Annex No.3
Assessment of Wonogiri Reservoir Sedimentation

120THE STUDY ON
COUNTERMEASURES FOR SEDIMENTATION
IN
THE WONOGIRI MULTIPURPOSE DAM RESERVOIR
IN
THE REPUBLIC OF INDONESIA

FINAL REPORT

SUPPORTING REPORT I

Annex No.3 Assessment of Wonogiri Reservoir Sedimentation

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CHAPTER 1 WONOGIRI MULTIPURPOSE DAM

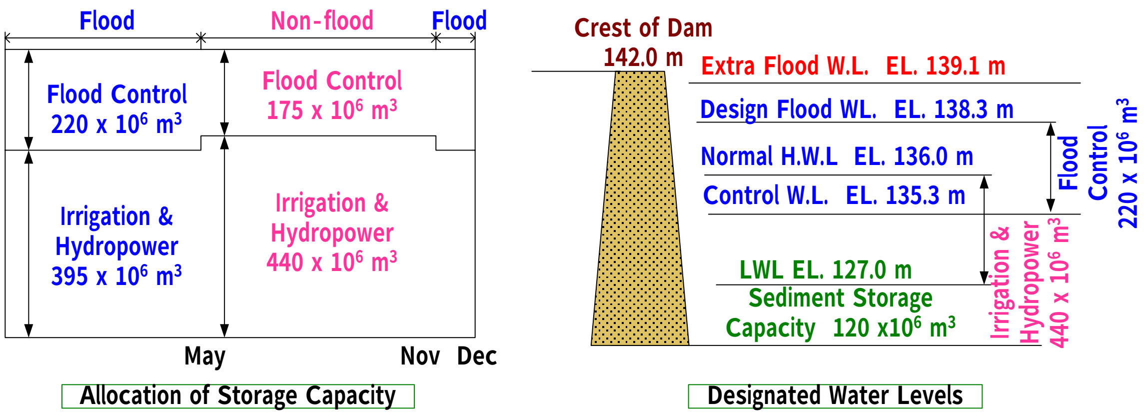
1.1 Principal Feature of Wonogiri Multipurpose Dam

The principal feature of the Wonogiri Multipurpose Dam Reservoir is summarized in Table 1.1.1 below and the allocation of the storage capacity and designated water levels are also shown in Figure 1.1.1 below.

Table 1.1.1 Principal Features of Wonogiri Multipurpose Dam and Reservoir

Dam type	Rockfilll	Normal Water Level	EL. 136.0 m
Dam height	40 m	Design Flood Level	EL. 138.3 m
Crest length	830m	Extra Flood Water Level	EL. 139.1 m
Embankment volume	1,223,300 m^3	Spillway (Radial gate)	7.5 m x 7.8 m x 4 nos.
Catchment area	1,350 km^2	Crest height	EL. 131.0 m
Reservoir area	90 km^2	Flood inflow discharge	4,000 m^3/s
Gross storage capacity	735 x 106 m^3	Flood outflow discharge	400 m^3/s
Active storage capacity	615 x 106 m^3	Design flood discharge	5,100 m^3/s
Flood control storage capacity	220 x 106 m^3	PMF	9,600 m^3/s
Irrigation & hydro power storage capacity	440 x 106 m^3	Installed capacity	12.4 MW
Sediment storage capacity	120 x 106 m^3	Design head	20.4 m
Sediment deposit level	EL. 127.0 m	Max. discharge	75 m^3/s
Limited water level in flood during flood season	EL. 135.3 m	Annual energy output	50,000 MWh

Source: PBS



Source: PBS

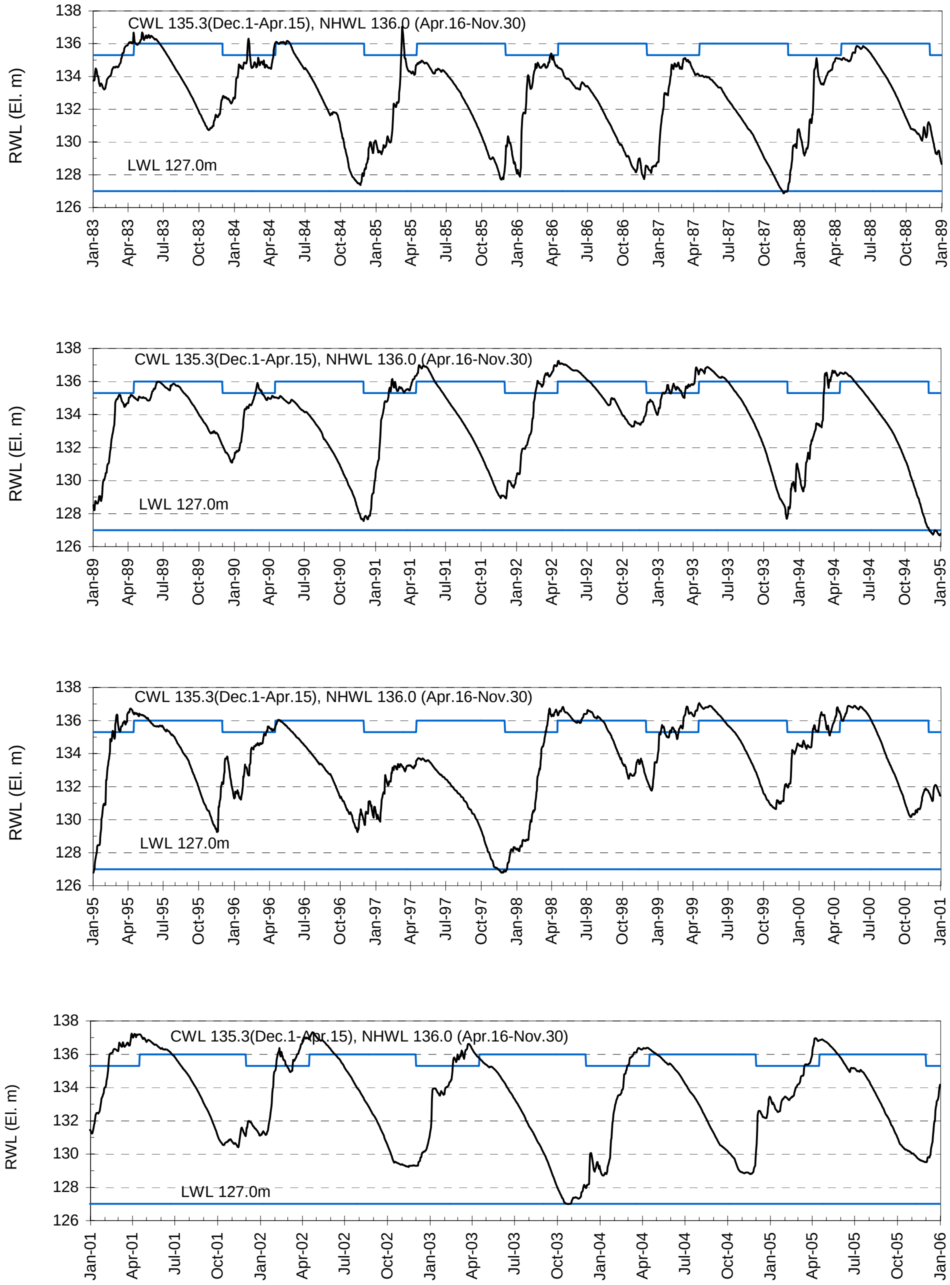
Figure 1.1.1 Allocation of Storage Capacity and Water Levels of Wonogiri Dam

1.2 Performance of Wonogiri Dam Reservoir Operation

1.2.1 Reservoir Operation

The mean annual inflow volume of approximately 1.23 billion m^3 in 1983-2005 (see Figure 1.2.2 in the next page) exceeds the reservoir volume of 735 million m^3 at the design flood water level of EL. 138.3 m. The reservoir water level hydrograph in

1983-2005 is presented below.

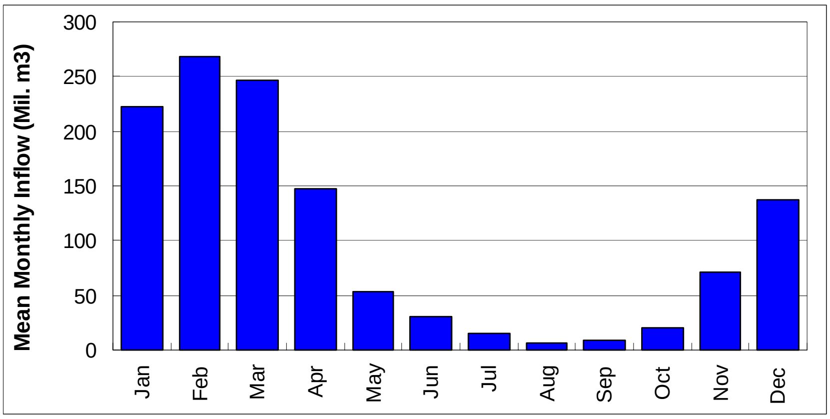


Source: Wonogiri Reservoir Operation Record obtained from PJT-1 and PLTA Wonogiri

Figure 1.2.1 Wonogiri Reservoir Water Level Hydrograph in 1983-2005

Figure above shows the annual sequence that water storage during the wet season and followed by irrigation and hydropower generation releases during the dry season. Because of the progress of sedimentation in front of the intake, the Wonogiri reservoir has been operated since 1996 not to lower the El. 130.0 m (except in 2003 when the dredging of sediments at the intake was made under the JICA Grant Aid Program).

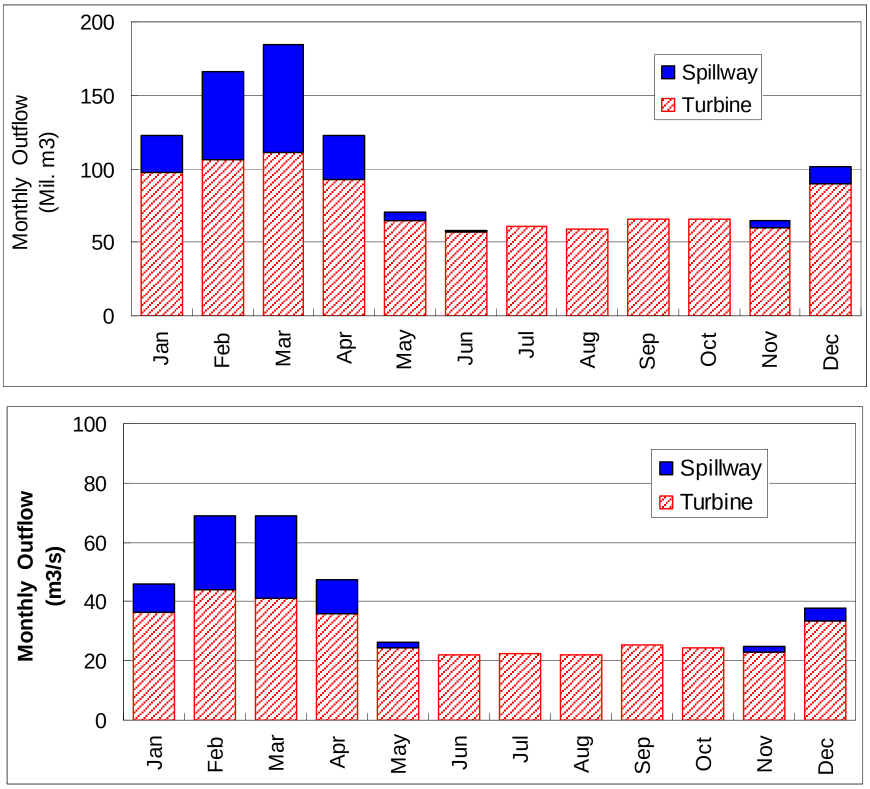
Figure below shows the estimated mean monthly inflow into the Wonogiri reservoir in 1983-2005. Mean monthly inflow of 110.8 m^3/s (268 million m^3) is the highest in February, and August becomes the lowest of 2.3 m^3/s (6 million m^3). The estimated runoff coefficient is 0.46 and its annual runoff depth is 912 mm.



Source: JICA Study Team

Figure 1.2.2 Estimated Mean Monthly Inflow into Wonogiri Reservoir (1983-2005)

Figure 1.2.3 below shows the mean monthly outflow from the Wonogiri reservoir in 1983-2005. The outflow comprises the water release through spillway and hydropower generation. As shown, the mean annual water release from spillway (spillout) is around 18% of the total outflow volume or 210 million m^3. The remaining volume (82% or 932 million m^3) is used for hydropower generation.

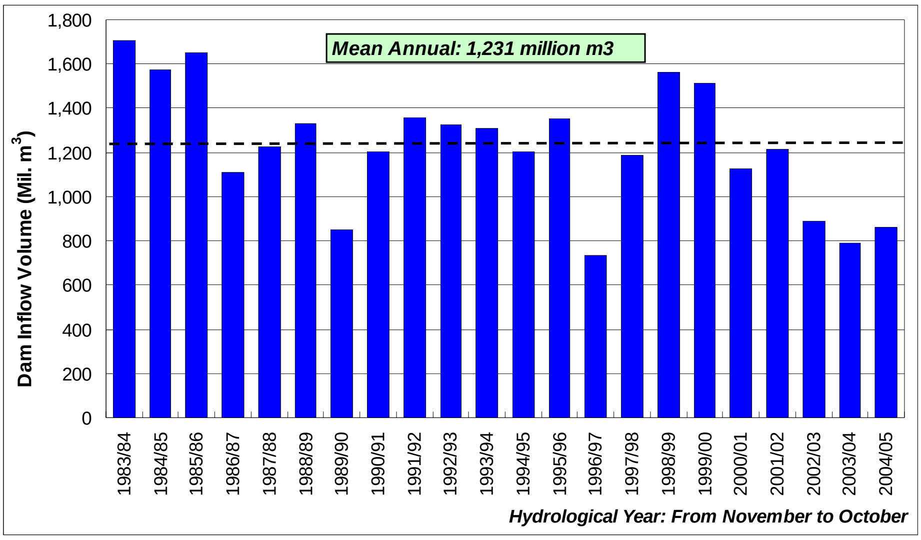


Source: Wonogiri Reservoir Operation Records obtained from PJT-1 and PLTA Wonogiri

Figure 1.2.3 Mean Monthly Outflow from Wonogiri Reservoir in 1983-2005

It is noted that the excessive water release from the spillway in the beginning of wet season unusually occurred in November only in 1998 and in December only in 1995 respectively. Figure below shows the monthly inflow into Wonogiri reservoir in 1983-2004 in terms of the hydrological year basis November to October. Severe drought occurred in 1989/90, 1996/97, 2003/2004 and 2004/2005. The most severe one occurred in 1996/97, when the Wonogiri reservoir water level could not reach NHWL El. 136.0 m.

The Wonogiri dam experienced consecutive three-year droughts in 2002/03 to 2004/05. In the last two years, no water release through spillway has been practiced.

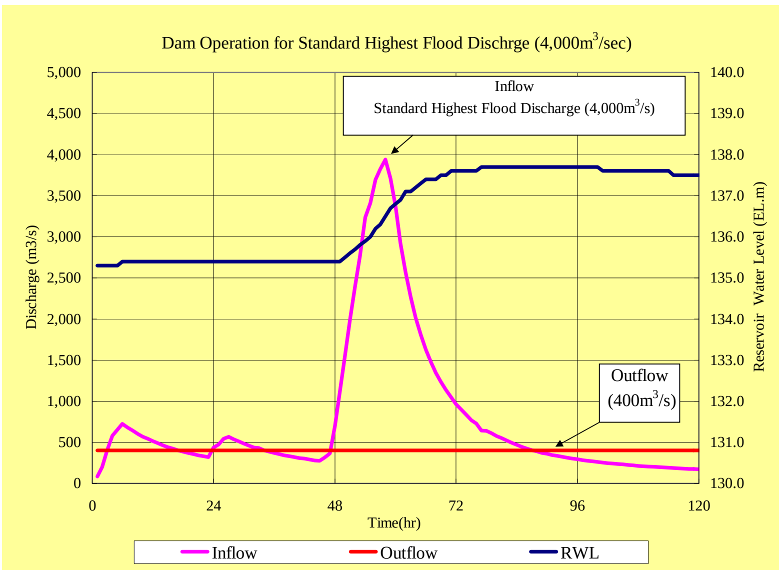


Source: JICA Study Team

Figure 1.2.4 Estimated Monthly Wonogiri Reservoir Inflow in 1983-2004

1.2.2 Flood Control

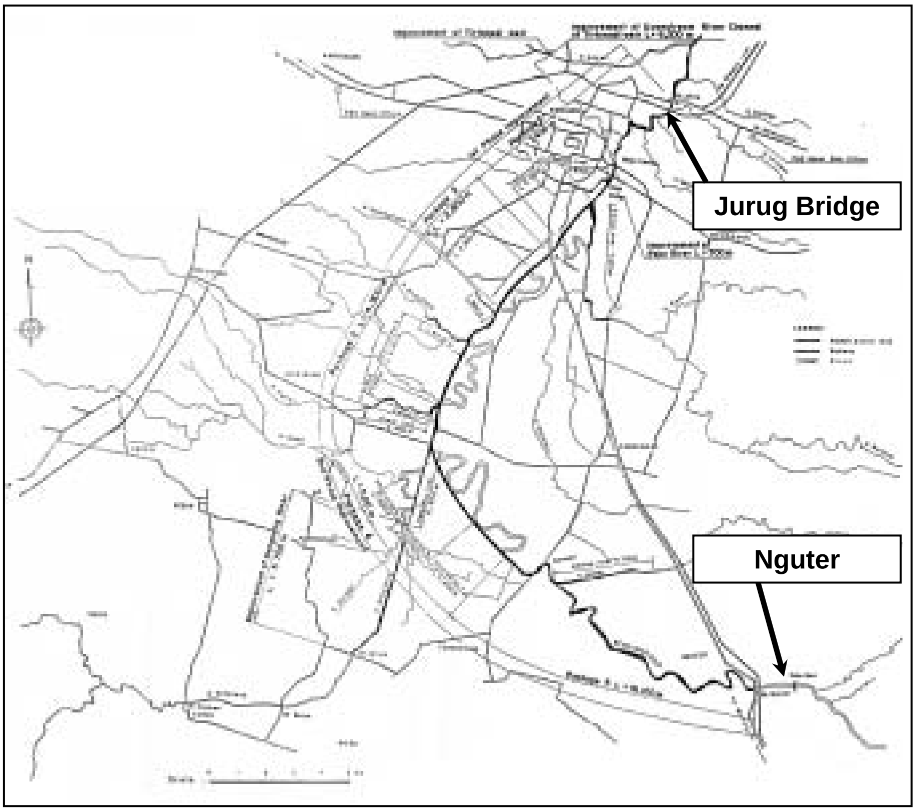
The reservoir water level is controlled not to exceed the Control Water Level (El.135.3 m) during the flood season from December 1st to April 15th for eliminating the possibility of overtopping of a Probable Maximum Flood (PMF) on the dam crest. The reservoir provides 220 million m^3 of flood control capacity to regulate the standard highest flood discharge (SHFD) with peak discharge of 4,000 m^3/s to the constant outflow of 400 m^3/s (see Figure 1.2.5 in the next page). The peak outflow discharge is 1,170 m^3/s for the design discharge of 5,100 m^3/s for spillway, which is equivalent to 1.2 times a 100-year probable flood, and 1,360 m^3/s for PMF of 9,600 m^3/s. Since the completion of the Wonogiri Dam in 1980, no flooding events have so far occurred in Surakarta, largest city in the Bengawan Solo River Basin. The Wonogiri Dam has much contributed to social welfare in the basin and has greatly benefited the people in the downstream area.



Source: Detailed Design Report on Wonogiri Multipurpose Dam Project, 1978

Figure 1.2.5 Typical Flood Control Operation of Wonogiri Dam

The Upper Solo River Improvement Project was completed in 1994. The objective river stretch is of around 53 km from Nguter to Jurug bridges. The location map of the Project is presented in Figure 1.2.6 below.



Source: Completion Report for Upper Solo River Improvement Project, 1994

Figure 1.2.6 Location of Upper Solo River Improvement Project in 1994

The Nguter bridge is located downstream of the Colo weir and the Jurug brigde is located about 5 km downstream of Surakarta city. The catchment area of Bengawan Solo at Jurug is around 3,220 km^2. The river stretch was improved against the 10-year flood incorporating significant flood control effect of the Wonogiri Dam. Seven short-cut channels in total 13 km long were constructed. Design flood discharge distribution along the stretch is illustrated in Figure 1.2.7 below.

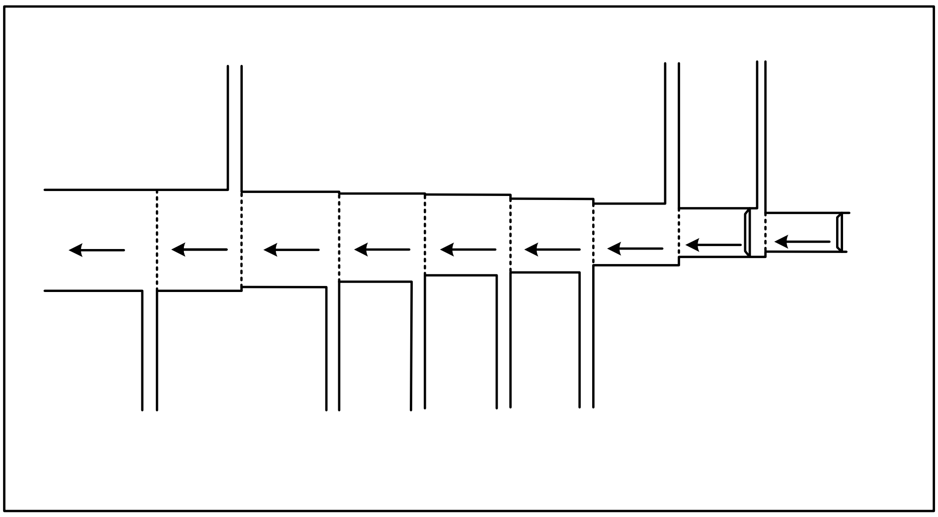


Figure1.2.7 Design Flood Discharge Distribution for Upper Solo River Improvement Project

Large flood inflows into the reservoir were estimated based on the hourly basis reservoir operation records of 1983-2004. The estimated large flood inflows are listed below.

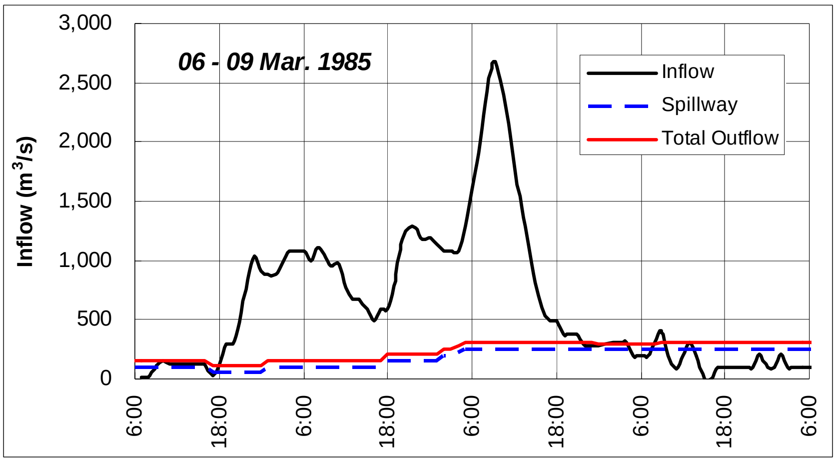
Table 1.2.1 Estimated Large Floods into Wonogiri Reservoir

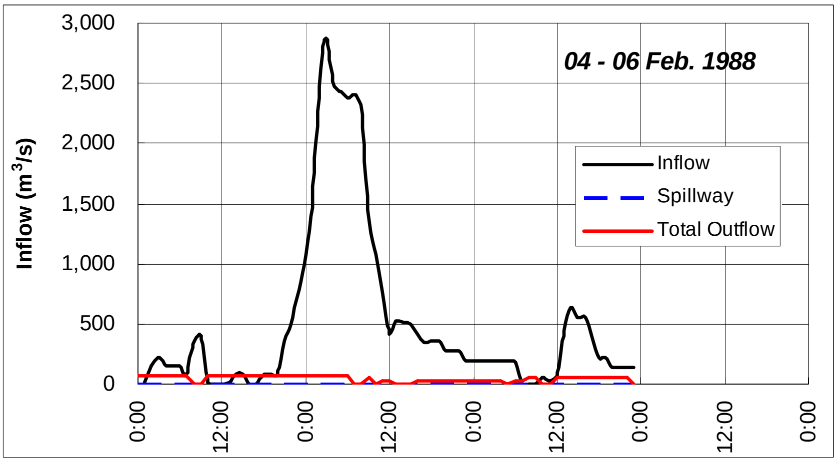
Year	Occurrence Date	Peak Discharge (m^3/sec)	Inflow Volume (million m^3)
1983	April 14 to 18	2,660	80.8
1984	January 4 to 5	1,650	52.3
1985	March 6 to 9	2,720	223.0
1988	February 4 to 6	2,880	130.3
1991	February 9 to 12	1,210	94.0
1992	February 12 to 15	1,210	109.6
1994	March 7 to 10	1,760	106.1
1998	December 22 to 26	1,350	37.2
2000	February 3 to 7	1,600	26.1
2003	January 2 to 5	1,010	104.9
2004	December 3 to 4	1,330	32.0

Source: JICA Study Team

As seen in the table above, the Wonogiri reservoir experienced the largest flood with peak discharge of 2,880 m^3/sec on February 5, 1988, followed by the 1985 year flood of 2,720 m^3/sec. Large flood inflows exceeding 2,000 m^3/s have occurred in 1980s.

The figures below shows actual flood operations of Wonogiri reservoir.





Source: JICA Study Team

Figure 1.2.8 Actual Flood Operations of Wonogiri Reservoir

1.2.3 Wonogiri Irrigation System

Colo Intake Weir

Immediately after completion of the Wonogiri Irrigation Project in 1986, the water supply to the Wonogiri irrigation system was commenced. Irrigation water is taken from the Colo intake weir located about 13 km downstream of the Wonogiri Dam. The Wonogiri irrigation system comprises 94 km long main canal and 105 km long secondary canal. Water released from the Wonogiri dam is taken to the West and East main canals at the Colo intake. At present, the irrigation area has been extended from 24,000 ha in the original plan to 29,330 ha where triple or double cropping farming is being practiced. The present irrigation area of Wonogiri irrigation system is as follows:

Table 1.2.2 Present Irrigation Area of Wonogiri Irrigation Project

(Unit: ha)

	Office	East Main Canal			West Main Canal			Total
		Surface	Pumping-up	Sub-Total	Surface	Pumping-up	Sub-Total	
1	Wonogiri	0	0	0	440	250	690	690
2	Sukoharjo	2,860	300	3,160	3,610	200	3,810	6,970
3	Kartosuro	490	100	590	0	0	0	590
4	Bekonang	5,110	350	5,460	0	0	0	5,460
5	Klaten	0	0	0	3,640	0	3,640	3,640
6	Karranganyar	1,770	350	2,120	0	0	0	2,120
7	Sragen Hulu	5,970	400	6,372	0	0	0	6,370
8	Sragen Hilir	3,290	200	3,494	0	0	0	3,490
	Total	***19,490***	***1,700***	***21,190***	***7,690***	***450***	***8,140***	***29,330***

Source : Balai PSDA Bengawan Solo Wilayah Surakarta

Mean monthly discharge at the Colo intake in 1986-2005 are presented in the table below.

Table 1.2.3 Mean Monthly Discharges at Colo Weir in 1986-2005

(unit : $m^{3/}$sec)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Release for maintenance flow	30.7	51.4	54.7	32.0	4.8	3.3	3.2	3.2	4.5	6.8	11.8	17.8
Left canal intake	2.4	2.8	2.5	3.1	3.3	3.5	3.4	3.2	3.4	2.7	2.3	2.7
Right canal intake	15.2	13.8	15.7	16.5	16.9	15.7	16.0	15.6	17.0	15.5	14.4	16.6
Total Inflow at Colo	48.3	70.2	74.0	54.1	26.2	23.3	23.3	22.5	25.6	26.0	29.0	35.5

Source: Balai PSDA Bengawan Solo Wilayah Surakarta

1.2.4 Power Generation at the Wonogiri Hydropower Station

The power house is located just downstream of the Wonogiri Dam. It accommodates the generating equipment with an installed capacity of 12.4 MW to produce annual energy output of 55,000 MWh. The maximum discharge for power generation is 75 m^3/s. In the dry season of May-November, around 50-60 million m^3 of the stored water in reservoir is used for power generation. In terms of a mean monthly discharge, they are around 20-25 $m^{3/}$sec. Power generation is of no consumptive water use. Thus the majority of released water through power generation is then used for irrigation water taken at the Colo weir. The lowest reservoir water level for power generation is currently set El. 130 m due to the sediment deposits in front of power intake.

Wonogiri Power Station

1.2.5 Operation and Maintenance

PJT I Bengawan Solo was established on March, 2003 based on the Presidential Decree No. 129/2000. With this, the operation and maintenance of the Wonogiri Dam was transferred to PJT I Bengawan Solo branch from PBS. The main revenue of PJT I Bengawan Solo is water charge for hydropower generation (PLN) and municipal/industrial water use (PDAM and industrial water utility). The Wonogiri Dam is mainly managed by these revenues.

CHAPTER 2 GARBAGE PROBLEMS AT WATER INTAKE

2.1 Garbage Problems

The intake supplies the reservoir water to the power station and for irrigation releases. The considerable quantity of vegetative debris and garbage washes into the intake forebay area at the beginning of the wet season. Partial blockage of the power intake by garbage frequently occurs. Approximately 20 days per rainy season the intake trash racks are blocked by vegetative debris causing the hydraulic head across the turbines to drop and the turbines to shut down. The trash racks are then cleaned by force of divers. Table below gives the record of power stoppage in 1996-2002 due to cleaning at the Wonogiri power station.

Table 2.1.1 Number of Days of Power Stoppage due to Trash Rack Cleaning at Wonogiri Power Station

Year	Days of Power Stoppage
1996	39
1997	19
1998	21
1999	7
2000	34
2001	16
2002	10
2003	6

Source: PLTA Wonogiri

The sediment deposited in the forebay consist of very fine grained materials (wash load). No sands in the deposits. No wear (abrasion) or related problems have occurred with the power turbines and no parts of the turbines have been replaced since operation began in the mid 1980s. This indicates that only very fine sediment materials such as clay and silt have passed through the turbines. According to the Wonogiri power station (PLTA Wonogiri), there is a clearance of 200 mm at the power turbines that might be enough to pass through the sediment materials.

Photos below the debris and garbage at the intake, and latest debris flushing through the spillway conducted on December 29, 2004 at RWL El. 133.4 m. The volume of debris that was gathered in front of the spillway is roughly estimated to be 1,250 m^3 (= 2,250 m^3 in area x 0.5 m in depth). In the flushing, 3 gates were fully opened respectively. The flushing duration was around 50 minutes.


Photo: Removed vegetative debris and garbage at intake (December 29, 2004)


Photo: Debris flushing on December 29, 2004

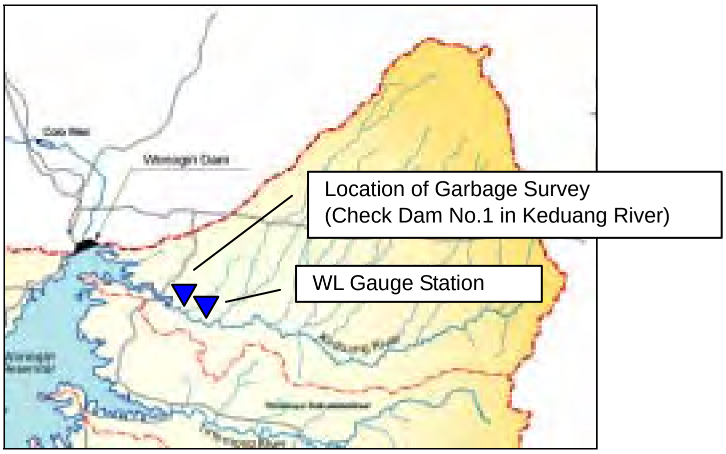

Photo: Debris removal in January, 2004


Photo: Debris flushing on December 29, 2004

2.2 Garbage from the Keduang River

2.2.1 Garbage Survey in the Keduang River

In the Study, garbage survey was carried out to estimate the garbage volume conveyed from the Keduang River in the period of November 2006 to February 2007. The garbage trap made of bamboo was installed on the existing check dam on the Keduang River as shown in Figure 2.2.1. During the garbage survey, water level at 800 m upstream of the garbage trap in the Keduang River was periodically observed with intervals of hourly in flood period and 2 times per day in non-flood period.



Source: JICA Study Team

Figure 2.2.1 Location Map of Garbage Survey

Installation of garbage trap by bamboos

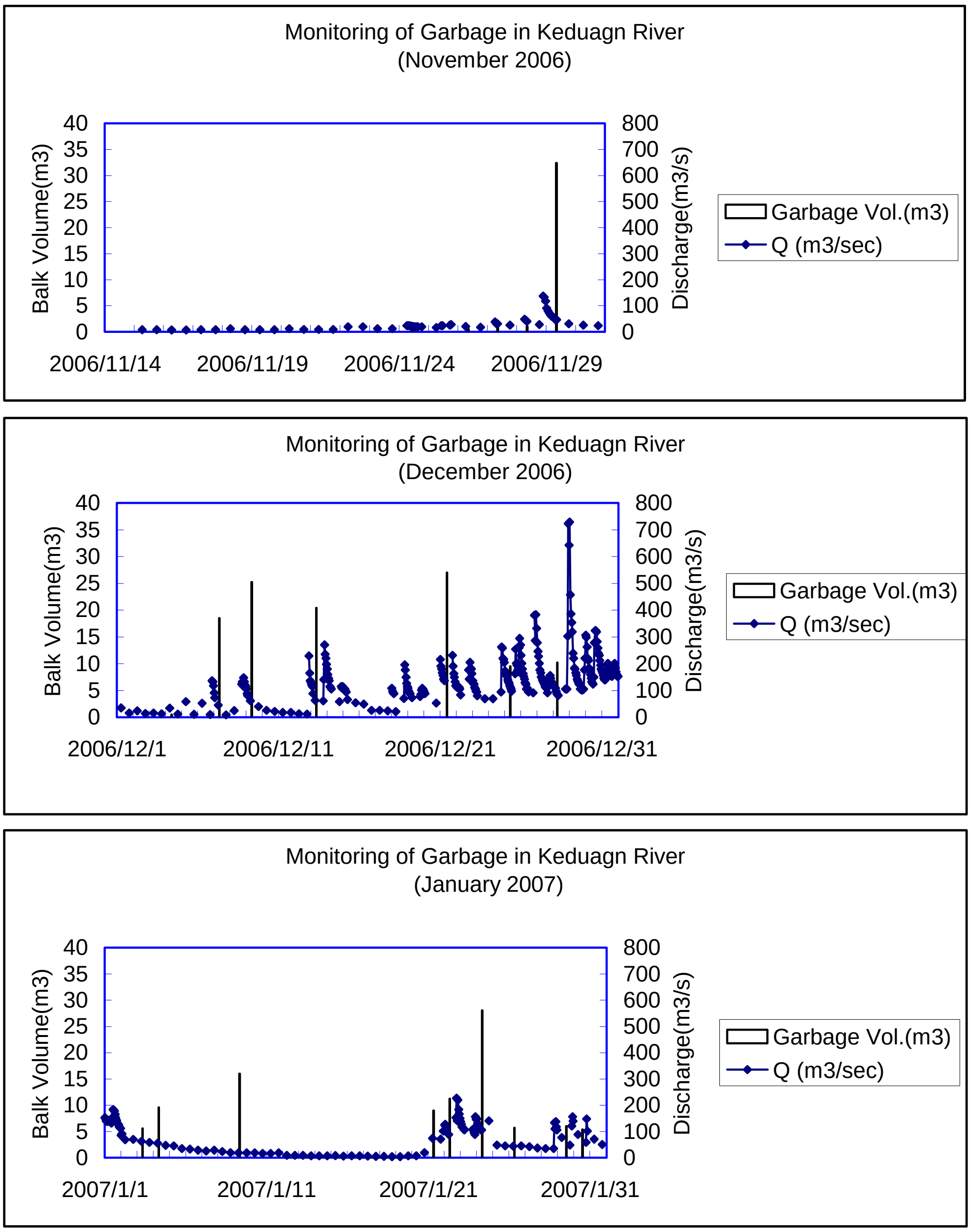
Broken garbage trap by flood

Garbage taking

Garbage burning after measurement of volume

2.2.2 Results of Garbage Survey

As shown in the photos, the conveyed garbage from the Keduang River was mainly composed of organic materials such as bushes, branches and harvested crops as same as the deposited garbage around the Intake. The volume of trapped garbage with discharge from November 2006 to January 2007 is shown in Figure 2.2.2 below. Monitoring result of the garbage survey is presented and attached in Annex 1. The volume of trapped garbage is 36 m^3 in November, 120 m^3 in December, 97 m^3 in January Totally 253 m^3 of garbage was trapped. Floods at the beginning of wet season convey larger quantity garbage into the Wonogiri reservoir. As the reservoir water level is the lowest at the beginning of wet season, garbage from the Keduang River is likely to reach the intake forebay.



Source: JICA Study Team

Figure 2.2.2 Result of Garbage Survey from November 2006 to January 2007

CHAPTER 3 CURRENT STATUS OF THE WONOGIRI RESERVOIR SEDIMENTATION

3.1 Previous Monitoring Studies on the Wonogiri Reservoir Sedimentation

A number of studies to evaluate the reservoir sedimentation have been so far completed by PBS since the completion of Wonogiri Dam in 1981. The most recent study before the current Study was by PT Citra Mandala Agritrans (PT CMA) in 1993. This section summarizes the results of the earlier studies. Major studies were by:

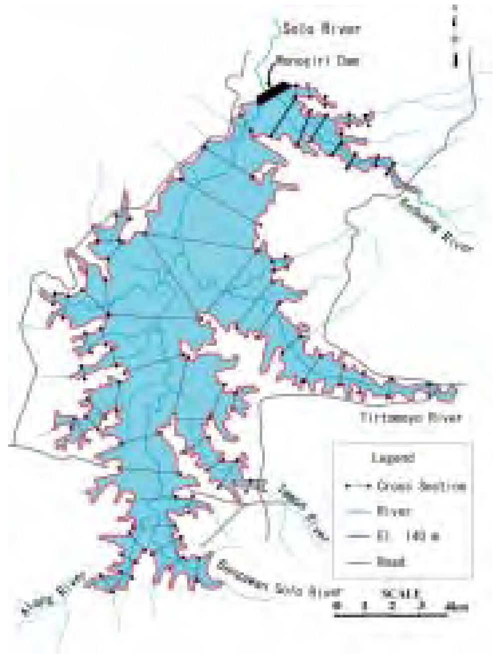
- Gadjah Mada University, Yogyakarta, 1985 & 1990.
- Bengawan Solo River Basin Development Project (PBS),1986,1987 & 1989.
- PT Citra Mandala Agritrans (PT CMA), 1993

These studies used one of following three methods to assess the sedimentation of Wonogiri reservoir:

i) Bed profiles were surveyed across the reservoir at set locations (see Figure 3.1.1 on the right). The new reservoir capacity was then determined by computing the volume between adjacent profiles. The total volume of sediment trapped in the reservoir was the difference between the original (pre-reservoir 1:10,000 scale map in 1980 with 2 m contour intervals as the initial condition) and newly computed capacities (by Gadja Mada University).

ii) Reservoir sediment inflow computed from suspended and bed load sediment transport measurements in the six tributaries entering the reservoir (by PBS).

iii) A contour map was drawn from profiles surveyed at the Figure 3.1.1 set locations. A 500 m by 1,000 m grid was superimposed over the map. Areas and volumes of individual grid blocks for the full range of water levels were computed using the "cubic spline method". The total reservoir area and capacity was the sum of the values of all the individual blocks. Areas and capacities were given for incremental water levels of 0.01 m from El 127.0 to 138.5 m (by PT CMA).



Source: JICA Study Team

Figure 3.1.1 Location Map of Cross Sections for Sedimentation Survey

Main results of these studies are briefed below.

3.1.1 PBS in 1989

PBS estimated the sediment inflow into the Wonogiri based on the sediment measurements in the major six tributaries as follows:

Table 3.1.1 Estimated Annual Wonogiri Reservoir Sediment Inflows by Tributary

(Unit: 1,000 ton/year)

River	1981	1982	1983	1984	1985	1986	1987	1988
Tirtomoyo	951	1,048	757	1,103	751	958	740	617
Keduang	299	-	398	395	357	461	94	30
Solo	-	283	343	564	282	478	248	257
Alang	54	22	224	150	66	35	123	38
Temon	44	33	61	81	102	51	27	35
Wuryantoro	3	2	4	24	15	5	6	3
Total	4,046	1,389	1,787	2,317	1,574	1,988	1,239	949
Accumulated	4,046	5,435	7,222	9,539	11,113	13,101	14,340	15,289
Total Volume (10^3 m^3)	***2,549***	***3,424***	***4,550***	***6,010***	***7,001***	***8,254***	***9,034***	***9,632***

Source: Monitoring Reports by PBS

As shown above, the total sediment volume into the Wonogiri reservoir in 1981-1988 was estimated 9.63 million m^3. Thus the annual average sediment inflow was estimated around 1.2 million m^3/year.

3.1.2 Gadjah Mada University in 1985 and 1990

The Wonogiri reservoir capacity estimates of Gadjah Mada University were conducted both in 1985 and 1990. These estimates were based on the reservoir bed cross-sectional profiles across the reservoir at the pre-determined locations as shown in Figure 3.1.1. Both surveys were made by echo sounding. The estimated sediment deposits (loss of storage volume below El. 138 m) were around 86.2 million m^3 in 1981-1985 and 156.4 million m^3 in 1980-1990, respectively as listed below. The estimated annual average sediment deposition is around 15.6 million m^3/year in 1981-1990.

Table 3.1.2 Estimated Sediment Deposits in the Wonogiri Reservoir

(Unit: m^3)

Elevation Range	below El. 127 m	below El. 138 m
Storage	123,590,000	718,044,000
1981-1985	41,476,804	86,165,280
1985-1990	31,654,637	74,245,750
1981-1990	68,184,603	156,389,980

Source: Gadja Mada University Faculty of Geology (GMU), 1985 and 1990, Monitoring Soil Erosion in Upper Solo by Monitoring Sedimentation in Wonogiri Reservoir

3.1.3 PT CMA in 1993

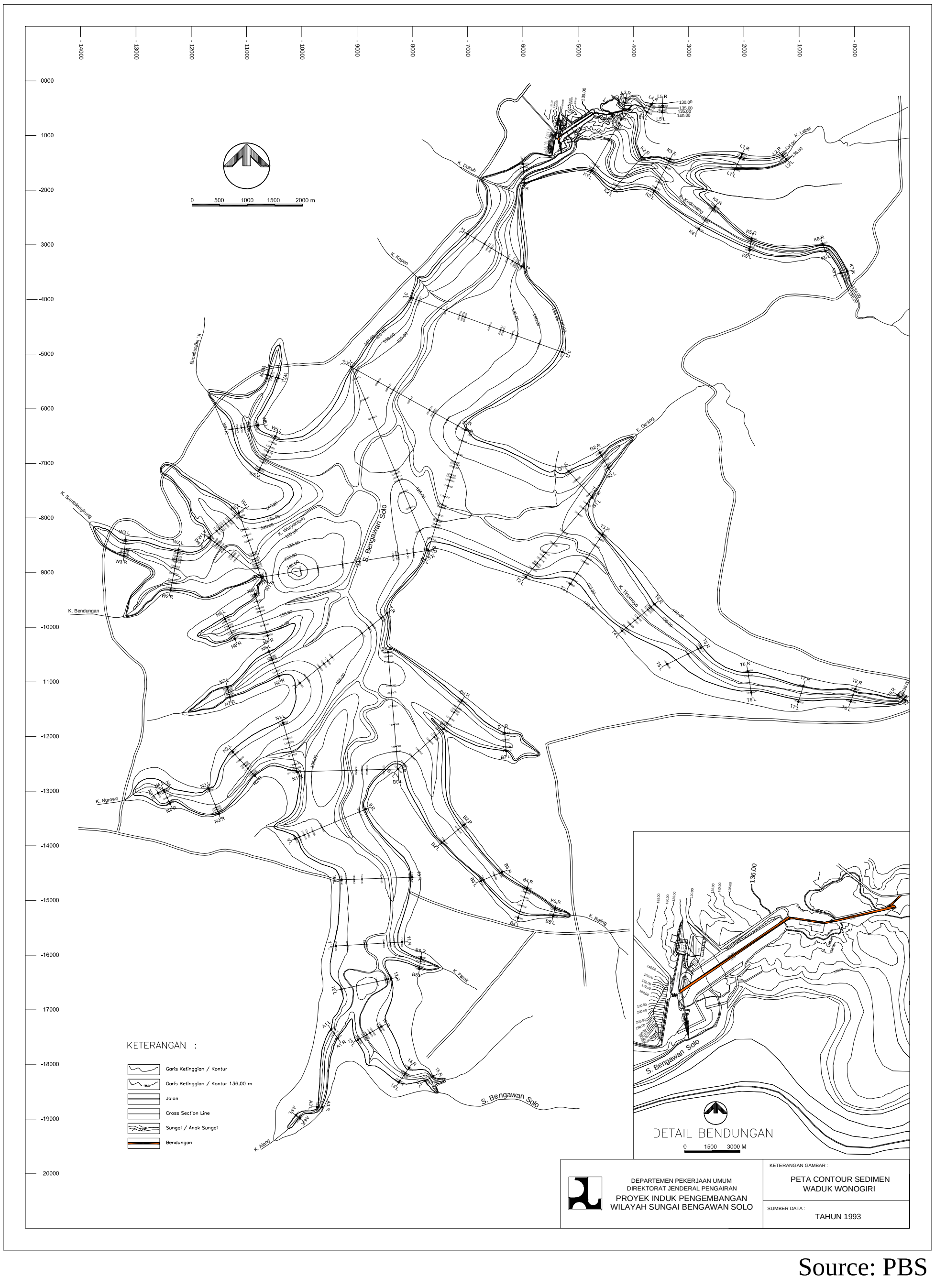
For 1993, PT CMA produced a reservoir contour map from the surveyed profiles and used this to compute the reservoir capacity. Only a rough copy of PT CMA contour map was available. The map was originally at an approximate scale of 1:30,000 with 5 m contour intervals. Figure 3.1.2 in the next page shows a contour map re-produced by PBS. From the change of H-V curves, a significant reduction in reservoir capacity due to sedimentation occurred between 1981 and 1993. The loss of storage capacity to due sedimentation below El. 138 m is 240 million m^3 and the annual loss of capacity below El. 138 m is 18.5 million m^3/year.

The loss of capacity due sedimentation by storage zone between 1980 and 1993 is summarized below.

Table 3.1.3 Wonogiri Reservoir Capacity Loss by Storage Zone between 1980 and 1993

Reservoir Zone	Reservoir Capacity (million m^3)		Capacity Lost due to Sedimentation	
	in 1980	in 1993	Value (million m^3)	of Original (%)
Flood Control Storage (El. 135.3 – 138.3 m)	220	160	60	27
Effective Storage (El. 127.0 – 136.0 m)	440	306	134	30
Dead Storage (below El. 127.0 m)	120	56	64	53
Total Volume	**780**	**522**	**258**	**-**

Source: JICA Study Team



Source: PBS

Figure 3.1.2 1993-year Reservoir Contour Map Reproduced by PBS

3.1.4 Comparison of Estimated Wonogiri Reservoir Capacity

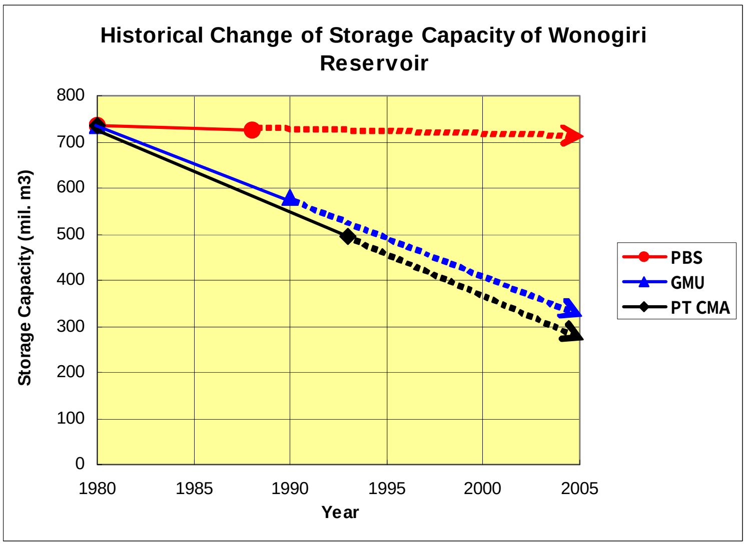
Figure 3.1.3 below shows the comparison of estimated Wonogiri reservoir capacities and linear projections for future sedimentation by the past monitoring studies. As predicted above , capacity of Wonogiri reservoir is expected to decrease to around 330 million m^3 applied by the estimate of Gadja Mada University (15.6 million m^3/year in 1980-1988) and to 270 million m^3 by PT. CMA (18.5 million m^3/year in 1981-1993). By both projections, the Wonogiri reservoir would lose about 55-63% of its capacity around by year 2005.

The detailed results of these studies are not presented herein because poor procedures were used to compute the sediment deposition, for the following reasons.

i) Determination of reservoir capacity by summing the computed volumes between adjacent profiles probably gives inaccurate results in a reservoir with many bays as in the Wonogiri. The more accurate procedure for a reservoir such as Wonogiri is to collect more survey data than that obtained from only the Figure 3.1.1 sections to enable a detailed contour map to be produced. The reservoir capacity is then the sum of the volumes computed between incremental contour intervals.

ii) The accurate estimation of sediment inflow to a reservoir using sediment transport measurements in tributary rivers requires the collection of extensive field measurements over many years with the emphasis on measurements during short-duration flood events. Such intensive measurement was not conducted.

iii) The PT CMA results might be of low reliability due to large grid size of 500 m x 1,000 m.



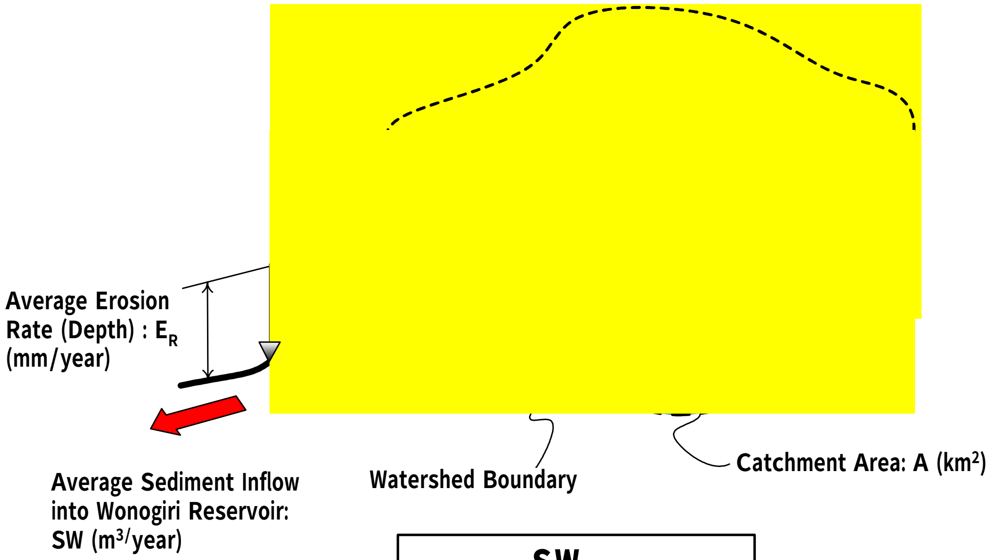
Source: JICA Study Team

Figure 3.1.3 Projection of Wonogiri Reservoir Sedimentation by Past Monitoring Studies

In summary, the results of all the reservoir studies in the past are considered more or less inaccurate, and particularly the PT CMA results. The capacity estimate of PT CMA (1993) was reevaluated later under the Study by use of the re-produced reservoir contour map.

3.1.5 Comparison of Average Erosion Rate (Depth) in the Wonogiri Watershed

An erosion rate is estimated as illustrated below. The erosion rates are estimated for the past three studies as summarized below.



$$E_R = \frac{SW}{A \times 10^3} \text{ (mm)}$$

Source: JICA Study Team

Figure 3.1.4 Illustration of Average Erosion Rate over the Watershed

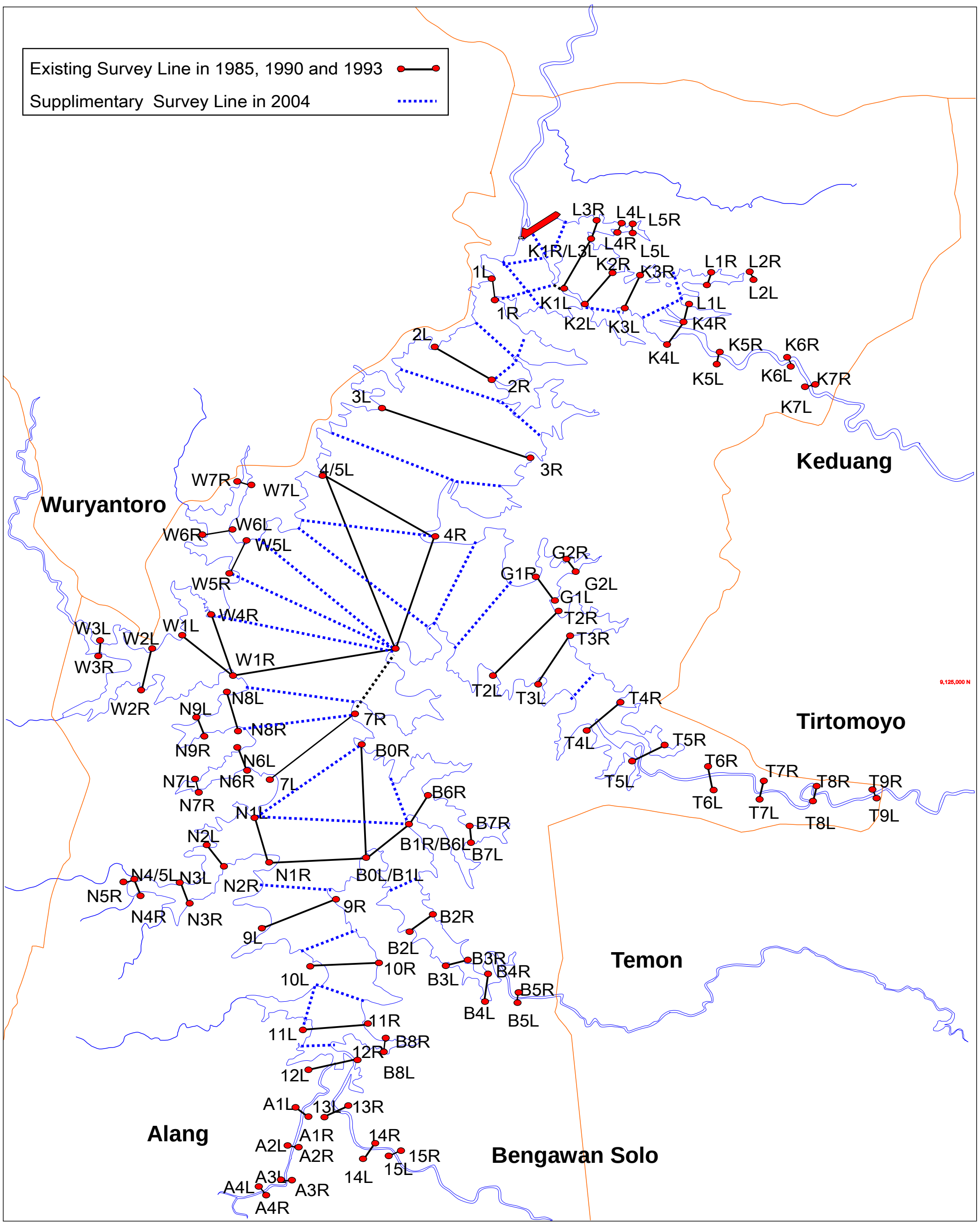
Table 3.1.4 Comparison of Average Erosion Rates by Past Studies

Past Study	Average Sediment Deposition (million m^3/year)	Average Erosion Rate (mm/year)	Example: Erosion Depth in 100 years (cm)
PBS in 1989	1.2	0.9	9
UGM in 1985 & 1990	15.6	11.6	116
PT CMA in 1993	18.5	13.7	137

Source: JICA Study Team

3.2 Current Status of the Wonogiri Reservoir Sedimentation

An echo sounding survey with GPS on the Wonogiri reservoir was undertaken in two times from October to November 2004 (before entering the wet season) and June to July 2005 (after the wet season) under the current Study in order to estimate the current status of the Wonogiri reservoir sedimentation as well as incremental sediment deposit in the wet season in 2004/2005. Figure 3.2.1 below shows the location of cross sections for reservoir sedimentation survey. As seen, 35 supplementary cross sections was added to the pre-set 64 sections in 1985, 1990 and 1993 to enable more accurate contour map of the reservoir bed.

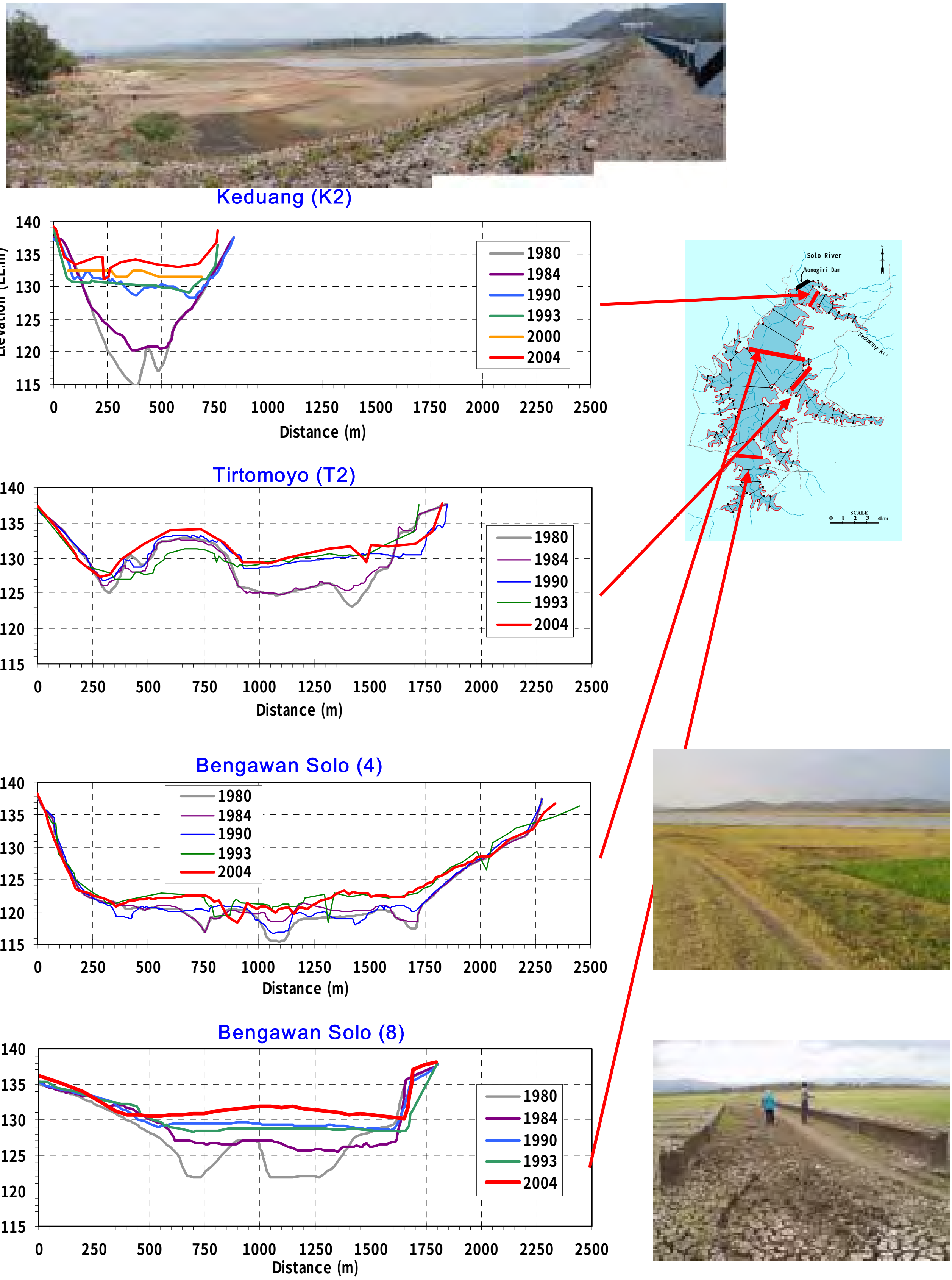


Source: JICA Study Team

Figure 3.2.1 Location Map of Cross Sections for Reservoir Sedimentation Survey in 2004 and 2005

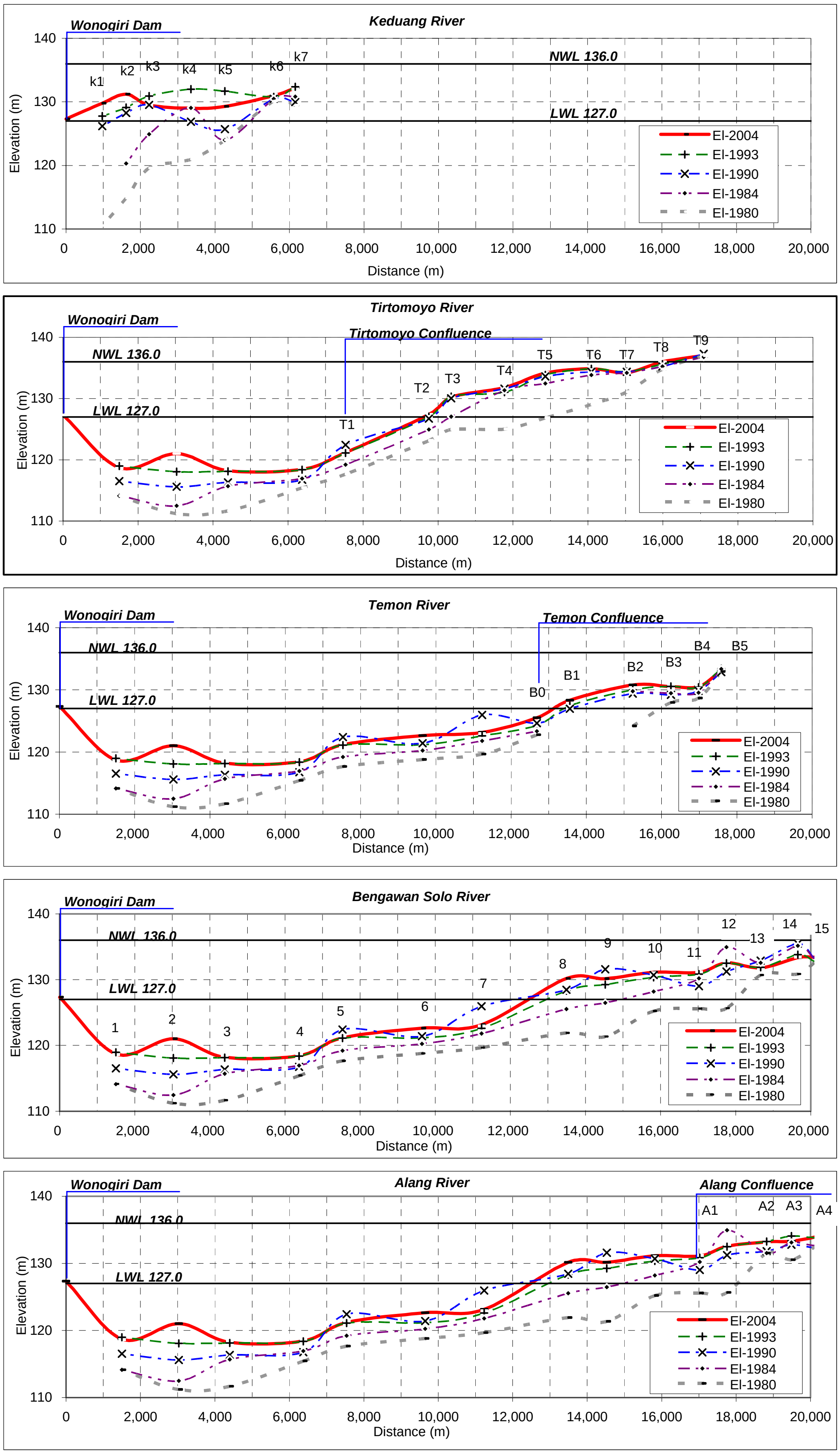
3.2.1 Reservoir Sections and Profiles in 1980-2004

Longitudinal and cross-sectional profiles in the reservoir and principal tributaries are developed. These profiles show the 1980, 1993 and 2004 reservoir bed conditions. The location of cross sections is already given (see Figure 3.2.1 above). Figures below are the cross-sectional and longitudinal profiles of major tributaries. All reservoir sections in each river are attached in Annex 2.



Source: JICA Study Team

Figure 3.2.2 Reservoir Sections in 1980-2004

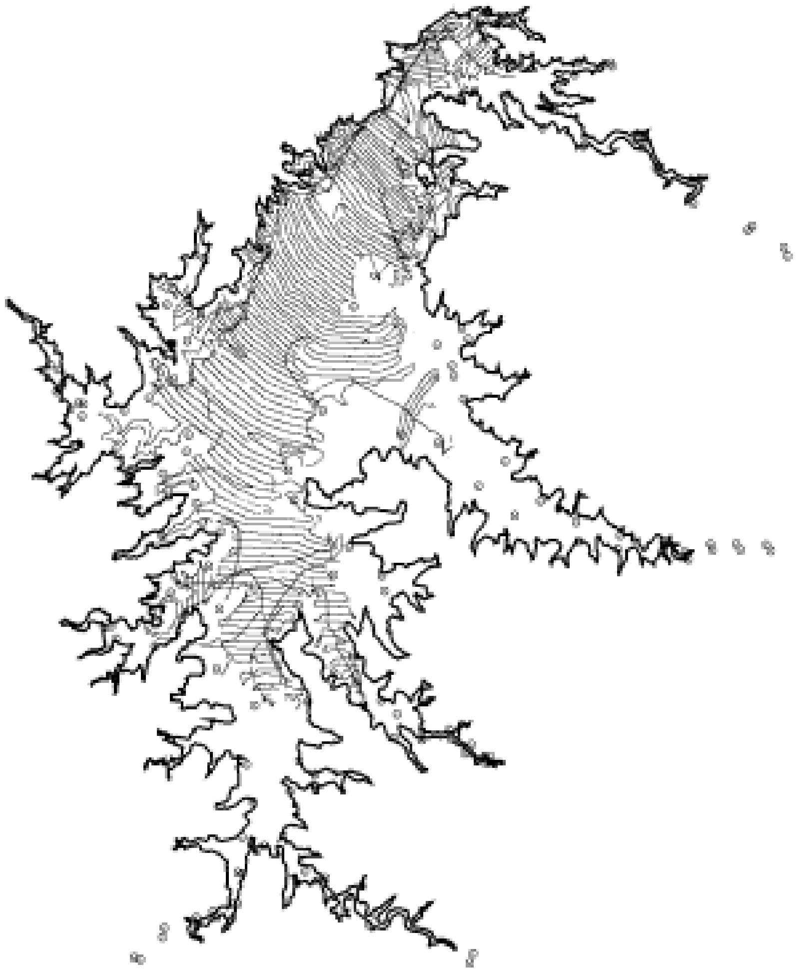


Source: JICA Study Team

Figure 3.2.3 Reservoir Profiles in 1980-2004

3.2.2 Reservoir Sedimentation Survey in 2004 by PBS

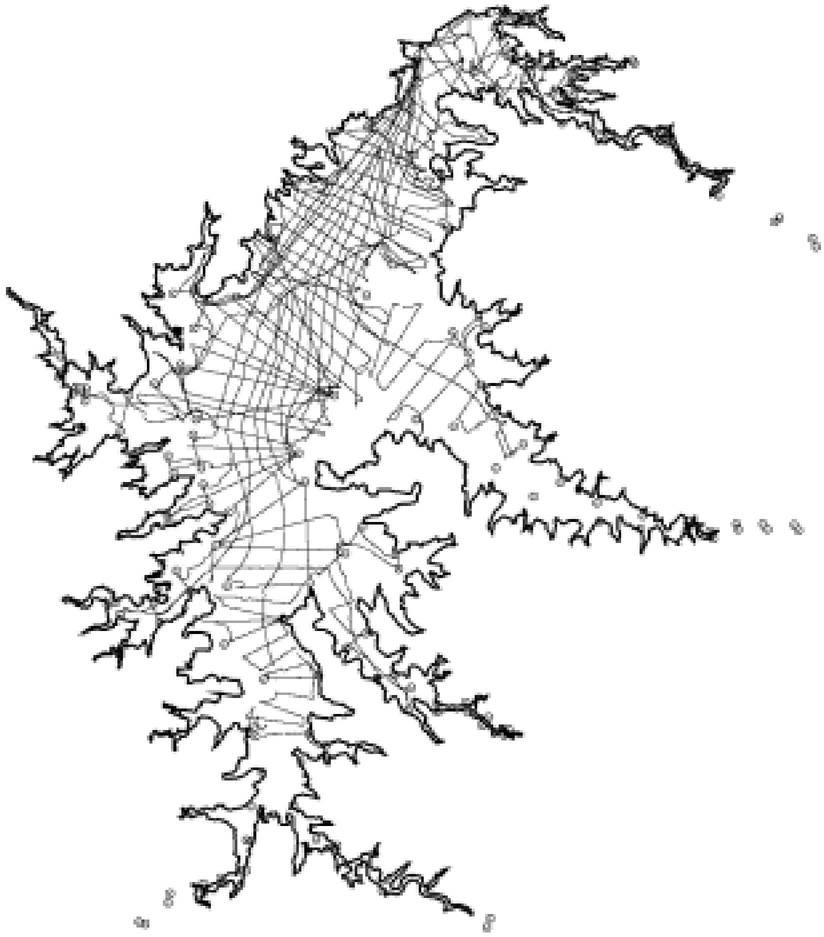
PBS carried out the reservoir sedimentation survey independently subletting the sub-contractor. The survey was made in July to September 2004. However the final report was completed in May 2005. The eco soundings were made as many locations as possible to increase the density of data points so that an accurate reservoir topographic map can be produced. Totally around 100,000 points with an interval of around 10 m were surveyed. The location map of data points is shown below. Very unfortunately, the survey was made only within the reservoir water surface at the time of survey (below the reservoir water level El. 132 m). The perimeter (ground surface) survey from the water's edge to the maximum reservoir area was not conducted.



Source: JICA Study Team

Figure 3.2.4 Location Map of Data Points by PBS Survey in 2004

In order to increase an accuracy of reservoir topographic mapping in 2005, data points were added under the Study, mainly for several reservoir profile directions as shown in Figure 3.2.5 below.



Source: JICA Study Team

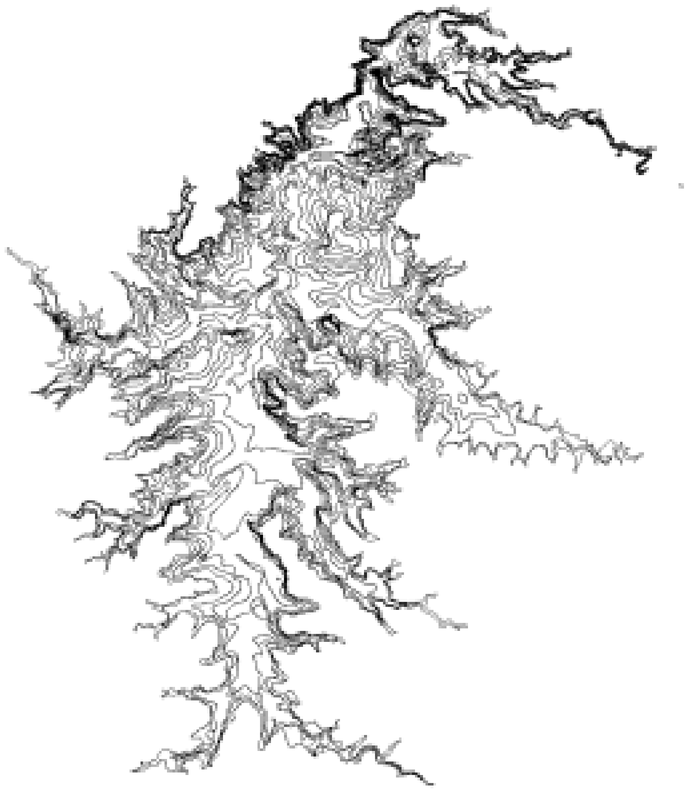
Figure 3.2.5 Location Map of Data Points by JICA Survey in 2005

3.2.3 Current Wonogiri Reservoir Conditions in 2004 and 2005

The current reservoir capacity was estimated based on the contour mapping of reservoir bed and DEM (Digital Elevation Method) as given below. Past sedimentation survey results in 1993 was re-assessed by means of the same procedure.

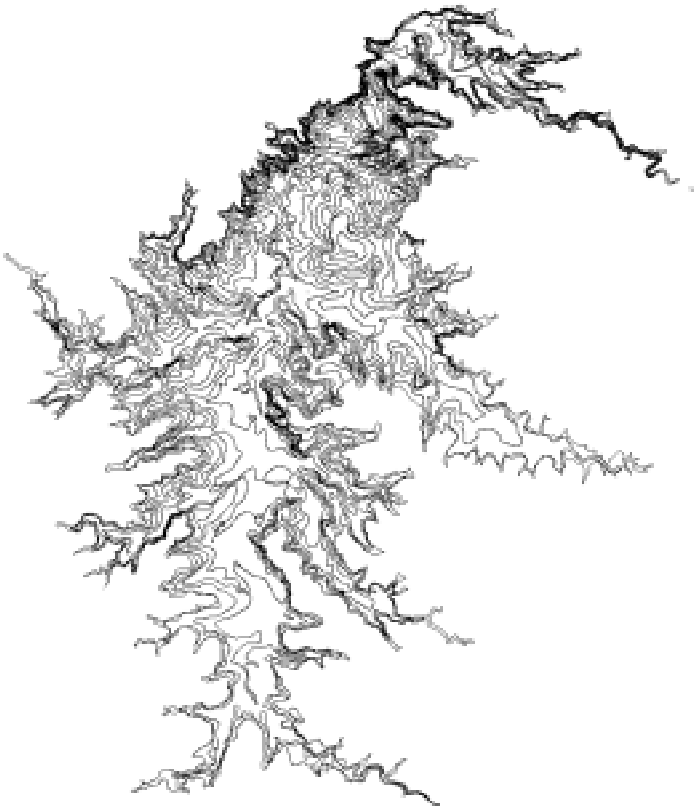
Echo Sounding Survey → **Contour Map of Sedimentation** → **Preparation of DEM (10 m x 10 m)** → **H-A and H-V Curves**

The result of reservoir sedimentation survey by PBS in 2004 was very useful for cross-checking the survey results in 2004 undertaken by the current Study. Finally the contour map from the 2004 survey result was modified incorporating with the PBS survey results in 2004. Figures below show the reservoir contour maps in 1993 and 2004.



Source: JICA Study Team

Figure 3.2.6 Reservoir Contour Map in 1993



Source: JICA Study Team

Figure 3.2.7 Reservoir Contour Map in 2004

Elevation-area-capacity relationships of Wonogiri reservoir for 1980, 1993, 2004 and 2005 were developed by use of DEM (around 900,000 meshes in total) as shown in Figure 3.2.9 in next page. Table below presents the estimated Wonogiri storage capacity.

Table 3.2.1 Estimated Wonogiri Reservoir Storage based on DEM

Reservoir Zone	Reservoir Capacity (million m^3)				Sediment Deposit (million m^3)	
	1980	1993	2004	2005	1993	2005
below El. 127.0 m (DWL)	114	69	58	58	45 (39%)	56 (49%)
below 136 m (NHWL)	547	468	435	433	79 (14%)	114 (21%)
below 138.3 m (DFWL)	730	650	618	616	80 (11%)	114 (16%)

Source: JICA Study Team

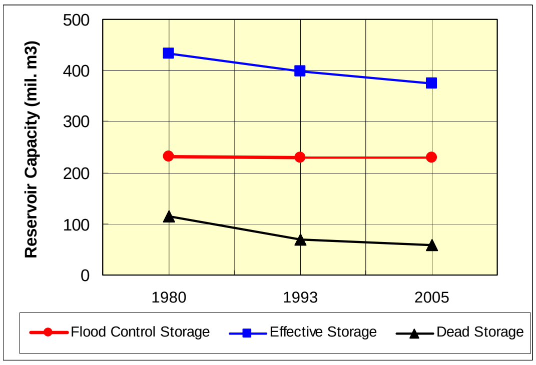
As seen above, approximately 114 million m^3, or 16% of the total capacity 730 million m^3 was lost due to sedimentation in 1980-2005. The estimated current loss of capacity due to sedimentation in the three storage zones between 1980 and 2005 is summarized below.

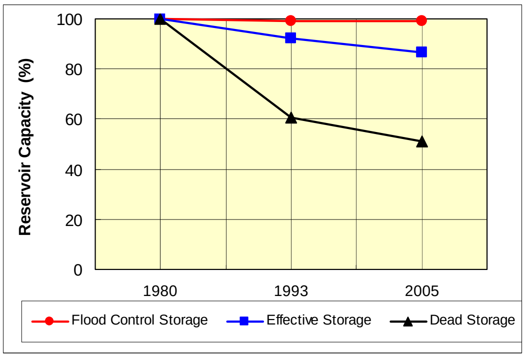
Table 3.2.2 Wonogiri Reservoir Capacity Loss by Storage Zone between 1980 and 2005

Reservoir Zone	Reservoir Capacity (million m^3)		Capacity Lost due to Sedimentation	
	1980	2005	Value (million m^3)	of Original (%)
Flood Control Storage (El. 135.3 – 138.3 m)	232	230	2	0.9
Effective Storage (El. 127.0 – 136.0 m)	433	375	58	13.4
Dead Storage (below El. 127.0 m)	114	58	56	49.1

Source: JICA Study Team

As shown above, around 13% of the original effective storage zone (between El. 127.0 m and El. 136.0 m) has been filled with sediment deposits by 2005. In other words, around 87% of the original effective storage zone is still usable. Historical change of each reservoir zone is illustrated below.

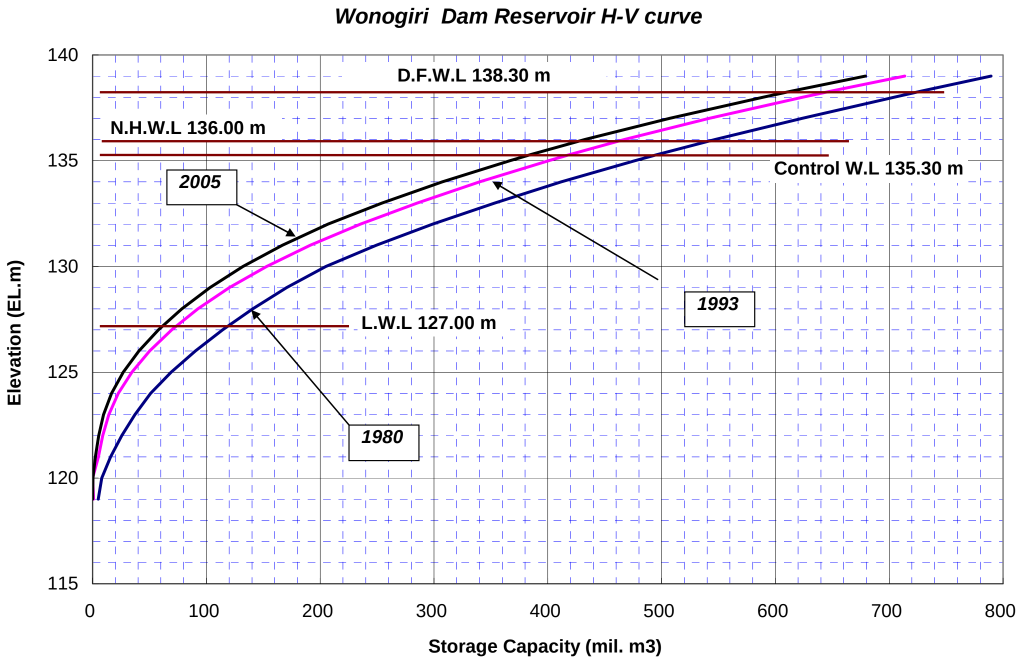




Source: JICA Study Team

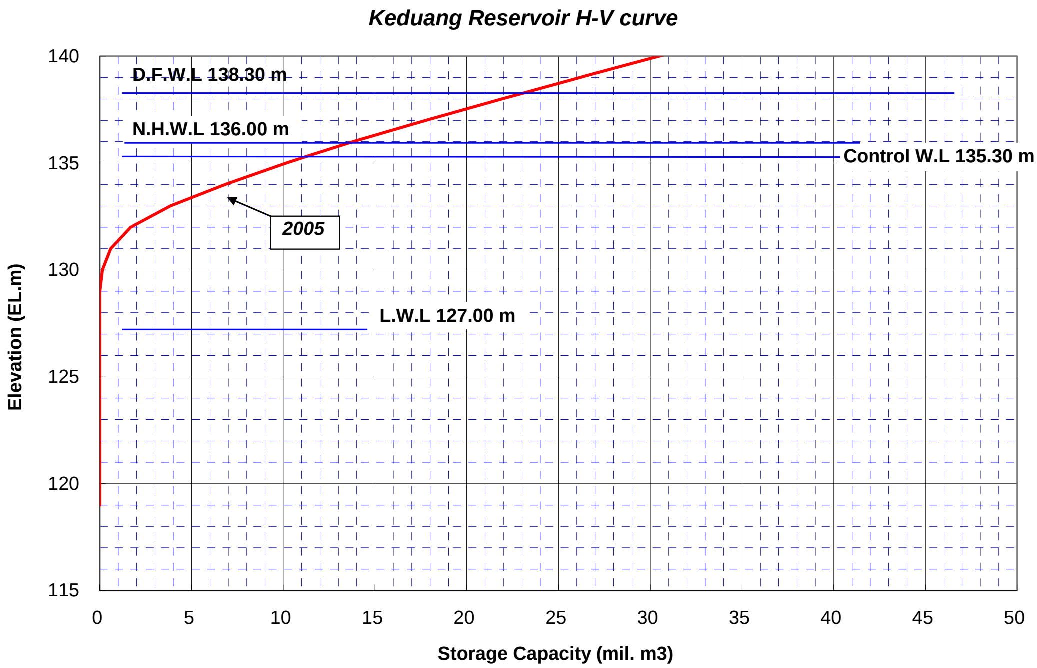
Figure 3.2.8 Change of Wonogiri Reservoir Capacity by Storage Zone between 1980 and 2005

Three dimensional views of the topography on the Wonogiri reservoir bed were produced from the contour line data before construction of the dam in 1980 and in 2004 as presented in Figure 3.2.11 in the next page.



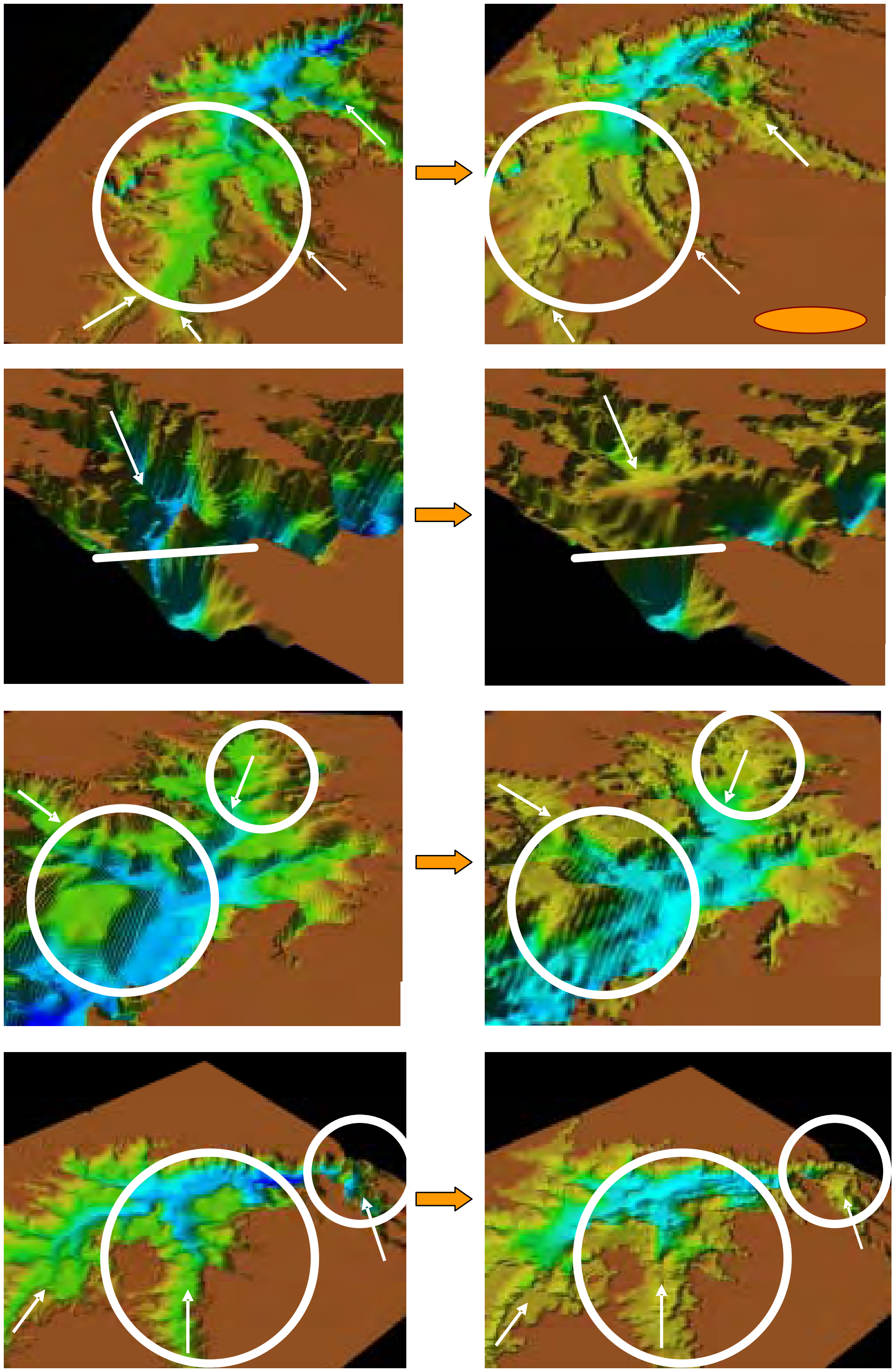
Source: JICA Study Team

Figure 3.2.9 Wonogiri Dam Reservoir Elevation-Capacity Curves in 1980, 1993 and 2005



Source: JICA Study Team

Figure 3.2.10 Keduang Reservoir Elevation-Capacity Curves in 2005



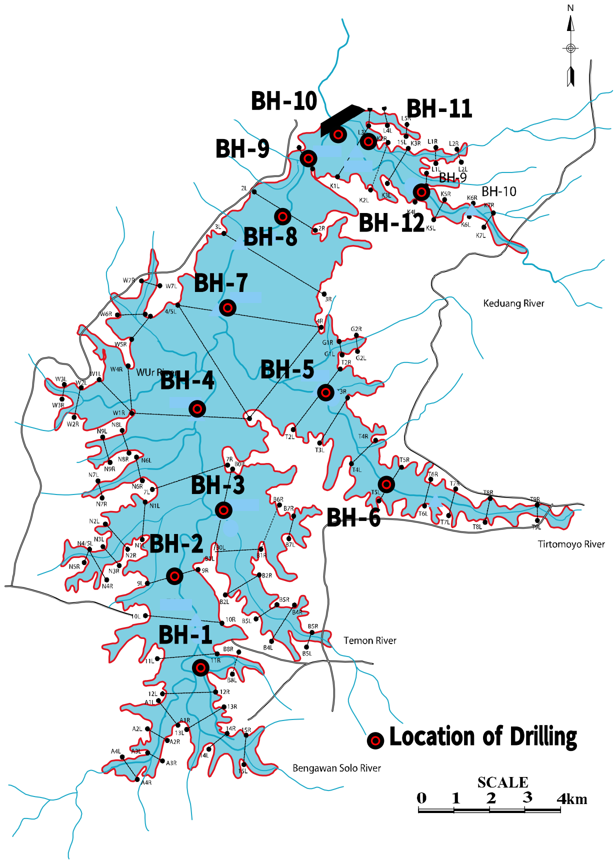
Source: JICA Study Team

Figure 3.2.11 3D View of Wonogiri Dam Reservoir Sedimentation

CHAPTER 4 RESULTS OF GEOLOGICAL INVESTIGATIONS

4.1 Drilling Works

A drilling survey was carried to clarify geological condition in the reservoir area in the first phase of the Study in 2004. Standard penetration test with core sampling were performed at 12 drilling holes as presented in the location map Figure 4.1.1. Results of drilling works are summarized in Table 4.1.1 below. The grain size distributions of each drilling hole is presented in the Table 4.1.2 and Figure 4.1.3. The sediment deposited in the Wonogiri reservoir consists of very fine grained materials (wash load) with 87% of total volume as presented in the Figure 4.1.2. Almost no sands are composed in the deposits.



Source: JICA Study Team

Figure 4.1.1 Location Map of Drilling Works

Table 4.1.1 Results of Drilling Works

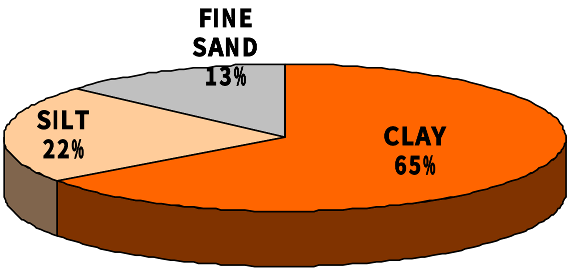
Drilling No	Name of River	Length (m)	Geological condition (m)			
			Sediments after the dam was completed	Original river deposit, Terrace deposit	Base rock (rock type)	Remarks
BH-1	Solo	15	0.0-2.5		2.5-15.0 (tuffaceaous sand)	2.5-4.0 Organic soil
BH-2	Solo	16	0.0-2.0	2.0-8.0	8.0-16.0 (tuffaceaous sand)	2.0-5.0 Organic soil
BH-3	Temon	9	0.0-7.6	7.6—9.0		
BH-4	Solo	12	0.0-3.6	3.6-9.2	9.2-12.0 (tuff)	
BH-5	Tirutomoyo	12	0.0-1.5		1.5-12.0 (tuffaceous sand)	1.5-3.0 Organic soil
BH-6	Tirutomoyo	13	0.0-3.5		3.5-13.0 (tuff)	
BH-7	Solo	13	0.0-0.8	0.8-1.5	1.5-12.0 (tuff)	
BH-8	Solo	14	0.0-2.0		2.0-14.0 (lappili tuff, tuffaceous sand)	
BH-9	Solo	13	0.0-1.7		1.7-13.0 (lapilli tuff)	
BH-10	Solo	23	0.0-3.2		3.2-23.0 (lappili tuff)	
BH-11	Keduwang	25	0.0-17.5	17.5-25.0		
BH-12	Keduwang	17	0.0-8.0		8.0-17.0 (tuff breccia)	

Source: JICA Study Team

Table 4.1.2 Grain Size Distribution of Sediments

Boring No.	Depth of Sediment	Sampling Depth	Grain size (μm)								
			Clay		Silt			Sand			Gravel
			0.24-1.3	1.3-5	5-16	16-31	31-75	75-250	250-850	850-2000	2000-9500
	(m)	(m)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
BH-1	2.5	0.20-0.40	64.0	2.5	8.5	11.0	8.8	3.8	1.0	0.5	0.0
		0.60-0.80	66.0	6.0	10.0	6.0	7.7	3.1	0.6	0.4	0.1
		1.55-1.75	62.5	6.5	11.0	6.5	5.6	2.8	2.8	1.4	0.9
BH-2	2	0.30-0.50	65.6	4.4	11.0	9.0	7.1	2.0	0.9	0.0	0.0
		0.60-0.80	60.7	8.3	16.0	8.0	4.7	1.2	1.0	0.0	0.0
		1.50-1.70	46.5	5.5	10.0	6.0	9.6	17.3	4.1	0.8	0.2
BH-3	7.6	0.30-0.50	61.5	5.5	9.5	7.5	9.1	6.3	0.4	0.2	0.0
		0.70-0.90	49.5	4.5	8.0	7.0	9.2	17.4	3.5	0.8	0.1
		1.50-1.70	73.7	4.3	8.0	5.0	5.7	2.1	0.4	0.8	0.1
		2.00-2.50	73.6	5.4	9.0	4.5	4.4	2.2	0.4	0.3	0.2
		5.00-5.50	66.4	4.1	7.5	7.5	6.4	7.8	0.3	0.1	0.0
BH-4	3.6	0.20-0.40	42.4	2.6	4.0	3.0	8.8	22.8	11.9	3.8	0.7
		0.65-0.90	46.8	4.2	6.0	5.5	8.8	15.3	10.3	3.0	0.0
		1.50-1.70	74.8	5.2	3.0	5.0	5.3	3.3	1.0	1.9	0.5
		2.00-2.50	61.5	6.5	7.0	3.5	6.0	10.6	3.9	0.9	0.2
BH-5	1.5	0.25-0.45	61.3	3.7	6.0	4.0	5.3	12.0	6.3	1.3	0.2
		0.75-1.00	68.2	3.8	5.0	3.5	4.5	9.6	4.4	0.6	0.3
		1.20-1.50	37.0	2.5	4.5	4.0	6.4	30.6	14.2	0.6	0.1
BH-6	3.5	0.30-0.50	14.2	1.8	5.0	7.0	11.1	16.1	34.3	9.8	0.7
		0.60-0.80	29.7	5.8	7.5	6.0	9.8	18.7	15.8	5.7	1.0
		1.50-1.70	37.6	3.9	4.5	4.0	5.5	8.1	25.1	10.5	0.8
		2.00-2.50	24.5	2.5	4.0	2.0	6.3	27.0	25.7	6.0	2.0
BH-7	0.8	0.15-0.35	79.8	3.2	3.5	1.5	3.8	4.4	2.1	1.4	0.3
		0.55-0.75	70.0	6.0	6.0	4.0	3.2	4.7	3.0	1.8	1.3
BH-8	2	0.30-0.50	84.2	3.3	3.5	2.0	4.8	1.6	0.5	0.2	0.0
		0.60-0.80	43.9	7.1	7.0	9.0	12.7	15.1	4.7	0.4	0.1
		1.50-1.70	81.4	5.6	5.0	5.0	1.2	1.2	0.5	0.2	0.0
BH-9	1.7	0.30-0.50	77.2	4.8	7.0	7.0	3.0	0.6	0.3	0.1	0.0
		0.70-0.95	79.6	5.9	7.5	4.0	2.1	0.4	0.3	0.1	0.0
		1.50-1.70	86.9	3.1	4.0	2.0	2.7	0.9	0.3	0.1	0.0
BH-10	3.2	0.40-0.60	28.9	6.1	9.0	9.0	14.2	27.7	5.1	0.0	0.0
		0.60-0.80	50.4	11.6	16.0	12.0	9.0	0.8	0.2	0.0	0.0
		1.45-1.70	43.7	9.8	16.5	14.0	11.9	3.5	0.5	0.0	0.0
		2.00-2.50	34.1	12.9	19.0	16.0	12.2	4.3	1.5	0.0	0.0
BH-11	17.5	0.30-0.50	52.3	10.7	12.0	13.5	10.8	0.5	0.1	0.1	0.0
		0.60-0.80	44.1	11.4	22.5	12.0	7.5	2.5	0.0	0.0	0.0
		1.50-1.70	51.1	13.9	20.0	7.0	5.8	2.0	0.2	0.0	0.0
		2.00-2.50	19.2	5.8	9.0	8.0	14.0	34.3	9.3	0.4	0.0
		5.00-5.50	20.0	7.5	11.5	8.0	14.9	27.0	10.6	0.5	0.0
		8.00-8.50	32.5	11.5	24.0	14.0	11.1	5.6	1.2	0.0	0.0
		11.00-11.50	38.2	8.4	15.5	16.0	17.6	4.0	0.3	0.2	0.0
		14.00-14.50	46.3	14.2	22.5	10.0	5.7	0.8	0.4	0.0	0.0
		17.00-17.50	44.9	23.1	20.0	7.0	3.9	0.7	0.2	0.2	0.0
BH-12	8	0.30-0.50	47.1	6.4	8.5	7.0	12.7	15.7	2.4	0.2	0.0
		0.70-0.90	61.4	5.6	14.0	8.5	7.3	2.4	0.6	0.2	0.0
		1.70-2.00	61.4	4.6	16.0	12.0	4.9	0.7	0.3	0.2	0.0
		2.50-3.00	51.5	7.5	17.0	14.5	7.7	1.2	0.4	0.2	0.0
		5.50-6.00	54.9	4.1	8.0	7.0	7.6	9.5	7.2	1.7	0.0

Source: JICA Study Team



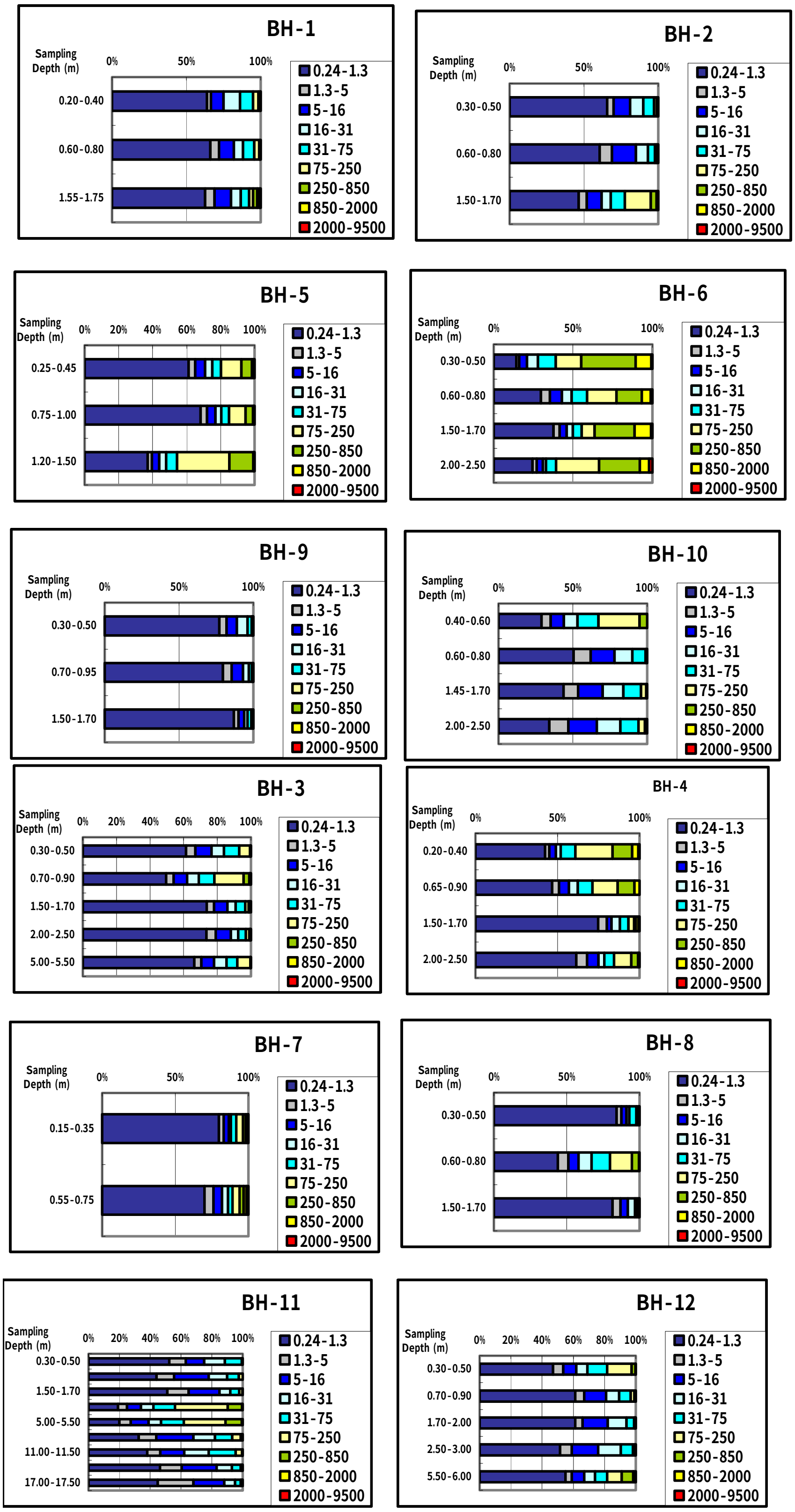
Source: JICA Study Team

Figure 4.1.2 Percentage of Sediments Composition in the Wonogiri Reservoir

4.2 Geological Sections

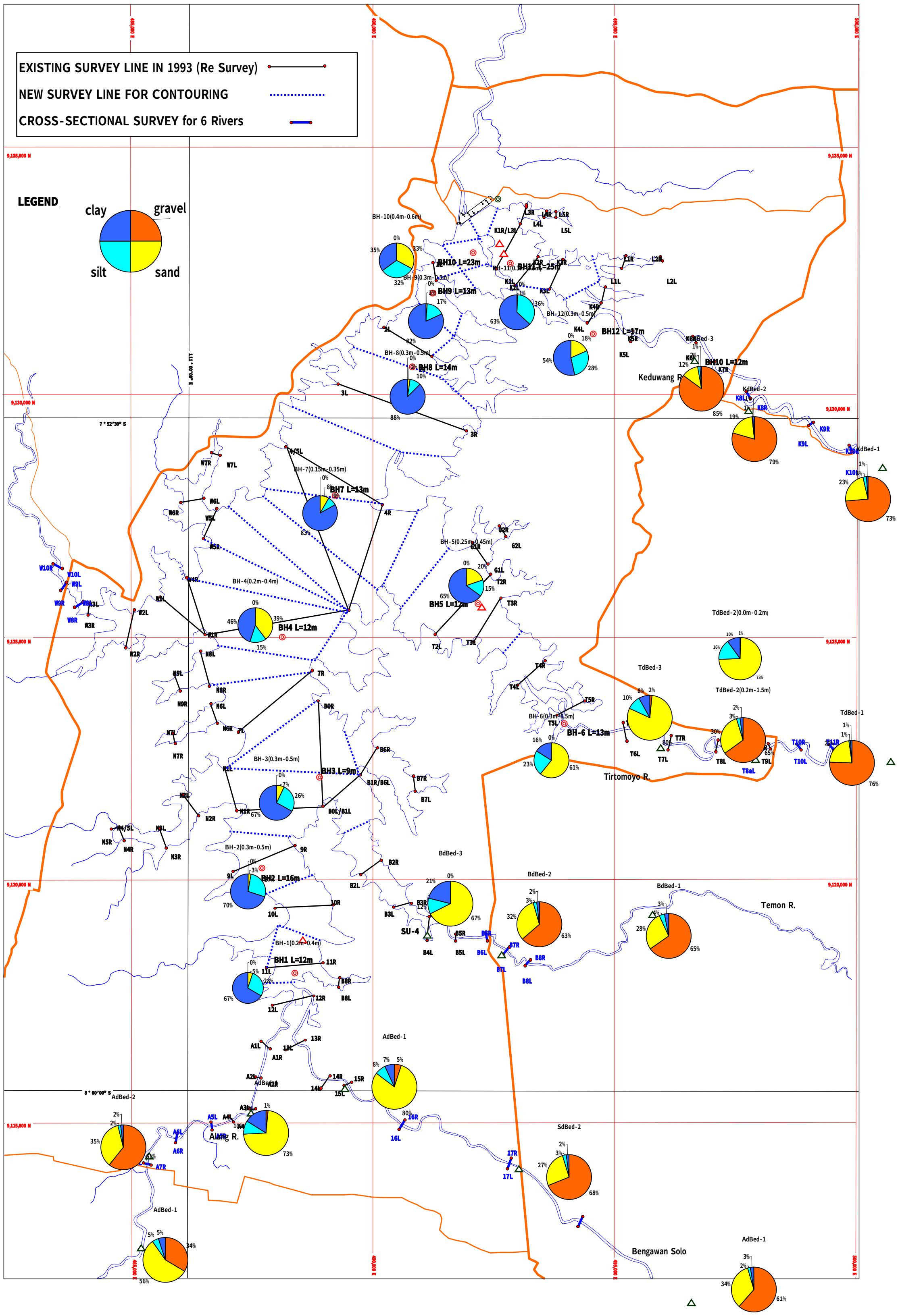
The longitudinal geological sections in the reservoir along Keduang, Tirtomoyo, Temon, Solo Rivers are presented in Figure 4.2.1. The character of sediment material component of main tributaries in the Wonogiri dam catchment area is described below.

- Sediment materials in the reservoir derived from the Keduang River are composed mainly of silt and clay, which are inferred to have been transported as suspended load.
- Sediment of the reservoir from the Alang River, Solo River, Temon River and Tirtomoyo River gradually become finer downstream ward and form sandy to clayey fore-set bed in the vicinity of the upstream end of the reservoir. Transportation analysis of the sediment from these rivers needs to consider tractional load in addition to suspended load.



Source: JICA Study Team

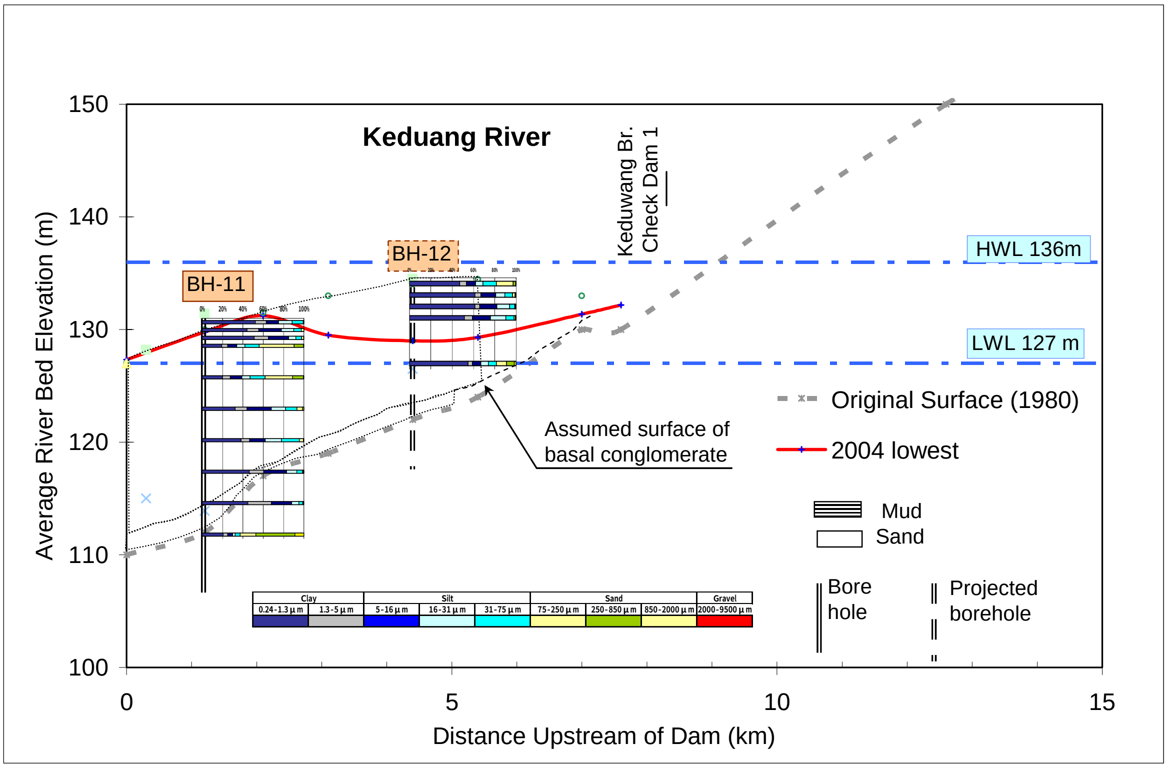
Figure 4.1.3 Grain Size Distribution of Drilling Cores

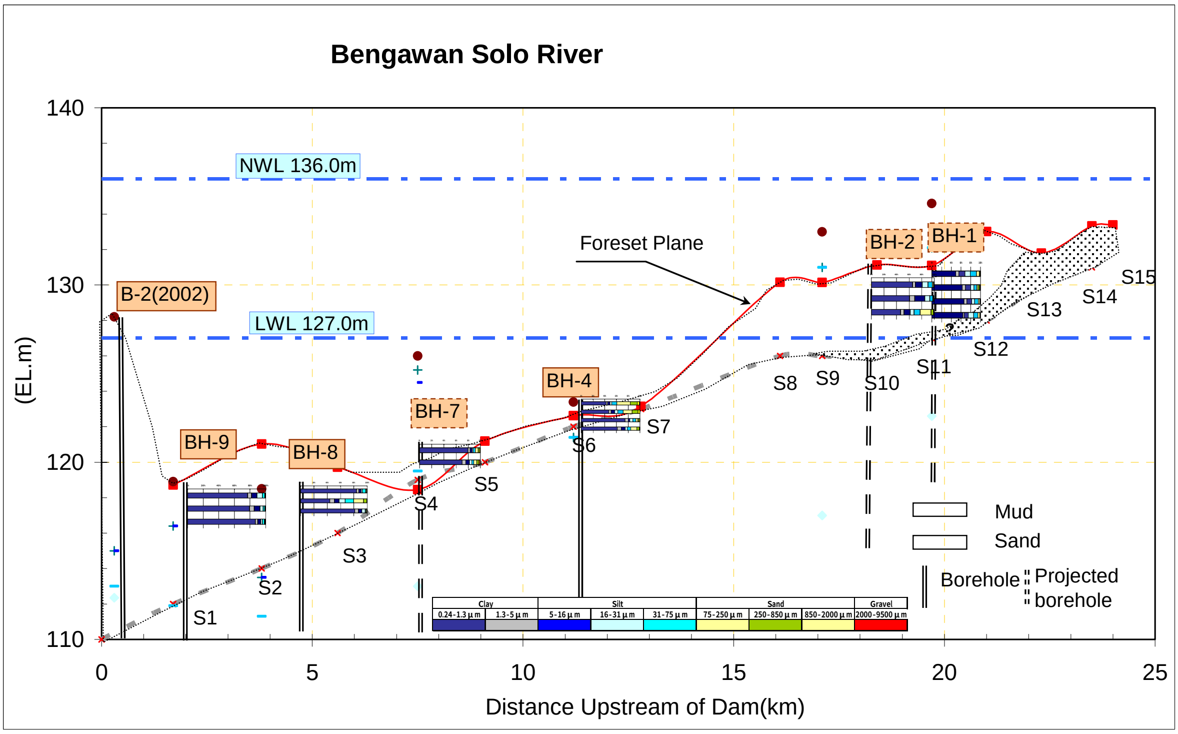


Source:JICA Study Team

Note: Sediment materials were sampled in the section of the boring core between 0.2 m - 0.6 m in depth and test pitting samples of 0.5 m in depth.

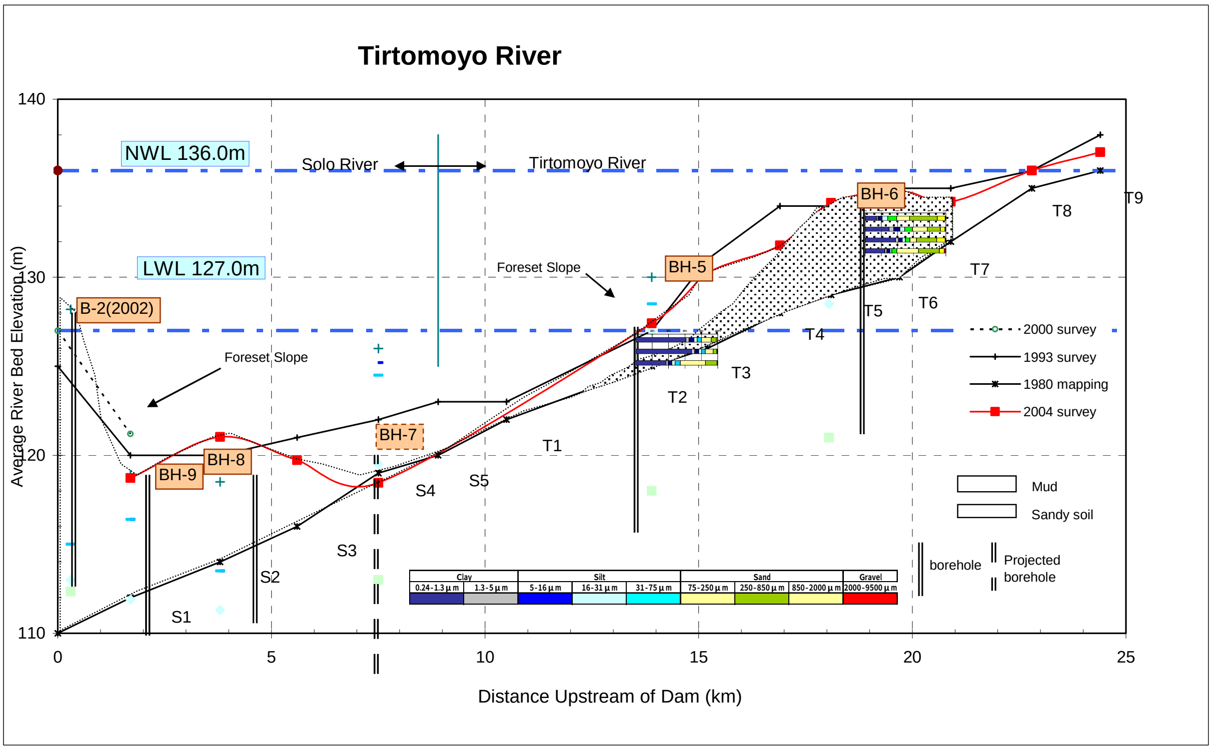
Figure 4.1.4 Composition of Surface Sediment Materials in Wonogiri Reservoir and Five (5) Major Tributaries

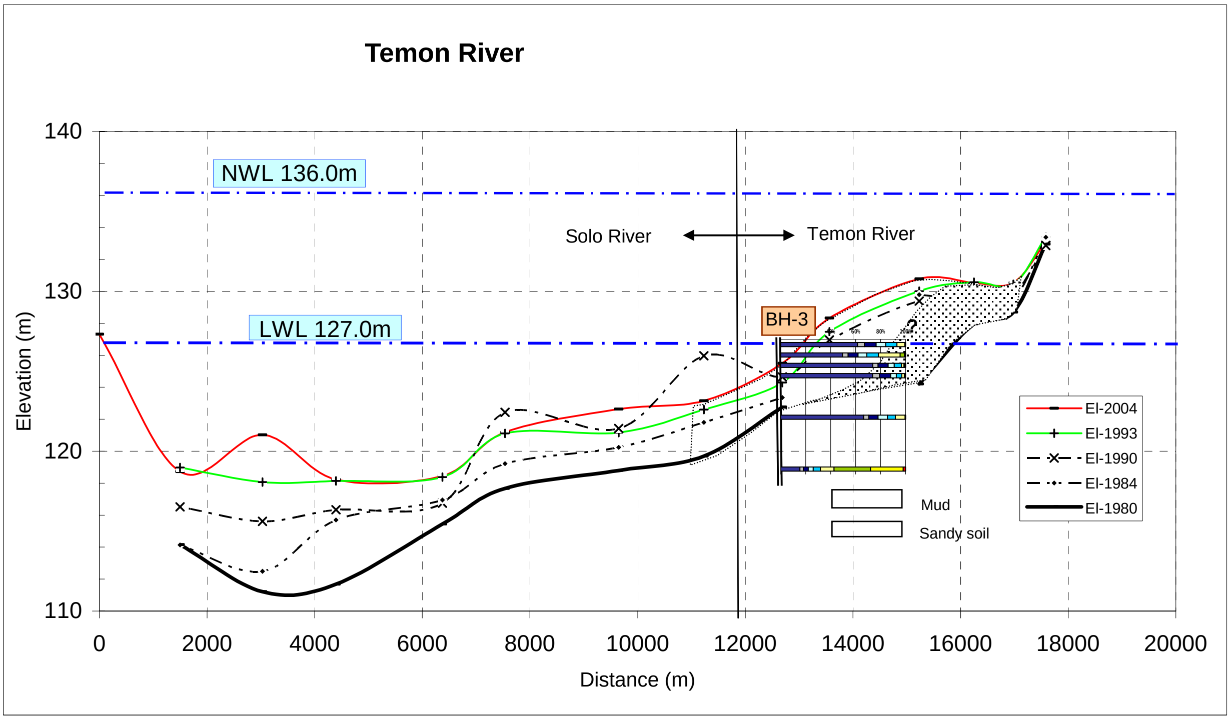




Source: JICA Study Team

Figure 4.2.1 Geological Sections in Wonogiri Reservoir (Keduang River and Solo River)





Source: JICA Study Team

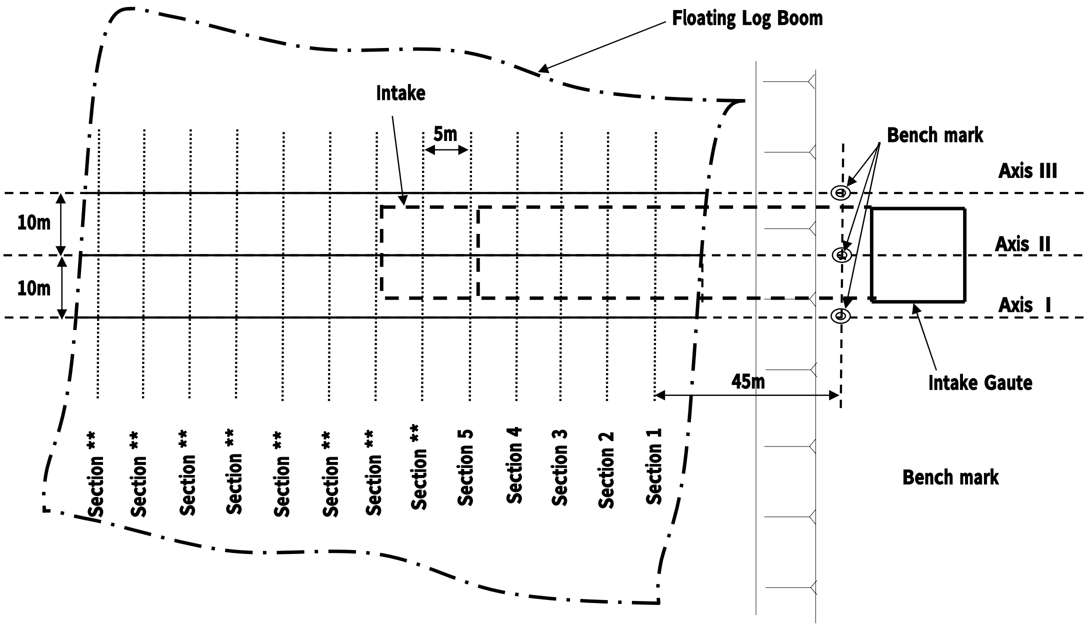
Figure 4.2.2 Geological Sections in Wonogiri Reservoir (Tirtomoyo River and Temon River)

CHAPTER 5 MONITORING ON SEDIMENTATION IN FRONT OF INTAKE

5.1 Method of Monitoring

The intake structure of the dam has been seriously affected by sediment inflow from the Keduang River. After completion of the Project for Urgent Countermeasures for Sedimentation in the Wonogiri dam reservoir in March 2004, PBS has been being monitoring periodically sediment levels on the approach channel to the water intake. The method of monitoring is outlined below.

Area	: Approach channel and the forebay of the intake (see Figure 5.1.1 below) (20 m (W) x 120 m (L) by 3 sections with an interval of 5 m)
Method	: Echo Sounder (RAYTHEON COMPANY)
Schedule	: Monthly basis



Source: JICA Study Team

Figure 5.1.1 Monitoring Locations in the Forebay of Intake

Intake after Completion in 1980

Monitoring Survey in May 2005

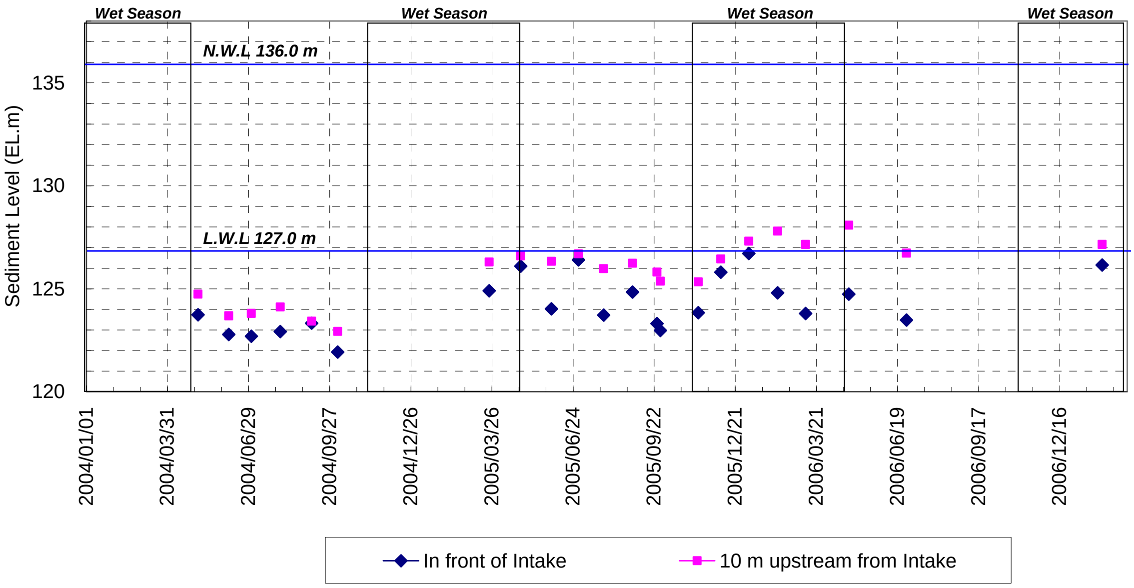
River bed conditions around Intake on Driest Season: RWL was approx. EL. 127.0 m

5.2 Result of Monitoring

The result of sedimentation monitoring to date is summarized in Annex-3. Figure 5.2.1 below shows the comparison of sediment levels on the approach channel just in front of and 10 m upstream of the intake. It is appeared that:

i) Sediment level was EL. 123.7 m in front of trash lack in July 2005.
ii) Sediment level rose by 2.1 m from October 2004 to July 2005 during the wet season.
iii) Opening space between the sediment level and top of the intake is approximately 3.3 m in July 2005.
iv) Sediment levels were stable during the dry season from May 2004 to October 2004.
v) During the succeeding wet season, sediment levels increased by around 3 m from November 2004 to February 2005.
vi) However, sediment levels were almost stable from March to May 2005.
vii) Stable slope of sediment deposits might be approximately 1/20-1/30 from the longitudinal sediment profiles.

Echo Sounder



Source: JICA Study Team

Figure 5.2.1 Comparison of Sediment Levels in front of Intake

5.3 Topographic Survey at Intake Forebay on October 2006

A leveling survey was conducted by PJT-1 in the surrounding area of the intake on October 2006, while the reservoir water level dropped below EL.130.0 m in the end of dry season and sediment deposits around the intake were appeared on the ground.

The method of monitoring is outlined below.

Survey Period	: October 2006
Survey Area	: 250 m x 400 m in forebay of intake and spillway
Interval	: approx. 10 m
Method	: leveling

The obtained contour map is presented in Annex-4

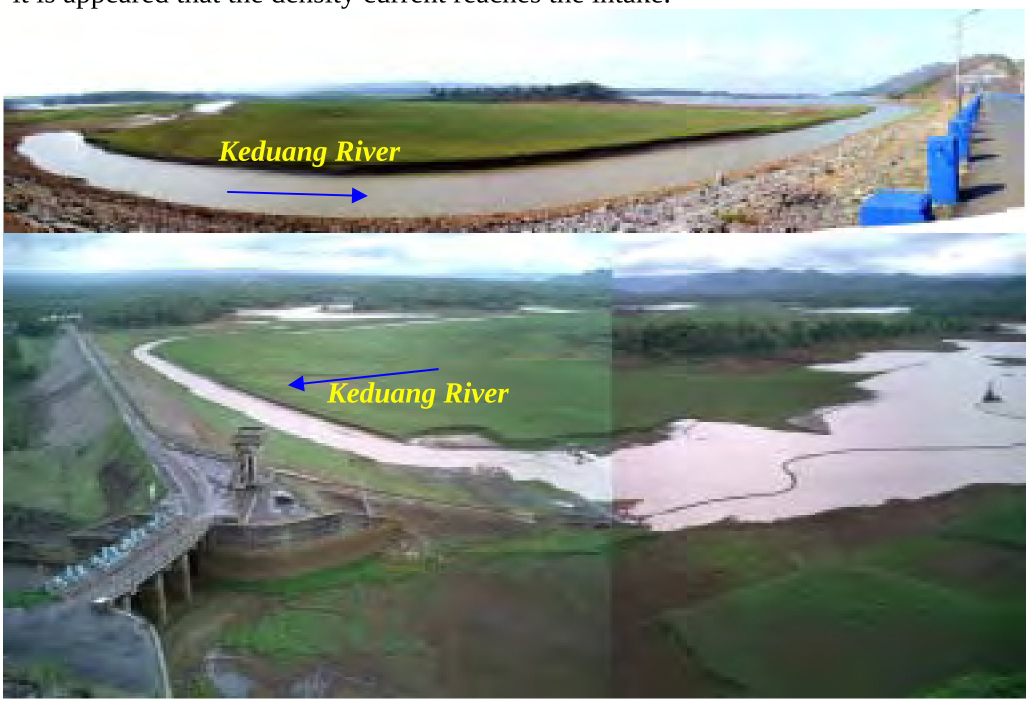
5.4 Preliminary Analysis on Sedimentation at Intake

5.4.1 Sediment Inflow from the Keduang River

The Keduang River is the primary cause of the current sedimentation problems in front of the intake because it enters the reservoir close to the dam.

There are two hydraulic mechanisms of sediment inflow from the Keduang River.

- At the beginning of the wet season (the reservoir is around at the low water level), extremely high turbid water due to the Keduang flood directly flows into the intake forebay area along the low water channel which is naturally formed along the dam.
- In the middle and later stage of wet season, turbid water penetrates into the reservoir as a density (muddy) current. From the result of water quality monitoring in the Study, it is appeared that the density current reaches the intake.



Photos: Keduang River within Wonogiri Reservoir

5.4.2 Topographic Feature at Intake

Topographic feature on sedimentation at the intake are described below:

- Sediments have already been deposited on the approach channel (cut-off channel) to the intake because the sediment levels has already risen over LWL El. 127 m.

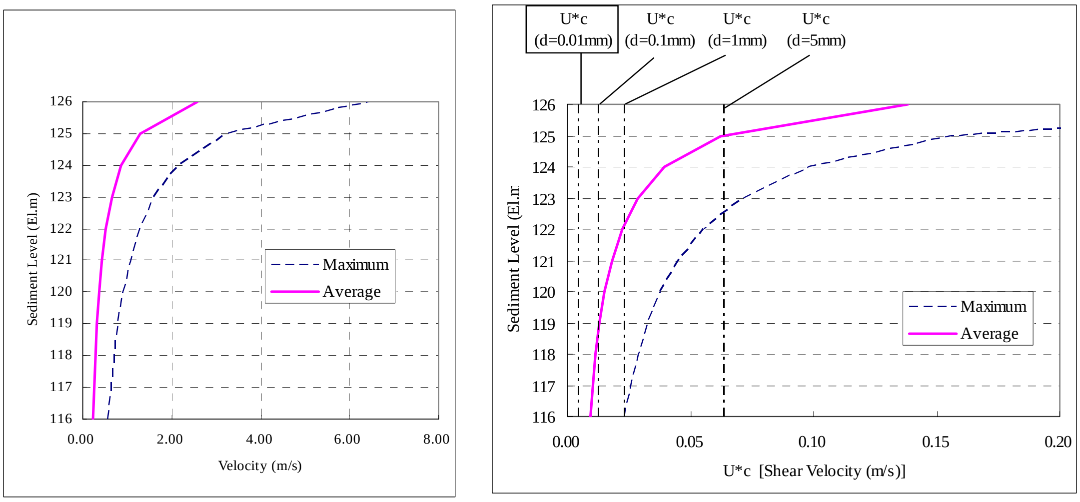
- Therefore the existing approach channel connecting the intake and original river can not function due to almost full sedimentation up to LWL.

5.4.3 Suction Effect of Intake

The inlet of the intake is designed as bellmouth (11.6 m (W) x 11.0 m(H)) to secure the smooth stream line and reduce the head loss at the inlet. As a brief quantitative analysis, the suction effect of the intake was examined below.

(1) Sediment Level and Shear Velocity:

The relations among sediment level and inflow velocity, shear velocity (U*) and critical shear velocity (U*c) at the inlet are analyzed and summarized in Figure 5.4.1 below. The basic conditions, formulas and calculation results is attached in Annex 5. In this analysis, the objective discharges are applied 75 m^3/s for the maximum power discharge and 30 m^3/s for the average.



Note) Iwagaki formula is applied for the calculation of the critical shear velocity (U*c),.

Source: JICA Study Team

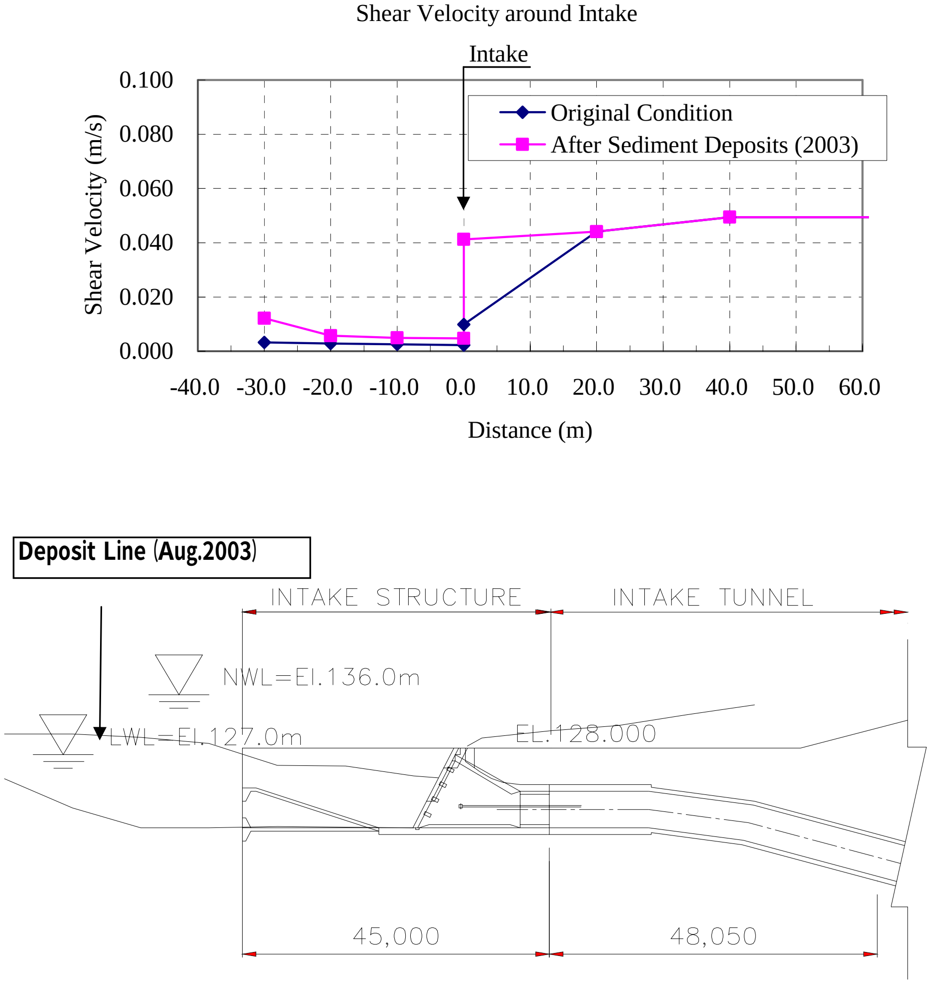
Figure 5.4.1 Relations among Sedimentation Level, Inflow Velocity, Shear Velocity(U*) and Critical Shear Velocity (U*c)

As the sediment level is higher, the inflow velocity and U* become larger. Considering as a smallest case, however, immediately after construction of the intake, the inflow velocity was around 0.24 m/s for the average power discharge with the sediment level of El.116.0 m. On the other hand, focused on the critical shear velocity (U*c), it can be estimated as 0.009 m/s against the sediment deposits at the intake, D60 of which is assumed 0.01 mm.

The relation above indicates that inflow velocity is usually faster than the critical shear velocity. If there is no obstruction, the sediment deposits in front of the intake can be washed into the inlet by the suction effect at the intake. In fact, however, there are some obstructions as i) garbage blocking at the trash lack, ii) consolidation of sediment deposits, and iii) characteristics of re-suspension and repose angle of a cohesive sediments. As the results, the suction effect of the intake cannot function well and sediment level has risen up to EL.124 m as of July 2005.

(2) Sediment Velocity along the Longitudinal Section of the Intake:

The shear velocity along the longitudinal section on the approach channel is shown in Figure 5.3.2 below. As seen, in front of the intake, the shear velocity is very low due to wider section. At the inlet, the shear velocity depends on the sediment level as mentioned above. In the original condition, the shear velocity was approx. 0.01 m/s at the inlet, but at present, it has increased to 0.04 m/s which is almost the same as that of the inside of intake tunnel.



Source: JICA Study Team

Figure 5.4.2 Shear Velocity around Intake