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MODELIRANJE SEZONSKIH PROMENA TEMPERATURE VODE AKUMULACIJE ĆELIJE

NUMERICAL MODELING OF WATER TEMPERATURE CHANGES IN RESERVOIR CELIJE

REZIME

U radu je dat prikaz rezultata merenja i modeliranja sezonskih promena temperature vode u akumulaciji Ćelije u periodu od aprila do oktobra 2012. godine. Akumulacija Ćelije na Rasini, već duži niz godina privlači pažnju šire javnosti i istraživača, obzirom na vodoprivredni značaj i stepen ugroženosti otpadnim vodama iz gornjeg dela sliva. Akumulacija Ćelije je glavno izvorište kruševačkog vodovoda, ali je ujedno i recipijent komunalnih i industrijskih otpadnih voda iz opština Brus i Blace. U radu je korišćen dvodimenzionalni model (CE QUAL W2), sa poprečno osrednjenim hidrodinamičkim jednačinama za modeliranje polja brzina i polja temperatura u vertikalnoj podužnoj ravni. Podaci o temperaturi vode su prikupljeni u kampanjama terenskih merenja, primenom multiparametarskih sondi. Kalibracijom modela, postiglo se dosta dobro poklapanje izmerenih i izračunatih temperatura, sa prosečnim apslutnim odstupanjem od oko 0,7°C. Za unapređen učinak modela, potrebno bi bilo smanjiti neodređenost ulaznih podataka, što bi se postiglo ponovnim puštanjem u pogon merne stanice Ravni (uzvodno od akumulacije) i postavljanjem kompletne automatske meteorološke stanice u blizini pregradnog profila.

Ključne reči: numerički model, temperatura vode, stratifikacija

RESUME

This paper presents the results of measurements and numerical modeling of water temperature changes in reservoir Celije in the period from April to October 2012. Reservoir Celije on the river Rasina, for many years attracts the attention of the general public and researchers, due to the importance of water management and impact of wastewater from the upper part of the basin. Reservoir Celije is a major source of PUC Krusevac Waterworks, but is also the recipient of municipal and industrial wastewater from the municipalities of Brus and Blace. Paper uses a two-dimensional model (CE QUAL W2), with transverse averaged hydrodynamic equations for the velocity and temperature field modeling in the vertical longitudinal plane. Data on the water temperature were collected in the field sampling campaigns, using multi - parameter probes. Model calibration enabled good comparison of measured and calculated temperatures, with average absolute deviation of about 0.7 °C. For enhanced model performance, it would be necessary to reduce the uncertainty of the input data, which can be achieved by re- commissioning of the measuring station Ravni (upstream of the reservoir) and setting automatic weather station in the vicinity of the barrier.

Key words: numerical model, water temperature, stratification

1. UVD

Poznavanje sezonske termalne dinamike, smatra se jednim od najbitnijih saznanja o određenom akvatičnom ekosistemu. Gotovo svi procesi koji se mogu sresti u hidroekosistemu su termički zavisni. Temperatura vode utiče na procese transporta i mešanja, obzirom da je gustina vode zavisna od temperature (Fisher, 1979; Hutter, 2011; Boehrer and Schultze, 2007). Temperatura vode utiče na rastvorljivost, zatim na sadržaj rastvorenih gasova u vodi. Brojna literatura dokumentuje uticaj termalne dinamike jezera i akumulacija na biološke i hemijske procese koji se u njima odvijaju (Chapra, 1997; Welch and Jacoby, 2005).

Krajem zime i početkom proleća, jezera i akumulacije

1. INTRODUCTION

Knowledge of seasonal thermal dynamics is considered one of the most important information about a particular aquatic ecosystem. Almost all processes that can be found in hydroecosystems are thermally dependent. Water temperature affects the processes of transport and mixing, since the water density depends on the temperature (Fisher, 1979; Hutter, 2011; Boehrer and Schultze, 2007). Water temperature affects the solubility and the content of dissolved gases in the water. Numerous literature presents the impact of the thermal dynamics of lakes and reservoirs on the biological and chemical processes that take place in them (Chapra, 1997; Welch and Jacoby, 2005).

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kontinentalnog klimata su potpuno izmešana. Temperatura vode je približno konstantna od površine do dna, ne postoji vertikalni gradijent gustine, pa i slab vetar unosi dovoljno energije da se vodena kolona potpuno pomeša. Dolaskom proleća, raste intenzitet i trajanje sunčevog sjaja, pa se površinski sloj polako zagreva. U toku leta, uočljiva su dva sloja različite temeprature i gustine. Epilimnion, površinski sloj vode, velike temperature i male gustine, leži preko donjeg sloja-hipolimniona, u kome se nalazi hladna voda veće gustine. Na kontaktu ova dva sloja, nalazi se termoklina, izražen gradijent vetikalnog profila temperature, koji sprečava vertikalni transfer materije i količine kretanja, između dva sloja različitih gustina. Zbog toga jezera i akumulacije, pored termičke stratifikacije, ispoljavaju i bio-hemijsku stratifikaciju, tj. epilimnion i hipolimnion imaju značajno različite fizičke i bio-hemijske karakteristike. Početkom jeseni, dolazi do postepenog hlađenja gornjeg sloja, termoklina polako tone i pred početak zime, jezero je potpuno pomešano. Ukoliko je zima dovoljno hladna, tako da dodje do formiranja ledenog pokrivača, zahvaljujući činjenici da voda ima najveću gustinu na 4 °C, ostvaruje se inverzna stratifikacija, kada je voda ispod leda najhladnija, a temperatura se povećava prema dnu akumulacije. Otapanjem leda početkom proleća, dolazi do ponovnog uspotavljanja uniformne gustine po dubini, pa je vodena kolona ponovo potpuno pomešana (Chapra, 1997; Henderson-Sellers, 1984).

Sezonski termalni ciklus jezera i akumulacija se godinama unazad uspešno modelira primenom modela različitih formulacija. Što se tiče dimenzionalnosti modela, najčešće se koriste 1D modeli u vertikalnom pravcu i 2D modeli u vertikalnoj ravni. Za primenu 3D modela uglavnom nema dovoljno podataka za kalibraciju i verifikaciju, pa se oni koriste uglavnom za simulacije fenomena koji imaju dnevnu ili nedeljnu dinamiku (Hodges et al., 2000, Johnk and Umlauf, 2001).

Modeliranje transportne jednačine termalne energije, razlikuje se od modeliranja transportnih jedanična drugih konstituenata u vodi, u smislu da temperatura vode utiče na gustinu vode, pa se jednačine hidrodinamike i transporta toplote, moraju rešavati simultano (Patankar, 1980). U ovom radu, za potrebe modeliranja sezonskog termalnog ciklusa akumulacije Ćelije, koristili smo model CE Qual W2 (Cole and Wells, 2011). Model je zasnovan na lateralno osrednjenim hidrodinamičkim jednačinama i na pretpostavci o hidrostatičkoj raspodeli pritisaka. Podaci potrebni za kalibraciju modela, obezbeđeni su terenskim merenjima primenom multiparametarskih sondi, opremljenih senzorima za merenje temperature.

U smislu fizičke limnologije, akumulacije Ćelije pripada umerenom klimatu. Akumulacije je uglavnom monomiktična (jedno, jesenje mešanje vodene kolone), a u slučaju oštrih zima (npr. 2012. godine), kada dolazi do formiranja ledenog pokrivača i zimske inverzne stratifikacije, akumulacije je dimiktična (jesenje i prolećno mešanje vodene kolone). Letnja termička

In late winter and early spring, lakes and reservoirs of the continental climate are completely mixed. Water temperature is approximately constant from the surface to the bottom, there is no vertical gradient of density, and even low wind gets enough energy to fully mix water column. Arrival of spring increases the intensity and duration of sunlight, and the surface layer is slowly heated. There are obviously two layers of a variety of temperatures and densities during the summer. Epilimnion, the surface layer of water, with high temperature and low density, lies across the lower layer - hypolimnion, where the cold water is denser. At the contact of the two layers is the thermocline, expressed vertical profiles of temperature gradient, which prevents vertical transfer of matter and motion, between two layers of different density. Therefore, lakes and reservoirs, in addition to thermal stratification, express biochemical stratification, i.e. epilimnion and hypolimnion have significantly different physical and bio chemical characteristics. In early fall, there is a gradual cooling of the upper layer, thermocline is slowly sinking and at the beginning of winter, the lake is completely mixed. If the winter is cold enough to come to the formation of ice cover, due to the fact that water has a maximum density at 4 °C, inverse stratification is achieved, when the water under the ice is the coldest, and the temperature increases towards the bottom of the reservoir. Melting ice in early spring creates uniform density, and the water column is again completely mixed (Chapra, 1997; Henderson-Sellers, 1984).

Seasonal thermal cycle of lakes and reservoirs has been successfully modeled for years using models of different formulations. As for the dimensionality of the model, the most commonly are used 1D models in the vertical direction and 2D models in the vertical plane. For the application of 3D models there is generally lack of data for calibration and verification, and they are used mainly for the simulation of phenomena that have daily or weekly schedule (Hodges et al., 2000 JohnK and Umlauf, 2001).

Modeling of thermal energy transport equation is different from modeling transport equations of other water constituents, meaning that water temperature affects the density of water, and the equations of hydrodynamics and heat transport, must be solved simultaneously (Patankar, 1980). In this paper, for the purposes of modeling the seasonal thermal cycle of the Celije reservoir, we used a model of CE Qual W2 (Cole and Wells, 2011). Model is based on the laterally averaged hydrodynamic equations and the assumption of hydrostatic pressure distribution. Data required for calibration, are provided by field sampling using a multi-parameter probe, equipped with temperature sensors.

In terms of physical limnology, Celije reservoir belongs to a moderate climate. Reservoir is mainly monomictic (one, autumnal mixing of water column), and in the case of severe winters (e.g. 2012.), when it comes stratifikacija je izražena, a površinske temperature vode dosežu do 30°C (Ivetić et al., 2012, Nenadić et al., 2013). Kalibracijom modela, postiglo se dosta dobro poklapanje izmerenih i izračunatih temperatura, sa prosečnim apslutnim odstupanjem od oko 1°C. Za unapređen učinak modela, potrebno bi bilo smanjiti neodređenost ulaznih podataka, što bi se postiglo ponovnim puštanjem u pogon merne stanice Ravni (uzvodno od akumulacije) i postavljanjem kompletne automatske meteorološke stanice u blizini pregradnog profila. Takođe, snimanje polja brizina omogućilo bi kalibraciju, hidrodinamičkog dela modela, koja je ovog puta, zbog nedostatka podataka, izostala.

2. METODOLOGIJA

Višenamenska akumulacija Ćelije (43°23'22''N; 21°09'48''E) formirana je 1978. godine pregrađivanjem reke Rasine kamenom nasutom branom, udaljenom oko 20 km uzvodno od grada Kruševca. Akumulacija ima izdužen oblik, sa tri uočljiva basena: Vodozahvat (u blizini pregradnog mesta), Vasići (srednji deo akumulacije) i Zlatari (uzvodni deo akumulacije), slika 1. Akumulacije Ćelije je projektovana sa prvobitnom namenom prihvatanja nanosa i zaštite od poplava. Prihvatanjem nanosa, štiti se Đerdapska akumulacija od zasipanja, a od poplave se brane Kruševac i dolina Rasine nizvodno od akumulacije. Vremenom je akumulacija Ćelije, postala glavno izvorište kruševačkog vodovodnog sistema, iz kog se snabdeva stanovništvo i lokalna industrija, ali i popularno izletište i omiljena ribolovačka destinacija.

Dužina akumulacije je 9,4 km, kota normalnog uspora je na nadmorskoj visini od 277 m n.m, a pri koti maksimalnog uspora (284 m n.m.), zapremina akumulacije iznosi 64 miliona m^3, maksimalna dubina 45 m, a maksimalna širina 800 m. Površina sliva do profila brane iznosi 606 km^2, a višegodišnji srednje-mesečni proticaj u profilu brane iznosi 5,84 m^3/s. Srednje vreme izmene vode iznosi 80 dana.

U akumulaciju Ćelije se ulivaju netretirane komunalne i industrijske otpadne vode iz opština Brus i Blace. Zbog povećanog unosa nutrijenata i organske materije, akumulacija pati od ubrzane eutrofizacije, koja ugrožava kvalitet vode i dovodi do hipoksije i anoksije u hipolimnionu u toku leta (Anđelković et al., 2010). Analizom sedimenta utvrđen je povišen nivo huminskih kiselina (Jokic et al., 1995). Mikrobiološkim analizama otkrivena je visoka brojnost bakterioplanktona koji je indikator sredine bogate nutrijentima (Ćirić et al., 2012). Poseban problem akumulacije vezuje se za prisustvo toksičnih vrsta modro-zelenih algi u poslednjoj deceniji (Grašić et al., 2004, Svirčev et al., 2007), kao i pojava gvožđa i mangana u povišenim koncentracijama (Nikić et al., 2008).

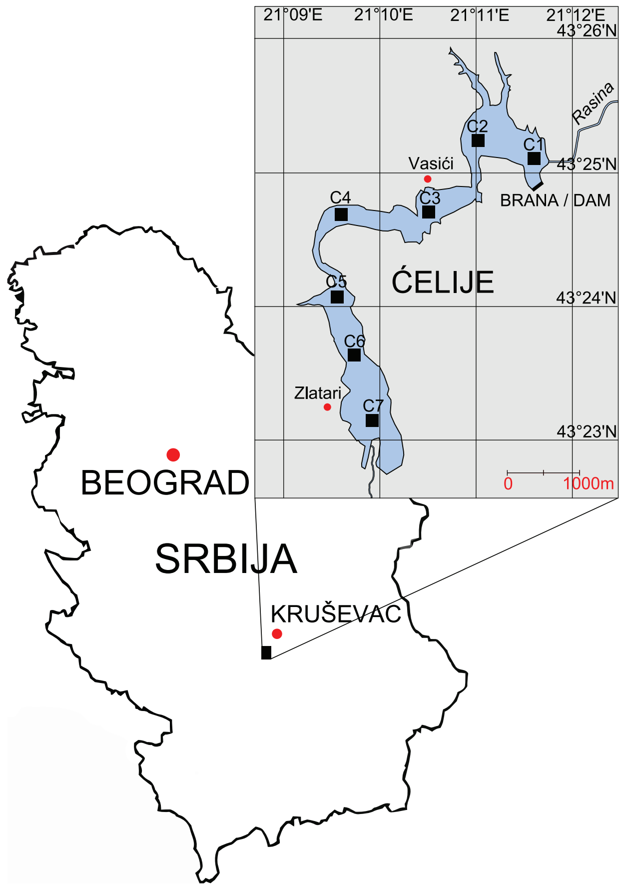
to the formation of the ice cover and winter inverse stratification, reservoir is dimictic (fall and spring mixing of the water column). Summer thermal stratification is expressed, and surface water temperature reaches up to 30 °C (Ivetić et al., 2012, Nenadic et al., 2013). Calibration of the model enabled a good superposition of measured and calculated temperatures, with an average absolute deviation of about 1°C. For enhanced model performance, it would be necessary to reduce the uncertainty of the input data, which can be achieved by re-commissioning of the Ravni measuring station (upstream of the reservoir) and setting completely automatic weather station in the vicinity of the barriers. Also, recording of velocity field would allow calibration of the hydrodynamic part of the model, which is missing, due to lack of data.

2. METHODOLOGY

Multipurpose reservoir Celije (43°23'22"N; 21°09'48"E) was formed in 1978, damming of the river Rasina using stone embankment dams, located about 20 km upstream from the town of Krusevac. Reservoir has an elongated shape, with three distinct basins: Vodozahvat (near the dam) Vasici (middle part of the reservoir) and Zlatari (upstream part of the reservoir), Figure 1. Reservoir Celije is designed with the original purpose of accepting deposits and flood protection. Accepting deposits protects the Djerdap accumulation from siltation and flooding of the Krusevac and the valley of Rasina downstream from the reservoir. Over time, the Celije reservoir, become the main source of Krusevac water supply system that supplies the population and local industry, as well as a popular resort and a favorite fishing destination.

Length of the reservoir is 9.4 km, elevation of the normal slowdown is at an altitude of 277 m above sea level, and at the elevation of maximum gradient (284 m asl), storage capacity is 64 million m^3, maximum depth is 45 m and a maximum width 800 m. Catchment area up to the dam profile is 606 km^2, and the long-term mean-monthly flow in the profile of the dam is 5.84 m^3/s. Median time of the water change is 80 days.

Reservoir Celije accepts untreated municipal and industrial wastewater from the municipalities of Brus and Blace. Due to the increased input of nutrients and organic matter reservoir suffers from accelerated eutrophication, threatening water quality and leads to hypoxia and anoxia in hypolimnion during summer (Andjelkovic et al., 2010). Sediment analysis showed elevated levels of humic acid (Jokic et al., 1995). Microbiological analysis revealed a high abundance of bacterioplankton, an indicator nutrient-rich environment (Ciric et al., 2012). Particular problem of the reservoir is related to the presence of toxic species of blue-green algae in the last decade (Grašić et al., 2004 Svirčev et al., 2007), and the occurrence of iron and manganese in elevated concentrations (Nikic et



Slika 1. Akumulacija Ćelije, nalazi se 20-ak kilometara uzvodno od Kruševca. Crnom bojom ispunjenji kvadratići, označavaju lokacije uzorkovanja
Figure 1. Study area-Reservoir Celje, 20 kilometers upstream Krusevac; Black squares stand for sampling sites

2.1 Merenja temperature vode u akumulaciji Ćelije

Merenja kvaliteta vode u akumulaciji Ćelije, Građevinski fakultet iz Beograda, započeo je u aprilu 2012. godine, najpre za potrebe izrade *Studije o proceni rizika i osetljivosti pokazatelja kvaliteta vode u akumulacijama Gruža i Ćelije* (investitor: Republička Direkcija za vode), da bi ih nastavio pod pokroviteljstvom naučnog projekta *Merenje i modeliranje fizičkih, hemijskih, bioloških i morfodinamičkih parametara reka i vodnih akumulacija-MORE* (Ministarstvo prosvete, nauke i tehnološkog razvoja Republike Srbije).

Temperatura vode, meri se na ukupno sedam lokacija, ravnomerno raspoređenih po podužnoj osovini akumulacije. Temperatura se meri multiparametarskim sonadama (Horiba U54G i YSI ProODO), od površine do dna, sa inkrementima dubine od po jedan metar. Senzor temperature je na bazi pt100 otpornog termometra, sa malom vremenskom konstantom. Na slici 2, prikazani su korišćeni merni uređaji. Na slici 3, prikazani su neki od prizora sa terenskih merenja u specifičnim vremenskih uslovima.

al., 2008).

2.1 Water temperature measurements in the Celije reservoir

Water quality measurements in the Celije reservoir by the Faculty of Civil Engineering, Belgrade, started in April 2012, at first for the preparation of the *Risk assessment and vulnerability of water quality indicators in the reservoirs Gruza and Celije* (Investor: Water Directorate), only to be continued under the auspices of the research project *Measurement and modeling of physical, chemical, biological and morpho-dynamic parameters of rivers and water reservoirs-MORE* (Ministry of Education, Science and Technological development of the Republic of Serbia).

Water temperature, is measured at seven locations evenly distributed along the longitudinal axis of the reservoir. Temperature is measured by multiparameter probes (Horiba U54G and YSI ProODO), from surface to bottom, with incremental depth of one meter. Temperature sensor is based on the resilient pt100 thermometer with a small time constant. Figure 2, shows the used instrumentation. Figure 3, shows some of the scenes from field sampling in specific weather conditions.

Slika 2. Multiparametarska sonda HORIBA U54G (a) i sonda za temperaturu i rastvoreni kiseonik YSI ProODO
Figure 2. Multiparemeter probe HORIBA U54G (a) and two-paremeter (temeprature and DO) probe YSI ProODO with optical dissolved oxygen sensor

2.2 Simulation model of seasonal water temperature changes in the Celije reservoir

Seasonal thermal dynamics of Celije reservoir, is simulated using a two dimensional model in the vertical plane, CE QUAL W2 (version 3.71; Portland State University and the U.S. Army Corps of Engineers). Model relies on cross-averaged hydrodynamic equations and the equation of heat transport, as well as the assumption of hydrostatic pressure distribution. Diffusion coefficients in the horizontal plane are the input data, and the coefficients of turbulent viscosity

Slika 3. Prizori sa terenskih merenja u najtežim vremenskim uslovima
Figure 3. Scenes from field measurements under harsh weather conditions

2.2 Simulacioni model sezonskih promena temperature vode u akumulaciji Ćelije

Sezonska termalna dinamika akumulacije Ćelije, simulirana je primenom dvodimenzionalnog modela u vertikalnoj ravni, CE QUAL W2 (verzija 3.71; Portland State University i U.S. Army Corps of Engineers). Model se oslanja na poprečno osrednjene hidrodinamičke jednačine i jednačinu transporta toplote, kao i na pretpostavku o hidrostatičkoj raspodeli pritiska. Koeficijenti difuzije u horizontalnoj ravni su ulazni podatak, dok se koeficijenti turbulentne viskoznosti u vertikalnom pravcu računaju pomoću nekoliko ponuđenih modela turbulencije. Modelom ovakve formulacije, korektno se modeliraju relativno dugačka i uska vodna tela, sa izraženim longitudinalnim i vertikalnim gradijentima pokazatelja kvaliteta (Cole and Wells, 2011).

U nastavku su nabrojani potrebni ulazni podaci:

- **Podaci o reljefu dna akumulacije – batimetrija:** računska mreža podužnih i vertikalnih segmenata sačinjena je na osnovu digitalnog modela jezerskog dna koji je izrađen digitalizacijom karata razmere 1:25000. U plitkom uzvodnom delu akumulacije, koji pripada opštini Brus, mreža je profinjena sa dve tačke trigonometrijske mreže i sa 95 tačaka poligonske mreže. Rezultat je računska mreža prikazana na slici 3, sa tri grane, od kojih prva, koja predstavlja glavni tok akumulacije, ima ukupno 18 podužnih segmenata promenljivih dužina, dok grane 2 i 3, koje predstavljaju rukavce u basenu vodozahvata imaju po dva podužna segmenta. Dužine su određivane na osnovu kriterijuma kojim se zahteva približno ista zapremina susednih segmenata, a zarad obezbeđivanja numeričke stabilnosti modela. Zapremina akumulacije je u vertikalnom pravcu diskretizovana slojevima visine 1,0 m.

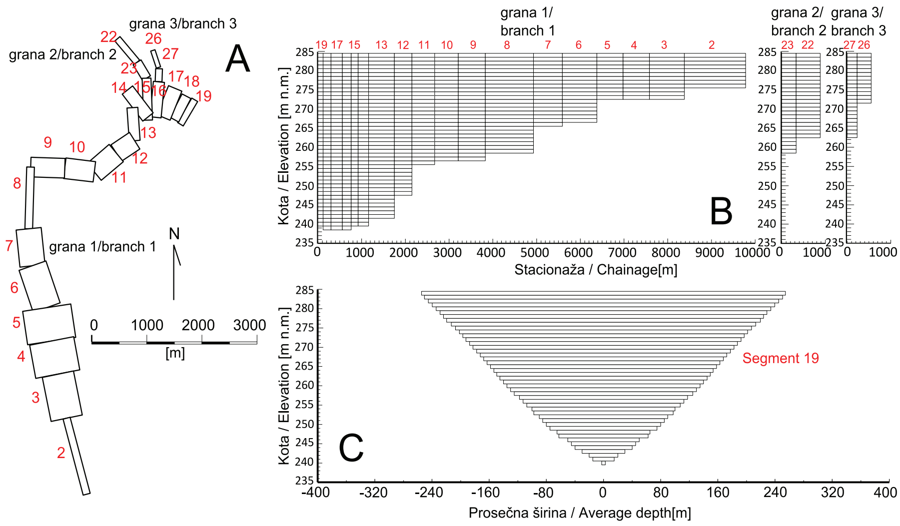
in the vertical direction are calculated using several models of turbulence. Such formulated model enables modeling of relatively long and narrow water bodies, with strong longitudinal and vertical gradients of quality indicators (Cole and Wells, 2011).

Below are the necessary input data:

- **Data on the relief of the reservoir bottom - bathymetry:** numerical grid of longitudinal and vertical segments was made based on a digital model of lake bed that is made by digitizing maps of scale 1:25000. In the shallow upstream part of the reservoirs which belongs to the municipality of Brus, the network is a sophisticated with two points of trigonometric network and 95 points of polygonal network. Result is a numerical network shown in Figure 3, with three branches, of which the first, which is the main stream of the reservoirs, has a total of 18 longitudinal segments of variable length, and branches 2 and 3, which are backwaters in the water catchment basin have two longitudinal segments. Lengths are measured on the basis of criteria which require approximately the same volume of adjacent segments, and for ensuring the stability of the numerical model. Volume of the reservoir is in the vertical direction discretized by 1.0 m high layers.
- **Simulated period, initial and boundary conditions:** simulated changes of water temperature in the reservoir between January 1st until October 31st, 2012. Since the measured data are as of April 2012, the temperature at the beginning of the simulation is adopted as a constant amount of 4 °C. The most important boundary conditions are:
    - elements of the mass and thermal energy balance (input and output water flow and temperature) and
    - meteorological input data

Upstream boundary condition of the model is the river Rasina input water flow. However, the time series of measured values of the flow rate for a given period were not available during model development as measuring station Ravni upstream of the reservoir was not operational. Input flows are therefore obtained from the known output of the system (water supply

- **Simulirani period, početni i granični uslovi:** simulirane su promene temeperature vode u akumulaciji od 1. januara do 31. oktobra 2012. godine. Obzriom da mereni podaci postoje od aprila 2012., temperatura na početku simulacije je usvojena kao konstanta u iznosu od 4 °C. Od graničnih uslova najbitniji su:
  - elementi bilansa mase i toplotne energije (protok i temperature vode koja dotiče i protok i temperature vode koji napuštaju akumulaciju) i
  - meteorološki ulazni podaci



Slika 3. Prostorna diskretizacija akumulacije Ćelije; A: osnova, B: podužni presek i C: poprečni presek u najnizvodnijem preseku (segment 19)

Figure 3. Spatial numerical grid for reservoir Celije; A: plan view, B: longitudinal profile and C: cross section through the most downstream segment (segment no. 19)

Uzvodni granični uslov modela predstavlja doticaj rekom Rasinom. Međutim, vremenske serije merenih vrednosti ovih protoka za razmatrani period nisu bile dostupne tokom razvoja modela obzirom da merna stanica Ravni, uzvodno od akumulacije nije bila u funkciji. Ulazni protoci su zbog toga dobijeni na osnovu poznatog izlaza iz sistema (vodosnabdevanje i oticaj Rasinom) i registrovanih promena nivoa vode u akumulaciji. Korišćeni su mesečni bilansi, usled čega su sračunate vrednosti doticaja srednje-mesečne. Ovom metodom su u doticaje Rasinom uračunati i svi ostali elementi bilansa (padavine, dotoci manjim tokovima, slivanje sa okolnih padina, isparavanje vode, procurivanje itd.). Obzirom da ni podaci o temperaturi Rasine nisu bili na raspolaganju, usvojena je smela i na prvi pogled gruba pretpostavka kojom se korelišu temperatura vode u Rasini i temperature vazduha sa najbliže meteorološke stanice Kruševac. Upotrebili smo linearnu regresionu funkciju, do koje su došli Pilgrim i saradnici (1995) na uzorku od 43 manja vodotoka u Američkoj saveznoj državi Minesoti:

$$Tvode = 1{,}9 + Tvazduha$$

gde temperature, date u °C, predstavljaju nedeljno osrednjene vrednosti. Ova pretpostavka na sreću nije u mnogome uticala na krajnje rezultate modela. Meteorološki podaci u vidu vremenskih serija sa rezolucijom od jednog sata, preuzeti su sa najbliže meteorološke stanice "Kruševac", udaljene oko 21 km od profila brane, na 118 m manjoj nadmorskoj visini od kote normalnog uspora akumulacije.

Kalibracija modela: podaci za kalibraciju obezbeđeni su u kampanjama terenskih merenja u aprilu, junu, septembru i oktobru, 2012. godine, prema prethodno opisanoj metodologiji. Korekcijom parametara koji opisuju zasenčenost akumulacije i parametara koji opisuju slabljenje intenziteta svetlosti niz vodenu kolonu, postiglo se zadovoljavajuće slaganje računatih

and runoff of the river Rasina) and registered changes of water levels in the reservoir. Monthly balance was used, calculating the values of average-month inflow. This method includes all the other elements of balance (precipitation, smaller inflows, interflow from surrounding slopes, water evaporation, seepage, etc.). Since no water temperature data of the river Rasina were available, it was adopted at first glance a rough assumption which makes correlation between the river Rasina water temperature and air temperature from the nearest weather station Krusevac. We used linear regression function reached by the Pilgrim et al. (1995) in a sample of 43 small streams in the U.S. state of Minnesota:

$$Tvode_{/water} = 1{,}9 + Tvazduha_{/air}$$

where temperatures are given in °C, and represent weekly averaged values. This assumption, fortunately, does not greatly affect the final results of the model. Meteorological data in the form of time series with a resolution of one hour, are taken from the nearest meteorological station "Krusevac", located about 21 km from the dam profile at 118 m lower sea level than the level of normal slowdown of the accumulation.

Model calibration: Calibration data are provided in the campaigns of field sampling in April, June, September, and October, 2012, according to previously described methodology. Correction of parameters describing shade of the accumulation and parameters that describe the attenuation of light intensity down the water column, enabled a satisfactory comparison of calculated and measured water temperatures, with a absolute mean error (AME) of 0.7 °C. Given the assumption of hydrostatic pressure distribution, the model showed significant sensitivity of downstream and upstream boundary condition. It is assumed that the upstream water of the river Rasina i merenih temperature vode, sa srednjom apsolutnom greškom (AME - Absolute Mean Error) od 0,7°C. Obzirom na pretpostavku o hidrostatičkoj raspodeli pritisaka, model je ispoljio značanju osetljivost na nizvodni i uzvodni granični uslov. Pretpostavljeno je da se voda iz Rasine na uzvodnom kraju u potpunosti meša sa vodom u uzvodnom segmentu, umesto da "pronalazi" vertikalni sloj odgovarajuće ambijentalne gustine.

3. REZULTATI I DISKUSIJA

Na slici 4, dat je uporedni prikaz merenih i modeliranih vertikalnih profila temperature. Dijagrami na slici 4a, odnose se na profil u blizini brane (segment 18 modela, odn. merno mesto C1), za mesece u kojima postoje podaci merenja: april, jun, septembar i oktobar. Evidentno je dobro poklapanje izmerenih i izračunatih temperatura. Odstupanja su nešto veća u slučaju površinskih temperatura i model ima tendenciju precenjivanja površinskih temperatura. U septembru i oktobru, kada termoklina počinje da tone, model ispoljava manju inertnost (odziv na promenu graničnih uslova) od realne, pa je i položaj modelovane termokline, nešto niži od izmerene. Slične konstatacije odnose se i na dijagrame na slici 4b, koji prikazuju merene i modelirane profile temperature na sredini akumulacije (segment 11 modelske mreže, odn. merno mesto C3 sa slike 1). Kao i u prethodnom slučaju, najveća odstupanja modela od izmerenih vrednosti su u aprilu i to se verovatno može objasniti velikim protokom Rasine, kojim se unosi i nedovoljno poznata količina toplote. Uzvodni profil (segment 4, merno mesto C7), je pod najvećim uticajem pritoke. Međutim i u njemu su odstupanja merenih i modeliranih vrednosti prihvatljiva (slika 4c), pa se može reći da je pretpostavka o proceni temperatura vode u Rasini, opravdana u uslovima nedostatka merenih podataka. Izmerene površinske temperature kreću se od nekih 12°C do skoro 30°C u uzvodnom delu akumulacije.

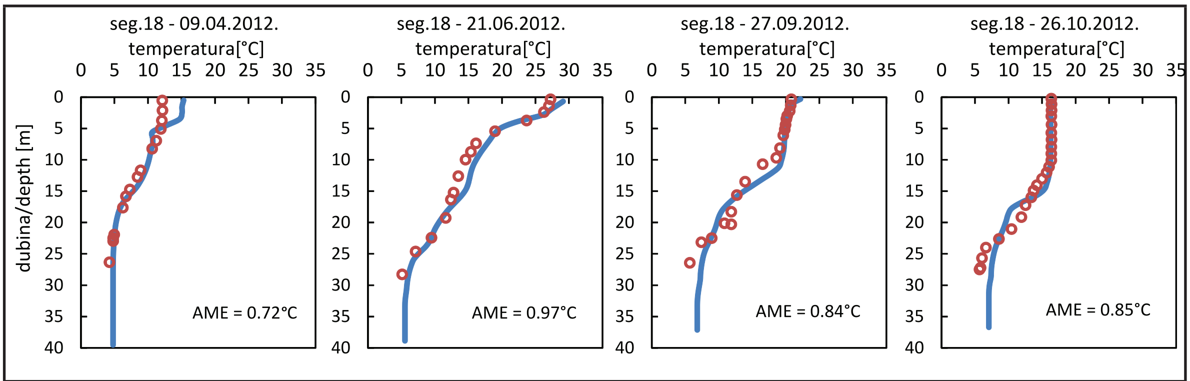
Na slici 5, dat je grafički prikaz rezultata kalibrisanog modela u vidu podužnih profila sa konturnim linijama. U januaru, na početku perioda koji se simulira, akumulacije je potpuno izmešana, sa uniformnom temperaturom po celoj zapremini od 4°C. Niske temeprature vazduha u februaru, uslovile su inverznu stratifikaciju i pojavu ledenog pokrivača. U martu počinje postepeno povećanje temperature vode od uzvodnog ka nizvodnom kraju i od površine prema dnu, usled dolaska nešto toplije vode iz Rasine i usled povećanja trajanja i intenziteta sunčevog sjaja. Treba napomenuti da su se prethodno stvorili uslovi za otapanje ledenog pokrova i mešanje vodene kolone. U aprilu se nastavlja trend rasta temperatura i dolazi do uspostavljanja slabe termičke stratifikacije. U avustu je evidentna izražena termička stratifikacija. Računate površinske temperature u uzvodnom delu akumulacije dostižu i 30°C. U septembru započinje značajnije hlađenje površinskog sloja i teroklina se povlači ka većim dubinama. Treba napomenuti da se tempera-

is fully mixed with water in the upstream segment, instead of "finding" vertical layer of the appropriate ambient density.

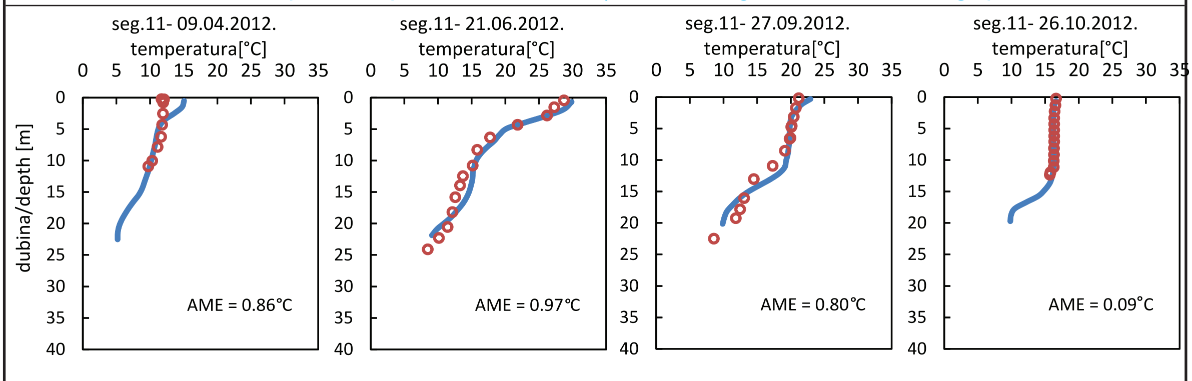
3. RESULTS AND DISCUSSION

Figure 4 shows a comparative view of the measured and modeled vertical temperature profiles. Diagrams in Figure 4a, refer to the profile near the dam (segment 18, sampling point C1), for the months in which there are data measurements: April, June, September and October. It is evident a good agreement between measured and calculated temperatures. Deviations were slightly higher in the case of surface temperature, because the model tends to overestimate surface temperatures. In September and October, when the thermocline begins to sink, the model shows less inertia (response to changing boundary conditions) of the real and the position of the modeled thermocline is somewhat lower than measured. Similar observations apply to the diagrams in Figure 4b, showing the measured and modeled temperature profiles in the middle of the reservoir (segment 11, sampling point C3 in Figure 1). As in the previous case, the maximum deviations of the measured values of the model are in April, and it probably can be explained by the large water flow of the river Rasina, which enters undefined amounts of heat. Upstream profile (segment 4, sampling point C7), is the most affected by tributaries. However, differences in the measured and calculated values are acceptable (Figure 4c), so we can say that the assumption of estimated water temperatures of the river Rasina are justified in terms of the lack of measured data. Measured surface temperatures range from about 12°C to almost 30°C in the upstream part of the reservoir.

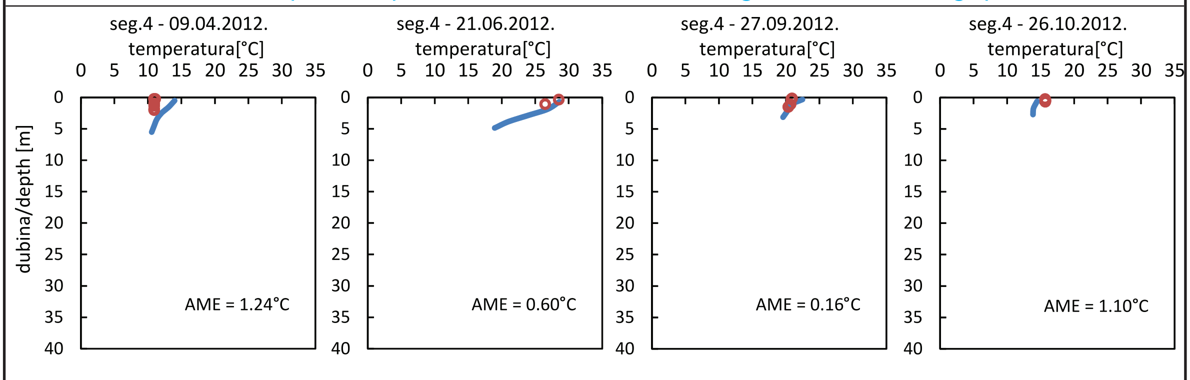
Figure 5 shows a graphic presentation of the results of calibrated models in the form of longitudinal profiles with contour lines. In January, at the beginning of the simulated period, reservoir is completely mixed, with uniform temperature over the entire volume of 4 °C. Low air temperatures in February, resulted in an inverse stratification and the emergence of the ice sheet. In March, begins a gradual increase in water temperature from the upstream to the downstream end and from the surface to the bottom, due to the arrival of some warmer water from the river Rasina and due to the increased duration and intensity of sunshine. It should be noted that were previously created conditions for ice sheet melting and mixing of the water column. In April, the trend of temperature growth is continuing and leads to the formation of weak thermal stratification. In August there is an expressed thermal stratification. Calculated surface temperatures in the upstream part of the reservoir reach 30°C. In September begins a significant cooling of the surface layer and thermocline retreats to greater depths. It should be noted that the water temperature in the innermost layer is moving in a very narrow range of 4 to 7 °C.



a) Vertikalni profili temperature u blizini brane (segment 18, merno mesto C1)
a) Vertical temperature profile in the vicinity of dam (segment 18, measuring spot C1)



b) Vertikalni profili temperature na sredini akumulacije (segment 11, merno mesto C3)
b) Vertical temperature profile in the middle section (segment 11, measuring spot C3)



c) Vertikalni profili temperature u najuzvodnijem delu akumulacije (segment 4, merno mesto C7)
c) Vertical temperature profile in the upstream part of the reservoir (segment 4, measuring spot C7)

Slika 4. Vertikalna distribucija temperature u segmentima 18, 11, i 4 (C1, C3 i C7); plava linija - model; crvene kružnice - merenja.

Figure 4. Vertical distribution of temperature in segments 18, 11, and 4 (C1, C3 and C7); blue line - model; red circles - measured values.

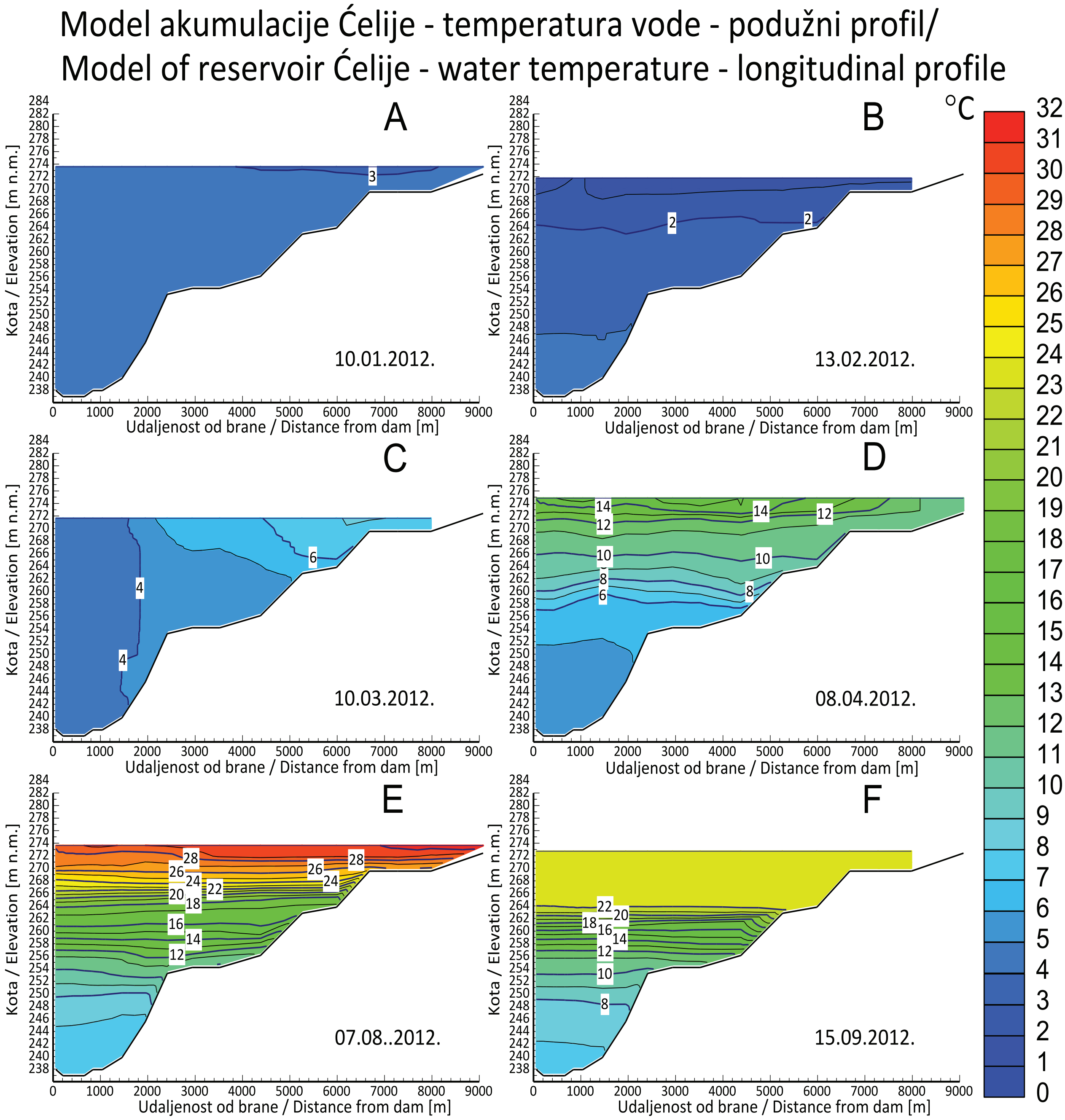
ture vode u najdubljem sloju kreću u vrlo uskom opsegu od 4 do 7°C.

5. ZAKLJUČAK

Poznavanje sezonske termalne dinamike, smatra se jednim od najbitnijih saznanja o određenom akvatičnom ekosistemu. Gotovo svi procesi koji se mogu sresti u hidroekosistemu su termički zavisni. Kalibrisan i verifikovan matematički model predstavlja koristan alat za dispečera, koji je odgovoran da upravlja

4. CONCLUSION

Knowledge of seasonal thermal dynamics is considered to be one of the most important information about a particular aquatic ecosystem. Almost all processes that can be found in hydroecosystems are thermally dependent. Calibrated and verified mathematical model is a useful tool for dispatcher, who is responsible to manage the reservoir. Different management models and their effects, in terms of different meteorological scenarios, are useful to evaluate on the model before into practice. In this study, a



Slika 5. Distribucija temperature u podužnom profilu akumulacije, u karakterističnim vremenskim presecima.
Figure 5. Distribution of water temperature in longitudinal profile, captured in characteristic periods of time

akumulacijom. Različite modele upravljanja i njihove efekte, u uslovima različitih hidrometeoroloških scenarija, korisno je vrednovati na modelu, pre nego što se sprovedu u praksi. U ovom radu je korišćen model CE QUAL W2 (ver 3.71) sa poprečno osrednjenim hidrodinamičikim jednačinama, koji je pogodan za modeliranje sezonske dinamike dubokih, izduženih i relativno uskih vodnih tela. Model nije pogodan za modeliranje složenih prostornih strujanja kakva se mogu sresti na mestu uliva pritoke ili u okolini vodozahvata, obzirom da je sam model dvodimenzionalan i da se oslanja na pretpostavku o hidrostatičkoj raspodeli pritisaka kojom se u dinamičkoj jednačini za vertikalni pravac zanemaruju vertikalna ubrzanja. Kalibracijom modela došlo se do dobrog slaganja

model of CE QUAL W2 (ver 3.71) was used with a transversely averaged hydrodynamic equations, which is suitable for modeling the seasonal dynamics of deep, elongated and relatively narrow water bodies. Model is not suitable for modeling complex spatial flows which may be encountered at the inflow site or in the vicinity of the water catchment area, due to the fact that the model is two-dimensional and is based on the assumption of hydrostatic pressure distribution, which is neglecting vertical acceleration in the dynamic equation for the vertical direction. Calibration of the model led to the good agreement of measured and calculated temperature fields (absolute mean error of 0.7 °C), which can be considered a success in conditions of high uncertainty of input data. For enizmerenih i računatih temperaturnih polja (srednje apsolutno odstupanje 0,7 °C), što se u uslovima velike neodređenosti ulaznih podataka, može smatrati uspehom. Za unapređen učinak modela, potrebno bi bilo smanjiti neodređenost ulaznih podataka, što bi se postiglo ponovnim puštanjem u pogon merne stanice Ravni na Rasini (uzvodno od akumulacije) i postavljanjem kompletne automatske meteorološke stanice u blizini akumulacije Ćelije.

Zahvalnost

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hanced performance models, it would be necessary to reduce the uncertainty of the input data, which can be achieved by re-commissioning of the measuring station Ravni on the river Rasina (upstream from the reservoir) and setting completely automatic weather station in the vicinity of the Celije reservoir.

Gratitude

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