RISK OF THERMAL POLLUTION OF THE DANUBE PASSING THROUGH SERBIA DUE TO THERMAL POWER PLANTS

by

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A thermal power plant (TPP) uses large amounts of fresh water, mostly for cooling purposes. Among different types of cooling systems, once-through cooling is the most water-intensive and has the greatest environmental impacts. From the viewpoint of the steam cycle efficiency, this type of cooling still provides the most efficient electricity production, and therefore is widely used. Water is withdrawn from nearby water bodies, absorbs heat from the steam in a condenser, and then discharged back to its original source at higher temperatures causing severe environmental impacts, including fish killing, disturbing ecosystems, and heating-up natural water bodies. The total installed capacity of almost 1100 MW on the right bank of the Danube in Serbia threatens the ecosystem of this large international river due to thermal pollution. This problem will be even more pronounced in the near future, due to an inevitable increase in production capacity for new 350 MW, currently under construction. Herein, analysis of the legal framework for the protection of water from thermal pollution as well as analysis of the actual situation on the site of the TPP "Kostolac" in Serbia are presented. Based on meteorological and hydrological parameters, configuration and operation parameters of the plant, the numerical simulation of the condenser was carried on. The temperature of the water leaving condenser and amount of heat discharged back to the river are obtained. According to those results, the analysis of the existing thermal pollution of the Danube River in the flow through Serbia is given by numerical simulation using software ANSYS CFX. Analysis of thermal discharge into the Danube for the five-year period has been carried out. The cooling water effluent causes a temperature increase in the area of the right bank of the Danube, and this thermal disturbance extends along the right river bank for kilometers. Note that the flow rate of the Danube is currently large enough to compensate this thermal disturbance, but for a smaller river and/or larger electricity production capacities, this influence would have even more significant consequences on the ecosystem, making those results even more useful for further analysis.

Key words: *once-through cooling system, numerical simulation, power plant, thermal pollution*

Introduction

Thermal power (TPP) plants, especially those fueled by coal, today are considered as one of the biggest polluters of air and water. The primary source of environmental pollu-

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tion from TPP comes from the emission of harmful gasses due to combustion. Full attention is devoted to minimizing this problem, in terms of reducing emissions of SO_2, NO_x, and CO_2. In regard to water pollution from power plants, most attention is devoted to the intake of dissolved toxic substances dissolved in wastewater into natural waterways, both from TPP processes, the slag, and ash disposal. Installations for the protection of air pollution caused by combustion of fossil fuels, built in the last few decades, resulted in the production of a new amount of sewage carrying toxic substances into natural waterways. Therefore, the US Agency for Environmental Protection (EPA) at the end of 2015 passed new rules to protect water from toxic substances such as arsenic, mercury, selenium, *etc.*, which emerge as a result of the installation of desulfurization, fly and bottom ash, gasification of coal, *etc.* [1]. Milutinovic *et al.* [2] discussed the environmental indicators different scenarios for Serbia, but the thermal pollution of the rivers is not considered in this research.

However, one of the most important factors of natural ecosystems degradation is the thermal pollution caused by the emission of warm wastewater into natural water habitats. The problem of thermal pollution is equally expressed in both, TPP, as well as in nuclear plants. For proper operation of these plants working in Rankine cycle, it is necessary to provide an adequate heat sink. Therefore, the use of large amounts of cooling water, in order to condense steam from the low-pressure turbine is necessary for the operation of these plants [3].

For the cooling of the condenser, steam power plants basically use two types of cooling systems – closed (re-circulation) and open (once-through) system. Plants using the closed cooling system with wet cooling towers require a small amount of fresh water needed to compensate evaporation losses. In this case, waste heat is transferred to the atmospheric air by evaporation and convection, and the immediate surroundings of the power plant are exposed to warming and moisturizing. In the closed-cycle cooling systems, dry and hybrid cooling towers are also in use, but with limited capacity.

In power plants with the once-through cooling system, the necessary quantity of cold water is taken directly from rivers, lakes or the sea. After condensing the steam in plant's condenser, heated water is discharged back into the downstream natural water source. In this way, discharged heated water raises the temperature of the natural watercourses, causing disruption in the natural temperature and ecosystems balance. Definition of thermal pollution is precisely the change in temperature of natural waters (rivers, lakes, oceans) due to human activity [4, 5]. It should be kept in mind that the energy efficiency of power plants with once-through cooling is higher up to 5% compared to plants with a closed-cycle cooling, due to lower temperature of the cooling water [6]. Therefore, wherever possible, large thermal power capacities are being built on the banks of large rivers, in order to simultaneously provide the required amount of cooling water and obtain better energy efficiency of plants producing electricity. Although once-through cooling systems are the simplest, most energy efficient, have lowest exploitation costs, and lowest water loss due to evaporation, because of the large amounts of waste heat returned to natural watercourses, new technological solutions are researched in order to achieve these objectives and to conserve water resources [7].

As it is noted in [8], the greatest share of electricity produced from TPP today have the United States, China, and France, with overall thermal effluent into rivers achieving 26%, 16%, and 12%, respectively. Participation of the once-through cooling system in these countries is 17%, 8%, and 25%, respectively. In the US, one of the measures to protect surface waters from thermal pollution is limiting the temperature of wastewater to 32 °C [9]. In the EU, water temperatures downstream from the point of discharge is limited to maximum 3 °C above natural temperatures [10]. China is also acting in the direction of restricting water withdrawals, and more attention is paid to protection from thermal pollution of rivers in continental parts of China [11].

The thermal regime of the river plays an important role in preserving its ecosystem and is closely linked to protection against thermal pollution. The increase in water temperature can be predicted using three groups of models, deterministic, stochastic, and regression models [12], that include atmospheric, topographical, and human impacts on the change in the temperature regime of the river. Besides irrigation and deforestation in coastal areas, waste heat from industrial and power plants has the greatest significance in the change of thermal regime and thus on maintaining the population of certain groups of organisms sensitive to temperature changes in habitat. One of the most important factors that determine the conditions for maintaining the quality of life of aquatic ecosystems is variability of dissolved oxygen in the water, which significantly decreases with increasing temperature. Higher temperatures lead to decreased oxygen solubility in water while at the same time causing increased metabolic rates that affect sediment oxygen demand, nitrification, photosynthesis, and respiration [13].

On the other hand, a great need for cooling water in TPP in conditions of pronounced global warming and frequent droughts, limits the production of electricity, especially in the summer. Due to these climatic conditions, some plants have to curtail operations due to lack of sufficient flow of cooling water [9].

Electricity and water resources of Serbia

In Serbia, the total installed electricity generation capacity is 8359 MW. A 5171 MW (or nearly 70%) is electricity generation in lignite TPP, 353 MW in combined heat and power plants fueled by natural gas and liquid fuels and 2835 MW in hydropower plants. Out of 18 TPP units, 13 have a once-through cooling system. The highest concentration of capacities is at the banks of Sava river in TPP *Nikola Tesla A and B*, where 8 units have a total output of 2880 MW. On the banks of Danube, 4 units of 110 MW, 210 MW, 2 × 348.5 MW in TPP *Kostolac A* and *Kostolac B* are in operation, [14]. In addition, a new 350 MW TPP unit *Kostolac B3* is currently under construction on the site of TPP *Kostolac B* [15].

The Danube is an international waterway river, second largest in Europe, with a total length of 2800 km. It belongs to the Black Sea Basin. A large number of industrial and electricity production plants are located on the banks of this river, as can be seen in fig. 1 [16]. In Serbia, the only thermal power plant located on the banks of Danube is power plant *Kostolac*.

Large number of studies on contamination of the river Danube has been done. International organizations are formed and engaged in monitoring the water quality of the Danube, such as the International Commission for the Protection of the Danube River (ICPDR) and the IAWD (The International Association of Water Supply Companies in the Danube River Catchment Area). In Sofia, Bulgaria, in 1994, Danube River Protection Convention was signed, in order to form the legal instrument for transboundary water management in the Danube River Basin [17]. The Republic of Serbia has been a full member of the ICPDR since 2003, ratifying the Danube River Protection Convention. However, less attention is devoted to thermal pollution in these documents, in comparison to the intake of toxic substances from the wastewater.

The risk of thermal pollution of the Danube due to TPP Kostolac with a total installed capacity of 1017 MW is discussed in this paper. The 100 MW and 210 MW units are located around 2 km upstream of 2 × 350 MW units cooling water intake. Effluent water from

Figure 1. Electricity production plants on the banks of Danube River

those 2 units has a small influence on Danube water temperature, due to the small flow rate of the effluent and large flow rate of Danube. This impact is reflected in the slight increase in cooling water intake temperature, which affects the slight reduction in the energy efficiency of the 350 MW unit. In this manner, the greatest influence on the thermal pollution of the Danube downstream of the power plant comes from TPP units *Kostolac B1* and *Kostolac B2*. The case study was done for the 350 MW unit TPP *Kostolac B1*.

The 350 MW power plant thermal discharge into Danube

For the condenser cooling purposes, power plant *Kostolac B* uses water from the Danube. Cold water from the Danube is directed to the pump station by cold water channel. After cooling the condenser, heated water is discharged back to the Danube. As an effluent channel, deepened riverbed of the river Mlava is used, fig. 2.

The average annual water flow rate of the Danube is around 5500 m^3/s, with low hydrology sensitivity. The influence of the effluent cooling water from TPP *Kostolac B* on the thermal pollution is expected to be very small. However, the Danube is, on its course, very liable to the different influences of the numerous energy and industrial facilities, and it is important to evaluate thermal pollution in the particular location and keep it to the minimum level. As other authors have shown, in the last decade, the mean annual temperature in the course of the Danube through Austria increased by 1 °C [18], while other authors indicate that in Croatia the rise in water temperature of Danube starts since 1988 [19].

Republic Hydrometeorological Service of Serbia obtains data from 15 reporting surface water stations along the Danube in Serbia. Figure 3 shows surface water station network of the Danube basin, [20]. Relevant reporting water stations for the case of *Kostolac B* are city of Smederevo (upstream) which is 10 km from TPP *Kostolac* and city of Veliko Gradiste (downstream) which is about 25 km from TPP *Kostolac*.

Figure 2. Cold and hot water channels in TPP *Kostolac*

Figure 3. Part of the reporting surface water stations network in Serbia

Table 1 presents measured average annual water temperatures upstream and downstream of the TPP [20]. As can be seen, downstream from TPP average annual mean and maximum temperature are both higher for approximately 1 °C. There are no such large deviations in the data obtained from measuring upstream station Smederevo, suggesting that the concentration of electric power capacity in this part of the Danube causes such temperature growth downstream of the power plant.

Table 2 shows average annual Danube water level, temperature, and flow rate, measured for the summer period 2000-2016, in the closest measuring station upstream of TPP *Kostolac B* – Smederevo [20].

Table 1. Average annual water temperature upstream and downstream TPP *Kostolac B*

Year	Annual mean temperature, $T_{\text{A, mean}}$ [°C]		Annual maximum temperature $T_{\text{A, max}}$ [°C]	
	Upstream	Downstream	Upstream	Downstream
2010	12.3	12.9	26	27.6
2011	12.8	13.8	25.6	26.6
2012	12.7	13.6	26	27.8
2013	12.5	13.5	27.2	28
2014	13.4	13.8	24.6	25
2015	13.4	14.2	28	29

Table 2. Hydrology data, Smederevo station, for the summer 2000-2016

Year	Average water level			Average water temperature			Average water flow rate		
	July	Aug.	Sept.	July	Aug.	Sept.	July	Aug.	Sept.
2000	417	442	409	22.5	23.5	19.9	No data available		
2001	501	471	510	22.1	23.6	18	4860	3490	5330
2002	458	496	471	25.1	21.5	19.3	2970	5170	3590
2003	445	439	442	24.4	25.4	20.3	2170	1820	1780
2004	491	469	450	21.9	21.7	20.3	4720	3560	2670
2005	532	520	530	22.5	21.7	18.9	5640	5510	5430
2006	502	481	477	25.2	22.3	18.8	4520	3850	3610
2007	455	444	490	24.8	23.4	18.1	3260	3260	3260
2008	479	485	446	23.5	22.5	19	4160	4350	2730
2009	554	473	453	No data available			6510	3770	3190
2010	568	531	507	22.6	22.2	17	7000	5740	5640
2011	467	477	440	22.8	21.5	20.8	3680	3890	2470
2012	467	433	445	23.9	22.5	19.9	3680	2780	2960
2013	491	432	451	22.5	24.7	18.3	4490	2450	3230
2014	477	516	569	23.1	22.4	17.5	4100	5680	7410
2015	449	436	432	25.5*	27*	22*	3360	2880	2780
2016	504	487	453	22.9	22.8	21.5	5130	4410	3260

* Temperature measurements are obtained once a week.

Table 3 presents critical values of Danube water temperature and flow rate (minimum flow rate and maximum water temperature), measured upstream of the TPP [20].

Table 3. Hydrology data, Smederevo station, for the summer 2006-2016

Year	Maximal water temperature			Minimal water flow rate		
	July	Aug.	Sept.	July	Aug.	Sept.
2006	24	19.4	18	2800	2540	2530
2007	22.6	22.4	15	2530	2290	2450
2008	20	20.8	15.2	3040	3300	2380
2009	No data available			6510	3770	4520
2010	17.2	20.2	15.4	4110	3770	4120
2011	20	19	17.6	3200	2600	2140
2012	22	21.2	16.2	3250	2050	2350
2013	20.6	20.8	15.2	3050	2150	2250
2014	22	19.4	15.4	3600	4440	4750
2015	No data available			2950	2600	2520
2016	21.2	21.2	18.6	3610	3600	2650

The cold-end operation of the referent power plant

Power plant discussed in this paper is working under Rankine cycle. From thermal pollution of water point of view, the cold-end operation in off-designed mode is of importance. The mathematical model, based on the equations of mass and energy balance, and numerical model for the simulation of cold-end operation for this particular power plant is developed, and presented in [21]. The inlet temperature of the cooling water in the steam condenser of the power plant in design mode is 12 °C, for designed value of condensing pressure of 0.044 bar. The increase in cooling water temperature and in order to ensure designed power output causes an increase in condensing pressure, that leads to increasing the specific heat load of the plant [22]. Having in mind that need for electricity is constantly growing, this plant is working at full load in almost every season. The cooling water flow rate is constant, 13 m^3/s. Change of the inlet water temperature and condensing pressure will cause a change of the effluent water temperature as it is shown in fig. 4. Those results are obtained for power plant full load at 350 MW.

Taking into account the Danube temperature from tab. 2, the peak temperature of the effluent cooling water for summer 2010-2015 is shown in fig. 5.

Thermal discharge index

Thermal discharge index (*TDI*) is a representative of the thermal pollution from power plants, and can be calculated as the ratio between the amount of heat discharged to the environment and electrical power output of the plant [23]:

$$TDI = \frac{\text{Thermal discharge to the environment [MW]}}{\text{Electrical output [MW]}} \tag{1}$$

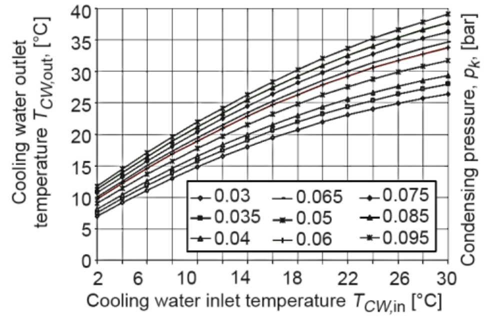


Figure 4. Temperature of the cooling water leaving condenser depending on condensing pressure

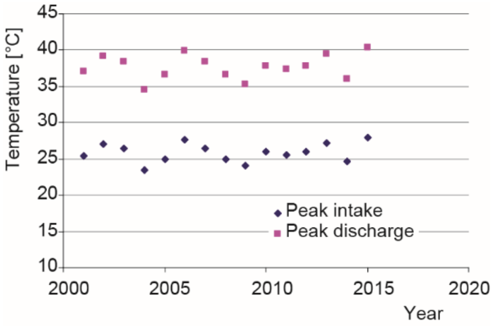


Figure 5. Effluent cooling water peak temperature 2000-2015

This index is strongly dependent on the thermal efficiency of the power plant. For the coal-fired power plant with efficiency near to 40%, the *TDI* is estimated to be near 1.5. The larger *TDI* value means a higher threat to the natural water bodies.

Taking into account change of energy efficiency of the plant due to change of condenser cooling water inlet temperature, as shown in fig. 6 [22], and temperature of the Danube during one year, it can be seen that *TDI* value will rise during the hottest months, as shown in fig. 7.

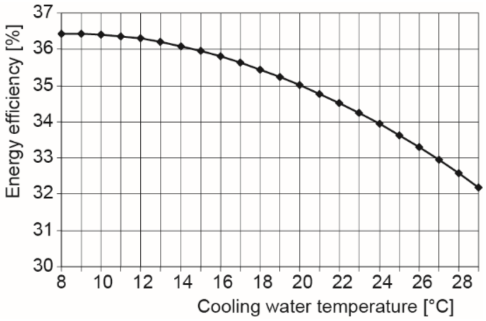


Figure 6. Energy efficiency of the power plant change due to cooling water temperature change

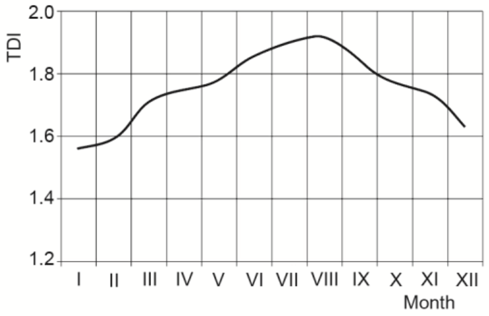


Figure 7. The *TDI* in referent TPP change in one year period

The *TDI* is relatively high, even for the design parameters, due to the relatively low efficiency of the plant, which is a consequence of using low-calorie lignite as a fuel. During the hottest period of the year, the efficiency of the plant is decreasing due to cooling water increase and consequently the *TDI* value increases. It means that risk of thermal pollution is increasing during the summer, with extensive electricity production at unfavorable hydrology conditions.

Danube temperature change due to effluent cooling water

To predict the mixing of hot water discharge, after cooling process in the TPP *Kostolac B*, and the water of the river Danube, several numerical simulations are conducted. Discharged water from the TPP *Kostolac*, through the effluent channel, flows into the junction area of the river Danube, causing the mixing of warmer effluent water and river water. Numerical simulations are performed taking into account critical periods of the year, which is the one with higher water temperatures and lower flow rates of the river Danube, into which the discharged water flows in. According to tab. 3, critical values of temperature and flow rate occur mostly in the summer period of the year, and they have been considered in this research. Cases of the minimal water flow rates with the maximal water temperatures in the summer months of the period 2006-2016 have been also considered in the paper (tab. 2).

Numerical simulations of the 3-D model were performed using the program ANSYS CFX. Using the recommendations given in the papers [24, 25] dealing with the mixing of two fluids in the junctions, a numerical model was created and obtained results are analyzed.

The geometric model is consists of Danube channel, 6 km long, with the effluent water channel which flows into the Danube after 1 km. Both the geometric model and its discretization mesh have been obtained using ANSYS ICEM CFD. A discretization mesh, which is consists of near $3.5 \cdot 10^6$ elements (tetrahedral 2387857, pyramids 197 and wedges 1106717), was formed [26], as shown in fig. 8.

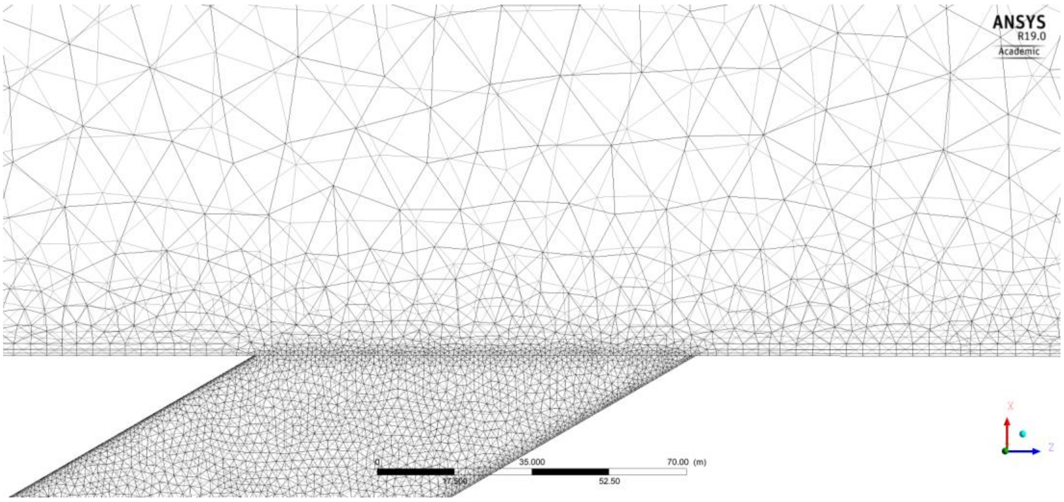


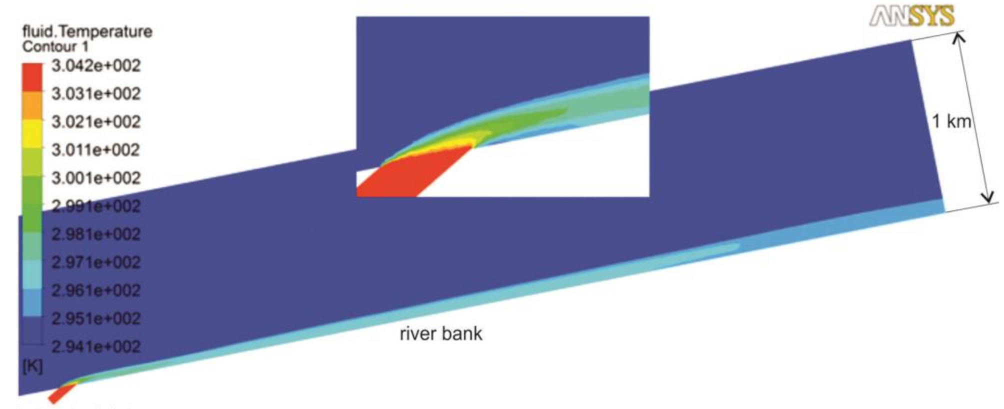
Figure 8. Thetrahedral mesh of the 3-D model

The boundary conditions used in this model are the input of the mass-flow and temperature of the water in the Danube, mass-flow and temperature at the entrance to the effluent channel (Mlava River Channel). The force of gravity is taken into account in numerical simulations. The other boundary conditions are given with appropriate pressure levels.

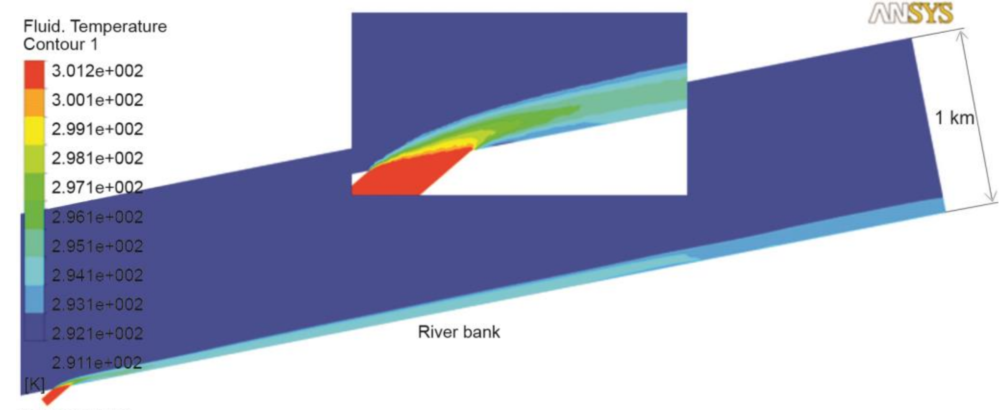
Turbulent flow is simulated using k-ε turbulent model, closuring RANS equations [27, 28]. Advection scheme is high-resolution scheme. The accuracy of the results is estimated to be 10^{-5}, which is satisfactory in technical practice.

The temperature distribution in the cross-sections of the river, starting from the junction area and downstream, is the result which gives us a preliminary picture of the thermal pollution of the river. Furthermore, important information is how much the temperature changes across the width of the Danube River, beginning from its right bank. The water higher by just one degree of Celsius can endanger certain plant and animal species, disturbing the existing ecosystem.

The obtained temperature change on the water surface due to effluent water intake into the Danube is presented in fig. 9. Presented results are obtained for atmospheric parameters and power plant operating conditions for the cases of minimum water flow rates in August and September (August 2012 and September 2011), showing a similar flow pattern and temperature distribution on the water surface. The difference is in the value of water flow rate and its temperature, as shown in fig. 10.



(a) hot water inlet

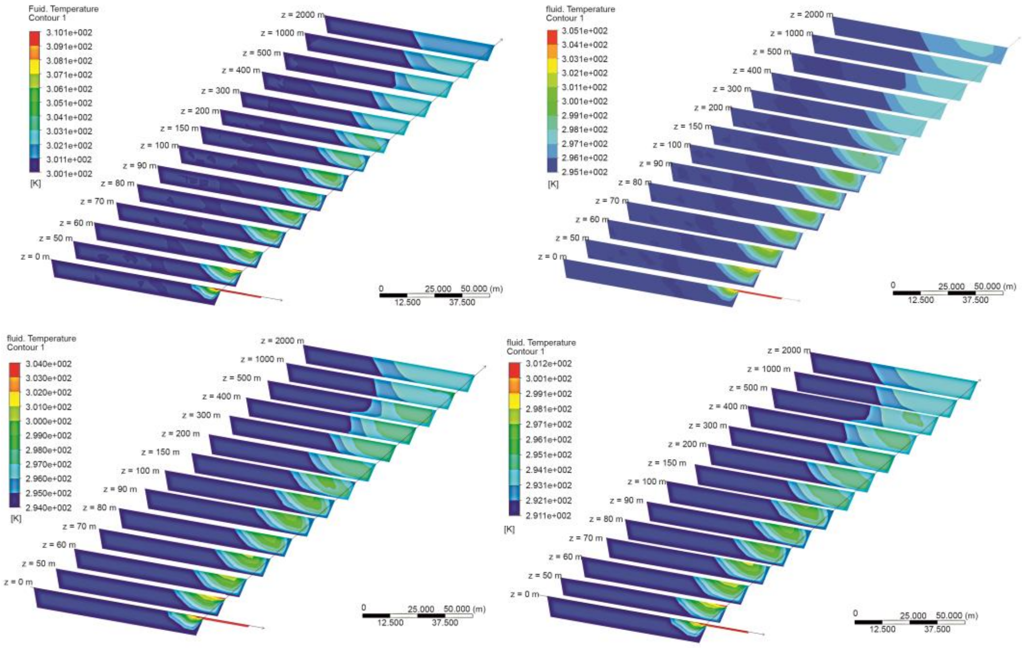


(b) Hot water inlet

Figure 9. Temperature change on the water surface; (a) August 2012, (b) September 2011
(*for color image see journal web site*)

The temperature change in different cross-sections along the Danube flow, downstream of the river junction is shown in fig. 9. The influence of effluent water stretches along hundreds of meters, or even a few kilometers downstream, by the right riverbank. Regarding the influence of the temperature change from the right bank to the left, it should be mentioned the fact that the Danube is the second largest river in Europe. The average flow rate of the Danube at the site, in the considered period of the year, is about 4000 m^3/s, and its width is about 1 km long. Even though, the temperature change which is greater than 10% of the river temperature is noticeable up to 30 m from the right bank. The change of temperature along the river depth is also illustrated in fig. 9. For example, 10 m from the right bank to the central part of the river, according to numerical simulations, a temperature change of 5 °C is obtained at 4 m depth.

Table 4 shows numerically obtained water temperature on the right bank of the Danube, on the surface level, downstream the junction area. Danube flow rate has been changing from 2050 m^3/s to 2880 m^3/s, while the effluent flow rate was 29.5 m^3/s. The average Danube temperature, before mixing with effluent water, was changing from 18 °C to 27 °C, depending on the hydrologic data given in previous tables. The average temperature change in the whole cross-section of the Danube is noticeable, although temperature does not rise dramatically. The large flow rate of the Danube compared to effluent flow rate gives a low sensitivity of the river to temperature changes due to local inflow.



(a)

(b)

Figure 10. Water temperature in cross-sections after affluent junction, along the Danube; (a) August and September 2015, (b) August and September for minimum flow rate regime in the period 2006-2016 (*i. e.* August 2012 and September 2011) (*for color image see journal web site*)

Table 4. Water temperatures of the surface level on the right bank of the Danube, in several points downstream the junction

Month	Distance [m]*	50	100	200	500	1000	2000	3000	4000	5000
August 2015	Temperature [°C]	37	28.07	28.73	29.44	29.36	29.06	28.87	28.76	28.62
September 2015		32	23.08	23.77	24.50	24.44	24.11	23.92	23.80	23.67
August 2012		31	22.17	23.44	23.95	24.09	23.42	23.16	23.09	22.85
Septtember 2011		28	19.00	20.33	20.88	20.56	20.36	20.14	20.00	19.79

[*] Distance is measured from the center of the junction.

Since the effluent (in the effluent channel) enters the river at a sharp angle (around 30°) in relation to the river flow, there is a small separation area behind the junction, where the water temperature is much lower than the temperature up and down stream. This is clearly seen in the table at a distance of 100 m, measured from the center of the junction.

According to presented simulation results, it is obvious that the right riverbank area downstream the power plant is directly exposed to the risk of change in the ecosystem due to thermal effluent from the plant. The main stream of the river still is not at risk, due to the small flow rate of the effluent water (only 10% of the river flow in the worst hydrology conditions). The change in the surface water temperature is noticeable in more than 30 m towards the center of the river stream, as shown on diagrams presented in fig. 11.

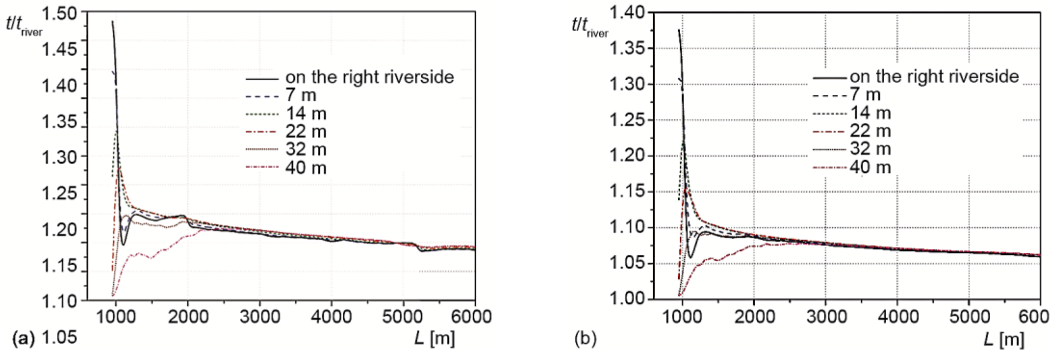


Figure 11. Water temperature ratio across the Danube on the right riverside and five different distances from the riverside, for the period: (a) August 2012, (b) August 2015 (*for color image see journal web site*)

The influence of the effluent temperature on the mixing width in the surface layer of the river is illustrated in fig. 11, showing relative temperature changes according to the mean water temperature in that period (t/t_{river}) even at distances over 30 m from the right river bank to the center of the Danube, and even much further along the river length (L).

Changes in river temperature are visible 5 km downstream, where the water temperature is still higher by about 9% for August 2012 and about 6% for August 2015.

According to the hydrology data provided by The Republic Hydrometeorological Service of Serbia [20], at the next measuring station Veliko Gradiste, which is located about 50 km from the measuring station Smederevo, during the observed period from 2006 to 2016, for specific months: July, August, and September, the increase of the average water temperatures is from 0.4 °C to 2.5 °C. Since there are no additional effluents in this part of the Danube River flow, one of the contributors to increased water temperature is certainly the effluent from the TPP *Kostolac*.

Conclusions

The Danube, as a major international river, in its flow, is burdened with a large number of industrial and power plants that use large amounts of water, especially for the cooling processes. Therefore, it is exposed to a risk of thermal pollution caused by effluent water. In this paper, the risk of thermal pollution of the Danube passing through Serbia due to thermal power plants located on its right bank is analyzed. Comparing the measured temperatures of the Danube from the measurement stations upstream and downstream of the power plants, we noticed an increase of around 1 °C in annual mean and maximum temperatures of the river. The only source of this increase is identified to be TPP *Kostolac*. For the 350 MW power plant, cold-end operation in off-designed mode is analyzed, in order to obtain effluent water temperature change during one year period, based on hydrology parameters. High electricity demand and power plant operation at maximum generated power maximize the energy efficiency problem during summer, due to increase in cooling water temperature. With efficiency decrease, thermal discharge index increases. It means that from the point of view of water thermal pollution risk, summer period is critical, and the ecosystem of the river is most vulnerable at that time. The numerical simulation of the effluent water flow into the river was done. Results shown in this paper implicates that increase of the Danube temperature due to thermal effluent from the power plant is significant few kilometers downstream, and at the distance of around 30 m from the riverbank. Due to a large flow of the Danube, this influence is still not alarming, but having in mind that new 350 MW unit is currently under construction at the same location, in the future, thermal pollution of water in this part of the Danube should be taken into account more seriously.

Nomenclature

p_k – condensing pressure, [°C]
$T_{\mathrm{A,\,mean}}$ – annual mean temperature, [°C]
$T_{\mathrm{A,\,max}}$ – annual maximum temperature, [°C]
T_{CW} – cooling water outlet temperature, [°C]

Subscripts

in – inlet
out – outlet
min – minimum
max – maximum

Acronym

TDI – thermal discharge index

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