SUSPENDED SEDIMENT CONSISTENCY DATA FOR MADEIRA RIVER AT PORTO VELHO, RO, BRAZIL

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Abstract – This paper covers the consistency of suspended-sediment data for the Madeira River at Porto Velho, period 2003/2007 for feasibility and basic project studies, and 2009/2013, while the construction of Santo Antônio dam located 5.0 km upstream.

The Madeira River, main tributary of the Amazonas, has basin of $1,42 \times 10^6$ km^2, occupying 23% of $6,112 \times 10^6$ km^2 of the Amazon, and extends through Bolivia, Peru and Brazil. It is named Madeira downstream the confluence of Beni and Mamoré Rivers, flowing 3,600 km from the springs in the Andes. It discharges in the Amazon River 1,300 km upstream the Atlantic Ocean.

Two measurements were done every month, having being reduced to one since 2010. Under operation are six stations in which the same technology of USGS/FISP was accomplished. Besides the samples of suspended and bed materials, it was realized measurements of water discharge by current meters and by ADCP, the latter recently. The sediment analyses are done in appropriate laboratory. The sediment discharge is calculated by the modified Einstein procedure.

Practically all the Madeira sediment load derives from the Andes region due to the metamorphic rocks, high precipitations, great declivities, weak vegetation cover, crescent anthropic actions, etc. Hence, the Madeira River and their tributaries present high sediment loads; on the confluence with the Amazonas River there is an equivalence of amount although it has three times less water discharge.

The consistency analysis was based on double-mass curves, on sediment transport curves, and also on hydrograph values of water discharge Q and sediment discharge Q_s, or concentration C. This procedure was considered more suitable than the mathematical analysis due to the small frequency of measurements. The curves presented good adjustment, demonstrating good consistency of the data. It was verified that part of the gross sediment was trapped by the cofferdam, discharging the fine material downstream.

INTRODUCTION

This work covers the sediment consistency data produced at the Madeira River station, in Porto Velho, Rondônia State, Brazil. The time periods refer to the interval 2003-2007, for the Feasibility and Master Plan projects on power plants building, and from 2009-2013, within the time period of construction of Santo Antônio dam. The first phase was accomplished by FURNAS Centrais Elétricas, by having PCE as advisor during the first period. At the second phase the works were done by PCE itself through SAE (Santo Antônio Energia), the power plant building consortium (PCE, 2009).

The Madeira River has a watershed of 1.42×10^6 km^2 and mean flow at its mouth of 31,200 m^3.s^{-1}. It is the largest watershed tributary of Amazonas, covering 23% of its area (ANA, 2004). At dam site, located at the medium reach of the Madeira River, the drainage area is 988,873 km^2, which corresponds to almost 70% of the total area; the mean flow is 18,636 m^3.s^{-1} (1967-2006). The rainfall in the Brazilian territory is almost 2,000 mm a year, whereas higher figures are observed at the top of the basin, which includes the upper reach of the Beni River (a tributary of the Madeira River), with mean rainfall of 5,000 mm a year.

The Madeira River watershed, tributary of the right bank of the Amazonas River, stretches to Bolivia (50%), Peru (10%) and Brazil (40%). From the springs of its tributaries in the Andes to its mouth it runs 3,600 km, being 1,300 km away from the mouth of the Amazonas River, at the Atlantic Ocean. The river is named 'Madeira' ('Wood', in English) downstream the reach of confluence of the Beni and Mamoré Rivers, at the border between Bolivia and Brazil (Figure 1).

Figure 1 – Location of the projects of hydroelectric power plants at the Madeira River, and gauging stations (Carvalho and others, 2005).

The Santo Antônio Power Plant (run-of-river), still under construction in 2014, is going to generate 3,150 MW by using 44 bulb turbines. Its building started in 2009.

Previous sedimentological studies (PCE, 2004, Carvalho and others, 2005), as well as works produced by other authors (Meade, 1985, and Filizola Jr., 1999) have shown that the mean sediment discharge in the Madeira River is equal or even higher than that in the Amazon River at the confluence of both water bodies. Thus, the companies responsible for the hydroelectric undertaking were already developing more robust studies. Along the same lines, IBAMA (Brazilian Institute for Environment) and regulatory agencies – ANA (National Water Agency) and ANEEL (National Electrical Energy Agency) – were also requiring several similar studies in order to release the environmental construction license. It was required the continuous monitoring: samplings and several studies during the construction and operation of the power plant.

LOCATION OF THE GAUGING STATION

The gauging station in the Madeira River at Porto Velho was regarded as essential for the feasibility and master plan projects of the Santo Antônio Plant. It is located 5 km downstream the dam site. The drainage area at the station is 988,997 km². Its coordinates are 8°44’12” and 63°55’13” (ANEEL, 2001).

There are other sedimentometric stations under operation by the project in the watershed (Table 1 and Figure 2), all of them showing the same measuring procedures and data consistency. In the topic study is presented only the consistency analysis for the gauging at Porto Velho, as an example.

Table 1 – Gauging and sedimentometric stations under operation which were used for the studies on the Santo Antônio Power Plant (PCE, 2009)

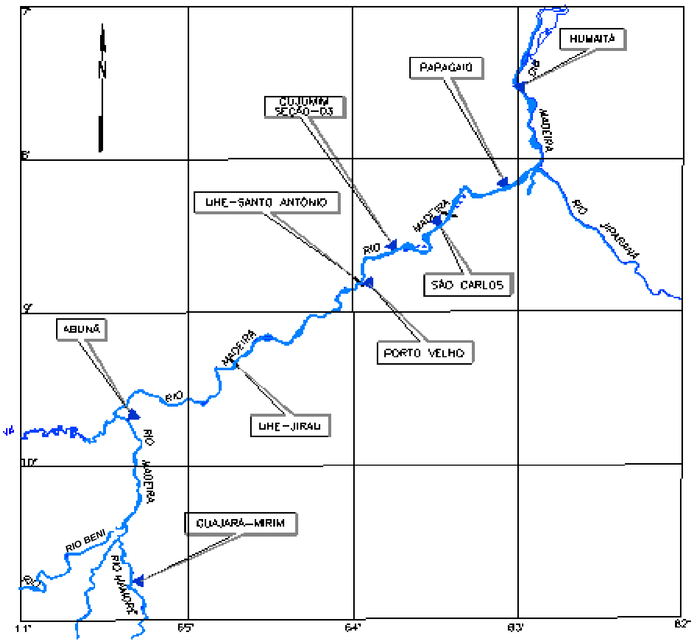
Gauging station name	**River**	**Coordinates UTM**		**Zero elevation (m)**	**Date (re) installation**
		North	**East**		
Abunã***	Madeira	8926370	240512	74,65	July.1988 *
Jusante Caldeirão do Inferno**	Madeira	8982304	323362	53,86	31.07.09
Porto Velho**	Madeira	9032851	399179	42,50	April.1967 *
São Carlos**	Madeira	9066528	444077	38,40	19.09.08
Humaitá**	Madeira	9170426	497816	24,65	March.1931 *
Jaciparaná**	Jaciparaná	8975978	346143	62,90	16.10.2008

* Stations installed by other entities, initially operated for level and water discharge.
** The Zero elevation of the ruler is under analysis (subjected to changes).
*** Abunã station was abolished at the end of 2013 owing to backwater effects caused by Jirau Power Plant (downstream), being substituted by a station closer to the confluence of the Beni and Mamoré rivers.

All the gauging stations have rulers, linigraphs (gage-height records) and pluviographs, whose data are transmitted by telemetry, as well as established cross section for flow and sediment discharge measurements. During the phase of feasibility and master plan studies, data collected by other entities were used (Figure 2).

The Porto Velho and Humaitá stations are regularly operated by ANA and count on four flow and suspended sediment samplings per year without interruption, even during the period when FURNAS and PCE ceased their operation there. The set of sediment data produced by ANA were not included in this study.

Figure 2 – Location of the gauging and sedimentometric stations in the Madeira River, used in the studies of the Santo Antônio Power Plant (PCE, 2009)



METHODOLOGY ADOPTED

The installation and operation of gauging stations follow the standards established by regulatory agencies (ANA and ANEEL), as well as the instructions dictated by WMO (World Meteorological Organization), of USGS (United States Geological Survey), and by ICOLD (International Committee on Large Dams).

The operation of the gauging stations consists now of daily observations of water level, and monthly flow and sediment discharge measurements, including determination of suspended and bedload sediment granulometry. The samplings of suspended sediment are accomplished by using the equal width increment method, with bag sampler. The number of verticals sampled range from 8 to 12. The collections of bedload material were done at 5 verticals, also equally distanced, and using the sampler BM-54 (Guy & Norman, 1970; Yuqian, 1989; Carvalho, 2008).

The crew during the first sampling period belonged to FURNAS, being the samplers analyzed by the Water Lab of FURNAS in Goiânia (GO), following the criteria established by the USGS, according to Guy (1969) and CESP (2009). The measurements frequency was done twice by month. The equipment used in the campaigns was Brazilian made, in reference to similar American samplers, which were designed by the Subcommittee on Sedimentation. To flow measurements were done by a current meter, hydro windlass nationally produced and, eventually, an ADCP (Acoustic Doppler Current Profiler).

During the second period of the works, due to contract with PCE, a sedimentologic lab was assembled in Porto Velho. The analyses were done by the evaporation and filtration processes, being the granulometry determined by using the bottom withdrawal tube, pipetting and sieving, depending on the amount of material collected or operational requirements.

The same sampling and analysis methodologies adopted before were applied, being the same sort of equipment, belonging to the American series. An ADCP was purchased so that the flow measurement on a wide river course, like the Madeira River, rendered more feasible.

The total sediment discharge was computed by using the Modified Einstein Procedure. Hence, the measured suspended sediment discharge, the bedload, total and the discharges per granulometric bands were determined (USBR, 1955). The computation was possible owing to the use of the software "Einstein.xls", developed by Braga (2008) using metric system. The river flow measure with the current meter was calculated by using the midsection method together with a software, being worth mentioning that the technicians usually do the calculus in the field, thus enabling the verification of typing mistakes in the office.

ANALYSIS OF DATA CONSISTENCY

Errors in the results of sediment discharge happen due to the use of unsuitable samplers, sampling mistakes, wrong laboratory analysis, river flow badly surveyed or computed, typing mistakes and others.

Even following strict sampling procedures, the admissible mean error is 10% for the suspended sediment discharge, whereas 25% for the bedload discharge (Yuqian, 1989).

The sediment data consistency analysis requires huge amounts of sampling data in order to reach a suitable result (Burkham, 1985). Owing to the scattered behavior of the sediment discharge in water bodies – large variations are noticed at every moment -, the use of several data is recommended, with the best sampling frequency possible. Besides, the samplings must be accomplished very cautiously and meeting the criteria established by the regulation, such as:

- To nominate experienced technicians for the field and lab crews;
- To sample river flow following the regulations;
- To use sediment samplers suitable to the water body conditions as regards depth and velocities, by bearing in mind the sampling method adopted;
- The samplings must cover all the possibilities of variation for the water elevation;
- To meet the requirements for sampling and collecting enough material so that the lab analyses can be done accordingly;
- To mind the importance of the samples and to label them correctly;
- To analyze the samples according to established methods;
- To choose suitable methods for computation;
- To avoid typing mistakes.

Sediment data must be accurate so that they can be considered trustworthy. Hence, bad-quality data used in studies and models may outcome in undesired results, most times not being noticed by the user. Therefore, previous consistency data is essential (Carvalho, 2008).

The sampling frequency during the raining season was twice a month, being once a month within the other seasons. Nowadays, the sampling is accomplished once a month (during raining season) and once every two months during drought.

Due to the low sampling frequency, the consistency analysis here presented was made by using the graphic method.

The use of Graphics

Once understood the measurement criteria presented above, it will be necessary to analyze the data consistency through graphics before their use.

Figure 3 shows the plotting of the data for the two periods under study; there was no operation from February 2007 to January 2009. By studying the graphic, it can be noticed that the sediment concentration peaks precede (some days) the river flow peaks.

Figure 3 – Madeira River at Porto Velho – river flow and suspended sediment concentration samplings – intervals 2003-2007 and 2009-2013 (courtesy PCE)

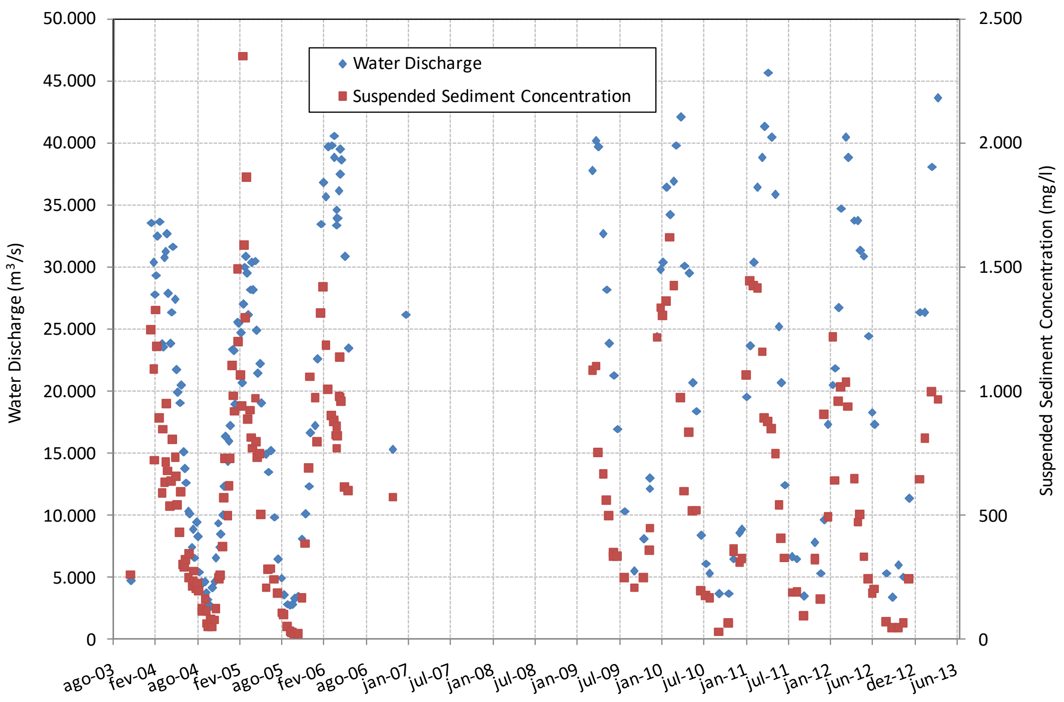


Figure 4 presents the rating curve of the river flow values versus water elevation. The campaigns of both periods were considered, being used the data produced by using the ADCP. The plotted curve refers to flow measurements for the first period (2003-2007). The data for the second period were plotted so that they did not interfere on the drawing of the curve. It can be observed that the data collected with ADCP are inferior to those measured by using the current meter, thanks to the reasons already known.

Figure 5 presents the sediment transport curve: suspended sediment discharge versus river flow. Similarly to the previous case, the curve refers to the period 2003-2007, plotting on it the values of the 2009-2013. The upper branch of the curve shows more scattered data.

Figure 4 – Madeira River at Porto Velho – flow rating curve for the periods 2003-2007 and 2009-2013 (courtesy PCE)

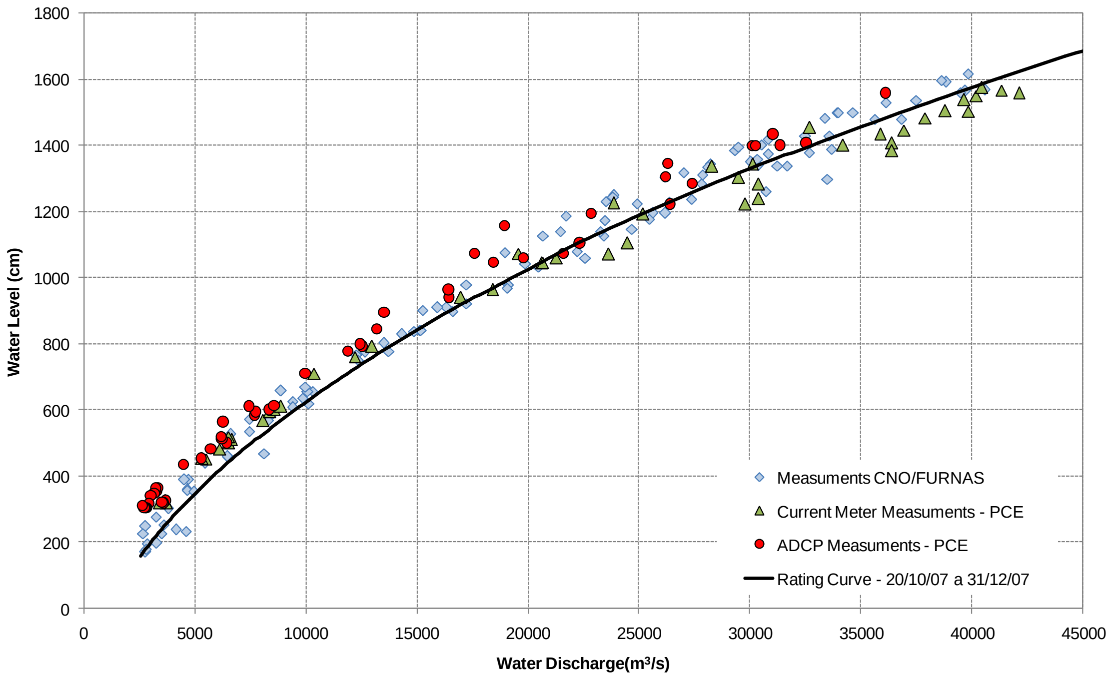


Figure 5 – Madeira River at Porto Velho – sediment rating curve for the periods 2003-2007 and 2009-2013 (courtesy PCE)

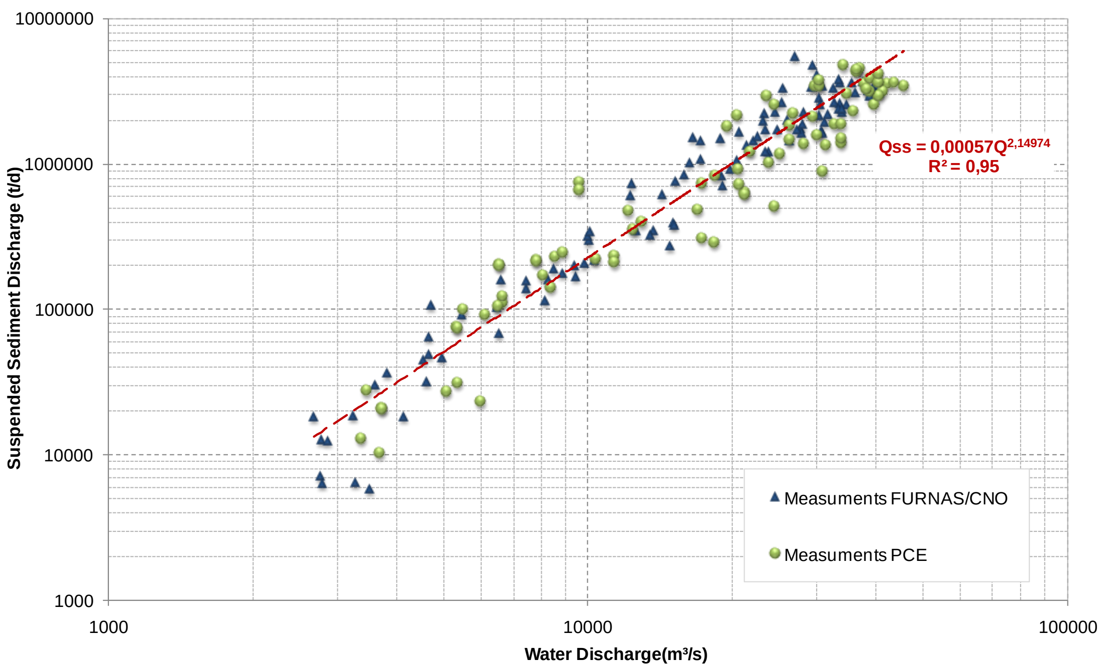
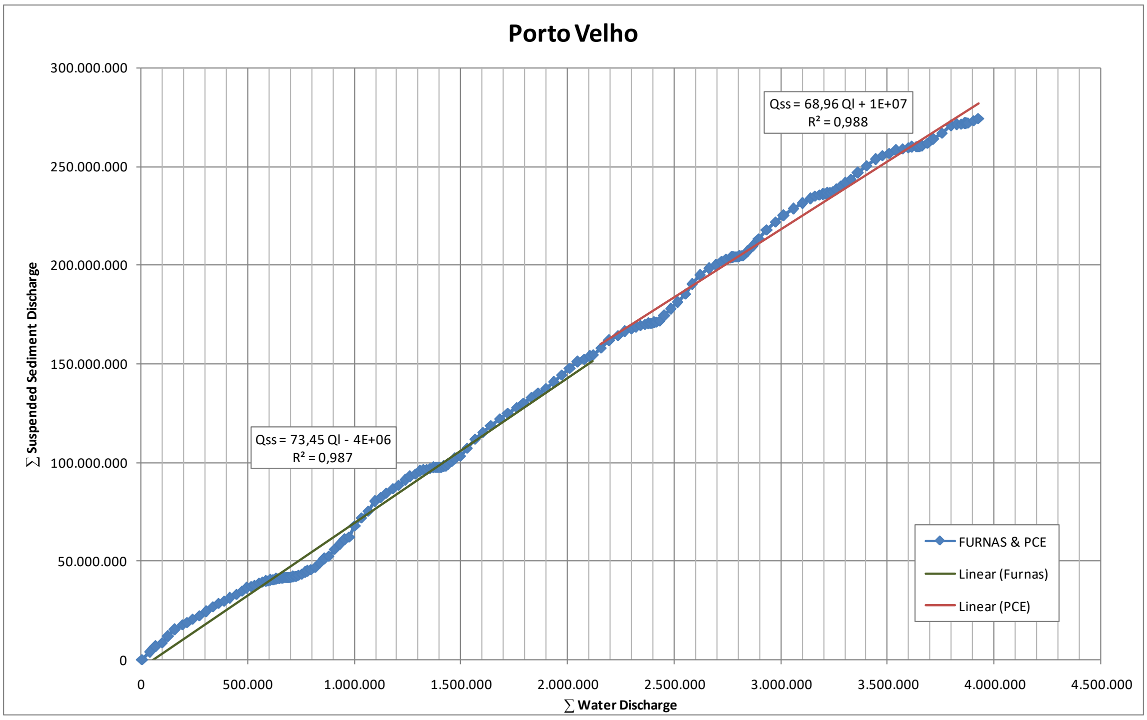


Figure 6 shows the mass curve for the station in question. The sinuosity of the curve indicates samplings during high and low water periods.

It is noticed the good quality of the measurement performed within both periods under analysis. During the first period (2003-2007) the tendency curve remained below the one for the second period (2009-2013) – phase of dam construction. During the second phase took place events of higher rainfall and river flows, as well as higher mean sediment discharge (almost 2.0 t/day). By considering the dam construction, higher figures were foreseen, even though part of the bedload is being trapped by the reservoir and cofferdam.

Figure 6 – Madeira River at Porto Velho – Mass curve for the suspended sediment data versus river flow – periods 2003-2007 and 2009-2013 (courtesy PCE)



CONCLUSION

In the Amazon rain forest it has been noticed that the tributaries with springs in the Andes present higher sediment loads when compared with those whose springs are in the forest. Thus, most of the sediment in those water bodies is derived from the Andes region, where there is more rainfall and active geology, presenting metamorphic rocks such as sandstone, more easily subjected to erosion.

The results of the samplings for the first period have shown that the mean annual suspended sediment discharge reaches the figure of 542 million t, with mean concentration of 848 mg/l. The non-sampled sediment discharge represented 6% of the whole suspended sediment discharge.

It also was observed that the fine material (clay and silt) represented 85% of the total sediment discharge, whereas 12% and 3% were composed of fine sand and gross material, respectively.

It was concluded that the river flow and sediment discharge samplings were accomplished following suitable methods, with good consistency. The curves presented good adjustment, demonstrating good consistency of the data.

ACKNOWLEDGEMENTS

A project like the topic one counts on the participation of several professionals (in the office, field and lab), all of them committed to the good execution of the tasks. The authors thank the whole staff, as well as the following Furnas engineers due to their support: Neiva Conceição Pereira Ruiz, Luiz Fernando Alves da Silva and Zedequias Bento dos Santos, the latter a Furnas' worker formerly, although an Odebrecht's employee nowadays. The authors thank to Anderson Braga Mendes, of Itaipu Binacional, the version to English the present paper.

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