MODELLING OF HYDRODYNAMICS AND WATER QUALITY IN A DIMICTIC RESERVOIR – JORDÁN RESERVOIR, CZECH REPUBLIC

Josef Hejzlar [1], Jiří Jarošík [1], Jakub Borovec[1], Martin Růžička[2]

[1]Hydrobiological Institute AS CR and Faculty of Biological Sciences USB, České Budějovice, Czech Republic, e-mail: hejzlar@hbu.cas.cz
[2]Institute of Hydrodynamics AS CR, Prague, Czech Republic, e-mail: martin_ruzicka@cbox.cz

Abstract: The two-dimensional, dynamic model CE-QUAL-W2 was used to model water quality of a small, highly eutrophic reservoir with intensive nutrient cycling between the water column and bottom sediment. The model was calibrated and evaluated for a 4-year, hydrologicly variable period and used in a scenario simulation study to analyse effects of the changing external and internal phosphorus loading and depth of outflow to trophic conditions and water quality. The reservoir hydrodynamics were simulated with good precision in all parts of the seasonal cycle and during the whole period. Water quality and nutrient cycling could be calibrated and simulated with satisfactory results for individual years, however, an extrapolation of model to conditions with different nutrient loading was problematic. It spite of this partial limitation, the model was found appropriate for water quality evaluation and prediction in Jordán Reservoir.
Keywords: CE-QUAL-W2, coupled hydrodynamics-water quality model, phytoplankton, phosphorus, nitrogen, outflow depth

1. Introduction

Water quality modelling of stratified reservoirs is an exacting but also very stimulating task. It sets great demands both on the model and the modeller. The model is required to cope with multiple, mutually interconnected processes of hydrodynamics and changes of water constituents due to physical, chemical, and biological actions. The reliable representation of hydrodynamics of water masses is crucial for water quality modelling because most chemical and biological reactions are strongly dependent on temperature, mixing, and indirectly or directly also on solar radiation. The water quality subsystem is very difficult to model because of the richness of aquatic life and much feedback within the food webs and between the biota and their environment. Reservoir modellers have a highly multidisciplinary task. They must understand processes in the whole aquatic ecosystem and select and use the most important representations for both hydrodynamics and water quality.

The aim of our contribution was to show the use of the 2-dimensional, laterally averaged, complex hydrodynamic and water quality reservoir model CE-QUAL-W2 (Cole and Wells, 2002; Růžička et al. 2002) for modelling a small, highly eutrophic reservoir with intensive nutrient cycling between the water column and bottom sediment (Borovec and Jan, 2004). The model was calibrated and evaluated for a 4-year continuous period and used in a scenario simulation study to analyse the effects of (i) varying external and internal phosphorus loads and (ii) depth of outflow on the trophic conditions of this reservoir.

2. Locality and methods

Jordán Reservoir (49.42°N, 14.67°E; maximum operational surface level – 424.26 m above sea level (a.s.l.; Balt); volume – 2×10^6 m³; surface area – 0.05 km²; mean flow – 0.401 m³ s⁻¹; maximum depth, length, and width – 12 m, 3 km, and 0,4 km, respectively; Figure 1) has been used as a water resource for the town of Tábor since the end of 15th century (Votruba et al., 1988). Its current uses include water supply to local industry and a fish hatchery and recreation activities (bathing, angling). The withdrawal by the municipal waterworks has been stopped since 2000, due to excessively high concentrations of phytoplankton biomass in water including toxic cyanobacteria (Maršálek et al., 1999). The dam of Jordán Reservoir has been

without a functional bottom outlet since 1830. Current outflow and withdrawal options include: (i) the spillway with crest gates and a sill at the elevation of 423.17 m a.s.l. at the right side of the dam, (ii) the withdrawal of the fish hatchery at the central part of the dam with the inlet at elevation ~418.6 m a.s.l., and (iii) the withdrawal of the waterworks situated from the left bank, approximately in the middle of the reservoir at elevation ~416.6 m a.s.l..
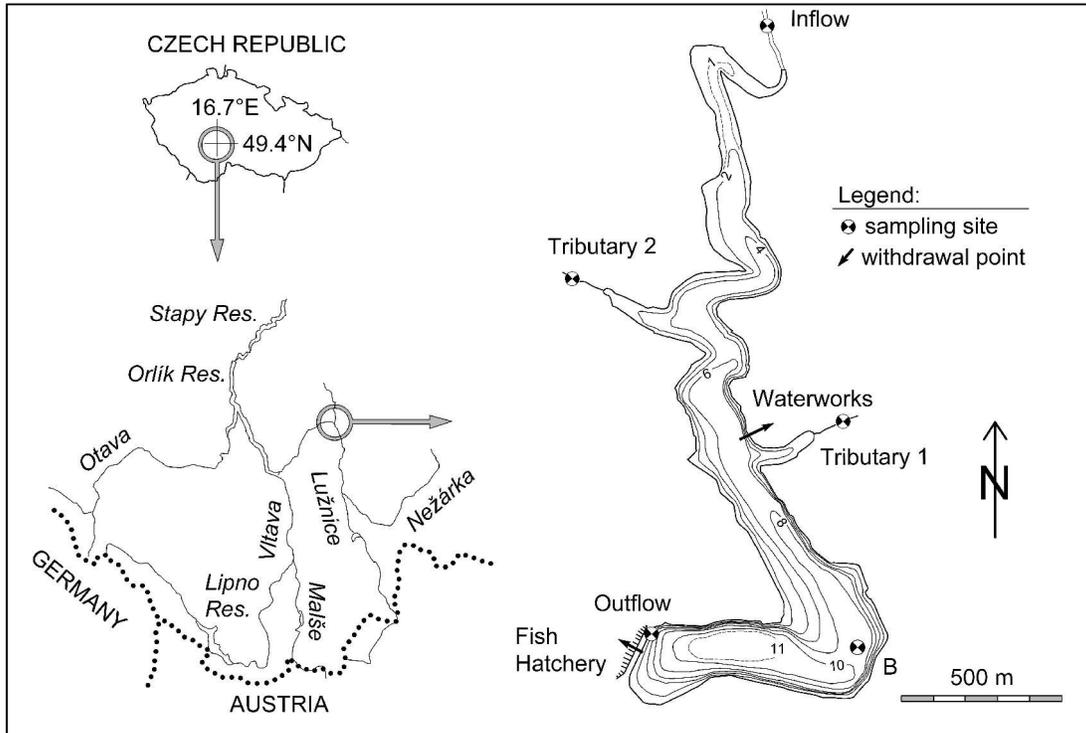
Figure 1. Maps showing the locality and sampling sites at Jordán Reservoir. The interval of depth contours is 1 m and the surface level is at the maximum operation elevation.

Measurements of reservoir hydrology and water sampling for the determination of representative boundary conditions needed for mathematical modelling were carried out from March 2000 to April 2004 with a break in water sampling from May 2002 to March 2003. The measuring and sampling sites are shown in Figure 1. The hydrological balance of the reservoir was set up on the basis of (i) continuous recording of discharge at the main inflow (Inflow), (ii) continuous records of the surface level in reservoir, (iii) daily precipitation amounts at the climatic monitoring station Tábor-Náchod (Czech Hydrometeorological Institute; CHMI) that was situated approximately 2 km northwest from the Jordán dam, (iv) point measurements of discharge in side tributaries (Tributary 1 and 2) that were taken during the sampling for water chemistry, (v) evaporation from the reservoir surface that was calculated with the modified Penmann formula (Monteith, 1965), and (vi) withdrawals from the reservoir according to the available information from the waterworks and fish hatchery. The total outflow from the reservoir was calculated from the daily water balance. The hypsographic curve of reservoir was used according to Votruba et al. (1988). The main inflow and the outflow were sampled in one-week and two-week intervals, respectively. The tributaries were sampled biweekly during 2000–2002 and once per two months in 2003. The reservoir was monitored at sampling site B in two-week intervals from March 2001 to April 2002 and in approximately two-month intervals during the other periods. Vertical profiles of temperature and dissolved (DO) were measured in 0.5-m intervals with a probe (DataSonde 4; HYDROLAB, USA). Depth samples were taken with a Friedinger sampler. Water chemistry analyses included total P (TP), dissolved P, dissolved

reactive P (DRP), ammonia N (NH₄-N), nitrate N (NO₃-N), nitrite N, total suspended solids (dry mass at 105 °C) and their loss on ignition (500 °C), dissolved and particulate organic carbon, and chlorophyll-a (Chla). Total N (TN) was the sum of inorganic N species and organic nitrogen that was calculated from total organic carbon assuming the average ratio of N/C in the aquatic organic matter to equal 0.076 (Hejzlar and Kopáček, unpublished). Meteorological data from the CHMI station at Tábor-Náchod included temperature, relative humidity, cloud cover, wind speed, and wind direction at 7:00, 14:00, and 21:00.

Table 1. Selected parameters of model CE-QUAL-W2 use after calibration for simulations of Jordán Reservoir. For the meaning of abbreviations and symbols see the model manual (Cole and Wells, 2002).

Initial conditions:		*Phytoplankton kinetics (ALG1/ALG2/ALG3):*		*Stoichiometry of OM mineralization:*	
T2I	-1				
ICEI	0	AG	2/2/2	BODP	0.005
WTYPEC	FRESH	AR	0.08/0.080.08	BODN	0.08
Heat exchange:		AE	0.08/0.08/0.06	BODC	0.45
SLHTC	ET	AM	0.03/0.03/0.02	*Kinetics of PO₄-P:*	
AFW/BFW/CFW	0.17/4.11/1	AS	0.16/0.12/0.08	PO4R	0.045
Ice formation:		AHSP	0.005/0.005/0.005	PARTP	0
ICEC	ON	AHSN	0.014/0.014/0.014	*Kinetics of NH₄-N:*	
SLICEC	DETAIL	AHSSI	0.05/0.00/0.00	NH4R	0.045
ALBEDO	0.75	ASAT	35/35/35	NH4DK	0.1
HWICE/BICE/GICE	10/0.6/0.07	*Temperature dependence of phytopl. (ALG1/ ALG2/ALG3):*		*Temperature dep. of NH₄-N:*	
ICEMIN/ICET2	0.01/3			NH4T1/NH4T2	1/20
Initial concentrations:		AT1	0/0/10	NH4K1/NH4K2	0.1/0.99
PO4	0.028	AT2	5/10/20	*Kinetics of NO₃-N:*	
NH4/NO3	0.06/6	AT3	15/20/25	NO3DK	0.045
DSI	4	AT4	30/40/40	NO3S	0.25
LDOM/RDOM	0.7/15	AK1	0.03/0.03/0.1	*Temperature dep. of NO₃-N:*	
LPOM/RPOM	0.1/0.1	AK2	0.99/0.99/0.99	NO3T1/NO3T2	1/25
ALG1/ ALG2/ALG3	0.1/0.1/0.1	AK3	0.99/0.99/0.99	NO3K1/NO3K2	0.1/0.99
DO	-1	AK4	0.01/0.01/0.01	*Kinetics of Si:*	
		Biomass composition of phytopl. (ALG1/ ALG2/ALG3):		DSIR/PSIS	0.1
Organic matter (OM) kinetics:				PSIS	0.1
LDOMDK	0.3	ALGP	0.005/0.005/0.005	PSIDK	0.3
RDOMDK	0.001	ALGN	0.08/0.08/0.08	PARTSI	0.2
LRDDK	0.01	ALGC	0.38/0.45/0.45	*Limit of anoxia:*	
RPOMDK	0.01	ALGSI	0.22/0.00/0.00	O2LIM	0.1
LRPDK	0.001	ALCHLA	100/100/100	*Sediment oxygen demand:*	
POMS	0.5	ALPOM	0.8/0.8/0.8	SOD	2.5
Temperature dependence of OM:		ANEQN	1/1/1	*Temperature dep. of SOD:*	
OMT1/OMT2	4/30	ANPR	0/0/0	SODT1/SODT2	0/30
OMK1/OMK2	0.10/0.99			SODK1/SODK2	0.01/0.99

The two-dimensional, laterally averaged numerical reservoir model CE-QUAL-W2 v. 3.1 (Cole and Wells, 2002) was used in this work. The reservoir was approximated with a finite-difference grid that consisted of a single main branch without side arms that was divided into 20 segments 100 to 300 m in length and 33 0.5-m thick vertical layers of varying width. Water quality simulations included the following quantities: temperature, water age, dissolved oxygen, biomass of 3 phytoplankton groups (ALG1, ALG2, ALG3), labile and refractory dissolved and particulate organic matter (LDOM, RDOM, LPOM, RPOM), orthophosphate P (PO₄-P), NO₃-N, and NH₄-N. Oxygen deficits in the hypolimnion were quantified with the hypolimnetic anoxic factor (AAF) that was calculated from the duration of anoxia (c_{O2}<1 mg l^{-1}) and the area of

anoxic layers in the reservoir (Nürnberg, 1995). The model was calibrated for the period from March 2001 to April 2002 and validated for the periods from March 2000 to March 2001 and from April 2002 to December 2003. The main parameters of the calibrated model are shown in Table 1.

3. Results and discussion

3.1. Characterization of study period

The individual years of the study period were characterized by very different hydrological conditions (Figure 2). The discharge in 2000 and 2003 was fairly below the long-term mean, in 2001 it was close to the mean value and in 2002 it was largely higher. The P and N concentrations showed distinct seasonal patterns. The highest TP concentrations occurred in the summer months (Figure 1b), while the highest TN concentrations were measured in the winter and spring months.
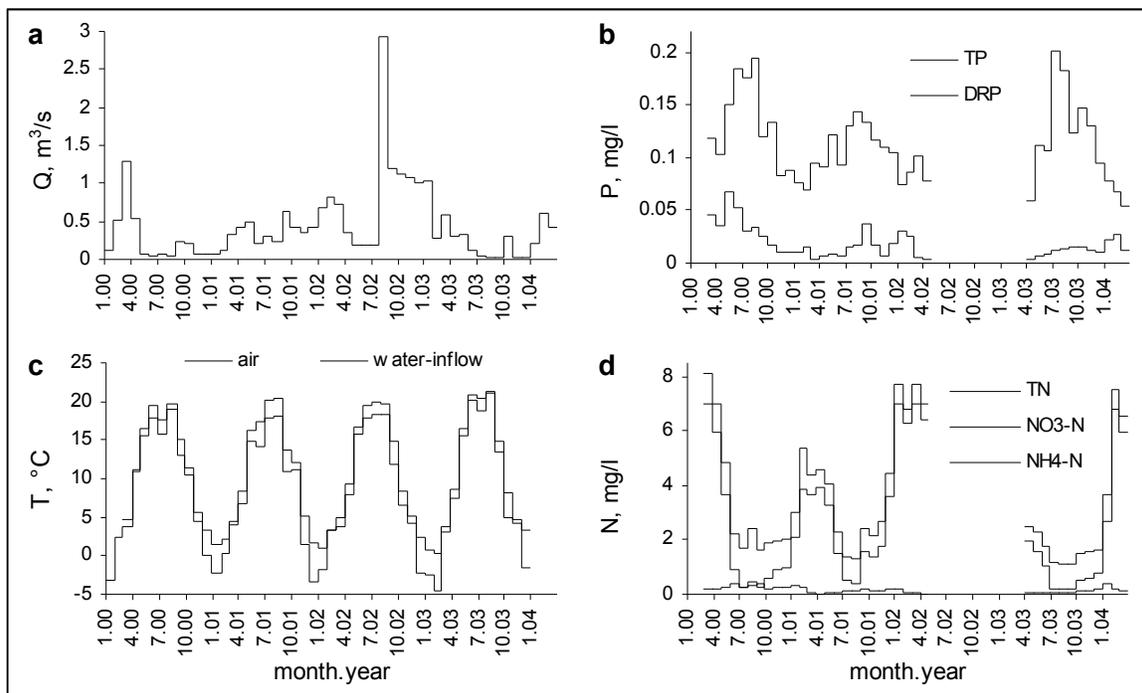
Figure 2. Mean monthly values of: (a) total inflow into the reservoir, (b) TP and DRP concentrations in total inflow, (c) air temperature (Tábor-Náchod) and water temperature (Inflow site), and (d) TN, NO$_3$-N, and NH$_4$-N volume weighted concentrations in total inflow

The predominant fraction of the inflow TP was bound in particles that were largely organic and contained high concentrations of Chla. This was caused mainly by the growth of phytoplankton in many ponds and pre-reservoirs in the catchment of Jordán Reservoir. The seasonal pattern of TP concentration in the outflow differed from the inflow. Minimum and maximum concentrations occurred in the summer and at the end of autumn, respectively. The autumnal maxima of TP consisted of a large proportion of PO$_4$-P that was released from the decaying phytoplankton biomass after its sinking to the hypolimnion and onto the sediment surface (Hejzlar et al., 2004). This PO$_4$-P was mixed during the autumnal period of circulation into the whole water column. The retention of TP in the reservoir was low and fluctuated between 0 and 15% in individual years (Table 2), apparently due to low P-binding capacity of sediment. The loss of the P-binding capacity of sediment was apparently connected with the development of long-lasting oxygen deficits above the bottom that resulted in the reduction of

sulphate and production of hydrogen sulphide in the sediment. The accumulation of hydrogen sulphide in the water column during summer stratification periods indicated that iron was largely precipitated into highly insoluble FeS (Kalff 2002) and the sediment lost its P-binding capacity through the loss of Fe-hydroxyoxide that is commonly the main P-binding component of neutral sediments (Borovec and Hejzlar, 2001).

The TN concentration of inflow was controlled mainly by the NO_3-N concentration. The high concentrations of NO_3-N in winter and spring periods (4 to 7 mg l^{-1}) decreased in summer months to values below 0.5 mg l^{-1} (Figure 1d). The annual values of TN retention in the reservoir ranged from 7 to 39% during the study period (Table 2).

Table 2. Mean flow, P and N inputs, and P and N retentions in Jordán Reservoir.

Year	Q, $m^3 s^{-1}$	TP input, kg	R, %	RRP input, kg	R, %	TN input, t	R, %	NO_3-N input, t	R, %	NH_4-N input, t	R, %
2000	0.160	560	15	120	-95	20	39	15	44	1.1	-43
2001	0.470	1570	15	270	-130	70	19	59	39	1.6	-440
2003	0.200	560	0	100	-42	28	7	23	7	1.0	-230

3.2. Model calibration and validation

The calibrated model relatively reliably reproduced the hydrodynamics (temperature stratification) and concentrations of dissolved oxygen and NO_3-N in the water column (Table 3). The simulations of PO_4-P, NH_4-N, and Chla deviated more from the measured time series (Table 2). The less accurate model results for PO_4-P and NH_4-N were apparently due to the significantly higher amounts of PO_4-P and NH_4-N that was released or accumulated in the hypolimnion during the summer stratification period of the calibration year (2002) than in the years used for validation (2000, 2003) (Table 2). Chla was simulated with the least precision. The modelled mean and maximum annual Chla concentrations were close to the measured values, but the seasonal dynamics of modelled results for phytoplankton were reproduced poorly. The main reason was the simplified mathematical description of the aquatic ecosystem in the model, i.e. the absence of herbivorous zooplankton grazing on phytoplankton.

Table 3. Absolute mean error (AME) for calibration (cal.) and validation (val.) simulations of selected quantities (mean/maximum value calculated from N vertical profiles) and the determination coefficient (r^2) of linear regressions between measured and simulated mean values for individual vertical profiles.

Vari-able	Temperature, °C		DO, mg l^{-1}		PO_4-P, μg l^{-1}		NO_3-N, mg l^{-1}		Chla, μg l^{-1}	
	cal.	val.	cal.	val.	cal.	val.	cal.	val.	cal.	val.
N	31	11	31	11	18	7	18	6	21	22
AME	0.7/1.8	1.1/2.2	2.8/5.9	1.7/6.2	90/340	108/231	0.5/1.6	1.1/1.7	25/69	24/63
r^2	0.99	0.98	0.79	0.76	0.83	0.81	0.88	0.87	0.32	0.03

3.3. Scenario study

Eight scenarios that combined two external P inputs, two release rates of P from the sediment, and two outflow depths were used in the scenario study (Table 4). The responses of in-reservoir concentrations of PO_4-P, Chla and DO to the decrease of external or internal P loading were different (Table 4). On the drop of external P-loading by 75%, the surface PO_4-P concentration decreased in the scenarios with and without P release from sediment (Nos. 3, 4 and 7, 8) on average by 34% and 93%, respectively. The mean bottom PO_4-P concentration decreased in the same scenarios by 4 and 98%, the mean Chla concentration by 49 and 68%, and the anoxic area factor by 24 and 33%, respectively. A closer look at these results suggested that the extrapolation of model into conditions different than that ones used in the

calibration have to be evaluated cautiously. In contradiction to our limnological experience, the bottom PO_4-P concentration in the scenarios with P release from sediment was decreased too little (by 4% only). This relative overestimation of the importance of P release from sediments after the drop in external P loading was apparently caused by the insufficient interconnection of sediment processes (mineralization of organic matter, sediment oxygen demand, release of nutrients from the sediment) within the model algorithms.
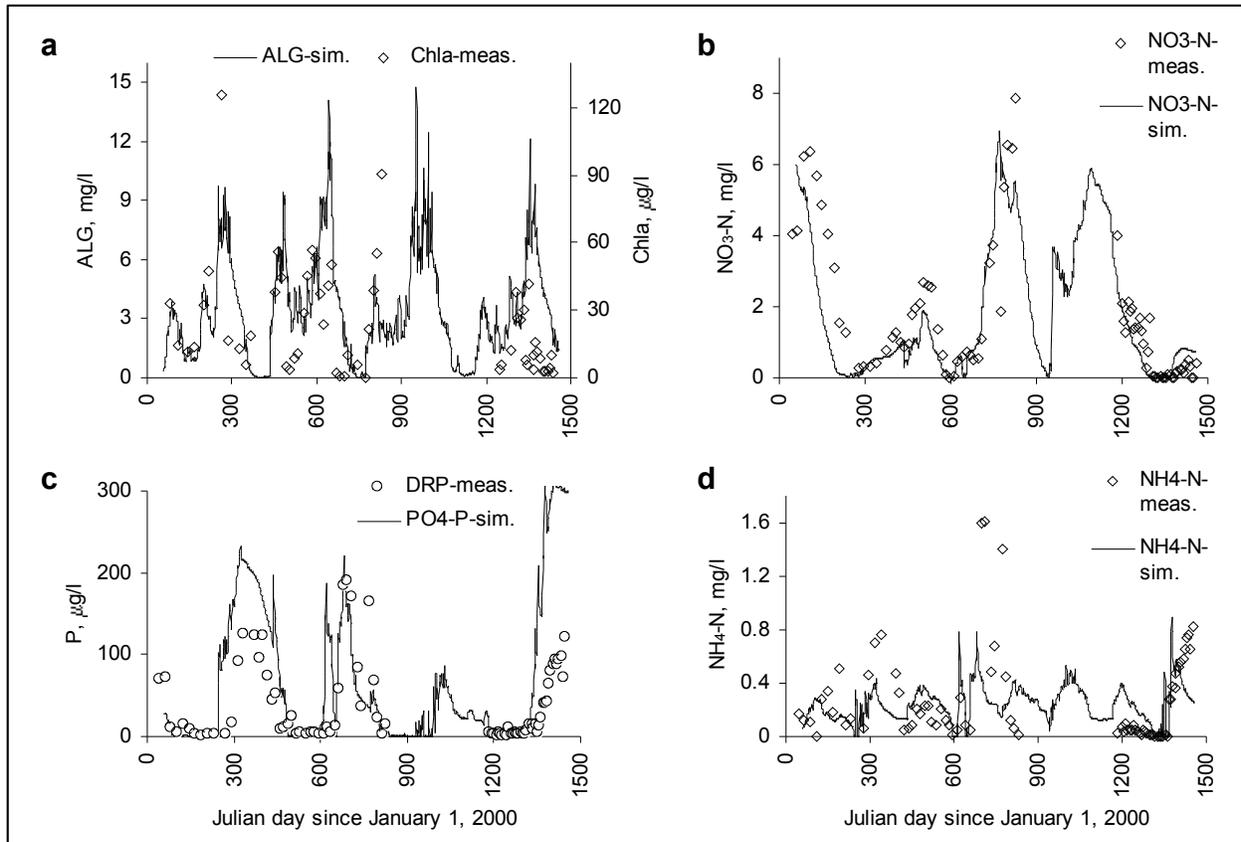
Figure 3. Measured and simulated concentrations of selected quantities in the surface layer of Jordán Reservoir at the dam (site B or outflow): (a) Chla and phytoplankton biomass (ALG), (b) NO_3-N,(c) DRP (measured) and PO_4-P (simulated),(d) NH_4-N.

Even in the contemporary version of the model (version 3.1; Cole and Wells, 2002), the sediment is not yet considered as a state variable within the simulated aquatic ecosystem. In it, organic particles that sink through the water column towards the bottom are active in DO consumption and nutrient release into the water column only when they are present in water. On reaching the bottom they become non-existent for the model. The backward release of nutrients to the water column and SOD are modelled by calibrated release coefficients that are mutually independent. The result of such a simplified approach is the impossibility of model calibration with universally valid parameters for different trophic conditions.

In spite of the reservations to the model that are described above, we have still gained some useful information from the nutrients impacts on phytoplankton which emerged in this scenario study. The response of Chla concentration to the parallel decrease of external and internal P loading gives a reasonable idea about the needed decrease of inflow P concentrations to achieve mesotrophic conditions that are required before the reservoir is again used as a drinking water source. The necessity of decreasing P input to one third or one fourth

in comparison with the present situation to achieve this goal is in concordance with the previous estimates that were done with the static Vollenweider model (Hejzlar et al., 1999).

Table 4. The results of the scenario study with model CE-QUAL-W2 for the determination of impacts of inflow TP concentration (TP_i), maximum intensity of P release from the sediment (PO4-R), and outflow depth to water quality and trophic conditions of Jordán Reservoir. Water quality was indicated by: anoxic area factor (AAF) calculated for the summer stratification period, mean concentrations of PO_4-P at the surface and 1 m above the bottom, and mean and maximum Chla concentrations at the surface (Chla and Chla-max, respectively). Calculated for the period from March 2000 to December 2003 in the segment close to the dam.

Scenario No.	TP_i, rel.value	PO4-R, mg m^2 d^{-1}	Outlet location	AAF, d	PO_4-P surface, µg l^{-1}	PO_4-P bottom, µg l^{-1}	Chla, µg l^{-1}	Chla-max, µg l^{-1}
1	1	0.045	surface	101	59	790	28	105
2	1	0.045	bottom	62	32	330	23	92
3	0.25	0.045	surface	82	41	780	17	95
4	0.25	0.045	bottom	42	20	290	9	78
5	1	0	surface	87	8.2	40	18	74
6	1	0	bottom	60	8.4	21	16	65
7	0.25	0	surface	72	3.1	17	8	31
8	0.25	0	bottom	37	3.1	9	8	31

The switch of reservoir discharging from surface to bottom induced a significant decrease of mean PO_4-P concentrations and a moderate decrease of Chla concentrations (Table 4). The decrease of PO_4-P concentrations was mainly due to withdrawals of bottom layers that were enriched by phosphorus released from the sediment. In contrast, the decrease of Chla concentration was caused mainly by the shortening of the stratification period and the earlier onset of autumnal circulation, which meant a restriction of fytoplankton growth due to less favourable light conditions in the water column. The switch to bottom discharge influenced the reduction of oxygen deficits in the hypolimnion very little. The increase in temperature in the water above the sediment and a consecutive increase of SOD was an apparent reason for such a small change at significantly shortened water residence time in the hypolimnion. However, any real reservoir would behave in this way only shortly after a change in outflow depth. Increased temperature and the increased availability of DO above the sediment would bring about more intensive oxidation of the sediment organic mater and SOD would gradually change to a new, lower equilibrium value.

4. Acknowledgements

5. References

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