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Reassessment of Porto Primavera Reservoir sedimentation in view of updated sediment measurements

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Abstract The Porto Primavera Dam is located on the Paraná River, Brazil, downstream of the Jupiá dam and upstream of the Itaipu dam. The reservoir capacity is 15.7 km^3. The sediment load impounded in the reservoir mainly comes from six tributaries located in a drainage area of 574 000 km^2. Low dam height and high intake flow have led to a very low intake crest elevation, which can affect dam operations due to sediment deposition at the dam. Previous sedimentological studies did not take into account two tributaries with significant sediment yields. A re-evaluation of present reservoir capacity, taking into account the additional tributaries and more recent sediment monitoring data, indicates that the sediment deposits at the dam will not reach the intake crest during the projected life expectancy of the Porto Primavera Dam and Reservoir. However, it is clear that a soil conservation plan could substantially extend the utility/life expectancy of the facility.

Key words Brazil; Paraná River; Porto Primavera Reservoir; sedimentation

INTRODUCTION

The Porto Primavera Dam is located on the middle reach of Paraná River, on the borders of the states of São Paulo and Mato Grosso do Sul in Brazil, downstream of the Jupiá Dam and upstream of the Itaipu Dam (Fig. 1). The drainage area of the basin is 574 000 km^2. Reservoir surface area and capacity are 2044 km^2 and 15.7 km^3 respectively, at full pool. Due to the existence of upstream dams, the sediment load carried to the Porto Primavera Reservoir mainly comes from six tributaries within a catchment area of 92 761 km^2; 69% falls within the Mato Grosso do Sul and 31% falls within São Paulo (Fig. 1).

Recently, the watershed has undergone intense erosion due to changing land use, high soil erosion susceptibility, and the lack of a coordinated soil conservation programme (IPT/DAEE, 1997; IBGE/Seplan 1992). The high soil erosion susceptibility is intrinsically related to the local lithology which mainly consists of sandstone. This rock, under humid tropical weathering conditions, facilitates development of a highly erodible sandy soil.

Erosion is more intense in São Paulo than in Mato Grosso do Sul due to steeper relief and shallower soils. Hence, the potential for soil loss and sediment transfer to

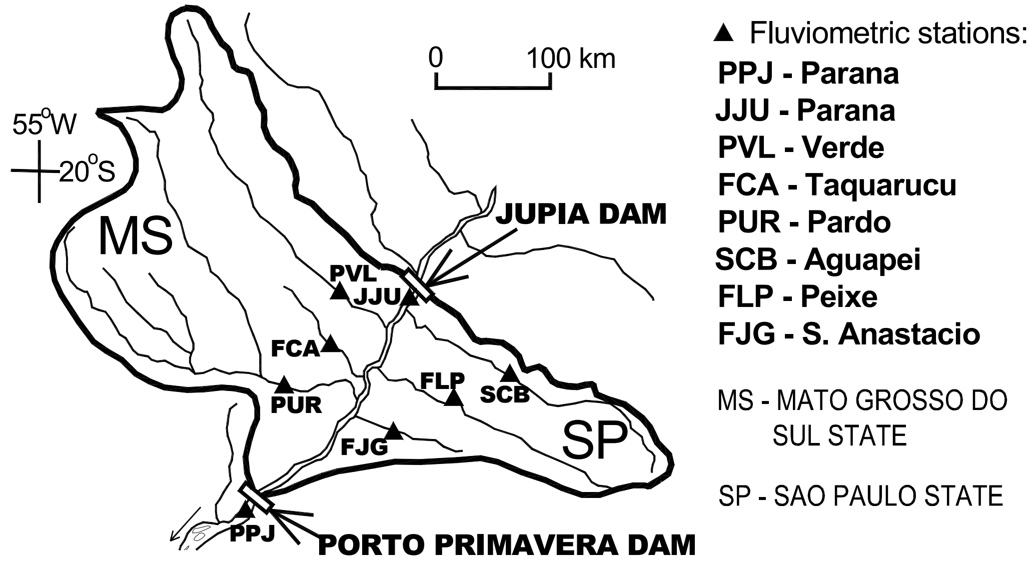

Fig. 1 Porto Primavera watershed and fluviometric stations.

Porto Primavera Reservoir is naturally greater in the São Paulo subwatersheds than in the Mato Grosso do Sul subwatersheds (Walm, 2003a). In addition, the São Paulo subwatersheds encompass areas of more intense soil utilization, larger areas of cultivation, and greater population densities. On the other hand, pasture and reforestation tend to predominate in the Mato Grosso do Sul subwatersheds; however, a boom in soybean farming is likely to lead to a greater soil loss in the future (Walm, 2003b).

Initial studies of the Porto Primavera catchments were performed prior to construction, and were reported in the Environmental Impact Study and Environmental Impact Report for the dam project (Themag *et al.*, 1994). Further work, recommended in these reports, includes additional sediment load measurements to re-evaluate reservoir capacity, measurement of sediment deposits at the dam face, and measurement of sediment distribution within the reservoir. These studies were performed between 2001 and 2004, and incorporate new data, including that from two minor rivers that were excluded from the initial evaluations due to a lack of existing observations. The results from these additional surveys are reported herein, and represent a complement to the work of Carvalho *et al.* (2004).

TOTAL SEDIMENT DISCHARGE

Total sediment discharge calculations were based on 257 measurements of sediment load carried out from August 2002 to May 2004 at eight monitoring sites (Fig. 1). These calculations exclude a limited amount of apparently inconsistent data. Total discharges were calculated using the Modified Einstein Method. Bed load discharges were disregarded in the Paraná River stations because only suspended sediment is expected to pass through the upstream dams.

Table 1 Average total sediment load and rating curves.

Station	River	Monitored area (km^2)	Equation $Q_{st} = f(Q_l)$	R^2	Q_{st} (t day^{-1})
JJU	Paraná	470000	$Q_{st} = 0.000123Q_l^{1.94}$	0.51	3818
PVL	Verde	21255	$Q_{st} = 4.437Q_l^{1.08}$	0.26	1411
FCA	Taquaruçu	2324	$Q_{st} = 0.134Q_l^{2.18}$	0.75	106.3
PUR	Pardo	31027	$Q_{st} = 0.597Q_l^{1.45}$	0.70	3037
SCB	Aguapeí	7671	$Q_{st} = 0.0082Q_l^{2.75}$	0.96	3292
FPL	Peixe	6807	$Q_{st} = 3.143Q_l^{1.64}$	0.86	4409
FJG	S. Anastácio	1878	$Q_{st} = 33.850Q_l^{1.36}$	0.76	1568
PPJ	Paraná	574000	$Q_{st} = 0.049Q_l^{1.26}$	0.23	4120

Table 2 Subwatershed sediment yield and total sediment discharge.

Subwatershed	Drainage area (km^2)	Sediment yield (t km^{-2} $year^{-1}$):		Q_{st} (t $year^{-1}$)
		Monitored area	Total area	
Verde	22325	24.2	23.9	533918
Taquaruçu	2575	16.7	16.3	41842
Pardo	32889	35.7	35.2	1157209
Aguapeí	12055	156.6	139.0	1675746
Peixe	9979	236.4	213.6	2132543
S. Anastácio	2073	304.7	296.8	615292

The calculated sediment loads (Q_{st}) and discharge measurements (Q_l) were combined to develop sediment rating curves [$Q_{st} = f(Q_l)$]. The equations, derived from the sediment rating curves, were then applied to discharge measurements covering the 1964–2004 period (except for the FCA and FJG stations, where data were only collected from 2002 to 2004) to obtain average total sediment loads for each station (Table 1).

The Q_{st} value for the whole subwatershed was estimated using curves obtained by Khosla (cited in Carvalho, 1994) that relate catchment area to sediment yield. Q_{st} measured at each station was divided by a factor corresponding to decreases in sediment yield associated with increasing catchment area, resulting in a Q_{st} estimate for the river mouth (see Table 2).

The Khosla correlation also was used to obtain Q_{st} for the whole watershed. The total sediment load determined was 6.8×10^6 t $year^{-1}$, a value slightly higher than the sum of Q_{st} from the six subwatersheds (6.2×10^6 t $year^{-1}$). The total Q_{st} flowing into Porto Primavera Reservoir is the sum of the Q_{st} of the watershed basin (6.8×10^6 t $year^{-1}$) and the Q_{st} measured downstream of the Jupia Dam (JJU, Fig. 1; 1.4×10^6 t $year^{-1}$) or 8.2×10^6 t $year^{-1}$.

Numerous studies in Brazilian rivers have shown increasing sediment loads over time (e.g. Carvalho *et al.*, 2001; Carvalho, 2003; Carvalho & Mendes, 2003). These larger loads appear to result from increases in erosion due to land-use changes and increases in precipitation that have caused higher water flows and which may be related to global climate changes. For purposes of evaluating the Porto Primavera watershed, precipitation, sediment concentrations, and discharge data from Carvalho *et al.* (2004) were analysed. The results indicate an increase in sediment yield of the order of 1% per year for the entire catchment area.

SEDIMENT DEPOSITION

The volume of sediment deposition per year in the Porto Primavera Reservoir was obtained by:

$$S = Q_{st}\, E_t\, W_{ap}^{-1} \qquad (1)$$

where S is sediment volume (m^3); Q_{st} is total sediment discharge entering the reservoir (t year^{-1}); E_t is trapping efficiency (%); and W_{ap} is apparent specific weight (t m^{-3}). All the terms are time dependent. Q_{st} increases 1% per year, E_t decreases as reservoir volume declines, and W_{ap} increases as sediment is deposited and previous layers are compacted.

The initial value for E_t was calculated by two methods, Brune's and Churchill's (cited in Strand, 1974), resulting in an estimated trapping efficiency of 82 and 58%, respectively. Brune's 82% was chosen because it represents the worst-case scenario and is similar to the rate effectively measured (81.5%). Brune's method was applied considering the volume of the reservoir at normal full pool (15.7 km^3) and a mean annual discharge of 7150 m^3 s^{-1} (Eletrobrás, 2003).

The initial value for W_{ap} was estimated as 1.2 t m^{-3}, according to the method of Lara & Pemberton (cited in Strand, 1974), using the average grain size distribution of the deposited sediment (pebble and sand (56%), silt (23%), and clay (21%)) that was determined by laboratory gravimetric analyses of all the sediment samples, weighted by the sediment load at each station, and assuming that the deposited sediment remained predominantly submerged.

Although Lara & Pemberton (cited in Strand, 1974) proposed two potential equations for estimating W_{ap} over time, equation (2) was selected because it is likely to yield a larger volume:

$$W_{ap,\mathrm{t}} = W_{ap,i} + K \log T \qquad (2)$$

where $W_{ap,\mathrm{i}}$ is initial W_{ap} (t m^{-3}); $W_{ap,\mathrm{t}}$ is average W_{ap} in T years (t m^{-3}); and K is a constant dependent on sediment grain size and type of reservoir operation.

Calculations involving equations (1) and (2), based on the assumptions cited above, made it possible to estimate the volume of sediment deposition through time using a software package entitled Sediment (Mendes & Carvalho 2003), that was developed specifically for this purpose. The results led to an estimated volumetric deposition of some 860 hm^3 after 100 years, or some 6% of the reservoir volume.

VOLUME DEPOSITION AT THE DAM FACE AND SEDIMENT DISTRIBUTION

The Empirical Area Reduction Method, described by Borland & Miller (cited in Strand, 1974), was used to estimate sediment deposition at the dam face, as well as sediment distribution throughout the reservoir, for 5-year intervals covering the period from 55 to 100 years of reservoir operation. In the case of this study, a mathematical model developed by Mendes & Carvalho (2001) was used to apply the method. Model input data included: (a) volume of sediment deposited relative to the time period under consideration; (b) appropriate values from the elevation-area-volume reservoir curve, including those for a null volume (CESP, 2003); (c) normal full pool for the reservoir (257 m); and (d) the shape of the reservoir.

Reservoir shape classification is defined by the ratio of depth to capacity (Strand, 1974). These data are plotted to determine the reservoir classification coefficient (*m*), which is the reciprocal of the slope of the depth-to-capacity plot and which normally plots as a straight line on a log–log scale. There is an intrinsic relation between reservoir shape and sediment deposition along a river bed for different water elevations (Carvalho, 1994). The value of *m* depends on the submerged relief of the impoundment, and defines four types of reservoirs (Strand, 1974). A value of $m = 2.5$ was computed for Porto Primavera; this corresponds to a Type II reservoir (flood plain–foothill), which is considered to be suitable for the local relief.

The mathematical model developed by Mendes & Carvalho (2001) generated estimates of the relative height of the sediment deposited at the dam face, and then the elevation of the deposits. Plots of the values (Fig. 2) led to an estimate of 67 years for sediment infilling to reach the dam intakes: an elevation of 229 m (Themag, 1982). Further, sediment distribution within the reservoir was expressed by a set of elevation–area–volume curves for the period under consideration (Fig. 3). Based on the data used as input for the mathematical model, as well as the results from the model, some observations can be made: (a) the model results were derived from a relatively small number of load measurements (less than two years); longer term monitoring would be highly desirable to get more accurate results; (b) the computed value of *m* (reservoir classification coefficient) also could correspond to a type III, which would alter the calculations because sediment deposition would be faster and, in turn, this would shorten the predicted useful life of Porto Primavera Reservoir; and (c) the Empirical Area Reduction Method was developed experimentally for USA rivers and is of great practical value; however, it needs to be validated for Brazilian rivers (Carvalho 2003b), because of the diversity of climate, precipitation, soil type, etc.

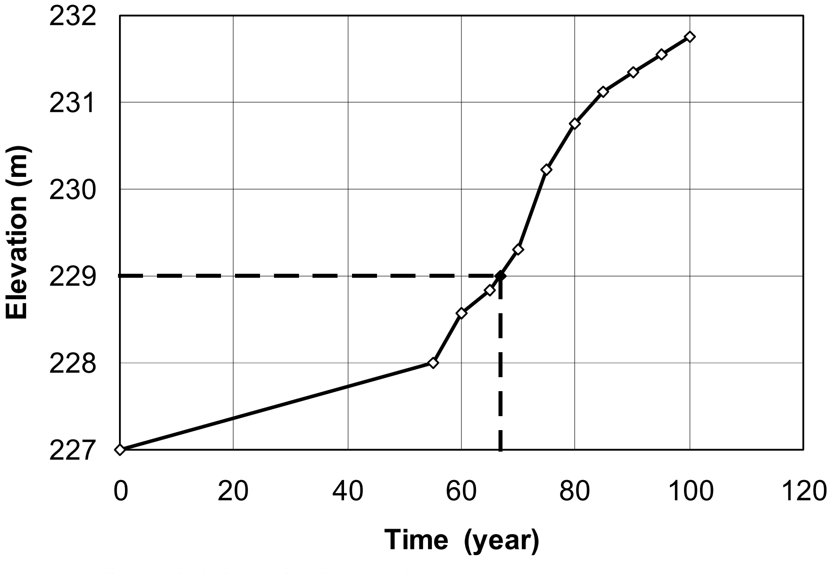

Fig. 2 Sediment height at the dam *vs* time.

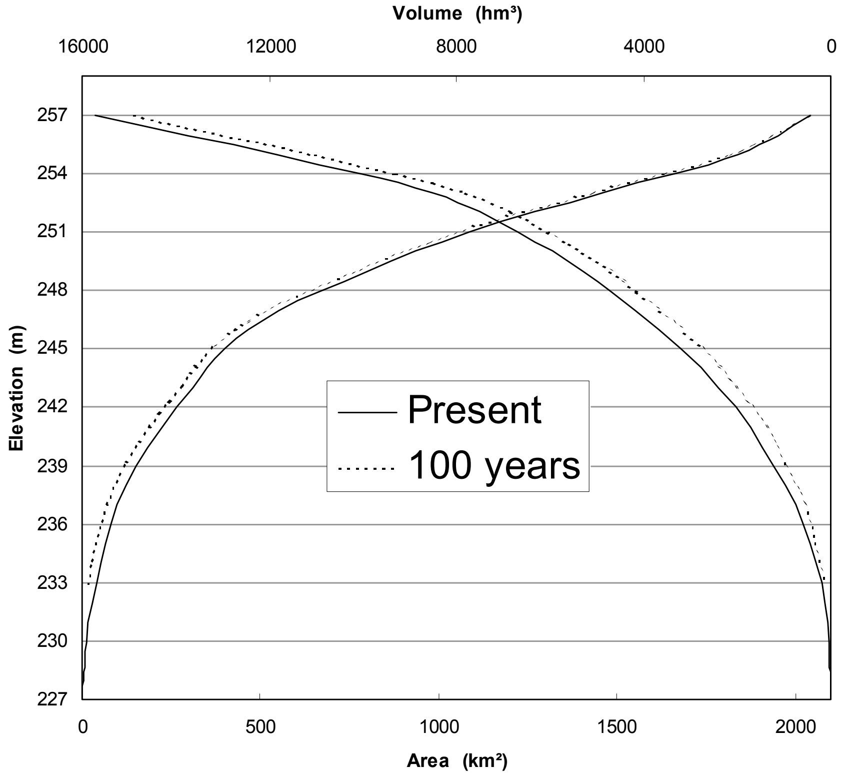

Fig. 3 Elevation–area–volume curves.

CONCLUSIONS

Based on the most recent data available, sediment deposited in the Porto Primavera Reservoir could reach the dam intakes in 67 years, at which point energy generation would be affected by a loss of turbine efficiency. A previous study had indicated that the same event would occur after 75 years (Carvalho *et al.*, 2004). Estimates of the sediment volume deposited after 100 years were on the order of 860 hm^3; this volume is not significant relative to total reservoir volume (15.7 km^3). Model results indicated that sediment yields along the left margin of the Paraná River (State of São Paulo) are far larger than in the State of Mato Grosso do Sul; hence, a programme of soil conservation to reduce sediment yields and subsequent reservoir infilling is more urgent in the former than the latter. As a result of increasing soybean production in Mato Grosso do Sul, sediment yields are increasing substantially; hence, a soil conservation programme also should be implemented in this region. Finally, periodic bathymetric surveys should be carried out in the Porto Primavera Reservoir to monitor changes in sediment deposition, particularly near the dam face.

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