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Practical Case Study

SEDIMENTATION CONTROL: PART I. INTENSIVE MEASURES OUTSIDE OF THE WONOGIRI RESERVOIR, CENTRAL JAVA

SOEWARNO* and SUTIKNO HARDJOSUWARNO

The Experimental Station for Sabo, Research Centre for Water Resources Development, Sopalan Maguwoharjo, Yogyakarta 55282, Indonesia
*Corresponding Author: Phone: +62 274 886350, Fax: +62 274 885341, E-mails: soewarnohd@yahoo.com; sutiknohs@hotmail.com

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Abstract: Wonogiri reservoir is one of the large reservoirs in Java Island, the construction of the reservoir started in 1976 and the inundation finished in 1982, functioned as a multi-purpose dam. The catchments area of the reservoir is 1,350 km^2 and the inundated area is 90 km^2. One of the problems arouse in the operation of Wonogiri Reservoir is sedimentation which decreases its capacity. Research was conducted in 2005 to 2006 using data collection provided by local authority and field measuerement and observation. The result of the research identified 1) the sedimentation rate and the remaining capacity and the remaining service period, 2) the sediment source catchments and percentage of bed load to the suspended load, and 3) efforts to maintain the remaining capacity of Wonogiri reservoir, covering some efforts to decrease sedimentation rate in the reservoir and to decrease the incoming sediment flow into the reservoir.

Keywords: Excavation of sediment, cleaning up of garbage, land conservation, Sabo dams, sand mining, small reservoirs

INTRODUCTION

Under natural conditions, sediment is transported from land to water in runoff. The increased rate of delivery of sediment can cause stream sedimentation problems [1-2]. Therefore, sedimentation in reservoir is a natural process. However, sedimentation can be enhanced by anthropogenic activities such as deforestation and mismanagement of riparian zone [3]. A lot of reservoirs in the world have been covered with sediment and the reservoirs function changed to runoff reservoir only [4]. Some examples were the rate of decrease of the reservoir capacity in the arid and semi arid varies about 1-2% annually, the storage capacity of Welbedacht reservoir in South Africa was lost of about 66% after 13 years in operation, and the measurement of 9 most important reservoirs in India showed that the reservoir capacity decreases, ranging from 0.34% to 1.79% annually.

Java land area has only 7% of the total Indonesian land area and should suffice freshwater for 65% of the total population. Wonogiri reservoir that is called Gadjah Mungkur Reservoir is one of the large reservoirs in the island. The inundation area was 90 km^2, collecting water from the catchment area of 1,250 km^2. The construction of the reservoir began in 1976 and totally completed in 1982. The use of Wonogiri reservoir were among others for flood control of Solo river, water supply for hydro power of 55,000 MWh to provide electricity for 61,000 households, water supply for agricultural irrigation of 27,000 ha, water supply for domestic, industry, fishing and tourism. Based on the study for master plan of Wonogiri Reservoir in 1978, it was estimated that yearly erosion rate was 1.17 mm and the effective time of the reservoir was designed at 100 years. However, the present condition of the water resources is so bad such as floods and drought occur alternately in many places during rainy season [5]. The water quality decreased due to on going pollution by urban, agricultural and industrial wastes in addition to soil erosion and re-suspension of river sediment. The sediment is a pollutant in its own right, causing turbidity in the water that limits light penetration and prohibits healthy plant growth on the river bed. Sediment also covers much of the river bed with a blanket of silt. Sediment is an important carrier of a critical pollutant: phosphorus. This nutrient stimulates excessive algae growth in the water column. When the algae decompose, it depletes dissolved oxygen from the water, reducing the quality of life forms that are able to survive. Meanwhile, soil erosion and flood that increased sedimentation in Wonogiri reservoir was probably due to the decrease of forest conservation with an amount of 1.6 ha annually [5]. As a result, the reservoir volume decreased and its service period shortened.

One of the problems arising from the reservoir operation was the sedimentation of the reservoir. The decrease of reservoir volume due to high rate of erosion has caused the shorter service period compared with the designed one and hence, the usefulness of the reservoir was certainly decreasing faster. Therefore the objectives of this research were to measure the sedimentation rate, the remaining capacity of the reservoir, the remaining service period of the reservoir, the sediment sources of the catchments, percentage of bed load to the suspended load, and assessment of the measures for maintaining the remaining capacity of Wonogiri reservoir.

MATERIALS AND METHODS

The authors conducted the research in Wonogiri reservoir catchments during the year of 2005 – 2006. More than 90% of the catchments are situated in the Regency of Wonogiri, Province of Central Java, small portion of the catchments belong to the Province of Jogjakarta Special Region and the remaining catchments belong to the Regency of Pacitan, the Province of East Java. Figure 1 shows the location of research of Wonogiri reservoir catchments.

The following data were obtained. Time series of reservoir sounding data, reservoir inflow, discharge and sediment concentration, land use and 13 sheets of topographical map published by Agency for National Survey and Mapping (Bakosurtanal) on the scale of 1:25.000, covering the whole Wonogiri reservoir catchments. Interview to several institutions i.e. Management of Wonogiri Reservoir, Bengawan Solo Project Office, Experimental Station for Bengawan Solo Water Resources Management and Regional Planning Board (Bappeda) of Wonogiri Regency. Other data were excavation and disposal of garbage, flushing, conservation, Sabo dam facilities and small reservoirs that were assessed using descriptive and qualitative analysis.

Field measurements consists of inflow to Wonogiri reservoir, water level, discharge and sediment load inflowing to the reservoir at the hydrometrical stations of Keduang, Tirtomoyo, Temon, Upper Solo, Alang and Wuryantoro rivers. The discharge measurement was conducted using current meter of propeller type. The suspended sediment was sampled using suspended sampler adjusted to the discharge at the time measurement. The result of the measurement was used for the analysis of rating curve and sediment rating curve at the point of measurement.

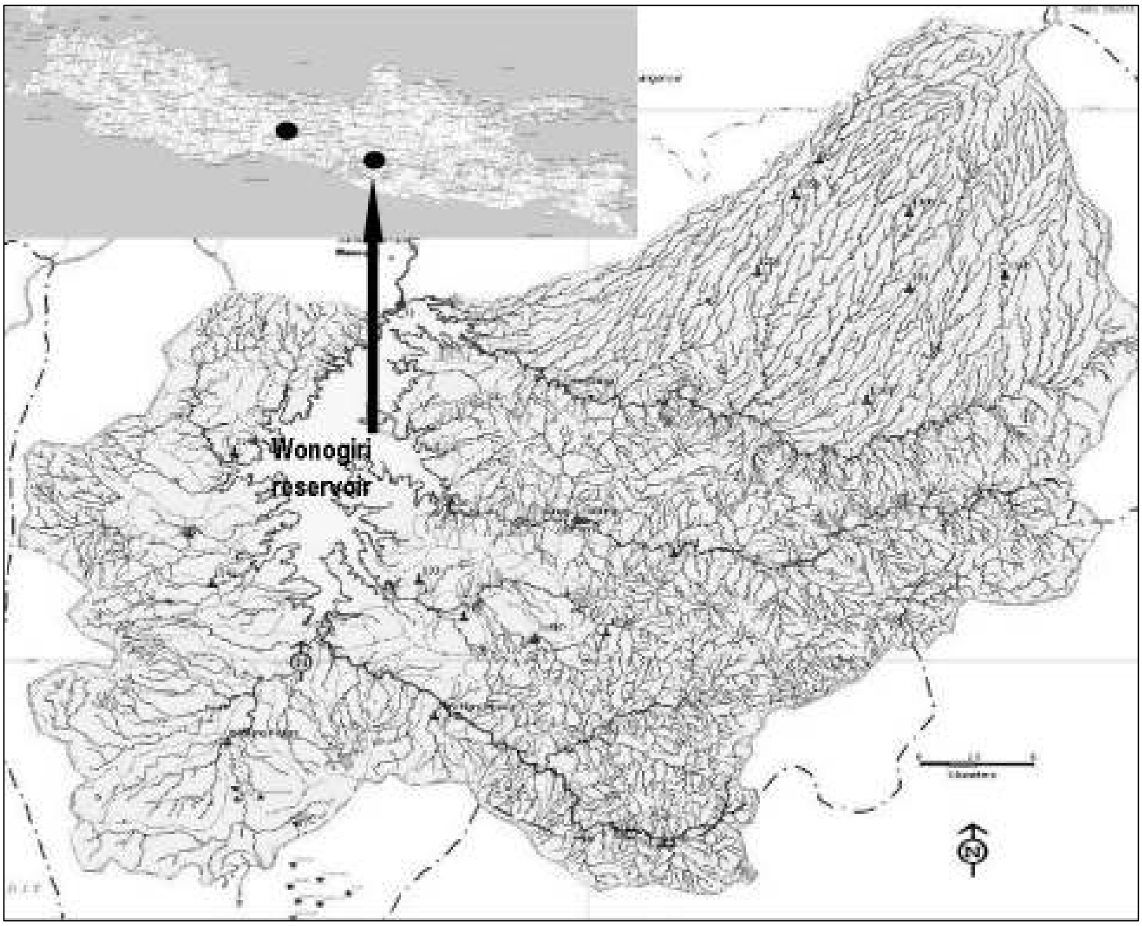

Fig. 1: Wonogiri reservoir catchments Central Java

The rate of reservoir sedimentation was determined by comparing the designed capacity and the capacity based on sounding in 2004.The prediction of the period of reservoir life based on the analysis of storage capacity of the reservoir resulted from sounding. The catchments area of sediment sources was identified by comparing the largest sediment load measured in the catchments area of Keduang, Tirtomoyo, Temon, Upper Solo, Alang and Wuryantoro rivers.

RESULTS AND DISCUSSION

Sedimentation Sources and Rate

Sediment produced in the upstream of Wonogiri reservoir carried downstream through rivers by floodwaters, and then deposited on the land inundated by these rivers. During flood periods, rivers carry large quantities of sediment, entering Wonogiri reservoir. The sediment sources in the catchments were identified by measuring and processing discharge and suspended load data taken from 6 hydrometric stations inflowing to Wonogiri reservoir. Those stations were located near the river mouth to the reservoir but beyond the influence of backwater effect of Wonogiri. Table 1 shows the equation of suspended sediment rating curve of the 6 hydrometric stations. It was calculated that the sedimentation rate was 6.80 millions m^3 $year^{-1}$. The sedimentation rate was originated from suspended sediment load of sub catchments area in Wonogiri reservoir. The total sediment deposited in Wonogiri reservoir was 7.50 millions m^3 $year^{-1}$, therefore the volume of bed load was 0.70 millions m^3 $year^{-1}$ or about 10.30% of suspended sediment volume yearly.

Table 1: Suspended sediment rating curve of hydrometric station in Wonogiri reservoir catchments

Sub.Catchments of Wonogiri reservoir catchment	Regression analysis between sediment discharge (Q_s) and water discharge (Q_w)	Coefficient of determintion
Keduang – Ngadipiro	$Qs = 16.667\ Qw^{1.3973}$	0.8702
Tirtomoyo – Sulingi	$Qs = 19.634\ Qw^{1.6093}$	0.8886
Temon – Duwet Lor	$Qs = 22.037\ Qw^{1.5066}$	0.8469
Bengawan Solo – Ngrembang	$Qs = 26.508\ Qw^{1.4288}$	0.6646
Alang – Jatisawit	$Qs = 26.780\ QW^{1.7397}$	0.9010
Wuryantoro – Tiken	$Qs = 20.554\ Qw^{1.5039}$	0.7264

An example of suspended sediment rating curve equation is shown on Fig. 2 that is the suspended sediment rating curve for Keduang – Ngadipiro.

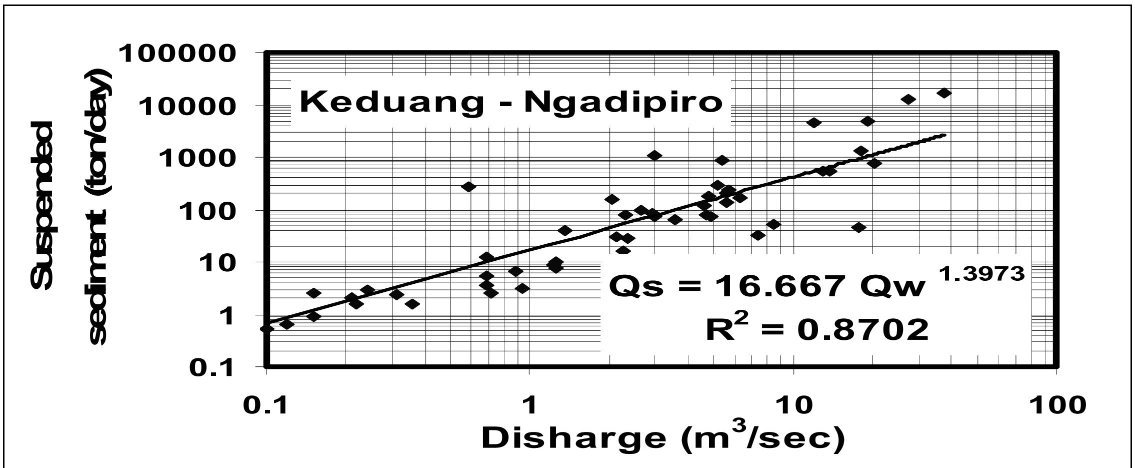

Fig. 2: Suspended sediment rating curve for sub catchment Keduang - Ngadipiro

The descending order of contributing suspended sediment to Wonogiri reservoir were sub catchments of Tirtomoyo-Sulingi (39.9 %), Bengawan Solo – Ngrembang (23.2%), Keduang – Ngadipiro (22.2%), Alang – Jatisawit (11.1%), Wuryantoro – Tiken (1,9%), and Temon – Duwet Lor (1.7%). The order of magnitude of suspended sediment might indicate the magnitude of erosion rate in Wonogiri Reservoir.

Remaining Storage Capacity and Service Period

Based on the sounding data obtained from Bengawan Solo Project, it showed that the storage capacity at the elevation +138.30m was 780 millions m^3 at the beginning of inundation in 1980. The storage capacity decreased to 601 millions m^3 in 2004. Therefore, the decreasing rate of the storage capacity was rounded to 7.50 millions m^3 $year^{-1}$, and this accounted for the sedimentation rate of Wonogiri reservoir. Table 2 shows the remaining storage capacity of Wonogiri reservoir within the last 25 years operation. An example, the volume of dead storage with an amount of 120 millions m^3 (1980) was the storage capacity below the elevation of +127.0 m that remains 45% in 2004. The effective capacity still remains 73.87 %, or 26.13 millions m^3 has lost. The total capacity has lost 22.94 % out of the design capacity.

Table 2: Estimated remaining storage capacity of Wonogiri Reservoir

Zone of capacity	Elevation (+ m)	Volume, millions m^3		Decrease of capacity		Remaining storage capacity %
		1980	2004	Million m^3	%	
Flood control	135.3 -138.3	220	222	-	-	-
Effective	127.0 – 135.3	440	325	115	26.13	73.87
Dead storage	Below 127.0	120	54	66	55.00	45.00
Total capacity	Below 138.3	780	601	179	22.94	77.05

The capacity of flood control zone at the elevation between +135.3m and + 138.3m did not decrease. The stable capacity was due to the operation of the reservoir in the dry and rainy seasons were kept at the elevation +136.0m and maximum +135.3m respectively. The fine sediment did not deposit in the flood control zone.

Due to the lack of sounding data series, the estimation of the remaining service period should consider discharge of inflow, reservoir storage capacity, sediment inflow to reservoir, and percent of sediment deposited in reservoir [6-7]. The inflow of Wonogiri reservoir was calculated based on water level data of reservoir 1983-2003. The annual inflow analysis uses water balance method that resulted in 1.175 millions m^3 $year^{-1}$, flowing into Wonogiri reservoir. Since the inundation of the reservoir, the sedimentation did not only deposit in the dead storage, but it also deposited on the effective capacity. In summary, the service period of Wonogiri reservoir is shown in Table 3, suggesting the service period of 63 years. Since the reservoir has been in operation for 25 years and hence, the remaining service period is 38 years. The authors predicted the capacity for irrigation and hydropower of Wonogiri reservoir remains only 112 millions m^3 (20 %) up to the year of 2045 that is 16 years faster than previously projected.

Table 3: Estimation of remaining service life of Wonogiri Reservoir

No	Capacity (C)	Dicharge inflow (I)	(C/I)	Trapped sediment		Avg. eff sed.	Inrement volume	Filling period
1	560.00	1175	0.48	0.98				
2	448.00	1175	0.38	0.97	0.98	7.35	112.00	15.24
3	336.00	1175	0.29	0.96	0.97	7.28	112.00	15.40
4	224.00	1175	0.19	0.94	0.95	7.13	112.00	15.72
5	112.00	1175	0.10	0.89	0.92	6.90	112.00	16.23
							Sum	62.58

Sedimentation Control

Wonogiri reservoir has been experiencing sedimentation that resulted in decreasing of storage capacity or service period. The sedimentation rate in Wonogiri reservoir was 750 millions m^3/100 years (S) and the total capacity of Wonogiri reservoir was 780 millions m^3 (C), therefore, the ratio of S/C was approached to 1. The high S/C ratio suggested to control the sedimentation rate that confirms to USBR criteria [2] for the ratio of more than 0.05. The sedimentation control for Wonogiri reservoir was carried out mainly using technological approach as follows: 1) flushing deposited sediment in reservoir, 2) excavation of sediment, 3) cleaning up of garbage, 4) land conservation, 5) construction small reservoirs, 6) construction of Sabo dams, and 7) sand mining. Except flushing, all of the sediment controls were conducted outside the reservoir.

Flushing

Flushing was used to dispose sediment from reservoir through disposal channel with sudden flow with low water level on the reservoir. The reservoir was kept in empty state during flushing. Experience in intermittent flushing showed that downstream populated area was affected. Especially river water was polluted to the extent that the existing treatment plant could not produce acceptable quality of clean water. Taking into consideration that on the downstream of Wonogiri reservoir there are urban area such as the city of Wonogiri which is densely populated, therefore the regular flushing through 3 spill way gates was not suitable. It also considered that the sudden release of large amount of water might cause flood on the downstream of the reservoir due to the limited capacity of river channel in addition to negative effect towards water quality in downstream area [8].

Excavation

In order to reduce the sedimentation, excavation in front of reservoir intake and its vicinity was conducted in 2003. The sediment deposited in front of intake consists of particularly mud or clay, the volume of excavation was 250,000 m^3. Keduang river catchments contributed at least 1.5 millions m^3 $year^{-1}$ of suspended load. The vacant space as a result of excavation would be filled up to 6 years. In addition, Keduang river catchments transported agricultural and household wastes. It was estimated that about 5 years after excavation, the area in front of intake of Wonogiri reservoir will be full of sediment. Therefore, excavation was a good practicable means to dispose the reservoir sediment even it was expensive and required a lot of space for spoil bank. In addition, based on the field observation, excavated material disposed near reservoir was sufficiently fertile for the growth of one seasonal plant such as cereal, corn and the other dry cultivation.

Sanitation

Field observation showed that excavated material near reservoir is sufficiently fertile mass for the growth of seasonal plants such as cereal, corn and the other dry cultivation. The cropland nearby reservoir produced plant debris that entering river when rain. In addition, sanitation practice such as garbage disposal was not properly managed in Wonogiri reservoir catchment. An experience in rainy season, an observed amount of garbage of 1,250 m^3 was found in front of the intake screen of the reservoir. The amount of garbage, which was approximately equivalent to 125,000 households-days, disturbed turbine operation for 10 – 30 days. Therefore, cleaning of garbage in front of the intake screen used to be conducted by flushing through spillway.

Land Conservation

Wonogiri reservoir catchments have forest area only 14.53%, meanwhile the dry field and settlement cover 63.63% that the conditions triggered the soil erosion. The dry field spreads throughout Wonogiri reservoir catchments, in the form as terraces used for seasonal and multi seasonal plants with a various density. Based on the field observation, the cause of large sedimentation in Wonogiri reservoir could be identified as the area of critical land, improper land cultivation, and increasing population density from 510 persons km^2 (1983) to 611 persons km^2 (2003). A multidimensional crisis which has been lasted since 1998 caused the increase of poverty rate. The people damage the environment such as deforestation to maintain their life. In addition, the forest land consisting of national forest, society forest and plantation tended to change their function. As a result, soil erosion increased as well as sedimentation in reservoir..

Reforestation has been in progress through National Movement Program for Land and Forest Rehabilitation (GERHAN) that commenced in 2003. The idea was ground cover is the most important factor in terms of preventing erosion. Any existing vegetation that can be saved will help prevent erosion. Vegetative cover shields the soil surface from raindrop impact while the root mass holds soil particles in place. Vegetation also can filter sediment from runoff. Therefore, the objective of GERHAN is to achieve well function of the catchments, rehabilitation of forest and natural resources, hazard mitigation of flood, bank collapses and draught. Some activities for catchments management in the Regency of Wonogiri were conducted from 1994 to 2003. These were provision of various sizes of gully plug, absorption well, stream bank protection, construction of small reservoir, check dam, terrace rehabilitation, society forest, bamboo plantation, and provision of green space in urbanized area.

Land and water conservation comprised physical and non physical activities. The physical activity consisted of mechanical and agronomical conservation. Examples were slope management by making terraces bar, land management with reforestation, the development of society forest, channel management by making gulley plug, ponds etc. These were in conformity to shading of larger streams and rivers by riparian vegetation that can reduce sedimentation [9-10]. Non physical activity was mainly to increase society awareness to support agricultural conservation business, attempting to increase community participation in re-greening and land rehabilitation.

Small Reservoirs

Some small reservoirs were constructed in the upstream of Wonogiri reservoir catchments. The small reservoirs provided water for irrigation, reduced sedimentation rate inflowing into Wonogiri reservoir, and acted as flood control. There were five reservoirs comprising Ngancar, Nawangan, Song Putri, Plumbon and Parangjoho with the capacity of 2.050, 0.725, 0.725, 1.050 and 1760 millions m^3 respectively. Based on the field observation, all of the reservoirs were in good condition and effectively control the sedimentation rate in the total catchment area of 26.71 km^2. These effective reservoirs conform to water management strategy for small reservoir, focusing in controlling sedimentation [8, 11].

Sabo Dams

Gully plug and check dam were generally constructed on the tributaries of the upstream Wonogiri reservoir catchments. The function of the structures is to retain the sediment from the tributaries and on the hilly area where coarse material was originated. In addition, four Sabo dams were constructed on the tributaries of Wonogiri reservoir catchments, particularly in the main river inflowing into Wonogiri reservoir. They were three in Keduang river and one in Tirtomoyo river. The total capacity of the dams was 400.000 m^3 that retained the bed load of about 0.70 m^3 $year^{-1}$. Field observation to four Sabo dams showed that they have been full of sediment of various sizes. Almost all river courses in the downstream of Sabo dams in Keduang river suffered from degradation and bank erosion. Due to the degradation and bank erosion, the sedimentation increased at the river mouth of Keduang river, entering to Wonogiri reservoir in which water color was browner than its vicinity. Particularly in Tirtomoyo river, bank erosion had occurred intensively. The height of the bank on the river segment varies from 0.50 – 2.0 m that easily collapsed along 10 km length. However, the effectiveness of Sabo dams on the sedimentation rate was difficult to determine due to lack of data and the absence of reservoir sounding data.

Sand Mining

The river flow of Alang and upper Solo river transported sand particles. The deposited sand in the rivers attracted people to conduct mining even only for local use. Sand mining significantly reduced sedimentation rate. In comparison to dredging that each time it is done, only the amount accumulated at the time of the dredging is removed, so although it is not an expensive process, it must be done every year and in the long term is often a costly solution [6, 12]. Therefore, sand mining by individuals would be desirable, suggesting the river authority to provide access road and the Government to facilitate the marketing facilities.

CONCLUSIONS

Storage capacity of Wonogiri reservoir decreased as result of sedimentation. The sedimentation rate/100 years over the storage capacity was nearly 1, suggesting sedimentation control was necessary. Wonogiri reservoir was a case of comprehensive countermeasure against sedimentation outside the reservoir to keep the effective life of the reservoir in accordance with its design life. Excavation of sediment and cleaning up of garbage, sediment flushing, land conservation, construction small reservoirs and Sabo dams were carried out effectively outside reservoir. However, flushing in reservoir was not recommended since it will cause flooding on the downstream of reservoir which are densely populated and may cause degradation of water quality. Moreover, sedimentation control related to erosion control and hence, it is necessary to 1) prevent hillside erosion by means of reforestation, 2) manage riparian zone along rivers, 3) establish more representative hydrological network, 4) conduct reservoir sounding periodically, 5) study the possibility of bypassing from Keduang river to the downstream of Wonogiri reservoir, and 6) involve local community in the implementation of land and water conservation, particularly in good sanitation practices such as well managed garbage disposal.

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