Improved dam operation in the Amu Darya river basin including transboundary aspects

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Oliver Olsson
Leuphana University Lüneburg

Melanie Bauer
Technische Universität Braunschweig

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J. Froebrich & O. Olsson & M. Bauer
Water Quality Protection and Management, University of Hannover, Am Kleinen Felde 30, D-30167 Hannover

I. Normatov & G. Petrov
Instutute of Water Problems, Hydropower and Ecology AS RT, 12,Parvin str., 734002, Dushanbe, Tajikistan

ABSTRACT: Glacial and snowmelt is essential for the well being of all the states of Central Asia and provides over 90 % of their water requirements. Unfortunately, climate change is causing rapid recession of the glaciers, which in the short-term helps meet the states ambitious water requirements, but in the long term, will result in decreased runoff and increased evapotranspiration from higher temperatures. Because of the comparably geological young nature of the mountain ranges their instability result in rapid siltation of existing reservoirs and leading to very limited life expectances, also for potential reservoir sites. Vast quantities of water are wasted also by inefficient and poorly managed irrigation schemes in the entire basin. The water resources of the region are already overstretched and hence, in the foreseeable future the very existence of their agricultural economies is at stake.

Large dams at the two Aral Sea tributaries, Amu Darya and Syr Darya, control and regulate the annual flow regime and water availability at the downstream regions. Results of past project studies for the Amu Darya river point out, that the multi-reservoir system of the Tuyamuyun Hydro Complex (6.8 km³) provide attractive capabilities to improve the availability of high quality water by applying modified release and filling strategies. The Nurek dam (10.5 km³) and the Rogun dam (under construction, height of the dam: 335 m) provide further options for improving the rational operation and sustainable management of water resources.

However, the current rational management of transboundary water resources in the Amu Darya basin is hampered by difficulties to have reliable hydrological data and to predict the short and long term availability from the glacier run-off. Major uncertainty has been identified for knowledge on current capacity losses of dams, located in the upstream part of the basin. The development of risk-management strategies for securing future water supply under varying conditions of water shortage needs therefore (i) to revise the existing storage capacities, (ii) to improve the forecasting methods, (iii) to associate possible water saving mechanisms and improved crop growth patterns at the downstream areas, and finally (iv) to adapt the dam operation at upstream and downstream regions accordingly.

1 INTRODUCTION

1.1 *Background*

Under the Soviet system, river basin management was integrated so as to provide for regional requirements of water, energy and food (Wegerich, 2004). The majority of dams in the Amu Darya and Syr Darya basins were built upstream where geological (Lange, 2001) and hydrological conditions were suitable. Before the independence of the Central Asian republics, the predominant water use was for irrigation along the middle and downstream water courses of the Aral Sea tributaries. The area under irrigation increased dramatically from 1960 to 1994 when, when, based on the 1995 TACIS report, the total irrigated area in the Aral basin reached a maximum of 7,400,000 ha. (Tanton & Heaven, 1999). Water from the upstream dams was mainly released during the summer months. Because all the republics were part of the USSR, energy was provided during the winter from regions which were rich in energy resources and integrated management provided sufficient water for intensive agriculture (Wegerich, 2004).

The political and economic independence of the Central Asian republics resulted in a number of changes. While the downstream republics Uzbekistan and Turkmenistan sought to maintain their intensive irrigation, the upstream republics Tajikistan and Kirgistan, having few other options for improving energy supply, built new dams and modified the operation of existing dams to increase hydropower generation.

Currently Tajikistan has just over 4 GW of hydro capacity installed. The plants under construction will add another 4.6 GW. Assuming the successful installation of another 11.8 GW (Hydropower & Dams World Altlas, 2001), Tajikistan will reach a total hydro capacity of over 20 GW (Lafitte, 2001), becoming one of the worlds largest hydropower producers. The tensions caused by pressing water scarcity, shifts in the dam operation regimes, and the need to meet the water demands of other parties has been widely reported (e.g. Wegerich, 2004).

While it is clear that Tajikistan has not maintained past operating regimes, it is unclear how exactly the monthly releases have been modified and what further changes are to be expected in the future. Information is kept at different institutions in the former Soviet Union and is often reported in fragments, aggregated in official reports, or remains unpublished. In most cases an assessment of the applicability and uncertainty of the given information is rendered impossible by a lack of comparative information.

To provide more precise information for the development of enhanced reservoir operation strategies, this paper addresses the introduction of recent information on the operating regime of the Nurek reservoir. Related to past operation during the period of the Soviet Union Based the operation regime received some recent changes. The initial compilation of information should reflect the current state of operation, but also provide a basis for supporting the future analysis of data and the development of enhanced operating rules in the context of transboundary water management. This is regarded as essential to achieve more sustainable water management of the Aral Sea basin.

The work presented was carried out during the initial part of the project JAYHUN, which is funded by the European Commission within the INCO program. The main aim of the project is to identify adapted risk management in both the short and long term. A particular focus is given to the interaction of upstream and downstream dam operation, especially related to the Nurek reservoir and Tuyamuyun Hydro Complex at the lower reach of the Amu Darya (Fig. 1). A more precise understanding of the Nurek operating regime will help in assessing management options during dry years and the impact of climate change on water availability during the next 50 years.

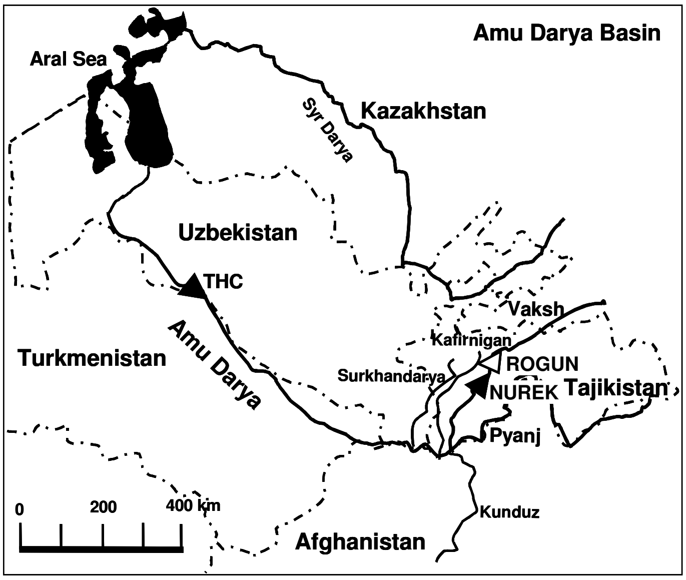

Figure 1. Aral Sea tributaries and location of Nurek reservoir in the Amu Darya basin.

1.2 *Hydrological background information*

With a total length of 1415 km (GRDC/UNH) (Froebrich & Kayumov, 2004), the Amu Darya is the biggest river in Central Asia and its basin includes territories in Afghanistan, Tajikistan, Uzbekistan and Turkmenistan.

The Amu Darya is formed by the confluence of its main headwater tributaries, the Vaksh and Pyanj rivers. The Vaksh river originates in the alpine regions of the Pamir Alai in the north-west territory of Tajikistan, where parts of the Abramov glacier and the Fedchenko glacier contribute to run-off generation. The Pyanj originates at the glacier in the Vakjdjir Pass in southeast Tajikistan, close to the borders of Pakistan's northern territories.

The Amu Darya receives water from the Kunduz (from Afghanistan), the Kafirnigan (from Tajikistan), the Sherabad and Surkhandarya (from Uzbekistan) rivers. All its natural tributaries enter the Amu Darya within 180 km of its source.

Estimates of the relative proportion of runoff generation coming from the Tajikistan vary widely. McKinney & Akmansoy (1998) estimated that Tajikistan provides 80 % of the total discharge to the Aral Sea (including the Syr Darya); Giese et al. (2004) report a contribution of only 63 % to the Amu Darya.

Giese et al (2004) reports for the Amu Darya tributary Vaksh an annual mean discharge of 20.0 km³/a and for the Pyanj river a mean discharge of 34.3 km³/a, which corresponds to 68 % to the total mean Amu Darya discharge of 79.3 km³/a. Kayumov (unpubl. 2003) reports for the Pyanj (Low Pyanj) 33.4 km³/a and for the Vaksh (Tigrovaya balka) 20.2 km³/a, or a total of about 69 % of their estimate of 78 km³/a for the mean Amu Darya discharge. These estimates reflect the importance of the mountainous region in Tajikistan for the water supply of the Amu Darya river basin. In the Tajikistan part of the Amu Darya basin there are at present 14 dams, with 7 dams in the Vaksh, 4 in the Pyanj and 3 in the Kafrinigan river basins (FAO, 1994). A number of dams are also under construction or just in planning stage. Table 1 provide information on hydro power stations (HPS) which are currently under operation.

Table 1. Overview on operating hydropower stations (HPS) at the Amu Darya tributaries Pyanj and Vaksh (Petrov, 2003)

	Parameters			
Name	Hydro-power MW	Electricity production TWh/a	Head m	Usable volume km^3
Vaksh river				
Nurek	3000	11.2	250	4.5
Baypaza	600	2.5	54	0.08
Golovnaya	240	1.3	26	0.004
Perepadnaya	30	0.3	39	
Central	18	0.1	22	
Total	3888	15.4	391	4.584
Pyanj river				
Barsha	300	1.6	100	1.25
Anderob	650	3.3	185	0.1
Pish	320	1.7	90	0.03
Horog	250	1.3	70	0.01
Yazgulem	850	4.2	95	0.02
Granitevorota	2100	10.5	215	0.03
Shirgovat	1900	9.7	185	0.04
Hostavs	1200	6.1	115	0.04
Jumars	2000	8.2	155	1.3
Moscow	800	3.4	55	0.04
Kokchins	350	1.5	20	0.2
Nizhnee-Pyanj	600	3.0		
Total	11,320	54.5		3.06

The upstream part of the Amu Darya basin is dominated by the Nurek reservoir. The Nurek Dam is a large earth-fill dam with a height of 300 m. It controls the Vaksh River and is located about 75 km east of Dushanbe. The reservoir of the Nurek Dam, is the largest reservoir in Tajikistan with a capacity of 10.5 km³. The reservoir length is over 70 km and surface area is over 98 km². In addition to electricity generation, the reservoir supplies irrigation water for about 70,000 hectares. Irrigation water is transported 14 km through the Dangara irrigation tunnel.

Construction of the Nurek's hydro unit was begun in 1961 and the first turbine began operation in 1972. The original power plant had 9 turbines, with a capacity of 300 MW each for a total of 2700 MW. The project capacity was reached in 1979 and the hydro unit was completed in 1985. In 1988 the hydropower capacity was increased up to 3000 MW. The long term average of the annual hydropower production is 11.2 TWh.

In 1994, the hydropower generation by Nurek was three quarters of the nation's 4 GW hydroelectric generating capacity, by which 98 % of the electricity demand of Tajikistan was met.

The only dam downstream of the Nurek is the Tuyamuyun Hydrocomplex (THC), located 300 km south of the Aral Sea. THC was constructed to provide water for irrigation, industry, and drinking water for the lower Amu Darya region. During the period of 1981 to 1983, the construction was completed. At present there are four main reservoirs: the Channel Reservoir (Amu Darya main stream), the Kaparas reservoir, the Sultansanjar reservoir, and the Koshbulak reservoir. Initially, THC had a total storage capacity of 7.8 km³ but due to siltation losses, by 2001 the total storage was reduced to 6.8 km³. The operation of the THC depends largely on the inflow regime, and this is strongly influenced by releases from the Nurek reservoir.

2 RESULTS AND DISCUSSION

2.1 *Current status of the Nurek reservoir*

The river basin upstream of the Nurek reservoir is subject to frequent land slides and avalanches. In addition the mean slope of the Vaksh is very high resulting in a very high transport capacity and scour. Together the potential loads of suspended matter and sediments are high and lead to a continuous loss of storage capacity.

There is no reliable database for estimating sediment delivery to the Nurek. Nevertheless, as a first approximation, a recent survey of the reservoir bathymetry provides an indication of potential storage capacity losses.

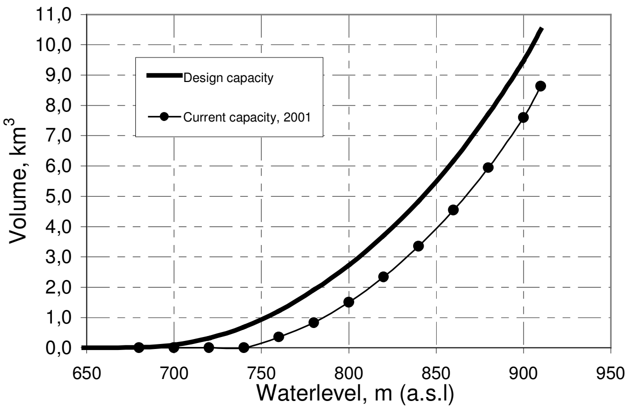

Figure 2. Volume elevation rating curves of Nurek reservoir.

Figure 2 show the original design capacity of the Nurek reservoir for different water levels (bold line). Processed data were obtained from the WB/GEF project – Security of the dams and reservoirs, 2003.

Since the initiation of impoundment of the Vaksh in 1987, at the maximum water level of 910 m, storage capacity has been reduced from 10.5 km³ to 8.7 km³, a loss of 1.8 km³ or 17 % in storage capacity. This is an average of slightly over 100 million m³/a.

2.2 *Past operation regime*

Basically the operation of the Nurek reservoir is characterized by water level variations between the maximum water level of 910 m (a.s.l) and minimum operating level of 857 m (a.s.l.). Within this range the active storage comprise 4.7 km³, while in total the inactive storage and dead storage amounted to 4.0 km³ according to the design capacity.

As stated above, during the Soviet period, the Nurek operation served mainly to the provision of irrigation water during the summer months.

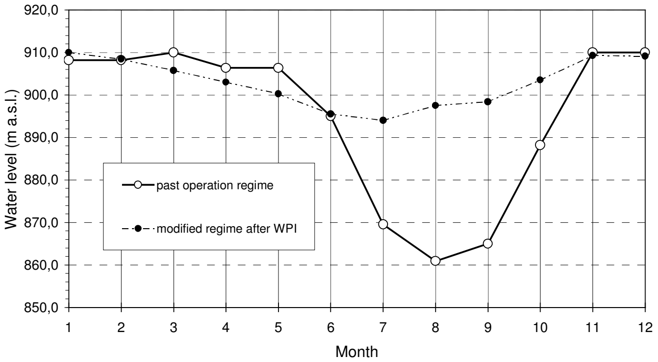

Figure 3. Comparison of past Nurek operating regime (1998) and recommendations of the Institute of Water Problems (Tajikistan) for adapted operation.

Figure 3 shows mean monthly averaged water levels (bold line) during this time, based on monthly water levels from 1998 (Institute of Water problems, Hydropower and Ecology AS RT, 2004). The past operation maintained the maximum water level of around 905 – 910 m a.s.l. from November until May. From May to August there was intensive release for irrigation and a rapid lowering of the water level to the minimum operational level of 860 m. The period of refilling and rise of water level occurred thereafter until November.

Figure 3 (dotted line) show the results of calculations made at the Institute of Water Problems (Institute of Water problems, Hydropower and Ecology AS RT, 2004). They present a first attempt to integrate both, hydropower production (national energy needs) and irrigation requirements. An optimisation of varying the water levels h_1 (minimum operation level) and h_2 (maximum storage level) was carried out on the basis of two main considerations: first, the resulting duration of hydropower production t and secondly the released discharge Q_o, determining the water availability and its impact on the irrigation economy. These requirements may be expressed as:

$$t \le \frac{A \cdot (h_1 + h_2)}{86400 \cdot Q_0}, \tag{1}$$

and

$$Q_0 \le \frac{A \cdot (h_1 + h_2)}{86400 \cdot t} \tag{2}$$

More details are given in (Petrov et. al., 2003b). The operational strategy developed results in a lowering of the reservoir water level from March onwards, supporting energy production. The additional release to support the natural flow maximum continues until July but the water level is not lowered below 895 m (a.s.l.). Refilling is scheduled during the period from August to November.

Even if the results are still under revision to include more realistic details regarding flood protection, hydropower production and irrigation, the figures provide an outline of the potential range of adapting the operational regimes.

2.3 *Recent actual operation*

Data provided by the Institute of Water Problems, Hydropower and Ecology were also used to review the current actual operation. A major aim of this exercise was to determine the actual modification to operations since the demise of the Soviet Union and to provide more precise data for supporting the development of a transboundary water allocation strategy.

For the year 2004 daily water level variations of the Nurek reservoir were based on data provided by the Ministry of Energy.

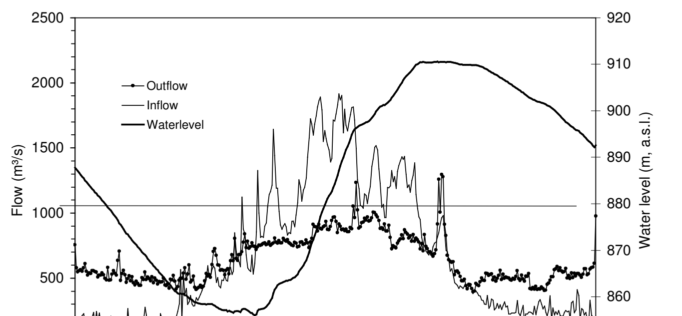

Figure 4. Daily water level variations, in- and outflow for Nurek reservoir for 2004 (Ministry of Energy RT, 2004).

Figure 4 shows the 2004 daily values for water levels, inflow and outflow. The water level variation (dashed line) is characterised by a continuous decrease during the winter and spring months until the minimum level of 856 m, which is reached on 6 May 2004. Directly after passing the minimum level refilling of the reservoir commenced and the maximum water level of 910,5 m was reached on 11 September. Subsequently there was a continuous decrease until May 2005 (not shown here).

Both the inflow and outflow in Figure 4 are daily average values. The minimum inflow, 64 m³/s, occurred during February, with a rapid increase of inflow beginning in March. There is a characteristic sequence of individual flood events leading to a continuous increase of the average flow. The absolute maximum of 1916 m³/s occurred on July 4.

The releases of around 500 m³/s were relatively constant during the winter months. After April there was an increase in reservoir release with a period of high outflows from May to mid September of about 800 m³/s. The summer maximum of 1234 m³/s was measured on July 16. After the maximum filling of the reservoir, an additional flood event occurred, leading to an exceptional release of 1295 m³/s, 963 m³/s passing through the turbines and the remainder being discharged directly to the downstream river.

For comparative purposes, data from 2005 provide the most recent information. Unfortunately only data up to August has been available and were obtained from the Ministry of Energy. Water levels, inflows and outflows are given only as monthly averages and are shown in Figure 5.

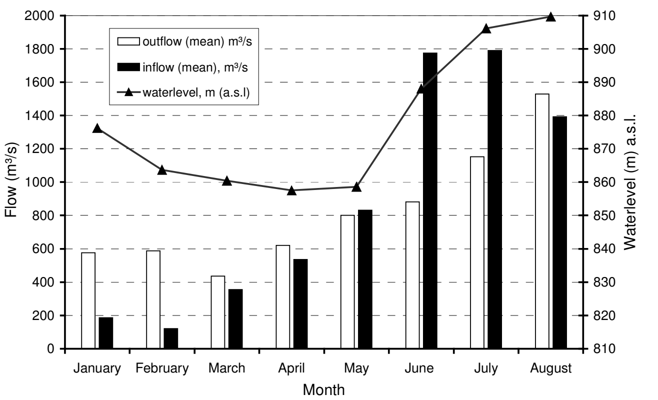

Figure 5. Water level, inflow and outflow for spring and summer 2005.

As in 2004, the water level (Fig. 5, solid line) declined until April/ May reaching a level of 857 m (a.s.l.). A significant increase in storage volume occurred from June to August. As the maximum level of 910 m (a.s.l.) was reached August, there is no further increase in the remaining months of the year. The inflow (Fig. 5, black bars) in 2005 shows a comparable seasonality to 2004. Lowest flows are in February with a mean value of 120 m³/s. Maximum mean inflows of around 1800 m³/s were recorded in June and July.

As in 2004, in 2005 the winter and spring months are characterized by comparable constant releases with mean flows of around 600 m³/s (Fig. 5, black bars). From May to August similarly to 2004 a significant increase of outflow up to 1500 m³/s is indicated.

2.4 *Actual discharges provided to the Amu Darya lowers*

As both 2004 and 2005 showed similar operation regimes, it is of interest to review the available data on monthly discharges to the downstream regions.

Table 2 indicates for 2004 a total inflow volume of 20.5 km³ and a total release volume of 20.4 km³, which represents more than a quarter of the total mean annual Amu Darya flow volume. The seasonal variation ranged from 1.2 km³ in March and November to 2.5 km³ in July.

Table 2. 2004: Monthly aggregated data for the water balance of the Nurek reservoir (Ministry of Energy RT, 2004)

Date 2004	Q infl (m³/s)	V infl (km³)	Q outfl (m³/s)	V outfl (km³)
Jan	181.4	0.49	550.1	1.47
Feb	148.6	0.37	496.8	1.25
Mar	278.7	0.75	474.8	1.23
Apr	591.3	1.53	626.5	1.62
May	936.5	2.51	765.4	2.05
Jun	1437.2	3.73	832.9	2.16
Jul	1502.4	4.02	939.4	2.52
Aug	1203.1	3.22	817.0	2.19
Sep	662.7	1.72	905.5	1.90
Oct	334.2	0,90	483.2	1.29
Nov	251.3	0.65	466.3	1.21
Dec	243.8	0.65	560.1	1.50
Total		20.54		20.43

Table 3. 2005: Monthly aggregated data for the water balance of the Nurek reservoir (Ministry of Energy RT, 2005).

Date 2005	V infl (km³)	V outfl (km³)
Jan	0.50	1.50
Feb	0.29	1.42
Mar	0.95	1.16
Apr	1.39	1.63
May	2.22	2.14
Jun	4.60	2.28
Jul	4.80	3.09
Aug	3.73	4.09
Total	18.49	17.36

The seasonal pattern was similar in 2005. In March the monthly releases provided 1.2 km³ to the downstream region. However the maximum releases were higher than in 2004, resulting in 3.1 km³ in July and 4.1 km³ in August. Up until August a total of 17.4 km³ had been provided to downstream areas.

2.5 *Review of calculated storage volumes*

The data provided for 2004 also indicate the total available storage capacity of the Nurek reservoir, calculated on a daily basis, balancing the inflows and outflows, the evaporation losses and cumulatively adding the computed volume differences. These results were compared with estimated reservoir volumes using the volume elevation rating curves. (Fig. 6).

To enable a continuous calculation of the reservoir volumes, the V=f(z) relationships were either generated by an linear interpolation between the data given for the volume elevation rating curves or represented by 2nd and 3rd order polynomial regressions. This was generated both for the information related to the original bathymetry as well as for the recent data of the 2001 bathymetric survey.

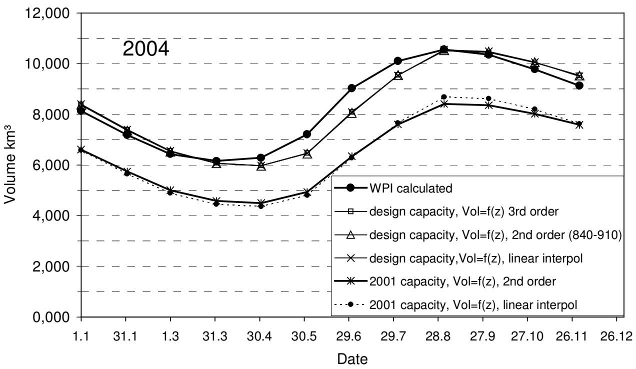

Figure 6. Estimated seasonal reservoir volumes based on reported water levels for 2004.

The results for the different seasonal variations of reservoir volumes are presented in Figure 6. All methods to represent the volume elevation rating curves provide nearly identical results. However, the reservoir volumes as calculated by WPI (bold line with circle symbols) indicate differences to those calculated reservoir volumes. Deviations are less distinct in the absolute minimum and maximum volume than in a phase shift.

Much more evident is the deviation from the figures used in the WPI calculations to those considering the reduced storage capacity. While the minimum reservoir capacity differs from 4.5 km³ to 6 km³, the estimations for the status of full storage differs from 8.5 km³ to 10.5 km³.

2.6 *Discussion and conclusion*

The results presented give a first approximation to the capacity losses. A comparison between the water balance and the reservoir volumes as a function of depth, revealed significant uncertainties in the available hydrological information. Without further comparative information in reservoir bathymetry it is impossible to have a more reliable estimate of the capacity losses and to reduce discrepancies in the volume calculations. This is of particular importance if water level variations are used to estimate the actual inflow volumes accounting for evaporation losses and recorded releases.

Currently, capacity losses have a marginal impact on the operable volume between water levels, due mainly to the very large non-operational “dead level volume” with around 4.0 km^3 between the water levels of 645 and 855 m. For the moment the operational volume corresponds to 4.0 km³, so the dam capacity of around 8.7 km³ is not fully used. However the impact will become significant, if there is a need (e.g. to cover multi-annual water deficits) to enlarge the operational volume to water levels below 855 m. The findings underline the need to focus on future trends in siltation losses in international discussion on sharing water resources in the Aral Sea basin, which until now has been predominantly based on old planning capacities. To narrow these uncertainties and to provide more realistic planning data an additional bathymetric survey is scheduled in the framework of the ongoing EC project Jayhun.

The data reviewed suggest an extension of the release period from around May – August to September – April. Compared to the past operating regime, where the reservoir releases were superposed on the natural high discharges, the present regime leads to a more equalised seasonal distribution. However, neither the past nor current regime contributes to a balancing of the spring water deficits in the lower Amu Darya region, where the water is needed for leaching irrigated fields. Related to the current irrigation practice at the Amu Darya, a significant water deficit frequently occurs during February and March (Froebrich et al., 2005).

Due to a lack of other substantial natural resources, Tajikistan has to rely in the future on hydropower production. The results show that a combination of hydropower production during the winter months and the provision of irrigation water cannot be exclusive. However, reducing water losses and energy demands will support a more rational use of limited resources. Ways must be developed to store additional water during wet years and to release additional water in dry years.

A revised knowledge of actual reservoir capacity and operation is considered to be an essential first step towards the development of adapted risk management strategies in the Aral Sea basin. Together with more refined information on recent siltation losses and adequate tools to simulate the water transfer from the upper Amu Darya to the lower part of the basin, the results presented will be used to investigate potential adaptations of the reservoir operation and its impact to both hydropower production in Tajikistan and water availability downstream.

2.7 *Acknowledgement*

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