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TOPLOTNA OBREMENITEV SAVE DOLVODNO OD TRBOVELJ
THERMAL LOAD OF THE SAVA RIVER DOWNSTREAM FROM TRBOVLJE

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Prikazani so bili rezultati študije "Toplotna obremenitev Save v zvezi z izgradnjo TET3", v kateri smo obravnavali vplive sedanje in načrtovane Termoelektrarne Trbovlje (TET), Nuklearne elektrarne Krško (NEK) in bazenov spodnjesavske verige HE na temperaturno stanje Save. V predavanju je bil na kratko podan uvodni del študije (analiza znanih podatkov), glavna pozornost pa je veljala prikazu rezultatov uporabljenih 1D in 3D modelov. Iz teh je razviden velikostni red vpliva posameznih bazenov spodnjesavske verige in točkovnih onesnaževalcev (TET3, NEK) na toplotno stanje reke. V vseh predstavljenih primerih je bil glavni poudarek študije na objektu v Trbovljah, medtem ko sta bili NE Krško in veriga hidroelektrarn obravnavani poenostavljeno.
Ključne besede: *toplotna obremenitev, akumulacije, pretočne hidroelektrarne, matematično modeliranje, termoelektrarna Trbovlje, nuklearna elektrarna Krško, reka Sava*

Results of the study "Thermal load of the Sava River related to the construction of TET3", are presented, where influences of the existing and of the planned Trbovlje Thermal Power Plant (TET), of the Krško Nuclear Power Plant (NEK) and of the reservoirs of the future chain of hydro power plants on the Lower Sava River on the thermal state of the river were studied. A brief presentation of the introductory part of the study (an analysis of the existing data) is given first during the presentation, which is followed by a presentation of the results of the 1D and of the 3D models. The aim of the latter was to illustrate the share of each future reservoir and of the point pollution sources (TET, NEK) on the thermal state of the Sava River. A simplified description of reservoirs and of the NEK cooling system were applied, while the TET was accounted for with all available details.
Key words: *thermal load, reservoirs, run-of-river hydro powerplants, mathematical modelling, Trbovlje thermal powerplant, Krško nuclear powerplant, the Sava River*

1. UVOD

Po izgradnji Termoelektrarne Trbovlje 3 (TET3) in zamenjavi uparjalnikov Nuklearne elektrarne Krško (NEK) se pričakuje povečanje toplotne obremenitve reke Save. Dodatne obremenitve bo prinesla tudi zajezitev v bodočih akumulacijah spodnjesavske verige hidroelektrarn. V dosedanjih študijah (VGI-VGL, 1989; VGI, 1991; IHR, 1995; Čehovin & Rodič, 1996) problematika ni bila obdelana v zadostnem obsegu. Zato je bila pred izdelavo idejnega projekta TET3 postavljena zahteva po jasno definiranih ekoloških in iz teh izhajajočih ekonomskih pogojih za obratovanje tega objekta. V tehnološko-ekološkem delu študije

1. INTRODUCTION

An increase of thermal pollution in the Sava River is expected after the construction of the new Trbovlje Thermal Power Plant (TET3), and after an increase of power at the Krško Nuclear Power Plant (NEK). Additional loads are expected, due to the retention of river water along a future chain of HPPs along the Lower Sava River. Since the problem was not sufficiently elaborated in some recent studies (VGI-VGL, 1989; VGI, 1991; IHR, 1995; Čehovin & Rodič, 1996), a clear definition of the environmental and economic conditions of operation was required prior to the construction of the TET3. Three combinations of power plants were elaborated upon in the

(Rajar et al, 1998) smo obravnavali tri temeljne kombinacije objektov: obstoječe stanje (analiza), bodoče stanje brez spodnjesavske verige in z novo TET3 ter bodoče stanje z verigo in TET3 (prognozi). Ekonomski del študije bo predvidoma končan v letu 2000.

2. PODATKI

Velik del študije je predstavljalo zbiranje, usklajevanje in dopolnjevanje podatkov, potrebnih za modele. Potrebni so bili hidrološki (pretok, rečna temperatura), meteorološki (temperatura in vlažnost zraka, insolacija, hitrost vetra) ter obratovalni parametri za posamezne elektroenergetske objekte (TET, NEK).

Sedanje stanje **pretokov** na obravnavanem odseku smo ovrednotili s karakterističnimi količinami: srednjimi, srednjimi nizkimi in nizkimi nizkimi (najnižjimi zabeleženimi) pretoki na posameznih vodomerskih postajah: VP Litija, VP Radeče in VP Čatež (preglednice 1 - 3). Zaradi medsebojne primerljivosti prikazujemo v treh preglednicah starejše rezultate (VGI, 1983), ki pa edini kažejo razmerje med posameznimi postajami. V konkretnih računih smo, kjer je bilo mogoče, uporabljali najnovejše ali vsaj novejše podatke. Okvirno velja, da so srednji in srednji nizki pretoki v Radečah aritmetična sredina tistih v Litiji in Čatežu. Za nizke nizke pretoke ni opaziti posebnih zakonitosti. Na VP Čatež je zelo izrazito upadanje pretokov v zadnjih desetletjih. To so potrdile kontrole na profilu Krško, vendar bi bilo za popolnoma zanesljivo trditev treba izdelati posebno hidrološko študijo. Glede na splošno neusklajenost podatkov iz različnih obdobij bi bila takšna študija potrebna pred začetkom ekstenzivnega izkoriščanja Save (termoenergetika, hidroenergetika), seveda pa bi morala temeljiti na najnovejših podatkih.

technological-environmental part of the study: existing state (analysis), future state with the TET3 and without the HPP chain and the future state with both the TET3 and the chain (both prognoses). The economic part of the study is to be completed during the year 2000.

2. DATA

A great deal of study was dedicated to the collection, harmonization and completion of the input model data. Hydrological (discharge, river temperature), meteorological (air temperature and humidity, insulation, wind speed) and operating parameters for the particular power plants (TET, NEK) were required.

Present **discharges** along the elaborated stretch of the river were evaluated by characteristic values: mean, mean low and (absolute) minimum discharges at particular gauging stations: GS Litija, GS Radeče and GS Čatež (Tables 1 – 3). In these tables, older data (VGI, 1983) are given which are only capable of displaying the mutual relations between the stations. If it was possible, the most recent, or at least the more recent data were applied in the calculations. In general, the mean and mean low discharges at Radeče can be obtained as the aritmetical means of the corresponding values at Litija and Čatež. There is no similar relation for the minimum discharges. A trend of decrease in discharges is evident at GS Čatež. Although it was confirmed by some controls in the Krško cross-section, a separate hydrological study related to this topic would be neccessary. In view of some further disagreements of data from different time periods, such a study, based on the most recent data, would also be necessary prior to an extensive exploitation of the Sava River (thermal power and hydropower).

Preglednica 1. Srednji pretoki Save za obdobje 1926-1975 (VGI, 1983).
Table 1. Mean discharges of the Sava River for the period 1926-1975 (VGI, 1983).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	leto *year*
Q_{sr-L}	149	147	196	210	199	169	127	106	141	193	268	200	175
Q_{sr-R}	198	197	255	273	260	225	172	145	183	246	339	256	229
$Q_{sr-Č}$	265	267	350	356	332	286	217	177	226	321	440	336	298

L = Litija, R = Radeče, Č = Čatež

Preglednica 2. Srednji nizki pretoki Save za obdobje 1926-1975 (VGI, 1983).
Table 2. Mean low discharges of the Sava River for the period 1926-1975 (VGI, 1983).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	leto *year*
${}_{sr}Q_{n-L}$	75.9	73.5	91.8	114	107	87.4	71.4	56.8	55.0	75.8	103	96.7	45.8
${}_{sr}Q_{n-R}$	106	104	129	155	145	120	99	81	76	101	140	129	64
${}_{sr}Q_{n-Č}$	139	133	168	193	175	147	119	98	94	128	170	160	79

L = Litija, R = Radeče, Č = Čatež

Preglednica 3. Nizki nizki pretoki Save za obdobje 1926-1975 (VGI, 1983).
Table 3. Minimum discharges of the Sava River for the period 1926-1975 (VGI, 1983).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	leto *year*
${}_{n}Q_{n-L}$	34.4	34.8	41.4	38.5	55.9	41.9	34.1	29.4	27.7	24.4	33.0	46.6	24.4
${}_{n}Q_{n-R}$	60.6	60.1	51.4	50.0	57.3	52.5	48.4	43.3	40.5	39.6	39.6	65.8	39.6
${}_{n}Q_{n-Č}$	60.8	61.7	70.7	69.0	85.9	78.5	52.3	50.0	47.1	47.1	48.5	62.0	47.1

L = Litija, R = Radeče, Č = Čatež

Za študijo ima poseben pomen spreminjanje **rečnih temperatur** na obravnavanem odseku med Litijo in državno mejo. V preglednici 4 podajamo srednje mesečne temperature za obdobje 1964 - 1975, kar pomeni, da je v njih deloma že zajet vpliv TET2, ki je začela obratovati v letu 1968. Poleg tega je zajet tudi vpliv TET1. Ta je bila zgrajena kmalu po vojni in je vzporedno s TET2 obratovala do leta 1986. V Čatežu še ni upoštevan vpliv NE Krško, ki je začela obratovati leta 1983. Iz navedenega je razvidno, da je pri oceni sedanjega stanja nemogoče govoriti o naravnem stanju, saj so vse analize temperatur nastale že po izgradnji prvega objekta v

Changes of **river temperatures** along the elaborated reach between Litija and the state border are of special importance for the study. The mean monthly river temperatures for the period 1964 – 1975 are given in Table 4. In these values, influences of the existing TET2 (in operation since 1968) and of TET1 (in operation since WW2 and until 1986, in parallel with TET2) are included, while there are not yet any intrinsic influences of the NEK (in operation since 1983) in Čatež. With all this in view, the natural state of the river can not be recovered, as all analyses were performed long after the beginning of electricity production in Trbovlje. Within the framework of our recent study, only the

Trbovljah. V okviru naše študije smo ocenili le vpliv TET2, ki ob polnem obratovanju zvišuje temperaturo Save za 0.16 (november) do 0.35 ºC (avgust), v letnem povprečju pa za 0.22 ºC. Za izključitev vpliva TET2 bi bilo treba te vrednosti odšteti od podanih v preglednici 4, vendar bi še vedno ostal vpliv TET1, ki ga nismo ocenjevali. Porast srednjih temperatur je v resnici manjši, ker TET2 ne obratuje ves čas s polno močjo, dejanski porasti v reki pa so lahko tudi višji, ker je pretok spremenljiv in pogosto nižji od srednjega.

Iz preglednice 4 je tudi razvidno, da se Sava v hladnejših mesecih vzdolž toka ohlaja, v toplejših pa v nekoliko večji meri segreva. Med Litijo in Radečami se ohlaja od decembra do marca, med Radečami in Čatežem pa od oktobra do marca. Na obeh odsekih, predvsem pa na zgornjem, je zaradi nestalnega in nedokumentiranega obratovanja TE objektov nemogoče oceniti dejansko naravno ohlajevalno zmogljivost reke. Zato smo prisiljeni sedanje stanje z obratujočimi TE objekti upoštevati kot izhodiščno. Edina izvedljiva alternativa za oceno naravnega stanja bi bil zelo natančen model, ki bi ga morali kakovostno umeriti, za kar bi potrebovali dobre in obsežne meritve.

Srednje vrednosti le malo povedo o vsakoletnih kritičnih poletnih razmerah, ki smo jih obravnavali v prognostičnih simulacijah. Za primerjavo s temi rezultati so ustreznejše srednje visoke temperature, ki so za navedena tri vodomerne postaje prikazane v preglednici 5, in visoke visoke temperature (absolutni maksimumi obdobja), ki so prikazane v preglednici 6. Pri razlagi zadnjih dveh preglednic moramo upoštevati, da so primerjave srednjih visokih temperatur v različnih profilih smiselne, primerjave visokih visokih pa ne, ker ne gre za sočasne dogodke. Ker gre torej pri preglednici 6 za informativne vrednosti, kako visoke temperature so bile tam že dosežene, razlike med profili niso prikazane. Poudarjene so le avgustovske vrednosti, ker smo tudi v naših simulacijah upoštevali avgustovske pretoke, hidrološke in meteorološke razmere.

influence of TET2 was evaluated, which increases the river temperature from 0.16 (in November) to 0.35 ºC (in September) with an annual average of 0.22 ºC. All these values assume power production at nominal full rate. We could thus eliminate the influence of the TET2 from the values in Table 4, but influences of the old TET1 would still remain unclear. In reality, the increase of the average river temperatures is smaller due to the usual operation with lower power. But on the other hand, it can be even greater, due to the frequent occurence of natural discharges which are lower than average.

From Table 4, a decrease of river temperature along the river is evident during the winter months, while a somewhat stronger increase is evident in the summer months. Between Litija and Radeče, cooling takes place from December to March, while between Radeče and Čatež, it occurs from October to March. Along both stretches, it is impossible to determine the natural cooling capacity of the river, due to the inconsistent and non-documented operation of the thermal power plants in Trbovlje. Therefore, the present state of operation for the TET2 power plant is assumed to be the initial state. The only alternative for determining the present natural state would be a precise and exactly verified mathematical model, which is presently not feasible due to extensive data requirements.

Average values give little information about the critical summer conditions which were elaborated in the prognostic simulations. More suitable for comparison with these results are the mean high temperatures shown for the three relevant gauging stations in Table 5, and the absolute maximum temperatures (of the period), shown in Table 6. It must be taken into account that comparisons of the mean high temperatures in different cross sections are acceptable, while those of the absolute maximum values are not, since the latter are not simultaneous events. As only informative values are given in Table 6 to show the possible extremes at different cross sections, the differences between the cross-sections are not calculated. August values are emphasised, because the August values of temperature, discharges and meteorological parameters were used in the prognosticated simulations.

Preglednica 4. Spreminjanje srednjih rečnih temperatur med Litijo in Čatežem pred izgradnjo NEK za obdobje 1964-1975 (VGI, 1983) na podlagi meritev enkrat dnevno.
Table 4. Changes of mean water temperatures between Litija and Čatež before the construction of the Krško NPP, period 1926-1975 (VGI, 1983) based on one measurement per day.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	leto *year*
T_{LIT}	4.4	5.1	6.3	8.6	11.1	13.1	14.7	15.0	13.1	10.2	7.7	5.3	9.6
T_{RAD}	3.5	4.4	6.2	8.8	11.7	14.2	16.3	16.7	14.3	10.9	7.8	4.7	10.0
Ḍ	**-0.9**	**-0.7**	**-0.1**	**0.2**	**0.6**	**1.1**	**1.6**	**1.7**	**1.2**	**0.7**	**0.1**	**-0.6**	**0.4**
T_{RAD}	3.5	4.4	6.2	8.8	11.7	14.2	16.3	16.7	14.3	10.9	7.8	4.7	10.0
$T_{ČAT}$	3.0	4.2	6.1	9.1	12.7	15.3	17.3	17.3	14.3	10.6	7.2	4.2	10.1
Ḍ	**-0.5**	**-0.2**	**-0.1**	**0.3**	**1.0**	**1.1**	**1.0**	**0.6**	**0**	**-0.3**	**-0.6**	**-0.5**	**0.1**

T_{LIT} - Litija, T_{RAD} - Radeče, $T_{ČAT}$ - Čatež

Preglednica 5. Spreminjanje srednjih visokih rečnih temperatur med Litijo in Čatežem pred izgradnjo NEK za obdobje 1964-1975 (VGI, 1983), na podlagi meritev enkrat dnevno.
Table 5. Changes of mean high water temperatures between Litija and Čatež before the construction of the Krško NPP, period 1926-1975 (VGI, 1983) based on one measurement per day.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	leto *year*
${}_{sr}T_{v-LIT}$	6.0	6.2	8.3	10.0	13.2	15.6	17.1	17.1	15.1	12.5	9.6	7.4	-
${}_{sr}T_{v-RAD}$	5.7	6.3	8.7	11.0	14.2	17.3	18.8	19.3	16.8	13.5	9.7	7.1	-
Ḍ	**-0.3**	**0.1**	**0.4**	**1.0**	**1.0**	**1.7**	**1.9**	**2.1**	**1.7**	**1.0**	**0.1**	**-0.3**	**-**
${}_{sr}T_{v-RAD}$	5.7	6.3	8.7	11.0	14.2	17.3	18.8	19.3	16.8	13.5	9.7	7.1	-
${}_{sr}T_{v-ČAT}$	4.8	6.4	8.9	11.6	15.5	17.8	19.6	20.1	16.9	13.9	10.1	6.4	-
Ḍ	**-0.9**	**0.1**	**0.2**	**0.6**	**1.3**	**0.5**	**0.8**	**0.8**	**0.1**	**0.4**	**0.4**	**-0.7**	**-**

${}_{sr}T_{v-LIT}$ - Litija, ${}_{sr}T_{v-RAD}$ - Radeče, ${}_{sr}T_{v-ČAT}$ - Čatežu

Preglednica 6. Spreminjanje visokih visokih rečnih temperatur med Litijo in Čatežem pred izgradnjo NEK za obdobje 1964-1975 (VGI, 1983), na podlagi meritev enkrat dnevno.
Table 6. Changes of maximum water temperatures between Litija and Čatež before the construction of the Krško NPP, period 1926-1975 (VGI, 1983) based on one measurement per day.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	leto *year*
${}_{v}T_{v-LIT}$	7.4	8.4	11.3	12.4	15.8	18.0	21.0	**20.5**	17.0	15.1	11.7	9.0	-
${}_{v}T_{v-RAD}$	8.0	8.4	10.4	13.0	17.2	19.0	21.2	**22.1**	18.5	16.6	12.4	8.7	-
${}_{v}T_{v-ČAT}$	6.2	8.5	11.0	16.0	17.1	21.5	22.5	**22.0**	19.4	17.2	12.2	7.4	-

${}_{v}T_{v-LIT}$ - Litija, ${}_{v}T_{v-RAD}$ - Radeče, ${}_{v}T_{v-ČAT}$ - Čatež

3. MODELIRANJE

Glavni del šudije je predstavljalo matematično modeliranje toplotne dinamike Save. Ustaljen pristop pri tovrstnih problemih je, da se daljši rečni odseki modelirajo enodimenzionalno, posamezne lokalne težave (bazeni, podrobnosti izpustov in zajetij) pa večdimenzionalno - 2D ali 3D (Fischer et al., 1979; Edinger & Geyer, 1965). Tako smo ravnali tudi v našem primeru, v katerem smo zaradi kratkega roka obdelali enodimenzionalno tudi večino bazenov. Ta korak smo upravičili s primerjavo s 3D modelom (za bazena Vrhovo in Suhadol), ki je kljub bistveno večji kompleksnosti dal zelo podobne rezultate kot 1D model. Največjo pozornost smo posvetili dopolnitvi 3D modela PCFLOW3D s toplotnimi členi in razvoju novega 1D termalnega modela za akumulacije, HOTLAKES. V začetni fazi smo razvijali tudi poenostavljeni 1D nestacionarni model THERMALS, ki pa ga zaradi pomanjkanja meritev nismo mogli zadovoljivo umeriti in je v študijo vključen zgolj informativno. Predvsem zato, ker ga nameravamo v morebitnih prihodnjih študijah dopolniti, saj je tako rekoč edino orodje za vrednotenje sedanjega, nezajezenega stanja. Vsi omenjeni programi so podrobneje opisani drugje (Rajar & Širca, 1998a; 1998b; Širca & Rajar, 1999).

Bazeni na Savi, zaradi večjih volumnov in posebno zaradi počasnejšega toka, drugače vplivajo na toplotne razmere kot sama reka Sava. Na nezajezenem delu Save je zaradi majhnih globin in večjih hitrosti pričakovati skoraj popolno premešanje (in izenačenje) toplote po globini, medtem ko v bazenih meritve kažejo, da se zgornji sloji čez dan močneje segrejejo kot spodnji. Razlika med izmerjenima temperaturama površinskega in spodnega sloja je poleti dosegla celo 3.6 ºC (profil most Vrhovo, 1995-07-18-17:30). Meritve, posebno pa še tridimenzionalni (3D) matematični model, so pokazali zanimivo toplotno dogajanje v bazenu. Po eni strani se toplotno sevanje iz ozračja prenaša v površinske sloje, ki se preko dneva grejejo, po drugi strani pa se toplota delno meša po

3. MODELLING

Mathematical modelling of the Sava River thermal dynamics was a main part of the study. The usual approach to such problems is to model longer river reaches in one dimension, while details of the local problems (e.g. reservoirs, discharges and intakes) are elaborated in more dimensions – 2D or even 3D (Fischer et al., 1979; Edinger & Geyer, 1965). This was also the case with our simulations, where the majority of reservoirs was modelled by an 1D model, due to short time schedules. This simplification was justified by comparisons of the 1D and 3D models for the Suhadol and the Vrhovo reservoirs, where a good agreement of results was obtained in both cases, despite the much higher complexity of the 3D model. Attention was mainly paid to the inclusion of thermal equations into the existing 3D model PCFLOW3D and to the development of a new thermal model for reservoirs, HOTLAKES. In the initial phase, the simplified 1D unsteady model THERMALS was also developed, but was not verified to an acceptable extent due to a lack of data. It is also presented informatively. The reason for this is that our intention for the further development of this model in future studies as this is practically the only tool for the evaluation of the present unobstructed flow (without dams). Details of all the programs are given elsewhere (Rajar & Širca, 1998a; 1998b; Širca & Rajar, 1999).

Reservoirs on the Sava River represent a different influence on the thermal state of the river, due to greater retention volumes and due to much lower velocities. Along unobstructed reaches, a complete mixing (and vertical temperature equalization) is expected, due to high velocities and low flow depths, while measurements in different existing reservoirs show stronger or weaker daily thermal stratification. In the Vrhovo Reservoir, the difference between the surface and bottom layers even reached 3.6 ºC (Vrhovo bridge, 1995-07-18-17:30). Both measurements and the 3D mathematical model have shown an interesting thermal dynamic in this reservoir. On the one hand, radiation from the atmosphere is transmitted into and stored in the surface layers during the daytime hours, globini in prenaša v globlje sloje. Poleg tega se voda giblje v smeri toka in z njo se prenaša tudi toplota. Tipični čas, ki ga voda potrebuje za prehod vzdolž celotnega bazena, je za nižje pretoke v poletnem času 10 do 12 ur. Tako je porazdelitev toplote v bazenu odvisna od oddaljenosti obravnavane točke od vtoka v bazen, globine in od časa. Kritične razmere smo v vseh primerih (1D in 3D) prikazali z dvema hidrometeorološkima scenarijema:

1. **z vsakoletnimi kritičnimi (poletnimi) razmerami**, ki so bile ponazorjene z dolgoletnim srednjim nizkim avgustovskim pretokom in srednjo avgustovsko rečno temperaturo. Klimatski vpliv smo upoštevali z merjenimi podatki s postaje v Krškem za povprečno vroč poletni dan 1995-07-18
2. **z ekstremnimi (poletnimi) razmerami** z majhno verjetnostjo nastopanja, ki so bile ponazorjene z absolutno najnižjim zabeleženim avgustovskim pretokom in najvišjo, v letih 1994 in 1995, zabeleženo rečno temperaturo. V tem primeru smo vpliv meteoroloških parametrov upoštevali v obliki teoretičnega vročega poletja, kot ga po nemških avtorjih povzema VGI-VGL (1989).

4. ZAKLJUČKI

V **sedanjih razmerah** obratovanje TE Trbovlje (TET2) z vidika toplotnega onesnaženja Save ni problematično. To potrjujejo tako izračuni, ki dokazujejo usklajenost z veljavnimi vodnogospo-darskimi pogoji (UL-RS, 1996a; 1996b; 1996c), kot izkušnje upravljalcev, ki navajajo, da do omejevanja proizvodnje do sedaj ni prihajalo (sliki 1 in 2). Dolvodno od Trbovelj se Sava v poletnem času segreva, v zimskem pa ohlaja. Analiza vpliva bazena Vrhovo kaže, da se vzdolž bazena voda v kritičnih razmerah segreva za 0.4 - 0.5 ºC bolj, kot se je v nezajezenem stanju. V izrednih razmerah se vzdolž bazena segreje za približno 1 ºC, primerjava z nezajezenim stanjem pa ni mogoča. V obeh primerih gre za povečanje povprečne temperature, ki mu moramo dodati

while on the other hand, the heat is also mixed and transported into the lower layers. Due to advection, a longitudinal transport of heat also occurs. A typical time scale of the longitudinal reservoir crossing (i.e. retention time) in the summertime is from 10 to 12 hours. The distribution of reservoir heat is thus dependent on the distance from the beginning of the reservoir, on depth and on time. Critical conditions for the simulations with both the 1D and 3D models were described by two hydrometeorological scenarios:

1. **Typical critical (summer) conditions** which were described by the long-term mean low August discharge and the mean August river temperature. Climatic conditions were assumed to equal (measured) the dynamics from a typically hot summer day, as recorded at the Krško Meteorological Station on 1995-07-18
2. **extreme (summer) conditions** with a low probability of occurence were approximated by the absolute low August discharge and the highest river temperature from the period 1994 – 1995. Meteorological parameters were taken from unknown German authors (in VGI-VGL, 1989) in the form of a » theoretically hot summer«.

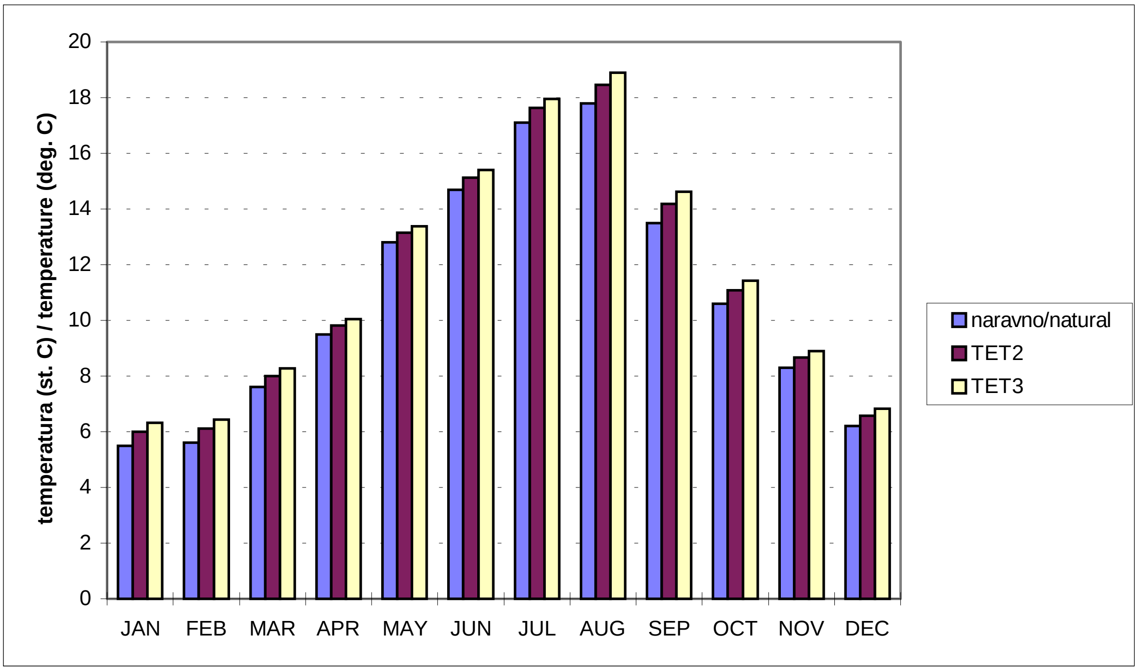
4. CONCLUSIONS

Operation of the Trbovlje TPP (TET2) in **present conditions** is not problematic from the point of view of the thermal polution of the Sava River. It is confirmed both by calculations which show the implementation of valid water management conditions (UL-RS, 1996a; 1996b; 1996c) and by up-to date experience without operative limitations of production (Figures 1 and 2). Downstream from Trbovlje, the Sava River is heated in summer and colder in the winter months. Analysis of the Vrhovo reservoir in critical conditions shows an additional longitudinal heating of 0.4 to 0.5 ºC, as compared to the initial state without the reservoir. Under extreme conditions, the longitudinal increase equals 1 ºC, while such a comparison was not possible for the unobstructed river. Both increases are given for average temperatures, but daily variations in the range ±1.5 ºC must še dnevna nihanja v razponu do ±1.5 ºC. Zaradi dolgoletne prisotnosti TE objektov v Trbovljah je njihov vpliv na toplotni režim Save težko ločiti od naravnega. S tem mislimo na prepletene vplive postopne izgradnje in režima obratovanja TE objektov v Trbovljah, dotoka Savinje, in morebitnih hidroloških in klimatskih sprememb. Pogoste izjemne hidrološke razmere v zadnjih 10 letih in očitno upadanje pretokov v zadnjih 20 letih kažejo potrebo po popravkih hidrologije Save za profil VP Čatež. Posredno kaže na spremembe pretokov in temperatur tudi pogostejše omejevanje proizvodnje NEK.

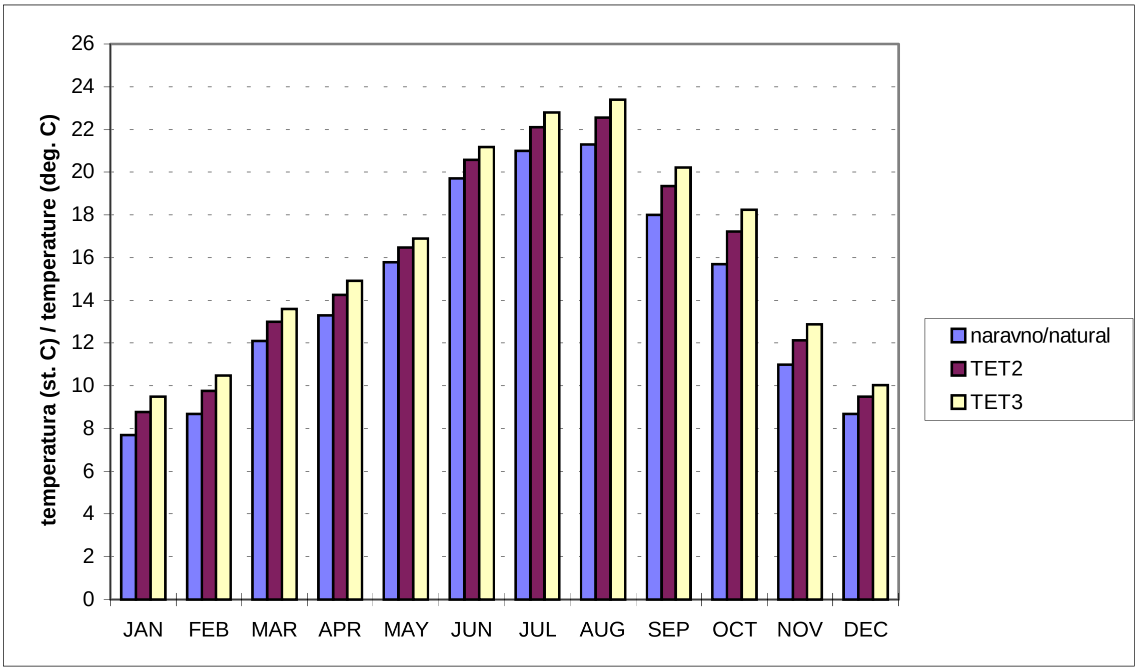
Bodoče stanje s TET3 in brez verige HE: Veljavne uredbe o emisijah toplote praktično ne omejujejo obratovanja bodočega objekta TET3. Povečanje toplotne moči objekta s sedanjih 157 MWt na 237 MWt bi povzročilo dvig temperature v Savi, ki je linearno odvisen od njenega pretoka. To pomeni ob obratovanju objekta s polno močjo ob vsakoletnih kritičnih razmerah povišanje temperature v Savi za največ 0.53 °C, v izrednih razmerah pa za največ 1.0 °C. Glede na rezultate računov z verigo se opisana razlika med sedanjo in bodočo obremenitvijo med Trbovljami in zajetjem NEK zmanjša v kritičnih razmerah za 12 odstotkov, v izrednih pa za 22 odstotkov. Vsi računi in ocene v nezajezeni Savi so bili narejeni ob predpostavki popolne premešanosti. V sedanjih razmerah ni jasno, ali je ta predpostavka izpolnjena, ker ustrezne meritve na odseku Trbovlje-Savinja ne obstajajo.

also be considered. Due to the long-term existence of the Trbovlje TPP with a gradual increase of power, changes in the operational regime, the Savinja River tributary and possible hydrological and meteorological changes, it would be very difficult to divide the influences of the TPP from the natural ones. Frequent extreme hydrological events in the last decade and the evident decrease of discharges during the last 2 decades require an update of the Sava hydrology for the Čatež cross-section. An additional sign of river temperature and discharge changes might also be the repeated limitations of the Krško NPP production in the summer months.

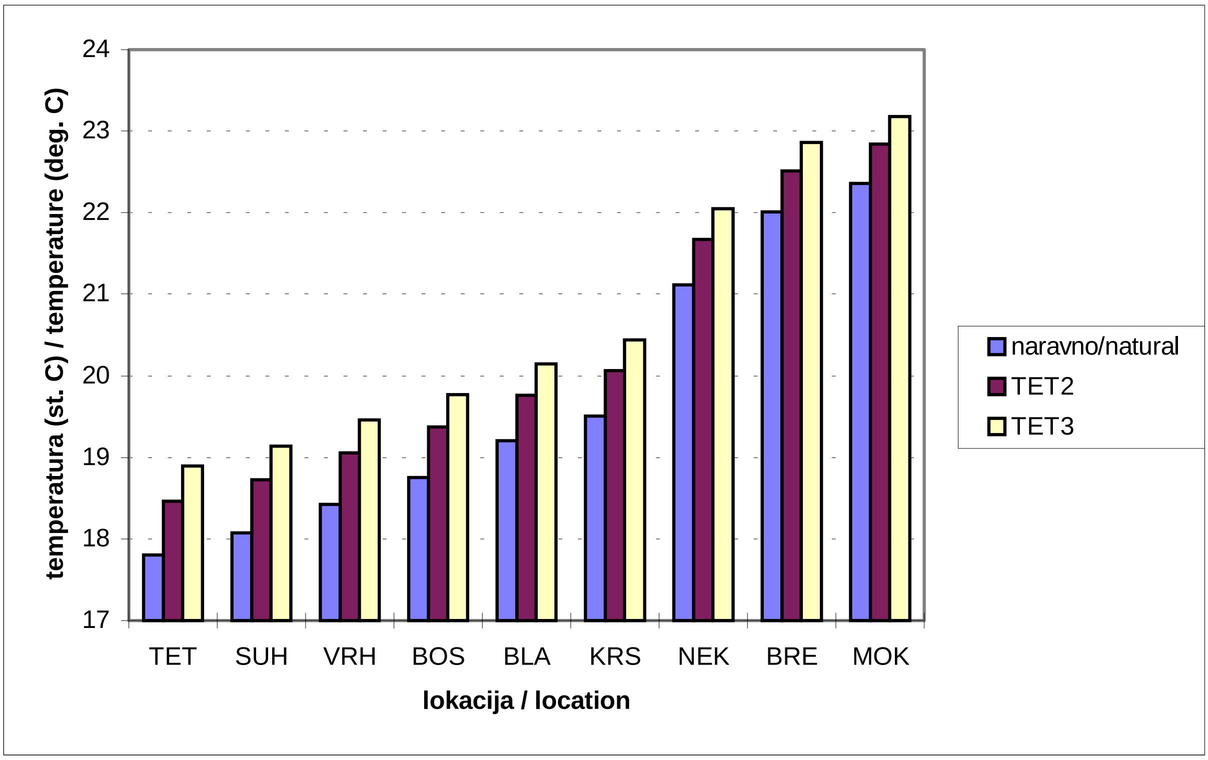
The future state with the TET3 and without the HPP chain: Valid legislation about heat emissions does not limit the operation of the future TET3 plant. An increase of thermal power from 157 MW_t to 237 MW_t would increase the Sava River temperature proportionally and linearly to the river discharge. Operation of the TET3 with full power in critical conditions would increase the river temperature by 0.53 ºC at the most, and by 1.0 ºC at the most in extreme conditions. According to the calculations with the HPP chain, a decrease of difference between the TET3 and TET2 influence is expected downstream, with a reduction of 12% in critical conditions and 22% in extreme conditions, at the NEK cross-section. All calculations for the unobstructed river assume complete mixing. It is not certain, however, whether this assumption is correct, as no measurements are available for the Trbovlje-Savinja tributary reach.



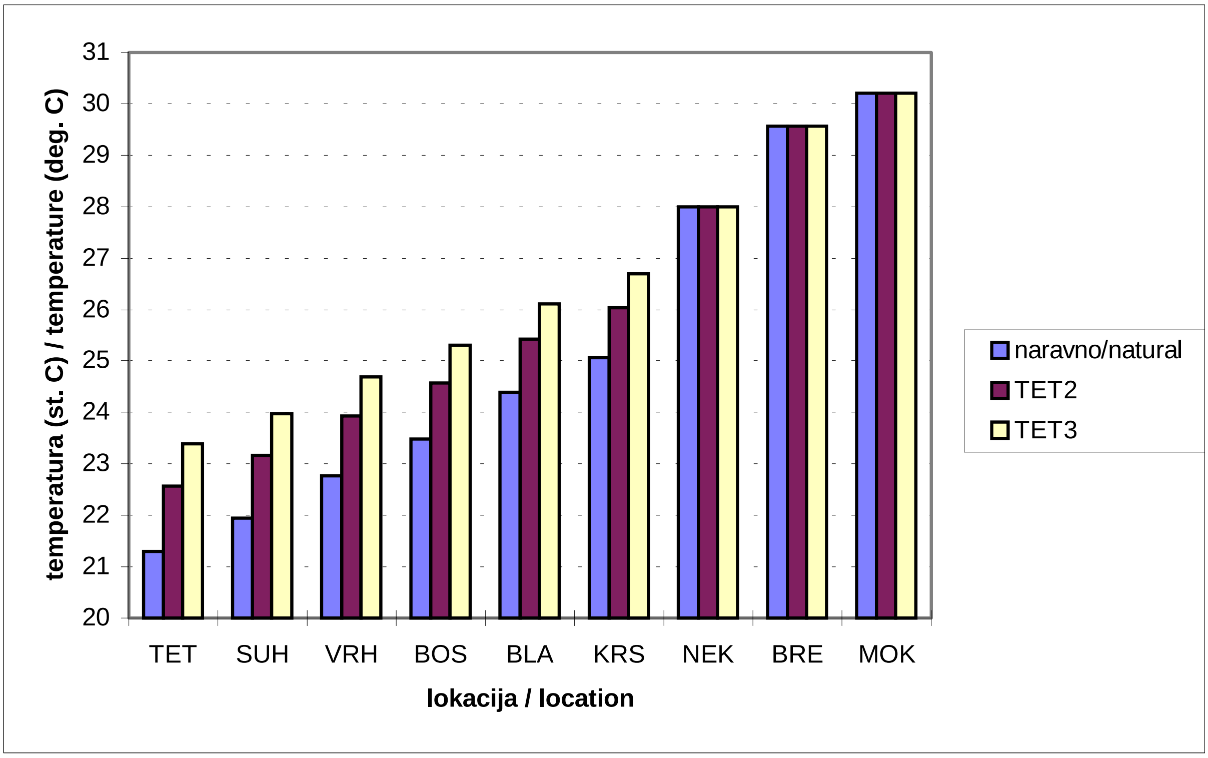
Slika 1. Temperatura Save pod Trbovljami ob srednjih nizkih pretokih.
Figure 1. Sava river temperature downstream from Trbovlje at mean low discharges.



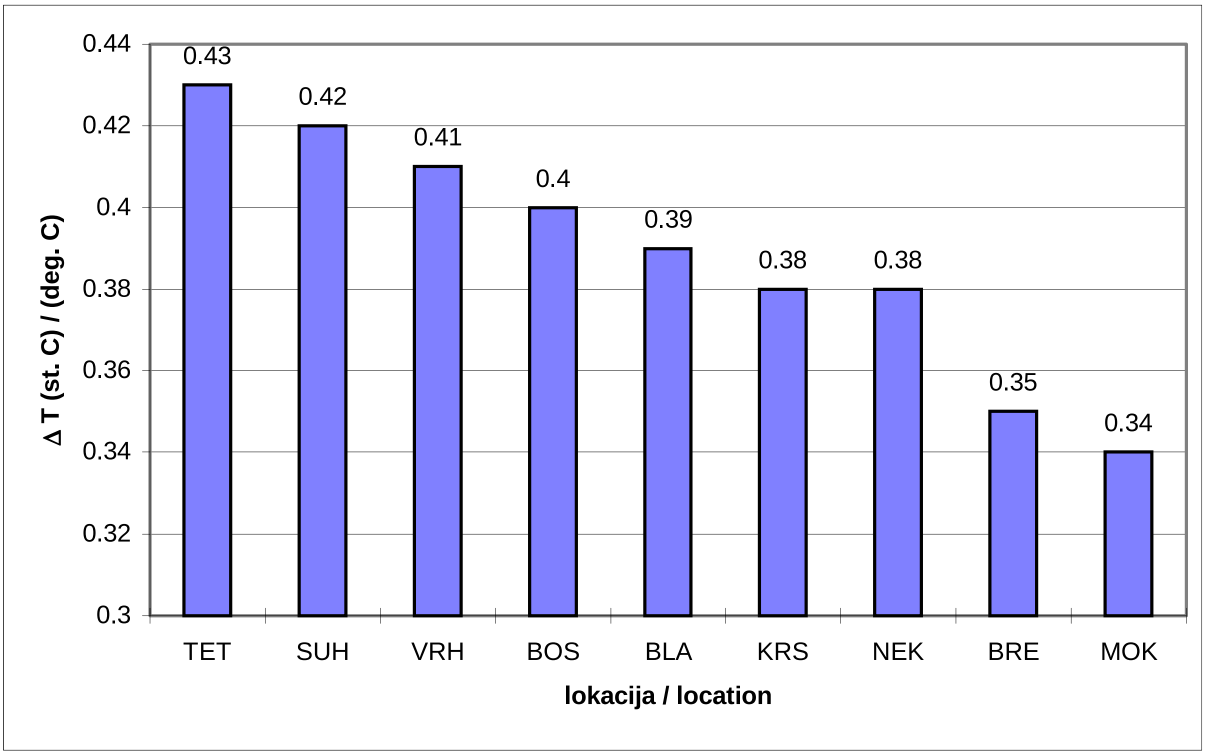
Slika 2. Temperatura Save pod Trbovljami ob nizkih nizkih pretokih.
Figure 2. Sava river temperature downstream from Trbovlje at minimum low discharges.



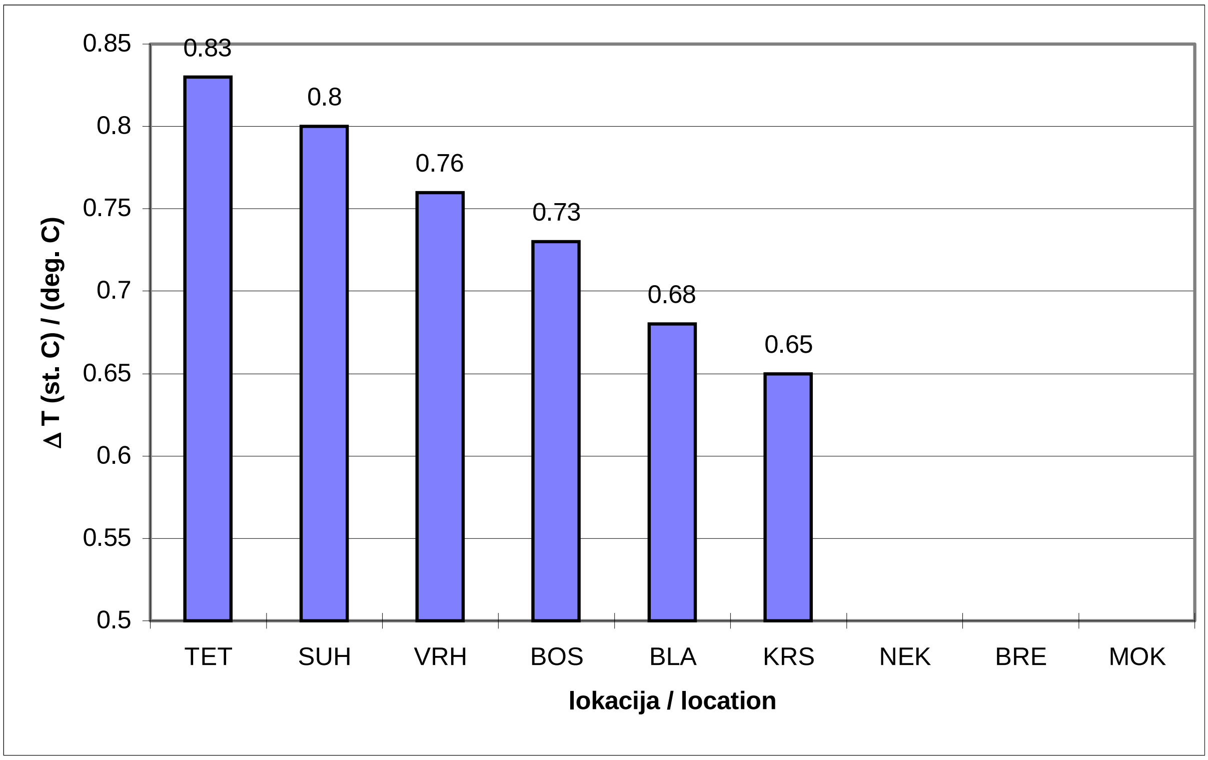
Slika 3. Naraščanje temperature Save vzdolž toka v kritičnih razmerah.
Figure 3. Increase of Sava river temperature along the stream in critical conditions.



Slika 4. Naraščanje temperature Save vzdolž toka v ekstremnih razmerah.
Figure 4. Increase of Sava river temperature along the stream in extreme conditions.



Slika 5. Zmanjševanje razlike med obremenitvama Save s TET2 in TET3 v kritičnih razmerah.
Figure 5. Decrease of the difference between TET2 and TET3 influences in critical conditions.



Slika 6. Zmanjševanje razlike med obremenitvama Save s TET2 in TET3 v ekstremnih razmerah.
Figure 6. Decrease of the difference between TET2 and TET3 influences in extreme conditions.

Bodoče stanje z verigo HE, TET3 in brez HE Suhadol. V študiji je bil prvikrat ovrednoten vpliv izgradnje spodnjesavske verige HE (IBE, 1963; 1995a; EIMV, 1996) na temperaturno stanje Save. Rezultati kažejo, da se vzdolž bazenov Vrhovo, Boštanj, Blanca, Krško in Brežice temperature Save v kritičnih poletnih razmerah zvišajo za 2.6 do 3.4 °C (v stanju brez bazenov med VP Radeče in VP Čatež 0.8 °C), v izrednih razmerah pa za 5.3 do 6.6 °C (sliki 3 in 4). Pri tem gre le za naravno ogrevanje zaradi pozitivne toplotne bilance na vodni gladini. Največji delež dviga ima zaradi velike površine bazen Brežice (0.9 - 1.2 °C v kritičnih in 1.6 - 1.8 °C v izrednih razmerah). Nižje ležeči bazen Mokrice z dvigi temperatur 0.4 - 0.5 °C v kritičnih in 0.6 - 1.1 °C v izrednih razmerah dodatno zvišuje temperaturo v mejnem profilu s Hrvaško. Ocenjeno je bilo, da bo izgradnja verige bazenov povzročila dvig temperature Save nad zajetjem NE Krško za približno 1.0 °C v vsakoletnih kritičnih (primerjava s srednjo visoko temperaturo) in do 5.3 °C v izrednih razmerah (primerjava z najvišjo zabeleženo temperaturo). V računih verige do državne meje smo upoštevali bodočo toplotno moč NEK 1379 MW_t (IBE, 1995b), vendar tako, kot da bi hladilni sistem še vedno obratoval po sedanjih pravilih vodnogospodarskega dovoljenja (IJS-SEPO, 1989).

Glavni zaključek študije je, da povečanje moči s TET2 na TET3 ne povzroča bistvenih težav termične polucije v Savi. Sama TET3 ne bi imela omejitev glede na veljavne zakonske predpise, razen v izrednih razmerah, ki pa bi predvidoma nastopile le nekajkrat v življenjski dobi objekta. Razlike med toplotnim onesnaženjem TET2 in TET3 so majhne in se vzdolž toka zmanjšujejo (sliki 5 in 6). Za zdaj ni potrebe po omejevanju obratovanja verige HE, razen v omejenem obsegu v bazenu Suhadol, vendar le v izrednih razmerah.

The future state with the HPP chain, the TET3 and without the Suhadol HPP. In this study the influence of the Sava River HPP chain (IBE, 1963; 1995a; EIMV, 1996) on the thermal state of the river was evaluated for the first time. Under critical summer conditions, an increase of temperature along the Vrhovo, Boštanj, Blanca, Krško and Brežice reservoirs is expected to equal 2.6 to 3.4 ºC (without the reservoirs, an increase of 0.8 ºC occurs between Radeče GS and Čatež GS), while under extreme conditions the increase would reach 5.3 to 6.6 ºC (Figs 3 and 4). This increase occurs due to the positive heat balance at the surface of the reservoirs. The greatest contribution to the increase is the one from the Brežice Reservoir, with its large surface area (0.9 - 1.2 °C in critical and 1.6 - 1.8 °C in extreme conditions). The downstream Mokrice Reservoir, with increases of 0.4 - 0.5 °C in critical and 0.6 - 1.1 °C in extreme conditions, is an additional factor for the increase of temperature at the SLO-CRO state border. According to these estimations, the Sava HPP chain might increase the intake temperature at the Krško NPP by about 1.0 °C in typical critical conditions, and up to 5.3 °C in extreme conditions. In these calculations, the future NEK thermal power of 1379 MW_t (IBE, 1995b) was assumed, but only when operating under presently valid water management permit (IJS-SEPO, 1989).

The main conclusion of this study is that an increase of power at Trbovlje would not cause additional thermal problems downstream. Except for some extreme events occuring only a few times in a lifetime, there would be no limitations in the operation of the TET3, allowing for present environmental legislation. The differences between the influences of the TET2 and the TET3 would be small, and would even decrease along the stream (Figs 5 and 6). No need for limitation of the HPP chain operation was detected, except, again under extreme conditions, in the Suhadol Reservoir.

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