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FACULTY OF CIVIL AND GEODETIC ENGINEERING

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CONTENTS - VSEBINA

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V S E B I N A - C O N T E N T S

UVODNIK

Tokratna številka Acta hydrotechnica prinaša razširjeni povzetek magistrskega dela mag. Irene Cvitanič, mlade raziskovalke na Inštitutu za zdravstveno hidrotehniko, Fakultete za gradbeništvo in geodezijo Univerze v Ljubljani, zaposlene na Hidrometeorološkem zavodu Republike Slovenije.

Mag. Irena Cvitanič je končala srednjo tehniško šolo na kemijski smeri v Celju. Študij je nadaljevala na Univerzi v Ljubljani, Fakulteti za naravoslovje in tehnologijo, na Oddelku za kemijo in kemijsko tehnologijo, kjer je leta 1992 diplomirala na kemijski tehnologiji, ožja usmeritev polimeri. Po opravljeni diplomi se je zaposlila na Hidrometeorološkem zavodu Republike Slovenije v Ljubljani, kjer je opravljala pripravništvo v sektorju za varstvo okolja, na oddelku za onesnaženost voda in v kemijskem laboratoriju. Leta 1994 se je na Univerzi v Ljubljani vpisala na podiplomski študij gradbeništva – hidrotehnična smer. Decembra 1998 je zagovorjala magistrsko nalogo s področja zdravstvene hidrotehnike. Pri podiplomskem študiju se je ukvarjala s preučevanjem sodobnih metod ekološke inženirike na področju zaščite in rabe voda, predvsem s prognostičnim modeliranjem kakovosti voda, ki spada med aktualna vprašanja ekološke - zdravstvene hidrotehnike. V okviru programa Tempus je bila leta 1995 na krajšem usposabljanju pri prof. Günthertu na Univerzi nemške vojske v Münchnu.

Magistrsko delo mag. Irene Cvitanič je usmerjeno v spoznavanje biokemijskih procesov v naravnih vodnih ekosistemih, ne samo v problematiko napovedovanja kakovostnih sprememb, temveč v določeni meri tudi k vsebinskemu oblikovanju kakovostnega monitoringa voda na način, da se zagotovi kar največja uporabnost zbranih kakovostnih in hidroloških podatkov. Namen naloge je bil, da se spremembe v zajezeni reki Savi kvantitativno opredelijo s pomočjo matematičnega modela v povprečnih in v ekstremnih hidroloških pogojih. Na tej podlagi naj se poda ocena kakovostnih sprememb v zajezeni Savi in njihov pomen za njeno kakovost v ožjem biološkem in v širšem vodnogospodarskem pogledu. V okviru naloge je najprej podana razlaga samega pojma, kakor tudi mehanizma evtrofikacije vodnih teles. Podani so temelji biokemičnih in fizikalnih procesov v rekah in jezerih. Opisane so posledice zajezitve rek, podana je primerjava lastnosti rečnih akumulacijskih jezer z naravnimi jezeri. V nadaljevanju so podani program gradnje hidroelektrarn na Savi, hidrološke lastnosti akumulacijskega jezera HE Vrhovo in kratek pregled kakovosti vode reke Save na obravnavanem območju pred in po zajezitvi reke Save.

Za izvedbo naloge je bil izbran večparametrski matematični model QUAL2E. Za uporabo modela so bile izvedene terenske meritve na vtoku in iztoku iz akumulacijskega jezera HE Vrhovo. Nato so bile izvedene vse faze modeliranja, od analize občutljivosti, umerjanja in preverjanja modela, do njegove potrditve. Tako je bil model uporabljen za napovedi kakovostnih sprememb Save v akumulaciji HE Vrhovo za raztopljeni kisik in BPK_5. V teoretičnem pogledu so izvedene meritve in rezultati modela opozorili na problematiko modeliranja klorofila, fosforja in amonija, to je na procese, pri katerih rezultati modela ne sledijo merskim rezultatom z enako natančnostjo, kot pri kisiku in BPK_5. Zato bo treba pri napovedih evtrofnosti v naslednjih predvidenih energetskih zajezitvah temu vprašanju posvetiti ustrezno pozornost, tako glede na formulacijo v modelu, kot glede na dopolnitve ali spremembe kemijske analitske tehnike. V praktičnem pogledu pa rezultati naloge z veliko stopnjo verjetnosti dokazujejo, da tudi v najbolj kritičnih sušnih obdobjih in pri najvišjih naravnih temperaturah vode ni pričakovati prekomernega padca koncentracije kisika v obravnavani zajezitvi HE Vrhovo, ki bi ogrozila obstoječo biocenozo v zajezitvi.

Ljubljana, julij 1999 Glavni urednik

EDITORIAL

This issue of Acta hydrotechnica is publishing an extended summary of a Master's Thesis by Irena Cvitanič, a junior researcher at the Institute of Sanitary Engineering, Faculty of Civil and Geodetic Engineering, University of Ljubljana, currently employed at the Hydrometeorological Institute of Slovenia.

Irena Cvitanič completed the Secondary Technical School in Celje in the field of Chemical Science. She continued her studies at the Faculty of Natural Science and Technology, Department of Chemistry and Chemical Technology where she graduated in 1992 from Chemical Technology in the field of polymers. After her graduation she obtained employment with the Hydrometeorological Institute of Slovenia where she has gained practical experience in the field of the determination of the physical, chemical and biological parameters of water quality and in the field of regulations for estimating the quality of surface waters. In 1994, she matriculated in the Master's Program of Civil Engineering. In December, 1998 she completed her study with a Master's Thesis in the field of Sanitary Engineering. During her postgraduate study, she dedicated her work to the research of contemporarily methods of ecological engineering in the field of water resources protection and use. She concentrated her work in particular to the prognostic modelling of water quality, which is one of the topical questions of sanitary engineering. Within the framework of the Tempus Program, she took a short postgraduate course at the University of Federal Arms in Munich in 1995.

Irena Cvitanič focuses her Master's Thesis on the understanding of the biochemical processes in natural water ecosystems. River impoundments change the natural water circulation in the stream regarding discharges and water quality. The goal of the Thesis was to develop a quantitative determination of these changes in the existing Vrhovo impoundment for average and extreme hydrological conditions using a mathematical model. Based on this, the Thesis was set to estimate the water quality changes in the impounded Sava River, as well as their influence on the water quality in the narrow biological sense and in the more extensive water management sense. The Thesis starts with the explanation of the concept and mechanisms of the eutrophication processes in bodies of water. It continues with the basis of the biochemical and physical processes in rivers and lakes and the consequences of river impoundments. Further on, the properties of river impoundments and natural lakes are compared. The Thesis also presents the program of constructing a chain of HEPP's on the Sava River, the hydrological properties of the Vrhovo impoundment and a short review of water quality in the Sava River both before and after the construction of the impoundment. The US EPA QUAL2E Water Quality model, which is a typical multiparametric mathematical model for river ecosystems, was chosen. For its application, field measurements at the inflow into and the outflow from the Vrhovo impoundment were performed, as well as a sensitivity analysis, calibration, verification and validation of the model. The model was used for quantitative water quality predictions of the Sava River in the Vrhovo impoundment for dissolved oxygen and biochemical oxygen demand. In a theoretical respect, the performed measurements and the modelled results warned of the problems of modelling chlorophyll, phosphorus and ammonium, i.e.: of the processes where the modelled results did not coincide with the measured results with the same precision as for O_2 and BOD_5. For the prediction of eutrophication for the future planned impoundments, adequate attention will have to be paid to this question, regarding the formulations in the model, as well as regarding the completion of the chemical analytical technique. In a practical respect, the results also prove with a strong likelihood that in the most critical dry period and when water temperatures are the highest, an excessive decrease in the concentrations of dissolved oxygen, which could have a negative influence on biocenosis in the impoundment, is not to be expected.

Ljubljana, July 1999 Editor-in-Charge

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ANALIZA MOŽNIH KAKOVOSTNIH SPREMEMB SAVE V AKUMULACIJI HE VRHOVO V POVPREČNIH IN EKSTREMNIH HIDROLOŠKIH POGOJIH S POMOČJO MATEMATIČNEGA MODELA

povzetek magistrskega dela
Fakulteta za gradbeništvo in geodezijo Univerze v Ljubljani
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ANALYSIS OF POSSIBLE QUALITY CHANGES OF THE SAVA RIVER IN THE VRHOVO IMPOUNDMENT IN AVERAGE AND EXTREME HYDROLOGICAL CONDITIONS WITH MATHEMATICAL MODEL

summary of the Master Thesis
Faculty of Civil and Geodetic Engineering, University of Ljubljana
the defence of the Master Thesis was on December 28, 1998

IZVLEČEK

Izgradnja hidroelektrarne (HE) Vrhovo je povzročila nastanek rečnega akumulacijskega jezera na reki Savi in s tem spremembo njenega naravnega vodnega režima, ki se odraža tudi v spremenjenih pogojih nebioloških in bioloških procesov samočiščenja vode in tako vpliva na njene kakovostne spremembe. Posledice energetske zajezitve reke na kakovost voda so lahko pozitivne ali negativne. V nalogi so obravnavani procesi evtrofikacije, biokemični in fizikalni procesi v rekah in jezerih, posledice zajezitev rek ter teoretični temelji matematičnega modeliranja in uporabljenega večparameterskega enodimenzionalnega modela QUAL2E. Model je bil uporabljen za modeliranje in napovedovanje možnih sprememb kakovosti vode v nastali zajezitvi. Opravljena je bila analiza občutljivosti modela. Številni parametri modela so bili določeni z umerjanjem modela tako, da je doseženo najboljše ujemanje rezultatov modela z izmerjenim stanjem. Potrditev modela je bila izvedena z rezultati meritev v letih 1996 in 1998. Na temelju dobljenih rezultatov je bil model uporabljen za kvantitativne napovedi raztopljenega kisika in biokemijske potrebe po kisiku v akumulaciji HE Vrhovo za ekstremne in povprečne hidrološke pogoje. Glede na rezultate modela in terenske meritve, izvedene pri nizkih pretokih in v pogojih poteka intenzivne primarne produkcije v zajezitvi, lahko zaključimo, da v akumulacijskem jezeru HE Vrhovo ne prihaja do prekomernega znižanja koncentracije raztopljenega kisika, ki bi povzročala negativne vplive na kakovost zajezene vode.
Ključne besede: *evtrofikacija, matematični modeli, modeliranje kakovosti voda, površinske vode, hidroelektrarna Vrhovo*

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ABSTRACT

The river impoundment on the Sava River was formed as a consequence of the construction of the Vrhovo Hydroelectric Power Plant (HEPP). The river impoundment changed the natural water circulation of the Sava River, a disruption which is also reflected in the changed conditions of the biological and non-biological self-purification processes in the water. Thus, it influences the water quality of the Sava River. River impoundments can affect water quality positively or negatively. This Thesis deals with the eutrophication, biochemical and physical processes in rivers and lakes, the impacts of river impoundments, the theoretical base of mathematical modelling and the employed multiparametric one-dimensional model QUAL2E. The QUAL2E model was used to model and predict the possible changes in water quality in the impoundment. A sensitivity analysis provided insight into the model operation and showed how the results of the model change when changing separate parameters. Many model parameters were determined by calibrating the model in such a manner that the best agreement between the results of the model and the measured state was achieved. The model validation was performed using the results of the measurements in 1996 and 1998. Based on the results obtained, the model was used for the quantitative prediction of dissolved oxygen and biochemical oxygen demand in the Vrhovo impoundment for extreme and average hydrological conditions. With regard to the model results and field measurements performed at low discharges and under conditions of intensive primary production in the dam, it can be concluded that an excessive decrease in concentrations of dissolved oxygen which could have negative influence on the dammed water quality does not appear in the Vrhovo impoundment.
Key-words: *eutrophication, mathematical models, water quality modelling, surface water, hydroelectric power station Vrhovo*

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VSEBINA

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SEZNAM SLIK

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SEZNAM SIMBOLOV - LIST OF SYMBOLS

oznaka *symbol*	**dimenzija** *dimension*	**opis** **pomen**	***description*** ***meaning***
A	mg(A)/l	koncentracija biomase alg	algal biomass concentration
AFACT		faktor povprečenja svetlobe	a light averaging factor
A_X	m^2	prečni prerez	cross-sectional area
BPK - BOD	mg(O_2)/l	biokemijska potreba po kisiku	biochemical oxygen demand
BPK_5 - - BOD_5	mg(O_2)/l	biokemijska potreba po kisiku v 5 dneh	5-day biochemical oxygen demand
BPK^C - - BOD^C	mg(O_2)/l	končna biokemijska potreba po kisiku za razgradnjo ogljikovih spojin	the concentration of ultimate carbonaceous biochemical oxygen demand
$BPK_5{}^C$ - - $BOD_5{}^C$	mg(O_2)/l	5-dnevna biokemijska potreba po kisiku za razgradnjo ogljikovih spojin	5-day concentration of ultimate carbonaceous biochemical oxygen demand
C	g/m^3	koncentracija	concentration
chl a	μg/l	koncentracija klorofila a	chlorophyll a concentration
CORDO		korekcijski faktor hitrosti nitrifikacije	nitrification rate correction factor
D_L	m^2/s	disperzijski koeficient	dispersion coefficient
f		delež dnevne svetlobe	fraction of daylight hours
F_1		delež amonija kot vir anorganskega dušika za alge	fraction of algal nitrogen uptake from ammonium pool
FL		omejitveni faktor svetlobe	algal growth limitation factor for light
FL_1		omejitveni faktor svetlobe, ki temelji na srednji dnevni intenziteti svetlobe	growth attenuation factor for light, based on daylight average light intensity
FL_{sr}		omejitveni faktor svetlobe, prilagojen trajanju dneva in metodi povprečenja	algae growth attenuation factor for light, adjusted for daylight hours and averaging method
FN		omejitveni faktor za dušik	algal growth limitation factor for nitrogen
FP		omejitveni faktor za fosfor	algal growth limitation factor for phosphorus
h	m	srednja globina toka	average depth
$\bar{I}_{a\lg}$	ly/day	srednja dnevna intenziteta fotosintetsko aktivne svetlobe	daylight average, photosynthetically active, light intensity
$I(h)$	ly/day	intenziteta svetlobe na globini h	light intensity at a given depth h

I_0	ly/day	intenziteta svetlobe na površini	surface light intensity
I_{tot}	ly	celotno dnevno fotosintetsko aktivno sončno obsevanje	total daily photosynthetically active solar radiation
K_1	day^{-1}	koeficient hitrosti razgradnje ogljikovih spojin	carbonaceous deoxygenation rate constant
K_2	day^{-1}	koeficient hitrosti reaeracije	reaeration rate constant
K_3	day^{-1}	hitrost izgubljanja BPK^C zaradi usedanja	rate of loss of *BOD* due to settling
K_4	g (O_2)/m^{2}day	hitrost ploskovne porabe kisika dna	benthic oxygen uptake
K_L	ly/day	konstanta Monodove enačbe za svetlobo	Monod equation constant for light
K_N	mg(N)/l	konstanta Monodove enačbe za dušik	Monod equation constant for nitrogen
K_P	mg(P)/l	konstanta Monodove enačbe za fosfor	Monod equation constant for phosphorus
KBPK	day^{-1}	koeficient hitrosti pretvorbe *BPK* v BPK_5	*BPK* conversion rate coefficient
KNITRF	mg/l	koeficient inhibicije nitrifikacije prvega reda	first order nitrification inhibition coefficient
KPK	mg(O_2)/l	kemijska potreba po kisiku	chemical oxygen demand

M	g	masa	mass
n	s/m$^{1/3}$	Manningov koeficient trenja	Manning roughness factor
N		dušik	nitrogen
$N_1 \cong NH_4^+$	mg(N)/l	koncentracija amonija	concentration of ammonium nitrogen
$N_2 \cong NO_2^-$	mg(N)/l	koncentracija nitrita	concentration of nitrite nitrogen
$N_3 \cong NO_3^-$	mg(N)/l	koncentracija nitrata	concentration of nitrate nitrogen
$N_4 \cong$ org.-N	mg(N)/l	koncentracija organskega dušika	concentration of organic nitrogen
N_d	h	število ur dnevne svetlobe	number of daylight hours per day
$N_e \cong N_{an}$	mg(N)/l	efektivna lokalna koncentracija razpoložljivega anorganskega dušika	the effective local concentration of available inorganic nitrogen
N_{tot}	mg(N)/l	koncentracija totalnega (celokupnega) dušika	concentration of total nitrogen
$O \cong O_2$	mg(O_2)/l	koncentracija raztopljenega kisika	dissolved oxygen concentration

O_p	mg(O_2)/l	nasičena koncentracija raztopljenega kisika pri nestandardnem zračnem tlaku	the saturation concentration of dissolved oxygen at non-standard pressure
O_s	mg(O_2)/l	nasičena koncentracija raztopljenega kisika pri lokalni temperaturi in tlaku	the saturation concentration of dissolved oxygen at the local temperature and pressure
P	-	fosfor	phosphorus
P_1 ≅ org.-P	mg(P)/l	koncentracija organskega fosforja	the concentration of organic phosphorus
P_2 ≅ ortho-PO_4^{3-}	mg(P)/l	lokalna koncentracija raztopljenega anorganskega fosforja (ortofosfata)	concentration of inorganic or dissolved phosphorus
P_N	-	prednostni faktor alg za NH_4^+	preference factor for NH_4^+
P_{tot} ≅ tot.-PO_4^{3-}	mg(P)/l	koncentracija totalnega (celokupnega) fosforja	concentration of total phosphorus
P_w	atm	parcialen tlak vodnih par	partial pressure of water vapor
Q	m^3/s	pretok	discharge
Redox	mV	redoks potencial	redox
R_x	m	srednji efektivni hidravlični radij	mean effective hydraulic radius
S	g/s	zunanji in notranji izvori ali ponori	external and internal source or sinks
S_e	-	naklon energijske črte	slope of the energy grade line
t		čas	time
T	K	temperatura vode	temperature of water
TN	mg(N)/l	totalni dušik	total nitrogen
$\bar{u}$	m/s	povprečna hitrost	mean velocity
x	m	razdalja	distance
X_{20}	-	vrednost koeficienta pri standardni temperaturi (20°C)	the value of the coefficient at the standard temperature (20°C)
X_T	-	vrednost koeficienta pri lokalni temperaturi T	the value of the coefficient at the local temperature
α_0	µg(*chl a*)/mg(A)	delež klorofila a v biomasi alg	ratio of chlorophyll-a to algal biomass
α_1	mg(N)/mg(A)	delež dušika v biomasi alg	fraction of algal biomass that is nitrogen
α_2	mg(P)/mg(A)	delež fosforja v biomasi alg	fraction of algal biomass that is phosphorus
α_3	mg(O_2)/mg(A)	hitrost produkcije kisika pri fotosintezi na enoto biomase alg	O_2 production per unit of algal growth

α_4	mg(O_2)/mg(A)	hitrost porabe kisika pri respiraciji na enoto biomase alg	O_2 uptake per unit of algae respired
α_5	mg(O_2)/mg(N)	hitrost porabe kisika na enoto oksidiranega amonija	O_2 uptake per unit of NH_3 oxidation
α_6	mg(O_2)/mg(N)	hitrost porabe kisika na enoto oksidiranega NO_2^-	O_2 uptake per unit of NO_2^- oxidation
β_1	day^{-1}	koeficient hitrosti biološke oksidacije NH_4^+ v NO_2^-	rate constant for the biological oxidation of NH_4^+ to NO_2^-
β_2	day^{-1}	koeficient hitrosti biološke oksidacije NO_2^- v NO_3^-	rate constant for the biological oxidation of NO_2^- to NO_3^-
β_3	day^{-1}	koeficient hitrosti hidrolize organskega dušika v amonij	rate constant for the hydrolysis of organic N to ammonia
β_4	day^{-1}	koeficient hitrosti razgradnje organskega fosforja v raztopljeni anorganski fosfor	rate constant for the decay of organic-P to dissolved-P
θ	-	empirična konstanta za posamezen reakcijski koeficient	an empirical constant for each reaction coefficient
κ	µS/cm	električna prevodnost	conductivity
λ	m^{-1}	koeficient upadanja svetlobe	light extinction coefficient
λ_0	m^{-1}	koeficient upadanja svetlobe za vodo, za vse komponente razen fitoplanktona	non-algal light extinction coefficient
λ_1	m^{-1}(µg(*chl a*)/l)$^{-1}$	linearni koeficient samoosenčenja alg	linear algal self-shading coefficient
λ_2	m^{-1}(µg (*chl a*)/l)$^{-2/3}$	nelinearni koeficient samoosenčenja alg	nonlinear algal self shading coefficient
μ	day^{-1}	specifična hitrost rasti alg	algal growth rate
μ_{max}	day^{-1}	maksimalna hitrost rasti alg	maximum algal growth rate
ρ	day^{-1}	hitrost respiracije alg	algal respiration rate
σ_1	m/day	hitrost usedanja alg	algal settling rate
σ_2	mg(P)/m^{2}day	hitrost sproščanja raztopljenega anorganskega fosforja z dna	benthos source rate for dissolved phosphorus
σ_3	mg(N)/m^{2}day	hitrost sproščanja NH_4^+ z dna	benthos source rate for ammonia nitrogen
σ_4	day^{-1}	hitrost usedanja organskega dušika	organic nitrogen settling rate
σ_5	day^{-1}	hitrost usedanja organskega fosforja	organic phosphorus settling rate

1. UVOD

Vodna energija je med vsemi znanimi vrstami energije še vedno najcenejša in verjetno najmanj ekološko oporečna. Vendar tudi izgradnja akumulacijskih jezer ni brez določenih ekoloških posledic. Pogosto ni več vprašanje, ali jez zgraditi ali ne, ker je ta odločitev predvsem socialno-ekonomskega ali političnega značaja. Ostaja pa vprašanje, kako jez zgraditi in s planiranjem zagotoviti največjo koristnost na eni in najmanj škodljivih oziroma nezaželenih posledic na drugi strani.

Načrtovane energetske zajezitve reke Save bodo povzročile spremembe naravnega vodnega režima reke in spremembe v prostoru ob reki. Spremembe naravnega vodnega režima se bodo odrazile v spremenjeni dinamiki pretokov, spremenjenih transportnih in erozijskih zmogljivostih reke, možnih spremembah režima podtalnice v ožjem in širšem območju zajezitve, spremembi biotopa in posledično v spremembi vodne biocenoze in obrežnega habitata. Glede na vse navedene spremembe je povsem jasno, da se bodo z zajezitvijo reke spremenili tudi pogoji, ki vplivajo na kakovost vode reke Save.

Posledice energetske zajezitve reke na kakovost voda so lahko negativne ali pozitivne. Med negativne posledice zajezitve spadajo znižanje koncentracije raztopljenega kisika, povišanje temperature vode in posledično zmanjšanje sposobnosti za sprejemanje toplotnega onesnaženja ter povečana rast alg z vsemi posledicami. Na drugi strani pa zajezitev lahko pozitivno prispeva h kakovosti vode z zmanjšanjem množine suspendiranih snovi ter z zmanjšanjem organske in bakteriološke onesnaženosti.

Namen naloge je bila kvantitativna opredelitev kakovostnih sprememb reke Save v obstoječi akumulaciji HE (hidroelektrarne) Vrhovo v povprečnih in ekstremnih hidroloških pogojih, z uporabo večparametrskega matematičnega modela. Uporabili smo model QUAL2E (Brown & Barnwell, 1987), ki je značilen primer večparameterskega modela rečnih ekosistemov

1. INTRODUCTION

Among all known types of energy, water energy is still the cheapest and probably the least ecologically opposable. However, the construction of reservoirs is not without ecological consequences, too. It is often no longer the question of whether to build a dam or not, as this is a socio-economic and political decision. But there is still the question of how to build a reservoir and how its planning can assure maximal usefulness on the one side and minimal harmful and undesired consequences on the other.

The planned impoundments for the hydroelectric power plants (HEPP) on the Sava River will change the existing natural runoff regime of the river and its riparian land. Changes in the natural river regime will be reflected in the changed dynamics of the flow, the changed transport and erosion capacities of the river, possible changes in the groundwater regime in narrow and extended impounded region, the changes of biotop and, consecutively, in the changes of water biocenosis and riverine habitats. Consequently, the conditions which influence the water quality of the Sava River will also be changed.

The impacts of river impoundments on water quality can be negative or positive. The decrease in the concentrations of dissolved oxygen, the increase in water temperature and, in some special conditions, enlarged algae production are the main negative effects. On the other hand, because of the decreased quantity of suspended substances and the organic and bacteriological load in the river downstream, the impoundments can be considered as a positive influence on water quality. These positive contributions directly contribute to the self-purification capacity of natural water.

The goal of the work was a quantitative determination of water quality changes in the Sava River in the existing Vrhovo Impoundment in average and extreme hydrological conditions using a multiparametric mathematical model. The US EPA QUAL2E Water Quality Model (Brown & Barnwell, 1987) was used, which is a ter je mnogostransko uporaben za modeliranje kakovosti površinskih voda. Simulacije so bile izvedene s stacionarno opcijo modela. Izvedena je bila analiza občutljivosti modela, s katero se pridobi vpogled v obnašanje modela in možnosti za njegovo umerjanje. Umerjanje, preverjanje in potrditev modela so bili izvedeni z eksperimentalnimi meritvami v akumulaciji HE Vrhovo v letih 1996 in 1998. Nato je bila z modelom izvedena kvantitativna napoved raztopljenega kisika in biokemijske potrebe po kisiku v akumulaciji HE Vrhovo za ekstremne in povprečne hidrološke pogoje.

Mehanizem evtrofikacije v vodnih ekosistemih in ukrepi za kontrolo evtrofikacije so podrobneje opisani v magistrski nalogi (Cvitanič, 1998), kjer so opisani tudi temelji biokemičnih in fizikalnih procesov v rekah in jezerih ter teoretični temelji matematičnih modelov.

typical multiparametric model for river ecosystems and is a comprehensive and useful stream water quality model. Simulations were carried out using the stationary model option. We performed a sensitivity analysis which gave us insight into the model operation and the possibilities of its calibration. Calibration, verification and validation of the model were done using experimental measurements in the impoundment in 1996 and 1998. After that, the model was used for the quantitative prediction of dissolved oxygen and biochemical oxygen demand in the impoundment for average and extreme hydrological conditions.

The Master's Thesis (Cvitanič, 1998) gives a detailed description of eutrophication processes in water ecosystems and the measures for controlling them, as well as the basis of biochemical and physical processes in rivers and lakes, and the theoretical basis of mathematical models.

2. PROBLEMATIKA KAKOVOSTI VODA V AKUMULACIJSKIH JEZERIH VODNIH ELEKTRARN

V oceni umetnega vodnega telesa nastopata dva vidika: gospodarski in ekološki. Gospodarski vidik utemelji koristnost za družbo, ekološki vidik oceni posledice za okolje in naravna vodna telesa (Rejic, 1988).

Mnoge vodne akumulacije so glede na dogajanja in procese bolj podobne rekam kot jezerom. To zlasti velja za vodne akumulacije, v katerih je vodni tok tako hiter in zadrževalni čas tako kratek, da termična stratifikacija ne nastopi (Taub, 1984).

2. WATER QUALITY PROBLEMS IN THE RESERVOIRS OF HYDROELECTRIC POWER PLANTS

In the evaluation of an artificial body of water, one has to consider two standpoints: economical and ecological. The economical standpoint substantiates the usefulness for society. The ecological standpoint evaluates the consequences for the environment and for natural bodies of water (Rejic, 1988).

Considering the processes in water reservoirs, many reservoirs are more similar to rivers than lakes. This is particularly true for those where the current is so fast and the retention times so short that thermal stratification does not appear (Taub, 1984).

2.1 IZGRADNJA AKUMULACIJSKIH JEZER

Akumulacijska jezera vodnih elektrarn nastanejo s pregraditvijo struge vodotoka ter dela doline ob vodotoku. Prištevamo jih k umetnim vodnim telesom, ki se od naravnih jezer razlikujejo po morfologiji, hidrologiji, nastanku, razvoju, gospodarski rabi in vplivih na okolje. Posledice njihove izgradnje so

2.1 CONSTRUCTION OF RESERVOIRS

HEPP reservoirs originate from impounding a river channel and part of the valley along the river. They belong to artificial bodies of water which differ from natural lakes according to their morphology, hydrology, origin, development, economic use and impacts on environment. The consequences of their številne, kompleksne in dolgoročne.

S stališča vodnega gospodarstva so bistvenega pomena vplivi izgradnje akumulacijskih jezer na hidrološki sistem in vodni biološki sistem (Polzer & Traer, 1990):

- sprememba morfologije vodotoka, povečanje globine vode ter površine gladine,
- zmanjšanje hitrosti vode in intenzitete turbulence,
- zmanjšanje prodonosnosti,
- pospešena sedimentacija lebdečih delcev,
- dolvodna erozija,
- sprememba svetlobnih razmer v vodnem telesu,
- podaljšanje zadrževalnih časov,
- povečana samočistilna sposobnost,
- sprememba vsebnosti kisika in dušika,
- vplivi na razvoj fitoplanktona, zooplanktona, fitobentosa, zoobentosa ter makrofitov,
- znižanje števila in diverzitete rib,
- vpliv na kakovost vode, posebno pri močno obremenjenih rekah z odpadnimi vodami,
- vpliv na bakteriološko obremenitev.

Zajezitev rek in s tem nastanek akumulacijskih jezer pomeni poseg v vodno bilanco reke. Namesto naravnega odtoka nastane kontroliran odtok, ki ga definira režim delovanja elektrarne ali verige elektrarn. Zadrževalni časi v akumulacijskih jezerih se gibljejo od nekaj ur do nekaj mesecev.

Kinetična energija vode v rekah povzroča erozijo in transport plavin. Ker se hitrost vode v akumulacijskem jezeru bistveno zmanjša, se transport plavin prekine, prod in lebdeče plavine se odlagajo v jezeru, s tem pa se manjša koristni volumen jezera. Visoke vode običajno odplavijo del sedimentov iz akumulacijskih jezer. Pod jezom pa ima reka spet veliko transportno zmogljivost, in ker je odložila plavine nad jezom, to povzroča dolvodno erozijo, ki najmočneje spodjeda strugo tik pod jezom (Krajnc, 1989). Problematiko je treba obravnavati s stališča masne bilance transportiranega materiala in s

construction are numerous, complex and lasting.

From the standpoint of water management, the impacts of reservoirs on the hydrological and water biological systems are of prime importance (Polzer & Traer, 1990):

- changes in stream morphology, greater water depth and surface area,
- decreased water velocity and turbulence intensity,
- decreased bed load transport rate,
- accelerated sedimentation of suspended particles,
- downstream erosion,
- modification of light conditions in the water body,
- longer retention times,
- increased self-purification capacity,
- changes in oxygen and nitrogen concentrations,
- impacts on the growth of phytoplankton, zooplankton, phytobenthos, zoobenthos and macrophytes,
- reduction in the number and diversity of fish species,
- impacts on water quality, especially for the rivers extremely loaded with sewage,
- impacts on bacteriological loads.

River impoundment and the resulting reservoir are an intervention into the water balance of the river. Instead of natural outflow, there emerges controlled outflow, which is defined by the working regime of the power plant or a series of power plants. Retention times in the reservoirs range from several hours to several months.

The kinetic energy of water in rivers causes erosion and sediment transport. Because water velocities in reservoirs are essentially reduced, sediment transport ceases, gravel or sand and suspended substances are deposited in reservoirs and this reduces their useful volume. High flows usually wash a portion of deposited sediments out of the reservoir. Downstream of the dam the river has large transport capacity, and because sediment is deposited upstream of the dam, the river erodes its bed primarily at a point closest to the dam outflow, a process called downstream stališča akumulacije toksičnih snovi v sedimentih (Rismal, 1997a).

Rečna voda lahko napaja podtalnico v prodnih naplavinah ob rekah, ali pa podtalnica odteka v reko. To je odvisno od vodostajev obeh. Ob izgradnji akumulacijskih jezer poskušajo graditelji čim bolj zmanjšati iztekanje vode iz jezer s posebnimi tehničnimi ukrepi (tesnenje bokov akumulacij). Obstaja tudi bojazen za onesnaženje podtalnice z vodo iz akumulacij, po drugi strani pa akumulirana voda omogoča dvig nivoja podtalnice, če za to obstaja potreba (Krajnc, 1989).

Pod pojmom samočistilna sposobnost vode razumemo sistem fizikalnih, kemijskih in bioloških procesov, ki vodijo do razgradnje razgradljivih snovi v vodi in vračanja produktov razgradnje v kroženje (Kolar, 1983). Snovne spremembe v procesu samočiščenja delimo na nebiološko ter biološko samočiščenje.

V procesih nebiološkega (abiotskega) samočiščenja (usedanje, izkosmičenje, obarjanje, absorpcija, adsorpcija, izhlapevanje, hidroliza, fotoliza, kompleksacija) poteka odstranjevanje nerazgradljivih snovi. Zmanjšanje hitrosti vode v akumulacijskih jezerih bistveno vpliva na intenzivnost fizikalno kemijskih procesov nebiološkega samočiščenja. Vse spremembe fizikalne limnologije vplivajo na kakovost vode (fizikalno-kemijske parametre) in vodni biološki sistem.

Pomembnejši pa je proces biološkega (biotskega) samočiščenja, ki je najpomembnejši nosilec kroženja snovi in energije v vodnem okolju. Razgradnjo organskih snovi izvedejo v vodi prisotni mikroorganizmi, ki s svojim metabolizmom presnavljajo organsko onesnaženje voda - organske snovi ob prisotnosti kisika oksidirajo. Z izgradnjo akumulacijskih jezer se spremenijo tudi pogoji biološkega samočiščenja.

Vodni tok se upočasni, torej se bistveno povečajo zadrževalni časi. Samočiščenje, ki je bilo pred zajezitvijo porazdeljeno na veliko

erosion (Krajnc, 1989). These problems should be addressed from the standpoint of the mass balance of the transported material and the accumulation of toxic substances in the sediments (Rismal, 1997a).

The river water can feed the groundwater in the alluvia along the river or the groundwater can flow off in the river, depending on the water levels of both. When constructing reservoirs, we attempt to reduce the outflow from reservoirs with special technical measures (the tightening of the sides of the reservoir). Further on, there exists some concern that the groundwater could get polluted by the water from reservoirs. On the other hand, the accumulated water can rise groundwater levels, if there is a need for that (Krajnc, 1989).

Self-purification processes include all physical, chemical and biological processes which lead to the degradation of decomposable substances in water and the return of decomposed products into circulation. Self-purification processes are divided into abiotic and biotic processes.

Non-biological self-purification processes (settling, flocculation, precipitation, absorption, adsorption, evaporation, hydrolysis, and photolysis) consist of the elimination of non-decomposable substances. The decreased water velocity in reservoirs has an important impact on the intensity of the physio-chemical processes of non-biological self-purification. All modifications in the physical limnology influence water quality (physio-chemical parameters) and the water biological system.

More important is the process of biological (biotic) self-purification, which is most important in the circulation of substances and energy in water environment. The decomposition of organic substances is performed by the microorganisms present in water which assimilate the organic pollution of the water by a process of metabolism – organic substances oxidize in the presence of oxygen. With the construction of reservoirs the conditions of biological self-purification also change.

The flow slows down so retention times are daljši odsek reke, se sedaj v bistveno večji meri odvija v akumulacijskem jezeru.

Zaradi bistveno manjših hitrosti vode in posledično intenzivnejših procesov usedanja, se delež biološkega onesnaženja, ki nastopa v suspendirani usedljivi obliki, veliko hitreje zmanjšuje kot v nezajezenem toku. Zaradi tega pa se bistveno poveča poraba kisika in posledično zmanjša vsebnost raztopljenega kisika v vodi. Problem je še večji, ker je vnos kisika preko gladine zaradi zmanjšane hitrosti vode občutno manjši. To povzroča velike spremembe v ekosistemu.

Zajezitev rek lahko izboljša bakteriološko kakovost vode. V primerih, ko je v rekah prvotno število bakterij nizko ali pa je zadrževalni čas znotraj zajezitve dovolj dolg, se zaradi odmiranja zmanjša število fekalnih koliformnih bakterij. Izboljšanje bakteriološke kakovosti vode glede na razredčenje pa je uspešno samo v primeru, če je dotok v zajezitev po prostornini zadosten in če je bakteriološko ustrezne kakovosti (Venter et al., 1997).

V slovenskih rekah, ki jih uvrščamo večinoma med alpske reke, predstavljajo največji del biocenoze prirasli organizmi (prerast), tako obrast (perifiton-producent kisika) kot heterotrofni organizmi (porabniki kisika). Z zajezitvijo rek se življenjski pogoji za to biocenozo poslabšajo zaradi manjšega vnosa kisika, večjih globin vode in posledično poslabšanih svetlobnih razmer, sprememb zrnavosti usedlin na dnu. Spremembe življenjskih pogojev se odražajo v spremenjeni sestavi prerasti, zoobentosa in v sestavi ribje favne (ciprinidi) v akumulacijskih jezerih (Rismal, 1985).

Pri dosedanjem opisovanju kakovosti vode v akumulacijskih jezerih smo imeli ves čas v mislih stabilizirano akumulacijsko jezero. Zavedati pa se moramo, da je vsaka akumulacija specifičen problem, pri katerem bo marsikateri od naštetih dejavnikov nepomemben, lahko se bodo pojavili novi ali pa bo samo eden med njimi močno prevladal (Kokol, 1988).

significantly increased. Self-purification, which was, before the impoundment, distributed along a longer reach of a river, is now performed to an increased extent in the reservoir.

The water velocity is smaller and settling processes are more intensive, so that the part of biological pollution in a suspended settling form decreases more rapidly than in an unimpounded flow. For this reason, the oxygen consumption is essentially increased, and the concentration of dissolved oxygen decreases. The problem is even greater when considering that the input of oxygen over the surface is much smaller, owing to the reduced water velocity. This causes substantial changes in the ecosystem.

River impoundment can improve the bacteriological quality of water. The level of faecal coliforms decreases because of die-off cases, when the original number of bacteria in rivers is low or when the retention time in the impoundment is long enough. The improvement of bacteriological quality by means of dilution is successful only if the inflow into the impoundment is of sufficient volume and if it is of a suitable bacteriological quality (Venter et al., 1997).

In Slovenian rivers, classified mostly among Alpine rivers, attached organisms represent the largest part of biocenosis, i.e. periphyton (oxygen producers), as well as heterotrophic organisms (oxygen consumers). With river impoundments, the living conditions for the biocenosis get worse because of the smaller input of oxygen, the greater depth of water and, consequently, the worsening light conditions and modifications in sediment size. The changed living conditions are reflected in the changed composition of the attached organisms, zoobenthos, and in the composition of fish fauna (cyprinid) in reservoirs (Rismal, 1985).

The above descriptions of water quality in reservoirs all refer to stabilised reservoirs. However, it has to be kept in mind that every reservoir represents a specific problem, where many of the listed factors will be unimportant, but some new could appear, or only one of all of them will be predominant.

2.2 GRADNJA HIDROELEKTRARN NA SAVI

Hidroelektrarna Vrhovo, ki so jo pričeli graditi leta 1987, predstavlja prvo v verigi hidroelektrarn na odseku Zidani Most – državna meja s Hrvaško. Investitor načrtuje še graditev HE Boštanj, HE Blanca, HE Brestanica, HE Krško, HE Brežice in HE Mokrice (Kokol, 1988). Stopnje posameznih HE so izbrane tako, da se gladina zajezitev sklenjeno nadaljuje od stopnje do stopnje. Zaradi bogatih vodonosnih stranskih pritokov (Savinja, Krka) so na tem odseku najugodnejši hidrološki pogoji. Vloga verige HE bo proizvodnja vršne energije oziroma regulacija moči in bo torej obratovala v dnevnem pretočno akumulacijskem režimu (SEL, 1994).

HE Vrhovo je pričela poskusno obratovati avgusta 1994 in je še vedno v fazi poskusnega obratovanja. Elektrarna je nizkotlačna s tremi turbinami za skupen inštaliran pretok 500 m^3/s in minimalnim odtokom 100 m^3/s zaradi težav s termičnim onesnaženjem Save pod NE Krško (Krajnc, 1994b).

Glede na spremenjen vodni režim reke Save na omenjenem odseku je povsem jasno, da se bodo spremenili tudi pogoji, ki vplivajo na kakovost vode reke Save. Te spremembe pa so lahko za bilanco kakovosti vode usodne, ker Sava služi kot odvodnik večinoma neprečiščenih odpadnih voda iz naselij in industrije gospodarsko najbolj razvitega dela Slovenije. Zato je bil sprejet »Program ukrepov za sanacijo kakovosti vode reke Save v obdobju 1986-1990«, ki temelji na zahtevi, da se izboljša kakovost reke Save nad profilom HE Vrhovo iz 3. do 4. kakovostnega razreda v 2. do 3. kakovostni razred. V program je bila uvrščena izgradnja komunalnih čistilnih naprav za vsa večja naselja ob Savi in Savinji ter modernizacija tehnoloških postopkov in izgradnja objektov za čiščenje odplak v industrijskih delovnih organizacijah.

2.2 CONSTRUCTION OF HYDROELECTRIC POWER PLANTS ON THE SAVA RIVER

The Vrhovo HEPP, whose construction began in 1987, represents the first HEPP in the series of HEPP's on the Sava River section between Zidani Most and the border with Croatia. In the future, the construction of HEPP Boštanj, HEPP Blanca, HEPP Brestanica, HEPP Krško, HEPP Brežice and HEPP Mokrice is also planned (Kokol, 1988). The stage of each HEPP is chosen in such a manner that impoundment levels continue without interruption from one stage to another. In this segment of the Sava River, the hydrological conditions are the best because of water-rich lateral tributaries (Savinja, Krka). The role of this series of HEPP's will be the production of peak energy, thus, they will operate in a daily accumulation regime (SEL, 1994).

The Vrhovo HEPP began operating in August, 1994, and it is still in the test phase of operation. The HEPP is a low-pressure plant with three turbines for the total installed discharge of 500 m^3/s and with a minimal outflow of 100 m^3/s due to the problems of thermal pollution of the Sava River below the NPP (nuclear power plant) Krško (Krajnc, 1994b).

Considering the changed water regime in the mentioned section of the Sava River, it is quite clear that the conditions which influence the Sava River water quality will also be changed. These changes can be fatal for the water quality balance because the Sava River serves as a drain for mostly untreated domestic and industrial waste waters of the economically best developed region in Slovenia. Because of this, the Programme of Interventions for the Improvement of the Water Quality in the Sava River for the period from 1986 to 1990 was adopted. It was based on the requirement to improve water quality in the Sava River above the HEPP profile from a quality class 3 to 4 into a quality class 2 to 3. The program included the construction of waste water treatment plants for all the larger towns along the Sava River and the Savinja River, as well as the modernization of technological processes and the construction of waste water treatment plants in industrial organizations.

2.3 HIDROLOŠKE LASTNOSTI AKUMULACIJSKEGA JEZERA HE VRHOVO

Povodje HE Vrhovo ima površino 7198 km^2, srednji pretok znaša 235 m^3/s, stoletna visoka voda 3102 m^3/s. Kota zajezitve je 191 m n.m., kota spodnje vode 182,88 m n.m., bruto padec znaša 8,12 m. Površina akumulacijskega jezera je 1,43 km^2 in prostornina $8{,}65 \cdot 10^6$ m^3 (SEL, 1994).

Teoretični zadrževalni časi v akumulacijskem jezeru HE Vrhovo se bodo povečali od 3,8 krat pri pretoku 330 m^3/s do 10,6 krat pri pretoku 56 m^3/s (preglednica 1). Ti zadrževalni časi so izračunani za odsek v dolžini 12 600 m gorvodno od pregrade HE Vrhovo (Krajnc, 1989). Kljub temu povečanju je maksimalni zadrževalni čas v akumulacijskem jezeru 1,94 dni, kar uvršča akumulacijsko jezero Vrhovo v skupino pretočnih jezer.

2.3 HYDROLOGICAL PROPERTIES OF THE RIVER IMPOUNDMENT OF THE VRHOVO HEPP

The river basin of the Vrhovo HEPP is comprised of 7189 km^2, the average discharge is 235 m^3/s. The impoundment lies at 191 m above sea level, the lowest water level is 182.88 m a.s.l., and the gross fall is 8.12 m. The surface of the impoundment is 1.43 km^2 and its volume is $8.65 \cdot 10^6$ m^3 (SEL, 1994).

Theoretical retention times in the impoundment of Vrhovo HEPP will increase from 3.8 times at a discharge of 330 m^3/s to 10.6 times at a discharge of 56 m^3/s (Table 1). These retention times were calculated for the reach in the length of 12 600 m upstream from the dam of the HEPP (Krajnc, 1989). In spite of this increase, the maximal retention time in the impoundment is 1.94 day, which classifies it among flowing lakes.

Preglednica 1. Teoretični zadrževalni časi Save pred zajezitvijo in v akumulacijskem jezeru HE Vrhovo (Krajnc, 1989).
Table 1. Theoretical retention times of the Sava River before the impoundment and in the impoundment of the Vrhovo HEPP (Krajnc, 1989).

Pretok *Discharge*	Zadrževalni čas - pred zajezitvijo *Retention time – before impoundment*	Zadrževalni čas - po zajezitvi *Retention time – after impoundment*
[m^3/s]	[h]	[h]
56	4,4	46,6
65	3,7	39,8
102	3,3	25,6
178	2,5	14,8
237	2,3	12,8
330	2,1	8,1

2.4 KAKOVOST VODA PRED IN PO ZAJEZITVI HE VRHOVO

Oceno kakovosti voda reke Save na odseku Hrastnik-Vrhovo lahko podamo na podlagi podatkov monitoringa kakovosti površinskih vodotokov v Sloveniji, ki ga izvaja Hidrometeorološki zavod Republike Slovenije. Na tem odseku se spremlja kakovost na zajemnih mestih v Hrastniku in Radečah za Savo in v Velikem Širju za Savinjo. V preglednici 2 je prikazano spreminjanje kakovosti voda na posameznih zajemnih mestih za obdobje 1987-1995 (HMZ, 1994; 1997a).

2.4 WATER QUALITY BEFORE AND AFTER THE IMPOUNDMENT OF THE VRHOVO HEPP

The estimation of water quality in the Sava River along the Hrastnik-Vrhovo reach can be based on the data of surface water quality monitoring in Slovenia performed by the Hydrometeorological Institute of Slovenia. In this reach, water quality is monitored at the Hrastnik and Radeče sampling points for the Sava River and at the Veliko Širje sampling point for the Savinja River. Table 2 shows the changes in water quality in the selected sampling points for the period between 1987 and 1995 (HMZ, 1994; 1997a).

Preglednica 2. Primerjava kakovosti voda za obdobje 1987-1995.
Table 2. Comparison of water quality for the period 1987-1995.

Vodotok *River*	Zajemno mesto *Sampling point*	Skupna ocena *Final evaluation*								
		1987	1988	1989	1990	1991	1992	1993	1994	1995
Sava	Hrastnik	-	-	3-4	3-4	3-(4)	3	3	3	3
Sava	Radeče	3-(4)	3-4	3-4	3-4	3-4	3	3	3	3
Savinja	V. Širje	3-2	3	2-3	(2)-3	3	(2)-3	(2)-3	2-3	2-3

Kakovost Save na odseku Hrastnik - Vrhovo se je v letu 1992 izboljšala iz 3. do 4. kakovostnega razreda v 3.kakovostni razred. Še vedno pa je bilo prisotno onesnaženje iz zasavskega industrijskega bazena. Za Savo na teh zajemnih mestih je bila značilna visoka vsebnost kisika. V reki Savi v Radečah je bila visoka kemijska potreba po kisiku (KPK) s $K_2Cr_2O_7$, povišana vsebnost dušikovih spojin (predvsem amonija in nitrita) in ortofosfata. V sedimentu so stalno prisotne težke kovine cink, svinec, nikelj in živo srebro, njihove koncentracije so odvisne tako od onesnaženja kot od hidroloških razmer. Po rezultatih saprobioloških analiz se je Sava v Hrastniku in Radečah uvrščala med zmerno obremenjene ali med kritično obremenjene vodotoke. Tudi bakteriološka slika na teh zajemnih mestih je bila zelo slaba. Vzorci vode so praviloma vsebovali veliko število bakterij fekalnega

The quality of the Sava River in the Hrastnik – Vrhovo reach improved in 1992 from a quality class 3 to 4 to a quality class 3. However, the pollution from the Zasavje Industrial Basin was still present. A high concentration of dissolved oxygen was significant for the Sava River at these sampling points. In Radeče we observed a particularly high chemical oxygen demand (COD) with $K_2Cr_2O_7$, and the concentration of nitrogen compounds (above all ammonium and nitrite) and orthophosphate. Heavy metals such as zinc, lead, nickel, and mercury were constantly present in the river sediment. The concentrations of heavy metals depended on pollution as well as on hydrological conditions. The results of the saprobiological analyses classified the Sava River in Hrastnik and in Radeče between a moderately to a critically charged river. The bacteriological situation was also very bad. Water samples generally contained a lot of faecal bacteria izvora (HMZ, 1994; 1997a).

Po zajezitvi leta 1994 so se kakovostne spremembe Save v zajezitvi HE Vrhovo spremljale z izvajanjem fizikalno-kemijskih in bioloških analiz. Fizikalno-kemijsko kontrolo kakovosti zajezene Save je v obdobju od leta 1995 do leta 1997 izvajal Inštitut za zdravstveno hidrotehniko (Rismal, 1997b).

Rezultati meritev v letu 1995 in 1996 so pokazali le manjše, komaj zaznavne posledice v zajezeni vodi. Vendar v tem opazovanem obdobju, zaradi nedokončanih gradbenih del v zajezenem območju, HE Vrhovo še ni trajno obratovala pri polni zajezitvi. Obratovalne razmere so se stabilizirale šele v drugi polovici leta 1996.

Na podlagi hitrega pregleda meritev temperatur na zajemnih mestih za obdobje od leta 1995 do leta 1997 je mogoče zaključiti, da je temperaturno stanje v posameznih profilih akumulacije Vrhovo homogeno, kar pomeni, da v akumulacijskem jezeru ne nastopa termična stratifikacija, značilna za naravna jezera.

V letih 1995 in 1997 je Inštitut za hidravlične raziskave iz Ljubljane opravil 6 dodatnih celodnevnih meritev temperature vode v petih prečnih profilih v akumulacijskem bazenu HE Vrhovo. Meritve so opravili zaradi določitve stanja po zajezitvi. V dveh meritvah v poletnih mesecih sta bili za razliko od rezultatov rednega monitoringa opaženi tako vertikalna kot horizontalna temperaturna slojevitost. Vertikalni temperaturni gradienti so posledica procesov toplotne izmenjave na površini zajezitve. Horizontalni gradienti pa so lahko posledica nepopolnega premešanja hladilne vode TET 2 Trbovlje ali dotoka Savinje v Zidanem Mostu. V zajezitvi so meritve temperature vode pokazale na opazno toplejši tok ob levem bregu, kar se kvalitativno ujema z ocenjenim vplivom dotoka Savinje, ki v poletnih mesecih segreva Savo (Rajar et al., 1998).

Vertikalne temperaturne gradiente smo zabeležili tudi v meritvah v avgustu 1998 na mostu Vrhovo, 680 m pred pregrado.

(HMZ, 1994; 1997a).

After the impoundment in 1994 the quality changes of the Sava River in the Vrhovo Impoundment were monitored by physio-chemical and biological analyses. The physio-chemical control of the quality of the impounded Sava River between 1995 and 1997 was performed by the Institute of Sanitary Engineering (Rismal, 1997b).

The results of the measurements in 1995 and 1996 indicated only small, hardly noticeable consequences in the impounded water. Owing to unfinished construction works in the impounded area, the Vrhovo HEPP was not in permanent operation during this time. The operation was stabilised during the second part of 1996.

A quick review of temperature measurements at the sampling points in the period between 1995 and 1997 shows that the temperature conditions in single profiles of the Vrhovo Impoundment were homogeneous. This indicates that thermal stratification, characteristic of natural lakes, does not appear in the Vrhovo Impoundment.

In 1995 and 1997 the Institute for Hydraulic Research in Ljubljana performed six 24-hour measurements of water temperature in five cross-sections in the Vrhovo Impoundment. The measurements were performed for the purpose of determining the situation after the impoundment. In two summer measurements, vertical and horizontal temperature stratifications were found. The vertical temperature gradients were the result of heat exchange on the surface of the impoundment. Horizontal gradients resulted from the incomplete mixing of the cooling water from the Trbovlje TET 2 or the inflow of the Savinja in Zidani Most. The measurements of the water temperature in the impoundment showed a significantly warmer water current on the left bank, which was in quantitative agreement with the estimated influence of the Savinja tributary which warms up the Sava River during the summer months (Rajar et al., 1998).

Vertical temperature gradients were also noted in the measurements performed on the Vrhovo Bridge in August, 1998, 680 m before

Vsekakor gre za meritve v obdobju vročega, stabilnega poletnega vremena. Meritve temperature vode, pH, električne prevodnosti, raztopljenega kisika, nasičenosti s kisikom in redoks potenciala so bile izvedene s sondo Hydrolab po vertikali v sredini profila.

the river dam. The measurements were made in stable hot summer weather. Water temperature, pH, conductivity, dissolved oxygen, oxygen saturation and the redox potential were measured by Hydrolab multiprobe along the vertical in the middle of the profile.

Preglednica 3. Rezultati meritev po vertikali na mostu Vrhovo, dne 13.8.1998.
Table 3. Rezultati meritev po vertikali na mostu Vrhovo, dne 13.8.1998.

Globina *Depth*	Čas *Time*	Temp. *Temp.*	*pH* *pH*	Elektroprevodnost *Conductivity*	O_2 O_2	O_2 O_2	Redoks *Redox*
[m]	[hh:mm:ss]	[°C]	[-]	[µS/cm]	[% nasičenosti] [*% saturation*]	[mg/l]	[mV]
0	10:25:59	22,64	8,1	417	89	7,7	393
0,5	10:16:06	22,38	8,1	418	89	7,7	372
1	10:17:11	21,89	8,1	416	88	7,7	380
2	10:18:11	21,63	8,1	417	88	7,8	384
3	10:18:53	21,41	8,1	416	88	7,8	387
4	10:19:28	21,15	8,1	413	85	7,5	391
5	10:20:03	21,10	8,0	412	83	7,4	393
6	10:20:31	21,00	8,0	413	79	7,1	396
7	10:21:17	20,98	7,9	413	74	6,6	398
8	10:22:01	20,91	7,9	415	69	6,2	402
9	10:22:34	20,87	7,9	414	68	6,1	403
10	10:23:49	20,81	7,8	416	60	5,3	406

Meritve v preglednici 3 kažejo, da nastopajo po vertikali temperaturni gradienti. Vendar pa ne gre za izrazito temperaturno slojevitost, značilno za jezera, kjer je za vmesni zaporni sloj značilen hiter padec temperature v sorazmerno ozkem vmesnem pasu. Temperaturni gradienti so višji v zgornjem 4-metrskem sloju vode, v spodnjem 6-metrskem sloju vode pa so neznatni.

Koncentracija raztopljenega kisika je tako rekoč konstantna v zgornjem 3-meterskem sloju. Z nadaljnjim večanjem globine pa se koncentracija kisika manjša, pri dnu akumulacije je izmerjena koncentracija raztopljenega kisika 5,3 mg(O_2)/l.

Združba rastlinskega planktona kaže, da so življenjske razmere v akumulaciji ugodne za razvoj vrst, ki hitro izkoristijo ugodne razmere (hranila, svetlobo, manjši pretok).

The measurements in Table 3 show that there appear to be vertical temperature gradients. However, it is not a matter of the explicit temperature stratification typical of lakes where a rapid decrease in temperature appears in a rather narrow intermediate layer. Temperature gradients are higher in the upper 4-meters of the water; in the lower 6-meters they are insignificant.

The concentration of dissolved oxygen was practically constant in the upper 3 meters and it fell with increasing depth. At the bottom, the measured concentration of dissolved oxygen was 5.3 mg(O_2)/l.

The appearance of phytoplankton showed that vital conditions in the impoundment are favourable for the growth of species, which rapidly take advantage of good conditions (nutrients, light, smaller discharge).

3. TEORETIČNE OSNOVE MATEMATIČNIH MODELOV

3.1 SPLOŠNO O MODELIRANJU

Dogajanja v naravi so prezapletena, da bi jih lahko opisali brez določenih večjih ali manjših poenostavitev. Ena od možnosti je, da si pri tem pomagamo z matematičnimi modeli, v katere vnesemo večje ali manjše poenostavitve realnega dogajanja v naravi.

Matematični modeli temeljijo na kvantifikaciji razmerij med specifičnimi parametri in spremenljivkami pri ponazarjanju (simulaciji) naravnih procesov. Zaradi tega so ti modeli abstraktni in ne pokažejo veliko v smislu povezave z realnimi razmerami, vendar pa pokažejo vpogled v funkcionalne odvisnosti med vzroki in posledicami v realnih razmerah. Tako lahko zelo hitro generiramo veliko podatkov in različne situacije za določen problem. Model lahko uporabljamo za napovedovanje procesov šele potem, ko je umerjen in verificiran. Kombinacija meritev na terenu in matematičnega modeliranja je zelo učinkovita metoda za preučevanje kakovosti voda (Rajar, 1997).

3.2 MATEMATIČNO MODELIRANJE KAKOVOSTI VODA

Gospodarjenje z vodnim bogastvom posameznih povodij in v celoti je neločljivo povezano tako z razpoložljivimi količinami kot s kakovostjo vodnih zalog. Zato mora izkoriščanje voda sloneti na poznavanju obstoječih hidroloških in kakovostnih lastnostih voda ter na napovedovanju sprememb, ki jih bodo načrtovani posegi povzročili v količinskem in kakovostnem pogledu (Rismal, 1985).

Hidrološki in hidravlični matematični modeli, s katerimi je mogoče predvideti količinske spremembe vodnega režima zaradi načrtovanih hidrotehničnih in drugih posegov, so v naši hidrotehnični praksi že vrsto let nepogrešljivo sredstvo za načrtovanje in

3. THEORETICAL BASE OF MATHEMATICAL MODELS

3.1 GENERALLY ON MODELLING

The activities in nature are too complicated to be described without defining some sort of simplification. One of the possibilities is to make use of mathematical models, implemented by some larger or smaller simplification of real activities in nature.

Mathematical models are based on the quantification of the relationships between specific parameters and variables with the illustration of natural processes. For this reason, models are abstract and do not show much in the sense of their relationship to actual conditions; however, they give an insight into the functional dependencies between cause and effect in actual conditions. In this way we can very quickly generate a large number of data and different situations for a specific problem. The model can be used for the prediction of processes only after it has been calibrated and verified. The combination of field measurements and mathematical modelling is a very effective method to study water quality (Rajar, 1997).

3.2 MATHEMATICAL MODELLING OF WATER QUALITY

Water resources management is inseparably connected with the available quantity, as well as the quality of water resources. For this reason, the exploitation of water must be based on the knowledge of the existing hydrological and quality characteristics of water and on the prediction of changes which will arise by the planned interventions in the quantitative and qualitative respects (Rismal, 1985).

Hydrological and hydraulic models make it possible to forecast quantitative changes in the water regime due to planned hydrotechnical and other interventions. In our hydrotecnical practise, they have been an indispensable tool for many years in the planning and management of the available water resources.

gospodarjenje z razpoložljivimi vodnimi zalogami. Bistveno manj pa se uporabljajo matematični modeli kakovosti voda, ki omogočajo prognozo sprememb kakovosti obravnavanih voda zaradi načrtovanih posegov. Vzrok za to je predvsem v dveh dejstvih:

– Problemi kakovosti voda so dobili svojo težo v vodnogospodarski problematiki šele v zadnjih desetletjih.
– Matematični modeli obravnavajo spremembe kakovosti voda s formulacijami, ki bolj ali manj točno ponazarjajo potek kakovostnih sprememb, ki so posledica fizikalnih, kemičnih in biokemičnih procesov v vodi. Razumljivo je, da z matematičnim zapisom poteka in vsebine zapletenih procesov, ki potekajo v vodi, ni mogoče docela ponazoriti. Zato matematičnih modelov kakovostnih procesov v vodnih telesih ne smemo razumeti kot docela natančnih posnetkov dejanskih procesov, temveč le kot poenostavitve, ki odkrivajo smernice ključnih kakovostnih sprememb, ki so odločilne za presojo kakovosti voda. Tak pristop pogosto povzroča neupravičeno nezaupanje v tovrstne modele, kar dokazujejo tudi svetovne izkušnje, ki potrjujejo upravičenost nadaljnjega razvoja tovrstnih modelov.

Bolj kompleksni večparametrski modeli kakovosti voda napovedujejo fizikalne, kemične in biološke medsebojne vplive mnogih komponent in organizmov, prisotnih v naravnih vodnih telesih. Ti modeli običajno zahtevajo več podatkov in računalniškega časa, ponujajo pa podrobnejše in bolj izčrpne informacije o količini in kakovosti voda. Pogosto za to vrsto modelov uporabljamo izraz *ekološki modeli*.

Mathematical models of water quality which make it possible to predict water quality changes after the planned interventions are, on the other hand, used much less frequently. The main reasons for this are:

– Water quality problems have become important water management problems only in recent decades.
– Mathematical models treat the changes in water quality with the expressions which illustrate, more or less accurately, the course of quality changes, which are the consequence of physical, chemical and biochemical processes in the water. It is understandable that the course and the content of the complicated processes in the water cannot be illustrated in detail with mathematical expressions. Therefore, mathematical models of water quality processes can not be understood as perfectly accurate imitations of real processes, but only as simplifications which uncover the guidelines for the main quality changes critical for water quality evaluation. Such an approach often causes unjustified distrust in these models. This has also been proved by world experience, which confirms the necessity for further development of these models.

The more complex multiparametric models of water quality predict physical, chemical and biological interactions of many components and organisms present in natural bodies of water. These models usually demand more data and computer time but they offer better, more exhaustive and detailed information on water quantity and quality. For these sorts of models, we frequently use the term *ecological models*.

4. MODEL QUAL2E

4.1 SPLOŠNO O MODELU

Model QUAL2E je značilen primer večparametrskega modela rečnih ekosistemov, ki je večstransko uporaben za modeliranje kakovosti površinskih voda. Lahko deluje kot stacionaren ali dinamičen model. Stacionaren model se lahko uporablja za preučevanje vpliva odpadnih voda (količina, kakovost in lokacija) na kakovost odvodnika ali za identifikacijo količinskih in kakovostnih lastnosti razpršene obremenitve z odpadnimi vodami, kot sestavni del programa terenskih meritev. Z uporabo dinamičnega modela pa se lahko modelirajo tudi vplivi dnevnih sprememb meteoroloških podatkov na kakovost voda (primarno raztopljeni kisik in temperatura) ali raziskujejo dnevna variiranja v koncentraciji raztopljenega kisika, kot posledica rasti alg in respiracije (Brown & Barnwell, 1987).

Model lahko simulira do 15 parametrov kakovosti tekočih voda: raztopljeni kisik, biokemijsko potrebo po kisiku, temperaturo, biomaso alg kot klorofil a, organski dušik kot *N*, amonij kot *N*, nitrite kot *N*, nitrate kot *N*, organski fosfor kot *P*, raztopljeni fosfor kot *P*, koliformne bakterije, poljubno neobstojno komponento v vodi, obstojne komponente v vodi.

Model je uporaben za vodotoke, ki so dobro premešani. Zahteva se, da so glavni transportni mehanizmi, advekcija in disperzija, značilni vzdolž glavne smeri toka.

Prvi korak v postopku modeliranja sistema je razdelitev rečnega sistema na odseke, ki predstavljajo neprekinjene odseke reke s konstantnimi hidravličnimi lastnostmi. Vsak odsek je nato nadalje razdeljen na računske elemente enake dolžine. Hidravlični podatki, reakcijski hitrostni koeficienti, začetni pogoji in podatki o porastu pretoka so konstantni za vse računske elemente znotraj odseka.

4. THE QUAL2E MODEL

4.1 GENERALLY ON THE MODEL

The QUAL2E Model is a typical multiparametric model for river ecosystems, which is universally useful for modelling surface water quality. It can operate as a steady state or as a dynamic model. The steady state model can be used to study the impact of waste loads (magnitude, quality and location) on instream water quality. It can also be used in conjunction with a field sampling program to identify the magnitude and quality characteristics of non point source waste loads. By operating the model dynamically, the user can study the effects of diurnal variations in meteorological data on water quality (primarily dissolved oxygen and temperature), and also the diurnal dissolved oxygen variations due to algae growth and respiration (Brown & Barnwell, 1987).

The model is capable of modelling up to 15 water quality constituents: dissolved oxygen, carbonaceous biochemical oxygen demand, temperature, algae as chlorophyll a, components of the nitrogen cycle as nitrogen (organic nitrogen, ammonium, nitrite, and nitrate), components of the phosphorus cycle as phosphorus (organic phosphorus and dissolved inorganic phosphorus), coliforms, an arbitrary nonconservative constituent, and three arbitrary conservative constituents.

The model is applicable to well-mixed streams. It assumes that the major transport mechanisms, advection and dispersion, are significant only along the main direction of the flow.

The first step in the process of modelling is to divide a river system into reaches that represent a continual river reach with constant hydraulic properties. Each reach is then divided into computational elements, each of the same length. The hydraulic data, reaction coefficients, initial conditions and data on flow augmentation are constant for all computational elements inside the reach.

4.2 MATEMATIČNE ZVEZE

Temeljna enačba, ki jo rešuje QUAL2E, je enodimenzijska enačba advekcijsko-disperzijskega masnega transporta, ki je numerično integrirana v prostoru in času za vsako komponento kakovosti voda. Enačba vključuje efekte advekcije, disperzije, razredčitve, reakcije in medsebojne vplive med komponentami ter zunanje in notranje izvore ali ponore. Zapis enačbe za katero koli komponento C:

4.2 MATHEMATICAL RELATIONSHIPS

The basic equation solved by QUAL2E is the one-dimensional advection-dispersion mass transport equation, which is numerically integrated over space and time for each water quality constituent. This equation includes the effects of advection, dispersion, dilution, constituent reactions and interactions, and sources and sinks. For any constituent C, this equation can be written as:

$$\frac{\partial M}{\partial t} = \frac{\partial \left(A_X \cdot D_L \cdot \frac{\partial C}{\partial x} \right)}{\partial x} dx - \frac{\partial \left(A_X \cdot \overline{u} \cdot C \right)}{\partial x} dx + \left(A_X \cdot dx \right) \frac{dC}{dt} + S \tag{1}$$

M masa [g].
x razdalja [m].
t čas [s].
C koncentracija komponente C [g/m^3].
A_x prečni prerez [m^2].
D_L disperzijski koeficient [m^2/s].
$\overline{u}$ povprečna hitrost [m/s].
S zunanji in notranji izvori ali ponori [g/s].

M mass [g].
x distance [m].
t time [s].
C concentration of constituent C [g/m^3].
A_x cross-sectional area [m^2].
D_L dispersion coefficient [m^2/s].
$\overline{u}$ mean velocity [m/s].
S external and internal sources or sinks [g/s].

Ker je $M = V \cdot C$ in če predpostavimo, da je pretok stalen, torej velja $\partial Q/\partial t = 0$ in nadalje $\partial V/\partial t = 0$, enačbo (1) preuredimo v enačbo (2):

Because $M = V \cdot C$, and if we assume steady flow, i.e.: $\partial Q/\partial t = 0$, and the term $\partial V/\partial t = 0$, Equation (1) is rearranged in Equation (2):

$$\frac{\partial C}{\partial t} = \frac{\partial \left(A_x \cdot D_L \cdot \frac{\partial C}{\partial x} \right)}{A_x \cdot \partial x} - \frac{\partial \left(A_x \cdot \overline{u} \cdot C \right)}{A_x \cdot \partial x} + \frac{dC}{dt} + \frac{S}{V} \tag{2}$$

Model QUAL2E predpostavi, da je hidravlični režim stalen, kar pomeni, da je $\partial Q/\partial t = 0$, zato lahko hidrološko bilanco za računski element zapišemo:

The model QUAL2E assumes that the stream hydraulic regime is steady, i.e.: $\partial Q/\partial t = 0$; therefore, the hydrologic balance for a computational element can be written as:

$$\left(\frac{\partial Q}{\partial t} \right) = \left(Q_x \right)_i \tag{3}$$

kjer je $(Q_x)_i$ vsota zunanjih vtokov in/ali odtokov v ta element. Ko je enačba (3) rešena za Q, druge hidravlične lastnosti rečnih

where $(Q_x)_i$ is the sum of the external inflows into and/or withdrawals out of that element. Once Equation (3) has been solved for Q, the odsekov določimo funkcionalno, kjer model računa hitrost po enačbi $\bar{u} = a \cdot Q^b$ in globino po enačbi $h = \alpha \cdot Q^\beta$, kjer so a, b, α in β empirične konstante, ki so običajno določene iz pretočnih krivulj.

V nadaljevanju podajamo matematične zveze, ki opisujejo individualne reakcije in medsebojne zveze med komponentami. Členov, ki predstavljajo advekcijo in disperzijo, v naslednjih enačbah ne prikazujemo, čeprav so vključeni v model.

Model predpostavlja proporcionalnost koncentracije klorofila s koncentracijo fitoplanktonske biomase alg, kar je opisano s preprosto zvezo:

other hydraulic characteristics of the stream segments can be determined by equations where the mean velocity is calculated according to equation $\bar{u} = a \cdot Q^b$ and the stream depth is calculated according to equation $h = \alpha \cdot Q^\beta$, where a, b, α and β are empirical constants, usually determined from stage-discharge rating curves.

The mathematical relationships that describe individual reactions and interactions are presented in the following paragraphs. The terms that represent advection and dispersion are not shown in the following equation, although they are incorporated in the model.

Chlorophyll a is considered to be directly proportional to the concentration of the phytoplanktonic algal biomass, which is described by the following simple relationship:

$$chl\ a = \alpha_0 \cdot A \tag{4}$$

chl a koncentracija klorofila a [μg/l].
A koncentracija biomase alg [mg(*A*)/l].
α_0 delež klorofila a v biomasi alg (podatek, preglednica 4) [μg(*chl a*)/mg(*A*)].

chl a chlorophyll a concentration [μg/l].
A algal biomass concentration [mg(*A*)/l].
α_0 ratio of chlorophyll a to algal biomass (data, Table 4) [μg(*chl a*)/mg(*A*)].

Produkcija biomase alg, ki variira po času, je odvisna od hitrosti rasti alg, hitrosti respiracije alg (ali specifične izgube), hitrosti usedanja alg in srednje globine toka, vse na določeni lokaciji *x* v rečnem profilu.

The production of algal biomass that varies in time is dependent on the growth, respiration, and settling rates of algae, and the average depth of the flow, all on a specific location *x* in the river profile.

$$\frac{dA}{dt} = \mu \cdot A - \rho \cdot A - \frac{\sigma_1}{h} \cdot A \tag{5}$$

t čas [dan].
μ specifična hitrost rasti alg, ki je temperaturno odvisna (podatek, preglednica 4) [dan^{-1}].
ρ hitrost respiracije alg, temperaturno odvisna (podatek, preglednica 4) [dan^{-1}].
σ_1 hitrost usedanja alg, temperaturno odvisna (podatek, preglednica 4) [m/dan].
h srednja globina toka [m].

t time [day].
μ the specific growth rate of algae, which is temperature dependent (data, Table 4) [day^{-1}]..
ρ the respiration rate of algae, which is temperature dependent (data, Table 4) [day^{-1}].
σ_1 the settling rate for algae, which is temperature dependent (data, Table 4) [m/day].
h average depth [m].

Specifična hitrost rasti alg, hitrost respiracije alg ter hitrost usedanja alg so odvisne od temperature in bodo korigirane znotraj modela, kot vse druge spremenljivke sistema. Postopek bo prikazan kasneje.

Hitrost rasti alg je odvisna od temperature, količine hranil (*C*, *N*, *P*) in svetlobe. Model ponuja tri možnosti za opis medsebojnih vplivov omejitvenih faktorjev na kinetiko rasti alg. Za simulacije z modelom smo uporabili opcijo omejitvenega hranila, ki predpostavlja, da je hitrost rasti alg omejena s svetlobo in s hranilom z manjšim omejitvenim faktorjem. Ta formulacija posnema Liebigov zakon minimuma ob predpostavki, da je ogljik v izobilju, in ima obliko:

The specific growth, respiration and settling rates of algae, are known to be dependent on the temperature and are then corrected in the model, as are all other variables of the system. The procedure will be shown later.

The specific growth rate of algae is known to be dependent on the temperature, the availability of required nutrients (*C*, *N*, *P*) and light. The model is capable of modelling the interaction among these limiting factors in three different ways. For modelling simulations, the option of limiting the nutrients was used, which represents the growth rate of algae as limited by light and by nutrients with a smaller algal growth limitation factor. The following formulation mimics Liebig's Law of the minimum at presumption that carbon is in abundance:

$$\mu = \mu_{\max} \cdot (FL) \cdot \min(FN, FP) \qquad (6)$$

$\mu_{\max}$ maksimalna hitrost rasti alg (podatek, preglednica 4) [dan^{-1}].
FL omejitveni faktor svetlobe.
FN omejitveni faktor za dušik.
FP omejitveni faktor za fosfor.

$\mu_{\max}$ maximum specific algal growth rate (data, Table 4) [day^{-1}].
FL algal growth limitation factor for light.
FN algal growth limitation factor for nitrogen.
FP algal growth limitation factor for phosphorus.

Poskusi pri konstantni temperaturi in spreminjanju razpoložljive svetlobe so pokazali, da fotosinteza narašča do maksimalnega nivoja pri naraščajočem sevanju. Nadaljnje naraščanje sevanja pa vodi k fotoinhibiciji in posledično k upadanju fotosinteze. Za odvisnost rasti alg od svetlobe model ponuja tri možnosti izračuna omejitvenega faktorja svetlobe *FL*. V simulacijah z modelom smo uporabili *Monodovo funkcijo:*

Experiments at constant temperature and changing available light showed an increasing rate of photosynthesis with increasing light intensity up to the maximum value. Further increase in light intensity leads to photo-inhibition, and, consequently, to a decreasing rate of photosynthesis. The model recognises three options for computing the algal growth limitation factor for light *FL*. In the simulations with the model, *the Monod function* was used:

$$FL = \frac{I(h)}{K_L + I(h)} \qquad (7)$$

$I(h)$ intenziteta svetlobe na globini h [ly/dan].
K_L konstanta Monodove enačbe za svetlobo; intenziteta svetlobe, kjer je hitrost rasti 50 odstotkov maksimalne hitrosti rasti, temperaturno odvisna (podatek, preglednica 4) [ly/dan].
h globina toka [m].

$I(h)$ light intensity at a given depth h [ly/day].
K_L constant of Monod equation for light; light intensity at the velocity of growth 50% of the maximal velocity of growth, temperature dependent (data, Table 4) [ly/day].
h depth [m].

Prodiranje (ali inverzno njeno upadanje) vstopajoče sončne energije opisuje model z Beer-Lambertovim zakonom, po katerem se intenziteta svetlobe eksponentno spreminja z globino:

Penetration of the incoming solar energy is described by the Beer-Lambert Law, according to which the light intensity changes exponentially with the depth:

$$I(h) = I_0 \cdot e^{-\lambda \cdot h} \tag{8}$$

I_0 intenziteta svetlobe na površini [ly/dan].
λ koeficient upadanja svetlobe [m^{-1}].

I_0 surface light intensity [ly/day].
λ light extinction coefficient [m^{-1}].

Intenziteta sončne energije, ki doseže zemeljsko površino, znaša okoli 0,56 kW/m^2. Dejanska intenziteta, ki prispe na vodno gladino, je odvisna od letnega časa, pokritosti z oblaki in reflektivnih lastnosti vode.

Velikost koeficienta upadanja svetlobe v vodnih telesih (λ) je odvisna od načina, kako koeficient definiramo. Simulacije daljših obdobij zahtevajo dinamičen izračun λ z upoštevanjem sezonskih sprememb motnosti vode, ki jih povzročajo vodne rastline in suspendirani delci v vodi. λ je odvisen od vsebnosti anorganskih trdnih delcev, delcev detritusa in nivoja fitoplanktona (Krajnc, 1994a).

Enačbo (8) vstavimo v enačbo (7) in jo integriramo po globini vode *h*. Rezultat integriranja je globinsko povprečena vrednost *FL*:

The intensity of solar radiation that reaches the surface of the earth is approximately 0.56 kW/m^2. The real light intensity at the surface is a function of location, time of year, meteorological conditions and the reflective properties of water.

The value of light extinction coefficient (λ) depends on the way it is formulated. In long term simulations, λ should be computed dynamically to account for seasonal variations in turbidity due to the shading of algae or variations in suspended solid load. λ depends on the amount of inorganic particles, particles of detritus and the phytoplankton level (Krajnc, 1994a).

Equation (8) is substituted into Equation (7) and integrated over depth *h*. The depth-averaged light attenuation factor *FL* is obtained:

$$FL = \frac{1}{\lambda \cdot h} \ln\left(\frac{K_L + I_0}{K_L + I_0 \cdot e^{-\lambda \cdot h}} \right) \tag{9}$$

Za simulacijo stacionarne rasti alg potrebujemo v računih srednje vrednosti omejitvenega faktorja za svetlobo FL_{sr} za dnevni cikel, ki jo izračunamo po enačbi (10). Vrednosti za I_{tot} in N_d priskrbi uporabnik modela.

Steady state algal simulations require a computation of the average value of FL_{sr}, the algal growth attenuation factor for light, over the diurnal cycle, which is computed according to Equation (10). Values I_{tot} and N_d are supplied by the user.

$$FL_{sr} = AFACT \cdot f \cdot FL_1 \tag{10}$$

$$FL_1 = \frac{1}{\lambda \cdot h} \cdot \ln\left(\frac{K_L + \bar{I}_{alg}}{K_L + \bar{I}_{alg} \cdot e^{-\lambda \cdot h}} \right) \tag{11}$$

$$\bar{I}_{alg} = \frac{I_{tot}}{N_d} \tag{12}$$

FL_{sr} omejitveni faktor svetlobe, prilagojen s trajanjem dneva in metodo povprečenja
$AFACT$ faktor povprečenja svetlobe, da zagotovimo podobnost med izračunom, ki uporablja srednjo dnevno vrednost sončnega obsevanja in izračunom, ki uporablja srednje urne vrednosti *FL* (obseg vrednosti od 0,85 do 1,00)
f delež ur dnevne svetlobe v 24 urah
FL_1 omejitveni faktor svetlobe, ki temelji na srednji dnevni intenziteti svetlobe
$\bar{I}_{alg}$ srednja dnevna intenziteta fotosintetsko aktivne svetlobe (podatek) [ly/dan].
I_{tot} celotno dnevno fotosintetsko aktivno sončno obsevanje [ly].
N_d število ur dnevne svetlobe [h].

FL_{sr} algae growth attenuation factor for light, adjusted for daylight hours and averaging method
$AFACT$ light averaging factor, used to provide similarity between calculations using a single average daily value of solar radiation and computations using the average of hourly values of FL (range of values is between 0.85 and 1.00).
f fraction of daylight hours.
FL_1 growth attenuation factor for light, based on daylight average light intensity.
$\bar{I}_{alg}$ daylight average, photosynthetically active, light intensity (data) [ly/day].
I_{tot} total daily photosynthetically active solar radiation [ly].
N_d number of daylight hours per day [h].

Odvisnost rasti alg od vsebnosti hranil računa model QUAL2E s pomočjo omejitvenega faktorja rasti alg za dušik *FN* in omejitvenega faktorja rasti alg za fosfor *FP*, ki sta definirana z Monodovim izrazom:

The dependence of algal growth on the availability of nutrients is calculated by the help of the algal growth limitation factors for nitrogen (*FN*) and for phosphorus (*FP*), which are defined by the Monod expressions:

$$FN = \frac{N_e}{N_e + K_N} \tag{13}$$

$$FP = \frac{P_2}{P_2 + K_P} \tag{14}$$

N_e efektivna lokalna koncentracija razpoložljivega anorganskega dušika [mg(*N*)/l].
K_N konstanta Monodove enačbe za dušik (podatek, preglednica 4) [mg (*N*)/l].
K_P konstanta Monodove enačbe za fosfor (podatek, preglednica 4) [mg(*P*)/l].
P_2 lokalna koncentracija raztopljenega anorganskega fosforja (ortofosfata) [mg(*P*)/l].

N_e effective local concentration of available inorganic nitrogen [mg(*N*)/l].
K_N Monod equation constant for nitrogen (data, Table 4) [mg(*N*)/l].
K_P Monod equation constant for phosphorus (data, Table 4) [mg(*P*)/l].
P_2 local concentration of inorganic dissolved phosphorus (orthophosphate) [mg(*P*)/l].

Model predpostavlja, da alge uporabljajo kot vir anorganskega dušika amonij in/ali nitrat. Efektivna koncentracija razpoložljivega dušika je podana z izrazom:

Algae are assumed to use ammonium and/or nitrate as a source of inorganic nitrogen. The effective concentration of the available nitrogen is given by:

$$N_e = N_1 + N_3 \tag{15}$$

N_1 koncentracija amonija (NH_4^+) [mg(N)/l].
N_3 koncentracija nitrata [mg(N)/l].

Empirični konstanti K_N in K_P imata funkcijo reguliranja hitrosti rasti alg, pri čemer upoštevata pomembnost faktorjev, ki omejujejo rast alg.

Transformacije dušika iz ene oblike v drugo so v modelu opisane z diferencialnimi enačbami od 16 do 20.

Bilanco organskega dušika določa enačba:

N_1 concentration of ammonium nitrogen (NH_4^+) [mg(N)/l].
N_3 concentration of nitrate nitrogen [mg(N)/l].

The empirical constants K_N and K_P are used to adjust the algal growth rate to account for those factors that can potentially limit algal growth.

The model describes the transformations of nitrogen from one form to another by differential Equations 16 to 20.

Organic nitrogen balance is defined by equation:

$$\frac{dN_4}{dt} = \alpha_1 \cdot \rho \cdot A - \beta_3 \cdot N_4 - \sigma_4 \cdot N_4 \qquad (16)$$

N_4 koncentracija organskega dušika [mg(N)/l].
β_3 koeficient hitrosti hidrolize organskega dušika v amonij, temperaturno odvisen (podatek, preglednica 4) [dan^{-1}].
α_1 delež dušika v biomasi alg (podatek, preglednica 4) [mg(N)/mg(A)].
σ_4 hitrost usedanja organskega dušika, temperaturno odvisna (podatek, preglednica 4) [dan^{-1}].

N_4 concentration of organic nitrogen [mg(N)/l].
β_3 rate constant for the hydrolysis of organic N to ammonium, temperature dependent (data, Table 4) [day^{-1}].
α_1 fraction of algal biomass that is nitrogen (data, Table 4) [mg(N)/mg(A)].
σ_4 rate coefficient for organic nitrogen settling, temperature dependent (data, Table 4) [day^{-1}].

Za transformiranje amonija velja enačba:

The transformation of ammonium is determined by equation:

$$\frac{N_1}{dt} = \beta_3 \cdot N_4 - \beta_1 \cdot N_1 + \frac{\sigma_3}{h} - F_1 \cdot \alpha_1 \cdot \mu \cdot A \qquad (17)$$

$$F_1 = \frac{P_N \cdot N_1}{P_N \cdot N_1 + (1 - P_N) \cdot N_3} \qquad (18)$$

β_1 koeficient hitrosti biološke oksidacije amonija, temperaturno odvisen (podatek, preglednica 4) [dan^{-1}].
σ_3 hitrost sproščanja amonija z dna, temperaturno odvisna (podatek, preglednica 4) [mg(N)/m^{2}dan].
F_1 delež amonija kot vir anorganskega dušika za alge.
P_N preferenčni faktor za amonij (podatek, preglednica 4).

β_1 rate constant for the biological oxidation of ammonium, temperature dependent (data, Table 4) [day^{-1}].
σ_3 benthos source rate for ammonium, temperature dependent (data, Table 4) [mg(N)/m^{2}day].
F_1 share of algal nitrogen uptake from ammonium pool.
P_N preference factor for ammonium nitrogen (data, Table 4).

Za koncentracijo nitritnega dušika velja:

The concentration of nitrite nitrogen is given by:

$$\frac{dN_2}{dt} = \beta_1 \cdot N_1 - \beta_2 \cdot N_2 \qquad (19)$$

N_2 koncentracija nitrita[mg(N)/l].
β_2 koeficient hitrosti biološke oksidacije NO_2^- v NO_3^- (podatek, preglednica 4) [dan^{-1}].

N_2 concentration of nitrite nitrogen [mg(N)/l].
β_2 rate constant for the biological oxidation of NO_2^- to NO_3^- (data, Table 4) [day^{-1}].

Koncentracijo nitrata model izračuna po enačbi (20):

The concentration of nitrate nitrogen is computed according to Equation (20):

$$\frac{dN_3}{dt} = \beta_2 \cdot N_2 - (1 - F) \cdot \alpha_1 \cdot \mu \cdot A \qquad (20)$$

Model ima zmožnost upoštevati inhibicijo nitrifikacije pri nizkih vsebnostih raztopljenega kisika z izračunom korekcijskega faktorja hitrosti nitrifikacije z enačbo prvega reda:

The model has the capability of inhibiting the rate of nitrification at low values of dissolved oxygen by computing an inhibition correction factor:

$$CORDO = 1 - e^{(-KNITRF \cdot O)} \qquad (21)$$

CORDO korekcijski faktor hitrosti nitrifikacije.
KNITRF koeficient inhibicije nitrifikacije prvega reda [mg/l].
O koncentracija raztopljenega kisika [mg/l].

CORDO nitrification rate correction factor.
KNITRF first order nitrification inhibition coefficient [mg/l].
O dissolved oxygen concentration [mg/l].

Korekcijski faktor, ki ima vrednost od 0 do 1, se nato uporabi za izračun zmanjšanih konstant hitrosti oksidacije amonija ($\beta_{1,inhib}$) in hitrosti oksidacije nitrita ($\beta_{2,inhib}$), kot sledi:

The correction factor with its value between 0 and 1 is then applied for computing the reduced rate constants of ammonium oxidation ($\beta_{1,inhib}$) and nitrite oxidation ($\beta_{2,inhib}$) by:

$$\beta_{1,inhib} = CORDO \cdot \beta_1 \qquad (22)$$

$$\beta_{2,inhib} = CORDO \cdot \beta_2 \qquad (23)$$

Fosforjev cikel je v mnogih pogledih podoben dušikovemu. Z odmiranjem alg se generira organski fosfor. Ta se nato spremeni v raztopljeno anorgansko obliko, ki jo lahko alge uporabijo za primarno produkcijo. Transformacije fosforja iz ene oblike v drugo ponazarjata diferencialni enačbi 24 in 25:

In many respects the phosphorus cycle operates like the nitrogen cycle. Organic forms of phosphorus are generated by the death of algae, then it converts to the dissolved inorganic state, where it is available to algae for primary production. The transformations of phosphorus from one form to another are described by differential Equations 24 and 25:

$$\frac{dP_1}{dt} = \alpha_2 \cdot \rho \cdot A - \beta_4 \cdot P_1 - \sigma_5 \cdot P_1 \qquad (24)$$

P_1 koncentracija organskega fosforja [mg(P)/l].
α_2 delež fosforja v biomasi alg (podatek, preglednica 4) [mg(P)/mg(A)].
β_4 koeficient hitrosti razgradnje organskega fosforja, temperaturno odvisen (podatek, preglednica 4) [dan^{-1}].
σ_5 hitrost usedanja organskega fosforja, temperaturno odvisna (podatek, preglednica 4) [dan^{-1}].

P_1 concentration of organic phosphorus [mg(P)/l].
α_2 fraction of algal biomass that is phosphorus (data, Table 4) [mg(P)/mg(A)].
β_4 organic phosphorus decay rate, temperature dependent (data, Table 4) [day^{-1}].
σ_5 organic phosphorus settling rate, temperature dependent (data, Table 4) [day^{-1}].

$$\frac{dP_2}{dt} = \beta_4 \cdot P_1 + \frac{\sigma_2}{h} - \alpha_2 \cdot \mu \cdot A \qquad (25)$$

P_2 koncentracija raztopljenega anorganskega fosforja (ortofosfat) [mg(P)/l].
σ_2 hitrost sproščanja raztopljenega anorganskega fosforja z dna, temperaturno odvisna (podatek, preglednica 4) [mg(P)/m^{2}dan].

P_2 concentration of inorganic or dissolved phosphorus (orthophosphate) [mg(P)/l].
σ_2 benthos source rate for the dissolved phosphorus, temperature dependent (data, Table 4) [mg(P)/m^{2}day].

Za opis končne ogljikove biokemijske potrebe po kisiku model predpostavlja reakcijo prvega reda. Uporabljena funkcija biokemijske potrebe po kisiku (BPK^C) upošteva tudi dodatno odstranitev *BPK* zaradi sedimentacije, izpiranja (odplavljanja) in flokulacije, ki ne kažejo potrebe po kisiku:

The model assumes a first order reaction to describe the deoxygenation of the ultimate carbon in the stream. The *BOD* function as expressed in the model (BOD^C) also takes into account the additional *BOD* removal due to sedimentation, erosion and flocculation, which do not exert an oxygen demand:

$$\frac{dBPK^C}{dt} = -K_1 \cdot BPK^C - K_3 \cdot BPK^C \qquad (26)$$

BPK^C končna biokemijska potreba po kisiku za razgradnjo ogljikovih spojin [mg/l].
K_1 koeficient hitrosti razgradnje ogljikovih spojin, temperaturno odvisen (podatek, preglednica 4) [dan^{-1}].
K_3 hitrost izgubljanja BPK^C zaradi usedanja, temperaturno odvisna (podatek, preglednica 4) [dan^{-1}].

BOD^C concentration of ultimate carbonaceous biochemical oxygen demand [mg/l].
K_1 carbonaceous deoxygenation rate constant, temperature dependent (data, Table 4) [day^{-1}].
K_3 rate of loss of BOD due to settling, temperature dependent (data, Table 4) [day^{-1}].

Model praviloma simulira končno (celotno) biokemijsko potrebo po kisiku, uporabniku pa je na voljo tudi simulacija 5-dnevne biokemijske potrebe po kisiku. Enačba povezave se glasi:

Generally the model simulates the ultimate BOD. However, the user may choose to use 5-day input and output BOD values. The conversion equation is:

$$BPK_5^C = BPK^C \cdot \left(1 - e^{5 \cdot KBPK}\right) \tag{27}$$

KBPK koeficient pretvorbe BPK^C v BPK_5^C (podatek; 0,23 dan^{-1}) [dan^{-1}].

KBPK conversion rate coefficient for BOD^C into BOD_5^C (data; 0,23 day^{-1}) [day^{-1}].

Bilanca kisika v vodotoku je odvisna od sposobnosti vodotoka za reaeracijo. Ta sposobnost je funkcija advekcijskih in difuzijskih procesov v sistemu ter notranjih virov in odtokov kisika. Poleg atmosferske reaeracije sta glavna vira kisika produkcija kisika s fotosintezo in raztopljeni kisik v dotokih v sistem. Odtoke raztopljenega kisika pa predstavljajo biokemijska oksidacija ogljikovih in dušikovih organskih snovi, poraba kisika dna (bentične plasti) in kisik, potreben za respiracijo (dihanje) alg. Poraba raztopljenega kisika za dihanje ostalih organizmov je zanemarljiva. Hitrost spreminjanja vsebnosti raztopljenega kisika opisuje diferencialna enačba:

The oxygen balance in a stream system depends on the capacity of the stream to reaerate itself. This capacity is a function of the advection and diffusion processes occurring within the system and the internal sources and sinks of oxygen. The major sources of oxygen, in addition to atmospheric reaeration, are the oxygen produced by photosynthesis and the oxygen contained in the incoming flow. The sinks of dissolved oxygen include the biochemical oxidation of carbonaceous and nitrogenous organic matter, the benthic oxygen demand and the oxygen utilised by algae respiration. The oxygen utilised by the respiration of other organisms is negligible. The rate of change of dissolved oxygen is described by the differential equation:

$$\frac{dO}{dt} = K_2 \cdot (O_s - O) + (\alpha_3 \cdot \mu - \alpha_4 \cdot \rho) \cdot A - K_1 \cdot BPK^C - \frac{K_4}{h} - \alpha_5 \cdot \beta_1 \cdot N_1 - \alpha_6 \cdot \beta_2 \cdot N_2 \tag{28}$$

- O koncentracija raztopljenega kisika[mg/l].
- O_s nasičena koncentracija raztopljenega kisika pri lokalni temperaturi in tlaku (izračun po enačbi 29) [mg/l].
- α_3 hitrost produkcije kisika pri fotosintezi na enoto biomase alg (podatek, preglednica 4) [mg(*O*)/mg(*A*)].
- α_4 hitrost porabe kisika pri respiraciji na enoto biomase alg (podatek, preglednica 4) [mg(*O*)/mg(*A*)].
- α_5 hitrost porabe kisika na enoto oksidiranega amonija (podatek, preglednica 4) [mg(*O*)/mg(*N*)].
- α_6 hitrost porabe kisika na enoto oksidiranega nitrita (podatek, preglednica 4) [mg(*O*)/mg(*N*)].

- O dissolved oxygen concentration [mg/l].
- O_s saturation concentration of dissolved oxygen at the local temperature and pressure (calculation according to Equation 29) [mg/l].
- α_3 rate of oxygen production per unit of algal photosynthesis (data, Table 4) [mg(*O*)/mg(*A*)].
- α_4 rate of oxygen uptake per unit of algae respired (data, Table 4) [mg(*O*)/mg(*A*)].
- α_5 rate of oxygen uptake per unit of ammonium nitrogen (data, Table 4) [mg(*O*)/mg(*N*)].
- α_6 rate of oxygen uptake per unit of nitrite nitrogen oxidation (data, Table 4) [mg(*O*)/mg(*N*)].

K_2 hitrost reaeracije, temperaturno odvisna (podatek, preglednica 4) [dan^{-1}].
K_4 hitrost ploskovne porabe kisika dna (podatek, preglednica 4) [g/m^{2}dan].

Hitrost reaeracije se najbolj pogosto izraža kot funkcija globine vodotoka in hitrosti. Qual2E ponuja 8 možnosti za ocenjevanje ali vnos vrednosti hitrosti reaeracije. Za globoke, počasne predele rek se lahko reaeracija računa z uporabo formul za reke ali z uporabo formul za jezera. Najbolj primerna iz skupine za reke za takšne odseke reke je metoda O'Connor-Dobbins, čeprav je za zelo počasne odseke rek napovedana hitrost reaeracije od 0,01 do 0,05 dan^{-1} (Bowie et al., 1985).

Topnost kisika v vodi upada z naraščanjem temperature in koncentracije raztopljenih soli v vodi ter z upadanjem zračnega tlaka. Model uporablja naslednjo enačbo za izračun nasičene koncentracije kisika:

K_2 reaeration rate constant, temperature dependent (data, Table 4) [day^{-1}].
K_4 benthic oxygen uptake (data, Table 4) [g/m^{2}day].

The reaeration rate constant is most often expressed as the function of stream depth and velocity. Qual2E provides eight options for estimation or reading of the reaeration rate constant values. In deep, slowly moving regions of river, reaeration can be calculated by using a river formula or lake formula. The O'Connor Dobbins method is probably the most appropriate stream formula to use, although for very slowly moving river regions, the predicted reaeration coefficient can be between 0.01 and 0.05 day^{-1} (Bowie et al., 1985).

The solubility of dissolved oxygen in water decreases with the increase of temperature and a dissolved solids concentration, and a decrease in atmospheric pressure. The model uses a predictive equation for the saturation concentration of dissolved oxygen:

$$\ln O_s = -139{,}34410 + \left(1{,}575701 \cdot \frac{10^5}{T}\right) - \left(6{,}642308 \cdot \frac{10^7}{T^2}\right) + \left(1{,}243800 \cdot \frac{10^{10}}{T^3}\right) - \left(8{,}621949 \cdot \frac{10^{11}}{T^4}\right) \quad (29)$$

O_s nasičena koncentracija kisika pri tlaku 1 atm [mg/l].
T temperatura vode [K].

O_s equilibrium oxygen concentration at 1 atm [mg/l].
T water temperature [K].

Za nestandardni zračni tlak se koncentracija raztopljenega kisika pri nasičenosti korigira, če se računa toplotna bilanca, z enačbo:

For non-standard conditions of pressure, the equilibrium concentration of dissolved oxygen is corrected only when the temperature is modelled by the equation:

$$O_p = O_s \cdot P_a \cdot \left[\frac{(1 - P_{wv}/P_a)\cdot(1 - \phi \cdot P_a)}{(1 - P_{wv})\cdot(1 - \phi)}\right] \quad (30)$$

O_p nasičena koncentracija raztopljenega kisika pri nestandardnem zračnem tlaku [mg/l].
P_a zračni tlak [atm].
P_{wv} parcialen tlak vodnih par [atm], ki se izračuna po enačbi:

O_p equilibrium oxygen concentration at non-standard atmospheric pressure [mg/l].
P_a atmospheric pressure [atm].
P_{wv} partial pressure of water steam [atm], calculated by the following equation:

$$\ln P_{wv} = 11{,}8571 - (3840{,}70/T) - (216961/T^2) \quad (31)$$

$$\phi = 0{,}000975 - \left(1{,}426 \cdot 10^{-5} \cdot t\right) + \left(6{,}436 \cdot 10^{-8} \cdot t^2\right) \tag{32}$$

t temperatura [ºC].

Večina koeficientov v enačbah je odvisna od temperature. Vstopni podatki so vrednosti koeficientov pri 20 ºC, njihove vrednosti pri temperaturi, ki nastopa v sistemu, pa se izračunajo po enačbi:

t temperature [ºC].

The majority of rate coefficients are temperature dependent. These coefficients are input at 20 ºC and are then corrected to the local temperature of the system by the equation:

$$X_T = X_{20} \cdot \theta^{(T-20°)} \tag{33}$$

X_T vrednost koeficienta pri lokalni temperaturi T.
X_{20} vrednost koeficienta pri standardni temperaturi (20 ºC).
θ empirična konstanta za posamezen reakcijski koeficient.

Vrednosti θ lahko poda uporabnik modela, če tega ne stori, pa model uporabi svoje vrednosti.

X_T value of coefficient at local temperature T.
X_{20} value of coefficient at the standard temperature (20 ºC).
θ an empirical constant for each reaction coefficient.

The values of θ may be specified by the user. In the absence of the user specified values, the default values are employed.

4.3 UTEMELJITEV IZBIRE MODELA

Uporabo modela QUAL2E utemeljujemo z naslednjimi argumenti:

- Zadrževalni časi v akumulacijskem jezeru so sorazmerno kratki. Za najmanjši nizki obdobni pretok Save v Radečah (39,7 m^3/s) znaša izračunan zadrževalni čas 54,6 ur, za pretoke v velikosti 100 m^3/s, ki jo mora HE Vrhovo spuščati za zagotovitev potrebne količine hladilne vode za jedrsko elektrarno Krško, pa 23,4 ur.
- Enodimenzionalni model smo uporabili ob predpostavki, da dolge, ozke zajezitve lahko obravnavamo na enak način kot nezajezene vodotoke, to je s popolno vertikalno in horizontalno premešanostjo polutantov v prečnih profilih.
- Model se je že uporabljal v slovenskem prostoru za napoved sprememb kakovosti voda v prihodnjih zajezitvah hidroelektrarn, ni pa se še izvedla njegova potrditev na že obstoječi zajezitvi.

4.3 REASONING OF OUR CHOICE FOR THE MODEL

The use of the QUAL2E Model is based on the following arguments:

- Retention times in the impoundment are comparatively short. For the minimal low discharge within a period in the Radeče cross section (39.7 m^3/s) of the Sava River, the calculated retention time amounts to 54.6 h. For the discharge of 100 m^3/s, which must be released from the Vrhovo HEPP to assure the necessary quantity of cooling water for the Krško NE, the retention time amounts to 23.4 hours.
- A one dimensional model was used on the presumption that long narrow impoundments can be treated in the same way as unimpounded streams, i.e. with a complete vertical and horizontal mixing of the pollution in the cross-sectional profiles.
- The model has already been used in Slovenia to predict water quality changes in the planned impoundments for the HEPP, but its validation on an existing impoundment has not yet been performed.

4.4 TERENSKE MERITVE IN VHODNI PODATKI MODELA

4.4.1 Vzorčevanje

Za umerjanje matematičnega modela in kvantitativno opredelitev sprememb kakovosti Save v akumulaciji HE Vrhovo z matematičnim modelom QUAL2E je bilo treba opraviti meritve na vtoku in iztoku iz akumulacije. Za določitev kakovosti vode na vtoku v akumulacijo smo izvajali vzorčevanja triurnih povprečnih vzorcev in meritve za Savo v Suhadolu in za Savinjo v Velikem Širju. Za določitev kakovosti vode na iztoku iz akumulacije pa smo izvajali vzorčevanja in meritve na pregradi HE Vrhovo. Prvo vzorčevanje je potekalo od 16.9.1996 do 20.9.1996. Vnovično vzorčevanje, katerega namen je bil pridobiti dodatne podatke za validacijo modela, je bilo izvedeno avgusta 1998.

4.4.2 Vhodni podatki modela

Vhodne podatke modela predstavljajo pretoki na VP Hrastnik za Savo in pretoki na VP Veliko Širje za Savinjo, rezultati fizikalno kemijskih analiz (temperatura vode, koncentracija raztopljenega kisika, biokemijska potreba po kisiku, koncentracije klorofila a, organskega dušika, amonija, nitrita, nitrata, raztopljenega ortofosfata in koncentracija organskega fosforja) na zajemnem mestu Suhadol na Savi ter na zajemnem mestu Veliko Širje na Savinji, podatki o srednjih dnevnih vrednostih energije globalnega sončnega obsevanja in povprečne vrednosti trajanja svetlega dneva v Sloveniji.

4.4.3 Razdelitev modeliranega odseka Save na odseke in računske elemente

Razdelitev modeliranega odseka Save od Suhadola do pregrade HE Vrhovo na odseke in računske elemente predstavlja prvi korak v postopku modeliranja z modelom QUAL2E. Modelirali smo odsek reke Save v dolžini 9,88 km gorvodno od pregrade HE Vrhovo.

4.4. FIELD MEASUREMENTS AND INPUT DATA FOR THE MODEL

4.4.1 Sampling

For the model calibration and for the quantitative determination of water quality changes in the Vrhovo Impoundment using the QUAL2E mathematical model, measurements at the inflow into the impoundment and at the outflow from the impoundment had to be done. We designed the sampling of three hour average samples at the inflow into the impoundment (for the Sava River in Suhadol and for the Savinja River in Veliko Širje) and at the outflow from the impoundment (on the Vrhovo HEPP dam). The first sampling campaign was carried out from 16 September, 1996 to 20 September, 1996. With the intention of acquiring additional data for the model validation, another sampling campaign was carried out in August, 1998.

4.4.2 Input data for the model

The input data for the model were: the discharges at the Hrastnik Water Gauge Station on the Sava River and the discharges at the Veliko Širje Water Gauge Station on the Savinja River; the results of the physical-chemical analyses (water temperature, the concentration of dissolved oxygen, biochemical oxygen demand, chlorophyll a, concentrations of organic nitrogen, ammonium, nitrite, nitrate, dissolved orthophosphate and organic phosphorus) at the Suhadol sampling site on the Sava River and at the Veliko Širje sampling site on the Savinja River; the data on average daylight solar radiation and the number of daylight hours per day in Slovenia.

4.4.3 Divisions of the modelled reach of the Sava River into sub-reaches and computational elements

The first step in the process of modelling with the QUAL2E model was the division of the modelled reach of the Sava River from Suhadol to the Vrhovo River Dam, a total length of 9.88 km, into a number of sub-reaches and computational elements. It was

Razdelili smo ga na 26 odsekov različnih dolžin, ti pa so razdeljeni na računske elemente dolžine 130 m.

Hidravlične lastnosti rečnih odsekov smo določili funkcionalno. Za različne pretoke od 65 m^3/s do 150 m^3/s poznamo hitrosti in globine v prečnih profilih. Na podlagi tega smo z matematičnim programom NONLIN (Sherrod, 1992) izračunali empirične konstante a, b, α, β v enačbah $\bar{u} = a \cdot Q^b$ in $h = \alpha \cdot Q^\beta$ za posamezne odseke.

Vtok Savinje v Savo v Zidanem Mostu smo modelirali kot točkovni vnos.

4.4.4 Parametri modela

V modelu QUAL2E nastopajo v preglednici 4 opisani parametri. Parametri nimajo fiksne vrednosti, ampak se gibljejo znotraj določenega intervala vrednosti, ki so navedeni po Brownu in Barnwelu (1987).

4.5 ANALIZA OBČUTLJIVOSTI

Z analizo občutljivosti smo ugotavljali reakcijo modela na spremembe vrednosti parametrov v modelu. Analizo smo izvedli s sistematičnim spreminjanjem vrednosti enega od parametrov, ki smo jo povečali oziroma zmanjšali za 50 odstotkov, pri konstantnih vrednostih ostalih parametrov in pri konstantnih vhodnih spremenljivkah. Opazovali smo vpliv spreminjanja tega parametra na rezultate modela. Vrednosti parametrov, navedene v preglednici 4 v zadnjem stolpcu so bile uporabljene kot osnovne vrednosti, ki smo jih pri izvedbi analize občutljivosti modela povečali oziroma zmanjšali za 50 odstotkov.

Analizo občutljivosti smo izvedli za parametre modela, katerih interval vrednosti je velik. Ti parametri so α_0, β_1, β_2, β_3, β_4, μ_{max}, ρ, K_1, K_3, K_4, K_L, K_N, K_P, σ_1, σ_4 , σ_5, λ_0, λ_1, P_N.

divided into 26 sub-reaches of varying lengths and into computational elements, each being 130 meters long.

The hydraulic characteristics of the stream sub-reaches were determined in a functional form. For different discharges (Q) from 65 m^3/s to 150 m^3/s, the average velocity ($\bar{u}$) and depth (h) of the corresponding cross-sections were known. Based on this, empirical constants a, b, α, β in equations $\bar{u} = a \cdot Q^b$ and $h = \alpha \cdot Q^\beta$ for each reach, were calculated using the NONLIN Mathematical Programme (Sherrod, 1992).

Savinja is a tributary of the Sava River. It was modelled as a point source to the main stream of the Sava.

4.4.4 Model parameters

The QUAL2E Model contains many system parameters; they are shown in Table 4. The parameters do not have fixed values, but they range within the defined interval of values listed according to Brown & Barnwel (1987).

4.5 SENSITIVITY ANALYSIS

With the sensitivity analysis we established the relative sensitivity of the model predictions to changes in the values of the model parameters. The analysis was performed with the systematic changing of the values of a single parameter, enlarged or reduced by 50 percent, while all other parameters and input variables remained constant. We observed the impact of the changes in this parameter on the model results. The parameter values, listed in the last column in Table 4, were used as the basic values for the sensitivity analysis enlarged or reduced by 50 percent.

The sensitivity analysis was performed for the model parameters for which the range of values is large. These parameters are α_0, β_1, β_2, β_3, β_4, μ_{max}, ρ, K_1, K_3, K_4, K_L, K_N, K_P, σ_1, σ_4 , σ_5, λ_0, λ_1, P_N.

Preglednica 4: Opis parametrov modela Qual2E
Table 4. Qual2E Model parameter specification.

Oznaka v tekstu *Description*	Enota *Unit*	Interval vrednosti *Interval of values*	Izbrana vrednost za analizo občutljivosti *Selected value for sensitivity analysis*
α_0	μg(*chl a*)/mg(*A*)	10-100	**50**
α_1	mg(*N*)/mg(*A*)	0,07-0,09	**0,085**
α_2	mg(*P*)/mg(*A*)	0,01-0,02	**0,0135**
α_3	mg(O_2)/mg(*A*)	1,4-1,8	**1,6**
α_4	mg(O_2)/mg(*A*)	1,6-2,3	**1,95**
α_5	mg(O_2)/mg(*N*)	3,0-3,5	**3,5**
α_6	mg(O_2)/mg(*N*)	1,0-1,14	**1,07**
β_1	day^{-1}	0,1-1,0	**0,5**
β_2	day^{-1}	0,2-2,0	**1,0**
β_3	day^{-1}	0,02-0,4	**0,2**
β_4	day^{-1}	0,01-0,7	**0,36**
μ_{max}	day^{-1}	1,0-3,0	**2**
ρ	day^{-1}	0,05-0,5	**0,2**
K_1	day^{-1}	0,02-3,4	**0,23**
K_2	day^{-1}	0,0-100,0	**opcija 3 *option 3***
K_3	day^{-1}	-0,36-0,36	**0,1**
K_4	g(O_2)/m^2day	spremenljivka *variable*	**0,5**
K_L	ly/day	7,85-39,24	**34,56**
K_N	mg(*N*)/l	0,01-0,3	**0,15**
K_P	mg(*P*)/l	0,001-0,05	**0,02**
σ_1	m/day	0,15-1,8	**0,5**
σ_2	mg(*P*)/m^2day	spremenljivka *variable*	**0,0012**
σ_3	mg(*N*)/m^2day	spremenljivka *variable*	**0,0005**
σ_4	day^{-1}	0,001-0,1	**0,05**
σ_5	day^{-1}	0,001-0,1	**0,05**
λ_0	m^{-1}	spremenljivka *variable*	**1,7**
λ_1	m^{-1}(μg(*chl a*)/l)$^{-1}$	0,0066-0,0656	**0,005**
λ_2	m^{-1}(μg(*chl a*)/l)$^{-2/3}$	0,0541	**0**
P_N	-	0,0-1,0	**0,2**

Ugotovili smo smiselno odzivanje rezultatov modela na spreminjanje posameznih parametrov. Model na nobenega od obravnavanih parametrov ni preobčutljiv, ne odziva pa se na spreminjanje naslednjih parametrov: konstante Monodove enačbe za dušik (K_N), prednostnega faktorja za amonij (P_N), linearnega koeficienta samoosenčenja alg (λ_1).

Podrobnejši opis in grafična predstavitev rezultatov analize občutljivosti modela sta podana v magistrski nalogi (Cvitanič, 1998).

We established the logical response of the model results to the changes in the values of single parameters. The model is not too sensitive to any of the treated parameters, but it does not respond to changes in the values of the following parameters: constant of Monod equation for nitrogen (K_N), algae preference factor for ammonium (P_N), linear algae self-shading coefficient (λ_1).

A detailed description and graphic presentation of the sensitivity analysis results are given in the Master's Thesis (Cvitanič, 1998).

4.6 UMERJANJE IN PREVERJANJE MODELA

Umerjanje modela izvajamo s prilagajanjem parametrov modela tako, da rezultati modela čim bolj ustrezajo izmerjenemu stanju. Zaradi pomanjkanja analitičnih rešitev istočasno z umerjanjem izvajamo preverjanje modela.

V letu 1996 so bili na voljo rezultati fizikalno-kemijskih analiz za 22 vzorcev na vsakem mestu vzorčevanja, ki predstavljajo triurne povprečne vzorce za 5-dnevno vzorčevanje. Zadnjih 15 rezultatov meritev smo uporabili za umerjanje in preverjanje modela, preostalih 7 pa za potrditev modela. Rezultate vzorčevanja v letu 1998 pa smo uporabili kot nov, neodvisen dogodek, ki smo ga uporabili za dodatno validacijo modela.

V posamezni simulaciji predstavljajo vhodne podatke triurne povprečne vrednosti. Z modelnim izračunom torej zasledujemo triurno povprečno stanje vzdolž toka in spremembe kakovosti vode na modeliranem odseku Save od Suhadola do pregrade HE Vrhovo.

Za BPK_5, O_2 in klorofil a smo dosegli zadovoljivo ujemanje med meritvami in rezultati modela, kar dokazuje izračunan integral ploščine pod krivuljami, ki so prikazane na sliki 1.

Za amonij z umerjanjem modela nismo dosegli boljšega ujemanja med izračunanimi in izmerjenimi vrednostmi. Rezultati so prikazani

4.6 MODEL CALIBRATION AND VERIFICATION

The calibration of the model is performed by adjusting the model parameters in such a manner that the simulated performance of the model is in correspondence with the measured state as much as possible. Due to the lack of analytical solutions, the verification of the model is performed simultaneously with the model calibration.

In 1996 the results of the physical-chemical analyses for 22 samples from each sampling point were available. These results represent 3-hour average samples for 5-days sampling. The set of the last 15 samples was used for the model calibration, while the set of the remaining 7 samples was used for the model validation. The sampling results from 1998 were used as a new, independent event for additional model validation.

Input data for each simulation were three-hour average values. Therefore, a three-hour average state of flow and water quality on the modelled section of the Sava River was simulated with model calculations.

A satisfactory agreement between the measured and the modelled results was achieved for BOD_5, dissolved O_2 and chlorophyll a. This is proved by the calculated integral of square dimension under curves, shown in Figure 1.

For ammonium such good agreement between the calculated and the measured results could not be reached. From the results na sliki 2, iz katere je razvidno, da so rezultati modela v nekem časovnem obdobju previsoki, v naslednjem pa znantno prenizki. Zaključili smo, da so v akumulacijskem jezeru neznani izvori in ponori amonija, ki niso vključeni v model. Vendar pa je ujemanje merjenih in izračunanih rezultatov v okviru reda velikosti.

Primerjava rezultatov modela in izmerjenih vrednosti za nitrit in nitrat na pregradi HE Vrhovo, prikazana na sliki 2, kaže, da je model za ti dve spremeljivki uspešno umerjen.

Rezultati modela za ortofosfat in organski fosfor so v večini izračunov, glede na izmerjene koncentracije prenizki, vendar s spreminjanjem parametrov, ki vplivajo na ti dve spremenljivki, ne moremo doseči višjih vrednosti. Primerjava meritev in izračunov modela za organski fosfor na sliki 3 kaže na zadovoljivo kvalitativno ujemanje, kvantitativno pa se pojavljajo precejšnje razlike, ki so v več kot polovici primerov večje od 20 odstotkov.

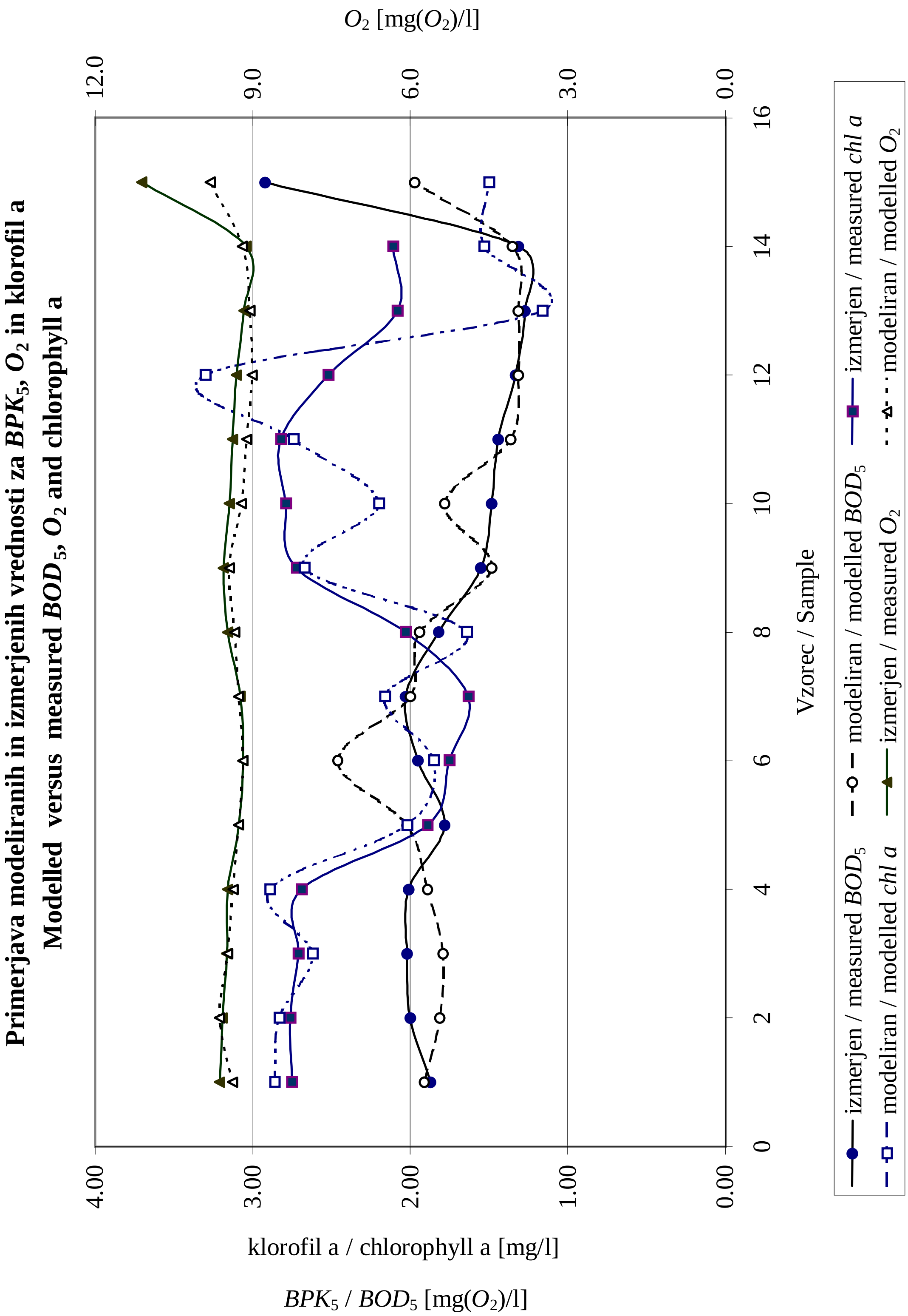
Na podlagi primerjave rezultatov modela z rezultati meritev smo zaključili, da je umerjanje in preverjanje modela ob danih možnostih uspešno zaključeno. Vzroke večjih razlik med izračunanimi in izmerjenimi vrednostmi, ki so se pojavile pri amoniju in organskem fosforju, bi bilo treba raziskati z nadaljnjimi kakovostnimi in načrtnimi meritvami v akumulacijskem jezeru HE Vrhovo. Določitve organskega fosforja bi bilo treba izvesti še v nefiltiranih vzorcih vode, ker bi s tem zajeli raztopljeni in partikularni organski fosfor v vodi, in izvesti izračune z modelom. Tako bi ugotovili, ali je ujemanje med izračuni modela in meritvami v tem primeru boljše (Cvitanič, 1998).

in Figure 2, it is evident that the results of the model were too high for one period and rather too low for the next. It can be concluded that there are unknown sources and sinks of ammonium in the impoundment, which were not included in the model. However, the modelled results were within an acceptable range.

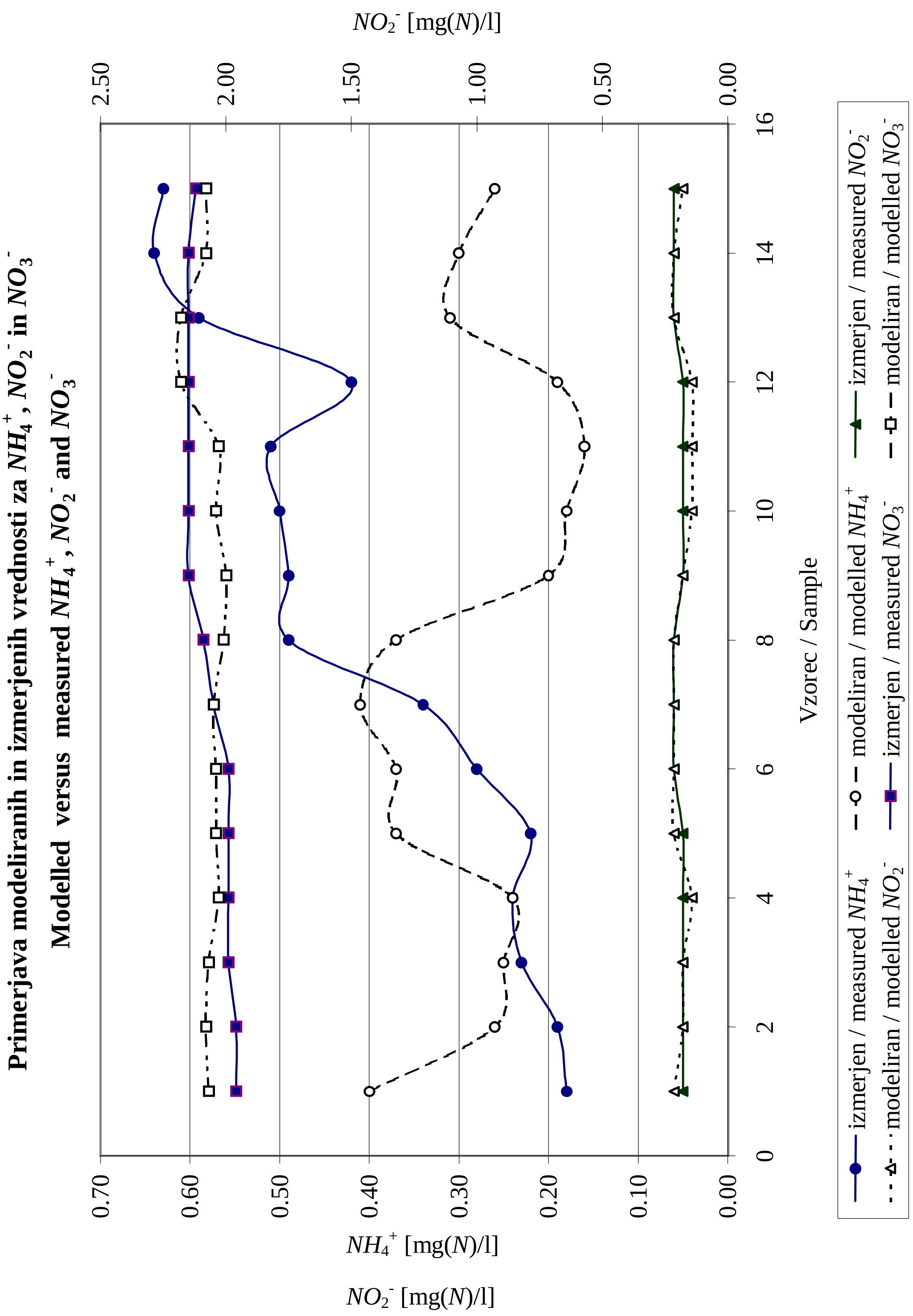
The comparison of the modelled and the measured results for nitrite and nitrate on the Vrhovo Dam showed that the model was successfully calibrated for these two variables (Figure 2).

The concentrations of orthophosphate and organic phosphorus calculated by the model were, in most simulations, lower than the measured concentrations. Higher values could not have been obtained by varying only those parameters that influence these two variables. The comparison of the modelled and the measured results for organic phosphorus (Figure 3) showed a satisfactory qualitative agreement, but there appeared quite large quantitative differences, which were, in more than half of the cases, larger than 20 percent.

Based on the comparison of the modelled and the measured results, it was concluded that the calibration of the model was successfully accomplished regarding the given input (measured) data. The causes for the greater differences between the calculated and the measured values of ammonium and organic phosphorus must be researched with additional quality and systematic measurements in the Vrhovo Impoundment. The determinations of organic phosphorus also have to be done in unfiltered water samples, because in this way dissolved and particular organic phosphorus would be determined. Then a new calibration test has to be done to obtain better agreement with the measurements (Cvitanič, 1998).

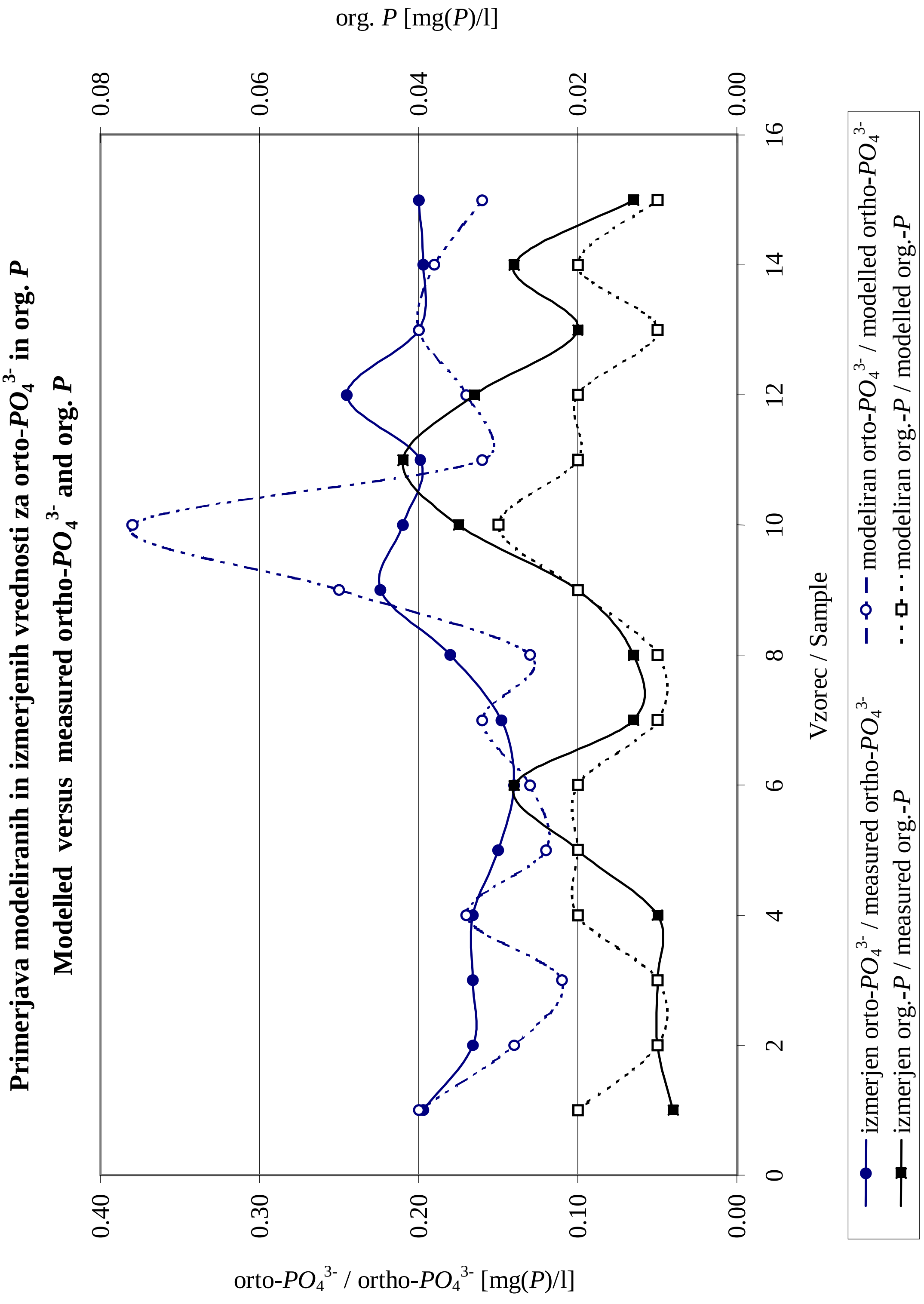


Slika 1. Primerjava z modelom izračunanih vrednosti BPK_5, O_2 in klorofila a
z meritvami na pregradi HE Vrhovo.
Figure 1. Modelled BOD_5, O_2 and chlorophyll-a in comparison to measured values at the Vrhovo HEPP Dam.



Slika 2. Primerjava z modelom izračunanih vrednosti NH_4^+, NO_2^- in NO_3^- z meritvami na pregradi HE Vrhovo.

Figure 2. Modelled NH_4^+, NO_2^- and NO_3^- as compared to the measured values at the Vrhovo HEPP Dam.



Slika 3. Primerjava z modelom izračunanih vrednosti orto-PO_4^{3-} in org-*P* z meritvami na pregradi HE Vrhovo.

Figure 3. Modelled ortho-PO_4^{3-} and org-P as compared to measured values at the Vrhovo HEPP Dam.

4.7 POTRDITEV MODELA

V prvi fazi smo izvajali potrditev modela z rezultati 7 meritev, ki niso bili uporabljeni za umerjanje modela, so pa del iste serije terenskih meritev, katere rezultati so bili uporabljeni za umerjanje modela.

Za BPK_5, O_2, klorofil a, amonij, nitrit in nitrat je potrjeno zadovoljivo kvantitativno ujemanje rezultatov modela z rezultati meritev, kar je razvidno iz grafičnega prikaza rezultatov na slikah 4 in 5. Čeprav so izračunane vrednosti BPK_5 in O_2 ves čas nižje od izmerjenih vrednosti na pregradi HE Vrhovo, so razlike med izračunanimi in izmerjenimi vrednostmi manjše od 10 odstotkov, kar je sprejemljivo za kvantitativno obravnavo problema. Za amonij lahko ugotovimo, da so razlike med izračunanimi in izmerjenimi koncentracijami manjše kot v fazi umerjanja modela ter so manjše od 20 odstotkov, razen pri zadnjem vzorcu, kjer se pojavi večja razlika. Na sliki 5 prikazana primerjava meritev in izračunov modela za nitrit in nitrat kaže na nekoliko previsoke izračunane vrednosti za obe spremenljivki. Vendar so razlike med izračunanimi in izmerjenimi vrednostmi za nitrit manjše od 20 odstotkov, za nitrat pa manjše od 10 odstotkov, kar je sprejemljivo za kvantitativno obravnavo problema.

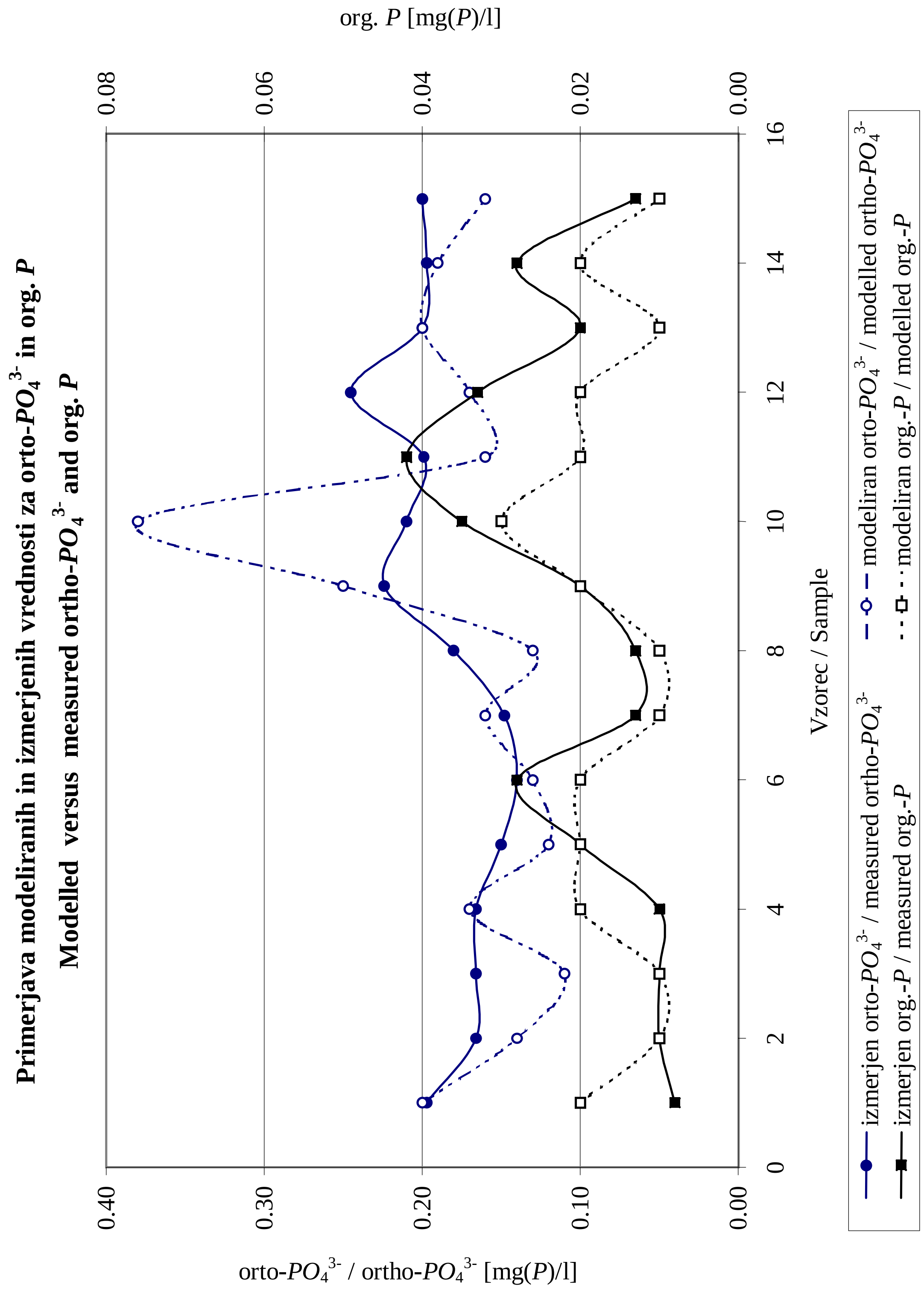
Z modelom izračunane koncentracije ortofosfata in organskega fosforja so v glavnem nižje od izmerjenih koncentracij (slika 6). Glede na dobljene rezultate v tej fazi, modela ne moremo povsem zanesljivo uporabiti za kvantitativne napovedi ortofosfata in organskega fosforja v akumulaciji.

4.7 MODEL VALIDATION

In the first phase the model validation was performed with a set of 7 measurements which belonged to the same measurement campaign, from which a different set of 15 measurements was used for the model calibration.

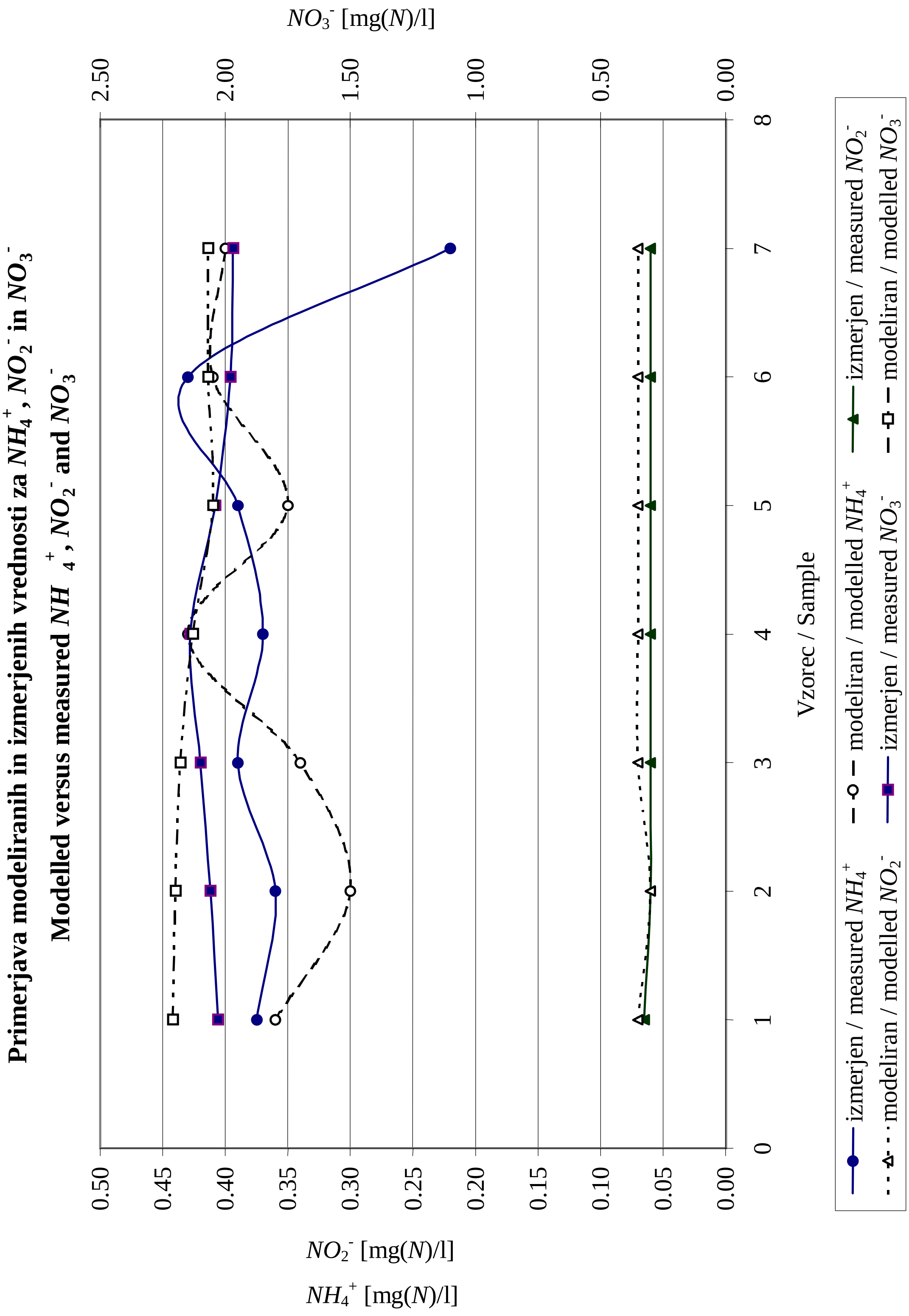
A suitable quantitative agreement between the simulated and the measured results was obtained for BOD_5, DO, chlorophyll a, ammonium, nitrite and nitrate. This is evident from the graphic presentation of the results in Figures 4 and 5. Although the calculated values for *BOD* and DO were lower from the measured values at the Vrhovo HEPP Dam throughout, the differences between the calculated and the measured values were smaller than 10 percent, which is acceptable for the quantitative treatment of the problem. For ammonium it can be established that the differences between the measured and the calculated results were smaller than in the model calibration phase and were smaller than 20 percent, with the exception of the last sample, where a larger difference appeared. The comparison between the measured and the modelled results for nitrite and nitrate are shown in Figure 5. It is evident that the modelled values were somewhat too high for both variables. However, the differences between the calculated and the measured results for nitrite were smaller than 20 percent, and for nitrate, smaller than 10 percent, which is acceptable for the quantitative treatment of the problem.

The modelled concentrations of orthophosphate and organic phosphorus were, in most simulations, lower than the measured concentrations (Figure 6). Considering the results of this validation, the model cannot be reliably applied for the quantitative prediction of orthophosphate and organic phosphorus in the impoundment.



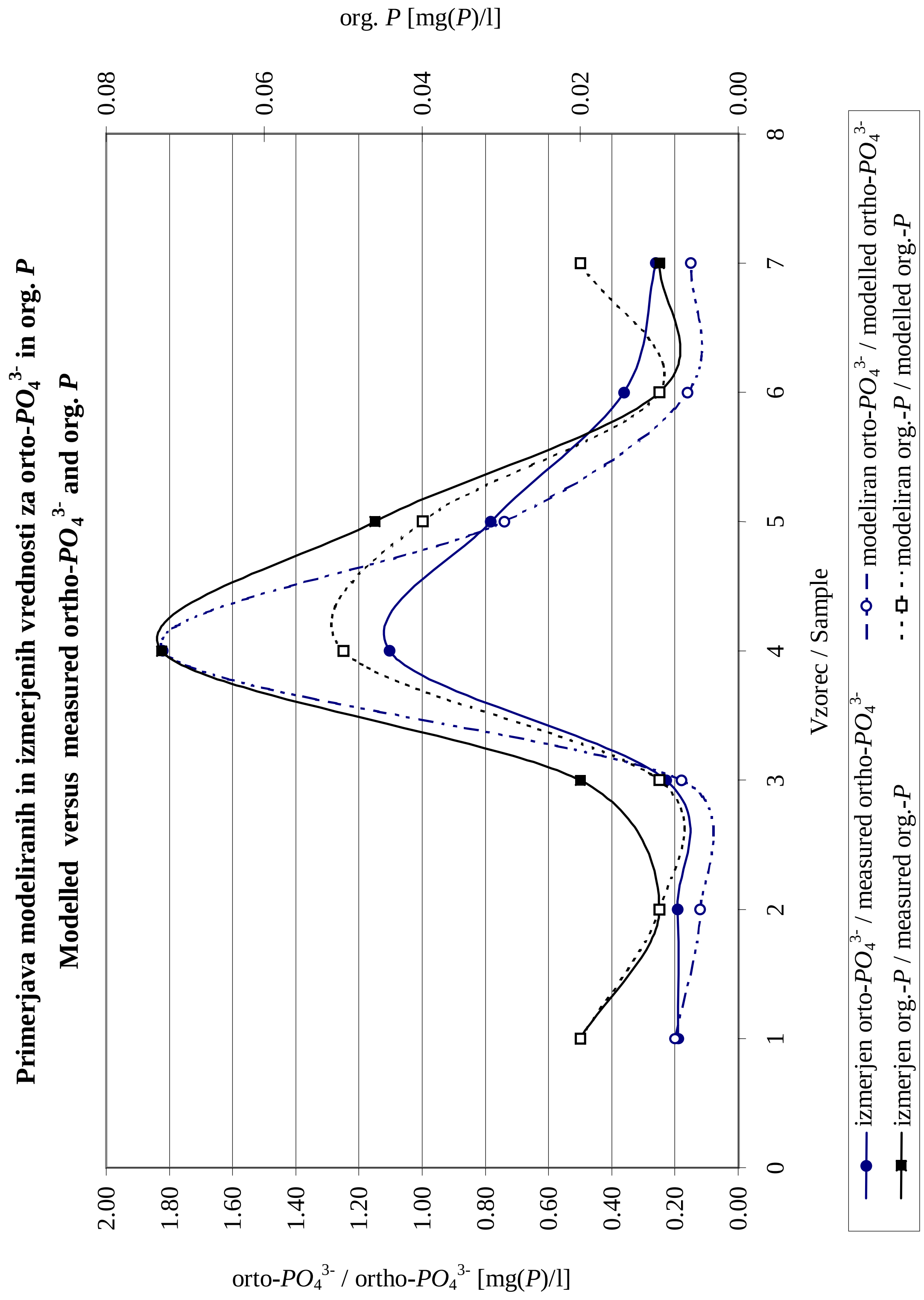
Slika 4. Primerjava z modelom izračunanih vrednosti BPK_5, O_2 in klorofila a z meritvami na pregradi HE Vrhovo.

Figure 4. Modelled BOD_5, O_2 and chlorophyll-a as compared to the measured values at the Vrhovo HEPP Dam.



Slika 5. Primerjava z modelom izračunanih vrednosti NH_4^+, NO_2^- in NO_3^- z meritvami na pregradi HE Vrhovo.

Figure 5. Modelled NH_4^+, NO_2^- and NO_3^- as compared to the measured values at the Vrhovo HEPP Dam.



Slika 6. Primerjava z modelom izračunanih vrednosti orto-PO_4^{3-} in org-*P* z meritvami na pregradi HE Vrhovo.

Figure 6. Modelled ortho-PO_4^{3-} and org-P as compared to the measured values at the Vrhovo HEPP Dam.

Treba bi bilo izvesti več kakovostnih vzorčevanj na vtokih v akumulacijo in iztoku iz akumulacije ter na nekem prečnem profilu v sami akumulaciji. Komponente fosforja je treba določiti v filtriranih in nefiltriranih vzorcih vode. Izračuni z modelom bi morali biti izvedeni za obe rezličici določitev fosforjevih komponent. Primerjava rezultatov za obe različici bo pokazala, ali se z določitvijo komponent fosforja v nefiltriranih vzorcih voda dobi kvantitativno boljše ujemanje modelnih izračunov z izmerjenim stanjem na pregradi HE Vrhovo.

Prav tako moramo upoštevati, da je model poenostavitev procesov v naravi in ne vključuje vseh komponent in procesov v naravi. Transformacije fosforjevih komponent v modelu vključujejo le kroženje fosforjevih komponent do primarne produkcije, ne vključujejo pa kroženja snovi in energije na višjih prehranjevalnih ravneh, ki vključujejo zooplankton, ribje populacije in druge organizme.

Rezultati potrditve modela z neodvisno serijo meritev, izvedenih avgusta 1998 pri nizkih pretokih in izrazito poletnih meteoroloških razmerah kažejo, da smo dosegli zadovoljivo kvantitativno ujemanje med meritvami in rezultati modela le za raztopljeni kisik, za vse ostale računane spremenljivke pa ni ustrezno, kar je razvidno iz slik 7, 8 in 9.

Z modelom izračunane vrednosti BPK_5 so v povprečju za 49 odstotkov nižje od izmerjenih vrednosti. Izmerjene vrednosti BPK_5 na pregradi HE Vrhovo vključujejo tudi razgradljivo organsko biomaso alg, katerih rast je, kot je razvidno iz določitev klorofila a, precej intenzivna. Model pa, kot je razvidno iz sheme interakcij med komponentami v modelu, ne upošteva novonastale biološko razgradljive biomase alg, ki nastane v primeru intenzivne rasti alg (primarne produkcije). Posledice navedenih ugotovitev pa so dobljene razlike med izmerjenimi in izračunanimi vrednostmi BPK_5. Poleg tega so izračunane vrednosti klorofila a v povprečju za 63

Several quality samplings at the inflow into the impoundment, at the outflow from the impoundment and on some cross-sectional profiles in the impoundment could have been performed. The components of phosphorus must be determined in both filtered and unfiltered water samples. Calculations with the model must be performed for both variants of determining phosphorus components. The comparison of results for both variants will show whether the determination of phosphorus components in unfiltered samples gives better quantitative agreement between the calculated and the measured results.

We also have to take into consideration that the model is a simplification of the processes in nature, and it does not strictly include all the components and processes in nature. The transformations of phosphorus components in the model include only the cycling of the phosphorus components up to primary production, but they do not include the cycling of substances and energy on higher nutrient levels, which include zooplankton, fish populations and other organisms.

In the second phase, the model validation was performed with an independent set of measurements carried out in August, 1998 at low discharges and at pronounced summer meteorological conditions. Suitable quantitative agreement between the measured and the modelled results was obtained only for dissolved oxygen. For all other simulated variables the agreement was not so good. The results are shown in Figures 7, 8 and 9.

The modelled values for BOD_5 were, on an average, 49 percent lower than the measured values. The measured values of BOD_5 at the Vrhovo HEPP Dam also included the decomposable organic algae biomass, for which the growth was rather intense, as it was evident from the determination of the concentration of chlorophyll a. The newly originated biologically decomposable algae biomass, originating in the case of intensive algae growth (primary production), is not considered in the model calculation of *BOD*. Because of this, the calculated values of BOD_5 were lower than the measured values. Besides that, the modelled values for chlorophyll a were, on an average, for 63 percent lower from the measured values. This means that in advantageous conditions for increased algae growth, the model did not respond correctly odstotkov nižje od izmerjenih vrednosti. To pomeni, da se model v pogojih, ko nastopijo ugodne razmere za povečano rast alg, ki so bili izmerjeni v teh meritvah, ne odziva pravilno s parametri, določenimi v postopku umerjanja modela. Zadovoljivo ujemanje med izmerjenimi in izračunanimi koncentracijami klorofila a bi dosegli z izračuni z 10-krat nižjim koeficientom upadanja svetlobe, kot je bil določen z umerjanjem modela. Ker množina klorofila a vpliva na koncentracijo raztopljenega kisika, bi bilo treba izvesti več nadaljnjih serij meritev klorofila a in prodiranja svetlobe v vodno telo s Secchijevim diskom za natančnejšo določitev koeficienta upadanja svetlobe (λ), ki ima dominanten vpliv na primarno produkcijo v obravnavani akumulaciji.

Kot je razvidno iz slike 8, potrditev modela glede dušikovih spojin ni zadovoljiva. Pri tej meritvi smo imeli na voljo tudi določitve organskega dušika v nefiltriranih vzorcih voda. Izračunane koncentracije organskega dušika so v primerjavi z izmerjenimi koncentracijami organskega dušika znatno prenizke. Nasprotno pa so izračunane koncentracije amonija previsoke glede na izmerjene koncentracije v vzorcih voda. Če pa primerjamo rezultate meritev in rezultate modela za totalni dušik, ki je seštevek vseh nastopajočih dušikovih komponent v dušikovem ciklu, vidimo, da so razlike zanemarljive. To pomeni, da parametri, določeni v fazi umerjanja modela, ki so dominantni za pretvorbo ene oblike dušika v drugo v vodnem telesu, niso ustrezni za novo neodvisno serijo meritev. Iz navedenega lahko zaključimo, da je za umerjanje tako kompleksnega sistema potrebno več neodvisnih serij meritev, ali pa se celo vrednosti parametrov časovno spreminjajo po do zdaj še neznani zakonitosti.

Glede na primerjavo rezultatov meritev in rezultatov modela za ortofosfat in organski fosfor, ki so grafično prikazani na sliki 9, ugotavljamo, da potrditev modela z neodvisno serijo meritev za ti dve spremenljivki ni kvantitativno zadovoljiva, čeprav se

with the parameters determined in the procedure of the model calibration. Satisfactory agreement between the measured and the calculated chlorophyll a concentrations would be reached with calculations with 10 times lower light extinction coefficient (λ) than was determined by the model calibration. Because the quantity of chlorophyll a influences the dissolved oxygen concentration, more additional sets of measurements of chlorophyll a and the penetration of light in the body of water with a Secchi Discus for more precise determination of the light extinction coefficient (λ), which has dominant influence on primary production in the impoundment, have to be performed.

As is evident from Figure 8, the model validation was not satisfactory in the case of nitrogen compounds. At this set of measurements, the determination of organic nitrogen in the water samples was also available. The calculated concentrations of organic nitrogen were considerably too low compared to the measured concentrations. On the other hand, the calculated ammonium concentrations were too high compared to the measured concentrations in the water samples. If the measured and the modelled results for total nitrogen (sum of all nitrogen components in the nitrogen cycle) are compared, the differences are negligible. This means that model parameters defined in the model calibration, which are dominant for the conversion of nitrogen from one form to another in the body of water, were not appropriate for another independent set of measurements. It can be concluded that for the calibration of such a complex system, more series of independent measurements are needed, or that even the values of the model parameters change in time.

The measured concentrations of orthophosphate and organic phosphorus compared to the modelled results are shown in Figure 9. It was discovered that the model validation with an independent set of measurements for these two variables was not quantitatively satisfactory, although the qualitative response was correct.

With regard to the stated results of the model validation, the following can be concluded:

A. The first part of the calculations for the model validation was performed with a set kvalitativno pravilno odziva.

Glede na navedene rezultate lahko za potrditev modela podamo naslednje ugotovitve:

A. Prvi del izračunov za potrditev modela je bil izveden z meritvami, ki pripadajo seriji meritev, s katero je bil model umerjen. Potrditev modela je bila zadovoljiva za vse računane spremenljivke, razen za ortofosfat in organski fosfor. Domnevamo, da je razlog za odstopanja med izmerjenimi in izračunanimi koncentracijami teh dveh spremenljivk sistemska napaka. Poleg tega smo pri modelnih izračunih za fosforjevi komponenti opazili, da z izračuni ni mogoče dobiti pravilnih rezultatov za kratkotrajno izrazito povečano onesnaženje s fosforjevimi spojinami na vhodu v akumulacijo. Maksimumi v onesnaženju se vzdolž toka v zajezitvi zmanjšajo zaradi vzdolžne disperzije, adsorpcije na mikroorganizme oziroma zaradi fizikalnih in biokemijskih pretvorb raztopljenega, koloidnega in adsorbiranega fosforja v partikularni fosfor.
B. Drugi del izračunov za potrditev modela je bil izveden z neodvisno serijo meritev, ki je potekala v bistveno drugačnih pogojih. Dobljeni rezultati so bili veliko slabši kot v prvem delu. Potrditev je kvantitativno ustrezna le za kisik, za vse druge računane spremenljivke pa ni ustrezna.

Razlogov za neuspešno potrditev modela je lahko več:

– Premalo podatkov za kakovostno umerjanje modela. Za natančnejše kvantitativno modeliranje parametrov kakovosti Save v zajezitvi HE Vrhovo bi bilo treba izvesti natančnejše umerjanje modela. Za to bi bilo nedvomno potrebnih več serij kakovostnih meritev v hidroloških in meteoroloških pogojih, za katere naj bi se z umerjenim modelom napovedovale spremembe kakovosti Save v akumulacijskem jezeru HE Vrhovo.
– QUAL2E je enodimenzionalni model, ki

of measurements which belonged to the same measurement campaign from which a different set of measurements was used for the model calibration. The model validation was satisfactory for all the calculated variables with the exception of orthophosphate and organic phosphorus. We believe that the reason for the differences between the measured and the calculated concentrations of these two variables is a systematic error. Besides that, at the model calculations for the phosphorus constituents, it was noticed that with the calculations it was not possible to obtain correct results for short-lived, markedly enlarged pollution, with phosphorus compounds at the inflow into the impoundment. Maximums in the pollution were reduced along the flow in the impoundment because of longitudinal dispersion, adsorption on microorganisms or because of the physical and biochemical transformations of dissolved, colloidal and adsorbed phosphorus into particulate phosphorus.

B. The second part of the calculations for the model validation was performed with an independent set of measurements, which were performed under essentially different conditions. The results were much worse than in the first part. The validation was quantitatively suitable for dissolved oxygen only; for all other simulated variables it was not suitable.

To find the possible reasons for poor performance, we checked the data, the analytical procedures, the model assumptions and the model concepts. We ended up with this list of possible reasons for the relatively unsuccessful model validation:

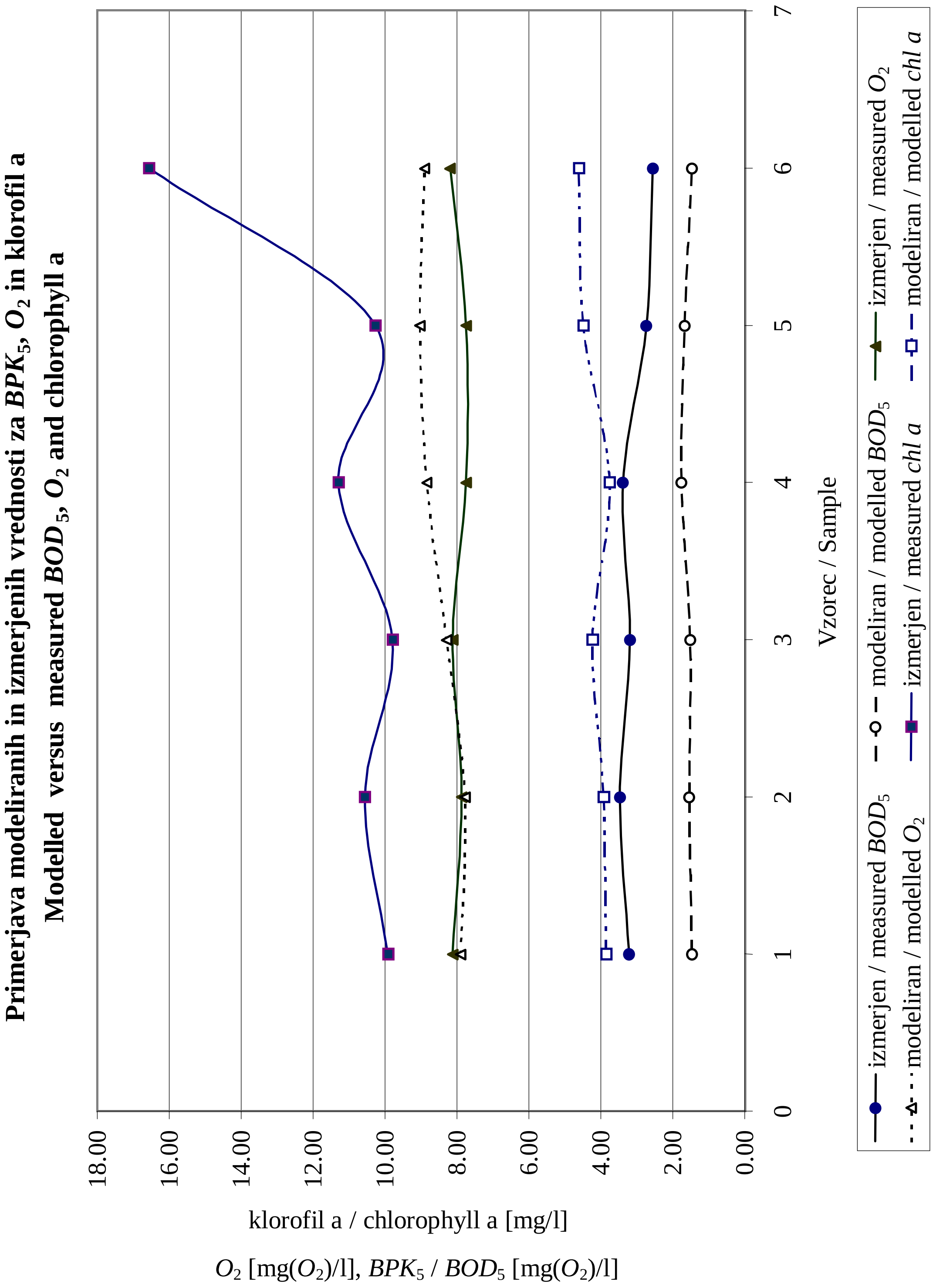
– Not enough data for quality model calibration. For a more accurate quantitative modelling of water quality parameters in the Vrhovo Impoundment, more accurate model calibration will have to be done. For this purpose, it would undoubtedly be necessary to perform more series of quality measurements in different hydrological and meteorological conditions, for which the calibrated model has to be used for the prediction of the change in water quality of the Sava River in the impoundment.
– QUAL2E is a 1D (one-dimensional) model,

zahteva, da so glavni transportni mehanizmi značilni vzdolž glavne smeri toka. Hidrodinamika modela ima pri transportu snovi in snovnih pretvorbah velik pomen. V poletnem času so bili v akumulacijskem jezeru HE Vrhovo izmerjeni horizontalni in vertikalni temperaturni gradienti, kar pomeni, da bi morala biti hidrodinamika modela zajeta vsaj z dvodimenzionalnim ali celo tridimenzionalnim modelom.

- Meritve v zajezitvi kažejo, da se zgornji sloji vode čez dan močneje segrejejo kot spodnji. Prav tako meritve parametrov kakovosti voda v poletnem obdobju kažejo na njihovo različno horizontalno in vertikalno razporeditev. Torej ne gre za popolno premešanost polutantov v prečnih profilih. Navedene ugotovitve kažejo, da bi bilo treba v modeliranje parametrov kakovosti vode v zajezitvi vključiti vsaj še vertikalno dimenzijo. To pomeni, da bi bilo treba kakovost vode v zajezitvi modelirati z dvodimenzionalnim modelom.
- Srednja vrednost energije globalnega sončnega obsevanja za Slovenijo za povsem jasen dan v avgustu znaša 564 ly. Model pa dovoljuje za vrednost srednje dnevne energije globalnega sončnega obsevanja vnos maksimalne vrednosti 400 ly, kar pomeni, da smo bili prisiljeni izvesti izračune s to vrednostjo.
- Med parametri modela ima prevladujoč vpliv na primarno produkcijo, izmerjeno kot klorofil a, v obravnavani akumulaciji, koeficient upadanja svetlobe (λ). Zato bi bilo treba za natančnejšo določitev koeficienta upadanja svetlobe v akumulaciji izvesti več nadaljnjih serij meritev prodiranja svetlobe v vodno telo s Secchijevim diskom in določitev klorofila a.
- Model v izračunu biokemijske potrebe po kisiku ne upošteva novonastale biološko razgradljive biomase alg. Zato so z modelom izračunane BPK_5 nižje od izmerjenih vrednosti.

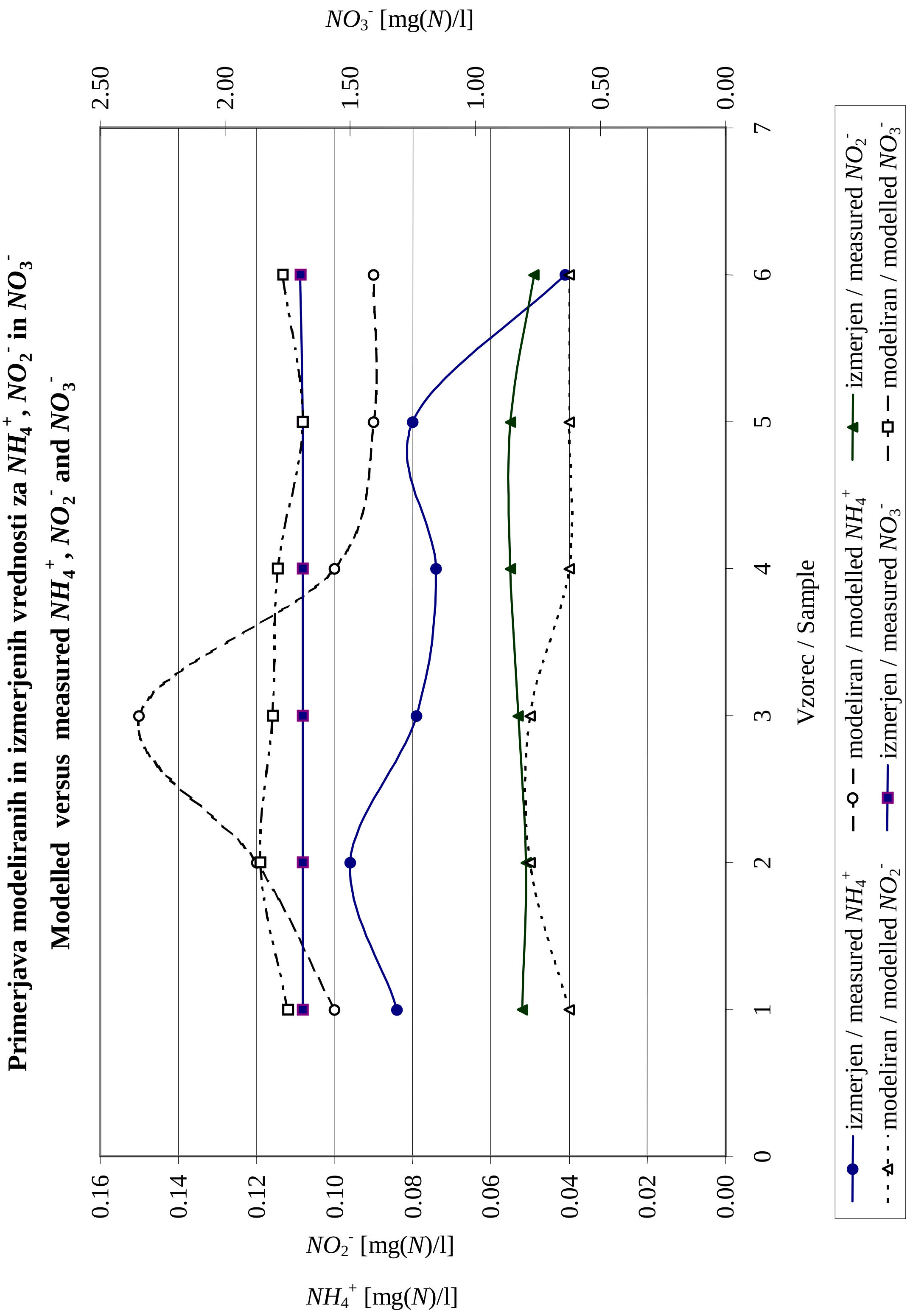
which assumes that the major transport mechanisms are significant only along the main direction of flow. The hydrodynamics of the model is of vital importance for pollution transport and transformation. In the summer period, horizontal and vertical temperature gradients were measured in the Vrhovo Impoundment. This means that the hydrodynamics of the model must be modelled with, at least, a two-dimensional model or even a three-dimensional model.

- The measurements in the impoundment showed that during the day the upper water layers heated up more than the lower ones. In the same way, the measurements of water quality variables in the summer period also showed non-homogeneous horizontal and vertical distribution. This means that we do deal with a complete mix of pollutants in the cross sections. This finding again points out that 1D model (in the longitudinal direction) is not appropriate. Thus, at least the vertical dimension has to be included in the modelling of water quality parameters, which means that water quality in the impoundment has to be modelled with (at least) a two-dimensional model.
- The average daily solar radiation for an absolutely sunny August day in Slovenia is 564 ly. The maximal input value for average daily solar radiation allowed by the model is 400 ly, which means that calculations were performed with this truncated value, instead with the true one.
- Among the model parameters, there is the extinction coefficient (λ), which has the most dominant influence on the system behaviour in the Vrhovo Impoundment (e.g. observed primary production, measured as chlorophyll a). Therefore, more additional sets of measurements of chlorophyll a and the penetration of light in the body of water using a Secchi Discus have to be performed for a more precise determination of the light extinction coefficient (λ) in the impoundment.
- The newly originated biologically decomposable algae biomass is not considered in the model calculation of *BOD*. Because of this, the calculated values of BOD_5 were lower than the measured values



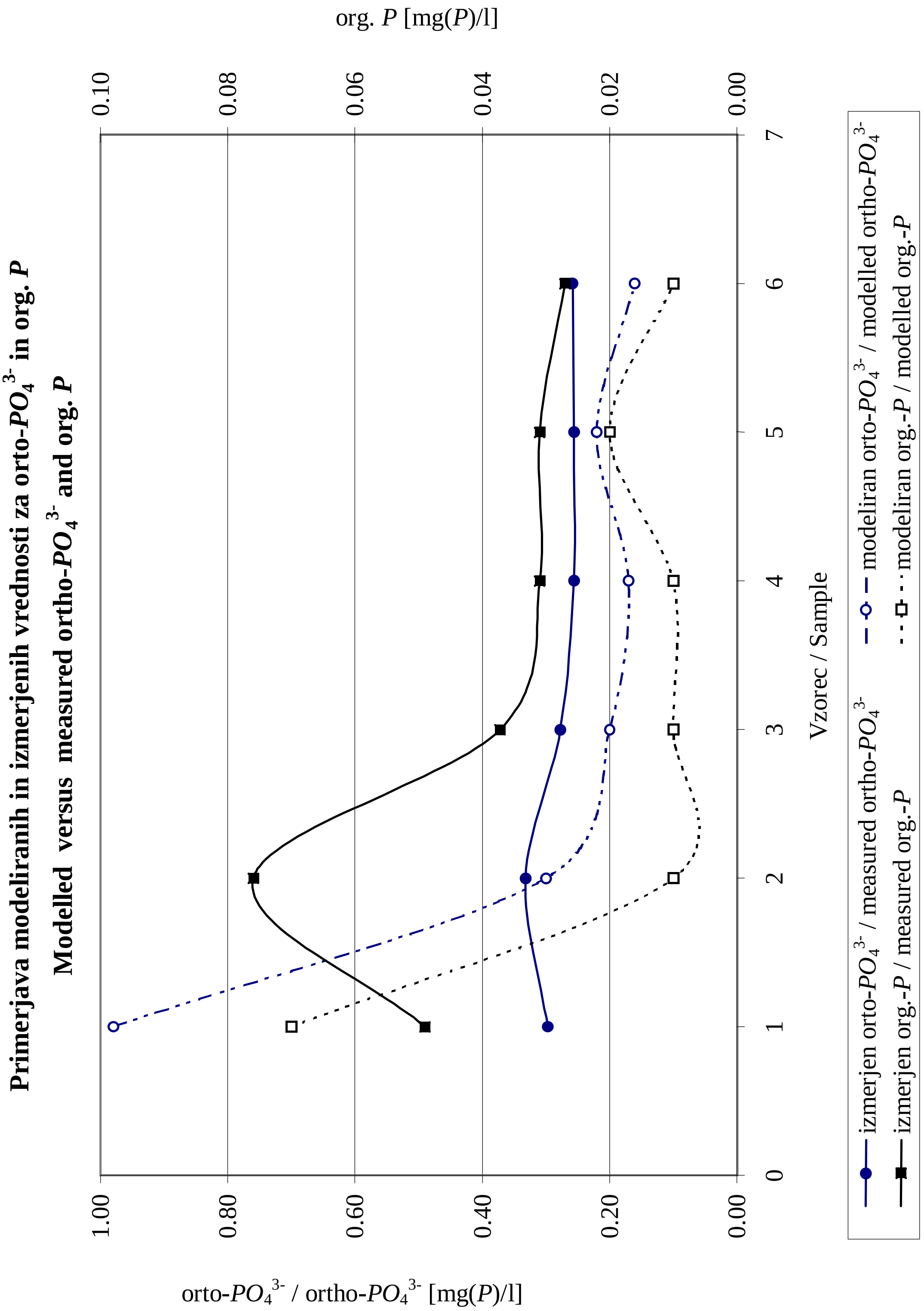
Slika 7. Primerjava z modelom izračunanih vrednosti BPK_5, O_2 in klorofila a z meritvami na pregradi HE Vrhovo.

Figure 7. Modelled BOD_5, O_2 and chlorophyll-a as compared to the measured values at the Vrhovo HEPP Dam.



Slika 8. Primerjava z modelom izračunanih vrednosti NH_4^+, NO_2^- in NO_3^- z meritvami na pregradi HE Vrhovo.

Figure 8. Modelled NH_4^+, NO_2^- and NO_3^- as compared to the measured values at the Vrhovo HEPP Dam.



Slika 9. Primerjava z modelom izračunanih vrednosti orto-PO_4^{3-} in org-P z meritvami na pregradi HE Vrhovo.
Figure 9. Modelled ortho-PO_4^{3-} and org-P as compared to the measured values at the Vrhovo HEPP Dam.

4.8 NAPOVED KAKOVOSTNIH SPREMEMB SAVE V AKUMULACIJI HE VRHOVO

Kvantitativno napoved kakovostnih sprememb Save v akumulaciji HE Vrhovo smo izvedli le za raztopljeni kisik in BPK_5. Vedeti pa moramo, da z modelom izračunane vrednosti BPK_5 ne vključujejo novonastale biološko razgradljive biomase alg v primeru intenzivne rasti alg v akumulaciji. S tem povzročena dodatna poraba po kisiku je vključena v modelu v določitvi raztopljenega kisika, potrebnega za respiracijo alg. Model torej privzema le zunanji vnos BPK_5, medtem ko so zunanji in notranji viri potrebe po raztopljenemu kisiku pravilno definirani v izrazu za raztopljeni kisik.

Napoved smo izvedli za ekstremne in povprečne hidrološke pogoje, in sicer za najmanjši nizki pretok v obdobju (simulacija A), srednji nizki pretok v obdobju (simulacija B) in največji nizki pretok v obdobju (simulacija C). Vhodna podatka za O_2 in BPK_5 pa sta iz naših meritev v letu 1998.

4.8 PREDICTION OF WATER QUALITY CHANGES IN THE VRHOVO IMPOUNDMENT

Quantitative water quality prediction of the Sava River in the Vrhovo Impoundment was performed only for DO and BOD_5. It has to be pointed out that the BOD_5 values calculated by the model do not include newly grown decomposable algae biomass, which could be a serious systematic error (compared to the measurements) in the case of intensive algae growth (eutrophication). Instead, this additional oxygen consumption is included in the determination of the DO in the impoundment. Thus, the model assumes the BOD_5 only as the external load, while all external and internal loads are properly conceptualised in the DO term.

The predictions were performed for extreme and average hydrological conditions, i.e.: for the minimal low discharge within a period (simulation A), the average low discharge within a period (simulation B) and the maximal low discharge within a period (simulation C). The input data for DO and BOD_5 are from the measurements in 1998.

Preglednica 5. Primerjava izmerjenih vhodnih podatkov v Suhadolu in rezultatov modela na pregradi HE Vrhovo.
Table 5. Measured input data in Suhadol as compared to the modelled results at the Vrhovo HEPP Dam.

Simulacija *Simulation*	Q [m^3/s]	Σt [h]	O_2 [mg(O_2)/l]		BPK_5 [mg(O_2)/l] BOD_5	
			Input *Input*	Izračun *Computation*	Input *Input*	Izračun *Computation*
A	39,7	54,6	8,53	7,70	2,54	1,00
B	58,8	37,4	8,53	7,82	2,54	1,30
C	84,0	27,1	8,53	7,91	2,54	1,55

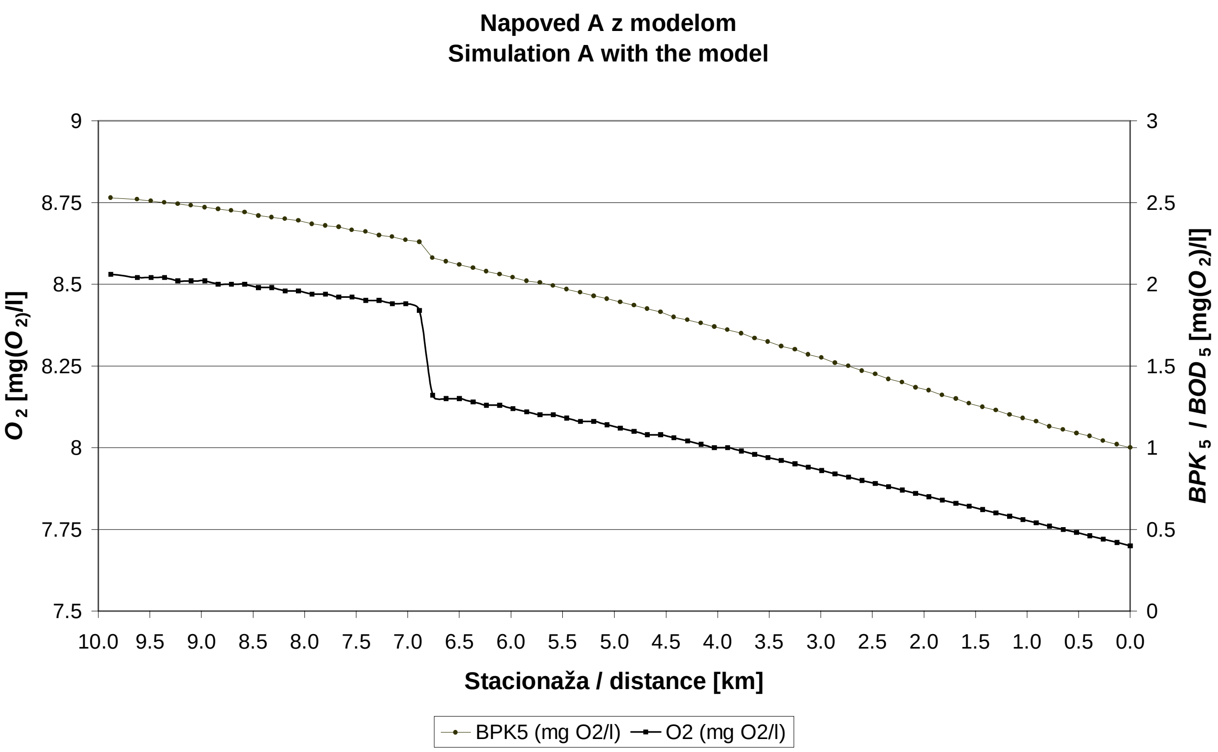
Kljub temu, da z modelom ne moremo izvesti kvantitativne napovedi za vse načrtovane parametre kakovosti voda, z izračunom spremembe koncentracije kisika v akumulaciji dobimo podatek o spremembi odločilnega parametra za presojo kakovostnih sprememb reke Save. Rezultati izvedenih

In spite of the fact that, due to the unfavourable validation results, quantitative predictions by the model cannot have been reliably done for all the planned water quality parameters, an approximate information on the changes of the most critical variables for the estimation of the quality changes in the Sava River was obtained with the calculation of izračunov so podani v preglednici 5. Vsebnost raztopljenega kisika se najbolj zmanjša pri najmanjšem nizkem obdobnem pretoku, kjer znaša zmanjšanje 0,83 mg(O_2)/l. Pri tem pretoku se tudi najbolj zniža organsko onesnaženje, izraženo kot BPK_5, znižanje znaša 1,54 mg(O_2)/l. Pri večjih pretokih je znižanje koncentracije kisika in BPK_5 še manjše. Manjše zmanjšanje BPK_5 je pri večjih pretokih posledica hitrejšega toka vode in s tem krajšega zadrževalnega časa opazovanega onesnaženja med vhodnim in izhodnim profilom.

Na sliki 10 je prikazano z modelom izračunano spreminjanje koncentracij kisika in BPK_5 vzdolž toka v akumulaciji, kjer je opazen vpliv vtoka Savinje v Zidanem Mostu.

dissolved oxygen concentrations in the impoundment. The results of the calculations are given in Table 5. The concentration of the dissolved oxygen was reduced most at the minimal low period discharge, where the reduction reached 0.83 mg(O_2)/l. Organic pollution expressed as BOD_5 was also reduced, the most at this discharge. The reduction of DO and BOD_5 was smaller for the larger discharges. Of course, the smaller BOD_5 reduction at the larger discharges was a consequence of faster stream current and the resulting shorter retention time of the observed element between the input and the output profile.

The changing of DO and BOD_5 along the flow in the impoundment calculated with the model is shown in Figure 10. Here the influence of the inflow of the Savinja River in Zidani Most is noticeable.



Slika 10. Z modelom izračunano spreminjanje koncentracije kisika in BPK_5 vzdolž toka v akumulaciji HE Vrhovo za pretok 39,7 m^3/s.
Figure 10. Changing of DO and BOD_5 along the flow in the impoundment calculated with the model for the discharge of 39.7 m^3/s.

Oceno kakovostnih sprememb Save v akumulacijskem jezeru lahko poenostavljeno podamo tudi na podlagi enodnevnih meritev, izvedenih avgusta 1998 v stabilnih razmerah pri visokih temperaturah vode in nizkih pretokih. Rezultati meritev so podani v magistrski nalogi (Cvitanič, 1998). Voda se je od Suhadola do pregrade HE Vrhovo segrela v zgornji 0,5-metrski plasti za približno 2,8°C. Če pa upoštevamo povprečno temperaturo vode, izmerjeno v vertikali na prečnem prerezu most Vrhovo, ki znaša 21,4 °C, pa znaša povišanje temperature vode 2,4°C. Vsebnost raztopljenega kisika se v akumulaciji zmanjša. Izmerjeno zmanjšanje koncentracije kisika vzdolž toka Save znaša od 0,38 mg(O_2)/l do 1,6 mg(O_2)/l. Organsko onesnaženje, izraženo kot BPK_5, se vzdolž toka poveča, ob upoštevanju, da meritev BPK_5 na pregradi vključuje dodatno organsko onesnaženje zaradi intenzivne rasti alg. Koncentracija amonija se vzdolž toka nekoliko zmanjša, enako velja za nitrit in nitrat. Nasprotno pa se vsebnost ortofosfata v akumulaciji poveča. V akumulaciji izmerjena koncentracija klorofila a na globini 0,5 m znaša 15 μg/l, kar kaže na intenzivno primarno produkcijo v akumulaciji.

Zaključimo lahko, da je na obravnavanem odseku Save prisotnih dovolj hranil za nastop evtrofikacije, ki pa se ne pojavlja v takšnem obsegu, da bi povzročala večje težave, ker so zadrževalni časi zaradi pretočnega tipa akumulacije prekratki. Največji izračunan zadrževalni čas vode v zajezitvi pri pretoku 39,7 m^3/s znaša 54,6 h (2,28 dni), rast alg pa je največja pri daljših zadrževalnih časih, približno od 3 do 20 dni. Z ekološkega vidika je najbolj kritična posledica evtrofikacije zmanjšanje koncentracije kisika, posebno v večjih globinah akumulacije, kot posledica razgradnje odmrlih alg. Vendar je iz meritev razvidno, da je na dnu akumulacije koncentracija kisika 5,3 mg(O_2)/l. V zajetem vzorcu vode v akumulaciji so bile zastopane vrste rastlinskega planktona, ki hitro izkoristijo

The estimation of the water quality changes of the Sava River in the impoundment can be given in a simplified form on the basis of one-day measurements performed in August, 1998 in stable conditions at high water temperature and low discharges. The results of the measurements are given in the Master's Thesis (Cvitanič, 1998). From Suhadol to the Vrhovo HEPP Dam, the upper 0,5 meter of the water layer was heated by approximately 2.8°C. However, if we consider the average water temperature, measured in the vertical at the cross sectional profile of the Vrhovo Bridge (21.4°C), the increase of the water temperature reached 2.4°C. The dissolved oxygen concentration in the impoundment was reduced. The measured reduction of the dissolved oxygen concentration along the flow of the Sava River was between 0.38 mg(O_2)/l and 1.6 mg(O_2)/l. Organic pollution, expressed as BOD_5, increased along the flow, considering that the measured BOD_5 at the Vrhovo HEPP Dam included additional organic pollution because of the intensive algae growth. The concentration of ammonium was slightly reduced along the flow; the same holds true for nitrite and nitrate. On the other hand, the concentration of orthophosphate in the impoundment was increased. The measured concentration of chlorophyll a at a depth of 0.5 m reached 15 μg/l, which indicates intensive primary production in the impoundment.

It can be concluded that there were enough nutrients present at the treated section of the Sava River for the entrophication to appear. But it did not appear to such an extent that it would cause greater problems, as the retention times in the impoundment were too short. The largest retention time in the impoundment at a discharge of 39.7 m^3/s was 54.6 h (2.28 days), but the growth of algae was the greatest at longer retention times, between approximately 3 and 20 days. From the ecological point of view, the most critical consequence of eutrophication is the decrease in oxygen concentration, particularly in the deeper parts of the impoundment. The decrease is the consequence of algae decomposition. However, from the measurements, it is clear that at the bottom of the impoundment the dissolved oxygen concentration was 5,3 mg(O_2)/l. The species of phytoplankton, which ugodne razmere za svoj razvoj.

V akumulaciji HE Vrhovo se glede na izvedene modelne izračune in terenske meritve, v pogojih, ugodnih za nastop intenzivne primarne produkcije, za zdaj ne pojavljajo zmanjšanja v koncentraciji raztopljenega kisika, ki bi bila skrb zbujajoča ali problematična. Jasno pa je, da lahko v poletnem času, ko nastopijo visoke temperature vode in nizki pretoki, pričakujemo intenzivno primarno produkcijo alg v akumulaciji. Posledica tega je sekundarna polucija, ki se odraža v upadanju koncentracije kisika v vodi in v povečani biokemijski potrebi po kisiku. Treba pa bi bilo proučiti vpliv teh procesov na parametre kakovosti voda v predvidenih zajezitvah vzdolž toka Save, še posebej, ker se predvidene zajezitve sklenjeno nadaljujejo od stopnje do stopnje. To pomeni manjšo reaeracijsko sposobnost vode, usedanje odmrlih alg in makrofitov na dno akumulacij in s tem povzročanje nizkih vrednosti raztopljenega kisika v večjih globinah akumulacij.

Pri višjih pretokih in s tem krajših zadrževalnih časih vode v akumulaciji izostanejo pogoji za povečano primarno produkcijo. Znižanje koncentracije kisika je neznatno, pokaže pa se vpliv akumulacije na redukcijo BPK_5, kar pomeni pozitiven prispevek k povečanju samočistilne sposobnosti vodotoka. Izvedeni izračuni z modelom kažejo, da se organsko onesnaženje v akumulaciji, izraženo kot BPK_5, pri pretoku 39,7 m^3/s zmanjša za 1,54 mg(O_2)/l, kar je ekvivalentno čistilni napravi za skoraj 90.000 populacijskih enot (ena populacijska enota pomeni obremenitev 60 g BPK_5/dan). Pri pretoku 58,8 m^3/s je zmanjšanje BPK_5 ekvivalentno čistilni napravi za 105.000 populacijskih enot, pri pretoku 84,0 m^3/s pa je zmanjšanje BPK_5 ekvivalentno čistilni napravi za skoraj 120.000 populacijskih enot.

rapidly take advantage of good conditions, were present in the water sample from the impoundment.

With regard to the model results and field measurements achieved at low discharges and in conditions of intensive primary production in the dam, it can be concluded that an excessive decrease of dissolved oxygen concentration, which can have a negative influence on the impounded water quality, did not appear in the Vrhovo Impoundment. Nevertheless, it is clear that in the summer time, when the water temperature is high and the discharges are low, intensive primary algae production can be expected. The consequence of this is secondary pollution, which is reflected in the decreased oxygen concentration and in an increased value of *BOD*. The influence of these processes on the water quality parameters in the foreseen impoundments along the Sava River have to be investigated, especially because the levels of each HEPP was chosen in such manner that the levels of the impoundments continue from one stage to another. This means a smaller reaeration capacity of water, a settling of the macrophytes and algae which died off on the bottom of the impoundment, and this causes low dissolved oxygen concentrations in the deeper parts of the impoundments.

At higher discharges and shorter retention times of the water in the impoundment, the conditions for increased primary production cannot fully develop. Thus, the decrease of DO is minimal, while the influence on the BOD_5 reduction can still be seen. This is a positive contribution to river's self-purification capacity. From the model calculations, it can be seen that the organic pollution, expressed as BOD_5, at a discharge of 39.7 m^3/s was reduced by 1.54 mg(O_2)/l. This was equivalent to a wastewater treatment plant of almost 90.000 PE (one population equivalent, PE, is the load of one person per day, and is 60 g BOD_5/day). At a discharge of 58.8 m^3/s the reduction of BOD_5 was equivalent to a wastewater treatment plant of 105.000 PE, and at a discharge of 84.0 m^3/s, the reduction of BOD_5 was equivalent to a wastewater treatment plant of nearly 120,000 PE.

5. ZAKLJUČKI

Matematični modeli kakovosti voda omogočajo napoved sprememb kakovosti voda zaradi načrtovanih posegov v vodni režim, proučevanje vplivov zunanjih in notranjih virov onesnaženja na kakovost voda, simuliranje možnih strategij gospodarjenja z vodnim bogastvom, izboljšanje razumevanja sistemov in določitev nedostopnih vhodnih podatkov iz merjenih izhodnih podatkov.

Za analizo možnih kakovostnih sprememb reke Save v akumulaciji HE Vrhovo, ki je nastala z zajezitvijo Save avgusta 1994, smo uporabili večparametrski enodimenzionalni model Qual2E. Enodimenzionalni model smo uporabili ob predpostavki, da lahko dolge, ozke zajezitve obravnavamo na enak način kot nezajezene vodotoke, to je s popolno vertikalno in horizontalno premešanostjo polutantov v prečnih profilih.

Model vsebuje veliko število parametrov, ki smo jih morali zaradi pomanjkanja izmerjenih vrednosti oceniti z umerjanjem modela. Interval vrednosti parametrov smo povzeli po literaturi. Pred umerjanjem modela smo izvedli analizo občutljivosti modela. S tem smo dobili vpogled v naravo modela in v možnosti za umerjanje modela. Ugotovili smo smiselno odzivanje rezultatov modela na spreminjanje posameznih parametrov. Preverjanje modela, izvedeno istočasno z umerjanjem modela, je potrdilo kvalitativno ujemanje modela z realnim stanjem.

Modeli so poenostavitve procesov v naravi in ponavadi vključujejo vse pomembne procese ter komponente obravnavanega problema, toda prezrte podrobnosti imajo lahko vpliv na končni rezultat. Te vplive lahko do določene mere upoštevamo s pravilno določitvijo parametrov modela v fazi umerjanja modela. Umerjanje uporabljenega modela, ki naj bi potrdilo še kvantitativno ujemanje modela z realnim stanjem, je bilo ob danih možnostih uspešno zaključeno. Vzroke za večje razlike med izračunanimi in izmerjenimi vrednostmi, ki so se pojavile pri amoniju in organskem fosforju, in katerih s

5. CONCLUSIONS

Mathematical water quality models make it possible to predict changes in water quality due to the planned interventions in the water regime, investigate the impacts of external and internal sources of pollution on water quality, simulate the possible strategies of water resource management, improve the understanding of systems and to define unapproachable input data from the measured output data.

The river impoundment on the Sava River emerged after the construction of the Vrhovo Hydroelectric Power Plant (HEPP). A multiparametric one-dimensional QUAL2E model was used to analyse and predict possible changes of the water quality in the Sava River in the formed impoundment. The one dimensional model was used on the presumption that long narrow impoundments can be treated in the same way as unimpounded streams, i.e.: with the complete vertical and horizontal mixing of pollution in the cross-sectional profiles.

The model contains a large number of model parameters. Due to the lack of measured values, these model parameters had to be estimated by calibrating the model. The usual range of values was taken from literature. Before the model calibration, a sensitivity analysis was performed. In this way we obtained insight into the model operation and the possibilities for its calibration. We established a logical response of the model results to changes in the values of a single parameter. The model verification was performed simultaneously with the model calibration. Qualitative agreement of the model with the real state was confirmed.

Models are a simplification of processes in nature and they usually include all the important processes and components of the treated problems. However, some overlooked details could have an impact on the final result. Such impacts could be considered, to a certain extent, with the correct determination of the model parameters in the model calibration phase. It was concluded that the calibration of the model, which has to also confirm the quantitative agreement of the model with the real state, regarding the given input (measured) data, was successfully spreminjanjem parametrov v danem intervalu nismo uspeli zmanjšati, bi bilo treba raziskati z nadaljnjimi kakovostnimi in načrtnimi meritvami v akumulacijskem jezeru HE Vrhovo.

Druga faza izvedene potrditve modela z neodvisno serijo meritev v spremenjenih pogojih v akumulaciji pa ni dala povsem zadovoljivih rezultatov. Primerjava izračunov modela z izmerjenimi vrednostmi je pokazala ustrezno kvantitativno ujemanje le za raztopljeni kisik. Ujemanje za druge spremenljivke je bilo slabše.

Ker nobene od naštetih komponent v danem času ni bilo mogoče bistveno izboljšati, smo se zadovoljili s sedanjo stopnjo točnosti modela. Z modelom smo izvedli kvantitativno napoved sprememb Save v zajezitvi za ekstremne in povprečne hidrološke pogoje za raztopljeni kisik in biokemijsko potrebo po kisiku. Ugotovili smo, da je znižanje koncentracije kisika največje pri najmanjšem nizkem pretoku obdobja in znaša 0,83 mg(O_2)/l. Glede na rezultate modela in terenske meritve, izvedene pri nizkih pretokih in pogojih poteka intenzivne primarne produkcije v zajezitvi, lahko zaključimo, da v akumulacijskem jezeru HE Vrhovo ne prihaja do prekomernega znižanja koncentracije raztopljenega kisika, ki bi povzročala negativne vplive na kakovost zajezene vode.

V danem primeru gre v zajezitvi predvsem za spremembe, ki vplivajo na rekreacijsko vrednost vode, na biocenozo vode ter uporabnost vode v tehnološke in druge namene. Spremembe biocenoze so predvsem posledica spremenjenih fizikalnih lastnosti vodnega toka, na katere po zajezitvi ni mogoče vplivati. Zato lahko na biocenozo in uporabnost zajezene rečne vode vplivamo samo z obvladovanjem parametrov kakovosti voda, ki so v celoti posledica zunanje (točkovne, disperzne) in notranje polucije zajezene vode.

Naše nadaljnje delo bi moralo biti usmerjeno v odpravo pomanjkljivosti, s katerimi smo se srečali pri dosedanjem delu. Pri tem se po eni strani kaže potreba po

accomplished. The reasons for the greater differences between the calculated and the measured values of ammonium and organic phosphorus, which could not have been reduced by only varying the parameters, have to be researched with additional quality and systematic measurements in the Vrhovo Impoundment

The second phase of the model validation was performed using an independent set of measurements, which were performed in the changed conditions in the impoundment. The results were not satisfying. The comparison of the modelled results and the measured values showed suitable quantitative agreement only for dissolved oxygen. The agreement for all other simulated variables was inadequate.

Since it was not possible to essentially improve any of the listed components in the given time, we accepted the present accuracy of the model. The quantitative water quality prediction of changes of the Sava River at the Vrhovo Impoundment was performed for extreme and average hydrological conditions for dissolved oxygen and biochemical oxygen demand. We established that the concentration of the dissolved oxygen was reduced the most at a minimal low period discharge where the reduction reached 0.83 mg(O_2)/l. With regard to the model results and the field measurements achieved at low discharges and under conditions of intensive primary production in the dam, it can be concluded that an excessive decrease in the concentration of dissolved oxygen, which could have a negative influence on the impounded water quality, does not appear in the Vrhovo Impoundment.

In the given case, the changes which influenced the recreational value of the water, the water biocenosis and the applicability of water for technological and other purposes took place in the impoundment. The changes in biocenosis were, in the first place, the consequence of the changed physical properties of the stream current, which can not be influenced after the impoundment. For this reason, we can influence the biocenosis and the applicability of the impounded river water only by controlling the water quality parameters, which were, as a whole, the consequence of the external (point sources, dispersed sources) and internal pollution of the impounded water.

obsežnejših terenskih meritvah in kakovostnih laboratorijskih analizah vzorcev, po drugi strani pa so potrebne tudi izboljšave matematičnega modela oziroma prehod na vsaj dvodimenzionalni model.

Pri modeliranju kakovosti voda se lahko s pravilno opravljenimi in s popolnejšimi meritvami ter z laboratorijskimi analizami izognemo mnogim dilemam in potrebi, da določene parametre modela, ki jih je mogoče izmeriti, računamo ali privzemamo iz literature. Predvsem pa je v prvi vrsti treba vedeti, kaj želimo z modeliranjem doseči. Če je namen izračunov modela napoved kritičnih razmer v poletnih razmerah, bodo vse nadaljnje meritve usmerjene na ta čas in je smiselno, da se z izvajanjem kakovostnih meritev pridobi čim več informacij o dogajanju v akumulacijskem jezeru. Temeljni cilj nadaljnjih terenskih meritev mora biti pridobitev natančnih vhodnih podatkov oziroma pridobitev natančnejših in ustreznejših rezultatov meritev, ki bodo omogočile izvedbo natančnejšega umerjanja modela.

Model bi bilo treba dograditi tako, da bi bilo za primer modeliranja zajezitve mogoče hidravlične lastnosti odsekov opisati geometrično, vključno z možnostjo vnosa kot gladin zajezitve, kjer je vsak odsek predstavljen kot trapezoiden kanal.

Opis biokemijske potrebe po kisiku v modelu je treba dopolniti tako, da bo v njem vključen tudi prirast biološko razgradljive biomase alg.

Model je treba dopolniti tako, da bo mogoče za vrednosti srednje dnevne energije globalnega sončnega obsevanja vnesti vrednosti, večje od 400 ly.

Če se bodo pri nadaljnjem umerjanju in potrditvi modela z neodvisnimi serijami meritev še vedno pojavljale večje razlike med izmerjenimi in izračunanimi vrednostmi spremenljivk kakovosti voda, bo treba v modelu parametre, za katere se bo izkazalo, da so problematični, definirati kot funkcijo vplivnih dejavnikov.

Our further work must be focused on making up the deficiencies that we encountered in our previous work. On one side, there appeared the need for more extensive field measurements and quality laboratory analyses of the samples; on the other, improvements of the mathematical model or a transition to at least a two dimensional model are required.

When modelling water quality, correctly performed and more thorough measurements together with laboratory analyses can help us to avoid many dilemmas and the need to assume from literature or calculate certain model parameters which can be measured. First of all, the goal of our modelling must be noted. If the intention of simulations is the prediction of critical states during summer conditions, all additional measurements will be directed into this time and the purpose of quality measurements will be to acquire as much information on the activities in the impoundment as possible. The main goal of the additional measurements must be the acquisition of accurate input data or the acquisition of more accurate and more appropriate measurement results, which will enable us to elaborate a more accurate model calibration.

The model has to be improved in such a manner that it will make it possible to geometrically describe the hydraulic characteristics of the sub-reaches in the impoundment, including the possibility of entering the surface level in the impoundment, where each reach is represented as a trapezoidal channel.

The description of *BOD* in the model has to be completed by also including the newly originated biologically decomposable algae biomass.

The model must be completed in such a manner that it will allow the entrance of values greater than 400 ly for the average daily solar radiation.

If, in the additional model calibration and validation with independent sets of measurements, there still appears some major differences between the measured and the calculated values of the water quality variables, the model parameters that prove problematical will have to be defined as a function of influential factors.

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NAVODILA ZA PRIPRAVO PRISPEVKOV

1. Prispevki za *Acta hydrotechnica*

1.1 *Acta hydrotechnica* je znanstveno-strokovna periodična publikacija, katere izdajatelj in založnik je Univerza v Ljubljani, Hidrotehnična smer Fakultete za gradbeništvo in geodezijo (FGG), ki jo sestavljajo Katedra za mehaniko tekočin z laboratorijem (LMTe), Katedra za splošno hidrotehniko (KSH) in Inštitut za zdravstveno hidrotehniko (IZH). Predstavniki omenjenih enot tudi sestavljajo izdajateljski odbor revije.

1.2 *Acta hydrotechnica* izhaja dvakrat na leto v obliki zaporednih številk, dodatno razvrščenih v letnik.

1.3 *Acta hydrotechnica* je namenjena objavam prispevkov strokovnjakov in raziskovalcev s področja vodarstva in hidrotehnike. *Acta hydrotechnica* objavlja prispevke s področja vodarstva in hidrotehnike v obliki izvirnih in preglednih znanstvenih člankov, preliminarnih objav in strokovnih člankov.

1.4 Prispevki so napisani enakovredno v slovenskem in angleškem jeziku, kar zagotavlja ohranjanje in razvijanje slovenskega strokovnega izrazoslovja na področju vodarstva in hidrotehnike ter obenem zagotavlja berljivost revije v tujini. Dolžina prispevka je omejena na 30 000 znakov. Dolžina prispevka, ki je povzetek magistrske naloge ali doktorskega dela, je omejena na 100 000 znakov. Prednost pri objavi imajo krajši prispevki.

1.5 Prispevke je treba oddati v elektronski in pisni obliki na uredništvo *Acta hydrotechnica*.

1.6 Vsi prispevki so oblikovno podvrženi uredniški recenziji v skladu s temi navodili in vsebinsko podvrženi recenziji dveh strokovnjakov s področja prispevka.

1.7 Pri oblikovanju prispevkov za *Acta hydrotechnica* je treba upoštevati slovenske standarde za dokumentacijo in informatiko.

1.8 Za vsebino prispevkov in prevod v angleški jezik odgovarjajo avtorji.

1.9 Vsi prispevki so lektorirani, tako slovensko kakor tudi angleško besedilo.

2. Oblikovanje prispevkov za *Acta hydrotechnica*

2.1 Vsak prispevek mora biti sestavljen iz naslednjih enot, enakovredno podanih v slovenskem in angleškem jeziku:

- ❑ naslov prispevka
- ❑ podatki o avtorju ali avtorjih
- ❑ izvleček (abstract) in ključne besede (key-words)
- ❑ glavno besedilo
- ❑ zahvala (acknowledgements) naročniku naloge, raziskave ali študije (neobvezno)
- ❑ pregled uporabljenih izrazov (terminology) in oznak (notations) (neobvezno)
- ❑ viri (references)

Njihov natančnejši opis je podan v naslednjih odstavkih.

2.2 Naslov prispevka naj bo jasen, jedrnat in naj izraža bistvo prispevka. Dolžina naslova je največ 90 znakov, razen ko gre za povzetke magistrskih in doktorskih del, kjer je lahko naslov prispevka enak uradnemu naslovu dela.

2.3 Podatki o avtorju obsegajo ime in priimek, opis znanstvene strokovne stopnje in poln naslov delovnega mesta.

2.4 Vsak prispevek mora spremljati izvleček (abstract) v obsegu okoli 150 besed v vsakem od obeh jezikov. Izvlečka morata strnjeno podati celoten prispevek vključno z zaključki.
Avtor naj navede do 8 ključnih besed.

2.5 Glavno besedilo naj bo razdeljeno po decimalnem sistemu (1. PRVO POGLAVJE, 1.1 PRVO PODPOGLAVJE, 1.1.1 Zadnja poddelitev).
Vire v besedilu navedemo z imenom avtorja in letnico objave (Manning, 1892), (Strickler & Nikuradse, 1924b), (Einstein et al., 1951), (Colebrook, 1932; 1934).
Merske enote naj bodo v skladu z veljavnim sistemom SI. Datum naj bo podan po naslednjem vrstnem redu : dan-mesec-leto (23.4.1998).

Kratice in opombe pod črto naj se uporabljajo le izjemoma.
Ilustracije (preglednice in slike) v besedilu naj bodo skozi vse besedilo enotno oštevilčene z arabskimi številkami in naj se ne okrajšujejo (preglednica 1, slika 14, Table 2, Figure 4). Praviloma mora biti ilustracija dvojezična. Če je ilustracija privzeta iz drugega že objavljenega dela, je potrebno ob njenem opisu dodati tudi njen izvor.
Enačbe v besedilu naj bodo oštevilčene z arabskimi številkami v okroglih oklepajih enotno skozi vse besedilo, pri daljših prispevkih (več kakor 1 avtorsko polo) lahko tudi enotno za vsako poglavje posebej. Navajanje enačb naj v besedilu ne bo okrajšano (enačba (11), enačba (2.17)).

2.6 V besedilu uporabljeni viri morajo biti navedeni v abecednem vrstnem redu in neoštevilčeno, na koncu prispevka, enotno za oba jezika. Če je vir pisan v jeziku, ki ni angleški, naj naslovu vira v oklepaju sledi prevod naslova v angleščino, na koncu navedbe pa dostavek, v katerem jeziku je pisan, npr. (in Slovenian). Glede na vrsto mora avtor navesti vire takole:

- ❑ knjige : Schumm, S.A., Mosley, M.P., Weaver, W.E. (1987). *Experimental fluvial geomorphology*. Wiley, New York, 413 p.
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- ❑ objave, kjer je avtor pravna oseba (skupinski avtor) : VGI (1993). Vodnogospodarski ureditveni načrt Save Dolinke - idejna zasnova (Water Management Master Plan of the Upper Sava River). VGI, Ljubljana, Report C-161 (in Slovenian).
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