposium on Reservoir Sedimentation Management; October; Toyama, Japan. 2000. pp. 109-118

[26] Habara S, Suzuki N, Tokito Y, Asaka M. The Measures for the Sediment at the Dam Reservoirs in Europe. Tokyo: Water Resources Environment Technology Center; 2001