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Applicability of Adapted Reservoir Operation for Water Stress Mitigation Under Dry Year Conditions

Oliver Olsson · Malika Ikramova · Melanie Bauer · Jochen Froebrich

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Abstract This paper introduces the conjunctive use of a deterministic water quality model and water balance criteria for supporting the assessment of simulation and to evaluate the effectiveness of proposed operation strategies. By this, the applicability of enhanced reservoir operation strategies addressing both water quality as well as water quantity aspects under water deficit conditions in dry years can be shown. Arguments will be developed to address stakeholders and decision makers in the context of a more conservative past operation regime. Results are presented for the Kaparas reservoir, which is located in the lower Amu Darya River, on the border of Turkmenistan and Uzbekistan. As being one out of four large reservoirs of the Tuyamuyun Hydro Complex (THC), the Kaparas reservoir could be increasingly used for drinking water supply for the lower Amu Darya region. The results for the dry year 2001 indicates that the combination of simulation together with practical assessment criteria confirm the applicability of adapted operation rules for THC reservoirs and ways can be found to supply the local population (of the lower Amu Darya region) with more potable water of higher quality even subject to a parallel reduction of water deficits. Future aggravation of water stress due to increasing population growth and water quality deterioration will require a more comprehensive consideration of water quality aspects in many arid and semi arid regions. The experience gained during this study emphasizes the fact that classical deterministic water quality models provide effective tools to address even more complex water quality problems under water stressed conditions, provided processing of results is performed, to support the decision making process.

O. Olsson (✉) · M. Bauer · J. Froebrich
Water Resources Management Division, Institute for Water Quality and Waste Management,
Gottfried Wilhelm Leibniz Universität Hannover, Callinstr. 14, 30167 Hannover, Germany
e-mail: oo@warb.uni-hannover.de

M. Ikramova
Central Asian Research Institute of Irrigation (SANIIRI),
Karasu-4, 11, 700187 Tashkent, Uzbekistan

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1 Introduction

Especially because of drought conditions, over-consumption of water resources and soil salinization in Central Asia remain key factors for water stress problems. Beside an increasingly reduction of water quantity, the availability of drinking water with tolerable salinity levels is limited (Kayumov and Ikramova 1997) and water security is seriously endangered. As in many other arid and semi-arid zones, surface waters in Central Asia are heavily regulated by extended river-reservoir systems, affecting both the quantity and the quality of water.

Several authors have emphasised the need to include reservoir management in the development of water stress mitigation options and its influence on water quality (Chaves et al. 2003; Arnold and Orlob 1989; Dandy and Crawley 1992). Considerable research has been carried out regarding the inclusion of quality parameters in different simulation models (Paredes and Lund 2006; Muhammetoglu et al. 2005). Numerous complex model approaches already available have combined tools from different disciplines to arrive at an integrated outcome and have demonstrated potential to provide support for decision making (Croke et al 2007). For example, Ewing et al. (2004) applied successfully a combined model approach for the prediction of future water quality conditions and the evaluation of different management strategies for several reservoirs and lakes in Australia. But, Croke et al (2007) argue also that contrary to common thinking, the more integration represented in the model, the simpler the model needs to be to allow for testing.

Deterministic water quality models have been used for a long time as robust application models in developing countries with data poor conditions. However, their application mostly ends up with a descriptive status of changed water quality and quantity for a variety of scenarios and leaves water managers to decide the most appropriate operation scheme.

Specific constraints are to be met during dry year conditions, both by the limited range of operation options due to the lack of inflow, as well as by increased socio-economic tensions leading to a limited willingness to escape from a conservative modus operandi. Therefore there is an additional need to formulate simulation models using simple assessment criteria, which support the decision making process from a practical point of view.

These criteria should be tailored to individual local problems and be used within a post-processing of results framework.

This paper presents an adapted and simplified method for assessing operating policies for multi-reservoir systems concerning water quality and quantity constraints in semi-arid and arid regions subject to dry year conditions. It introduces the combination of using a classical deterministic simulation model (Lac) and a simple water shortage characteristic. By this the applicability of enhanced reservoir operation strategies to improve the availability of high quality drinking water is evaluated in relation to the reduction of water deficits. The Kaparas reservoir, as part of the Tuyamuyun Hydro Complex (THC) at the lower section of the Amu Darya River was chosen for the case study.

The investigations were carried out within the framework of the INTAS/DFG project IWMT 'Development of integrated water management tools for the Tuyamuyun reservoir complex—Improvement of drinking water supply and public health in the disaster zone of lower Amu Darya'.

2 Description of the Study Site

2.1 The Tuyamuyun Hydro Complex (THC)

The Tuyamuyun Hydro Complex (THC) is located 300 km south of the Aral Sea on the border between the territories of Turkmenistan and Uzbekistan and impounds the Aral Sea tributary the River Amu Darya. The complex (Fig. 1) consists of four interconnected reservoirs (Channel Reservoir, Kaparas, Sultansanjar and Koshbulak) with a total storage capacity of 6.9 km^3 (in 2001). Water from THC is discharged to the lower Amu Darya and an extensive canal system supplying the regions Khorezm, Karakalpakstan and Tashauz and is used for agriculture, industry and drinking water supply (Kayumov and Ikramova 1997).

Water is also abstracted from Kaparas reservoir by a pumping station, with a current capacity of 5 m^3/s, and is used for the centralised supply of drinking water to the regions of Khorezm and Karakalpakstan together with their main cities Urgench and Nukus. Being an off-stream reservoir, Kaparas provides options for protected storage of high quality water and demonstrates the effect of enhanced reservoir operation. Kaparas reservoir is connected to the Channel Reservoir near the THC dam by an open channel. Filling and release are controlled by one combined intake/outlet. Filling of the Kaparas reservoir requires a water level in the Channel Reservoir above 117 m above sea level (a.s.l.) and lower levels within Kaparas in order to initiate open channel flow. The base of the Kaparas reservoir is at 95 to 115 m

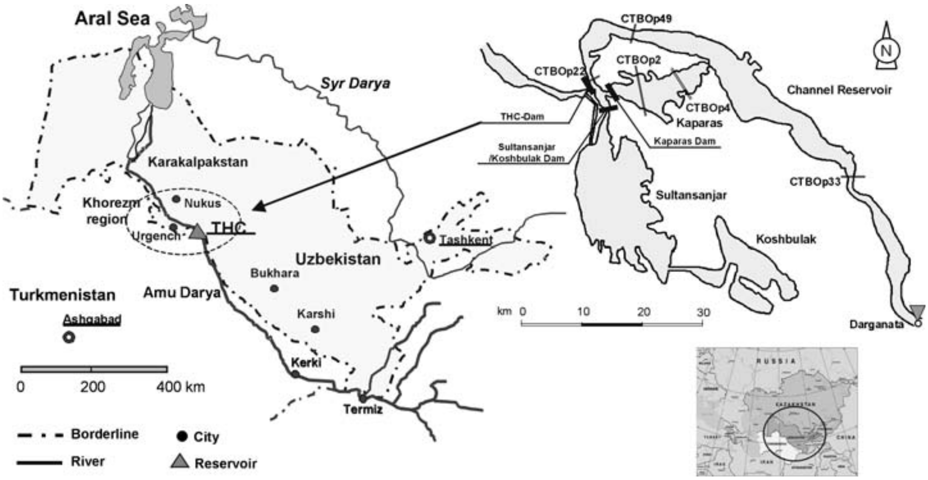

Fig. 1 The Aral Sea tributaries and location of the Tuyamuyun Hydro-Engineering Complex (THC) and sampling points CTBOpXX

(a.s.l.) and the normal pool level (NPL) is at 130 m (a.s.l.). Operation is characterized by water level variations between the NPL and the minimum operating level of 118 m (a.s.l.) with an operational storage capacity of approximately 610 million m^3, whereas the dead storage volume within the levels 95 to 117 m (a.s.l.) comprises 350 million m^3.

Operation modes to store only water of low salinity during the summer flood entail a modified operation of the other reservoirs too. The THC is not designed to store water for multiple year requirements, so that the operation of the whole of the THC complex under dry year conditions also has to address the monthly redistribution of water deficits.

2.2 Hydrology

The hydrologic regime of the lower Amu Darya River is presented for the THC inflow reference station Darganata in Table 1. Available data related to the monthly discharges within the period from 1981 to 2001 were summarized and categorized into dry (less than 25 km^3), median (from 25 to 45 km^3) and wet (more than 45 km^3) year flow volumes. The characteristic hydrologic regime with respect to the dry year flow volume can be described by mean monthly discharges (averages from all dry years within 1981–2001). The river is characterized by a low flow period during February/March (mean discharge for Feb. 381 m^3/s) and October/November (mean discharge for Oct. 320 m^3/s). The maximum flow during July results in a mean discharge of 1,184 m^3/s.

In 2001 the annual inflow to THC was only about 12.9 km^3, while in a medium year the average discharge amounts to 35.8 km^3 (Table 1).

During the dry years of the period from 1981 to 2001 the total inflow to THC was unable to cover the annual water demand of about 20.2 km^3 (Sorokin and Ikramova 2005) of the lower Amu Darya region (Fig. 2). In particular the high water demands during the leaching period February to March caused an average water deficit of around 1,500 million m^3 in March and required additional releases from the THC. Averaged values for all dry years between 1981 and 2001 have shown that excess inflows in January and from September to December could be used for seasonal compensation.

The annual variation of the Amu Darya River salt concentration apparently shows the opposite seasonal fluctuation compared to the flow regime, as low concentrations occur at high discharges. Especially from June to September, the concentrations are below the threshold value for drinking water of 1,000 mg/l (WHO 2004). This indicates that the suitable temporal window for the removal of water having acceptable salinity values occurs during the summer months (Crosa et al. 2006).

A review of the field data revealed that the salinity data, provided by the station Darganata show some significant differences to data measured at the station Lebab (CTBOp33, 70 km upstream of THC dam) which are still under discussion and could be caused by backwater effects or by differences in analytical methods. Therefore this study is based on using inflow concentrations measured at CTBOp22 (near THC dam) during the dry year 2001 until the onset of the summer flood 2002 as the representative scenario for dry years. Figure 3a depicts the salinity measurement data during the dry years 2001 and 2002. Here the gray line represents the recorded

Table 1 Mean monthly discharge (m^3/s) for dry years and averages for dry, median and wet years, Amu Darya River (1981–2001), Darganata station (80 km upstream of THC, reference station for THC inflow)

Year	Jan (m^3/s)	Feb (m^3/s)	March (m^3/s)	Apr (m^3/s)	May (m^3/s)	June (m^3/s)	July (m^3/s)	Aug (m^3/s)	Sep (m^3/s)	Oct (m^3/s)	Nov (m^3/s)	Dec (m^3/s)	Total (km^3)
Dry year													
1982	601	364	326	833	1,220	1,290	1,110	1,670	489	296	587	724	24.99
1986	356	271	320	254	513	769	1,780	1,280	300	238	233	645	18.29
1989	610	421	536	705	507	1,200	1,394	1,209	447	320	414	459	21.61
1997	453	358	360	429	932	947	1,309	1,298	1,123	540	449	523	22.92
2000	781	443	349	249	608	563	807	567	440	319	318	427	15.43
2001	438	428	257	230	307	928	701	495	352	206	233	356	12.96
Mean monthly discharge													
Dry year	540	381	358	450	681	950	1,184	1,087	525	320	372	522	19.37
Median year	629	473	506	838	1,557	1,919	2,457	1,965	1,156	727	639	772	35.84
Wet year	761	754	744	924	2,396	3,095	4,181	2,704	1,569	805	686	800	51.04

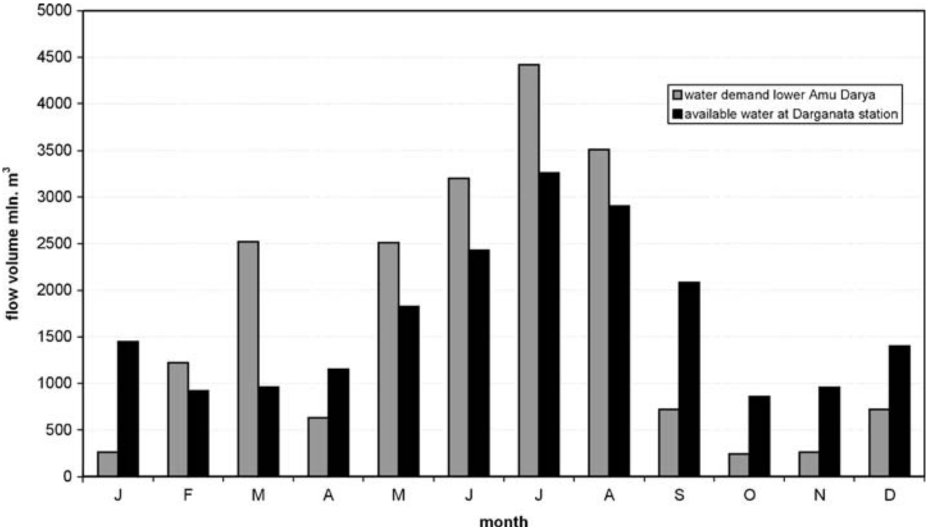

Fig. 2 Water demand of the lower Amu Darya region versus available discharge to the THC (million m^3), Darganata station (80 km upstream of the THC), (averaged values for the dry years from 1981 to 2001)

data from 27 May 2001–11 September 2002 and additionally the black line represents the monthly average data, both at CTBOp22. The deviations during this time are negligible and indicate no variations along the flow path. The decrease of salinity during the summer period coincided with the summer flow maximum up to 3,500 m^3/s (Fig. 3b). The rise of salinity started again with the decrease of flow in September. The maximum salinity during the winter months is temporarily lowered by some additional releases at the upstream dams for hydropower generation.

As the period of 2000 and 2001 represents an exceptional dry period the data from CTBOp22 are considered as representative for determining the model inflow conditions. The data records from 27 May 2001–11 September 2002 and the monthly averaged data have therefore been transformed into a synthetic multi-annual time series (Fig. 3a, black solid line).

3 Material and Methods

3.1 General Approach

The concept of enhanced reservoir operation is understood to mean changing time and volume of filling, storage, and releases to minimize the blending of high quality water stored with low quality inflowing water. Multi-reservoir systems can be used to store waters of different quality in different reservoirs and hence maintain high quality water in at least in one reservoir to secure drinking water or irrigation water for sensitive crops.

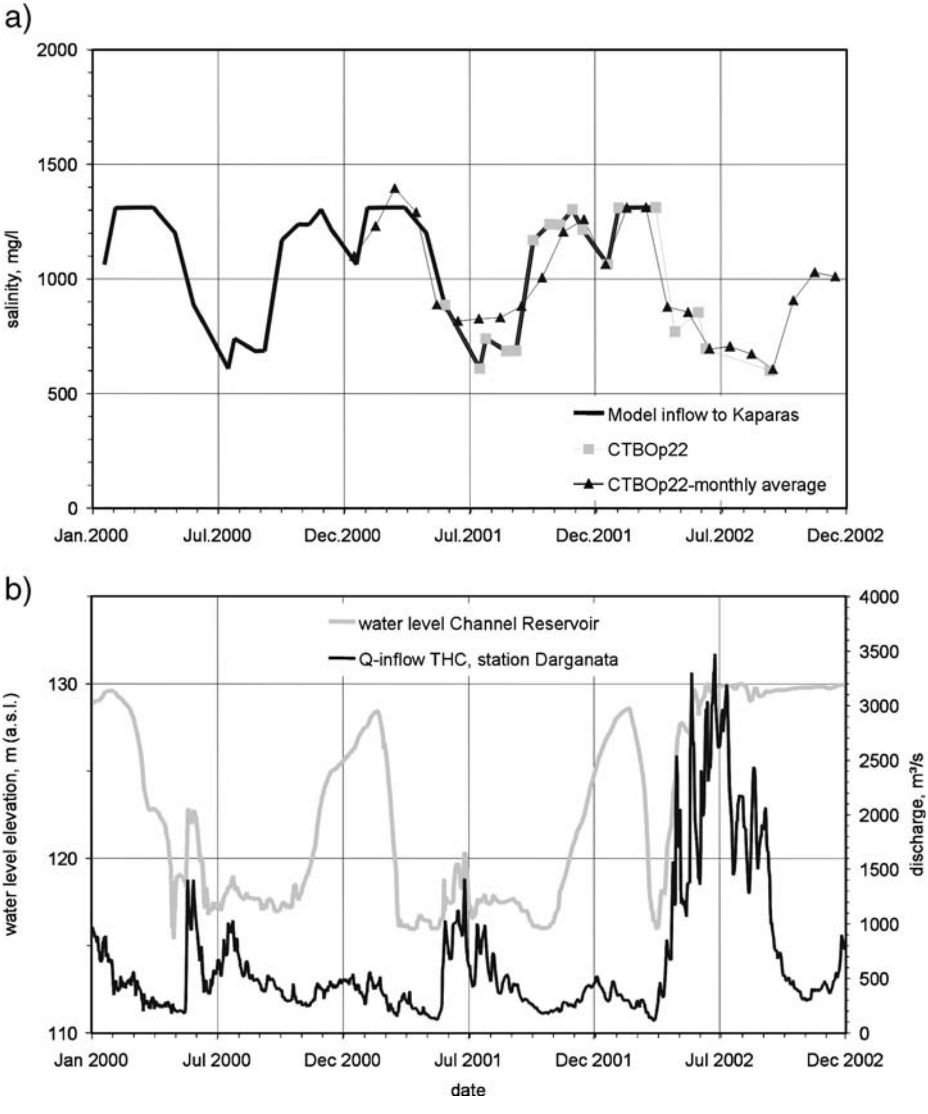

Fig. 3 **a** Recorded and monthly averaged salinity data (point of measurement, CTBOp22) and developed model salinity inflow for Kaparas, in dry years, **b** water level of the Channel Reservoir and discharge at station Darganata, 2000–2003

The Central Asian Scientific Research Institute of Irrigation (SANIIRI) and the Scientific Technical Center "Toza Darya" have identified improved operation strategies for all reservoirs within the THC based on the results of the water budget model. The model was designed to estimate the impact of changes in inflow and outflow for each reservoir of the Tuyamuyun Hydro Complex and hence provides an overall simulation for the entire complex. It is based on an extended water balance model, considering each reservoir as a complete mixed reactor

(Sorokin and Ikramova 2005). The development of the enhanced reservoir operation has been based on the approach to determine optimised rule curves for different hydrological events. These events have been classified in wet, median and dry year conditions, whereas the main focus of this study is on the assessment of the determined rule curves for dry year conditions.

For testing the effectiveness of the developed operation strategies two different assessment tools have been used in combination. First, the reservoir quality model Lac has been used to simulate time/depth dependent changes of salinity considering: (1) the results of the THC model describing the inflow and outflow regime together with (2) an estimation of inflow concentrations derived from field data.

In a second step the water shortage characteristic have been used to evaluate the feasibility of developed operational strategies related to their impact on water availability, water deficit and to satisfy water demands during dry years.

3.2 Lac—Reservoir Water Quality Model for Detailed Simulation of Temperature and Salinity Dynamics

Lac is a dynamic, deterministic 1 D vertical water quality model for lakes and reservoirs. In deep lakes and reservoirs vertical mass and energy gradients often greatly exceed the longitudinal differences and overcome the need in many cases to apply multi-dimensional models. Exceptions include very dendrite shapes of surface areas and complex bathymetries.

The model was jointly developed, especially for its application in arid and semi arid basins, by the Water Quality Protection and Management Section, University of Hannover, and the consulting company IFWU-Environmental Engineers, Hannover. The modelling of dissolved oxygen dynamics, biological processes, and concentration changes of dissolved substances have been successfully demonstrated for a number of cases such as the Sidi Salem reservoir in Tunisia (Froebrich 2000; Lehmann and Lehmann 2000).

Similar to many other models such as e.g. the CE-QUAL-R1 according to the WQRRS models (HEC 1974), the model Lac conceptualizes the reservoir as a continuum of fully mixed, horizontal slices. In these models, following an Eulerian viewpoint, heat or mass passes through the bounding horizontal planes by advection and by diffusion (Orlob 1983) with wind mixing algorithms [as described e.g. in Hurley Octavio et al. (1977), Bloss and Harleman (1980), Findikakis and Law (1999)] often included to simulate the fully mixed conditions in the epilimnion. A Lagrangian approach is also introduced by Imberger et al. (1978).

While e.g. the CEQUAL-R1 model considers a variable layer depth, the layers in the Lac model are of equal thickness. For each layer, the surface area has to be determined in correspondence to the volume/depth ratio of the reservoir. The depth of the layers has to be chosen by the user in usual ranges between one and two meter. The model is not restricted for a specific water depth, and has been applied for deeper, (up to 40 m depth) as well as more shallow impoundments (up to 2 m depth). Only for the surface layer, a variability of the water depth, depending on in-/outflow, precipitation, and evaporation, is considered.

The hydrophysical model approaches in Lac are largely based on the MIT model concept as presented by Hurley Octavio et al. (1977) and its following extensions for considering turbulent kinetic energy (Bloss and Harleman 1980). It differs by using an explicit finite difference scheme for solving the partial differential equations expressing conservation of mass and energy for each layer, and the approach for considering ice-coverage. Further differences comprise the conceptualisation of organic matter composition and its accumulation at the bottom sediment layer, which are not of relevance for the study presented here.

Density stratification, wind mixing, external in/outflows and withdrawals cause main hydraulic processes in reservoirs.

As with many other reservoir models, the hydrophysical simulation repeatedly calculates (1) the heat fluxes at the water surface and the internal heat transfer, (2) updating inflows and withdrawals with resulting advective transport processes, (3) the impact of vertical dispersion and diffusion, (4) density instabilities, and (5) finally the estimation of epilimnion depth taking into account density stratification versus wind mixing effects. Hence, the calculated depth of mixing determines the time variant onset and break-up of stratification.

3.2.1 Surface Heat Transfer and Internal Heat Transfer

The net heat exchange between atmosphere and water consists of radiative heat fluxes, resulting from solar radiation, infrared radiation emitted from the sky and the water surface, and the non-radiative heat fluxes due to evaporation/condensation and convection (flux of sensible heat) (Imboden and Wuest 1995).

After the several components of long-and short wave radiation are estimated as described by Hurley Octavio et al. (1977), first the net heat flux across the water surface is calculated. Heat and density changes in deeper strata are calculated according to the continuous exponential decline of radiation with depth.

3.2.2 Advective and Dispersive Heat and Mass Fluxes

To take into account multi-level outlet structures, different outflows can be assigned to different layers. Inflows are assigned to layers of similar density. For simplicity, entrainment and mixing with surrounding water volumes during the ascending or descending of density inflows is neglected as in the targeted applications usually only rare information for the validation of results is available.

In the model Lac, transportation of mass and heat due to currents is considered in the vertical direction. Vertical velocities are computed in from the continuity equation for each element, considering inflows and outflows.

The basic one-dimensional mass transport equation for constituents C such as dissolved salts for one internal element is obtained by considering mass and heat flow through an internal control volume:

$$\frac{\partial C}{\partial t} + \frac{1}{A} \cdot \frac{\partial}{\partial z}\left(Q_v C\right) = \frac{1}{A} \cdot \frac{\partial}{\partial z}\left(A\left(E_z + D\right)\frac{\partial C}{\partial z}\right) + \frac{\sum Q_{\mathrm{in},i}\, C_i}{V} + \frac{\sum Q_{\mathrm{out},i}\, C}{V} \pm RS \tag{1}$$

where A is the area of vertical through-flow through an element (m^2), D is the diffusion coefficient ($\mathrm{m}^2 \cdot \mathrm{s}^{-1}$), C is the concentration ($\mathrm{mg} \cdot \mathrm{l}^{-1}$), E_z is the dispersion coefficient in vertical orientation ($\mathrm{m}^2 \cdot \mathrm{s}^{-1}$), $Q_{\mathrm{in}i}$ is inflow i ($\mathrm{m}^3 \cdot \mathrm{s}^{-1}$), $Q_{\mathrm{out},i}$ is outflow i ($\mathrm{m}^3 \cdot \mathrm{s}^{-1}$), Q_v is vertical flow ($\mathrm{m}^3 \cdot \mathrm{s}^{-1}$) and V is the volume of the layer (m^3).

Advection is then calculated by considering mass exchanges between adjacent layers based on concentration gradients and vertical flows passing the layer boundaries.

For each time step and all layers, the mass transportation by diffusion and dispersion is calculated, based on the concentration gradients and a combined diffusion-dispersion coefficient, following the assumption that dispersion >> diffusion.

3.2.3 Water Quality Dynamics

Water quality dynamics are simulated at each time step in each layer for conservative and non conservative substances. For studying salinity as in the case presented, water quality dynamics, like plankton and bacterial processes are reduced to a simple consideration of the conservation of mass principle without internal transformation processes. High saline inflows will primarily enter the deepest layer, which is incorporated into the model by the calculation of density inflows. Natural salt releases from the lowest layers can also play an important role. They can be simulated indirectly as base layer salt release by assuming a flux of salt mass (mg s^{-1}) entering the lowermost layer.

3.2.4 Simulation of Mixing Processes

Following the approach described in Hurley Octavio et al. (1977) it is assumed that mixing and hence the rate of change of potential energy (E_p) is equal to the effective kinetic energy E'_kin. Basically the kinetic energy input by wind can be described as:

$$\frac{\mathrm{d}E_\mathrm{p}}{\mathrm{d}t} = \rho_\mathrm{w} u_*^3 A \tag{2}$$

where u_*^3 is the friction velocity (m·s^{-1}), calculated based on the surface shear stress (kg m^{-1} s^{-2}).

Results presented by Bloss and Harleman (1980) indicate a non-linear relationship exists for converting wind energy into kinetic energy (E_kin). For low wind velocities, the moment of mass inertia and for high wind velocities, the losses by energy dissipation have to be considered. The model allows a calculation of such relations, introducing a Richardson number, or may assume the $E_\mathrm{kin}/E_\mathrm{p}$ ratio to be constant.

Within this study the effect of energy dissipation is neglected and a constant surface shear stress coefficient of $c_\mathrm{z} = 0.002$ has been used.

Changes in mass concentrations and temperature due to mixing processes are calculated by averaging mass and temperature for all associated layers. Different to the approach of Hurley Octavio et al. (1977), wind mixing is computed only once at the end of each time step and is not repeated iteratively together with the heat transfer algorithms. Errors due to this simplification are considered as being small as long as small time steps are used.

3.2.5 Simulation of Ice Cover and Winter Stagnation

The model has been extended for its application in Central Asia with its harsh and cold winter climate by an approach to include the effect of ice cover on wind mixing.

If the reservoir water temperature drops below a given threshold $T_\mathrm{w} \leq T_\mathrm{crit}$ (with e.g. $T_\mathrm{crit} = 0°\mathrm{C}$), no further cooling is assumed and the calculation of wind mix is interrupted by setting $E'_\mathrm{kin} = 0.0$.

Even under the assumption of ice cover for each time step, potential temperature changes are calculated continually on the basis of the radiation and heat balance. If a positive temperature change is calculated, the increase in surface temperature is estimated. A rise above the threshold temperature T_{crit} then leads to an immediate assumption that no ice cover is present and wind mix restarts.

3.2.6 Required Initial and Boundary Information for the Lac Model

Integrated approaches for calculating the heat balance at the surface as well as physical formulations are directly applied using the given daily meteorological and climate data.

Modelling reservoir water salinity levels, needs to define following initial conditions: the reservoir depth-volume ratio, the reservoir bottom level, the definition of the inflow and outflow levels, the predefined water layer depth (1.0 to 2.0 m), and the water temperature and salinity distribution (°C and mg/l for each reservoir layer). The model set up requires also the definition of the entire simulation period and modelling time step (e.g. 10 min), as well as reservoir inflow and outflow time series with discharge, salinity concentrations and temperature for the boundary conditions.

The model output is designed to provide time series of in-lake concentration changes and water level elevation.

3.3 Water Shortage Characteristic for Multiple Reservoir Systems

In several studies the operating performance of a water supply reservoir were usually evaluated using the water shortages characteristics. The properties of water shortages are characterized by the theory of runs (Yevjevich 1967). According to this theory a drought is defined as a consecutive time interval where the selected hydrological variable such as stream flow is below a certain threshold representing water demand. The threshold level may be a constant or it may vary seasonally; usually it is chosen as the long-term mean under the assumption that the level of water demand corresponds to the mean availability of resources.

By use of this theory Shiau (2003) evaluated the operating performance of a water supply reservoir using the water shortages characteristics. For each operating period, a water shortage was defined as a deficit when the reservoir supply was insufficient to meet the established demand.

$$\mathrm{ST}_t = \begin{cases} \mid R_t - D_t \mid \\ 0, \text{otherwise} \end{cases}, \quad \text{if } R_t < D_t \tag{3}$$

where ST_t is the shortage at time period t; R_t is the reservoir supply at time period t; D_t is the demand at time period t.

Based on the methodology of the water shortage characteristics the Eq. 4 was adapted to evaluate multi-reservoir systems respective water deficit ($\mathrm{ST}_t << 0$) or water profit ($\mathrm{ST}_t >> 0$).

$$\mathrm{ST}_t = (V_R + V_{\text{Res}})_t - D_t \tag{4}$$

where the extended approach for ST_t includes an additional term for the reservoir supply, Rt. The river flow volume V_R at time period t and the provided storage volume of all reservoirs V_{Res} at time period t, addict the total available water volume for the downstream water supply. Here the V_{Res} considers the filling of the several reservoirs with a negative value ($-V_{Res}$) and the draw down of the reservoir system with a positive value ($+V_{Res}$).

3.4 Data Acquisition

The used data have been provided by SANIIRI (Central Asian Scientific Research Institute of Irrigation, Uzbekistan) from existing data archives and were complemented with existing data sets from Glavgidromet and the THC management organisation. Flow data have been obtained from the monitoring station Darganata (80 km upstream from THC). Water quality data have been derived from the measurement station Lebab (70 km upstream of THC dam), and the Stations CTBOp49 inside the Channel Reservoir and CTBOp22, representing the inflow water quality to Kaparas reservoir. Climate data for the calculation of temperature changes and stratification processes have been used from the station Urgench (distance 70 km).

3.5 Boundary Conditions for Simulating the Practiced Operation Regime in 2001

The analyses of the measured monthly water level variations (Fig. 4) show that the THC reservoir operation for the dry year 2001 aims to fulfil water demands during the leaching period in February and March. Basically the maximum stored water volumes were reached in February [Kaparas 129 m (a.s.l.), Channel Reservoir 128.5 m (a.s.l.)], followed by a significant release during March (from Kaparas and Channel Reservoirs) and April (from Sultansanjar and Koshbulak Reservoirs). During the irrigation period the water levels remained low (e.g. varying between 116 and 118 m (a.s.l.) in the Channel Reservoir) and nearly all the Amu Darya inflow

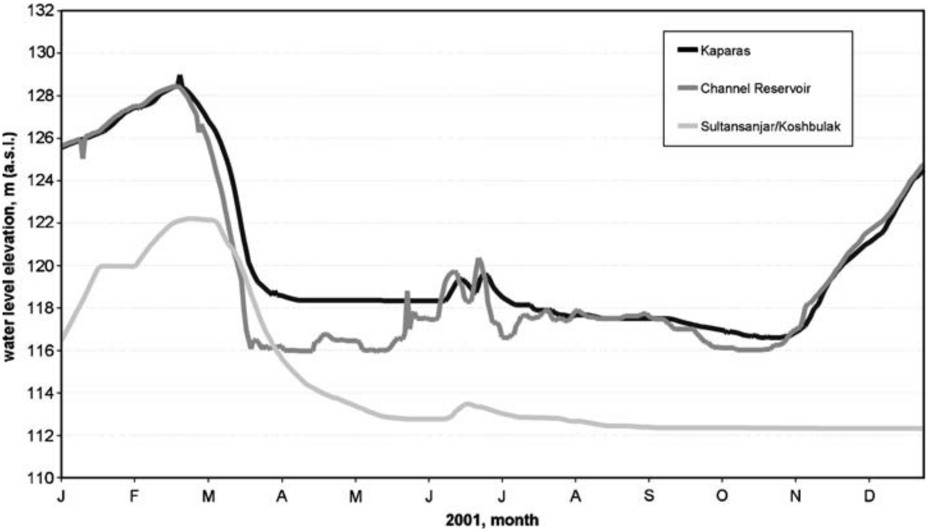

Fig. 4 Reservoir operation of the Channel Reservoir, Kaparas, Sultansanjar and Koshbulak during the dry year (2001), water level elevation m (a.s.l.)

was channelled directly through the THC. Significant refilling did not start before October.

3.6 Boundary Conditions for Simulating the Revised Management

Applying the concept of enhanced reservoir operation it is planned to store mainly the low salinity summer flood. The THC-model was used to identify the most suitable combination of water level regimes for all reservoirs of the THC, which are indicated in Fig. 5. The results are based on targeting a maximum water level in the Channel Reservoir at 130 m (a.s.l.) by the end of August. During September to January the stored water should be used for filling Sultansanjar and Koshbulak reservoirs. In order to provide water for the leaching period, the Channel Reservoir should be lowered to a level of 123 m (a.s.l.) from the beginning of February to the end of March. After refilling the reservoir in April to a level of 127 m (a.s.l.), it can be re-emptied to a water level of 118 m (a.s.l.) in May and June. For Sultansanjar and Koshbulak reservoirs filling between September to January is recommended up to a water level of 130 m (a.s.l.). The stored water is now available for irrigation, until the levels fall to 116 m (a.s.l.) during July and August. During this period, water stored in the Channel Reservoir can be used to fill the Kaparas reservoir. With this system it would be feasible to fill Kaparas reservoir with high quality water up to a water level of 130 m (a.s.l.) in August. In order to provide drinking water for the lower Amu Darya region the Kaparas must be lowered by a continuous withdrawal of 13 million m^3 per month to a level of 128 m (a.s.l.) between September and June. In order to enable this refill with high quality water in August, the Kaparas reservoir must be drained down to a water level of 118 m (a.s.l.) during June and July.

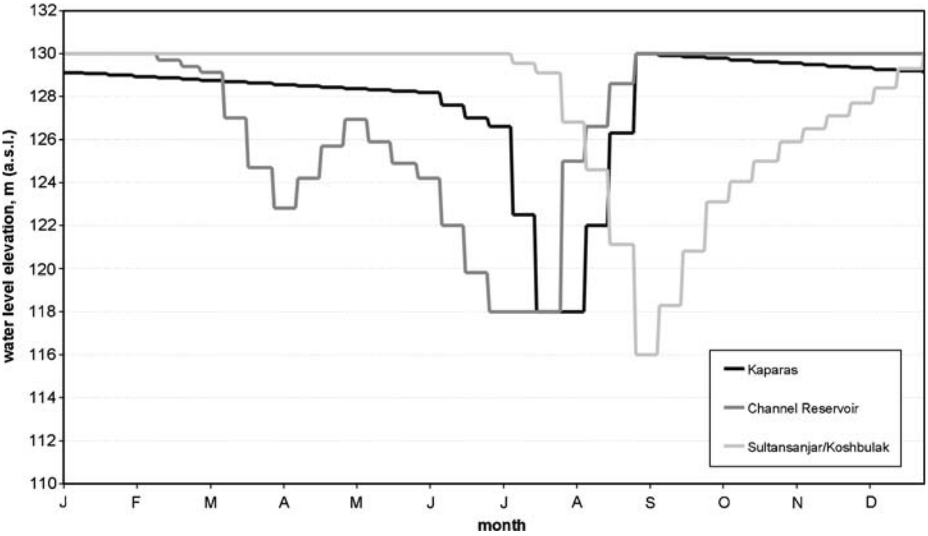

Fig. 5 Developed water level elevation (m a.s.l.) of the THC reservoirs, under dry conditions

Table 2 Basic settings used for salinity simulations of Kaparas reservoir in dry years

Kaparas reservoir, dry year	
Start water level	
Conventional	125.55 m a.s.l.
Enhanced	129.10 m a.s.l.
Outlet level	118.0 m a.s.l.
Simulation period	1 January 2001–31 December 2002
Weather/climate data	Measurements 1990, Urgench
Reservoir bottom	95.0 m a.s.l.
Initial salinity	1,200 mg/l, measurements from January 2001
Salt release	Constant daily flow of 0.9 m^3/s with salt concentration of 2,100 mg/l

3.7 Determination of Scenario for the Dry Year Simulation

The simulation of the Kaparas reservoir salinity was examined assuming a sequence of two successive dry years. The effects of conventional (related to Fig. 4) and enhanced operation modes (related to Fig. 5) have been investigated using the established representative inflow concentrations (related to Fig. 3a).

The basic settings determining initial conditions for the simulation by using the model Lac are summarized in Tables 2 and 3. If dry years follow in sequence after a wet or average year, the originally satisfying conditions, the intensity of the dry conditions, and the time-dependant effects are of interest.

Both applications have been used as basic input data measured salt concentrations of 1200 mg/l, recorded at Kaparas reservoir in January 2001. The simulation of the conventional operation starts with a water level of 125.55 m (a.s.l.) in the Kaparas reservoir, as recorded on 1 January 2001, whereas the enhanced operation starts with a water level of 129.10 m (a.s.l.). The use of different initial water levels is based on the method of the enhanced reservoir operation to fill Kaparas to its maximum water level of 130 m (a.s.l.) each year and it assumes that the reservoir was filled up to this maximum water level in the summer months of the preceding year. Past records of climate data from 1990 must be used as input, because no other data were available for dry year conditions. It is assumed that the salinity is much more sensitive to changes in inflow salinity than to different evaporations during dry years and median years during the summer months.

Table 3 Boundary conditions for salinity simulations, inflow and release/withdrawal values obtained from the THC-model results and developed model salinity inflow, Kaparas reservoir dry years

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Past practised operation 2001												
Inflow million m^3	293	102	0	0	0	14	0	0	0	0	46	155
Withdrawal million m^3	0	0	276	192	2	0	19	18	6	20	0	0
Inflow salinity (mg/l)	1,151	1,309	1,311	1,251	1,016	779	676	702	864	1,208	1,262	1,186
Enhanced operation mode												
Inflow million m^3	0	0	0	0	0	0	0	610	0	0	0	0
Withdrawal million m^3	13	13	13	13	13	97	396	0	13	13	13	13
Inflow salinity (mg/l)	1,151	1,309	1,311	1,251	1,016	779	676	702	864	1,208	1,262	1,186

4 Results and Discussion

4.1 Model Lac Performance

The model Lac was used according to simulate salinity dynamics in the Kaparas reservoir. Testing the performance of the model aims to provide the needed verification of the suitability of the Lac model for simulating reservoir operation schemes.

The performance of the model Lac (Fig. 6) was demonstrated by the good closure of paired salinity levels, measurements in 2001 and the model predictions. Despite the lack of measured data for the initial conditions in 2001, the predictions of the salinity levels tracked the observed salinity levels well, explaining ~53% of the observed variations according to linear least squares regression ($p < 0.0001$). Hence, modelling results for the simulation of salinity levels showed a sufficient congruence with the measured values.

4.2 Impact of Conventional and Enhanced Management on Water Quality Deterioration in Dry Years

The simulation results of the conventional operation, as depicted in Fig. 7a, show salinity concentrations in the range of 1,130 up to 1300 mg/l within the 2 years. The salinity level starts at about 1,200 mg/l at the beginning of the calculation and reaches levels of 1,250 mg/l by the end of May to be followed by a decrease to 1,130 mg/l in July. A further continuous increase up to 1,230 mg/l in May of the second year is followed again by a decrease to 1,150 mg/l.

The results demonstrate the impact of the past practice operation on variation of water levels, with increases in levels during the winter months and decreases starting in March, on the high salinity with minimal varying values. The minimum salinity levels of around 1,130 mg/l in July each year result from the inflowing water, about 40 million m^3, having low salinity levels of about 779 mg/l during June. As the filling occurs predominantly during December to February, even lower salinity during the Amu Darya summer discharge would not provide a notable difference. Especially in the summer months the influence of salt release from the lowermost

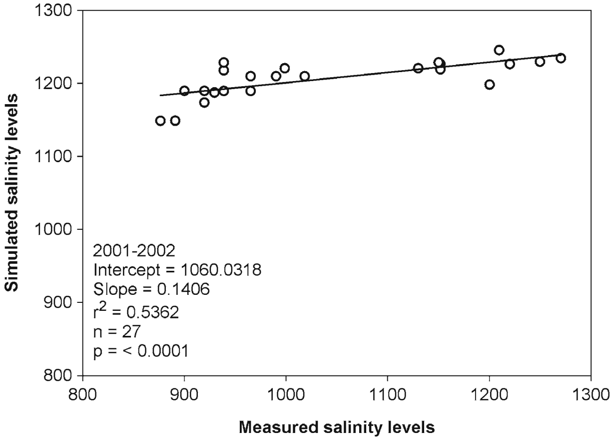

Fig. 6 Kaparas reservoir: Performance of the model in predicting salinity levels, evaluated as the relationship between measured and simulated values

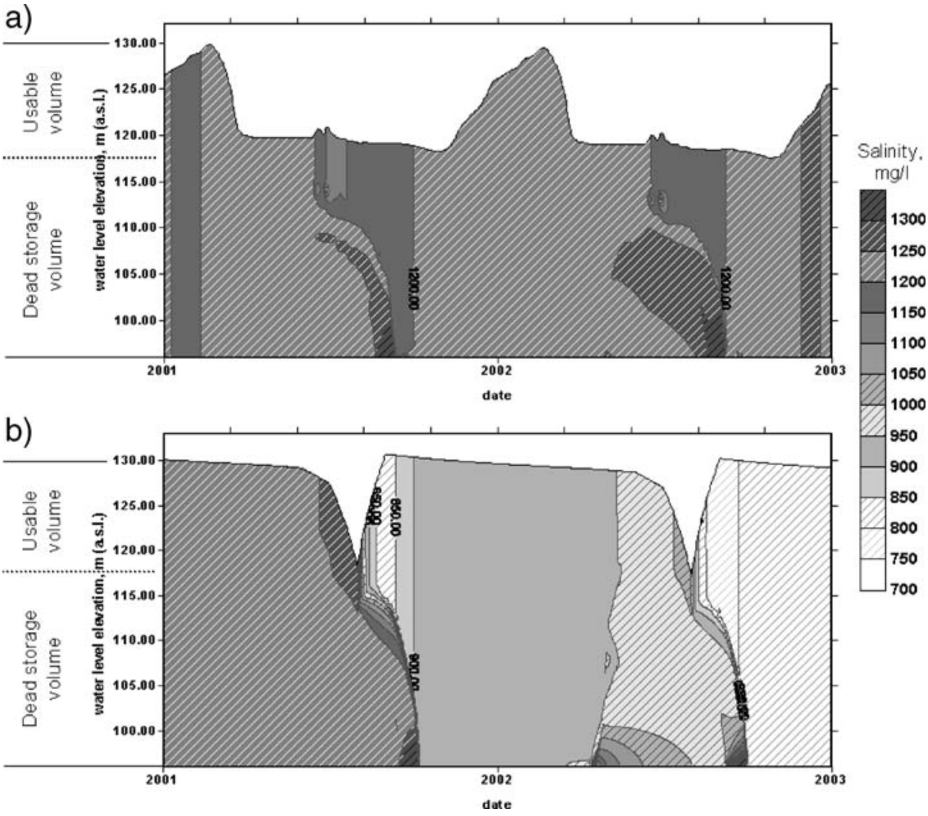

Fig. 7 Time depth plot of salinity concentration in Kaparas reservoir for two subsequent dry years; **a** based on past practice (2001) and **b** based on enhanced operation

layers is significant and contributes during the onset of the destratification towards an entrainment of highly saline water in the entire water column.

The results of the enhanced operation, as depicted in Fig. 7b, shows an increase of salinity levels from 1,200 mg/l in January up to the maximum of 1,290 mg/l by the end of July which is followed by a sharp decline, to 830 mg/l, by the beginning of September. Due to continuous increase in salinity, an increase to 1,000 mg/l by the end of June in the second year and then again a sharp decline to a minimum of about 770 mg/l by the beginning of September.

It is evident that the enhanced operation, with the continuous withdrawal from January up to June, and the releases in June and July, is responsible for the increased salinity levels during the first simulated year. Due to the refill with water of low salinity during August the salinity fell to its minimum level and then increased again due to the continuous withdrawal of water from September to June and the yearly releases in June/July during the second year. The releases are followed by the second refill, which results in a further decrease in salinity levels.

The results indicate that, after 2 years of dry conditions, the past practice operation will lead to constant salinity levels of 1,200 mg/l in the Kaparas reservoir. On the other hand applying the recommended enhanced operation scheme with an altered salinity inflow concentration, not exceeding the WHO guidance value of 1,000 mg/l, will achieve a reduction of salinity levels from 1,200 up to 770 mg/l. Furthermore the results demonstrate that it is even possible to achieve a reduction of salinity levels to below 1,000 mg/l, by using the enhanced reservoir operation even for one year.

4.3 Applicability of Enhanced Reservoir Operation and Impact on Water Deficits Under Drought Conditions

The study analysed the impact of the proposed enhanced reservoir operation strategy on water deficit reduction during drought conditions. The enhanced strategy has been compared to the existing practise to demonstrate its potential benefit for meeting the agricultural and municipal water demands of the lower Amu Darya region. For evaluating the covered water demands the water shortage characteristic, ST_t is used as shown in Fig. 8 together with the monthly average water inflow to the THC (V_R) during dry years, and the monthly water demands (D) for the lower Amu Darya region. Figure 8a presents the results according to the conventional reservoir operation, whereas Fig. 8b describes the expected results applying the developed operation mode.

Considering the results it becomes clear that the water demands (20.2 km^3/a) of the lower Amu Darya region, especially during the leaching period in spring and for irrigation in summer, exceed the available water volume, resulting in an annual water deficit of about 4.3 km^3, equivalent to 21.5% of the demand in 2001. By operating the reservoirs according to the enhanced mode, the difference between demand and availability can be reduced to an annual deficit of 2.0 km^3, which is equivalent to 9.9% of the demand. Although the demand cannot be completely met such a reduction provides a considerable improvement to the overall water supply situation under limited resources. During the critical month of February, the enhanced operation enables a reduction of the water deficit from 1,107 million to 109 million m^3 and consequently up to 91% of the water required for leaching can be supplied, i.e. a significantly higher value compared to the low percentage of 8% supply under existing reservoir operation modes. For the total unmet irrigation water demand during the summer months this is equivalent to a reduction between 30% and 60%. For example, in June a reduction in the water deficit from 835 million to 297 million m^3 or in July from 1,089 million to 468 million m^3 is achieved, by applying the enhanced reservoir operation.

Analyses of the different reservoir operation policies has shown that the conventional operation regime currently used during dry conditions is mainly based on filling the Kaparas reservoir with highly saline water during the winter months and does not consider the potential for taking in higher quality drinking water, which is available during the low saline summer floods even under dry year conditions, when comparably low salinities between 800 and 1,000 mg/l can be expected. Basically, this is determined by the need to transfer water from the low saline summer flood to the downstream irrigated areas. Another important constraint is the need to fill Kaparas by even higher water levels in the Channel Reservoir.

In contrast to the conventional operation the results of the enhanced reservoir operation strategy demonstrate an improvement of both the water quantity and water quality in the THC reservoirs. It shows the capability for improved water availability in the lower Amu Darya region and provides a reduction of the regional

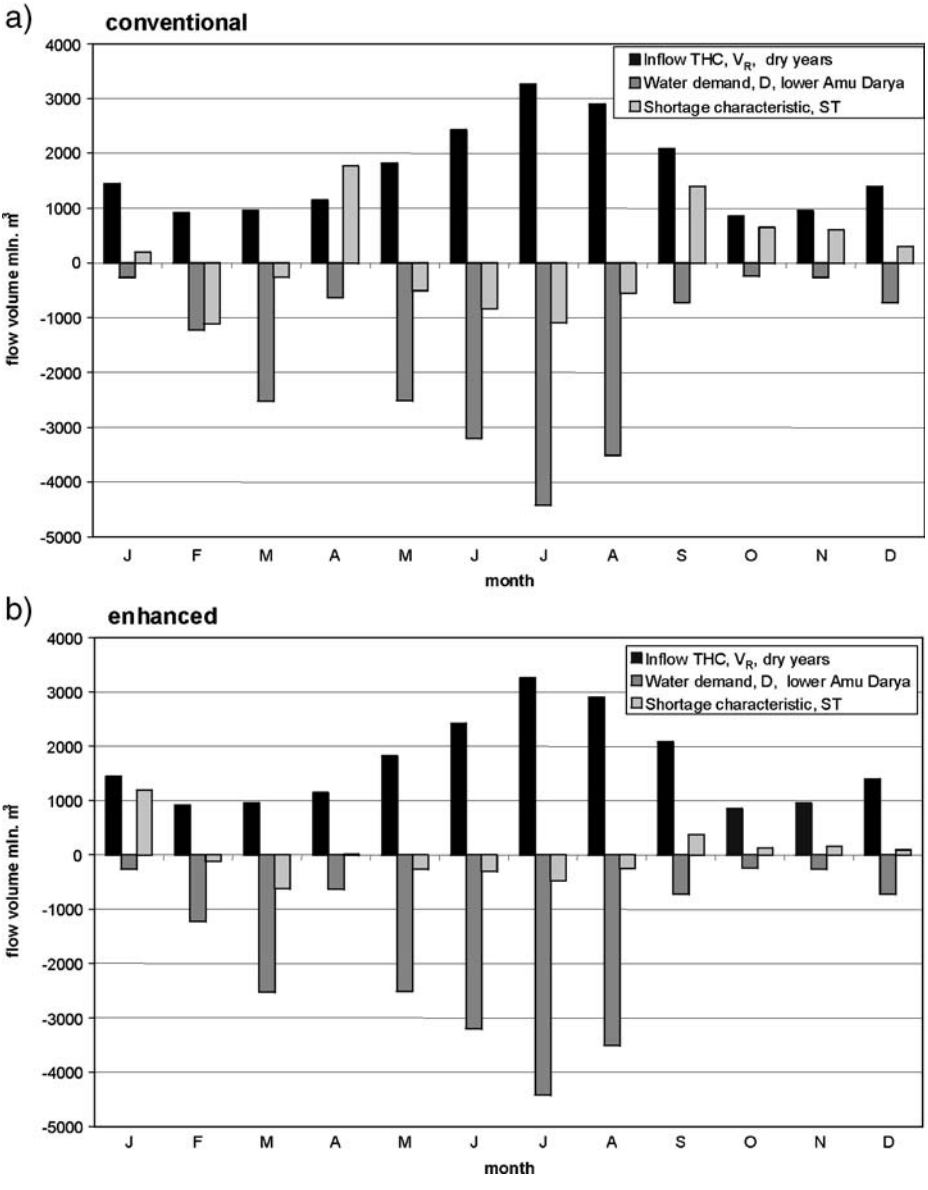

Fig. 8 Water demand, D_t, in lower Amu Darya, average water inflow, V_R, of the Amu Darya River, to THC and the water shortage characteristic ST_t (million m^3) for dry conditions, **a** based on past practise, **b** based on enhanced operation

annual water deficit up to 54% (2.3 km^3/a). Furthermore, the results for the drinking water reservoir Kaparas have demonstrated a possible reduction of salinity concentration of 35% to below the WHO standards even during just one year of enhanced operation, and a reduction as high as 62% after 2 years.

4.4 Applicability of the Combined Assessment Approach

The results for the assessment of reservoir operations have shown that traditional rather simple model concepts like a deterministic model provide helpful tools, when water quality dimensions have to be considered as well. Full 3D reservoir models require a considerable amount of data for calibration and validation (currents and mass fluxes between each model element, constituents for each cell as initial and boundary conditions). Therefore, they are restricted in their applicability, when the data availability is limited. The discretisation of the model Lac is vertical 1D and this allows a trade off between a detailed acquisition of vertical mass and energy gradients, and the available data.

The satisfactory performance of the model Lac was demonstrated and the model was successfully applied for the Kaparas reservoir. Therefore, the Lac is an applicable tool to simulate reservoir salinity dynamics under the data poor conditions such as in Central Asia and other developing countries.

However, without an additional assessment criterion to demonstrate the impact of reservoir operations on the water balances, it was difficult to demonstrate the practical benefit of the proposed strategy to the water managers. Therefore, the used assessment approach of a water quality model combined with a simple water shortage characteristic demonstrates an applicable and simple methodology, to provide useful information for water managers and operators.

5 Conclusions

This study has examined the assessment of operating strategies for a reservoir system in which water quality in combination with water quantity is an important consideration. For the particular system studied (the Tuyamuyun Hydroengineering Complex, Uzbekistan), it has been shown that enhanced reservoir operation can be an efficient tool to rapidly and comprehensively improve water quality in water crisis regions. The results investigating the dry year 2001 confirm the applicability of the adapted operation rules for the THC reservoirs and show that ways can be found to supply the local population (of the lower Amu Darya region) with more potable water of higher quality even subject to a parallel reduction of water deficits.

The methods herein presented support the assessment of reservoir operation strategies and are also suitable for determining reservoir water quality and estimating water shortages during water deficit events.

Although optimisation of operating strategies for multi-reservoirs including the quality parameter have been studied before, the information in this paper brings new insights to practically support the decision making process for operating multi-reservoir systems where there are water quality and quantity constraints in semiarid and arid regions, especially under dry conditions.

Moving the focus from the development of mathematically complex reservoir optimisation models to more simplified approaches, this study clearly show that classical deterministic water quality models provide effective tools for addressing even more complex water quality problems under water stressed conditions, as long as processing of results is performed.

The applicability of the methodologies is not restricted to the Tuyamuyun Hydro-Complex. They provide useful tools for the assessment of reservoir operation strategies in all semi-arid and arid catchments, where the impact of dry years in the context of water stress is apparent.

The results of this assessment approach will be utilized by a further study to investigate the impact of adapted reservoir operation strategies on sedimentation processes and water pollutants.

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