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# TOPLOTNA OBREMENITEV SAVE PO IZGRADNJI SPODNJESAVSKIH STOPENJ
# THERMAL LOAD OF THE SAVA RIVER AFTER CONSTRUCTION OF THE LOWER SAVA RIVER CASCADE

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*Uvodni del članka predstavlja zgoščen pregled dela na področju matematičnega modeliranja termike reke Save v obdobju 1997–2003. V nadaljevanju so opisane značilnosti uporabljenih matematičnih modelov ter računskih primerov, katerih namen je prikaz toplotnega stanja reke po izgradnji prve faze verige HE (2012) in po zaključku gradnje (2018) ter primerjava s sedanjim stanjem. Upoštevani sta dve varianti termoenergetskega objekta v Trbovljah ter sedanje stanje NE Krško (NEK). Analize so izdelane za topli del leta (april–september) za profila NEK in HE Mokrice. Srednje mesečne rečne temperature se bodo po izgradnji verige HE pri NEK povečale do +0,4 °C, pri HE Mokrice pa do +1,6 °C. V razmerah s povratno dobo 4 leta bo povišanje pri NEK znašalo +1,3 °C, pri HE Mokrice pa do +2,1 °C. Pri povratni dobi 40 let bosta ustrezni povišanji do 2,0 °C pri NEK in do 2,2 °C pri HE Mokrice. Vpliv TET na obratovanje NEK je manjši, kot je bil ocenjen v študiji iz leta 1998.*
**Ključne besede:** *toplotna obremenitev, pretočne hidoelektrarne, veriga hidroelektrarn, matematični modeli, reka Sava.*

*The introductory part of the paper brings a survey of the work performed in the sphere of mathematical modelling of the Sava river thermal load in the period 1997–2003. In the continuation, characteristics of the applied mathematical models as well as simulation cases are given, the purpose of which is to show a thermal condition of the river after construction of the first phase of the HPP chain (2012) and after its completion (2018) as well as comparison with the present state. Two alternatives of the thermal power unit in Trbovlje and the present state of the NPP Krško (NEK) have been considered. Analyses were done for the NEK and HPP Mokrice cross-sections for the warm part of the year (April–September). After the HPP chain construction, the average monthly river temperatures at NEK shall increase by up to +0.4 °C and at HPP Mokrice by up to +1.6 °C. In the 4-year return period conditions the increase at the NEK shall reach +1.3 °C while at HPP Mokrice it shall reach up to +2.1 °C. Considering the 40-year return period the relevant increases shall be up to 2.0 °C at the NEK and up to 2.2 °C at the HPP Mokrice. The TPP Trbovlje impact on the NEK operation is lower than estimated by the previous study from 1998.*
**Key words:** *thermal load, run-of-river hydro powerplants, chain of HPPs, mathematical models, the Sava River.*

## 1. UVOD

Na podlagi uvodnih eksperimentalnih (VGI-VGL, 1977; 1978; 1979; 1980; 1981) in teoretičnih analiz (VGI-VGL, 1989; 1991; 1993; 1995) toplotne obremenitve Save so se v letu 1997 začele izvajati podrobnejše raziskave, ki so vključevale terenske meritve in matematično modeliranje. Eksperimentalne

## 1. INTRODUCTION

Based on introductory experimental (VGI-VGL, 1977; 1978; 1979; 1980; 1981) and theoretic analyses (VGI-VGL, 1989; 1991; 1993; 1995) of thermal loads of the Sava river more detailed research started in 1997 which included field measurements and mathematical modelling. Experimental and theoretical basic research was upgraded in 1998 by an applied in teoretične osnovne raziskave so bile v letu 1998 nadgrajene z uporabno raziskavo toplotnega vpliva trboveljske termoelektrarne (TET) na Savo do državne meje, v letu 2003 pa s podrobnejšo študijo termičnih vplivov bodoče verige HE na Savi in NE Krško (NEK). Zadnja študija je vključevala tudi ekonomsko vrednotenje medsebojnih vplivov energetskih objektov. Eksperimentalni del raziskav je v bazenu Vrhovo izvajal Inštitut za hidravlične raziskave iz Ljubljane (IHR), matematično modeliranje pa Hidrotehnična smer FGG (HS-FGG), IBE, d.d. in IHR.

Vodilna ideja raziskav je bila razvoj 1D-modela za celotno Savo, obravnava posameznih bazenov in detajlov s 3D-modelom ter verifikacija modelov s terenskimi meritvami. Integralnemu poročilu o vplivu TET v sedanjih in bodočih pogojih obratovanja ob grobih predpostavkah t. i. kritičnih in ekstremnih razmer (HS-FGG, 1998) so sledili podrobnejši opis toplotnega modula v okviru 3D-modela PCFLOW3D in njegove verifikacije z meritvami iz leta 1995 (Rajar in Širca, 1998), opis v vseh 1D- in 3D-računih uporabljenega modela izmenjave toplote na vodni gladini HEATFLOW in modela HOTLAKE za vrednotenje termike v bazenih pretočnih HE (Širca in Rajar, 1999), analiza ustreznosti podatkov iz monitoringa rečnih temperatur HMZ (Širca in Gutierez, 1999) ter zgoščen pregled rezultatov (Širca, 2000). V nadaljevanju smo na podlagi rezultatov obsežnih meritev v letu 1998 podrobno analizirali termiko bazena Vrhovo, dodatno verificirali 3D-model in potrdili upravičenost uporabe 1D-modela (Širca et al., 2000). Sledili so verifikacija modela neoviranega rečnega toka HOTRIVER in prve točnejše ocene vpliva izgradnje verige HE (Širca, 2001) ter končno izračun termičnih vplivov različnih kombinacij objektov ob statistično utemeljenih predpostavkah srednjih (povprečnih) in izrednih (kritičnih in ekstremnih) razmer, nadgradnja modela enega bazena v model verige HOTCHAIN ter ekonomsko vrednotenje ugotovljenih sprememb termike (IBE, 2003a; Širca, 2003). V nadaljevanju so prikazani končni rezultati izračunov termike za različne kombinacije objektov in hidrometeoroloških pogojev.

study of the thermal impact of the TPP Trbovlje (TET) on the Sava river downstream to the state border, and in 2003 by a detailed study of thermal impact of the future HPPs chain on the Sava river and of the NPP Krško (NEK). The latter study also included economic evaluation of interrelating impacts of power plants. The experimental part of research in the Vrhovo basin was performed by the Institute of Hydraulic Research (IHR), while mathematical modelling was performed by the Hydraulic department of the Faculty of Civil and Geodetic Engineering (HS-FGG), IBE, Consulting Engineers and IHR.

The leading idea of investigations was to develop a 1D model for the complete Sava river, handling of individual basins and details with a 3D model and verification of these models by field measurements. The integral report on the TET impacts in present and future operating conditions by assuming the so-called critical and extreme conditions (HS-FGG, 1998) was followed by a more detailed description of a thermal model in the framework of the 3D PCFLOW3D model and its verification by measurements performed in 1995 (Rajar and Širca, 1998), description of a HEATFLOW model of heat exchange on the water surface, applied in all 1D and 3D calculations, and the HOTLAKE model of thermal loads evaluation in the run-of-river reservoirs (Širca and Rajar, 1999), analysis of HMZ river temperature monitoring data (Širca and Gutierez, 1999) and a condensed survey of results (Širca, 2000). Based on results of extensive measurements performed in 1998, a detailed analysis of thermal conditions in the Vrhovo basin and an additional verification of the 3D model were performed, and the 1D model application justified (Širca et al., 2000). They were followed by a verification of the HOTRIVER model of unobstructed river flow and the first more accurate assessment of the HPP chain construction impacts (Širca, 2001). Finally, a calculation of thermal impacts of different structures combination was made with statistically justified assumptions of middle (average) and exceptional (critical and extreme) conditions, upgrading of a single basin model into a HOTCHAIN model of the chain as well as an economical assessment of modified thermal conditions established (IBE, 2003a; Širca, 2003). In the continuation, the final results of thermal simulations made for different structures combination in different hydrometeorological conditions are given.

# 2. UPORABLJENI MATEMATIČNI MODELI

**HOTRIVER** je 1D nestacionarni model za simulacijo širjenja toplote v **nezajezenih rekah**. Temelji na poenostavitvi, da nestacionarne in kontinuirane izvire polutantov lahko obravnavamo kot vsoto trenutnih točkovnih izvirov (Širca in Rajar, 1997; Širca, 2001).

**HOTLAKE** je osnovni 1D-model za vrednotenje temperaturnih stanj v **bazenih rečnih (pretočnih) elektrarn**. Zgrajen je na predpostavki, da dolge, ozke bazene lahko obravnavamo na enak način kot nezajezene vodotoke, to je, s popolno vertikalno in horizontalno premešanostjo polutantov v prečnih profilih. Upravičenost predpostavke je potrjena z verifikacijo na bazenu Vrhovo in z rezultati 3D-modela (Širca et al., 2000).

**HOTCHAIN** je nadgradnja modela HOTLAKE **za več zaporednih bazenov**. Osnovna predpostavka je, da se na iztoku iz gorvodne HE začne koren bazena dolvodne HE, pri čemer se temperatura ob gorvodni pregradi uporabi kot vstopna temperatura za dolvodni bazen. Predpostavljeno je čisto pretočno obratovanje HE, kar pri pretokih nad 100 $m^3$/s lahko povzroči nekaj lokalne napake, pri manjših pa ne, ker HE v takšnih razmerah praviloma obratujejo po pretoku. Tudi pri večjih pretokih (nad 100 $m^3$/s) se lokalna napaka na celotnem računskem odseku izravna, saj čas potovanja vodnega elementa in s tem njegov čas izpostavljenosti atmosferskim vplivom ostaneta enaka.

Zelo pomemben korak razvoja modela HOTCHAIN je bil dodatno umerjanje člena, ki nadzoruje evaporacijo (IBE, 2003a). V vseh primerih verifikacij, ko so nastopale običajne meteorološke razmere, smo namreč upoštevali le 10 % srednje vrednosti evaporacije, dobljene iz empiričnih izrazov 9 avtorjev. V primerih ekstremnih razmer smo s takšnim modelom dobili zelo visoke vrednosti rečnih temperatur, zato smo na podlagi računa *ravnovesnih temperatur* v model vgradili korekcijo, ki pri naraščanju rečne temperature od 23 do 28 °C člen evaporacije linerano poveča od 10 na 100 %. Merodajni vrednosti

# 2. MATHEMATICAL MODELS APPLIED

**HOTRIVER** is a 1D unsteady-state simulation model of heat transfer in **undammed rivers**. It is based on a simplification that unstationary and continuous pollutant sources can be treated as a sum of instantaneous point sources (Širca and Rajar, 1997; Širca, 2001).

**HOTLAKE** is a basic 1D model for assessment of temperature conditions in **reservoirs of run-of-river power plants**. It is built on a presumption that long, narrow reservoirs can be treated in the same way as undammed rivercourses, i.e. with complete vertical and horizontal pollutants mixing in cross sections. This presumption has been justified by a verification performed in the Vrhovo reservoir and by results of a 3D model (Širca et al., 2000).

**HOTCHAIN** is an upgrade of the HOTLAKE model **for more successive reservoirs.** The basic presumption to be met is that at the upstream HPP outflow the downstream HPP reservoir begins and that the water temperature by the upstream dam is used as the input temperature for the downstream reservoir. A pure run-of-river HPP operation mode is foreseen which may cause some local error with flows above 100 $m^3$/s. With lower flows this should not be the case because in such conditions the HPPs normally operate in the run-of-river regime. Even with higher flows this local error shall be balanced along the complete calculation section since the travel time of the water element and consequently the time of its exposition to atmospheric impacts remain the same.

An important step of the HOTCHAIN model development was an additional calibration of the element controlling evaporation (IBE, 2003a). Namely, in all verification cases with usual meteorological conditions only 10% of mean evaporation calculated from empirical expressions of 9 authors were considered. In cases with extreme conditions extremely high values of river water temperatures were obtained with such a model. This is why a correction based on calculation of *equilibrium temperature (ET)* was introduced to the model which increased the evaporation value linearly from 10% to ravnovesne temperature pri privzeti zračni vlagi 65 % sta znašali 26,9 °C (pri temperaturi zraka 30 °C) in 30,7 °C (pri temperaturi zraka 35 °C).

100% at river water temperature increase from 23°C to 28°C. The decisive values of the ET at given air humidity of 65% so attained were 26.9 °C (at air temperature of 30 °C) and 30.7 °C (at air temperature of 35 °C).

# 3. OPIS RAČUNSKIH PRIMEROV

Obdelanih končnih 60 računskih primerov (preglednica 1) lahko delimo in medsebojno primerjamo po treh ključih:

1. glede na **število obratujočih elektro-energetskih objektov** (primeri A, B in C),
2. glede na **naravne pogoje** (povprečne razmere ter izredni dogodki) ter
3. glede na toplotno **moč objekta v Trbovljah** (brez objekta, 120 MW in 200 MW).

Za vse primere velja, da so nezajezeni rečni odseki modelirani s programom HOTRIVER (HR), akumulacije pa z modeli tipa HOTCHAIN, ki vsebujejo različno število bazenov (HC2, HC6 in HC7). Na lokaciji NEK se v skladu z načinom obratovanja, ki je v danih hidrometeoroloških razmerah možen, z modelom hlajenja NEK (IBE, 2003) določi prirastek rečne temperature in izračuna temperatura Save po popolnem premešanju.

## 3.1 KOMBINACIJE OBJEKTOV

**Primer A** potrjuje in določa sedanje stanje toplotne obremenitve Save, ko so zgrajene TE Trbovlje, HE Vrhovo in NE Krško. Simulacije so namenjene kontroli modelov ter prikazu ničelnih razmer pred začetkom gradnje verige HE (razen že zgrajene HE Vrhovo) ter prikazu vpliva obratovanja različno močnih objektov v Trbovljah.

**Primer B** napoveduje spremembe po izgradnji zgornjega dela verige do Krškega, ki bo zaključena do leta 2012. Poleg objektov primera A vključuje še HE Boštanj, HE Blanca in HE Krško. Simulacije so namenjene predvsem oceni vpliva verige HE na NEK, saj nadaljnja gradnja verige dolvodno od NEK s termičnega vidika ne bo imela vpliva gorvodno. Izjemoma se lahko ta pojavi lokalno v določenih hidroloških pogojih (nevarnost recirkulacije hladilne vode), vendar reševanje

# 3. SIMULATION CASES

The treated 60 calculation examples (Table 1) can be divided and mutually compared according to the following three keys:

1. regarding the **number of operating electric power units** (cases A, B and C),
2. regarding **natural conditions** (average conditions and extreme events) and
3. regarding **thermal power of the Trbovlje unit** (without the unit itself, 120 MW and 200 MW).

It is characteristic for all examples that undammed river sections have been modelled by the HOTRIVER (HR) model, while the reservoirs have been modelled by the HOTCHAIN model taking into account a different number of reservoirs (HC2, HC6 and HC7). At NEK location, in accordance with the operation mode possible in certain hydrometeorlogical conditions, the NEK cooling model (IBE, 2003) enables determination of the river water temperature increase and calculation of the Sava river water temperature after complete mixing.

## 3.1 STRUCTURES COMBINATIONS

**Case A** proves and determines the present state of thermal load of the Sava River with operating TPP Trbovlje, HPP Vrhovo and NPP Krško. Simulations are needed for models control and for description of initial state prior to the HPPs chain construction (with the exception of existing HPP Vrhovo) as well as to show the impact of operation of the Trbovlje units with different power output.

**Case B** anticipates changes after construction of the HPPs chain upper part down to Krško, which shall be terminated by 2012. Besides structures of Case A it includes Boštanj, Blanca and Krško HPPs. Simulations shall provide an assessment of the HPPs chain impact on the NPP Krško, since further construction of the chain downstream from NEK shall have no thermal impact on the upstream conditions. Exceptionally it may appear locally and in certain hydrological conditions (e.g. cooling water re-circulation) tega problema v tej fazi raziskav še ni bilo predvideno.

**Primer C** napoveduje spremembe po izgradnji celotne verige HE do Mokric, ko sta poleg objektov, naštetih v Primeru B, zgrajeni še HE Brežice in HE Mokrice. HE Mokrice kot zadnja stopnja verige predstavlja hkrati stanje v mejnem profilu s Hrvaško.

## 3.2 NARAVNI POGOJI

Navedene kombinacije objektov obravnavamo v **treh hidrometeoroloških stanjih**:

V **povprečnih mesečnih** razmerah (oznaka –**sred**), za katere privzemamo srednje mesečne pretoke v ustreznih prečnih profilih Save, srednje mesečne rečne temperature na ustreznih lokacijah ter srednje urne vrednosti meteoroloških parametrov.

V **kritičnih poletnih** razmerah (oznaka – **krit**), ki so definirane z nizkimi pretoki, ki trajajo 20 dni in imajo povratno dobo 2 leti, srednjo mesečno rečno temperaturo za avgust na vrhu obravnavanega odseka in srednjimi urnimi vrednostmi meteoroloških parametrov v dneh, ko najvišja dnevna temperatura preseže 27 ºC.

V **ekstremnih poletnih** razmerah (oznaka – **ekst**), ki so določene z nizkimi pretoki, ki trajajo 20 dni in imajo povratno dobo 25 let, srednjo mesečno rečno temperaturo za avgust na vrhu obravnavanega odseka, srednjimi urnimi vrednostmi meteoroloških parametrov v dneh, ko najvišja dnevna temperatura preseže 27 ºC.

Za hidrometeorološke podatke uporabljamo vhodne podatke iz obdobja 1980–2000 ali čim bližje aproksimacije. To manj ugodno predpostavko upravičujemo z izkazanim trendom večanja števila vročih poletnih dni, z izkazanimi spremembami rečnih režimov (nižje in dolgotrajnejše nizke vode v zadnjih dekadah) ter z večjim faktorjem varnosti pri napovedih. Nepričakovano potrditev pravilnosti te odločitve predstavlja nastop obdobja ekstremnega značaja v juniju 2003. Verjetnosti kritičnega (25 %) in ekstremnega dogodka (2,5 %) sta določeni kot produkt verjetnosti nastopa 20-dnevnih nizkih pretokov ter sočasnega 20-dnevnega obdobja toplih dni (prag 27 ºC), saj smo predpostavili, da sta dogodka neodvisna.

but solving of this problem has not yet been foreseen in this phase of research.

**Case C** anticipates changes to appear after construction of the whole HPPs chain down to Mokrice when besides the units given in the Example B, also Brežice and Mokrice HPPs will be built. HPP Mokrice as the last unit of the chain represents at the same time the border cross-section with Croatia.

## 3.2 NATURAL CONDITIONS

The given units combinations are treated in **three hydrometeorological states**:

In **average monthly conditions** (mark **sred**), where average monthly flows in relevant cross sections of the Sava River, together with average monthly river water temperatures at suitable locations as well as average hourly values of meteorological parameters are taken into account.

In **critical summer conditions** (mark – **krit**) defined by low flows lasting for 20 days and having a 2-year return period, average monthly river water temperature for August on the top of the section treated and average hourly values of meteorological parameters on days when the highest daily temperature exceeds 27 ºC.

**Extreme summer conditions** (mark – **ekst**), defined by low flows lasting for 20 days and having a 25 year return period, average monthly river water temperature for August on the top of the section treated and average hourly values of meteorological parameters on days when the highest daily temperature exceeds 27 ºC.

Input data from the period 1980–2000 or the closest approximations serve for hydrometeorological data. This less favourable presumption is justified by the trend of increasing number of hot days, by proved changes in river water regimes (lower and longer lasting low flows in the last decades) and by a higher safety factor in forecasting. An unexpected confirmation of such decision correctness came in June 2003 in form of a period of extreme character. Probabilities of critical (25%) and extreme events (2.5%) have been defined as a product of probabilities of a 20-day low flow event and a simultaneous 20-day period of warm days (threshold at 27 ºC), since it has been presumed that these two events are independent of one another.

### 3.3 OBJEKT V TRBOVLJAH

V vseh kombinacijah objektov (A, B in C) in naravnih pogojev (–sred, –krit in –ekst) je objekt v Trbovljah obravnavan z močjo 120 MW in močjo 0, ki pomeni, da TET ne obratuje. Ustrezni oznaki primerov sta TETja in TETne. Dodatno je samo za kritične in ekstremne razmere ob vseh konfiguracijah objektov (A, B in C) upoštevana povečana moč TET 200 MW (primer TETja+), pri čemer so upoštevani takšni projektni podatki morebitnega novega objekta, kot so veljali za opuščeno TET3.

Vstopna rečna temperatura na zgornjem koncu računskega odseka je za primere TETja enaka srednji rečni temperaturi v Radečah za obdobje 1980–1997. Za primer TETne je z upoštevanjem dotoka Savinje zmanjšana za obremenitev, ki jo v reko vnaša TET, za primer TETja+ pa na enak način ustrezno povečana.

### 3.4 POSEBNI PRIMERI

Pri računih kritičnih in ekstremnih situacij nastopa še **primer C1**, ki je enak primeru C, le da je bazen Brežice upoštevan v zmanjšanem obsegu, v okviru zgolj nadvišanih poplavnih nasipov. Ta varianta akumulacije bo izvedljiva v primeru soglasja Hrvaške k enotnemu obratovanju verige HE na obeh straneh meje, ko bi v Sloveniji odpadla potreba po dnevni kompenzaciji.

Izven obsega 60 rednih simulacij sta bili izvedeni še simulacija srednjih razmer julija 1998 kot osnovni verifikacijski primer ter teoretična prognostična simulacija stanja, kot bi nastopilo po izgradnji celotne verige HE (2018), če bi se ponovile hidrološke in meteorološke razmere iz julija 1998. Na podlagi neverificiranega modela za **zimsko stanje** je bila narejene tudi groba ocena hladilnega učinka bodočih akumulacij dolvodno od NEK.

### 3.3 TRBOVLJE UNIT

In all combinations of cases (A, B and C) and natural conditions (–sred, –krit in –ekst) the unit in Trbovlje has been treated as a unit of 120 MW power or 0 MW power which means that TET is out of operation. Relevant cases designations are TETja and TETne. Additionally, for all cases (A, B and C) but only for critical and extreme conditions, an increased power of TET of 200 MW has been considered (case of TETja+), where the same design data of eventual new unit have been considered as in case of the abandoned TET3.

The input river water temperature at the upper end of the calculation section, for TETja cases, is equal to the average river water temperature at Radeče for the period of 1980–1997. For cases of TETne, taking into consideration the Savinja inflow, it has been decreased for the load brought into the river by TET and for the case of TETja+, it has been relevantly increased in the same way.

### 3.4 SPECIAL CASES

**Case C1** is introduced aditionally for critical and extreme situation calculations which is the same as case C with the exception of decreased Brežice reservoir which appears only in the frame of enheightened flood embankments. This alternative of reservoir will be realistic in case of Croatia consensus regarding unified HPPs chain operation on both sides of the border, when in Slovenia no need of daily compensation would exist.

Apart from 60 regular simulations two other simulations have been performed, i.e. simulation of average conditions in July 1998 as a basic verification case and theoretic prognostic simulation of the state that would emerge after construction of the complete HPPs chain (2018) if hydrological and meteorological conditions of July 1998 occurred again. Based on an unverified model for **winter state** a rough estimation of a cooling effect of future reservoirs downstream NEK has been done as well.

Preglednica 1. Rezultati modeliranja – srednje rečne temperature v obravnavanih prerezih.
*Table 1. Results of modelling – average river temperatures in the considered cross-sections.*

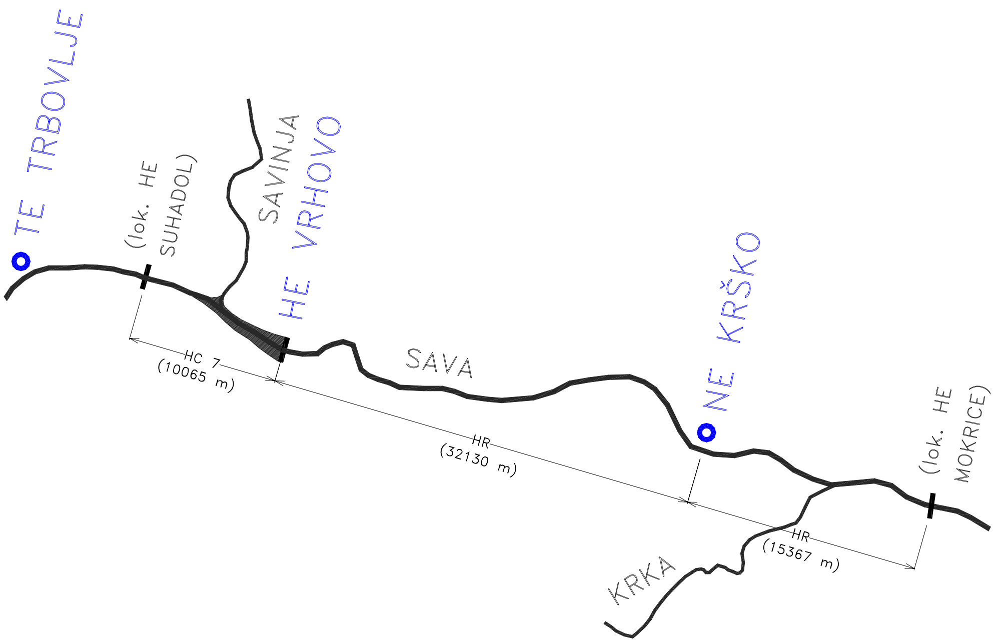
| naravni pogoji | obrat. objekti | obratov. TET | hidrometeorol. | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **natural conds.** | **operating units** | **TET operation** | **hydrometeorol.** | **SUH** | **VRH** | **BOS** | **BLA** | **KRS** | **NEKin** | **NEKout** | **BRE** | **MOK** |
| | | | | | | | | | | | | |
| **- sred** | Primer/Case A | TETja | April | 9,7 | 9,85 | | | | 10,37 | 11,66 | | 11,83 |
| | | | Maj/May | 12,7 | 12,96 | | | | 13,79 | 15,20 | | 15,48 |
| | | | Junij/June | 14,9 | 15,21 | | | | 16,17 | 17,68 | | 18,01 |
| | | | Julij/July | 17,6 | 18,01 | | | | 19,23 | 21,20 | | 21,62 |
| | | | Avgust/August | 18,1 | 18,56 | | | | 19,87 | 22,54 | | 22,95 |
| | | | September | 15,2 | 15,38 | | | | 15,96 | 17,94 | | 18,12 |
| | | TETne | April | 9,54 | 9,69 | | | | 10,22 | 11,51 | | 11,68 |
| | | | Maj/May | 12,53 | 12,79 | | | | 13,62 | 15,03 | | 15,31 |
| | | | Junij/June | 14,71 | 15,02 | | | | 15,98 | 17,49 | | 17,82 |
| | | | Julij/July | 17,35 | 17,77 | | | | 19,00 | 20,97 | | 21,39 |
| | | | Avgust/August | 17,77 | 18,23 | | | | 19,56 | 22,23 | | 22,65 |
| | | | September | 14,96 | 15,14 | | | | 15,73 | 17,71 | | 17,89 |
| | Primer/Case B | TETja | April | 9,7 | 9,85 | 10,01 | 10,22 | 10,36 | 10,44 | 11,73 | | 11,90 |
| | | | Maj/May | 12,7 | 12,96 | 13,23 | 13,61 | 13,85 | 13,98 | 15,39 | | 15,67 |
| | | | Junij/June | 14,9 | 15,21 | 15,54 | 15,98 | 16,27 | 16,43 | 17,94 | | 18,26 |
| | | | Julij/July | 17,6 | 18,01 | 18,44 | 19,02 | 19,41 | 19,60 | 21,57 | | 21,98 |
| | | | Avgust/August | 18,1 | 18,56 | 19,04 | 19,67 | 20,09 | 20,31 | 22,98 | | 23,37 |
| | | | September | 15,2 | 15,38 | 15,58 | 15,83 | 16 | 16,10 | 18,08 | | 18,26 |
| | | TETne | April | 9,54 | 9,69 | 9,85 | 10,07 | 10,21 | 10,29 | 11,58 | | 11,75 |
| | | | Maj/May | 12,53 | 12,79 | 13,07 | 13,44 | 13,68 | 13,82 | 15,23 | | 15,51 |
| | | | Junij/June | 14,71 | 15,02 | 15,35 | 15,8 | 16,09 | 16,25 | 17,76 | | 18,09 |
| | | | Julij/July | 17,35 | 17,77 | 18,2 | 18,78 | 19,17 | 19,37 | 21,34 | | 21,75 |
| | | | Avgust/August | 17,77 | 18,23 | 18,72 | 19,36 | 19,78 | 20,00 | 22,67 | | 23,07 |
| | | | September | 14,96 | 15,14 | 15,34 | 15,6 | 15,77 | 15,87 | 17,85 | | 18,03 |
| | Primer/Case C | TETja | April | 9,7 | 9,85 | 10,01 | 10,22 | 10,36 | 10,44 | 11,73 | 12,17 | 12,35 |
| | | | Maj/May | 12,7 | 12,96 | 13,23 | 13,61 | 13,85 | 13,98 | 15,39 | 16,17 | 16,49 |
| | | | Junij/June | 14,9 | 15,21 | 15,54 | 15,98 | 16,27 | 16,43 | 17,94 | 18,87 | 19,24 |
| | | | Julij/July | 17,6 | 18,01 | 18,44 | 19,02 | 19,41 | 19,60 | 21,57 | 22,75 | 23,23 |
| | | | Avgust/August | 18,1 | 18,56 | 19,04 | 19,67 | 20,09 | 20,31 | 22,98 | 24,07 | 24,45 |
| | | | September | 15,2 | 15,38 | 15,58 | 15,83 | 16 | 16,10 | 18,08 | 18,57 | 18,77 |
| | | TETne | April | 9,54 | 9,69 | 9,85 | 10,07 | 10,21 | 10,29 | 11,58 | 12,03 | 12,21 |
| | | | Maj/May | 12,53 | 12,79 | 13,07 | 13,44 | 13,68 | 13,82 | 15,23 | 16,02 | 16,34 |
| | | | Junij/June | 14,71 | 15,02 | 15,35 | 15,8 | 16,09 | 16,25 | 17,76 | 18,7 | 19,09 |
| | | | Julij/July | 17,35 | 17,77 | 18,2 | 18,78 | 19,17 | 19,37 | 21,34 | 22,54 | 23,03 |
| | | | Avgust/August | 17,77 | 18,23 | 18,72 | 19,36 | 19,78 | 20,00 | 22,67 | 23,83 | 24,24 |
| | | | September | 14,96 | 15,14 | 15,34 | 15,6 | 15,77 | 15,87 | 17,85 | 18,35 | 18,56 |
| | | | | | | | | | | | | |
| **- krit** | Primer/Case A | TETja | 25% verj/prob | 18,1 | 19,1 | | | | 21,60 | 24,60 | | 25,10 |
| | | TETja+ | 25% verj/prob | 18,35 | 19,34 | | | | 21,81 | 24,81 | | 25,28 |
| | | TETne | 25% verj/prob | 17,59 | 18,6 | | | | 21,17 | 24,17 | | 24,74 |
| | Primer/Case B | TETja | 25% verj/prob | 18,1 | 19,1 | 20,13 | 21,47 | 22,36 | 22,83 | 25,83 | | 26,15 |
| | | TETja+ | 25% verj/prob | 18,35 | 19,34 | 20,36 | 21,7 | 22,58 | 23,04 | 26,04 | | 26,33 |
| | | TETne | 25% verj/prob | 17,59 | 18,6 | 19,64 | 21,01 | 21,9 | 22,38 | 25,38 | | 25,77 |
| | Primer/Case C | TETja | 25% verj/prob | 18,1 | 19,1 | 20,13 | 21,47 | 22,36 | 22,83 | 25,83 | 26,75 | 27,00 |
| | | TETja+ | 25% verj/prob | 18,35 | 19,34 | 20,36 | 21,7 | 22,58 | 23,04 | 26,04 | 26,87 | 27,09 |
| | | TETne | 25% verj/prob | 17,59 | 18,6 | 19,64 | 21,01 | 21,9 | 22,38 | 25,38 | 26,5 | 26,80 |
| | Primer/Case C1 | TETja | 25% verj/prob | 18,1 | 19,1 | 20,13 | 21,47 | 22,36 | 22,83 | 25,83 | 26,41 | 26,73 |
| | | TETja+ | 25% verj/prob | 18,35 | 19,34 | 20,36 | 21,7 | 22,58 | 23,04 | 26,04 | 26,56 | 26,85 |
| | | TETne | 25% verj/prob | 17,59 | 18,6 | 19,64 | 21,01 | 21,9 | 22,38 | 25,38 | 26,08 | 26,47 |
| | | | | | | | | | | | | |
| **- ekst** | Primer/Case A | TETja | 2.5% verj/prob | 18,1 | 19,59 | | | | 22,75 | 25,75 | | 26,18 |
| | | TETja+ | 2.5% verj/prob | 18,48 | 19,95 | | | | 23,01 | 26,01 | | 26,39 |
| | | TETne | 2.5% verj/prob | 17,28 | 18,8 | | | | 22,15 | 25,15 | | 25,69 |
| | Primer/Case B | TETja | 2.5% verj/prob | 18,1 | 19,59 | 21,1 | 23,04 | 24,12 | 24,61 | 27,61 | | 27,78 |
| | | TETja+ | 2.5% verj/prob | 18,48 | 19,95 | 21,45 | 23,35 | 24,7 | 24,82 | 27,82 | | 27,97 |
| | | TETne | 2.5% verj/prob | 17,28 | 18,8 | 20,34 | 22,33 | 23,55 | 24,12 | 27,12 | | 27,34 |
| | Primer/Case C | TETja | 2.5% verj/prob | 18,1 | 19,59 | 21,1 | 23,04 | 24,12 | 24,61 | 27,61 | 28,03 | 28,19 |
| | | TETja+ | 2.5% verj/prob | 18,48 | 19,95 | 21,45 | 23,35 | 24,7 | 24,82 | 27,82 | 28,21 | 28,36 |
| | | TETne | 2.5% verj/prob | 17,28 | 18,8 | 20,34 | 22,33 | 23,55 | 24,12 | 27,12 | 27,66 | 27,84 |
| | Primer/Case C1 | TETja | 2.5% verj/prob | 18,1 | 19,59 | 21,1 | 23,04 | 24,12 | 24,61 | 27,61 | 27,85 | 28,03 |
| | | TETja+ | 2.5% verj/prob | 18,48 | 19,95 | 21,45 | 23,35 | 24,7 | 24,82 | 27,82 | 27,89 | 28,21 |
| | | TETne | 2.5% verj/prob | 17,28 | 18,8 | 20,34 | 22,33 | 23,55 | 24,12 | 27,12 | 27,45 | 27,66 |
| | | | | | | | | | | | | |
| **- jul98** | Primer/Case A | TETja | Julij/July 1998 | | 19,6 | | | | 20,94 | 23,03 | | |
| **- jul18** | Primer/Case C | TETja | Julij/July 1998 | 19.12 | 19,6 | 20,09 | 20,75 | 21,17 | 21,42 | 23,51 | 24,56 | 24,98 |
| | | | | | | | | | | | | |
| | **Značaj vrednosti iz preglednice (barvna legenda)** | | | | **Character of tabulated values (color legend)** | | | | | | | |
| | | | | | | | | | | | | |
| | | podana vrednost za 1D model = | | | = 1D model input value | | | | | | | |
| | | rezultat 1D modela = | | | = 1D model result | | | | | | | |
| | | rezultat modela hlajenja NEK = | | | = NEK cooling system model result | | | | | | | |
| | | izračun ni potreben ali ni možen = | | | = calculation not required or not possible | | | | | | | |

## 4. REZULTATI

Rezultati vseh računskih primerov so za profile HE Vrhovo (VRH), HE Boštanj (BOS), HE Blanca (BLA), HE Krsko (KRS), vtoka v NEK (NEKin), iztoka iz NEK (NEKout), HE Brežice (BRE) in HE Mokrice (MOK) zbrani v Preglednici 1.

## 4. RESULTS

Model results of all simulation cases are given in Table 1 for cross-sections of HPP Vrhovo (VRH), HPP Boštanj (BOS), HPP Blanca (BLA), HPP Krško (KRS), NEK inflow (NEKin), NEK discharge (NEKout), HPP Brežice (BRE) and HPP Mokrice (MOK).




Slika 1. Konfiguracija obstoječih objektov na in ob Savi (primer A).
*Figure 1. Configuration of the existing units on and along the Sava River (Case A).*

### 4.1 PRIMER A: OBSTOJEČE STANJE

Ker so bile verifikacije modelov že večkrat opisane, sami opisi sedanjega stanja pa so razmeroma nezanimivi, podajamo za primer A (slika 1) le komentar vrednotenja **vplivov obratovanja TE Trbovlje** na dolvodne toplotne razmere v Savi. Iz rezultatov v Preglednici 1 je razvidno, da znaša vpliv TE Trbovlje pri polni sedanji moči (leto 2003) in povprečnih razmerah pri NEK +0,31 °C v avgustu in +0,15 °C v aprilu. V kritičnih razmerah in sedanji moči bi bil vpliv TET na temperaturo pri NEK +0,43 °C, v ekstremnih razmerah pa +0,6 °C. Do zadnjega obravnavanega profila, HE Mokrice, bi se vpliv TET v ekstremnih razmerah zmanjšal na +0,49 °C. V primeru povečane moči TET (TET+) bi vpliv TET+ pri NEK v kritičnih

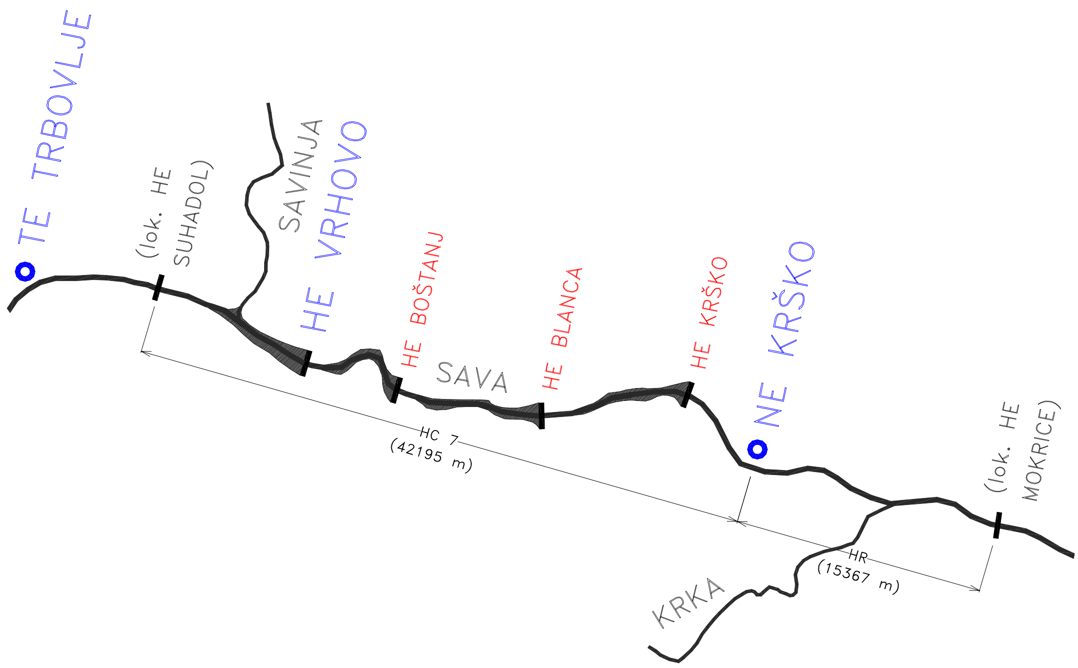
### 4.1 CASE A: EXISTING STATE (2003)

Since case verifications have been described already and the descriptions of the present state are uninteresting, we shall give here, for case A (Figure 1), only a comment on the evaluation of the **TPP Trbovlje operation impacts** on the downstream thermal conditions in the Sava River. It is evident from the Table 1 that the TPP Trbovlje impact at full present power (year 2003) and average conditions at NEK is +0.31 °C in August and +0.15 °C in April. In critical conditions and present power the TET impact on the temperature by NEK shall reach +0.43 °C, while in extreme conditions it shall reach +0.6 °C. At the last treated profile at HPP Mokrice, the impact of TET in extreme conditions would decrease to +0.49 °C. At increased power of TET (TET+) the impact of TET+ at razmerah znašal +0,64 °C, v ekstremnih pa +0,86 °C glede na ničelno stanje brez objekta TET.

Razlike med TET in TET+ (oziroma TET2 in TET3) so torej precej manjše, kot so bile ocenjene v letu 1998 v študiji TOPOS-TET3 (FGG, 1998). Razlogi za razliko so upoštevanje novejših in točnejših podatkov za pretoke in temperature Save in Savinje na sotočju, blažje, vendar z verjetnostnim računom utemeljene definicije kritičnih in ekstremnih razmer v tej študiji ter popravki modelov termike v definicijskem področju, kjer rečna temperatura preseže 23 °C.

NEK would reach +0.64 °C in critical conditions and +0.86 °C in extreme conditions, both compared with the state without TET.

Differences between TET and TET+ (i.e. between TET2 and TET3) are considerably smaller than those evaluated in 1998 (FGG, 1998). The reasons for this difference lie in new and more accurate flow and temperature data for the Sava and Savinja rivers at the confluence, in more moderate but statistically supported definitions of critical and extreme events as well as in thermal models corrections for cases when river water temperature exceeds 23 °C.




Slika 2. Konfiguracija predvidenih objektov na in ob Savi za primer B (2012).
*Figure 2. Configuration of anticipated units on and along the Sava River for Case B (2012).*

## 4.2 PRIMER B: STANJE PO IZGRADNJI HE KRŠKO (2012)

**Spremembe rečne termike zaradi gradnje verige HE** vrednotimo na podlagi primerjave rezultatov primerov A (slika 1) in B (slika 2) v profilih NEK in HE Mokrice (preglednica 1). Srednje rečne temperature na zajetju NEK se bodo zaradi izgradnje verige HE in ob hkrati obratujoči TET razmeroma malo spremenile: v aprilu bo sprememba manjša od 0,1 °C, v avgustu pa bo dosegla 0,44 °C. Večje spremembe bodo pri NEK

## 4.2 CASE B: STATE AFTER HPP KRŠKO CONSTRUCTION (2012)

**Changes in river water thermal load due to HPPs construction** have been evaluated by comparison of results of cases A (Figure 1) and B (Figure 2) in NEK and HPP Mokrice profiles (Table 1). Average river water temperatures at NEK intake shall face relatively small changes due to HPPs chain construction and due to simultaneous operation of TET: in April, this change will be smaller than 0.1 °C while in August it will reach 0.44 °C. At NEK, greater changes will opazne v kritičnih razmerah (+1,23 °C) in še večje v ekstremnih (+1,86 °C). V profilu HE Mokrice bodo srednje mesečne rečne temperature po izgradnji zgornjega dela verige HE višje za 0,07 °C v aprilu in za 0,42 °C v avgustu. V kritičnih razmerah bo povišanje glede na sedanje stanje +1,05 °C, v ekstremnih razmerah pa +1,6 °C. Pri HE Mokrice se bo srednja mesečna aprilska temperatura zaradi izgradnje zgornjega dela verige HE dvignila v aprilu z 11,83 na 11,9 °C, v avgustu z 22,95 na 23,37 °C, v kritičnih razmerah s 25,1 na 26,15 °C in v ekstremnih s 26,18 na 27,78 °C.

**Razlike med primeri z in brez obratovanja TET** se po izgradnji zgornjega dela verige HE ne bodo bistveno spremenile: Pri NEK bo razlika med stanjem brez in z obratovanjem TET v aprilu +0,15 °C, v avgustu +0,31 °C, v kritičnih razmerah +0,45 °C in v ekstremnih razmerah +0,49 °C. Morebitna TET+ bo rečno temperaturo v kritičnih razmerah dvigovala za +0,66 °C v ekstremnih pa za +0,7 °C, oboje v primerjavi z ničelnim stanjem brez objekta v Trbovljah. Obratovanje TET bo v primeru B v profilu HE Mokrice povzročalo podobne prirastke rečne temperature kot pri NEK. Tudi vpliv morebitne TET+ bo zelo podoben kot pri NEK, in sicer v kritičnih razmerah +0,56 °C in v ekstremnih razmerah +0,63 °C glede na ničelno stanje brez TET. Pri analizah vpliva TET na NEK je zanimivo, da bodo prirastki rečne temperature ob višjih obremenitvah nekoliko manjši, ker se zelo ogreta voda manj segreva od tiste pri običajnih temperaturah oziroma so procesi izmenjave z okolico intenzivnejši.

### 4.3 PRIMER C: STANJE PO IZGRADNJI CELE VERIGE (2018)

Spremembe rečnih temperatur **zaradi izgradnje celotne verige HE** vrednotimo na podlagi primerjav računov primera A (slika 1) in C (slika 3). Komentiramo jih le za lokacijo HE Mokrice, saj pri NE Krško med primeroma B (opisi v prejšnjem podpoglavju) in C ni razlike. Ob maksimalno obratujočih TET in NEK bodo srednje rečne temperature pri HE Mokrice po izgradnji verige HE znašale v aprilu 12,35 °C, v avgustu 24,45 °C, v

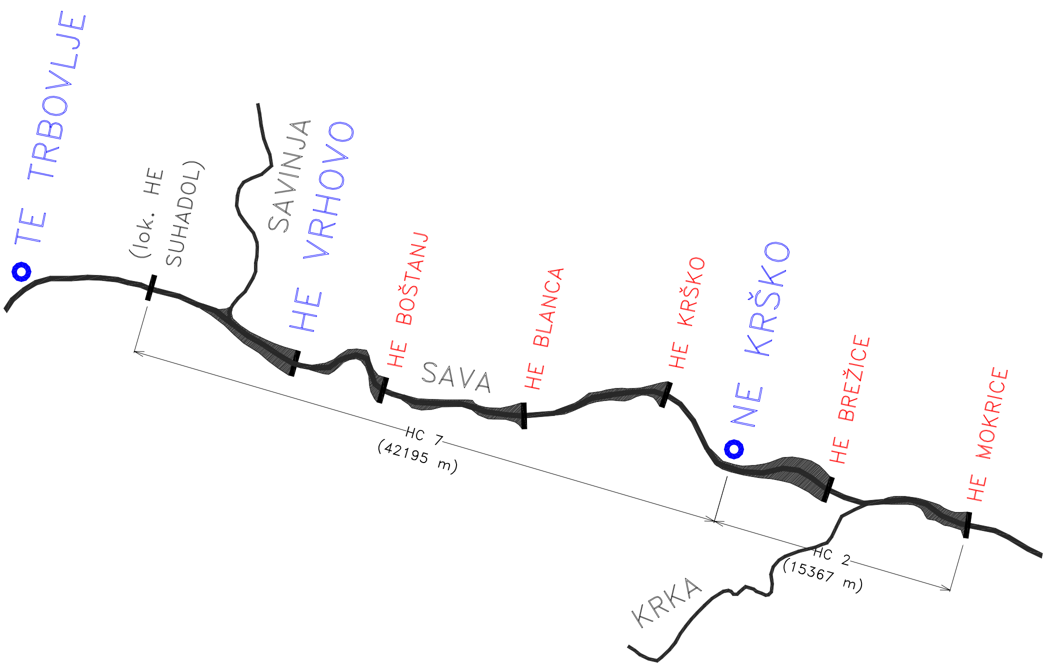
be evident in critical conditions (+1.23 °C) and even greater in extreme conditions (+1.86 °C). At the HPP Mokrice profile, after construction of the upper part of the HPPs chain, the average monthly river water temperatures shall increase for 0.07 °C in April and for 0.42 °C in August. In critical conditions, regarding the present state, this increase shall reach +1.05 °C, and in extreme conditions +1.6 °C. At HPP Mokrice, due to the upper part of the HPPs chain construction, the average monthly temperature shall increase from 11.83 to 11.9 °C in April and from 22.95 to 23.37 °C in August while in critical conditions the temperature will increase from 25.1 to 26.15 °C and in extreme conditions from 26.18 to 27.78 °C.

**Differences between cases with and without TET operation** after construction of the upper part of the HPPs chain will not be great: at NEK the difference occurring in case TET will operate or not shall reach +0.15 °C in April and +0.31 °C in August, in critical conditions +0.45 °C and in extreme conditions +0.49 °C. Eventual TET+ shall increase the river water temperature in critical conditions by +0.66 °C and in extreme conditions by +0.7 °C, both values being compared with the zero state without a unit in Trbovlje. The TET operation in Case B shall cause similar increase of the river water temperature in the profile of HPP Mokrice and at NEK. The impact of eventual TET+ will be also very similar to that occurring at NEK, i.e. in critical conditions it will reach +0.56 °C and in extreme conditions +0.63 °C, compared with the zero state without TET. In analyses of the TET impact on NEK it is interesting that the increases of the river water temperature at greater loads will be somewhat smaller since hot water heats less than water of normal temperature.

### 4.3 CASE C: STATE OF COMPLETED HPPS CHAIN (2018)

Changes in river water temperatures **due to construction of the complete HPPs chain** have been evaluated by comparison of results of Cases A (Figure 1) and C (Figure 3). The comment is given only for location of HPP Mokrice, since at NPP Krško there is no difference between Case B (see the previous subchapter) and Case C. At maximum operation of TET and NEK the average monthly river water temperatures at HPP Mokrice after construction of the HPPs chain kritičnih razmerah 27,0 °C in v ekstremnih 28,19 °C. Glede na sedanje stanje (primer A) znašajo prirastki v aprilu +0,52 °C, v avgustu +1,5 °C, v kritičnih razmerah +1,9 °C in v ekstremnih razmerah +2,01 °C.

will reach 12.35 °C in April, 24.45 °C in August, 27.0 °C in critical conditions and 28.19 °C in extreme conditions. Regarding present state (Case A) the increases reach +0.52 °C in April, +1.5 °C in August, +1.9 °C in critical and +2.01 °C in extreme conditions.




Slika 3. Konfiguracija predvidenih objektov ob in na Savi, primer C (2018).
*Figure 3. Configuration of the anticipated units on and along the Sava River, Case C (2018).*

**Obratovanje TET** bo imelo po zaključeni izgradnji verige nekoliko manjši vpliv na rečno temperaturo pri HE Mokrice (oz. na državni meji) kot v profilu NEK (glej tudi komentar primera B). V primerjavi s stanjem brez obratovanja TET bo prirastek na račun TET pri HE Mokrice v aprilu znašal +0,14 °C, v avgustu +0,21 °C, v kritičnih razmerah +0,2 °C in v ekstremnih +0,35 °C. V primeru obratovanja nadomestnega objekta TET+ (200 $MW_e$) bi prirastki pri HE Mokrice glede na stanje brez objekta v Trbovljah znašali v kritičnih razmerah +0,29 °C (temperatura 27,09 °C) in +0,52 °C v ekstremnih (temperatura 28,36 °C). Temperatura 28,36 je najvišja dosežena temperatura v tej študiji in pomeni precejšnje preseganje največje dovoljene temperature pod NEK, 28 °C, po popolnem premešanju. Pri tem se pojavlja vprašanje, ali je temperatura 28 °C dovoljena na izstopu hladilne vode NEK ali na državni meji. Če velja drugo (kar smo upoštevali v

After completion of the HPPs chain**, the TET operation** will have somewhat smaller impact on the river water temperature at HPP Mokrice (on the state border) than at the NEK profile (see also comment on Case B). In comparison with the zero state (without TET operation) the increase accounted to TET at the HPP Mokrice shall reach +0.14 °C in April, +0.21 °C in August, +0.2 °C in critical conditions and +0.35 °C in extreme conditions. In case of the substitutional unit TET+ (200 $MW_e$) operation the increases at HPP Mokrice, in comparison with the zero state, shall reach +0.29 °C in critical conditions (temperature 27.09 °C) and +0.52 °C in extreme conditions (temperature 28.36 °C). The temperature of 28.36 °C is the highest temperature achieved in this Study and exceeds the highest permitted temperature at NEK which is 28 °C after complete mixing. A question arises here whether the temperature of 28 °C is permitted at the cooling water outflow at NEK or at the state border. If the second is right (and what was considered in our Study as well), it is permissible for the naši študiji), je dopustno, da na odseku med NEK in mejo rečna temperatura še naraste, če pa je pogoj 28 °C postavljen na iztoku NEK, bi bilo v takšnem primeru že potrebno precejšnje omejevanje moči NEK.

## 4.4 PRIMER C1: MANJŠI BAZEN BREŽICE

V profilu HE Mokrice ter s polno obratujočima TET in NEK bi bila srednja rečna temperatura v kritičnih razmerah v primeru C1 26,73 °C, v primeru C pa 27,0, kar pomeni razliko 0,27 °C. V ekstremnih razmerah bi imeli v primeru C1 temperaturo 28,03 °C, v primeru C pa 28,19 °C, kar pomeni le razliko 0,16 °C. V takšnih razmerah torej znova velja, da so pri višjih absolutnih rečnih temperaturah razlike med variantami manjše. Ista zakonitost velja za vpliv TET+ oziroma pri primerjavi s stanjem brez objekta v Trbovljah. Razlika med primeroma C in C1 pri HE Mokrice znaša ob obratujočih TET+ in NEK v kritičnih razmerah 0,24 °C, v ekstremnih pa 0,15 °C. Če TET ne obratuje, obratuje pa NEK, je razlika med primeroma C in C1 pri Mokricah 0,33 °C v kritičnih razmerah in 0,18 °C v ekstremnih razmerah.

## 4.5 PRIMER D: ZIMSKO STANJE PO IZGRADNJI VERIGE

Namen izračunov primera D je bil ocena hladilne sposobnosti bodočih akumulacij v primeru zimskih nizkovodnih razmer. Poskusne simulacije modela HOTRIVER s podatki za 27. in 28. 11. 1995 so pokazale zelo slabo ujemanje računskih rezultatov in meritev pri NEK. Iz tega smo sklepali, da model, umerjen s povprečnimi temperaturami zraka in vode med 15–20 ºC (poletje), ne more zadovoljivo simulirati razmer pri povprečnih temperaturah okoli 0–5 ºC (zima). Osnovna ovira pri simuliranju zimskega termičnega stanja reke je bila pomanjkanje meritev rečne termike za hladno obdobje leta. Za zadovoljivo umerjanje modela je namreč treba imeti meritve vstopnih in izstopnih temperatur na nekem rečnem odseku vsaj za dva zaporedna dneva oziroma minimalno 24 ur, naš časovni niz pa je obsegal le nekaj več kot 12 ur. Zaradi

river water temperature to rise even more in the section from NEK to the State border. However, if the condition of 28 °C is set on the NEK outflow, the NEK power output shall be considerably limited.

## 4.4 CASE C1: SMALLER BREŽICE RESERVOIR

With TET and NEK in full operation, in the HPP Mokrice profile the average river water temperature will reach in critical conditions 26.73 °C in Case C1, and 27.0 in Case C which gives a difference of 0.27 °C. In extreme conditions the temperature shall reach 28.03 °C in Case C1, and 28.19 °C in Case C which gives the difference of only 0.16 °C. It is here evident again that at higher absolute river water temperatures the differences between alternatives are smaller. The same rule is valid for the impact of TET+ or in comparison with the zero state without the TET unit. The difference between Cases C and C1 at HPP Mokrice, with TET+ and NEK operating in critical conditions reach 0.24 °C, and 0.15 °C in extreme conditions. If TET is out of operation while NEK is operating, the difference between Cases C and C1 at Mokrice reaches 0.33 °C in critical conditions and 0.18 °C in extreme conditions.

## 4.5 CASE D: WINTER CONDITIONS AFTER HPPS CHAIN CONSTRUCTION

The purpose of calculating Case D was to evaluate the cooling capacities of future reservoirs in case of winter low flows. Trial simulations of the HOTRIVER model with data for November 27 and 28, 1995, showed very weak matching of computational results and measurements at NEK. A conclusion was that a model, calibrated by average (summer) air and water temperatures between 15–20 ºC cannot simulate the conditions at the average of 0–5ºC (winter) at a satisfactory level. The basic obstacle in simulating winter thermal state of the river was in the lack of river thermal state measurements during cool period of the year. To obtain a satisfactory model calibration, measurements of input and outlet temperatures at a certain river section for at least two successive days or 24 hours at a minimum shall be done, while the time period used in our case was only somewhat longer than 12 hours. This is why calculations of the tega so izračuni rečne termike v hladnem obdobju leta omejeni na poskus ocene hladilne sposobnosti bazenov Brežice in Mokrice, ki smo ga izvedli z obstoječimi modeli in nekaterimi predpostavkami.

V tem primeru za razliko od ostalih na odseku brežiškega bazena dolvodno od NEK in v bazenu Mokrice nismo predpostavili popolnega mešanja, temveč smo upoštevali le **zgornji sloj debeline 2 m**. S tem smo skušali zajeti vpliv stratifikacije (HS-FGG, 1998), ki bo v zimskih razmerah zanesljivo nastopil. Za tako definiran površinski sloj smo predpostavili računski pretok 40 $m^3/s$ ter zvišanje srednje februarske temperature 4,7 ºC zaradi vpliva NEK za 3 ºC (na 7,7 ºC) oziroma za 5 ºC (na 9,7 ºC). V takšnih razmerah bi na odseku med NEK in HE Brežice v primeru $\Delta T = 3$ ºC prišlo do ohlajanja sloja za –0,24 ºC, do HE Mokrice pa skupno za –0,30 ºC. V primeru $\Delta T = 5$ ºC bi ohlajanje do HE Brežice znašalo –0,51 ºC, do HE Mokrice pa že –0,67 ºC.

V drugi seriji računov smo predpostavili, da zgornji, **ogreti sloj debeline 2 m v bazenu Brežice sega le do polovice širine**, da se torej po izpustu iz NEK drži levega brega. Temu ustrezno je bil pretok sloja zmanjšan na 20 $m^3/s$. V takšnem primeru bi na odseku med NEK in HE Brežice pri $\Delta T = 3$ ºC prišlo do ohlajanja »polovičnega« sloja za –0,22 ºC, v primeru $\Delta T = 5$ ºC pa za –0,51 ºC. Nadaljnje ohlajanje do HE Mokrice v tem primeru ni bilo računano, saj je manj verjetno, da bi se oblak tople vode držal levega brega še tudi po prehodu pregrade HE Brežice. Približno takšno stanje »polovične obremenjenosti« reke je bilo za poletne razmere že tudi prognozirano s 3D-modelom v študiji »Vpliv NE Krško na obratovanje verige HE na spodnji Savi« (IBE, 1998). Hladilna kapaciteta bazena Brežice pri tem ni bila računana, kot tudi niso bile zaradi pomanjkanja podatkov računane splošne razmere v hladnejšem delu leta (pozimi).

Predstavljeni aproksimativni rezultati kažejo, da je ob ustreznih ukrepih (oblikovanje objektov) in sočasnem upoštevanju okoljske regulative možno računati na intenzivnejše naravno hlajenje toplotno obremenjene savske vode dolvodno od NEK. Podrobnejše in bolj zanesljive rezultate bo mogoče dobiti po

river thermal state in the cool period of the year have been limited only to an evaluation of the cooling capacity of the Brežice and Mokrice reservoirs which has been performed with the existing models and some presumptions.

In this case, and in contrast to the others, at the Brežice reservoir section downstream NEK and in the Mokrice reservoir no complete mixing but only **the upper layer of 2 m thickness** has been considered. In this way the stratification effect (HS-FGG, 1998) which definitely occurs in winter conditions has been taken into account. For so defined surface layer a calculated flow of 40 $m^3/s$ and an increase of the average February temperature of 4.7 ºC by 3 ºC (to 7.7 ºC) or by 5 ºC (to 9.7 ºC) being a consequence of NEK impact has been presumed. In such circumstances, at a section between NEK and HPP Brežice, in case of $\Delta T = 3$ ºC, the surface layer shall be cooled down by –0.24 ºC, while down to HPP Mokrice this cooling shall reach –0.30 ºC in total. In case of $\Delta T = 5$ ºC the cooling down to HPP Brežice shall reach –0.51 ºC and down to HPP Mokrice –0.67 ºC.

In the second calculation series it has been presumed that the upper, **warmed layer of 2 m thickness in the Brežice reservoir extends only to the half of the reservoir width** and that it sticks to the left bank after the outflow from NEK. Relevantly, the layer flow has been reduced to 20 $m^3/s$. In such case, between NEK and the HPP Brežice, at $\Delta T = 3$ ºC, cooling of the "half" layer by –0.22 ºC shall occur and in case of $\Delta T = 5$ ºC the temperature shall decrease by –0.51 ºC. Further cooling down to HPP Mokrice has not been calculated for it is less possible that the warm plume would stick to the left bank also after passing through the HPP Brežice dam. A similar state of »half thermal load« of the river has been forecasted for summer conditions by using a 3D model in the study »NPP Krško impact on the HPPs chain operation on the lower Sava River« (IBE, 1998). The Brežice reservoir cooling capacity as well as the conditions in the cooler part of the year (winter), due to lack of data, have not been calculated therein.

The presented approximative results show that by suitable measures (design of structures) and simultaneous consideration of environmental legislation more intensive natural cooling of the Sava water downstream NEK can be expected. More detailed and reliable results shall be obtained after the vzpostavitvi ustreznega monitoringa rečne temperature pri HE Vrhovo in prilagoditvi modela HOTRIVER / HOTCHAIN tudi za hladno obdobje leta. Najbolj zanesljivo in temeljito pa je možno izdelati podrobnejše prognoze z nadaljnjimi ciljnimi obravnavami s 3D modelom PCFLOW3D, ki predhodno prav tako zahteva verifikacijske podatke za zimsko obdobje.

## 5. ZAKLJUČEK

**Srednje mesečne rečne temperature** se bodo na račun izgradnje verige HE malo spremenile. Na zajetju NEK bodo prirastki rečne T manjši od +0,5 °C (avgusta +0,42 °C). V mejnem profilu bodo prirastki bolj opazni: po izgradnji celotne verige HE bodo julija znašali do +1,64 °C).

**V času izrednih dogodkov** bodo spremembe bolj opazne, še zlasti po zaključku gradnje celotne verige HE (primer C). Pri HE Mokrice bodo prirastki srednje rečne temperature v kritičnih razmerah znašali od +1,1 °C (primer B) do +2,1 °C (primer C), v ekstremnih razmerah pa od +1,7 °C (primer B) do +2,2 °C (primer C). Opazna bodo tudi povišanja na zajetju NEK, in sicer +1,3 °C v kritičnih in do +2,0 °C v ekstremnih razmerah. Pri NEK med primeroma B in C ni razlike v rezultatih.

**Zmanjšanje bazena Brežice** v okvir poplavnih nasipov (primer C1) povzroči znižanje rečne T pri Mokricah za 0,3 °C v kritičnih in za 0,2 °C v ekstremnih razmerah. Na nivoju srednjih mesečnih vrednosti varianta C1 zaradi pričakovanih minimalnih razlik glede na varianto C ni bila obravnavana.

**Vpliv obratovanja TET** s sedanjo močjo (stanje 2003) znaša v povprečnih razmerah <u>pri NEK</u> največ +0,3 °C (v avgustu), kar se z izgradnjo verige ne bo spremenilo. V kritičnih razmerah vpliva TET na rečno temperaturo pri NEK v višini 0,43 °C, kar bo po izgradnji verige naraslo na +0,45 °C. V ekstremnih razmerah se bo razlika zaradi TET pri NEK zmanjšala s sedanjih +0,6 °C na +0,49 °C. Zmanjševanje razlike je posledica močnejše izmenjave rečne toplote z atmosfero pri višjih rečnih temperaturah. V profilu <u>HE Mokrice</u> je

introduction of an adequate river water temperature monitoring system at HPP Vrhovo and adaptation of the HOTRIVER / HOTCHAIN model for the cooler part of the year as well. However, the most reliable and thorough prognoses can definitely be done by further PCFLOW3D 3D model targeted investigations which nevertheless require verification data for the winter period.

## 5. CONCLUSIONS

As a consequence of the HPPs chain construction **average monthly river water temperatures** shall slightly differ. At the NEK intake the water temperature increase shall not exceed +0.5 °C (in August +0.42 °C). At the state border the increase shall be more evident: after construction of the complete HPPs chain it shall reach up to +1.64 °C in July.

**During exceptional events** changes will be more evident especially after construction of the complete HPPs chain (Case C). At HPP Mokrice the increase of the average water temperature in critical conditions shall range from +1.1 °C (Case B) to +2.1 °C (Case C) while in extreme conditions it shall range from +1.7 °C (Case B) to +2.2 °C (Case C). Increase at NEK intake will be evident as well, i.e. +1.3 °C in critical conditions and up to +2.0 °C in the extreme ones. At NEK there is no difference in results as regards Case B and Case C.

**Reduction of the Brežice reservoir** within the frame of flood embankments (Case C1) shall cause reduction of water temperature at Mokrice by 0.3 °C in critical conditions and by 0.2 °C in the extreme ones. Due to expected minimal differences regarding the C alternative, the C1 alternative has not been treated on the level of average monthly values.

**The TET operation impact** at its present power output (year 2003) and in average conditions does not exceed +0.3 °C (in August) <u>at NEK</u> which shall not change with the HPPs chain construction. In critical conditions the TET impact on the river water temperature at NEK reaches 0.43 °C, which shall increase to +0.45 °C after the HPPs chain construction. In extreme conditions, the difference caused by TET shall decrease at NEK from the present +0.6 °C to +0.49 °C. The difference decrease is a consequence of greater river surface heat exchange at higher river water temperatures. At the site of future <u>HPP Mokrice</u> the present TET impact on the average river water temperature does not sedanji vpliv TET na srednjo rečno temperaturo največ +0,30 °C (avgust) in bo po izgradnji verige ostal nespremenjen. V kritičnih razmerah bo sedanji vpliv TET s +0,36 °C padel na +0,20 °C po izgradnji celotne verige in v ekstremnih razmerah s sedanjih +0,49 °C na +0,35 °C po izgradnji verige.

**Razlika med TET+ in TET** se pri NEK v kritičnih razmerah odraža z razliko srednje rečne temperature +0,21 °C, v ekstremnih pa +0,26 °C. Po izgradnji verige gorvodno od NEK bo razlika v kritičnih razmerah ostala +0,21 °C, v ekstremnih pa se bo zmanjšala na vrednost +0,21 °C. V profilu HE Mokrice je potencialna sedanja razlika med TET+ in TET +0,18 °C v kritičnih in +0,21 °C v ekstremnih razmerah, kar se bo po izgradnji celotne verige zmanjšalo na +0,09 °C v kritičnih in +0,17 °C v ekstremnih razmerah. Manjša razlika pri višjih absolutnih temperaturah je posledica intenzivnejše toplotne izmenjave med reko in ozračjem. V primerjavi s predhodno študijo TOPOS-TET3 (FGG, 1998) so ugotovljene precej manjše razlike med TET+ in TET. Razlogi za to so razlika v definicijah kritičnih in ekstremnih dogodkov, za zelo visoke rečne temperature dodatno umerjeni modeli, točnejše vrednotenje vpliva NEK ter točnejši izračun mešanja Save in Savinje v novejši študiji.

exceed +0.30 °C (August) and shall remain unchanged after the chain construction. In critical conditions after the construction of the chain the present TET impact shall be cut down from +0.36 °C to +0.20 °C and in extreme conditions from the present +0.49 °C to +0.35 °C.

**The difference between TET+ and TET** at NEK is reflected by the difference of the average river water temperature of +0.21 °C in critical conditions and of +0.26 °C in the extreme ones. After construction of the HPPs chain the difference will remain +0.21 °C in critical conditions, while in extreme contions it shall decrease to the value of +0.21 °C. In the HPP Mokrice profile the potential present difference between TET+ and TET attains +0.18 °C in critical conditions and +0.21 °C in the extreme ones which shall be reduced after construction of the complete HPPs chain to +0.09 °C in critical and to +0.17 °C in the extreme conditions. The smaller difference at higher absolute temperatures is a consequence of more intensive thermal exchange between the river and the air. Compared with the previous study TOPOS-TET3 (FGG, 1998) considerably smaller differences between TET+ and TET have been established. The reason lies in the difference of critical and extreme events definitions, additionally calibrated models for extremely high river water temperatures, more accurate evaluation of the NEK impact and more accurate calculation of the Sava and Savinja Rivers mixing in the more recent Study.

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