Changes in sediment discharge after the collapse of Mount Bawakaraeng in South Sulawesi, Indonesia

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Abstract The inner side of a caldera wall at Mount Bawakaraeng collapsed on a large scale in Sulawesi Island in the Republic of Indonesia on 26 March 2004. There were two landslides, located in the Jeneberang River basin (727 km^2), and the total volume of the collapse was 232 million m^3. The soil covered a wide area of the basin and it has since been eroded by rainfall and flowed into Bili-bili dam, 30 km downstream. Data of rainfall, flow discharge, turbidity of inflow water and water taken to supply Makassar City were recorded since before the collapse. These data were analysed to evaluate the magnitude of the impact of the change of the basin and how the impact decreases over subsequent years. How the basin and the condition of the river bed have changed was analysed in terms of restoration of vegetation, gully formation and armouring of the river bed. The relationship of rainfall and runoff was also analysed and compared from before and after the collapse. The turbidity increased sharply and was 400-times larger after the landslides. The turbidity decreased gradually through three rainy seasons, but it is still much higher than before the collapse. It is estimated that it will take several more years for it to fall back to the level of before the landslide. The rate of water discharge to rainfall decreased after the landslide, probably because the soil retained a lot of rainwater.

Key words Bawakaraeng; Bili-bili dam; sedimentation; turbidity; water discharge

INTRODUCTION

It has been more than three years since the collapse of the caldera walls of Mount Bawakaraeng in Indonesia. Nevertheless, the huge amount of deposited sediments is still generating various environmental and social issues.

Collapse of Mount Bawakaraeng caldera walls

On 26 March 2004, the caldera walls of Mt Bawakaraeng (elevation 2830 m) collapsed (Fig 1). The collapse was predicted because of the combination of weak geological structure, the steep and high walls of the caldera, and high rainfall intensity.

We use the term collapse, rather than landslide, because, according to eyewitnesses in the area, the collapsed mass flowed approx. 2 km downstream from the caldera outlet for 15–30 min before settling. The collapsed volume was estimated at 192.5 million m^3 (CTI, 2006); the sediments buried approx. 6 km of the Jeneberang River, 1500 ha of paddy fields and residential areas, and killed 635 cattle and 32 people. This collapse was one of the largest mass movements in the history of Indonesia.

Jeneberang River

The northwest edge of the caldera wall is where the Jeneberang River flows into Bili-bili dam. The total length of the main river is 75 km, and the catchment area totals 727 km^2 (Fig. 2). The deposit volume (calculated at approx. 232 million m^3) covers 7 km of the upstream portion of this river (Tsuchiya *et al.*, 2004). Five sabo (check) dams and sand pockets were built before the collapse, but Sabo Dam 4 is now completely buried with sediment. In the rainy season, deposited sediments are washed downstream, resulting in occasional debris flows, turbid water, and sedimentation onto the riverbed and in Bili-bili dam. With help from the Japanese Bank for International Cooperation (JBIC), the Public Works of Indonesia is currently building 10 new sabo dams to prevent secondary disasters and to mitigate the sedimentation of Bili-bili dam.

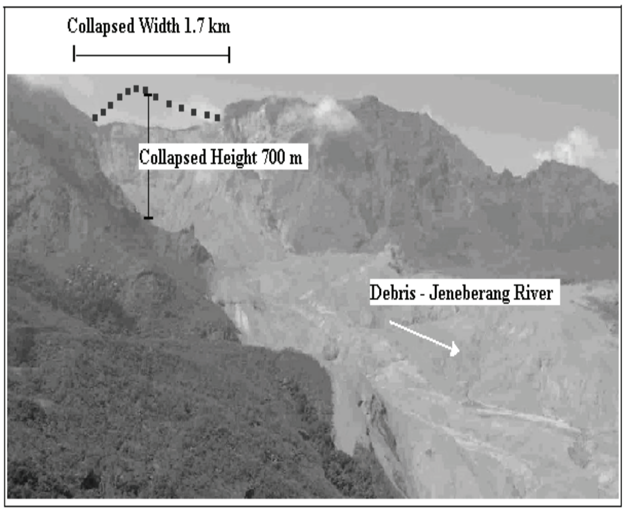

Fig. 1 The collapse area of Mount Bawakaraeng.

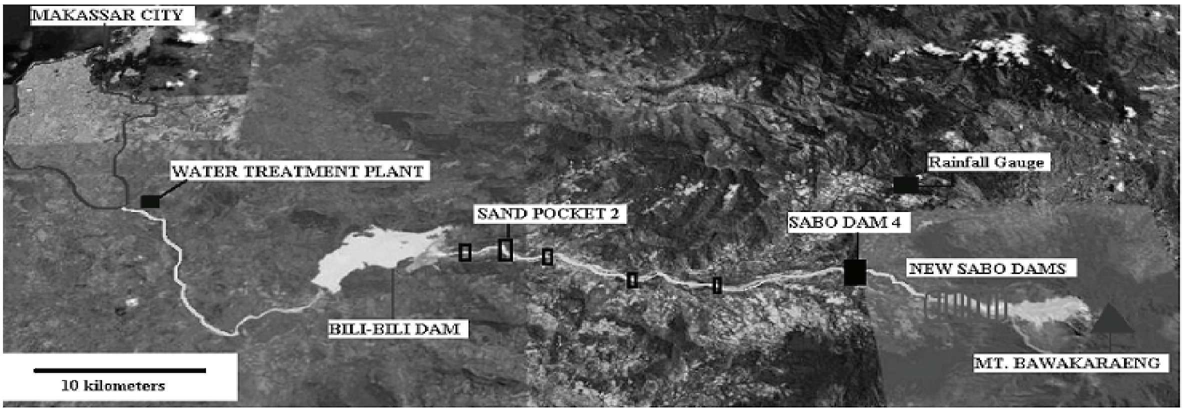

Fig. 2 Map of Mount Bawakaraeng, showing the location of Bili-bili dam, Jeneberang River, Makassar City, and the sabo dams (*modified map from Google Earth, taken on February 2008*).

Bili-bili dam

Bili-bili Dam is located 31 km downstream from Mount Bawakaraeng. With a height of 73 m and a length of 1800 m, this rock-filled-type dam has a water capacity of 346 million m^3 and a sediment storage capacity of 29 million m^3. Bili-bili dam is one of the three most multipurpose dams in Indonesia. It was expected to operate for flood control, water irrigation for 23 660 ha of paddy fields, and as a drinking water resource for the Makassar City population of 1.5 million. Following the collapse, the reduced sediment storage capacity and high turbidity rate are the key crises affecting this dam because high turbidity adds to the cost of treating drinking water. Consequently, despite the fact that Bili-bili dam spared Makassar City from two major floods, after the collapse of Mount Bawakaraeng, the local community believes that Bili-bili dam has lost its function.

METHODS

Change in water discharge

One way to identify watershed change is to analyse water discharge because changes made to the landscape alter the timing and amount of waterflow, which over time also affect channel shape and stability (Dunne, 1978). The daily inflow water discharge and daily rainfall data of the years 2001–2006 were obtained from the Bili-bili Dam Control Office and the Monitoring Office of Jeneberang River Basin Development Project (JRBDP) at Makassar Office. The changes in the relationship between rainfall and discharge before and after the collapse were analysed by calculating the daily, monthly, and annual rainfall–discharge coefficient:

$$Q = \alpha_{QR}\ R \qquad (1)$$

where α_{QR} is the rainfall discharge coefficient, Q is the amount of discharge (mm), and R is the amount of rainfall (mm).

Turbidity rate before and after the collapse

Turbidity is an expression of the light-scattering optical property of water (Dunne, 1978). Values of turbidity are expressed in nephelometric turbidity units (NTU); the value increases with increasing suspended organic or inorganic matter particulates. Daily water samples were taken at Bili-bili dam and at several points upstream in the Jeneberang River. These data were obtained from both the Bili-bili Dam Control Office and Japan International Cooperation Agency (JICA) Jeneberang Study Team. To evaluate the effect of the change in discharge on the turbidity rate, a turbidity–discharge coefficient was identified (assuming that turbidity is proportional to discharge):

$$T = \alpha_{TQ}\ Q \qquad (2)$$

where α_{TQ} is the turbidity–discharge coefficient, T is turbidity (NTU), and Q is the amount of discharge (mm).

RESULTS AND DISCUSSION

Change in water discharge

We used rainfall and discharge data from January 2001 to December 2006 to define the changes in water balance before and after the collapse. The rainy season in this area occurs from November to April and peaks in December. Table 1 illustrates the annual discharge and peak flow, as well as the annual rainfall intensity. In 2003, one year before the collapse, the rainfall intensity and discharge was particularly high.

Figure 3 illustrates the relationship between rainfall and discharge before and after the collapse through the rainfall–discharge (RD) coefficients of the daily, monthly, and annual amounts of rainfall and discharge. The RD coefficients substantially decreased after the collapse when analysed from a daily perspective (i.e. the daily amount of rainfall generates less daily water discharge). Before the collapse, 1 mm of rainfall commonly generated 0.67 mm of water discharge; after the collapse, in 2004, 2005, and 2006, 1 mm of rainfall generated only 0.45 mm of water discharge.

Table 1 Annual rainfall and discharge.

Year	Discharge: total (mm)	max. (mm/day)	Rainfall total (mm)
2001	3847.48	139.31	4186.00
2002	2960.84	155.50	2925.00
2003	4346.96	199.29	4628.00
2004	4064.73	110.69	4083.00
2004 (after the collapse)		28.54	
2005	2776.96	60.78	3131.00
2006	3391.25	125.23	4125.00

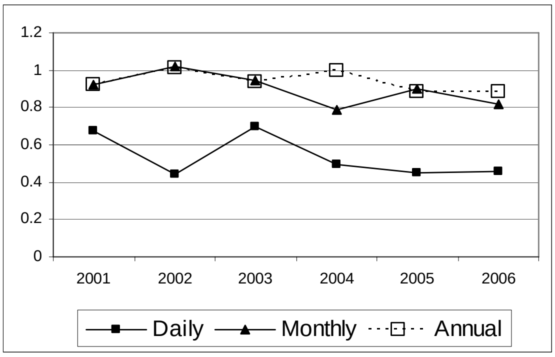

Fig. 3 Daily, monthly, and annual rainfall discharge coefficients for 2001–2006.

The decreasing trend in the daily discharge coefficient can be explained by the ability of upstream deposited sediments to store water. The sediment deposited upstream is not flat in most areas and has undulations that allow the formation of water pools. Moreover, the porosity of these sediments is rather high, at 0.40 (CTI, 2006), enhancing their ability to absorb and retain rainfall water. In addition, fresh sediments (from slope or gully erosion) arrive from time to time; these cover the natural and former drainages and convert surface flows into subsurface flows, thus slowing discharge. This accounts for the insignificant decrease in RD coefficients when analysed from monthly and annual perspectives.

Compared to the daily RD coefficients, the monthly and annual coefficients are similar before and after the collapse. Before the collapse, the monthly and annual RD coefficients were on average 0.96; these decreased to approx. 0.88 in 2005 and 2006. In the year of the collapse (2004), the monthly RD was 0.78, whereas the annual RD was 0.98. It is noteworthy that these figures may represent an underestimation of rainfall intensity because rainfall tends to become greater as elevation increases (the highest installed rainfall gauges at the Jeneberang catchment are only at 1010 m). Therefore, the annual coefficients of close to 1.0 might be overestimations due to the underestimation of rainfall.

Turbidity Rate before and after the Collapse

Figures 4 and 5 illustrate the significant difference in Bili-bili dam's raw water turbidity rates before and after the collapse (the collapse is indicated by the dotted vertical line). High turbidity rates occurred during the peak of the rainy season, in the months of December and January.

Three months before the collapse, the turbidity rate began an unusual increase. Thus, we suspect that small slope failures might have occurred from early December 2003. Before the collapse and the small slope failures, the maximum turbidity rate was 407 NTU. Within the first rainy season after the collapse, this rate increased by >300 times to 125 159 NTU. The maximum

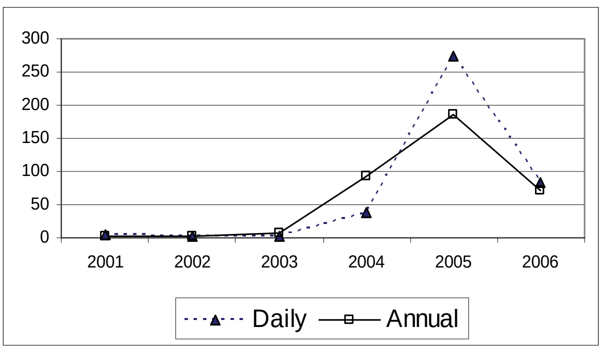

Fig. 4 Rainfall and turbidity at Bili-bili dam, 2001–2007.

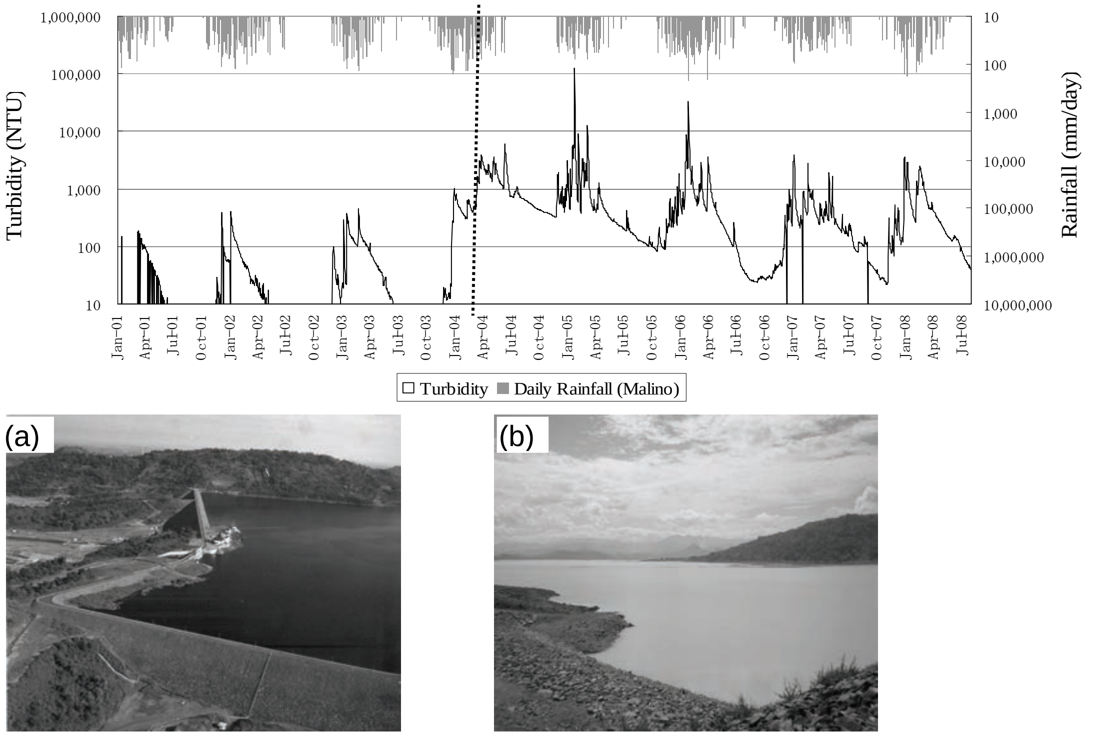

Fig. 5 Daily and annual turbidity–discharge coefficients, 2001–2006. Bili-bili dam water: (a) before, and (b) after, the collapse of Mount Bawakaraeng.

turbidity rate declined to 33 241 NTU in 2006 and 3933 NTU in 2007. Before the collapse, the minimum turbidity rates in the dry season were normally close to zero. However, after the collapse, the turbidity rate decreased to a minimum of only 22 NTU in October 2007.

Before the collapse, the daily turbidity–discharge coefficient averaged 3.22 (i.e. every 1 mm of discharge generated 3.22 NTU). The coefficient increased sharply to 37.06 in 2004 and 274.34 in 2005, before decreasing to 83.48 in 2006. In 2004, there was a large range in daily turbidity, which resulted in a higher annual coefficient (92.7) than the daily coefficient. However, in 2005, the annual coefficient (184.79) was lower than the daily coefficient. Both the annual and daily coefficients fell by 30% two years after the collapse.

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