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Analysis of flow regime changes due to operation of large reservoirs on the Zambezi River

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ABSTRACT: The Zambezi Basin, a semi-arid 1.4 Mio km^2 catchment area spreading across eight countries, constitutes a highly complex system. With several large dams, namely Kariba, Cahora Bassa, Kafue Gorge and Itezhi-Tezhi, the basin's hydrology is also influenced by vast wetlands with high ecological value such as the Barotse plains, the Mana Pools or the Kafue flats. The African DAms ProjecT (ADAPT) is an interdisciplinary research project aiming to develop an integrated set of methods that help assessing the ecological and socio-economic effects of dams. A comprehensive evaluation and characterization of the flow regimes before and after the dam's construction is a stepping stone towards this goal. The analysis is based on historical data, taking into account the evolution of existing reservoirs and hydropower plants. Three indicators are considered to describe the flow regimes in the basin. They allow quantifying the seasonal transfer of the water, the sub-weekly flow fluctuations and the intensity and frequency of the flow changes. In a further stage, a semi-distributed conceptual hydrological model will be built to simulate the flow regime with and without dams for actual and future hydrological scenarios.

1 INTRODUCTION

Africa is the continent with the smallest proportion of irrigated agriculture, water storage capacity and lowest degree of electrification. Dams offer solutions to improve this status and thereby contribute to the economic development. However, the urgent need for expanding water storage capacity and energy production by new dams in Africa may have negative social and ecological impacts.

The Zambezi River runs over 2574 km, from Angola into the Indian Ocean. Its basin, being the fourth largest in Africa, is home to approximately 38.4 million people and, with near 1.4 Mio km^2, spreads across eight countries: Angola (18.3%), Botswana (2.8%), Malawi (7.7%), Mozambique (11.4%), Namibia (1.2%), Tanzania (2.0%), Zambia (40.7%) and Zimbabwe (15.9%) (Vörösmarty 1991). The average rainfall is about 1000 mm/yr and the average runoff in the Delta between 7.5% and 8.0% of this value (Denconsult 1998, Beilfuss & Dos Santos 2001), mostly due to the effect of evapotranspiration.

The basin also has a very noticeable potential for hydropower energy production, its main assets being Kariba (1266 MW, active storage of 65 km^3 including 25 km^3 for flood control, (Mhlanga & Goguel 2007)), Cahora Bassa (2075 MW, active storage of 60 km^3, including 8 km^3 for flood control, (Hidrotécnica Portuguesa 1969)) and the Itezhi-Tezhi and Kafue Gorge system (900 MW, active storage of 5 km^3 in Itezhi-Tezhi, (Kapasa & Cowx 1991)). Besides their main purpose of hydropower energy production, Kariba, Cahora Bassa and Itezhi-Tezhi support significant fishing industries. The larger reservoirs, mainly Kariba but also Cahora Bassa, contribute to the increased protection against floods in the lower Zambezi. Interacting with the dams there are rich wetlands, such as the Kafue Flats, the Mana Pools or the Delta itself, which are havens for wildlife and present further challenges to an integrated water management approach. In the future, Cahora Bassa will improve its energy production capacity (to 3960 MW) and additional new impoundments are planned, namely Bakota Gorge (1600 MW), Devil's Gorge (1240 MW) and Mupata Gorge (1200 MW) (Zambezi River Authority 2010).

Large impoundments have acknowledgeable impacts in riverine ecosystems, both ecological and morphological. Of all the environmental changes wrought by dam construction and operation, the alteration of natural water flow regimes has had the most pervasive and damaging effects on river ecosystems and species (Richter & Thomas 2007). Bunn and Arthington (2002) summarized the mechanisms that link hydrology and aquatic biodiversity in four key principles: flow is a major determinant of physical habitat in streams, which in turn is a major determinant of biotic composition; aquatic species have evolved life history strategies primarily in direct response to the natural flow regimes; maintenance of natural patterns of longitudinal and lateral connectivity is essential to the viability of populations of many riverine species; the invasion and success of exotic and introduced species in rivers is facilitated by the alteration of flow regimes. In the past, several authors have studied effects of dams on the Zambezi (Munyati 2000, Beilfuss & Dos Santos 2001, Mumba & Thompson 2005, Mazvimavi & Wolski 2006, Ronco et al. 2010) with results showing the influence of the dams downstream and emphasizing the need for additional work. Several hydrologic models have also been proposed (Vörösmarty 1991, Landert 2008, Michailovsky 2008), but the difficulties related to the temporally and geographically sparse data have not yet been overcome.

The African DAms ProjecT (ADAPT) is an interdisciplinary research project aiming to develop an integrated set of methods that help assessing the ecological and socio-economic effects of dams in the Zambezi Basin. In this scope, a comprehensive evaluation and characterization of the flow regime before and after the construction of dams is essential to provide measures of their impact. Hydraulic-hydrologic models are valuable tools for flow regime alterations evaluation (Poff et al. 2010). In the scope of ADAPT, a set of models are planned to be produced and calibrated relying on different approaches.

In the present contribution a simple analysis of flow regime changes based on discharge data is proposed, assessing data quality and devising strategies for further studies.

2 METHODS FOR FLOW REGIME CHANGES ANALYSIS

Five main components regulate ecological processes in river ecosystems: the magnitude, frequency, duration, timing and rate of change of hydrologic conditions (Poff et al. 1997). As such, in order to adequately characterize flow regime changes, several aspects of the time series should be taken into account.

A number of methodologies along with various indices have been proposed. Many of these indices are correlated in some degree. Examining 171 published hydrologic indices, Olden and Poff (2003) worked on the redundancy and choice of hydrologic indices using principal component analysis to search for a reduced set that could adequately represent, critical attributes of the flow regime. Selecting the most revealing indicators for each case is not a straightforward matter, nor is their subsequent analysis and interpretation. In the present study, not all the series have daily time step, none having it sub-daily. Also, the available periods, locations of measurements relatively to the dams and series reliability differ greatly. As a consequence of this, a simplified engineering approach was sought as a first step.

Defined as the mean monthly discharge over the mean annual discharge, the monthly Pardé-coefficients describe the annual distribution of the discharge (Meile et al. 2010):

$$PC_{m,a} = \frac{Q_{mean\ month\ m,a}}{Q_{mean\ annual\ a}} \tag{1}$$

where $1 \leq m \leq 12$ indicates the month, and a indicates the year.

The sub-weekly flow fluctuations, I_1, can be expressed by the difference between the maximum and the minimum daily average discharge, normalized by the average discharge over a seven day period. Normally, this indicator is used with maximum, minimum and average hourly discharges, which are not available in the present study.

$$I_{1,i} = \frac{Q_{\max\,[i-3,i+3]} - Q_{\min\,[i-3,i+3]}}{Q_{mean\,[i-3,i+3]}} \tag{2}$$

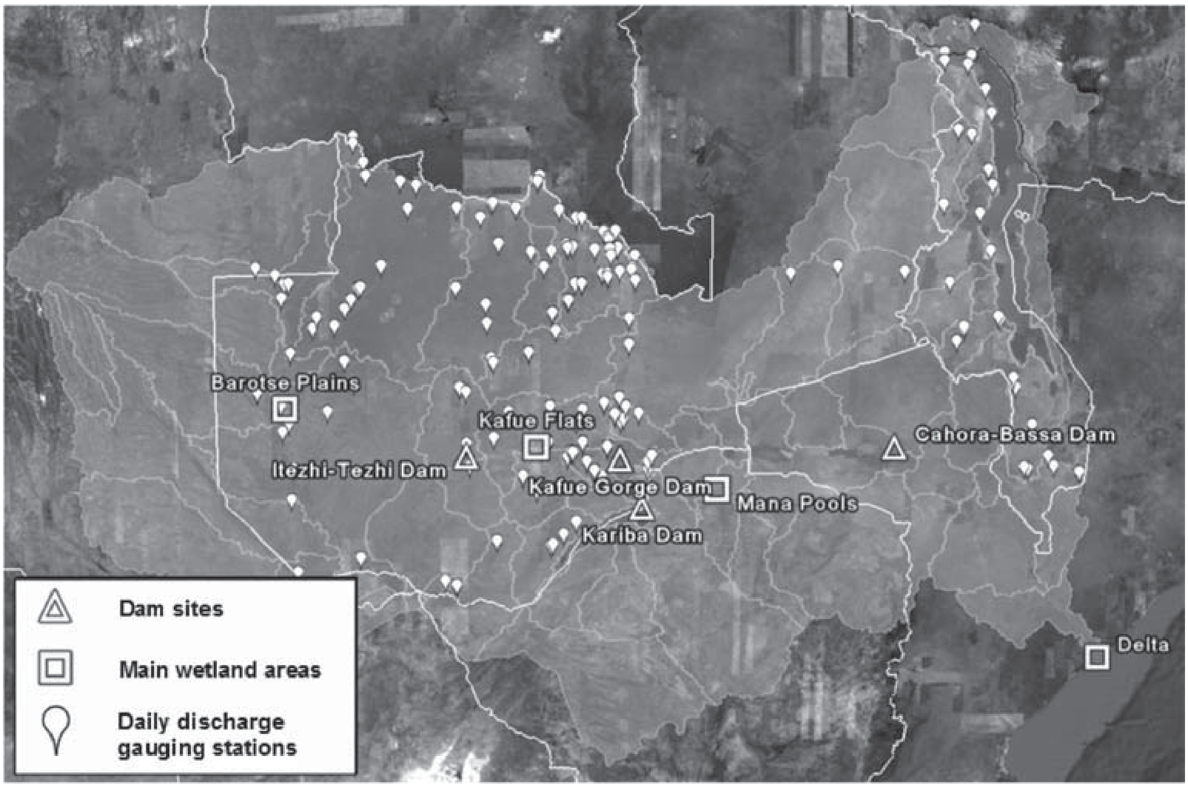

Figure 1. Scheme of the Zambezi Basin containing main dams, sites and daily discharge gauging stations (figure produced with Google Earth).

Table 1. Summary of the available data by dam site.

Dam	Mean discharge $[m^3/s]$	Construction		Data series			
		Start	End	Time step	Type	Start	End
Kariba	1180	1955	1959	Monthly	Outflow	11/1930	09/2007
Cahora Bassa	1990	1969	1974	Daily	Inflow/Outflow	10/1994	05/2008
Itezhi-Tezhi	210	1974	1977	Daily	Inflow/Outflow	09/1960	01/2007
Kafue Gorge	260	1967	1973	Daily	Outflow	03/1972	01/2007

where $1 \leq i \leq 365$ indicates the day of the year.

The flow change rate, I_2, is used as a second indicator. The parameter is defined as the change of discharge between two subsequent discharge measurements divided by the time interval between them:

$$I_{2,i} = \frac{Q_i - Q_{i-1}}{t_i - t_{i-1}} \tag{3}$$

3 DATA

Although numerous gauging stations exist in the basin, many refer to minor tributaries, not being useful for the present analysis. Among the interesting stations, several present too short, incomplete or incoherent data series. In Figure 1, a scheme of the Zambezi Basin along with discharge gauging sites is shown.

In order to assess the flow regime changes produced by Kariba (Zambezi River) and the Itez-hi-Tezhi – Kafue Gorge system (Kafue River), discharge data was analyzed for periods both before and after de construction of the dams. Also, simultaneous inflow and outflow data series were used for Cahora Bassa (Zambezi River) and the Itezhi-Tezhi – Kafue Gorge system. Table 1 refers to the summary of the available data.

Table 2. Summary of the used data series by dam site.

Dam	Data series				Missing/invalid data [%]
	Time step	Type	Start	End	
Kariba	Monthly	Outflow	Nov/1930	Sep/2007	0.0
Cahora Bassa	Daily	Inflow/Outflow	01/10/1999	31/05/2008	9.9
Itezhi-Tezhi	Daily	Inflow/Outflow	01/10/1980	16/01/2007	0.0

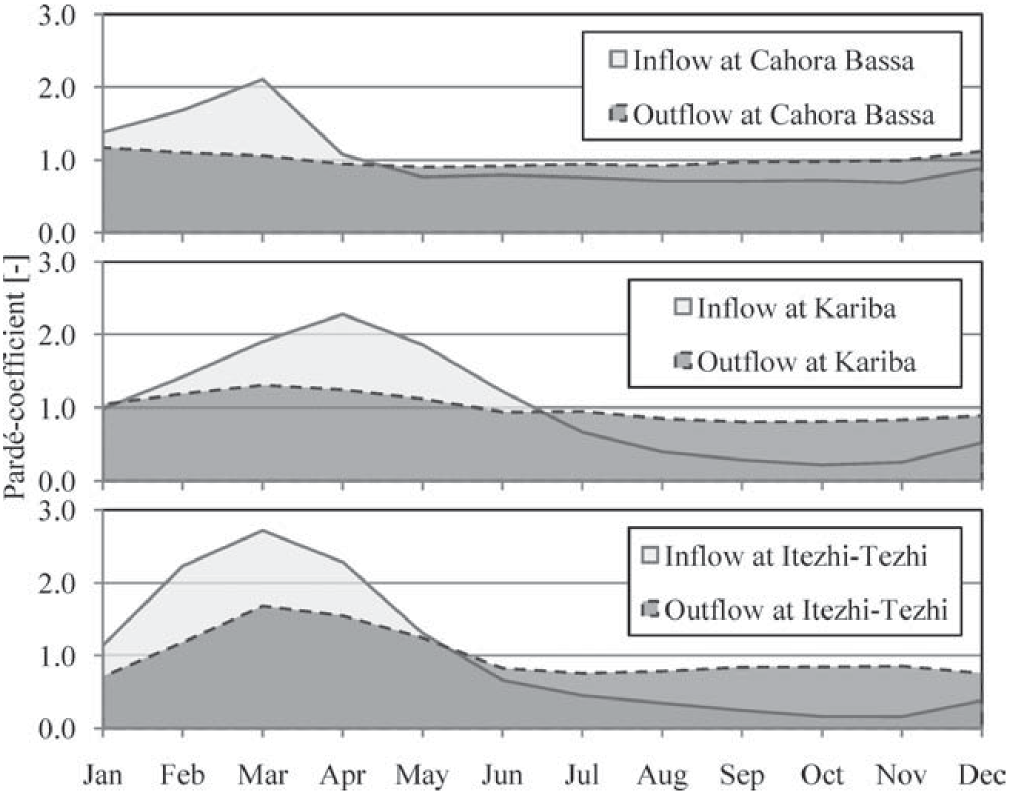

Figure 2. Mean values of the Pardé-coefficients for Kariba, Cahora Bassa and Itezhi-Tezhi. Calculations were based on the periods shown in Table 2 (for Kariba, inflows were computed from Nov/1930 to Oct/1966 and outflows from Jan/1963 to Sep/2007).

Finally, because of gaps and/or inconsistencies in the available data sets, the periods used for analysis were shortened. Furthermore, since no reliable data was available to achieve a simple computation of the inflows at Kafue Gorge the analysis for this site was abandoned. In Table 2 these periods are presented, as well as the percentage of missing data.

4 RESULTS AND DISCUSSION

Through the first chosen indicator, the Pardé-coefficient, the seasonal transfer of water can be evaluated. Figure 2 shows the mean values of the coefficient, for both inflows and outflows, at the three studied sites. The smoothing of the rainy and dry seasons is particularly evident at Kariba, where the outflow coefficients remain near 1.0 all through the year, but also important at Itezhi-Tezhi. In Cahora Bassa, seasonal transfers are of less magnitude as, in this particular case reservoir, the effect of the upstream Kariba dam greatly homogenizes inflows.

Considering the storage capacity to mean annual discharge ratio as a measure of seasonal water transfer capability, Kariba, with a storage volume 1.7 times larger than the mean annual discharge, can have a significant impact on downstream flows. Cahora Bassa and Itezhi-Tezhi, with ratios of 0.95 and 0.75 respectively, have a smaller potential for flow regulation.

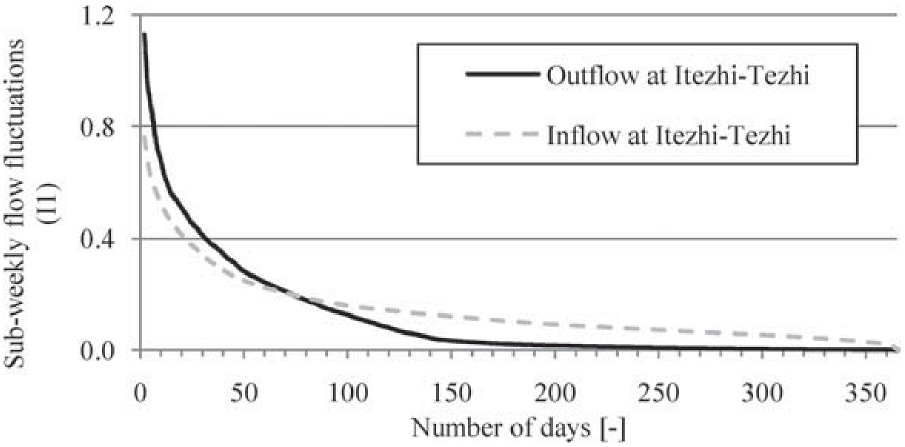

Figure 3. Sub-weekly flow fluctuations (I_1) duration curve for Itezhi-Tezhi (01/10/1980 – 16/01/2007).

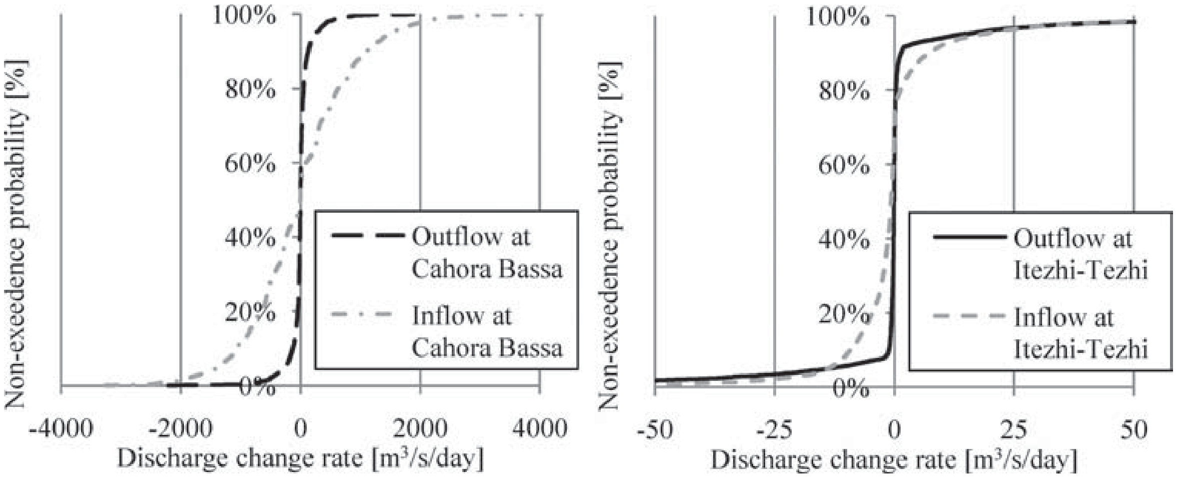

Figure 4. Empirical non-exeedence probability of average daily discharge change rate (I_2) for Cahora Bassa (1/10/1999 – 31/05/2008) and Itezhi-Tezhi (01/10/1980 – 16/01/2007).

The sub-weekly flow fluctuations, I_1, are a measure of the irregularity in discharges. The analysis of the duration curve of this indicator for Itezhi-Tezhi, presented in Figure 3, shows that the dam, on the one hand, increases the magnitude of low frequency high variability events but, on the other hand, nearly eliminates sub-weekly variations during most of the year. The same graph is not shown for Cahora-Bassa. In fact, it was noticed that the average weekly variability of inflows is several times bigger than that of the outflows, in a measure higher than expected. It is believed this happens due to the fact that the inflow series is calculated considering the water balance in the reservoir without enough accuracy regarding the daily flow estimations.

The variability resulting for the daily inflows at Cahora Bassa also has repercussions in the daily discharge change rate indicator, I_2, shown in Figure 4, being that it is likely related to an exaggeration in the spread of the computed values. Both for Itezhi-Tezhi and Cahora Bassa the graphs evidence, however, that the frequency of daily flow variations is significantly reduced downstream of the dams. Also, in the case of the Itezhi-Tezhi dam, it can be seen that low frequency high discharge reductions have become more likely to occur.

5 CONCLUSIONS

As existing and future impoundments in the Zambezi and its main tributaries may have considerable impacts, particularly in very valuable wetlands as the Kafue Flats, the Mana Pools or the Delta. The flow regime changes downstream of the three largest dams in the basin were evaluated through the analysis of Pardé-coefficients and two other indicators for sub-weekly discharge fluctuations and daily flow change rates.

Results indicate that all three of the dams have significant impacts downstream, where the flow regime has been greatly influenced. Both Kariba and Itezhi-Tezhi induce noteworthy seasonal transfers, laminating peak mean monthly flows by nearly half. Cahora Bassa, located downstream of Kariba, shows less influence on this parameter. Regarding sub-weekly flow fluctuations, computed for Itezhi-Tezhi, it seems that the operation enhances extremes as low frequency high variations increase their magnitude. High frequency low variations, on the contrary, are greatly reduced. Extreme daily discharge change rate variations tend to diminish both after Itezhi-Tezhi and Cahora Bassa, being that a range of moderate change rates (±2 to $10\,m^3/s/day$ for Itezhi-Tezhi and ±200 to $1500\,m^3/s/day$ for Cahora Bassa) is practically eliminated.

Shortcomings in the analysis have mainly arisen from short time series and lack of precise inflow data for Cahora Bassa, which might compromise computed sub-week flow fluctuations as well as daily flow changes. For Kariba, the assessment was made between discharges measured before and after the building of the dam and, although the length of both series is higher than 20 years, climate cycles and/or persisting changes can influence results.

The direct assessment of discharge data seems to be insufficient to precisely characterize the dam's impacts. Nonetheless, considering longer series for Cahora Bassa and contemporary inflow-outflow relations for Kariba might lead to more precise results. Future hydraulic-hydrological models should be calibrated using specific strategies addressed to reduce independent parameters and take the best profit of the sparse existing information.

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