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Assessing the Environmental Pollutant Vector of Wastewaters Discharged from a Chain of Coal-Fired Power Plants along a River

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Abstract: Reliable and safe operation of a coal-fired power plant is strongly linked to freshwater resources, and environmental problems related to water sources and wastewater discharge are challenges for power station operation. In this study, deals an evaluation on basis of wastewater pollutant vector is reported of the environmental impact of residual water generated and discharged in Jiu River during the thermoelectric units operation of the Rovinari, Turceni and Craiova coal-fired power plants. Wastewater pollutant vector Plane Projection is applied for assessing the water temperature evolution in the water flow lane created downstream of each power plant wastewater outlet channel. Simulation on the basis of an Electricity of France model, and testing validation of the results for thermoelectric blocks of 330 MW of these power plants, are presented.

Keywords: coal-fired power plant, environmental impact, pollutant vector, wastewater

1. Introduction

Within an Industrial Ecology framework, an estimation of the industrial metabolism should explore not only economic and social issues and benefits, but also the environmental impacts [1-3]. Coal-fired power plants often represent one of the larger contributors to acid rain of industrial activity, since they are a large source of sulfur oxides. The coal-fired sector is also a significant source of nitrogen oxides, with an impact comparable to that of transportation [4-7].

Beyond the environmental and human health impacts caused by the air pollutant emissions generated by coal-fired power plant operation, other environmental issues exist, including those related to water resources and pollutant wastewater generation. The thermoelectric units of the Rovinari, Turceni and Craiova power plants are equipped with a water recirculating system using wet cooling towers in order to dissipate heat from the cooling water to the atmosphere. In this wet recirculating system, the warmed cooling water is pumped from the steam condenser to the cooling towers. But for economic reasons the power stations are operating as open systems, meaning without recirculation of the water in the cooling system of the power plant. In other words, the necessary fresh water is provided from the river and the wastewater is discharged back to the same river, without using the cooling towers of the power plants.

Taking into consideration the case of three power stations connected in a cascading fashion from the viewpoint of the cooling systems, the wastewaters discharged in the same river could represent a significant environmental impact, concerning aquatic ecosystems in the river. In line with this idea, this paper deals with the assessment of temperature evolution in the river water downstream of the outlet, caused by a warm water discharge. This study reports an evaluation, on the basis of a wastewater pollutant vector, of the environmental impact of wastewater discharged from a chain of power stations into a single river. The wastewater is the spent water used to operate the cooling systems of the power stations.

2. Wastewater from Thermoelectric Unit Operation: Impact, Risks and Regulations

Reliable and safe operation of a coal-fired power plant is linked to freshwater resources [8-9]. Despite the worldwide pressure to retire existing coal-fired power plants and deny permits for new ones, the continuously increasing demand for electricity makes it likely that humankind will not discontinue the use of coal-fired power plants in the near future. But thermoelectric generation requires a sustainable and large freshwater source, mainly to cool and condense the steam after it exits the turbine. Subsequently, the thermoelectric plant operation causes industrial wastewater to be discharged into the water source, often a local river.

Due to water availability and quality issues, current and future water-related environmental regulations will likely lead to challenges in the traditional operation of power plants [10-12].

On a broader front, the United Nations Environment Programmes and EU Member States currently face many environmental challenges, and the implementation of European Union legislation should lead to environmental benefits, together with economic and social ones [10,13]. The benefits of compliance with EU environmental directives and regulations must be addressed meaningfully, together with a shift in education, both in environmental and economic terms. This way humankind can approach the capability of estimating the value of environmental benefits on the basis of people's willingness and decisions. For instance, clean drinking water can be contrasted with avoiding illness and cases of premature death caused by relevant environmental problems [10,13]. Such environmental challenges could include:

- Improving and extending water supply networks to ensure that safe drinking water is available to all settlements.
- Improving and extending wastewater collection and treatment plants.
- Ensuring that water and air pollutant emissions from thermoelectric power plants are reduced.
- Cleaning contaminated rivers and lands where water quality is unacceptable.
- Protecting ecosystems and habitats from economic pressure.

Addressing such challenges can lead to various environmental and human health benefits, including the following [10]:

- Reduced risk of water-related illness and improved water taste, as a result of better water quality.
- Better human health since the exposure to pollutants is reduced and, as result, the number of respiratory diseases and premature deaths is likely decreased.
- Lower consumption of raw materials as a result of cleaner production.
- Better protection of natural ecosystems for future generations.

Related to water benefits, compliance should be with the UNEP and EU Directives and Regulations encompassed by Environmental Acquis (Acquis communautaire) [10,13]:

- United Nations Environment Programme Clearing the Waters, Nairobi, Kenya, 2010;
- Environmental Impact Assessment Directive, 85/337/EEC, amended by 97/11/EC;
- Environmental Information Directive, 90/313/EEC;
- Water Quality Framework Directive: Urban Waste Water, 91/271/EEC, related decision 93/481/EEC; Nitrates, 91/676/EEC; Dangerous substances to the aquatic environment, 76/464/EEC, including seven 'daughter' directives, all amended by 91/692/EEC; Mercury discharges from industries, 82/176/EEC, 84/156/EEC; Cadmium discharges, 83/513/EEC; HCH discharges, 84/491/EEC; List one substances, 86/280/EEC, amended by 88/347/EEC and 90/415/EEC; Surface water for the abstraction of drinking water, 75/440/EEC, amended by 79/869/EEC and 91/692/EEC; Measurement and sampling of drinking water, 79/869/EEC, Fish water, 78/659/EEC, amended by 91/692/EEC;
- European Environment Agency Regulation, EEC/1210/90.

3. Case Study: Wastewater Pollutant Vector of a Chain of Coal-Fired Power Plants along Jiu River

Thermoelectric power generation in a coal-fired plant consists in the conversion of thermal energy into electrical energy. Coal is the fuel used to heat a liquid to produce a high pressure vapor (usually water is heated to produce steam) which then is expanded in a turbine that drives an electric generator [2,8,14]. An important step in this process is the change of phase of the vapor to a liquid following the turbine, and this is where the requirement for cooling water arises. A vacuum is created in the condenser, drawings the vapor over through the turbine; this low pressure is important to the thermodynamic efficiency of the process. The water requirement in coal-fired power plants mainly is as cooling water for condensing steam, typically in a shell-and-tube heat exchanger known as a condenser. The operating parameters of the cooling system affect the overall power generation yield.

In this study, the environmental pollutant vector of wastewaters discharged from Rovinari, Turceni and Craiova coal-fired power plants of Romania are analyzed. The three power stations considered receive freshwater from and discharging their wastewaters into the Jiu River [15]. From the viewpoint of the cooling systems, these power plants are connected in a cascading fashion.

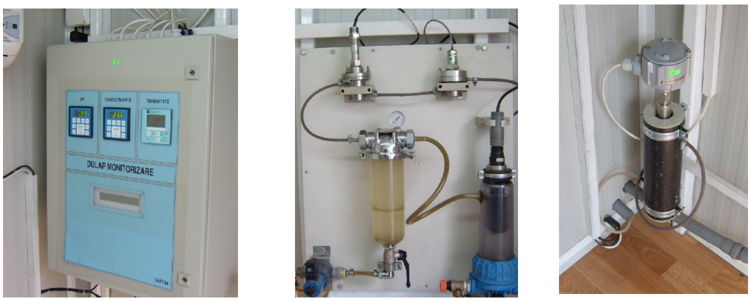
The waters supplied to the thermoelectric units of these power plants are surface waters with a varying temperature (usually in the range 0-30°C). The pollutant emission source for this river caused by these industrial facilities is mainly associated with the wastewater discharging process. Both the supply of freshwater and the discharge of wastewater are performed through the culvert channels provided with special inlets and outlets, respectively. These surface channels are comprised of concrete and embankment (see Figs. 1 and 2), with a slope of 1% to ensure a minimum water flow without destabilizing the optimum level of the natural pond. Figure 1 illustrates the process water culvert channel for the water inlet of the river Jiu. Figure 2 shows the technical platform on which is fixed the ultrasonic level sensor. That is the location of the inlet pipe for the test water to be treated in the monitoring cabin, presented in Figure 3.

Figure 1. Longitudinal view of the supply channel

Figure 2. Experimental platform for supply channel

The water flow supplied by the Jiu River to these power plants is provided through high capacity pumps and by modifying the upstream dam inlet level. Figure 3 shows the thermostatic and secured cabin for monitoring necessary water parameters, i.e., pH, conductivity, suspensions. The physiochemical parameters are routinely checked, in real time, through complex equipment installed in a monitoring cabin (Fig. 3), with a telemetric transmission of the collected data. This way, in the first stage, the following freshwater parameters are determined: conductivity, pH, temperature, water level in the channel, water flow rate, and inlet water flow. The physiochemical parameters of freshwater provided through the supply channel are valuated with the measuring transducers.

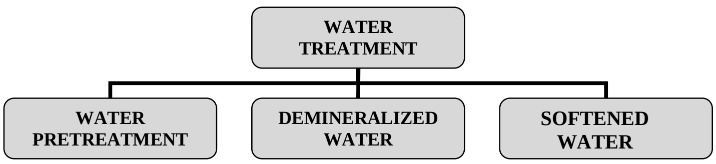
Figure 3. Monitoring cabin



Furthermore, water treatment in the Chemical Section (Fig. 4) is performed to provide the demineralized water necessary for steam production and the softened water to be added in the district heating network.

Water pretreatment is necessary to reduce the suspension in the raw water, using several decanters operating on the basis of coagulation and flocculation processes. Inside the decanters, a decarbonation process also occurs, by treatment with $Ca(OH)_2$ in order to obtain a precipitation of Ca and Mg soluble salts. Decanted water is stored in tanks, and through a pump system is provided to the demineralized water and softened water installations.

Figure 4. Water treatment in Turceni power plant chemical section



The installation for water demineralizing is necessary to produce an appropriate water for steam production. Water demineralization is carried out through the six units of ionic filters.

The water softening installation provides the softened water to be added to the district heating network.

3.1. Discharged Wastewater Pollutant Vector

The thermoelectric units of the Rovinari, Turceni and Craiova power plants are equipped with a water recirculating system using wet cooling towers in order to dissipate the heat from the cooling water to the atmosphere. In this wet recirculating system, the warmed cooling water is pumped from the steam condenser to the cooling towers [2,8,15].

The pollutant vector of discharged wastewater ($\vec{V}_{DWW}$) is completely specified (from a strictly vectorial viewpoint) by: direction, sense, magnitude, origin and head-arrow.

The vector direction is defined by the wastewater discharging channel that links the power plant with the river via an ecological wastewater treatment station [16-17]. The vector sense is defined by the wastewater flowing sense. The vector magnitude is related to the wastewater velocity that must be at minimum 1.5 m/s in order to avoid suspension sedimentation on the discharging channel bottom. The origin of the vector is at the power plant inlet location while the vector head-arrow is at the discharging channel outlet.

The physiochemical parameters of water that can be measured are: temperature, conductivity, particulate matter in suspension, water fixed residue, and pH value. Determination of pH value is necessary to establish the acidic or alkaline nature of the water. Electrometric measurement is a precise method, and the pH-meter has small dimensions and is mobile. Water acidity is associated with the presence of free carbon dioxide, mineral acids and salts of strong acids with weak alkalis. Water alkalinity is associated with the presence of alkaline carbonates, bicarbonates, and hydroxides.

3.2. Wastewater Pollutant Vector Plane Projection

The Plane Projection (PP) of wastewater pollutant vector allows the temperature evaluation in the water flow lane created at certain distances in the river from the wastewater outlet channel. This study deals with long distances (in the range of 1-10 km) on the Jiu River.

Basically, the plane projection of the wastewater pollutant vector is related to the water temperature (as a physical parameter). The discharged water can be a surface determined by a complex geometrical figure that can be reduced to an ellipse (point A in the wastewater outlet, and the ellipse center moved in the water flowing sense) [18-21].

An analytical equation of an ellipse with center point O* (x_0,y_0) and semi-axes a and b is:

$$\frac{(x-x_0)^2}{a^2}+\frac{(y-y_0)^2}{b^2}-1=0 \qquad (1)$$

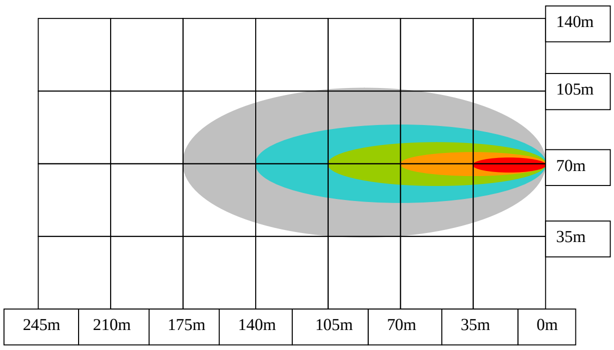
This is based on the phenomenon of a laminar flow of a pollutant vector of wastewater discharged into a natural environment, like the Jiu River. In such river areas, the temperature of the discharged water can lead to significant changes that can affect the aquatic fauna and flora.

The Plane Projection can be also developed for distances smaller than 250 meters. An example of a linear temperature distribution is provided if the Plane Projection can be developed for distances smaller than 250 meters inside the main isothermal curve. The distribution of isothermal curves (see Table 1) if the plane projection is on a distance of 175 meters in the main flowing lane of wastewater pollutant vector is depicted in Fig. 5. In Fig. 5, the horizontal and vertical axes of the reference system represent the longitudinal and transversal axes of the ellipse that models the wastewater discharged into the river. The reference system origin (namely, 0 meters) corresponds to the power station wastewater outlet.

Table 1. Distribution of isothermal curves

No.	Isothermal curve	Iso = Isothermal indicator	D_{isom} [m] = distance on isothermal curve	K [^oC/ m] = longitudinal linearization coefficient
1	Iso_{33}	33	35	1/35
2	Iso_{32}	32	35	1/35
3	Iso_{31}	31	35	1/35
4	Iso_{30}	30	35	1/35
5	Iso_{28}	29	35	1/35

Figure 5. Isothermal curves: Iso_{33}, Iso_{32}, Iso_{31}, Iso_{30}, Iso_{29}.



3.3. The EDF Methodology for Evaluating the Wastewater Pollutant Vector

From a design viewpoint, the discharged wastewater pollutant vector has as flowing frame of a river laminar layer, variable from the point of the discharging vector outlet. Factors that interfere in the calculation of temperatures within the river, downstream from the outlet discharge point of a warm water flow, are numerous, variable and hard to calculate or measure. This is the reason for applying over time [8,15,22] an approximate calculus mainly linked to field measurements. The most simple formula does not take into consideration the temperature evolution downstream of the outlet of the wastewater discharging vector, having been concerned only with ensuring the mixture of warm water (from the coal-fired power plant) and the river water does not exceed a limit.

Assessment of temperature evolution in the river water downstream of the outlet, caused by a warm water discharge, is based on a theoretical method consisting of a formula with exponential factors.

Electricity of France (EDF) Group developed a mathematical model of temperature evolution in river water (since a warm water flow had been discharged on downstream by outlets):

$$\Delta t = \Delta t_{\max} \cdot e^{-kx} \tag{2}$$

where Δt is the river water residual heating x kilometers downstream from the warm water outlet; Δt_{max} is the river water maximum heating of the water mixture in the warm water outlet; k is a climate correction factor, ranging between 0.001 and 0.01; and x is the distance from the warm water outlet to the river section where the residual temperature is determined.

The mathematic model of temperature evolution in the river water, downstream of the warm water outlet, through the wastewater pollutant vector allows a reliable and accurate evaluation for river lengths of 10 km up to 50 km. Numerical simulation is useful in the technical assessment of transient processes that vary slowly.

3.4. EDF Methodology Applied to Thermoelectric Units of 330 MW of the Rovinari Power Station

This case study takes into consideration operation of the thermoelectric power plant of Rovinari with an installed power corresponding to 3 energetic units (n=3) of 330 MW, resulting in a total power generation of 990 MW [17,23,24]. The investigation aims to assess the evolution of temperature, on the basis of the wastewater pollutant vector. This case study is performed under the following conditions:

- power plant capacity utilization of 75% of the installed power (n=3);
- the outlet allows the discharge of wastewater provided by the 3 thermoelectric units of 330 MW;
- temperature assessment is based on the EDF methodology.

A AMD multiprocessor computer system with StatSoft STATISTICA - Version 7.0 software is used for data acquisition and processing. The simulation process of the EDF pattern for the wastewater pollution vector involves four types of recordings on a 45 km river length, namely:

- temperature nomogram, for k =0.001 (n=3), as depicted in Figure 6;
- temperature nomogram, for k =0.003 (n=3), as depicted in Figure 7;
- temperature nomogram, for k =0.004 (n=3), as depicted in Figure 8.

Figure 6. Water temperature nomogram for k=0.001 (n=3)

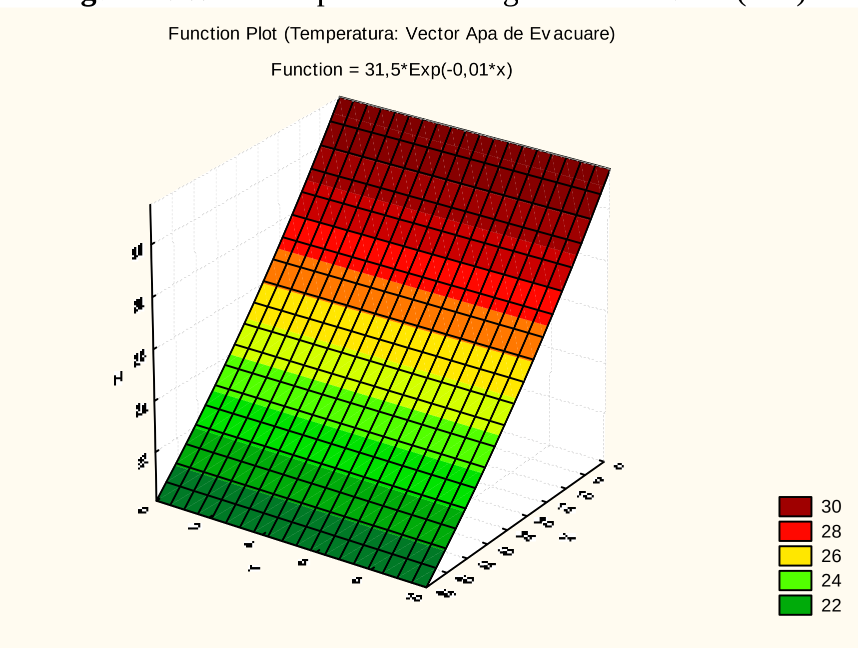


Figure 7. Water temperature nomogram for k=0.003 (n=3)

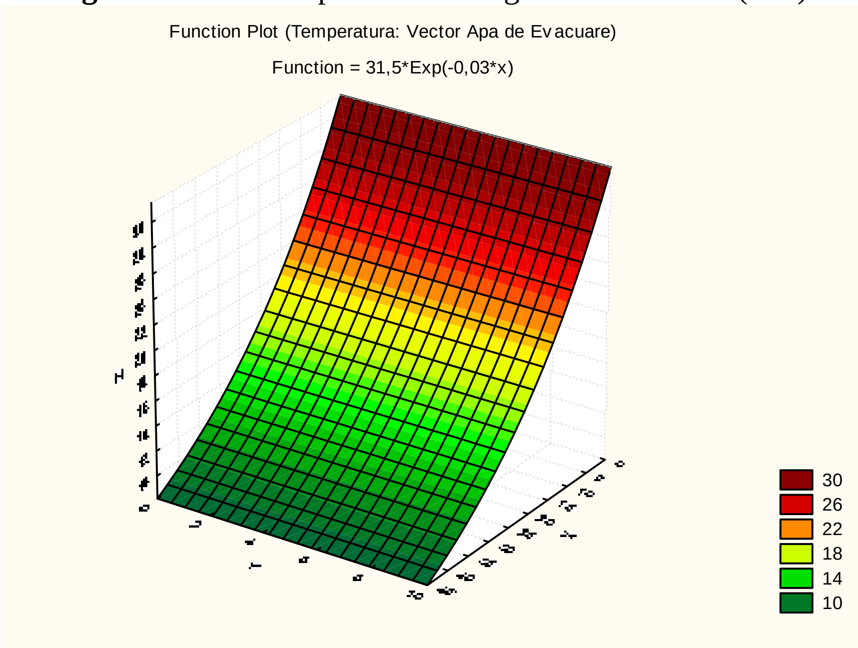
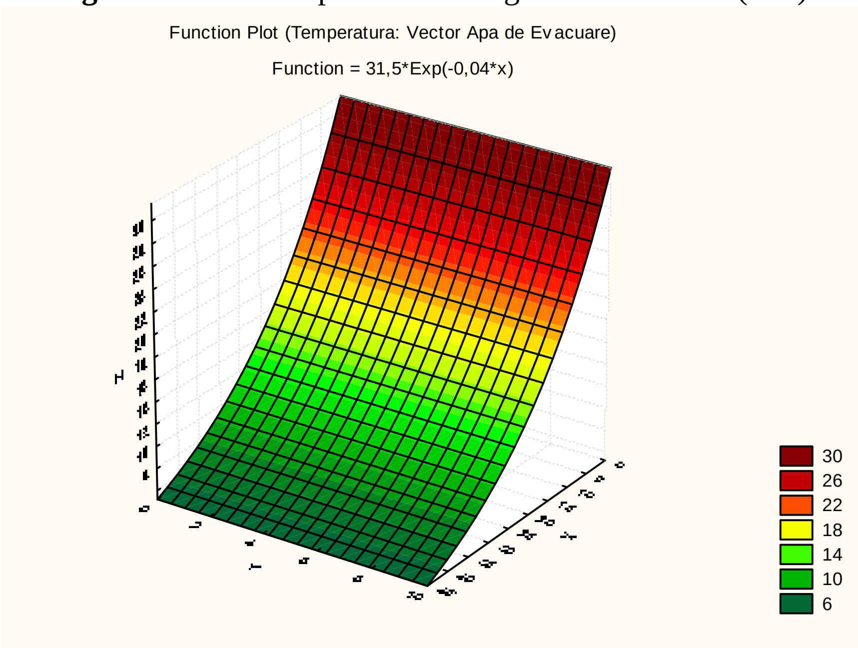


Figure 8. Water temperature nomogram for k=0.004 (n=3)



Note in Figs. 6-8 that the simulations have two variables:

- variable x, which represents the distance from the river outlet point of warm wastewater to the river section where the residual heating is calculated;
- variable y, denoted by k and representing the climate correction factor, with values ranging between 0.001 and 0.01.

The mathematical pattern response to the simulation is represented by the multivariable function z denoted by Δt (river water residual heating at x kilometers from the warm water discharging outlet). The red colour indicates high values of temperature, obtained in the wastewater outlet.

It is emphasized in the mathematical model that the parameter Δt_m represents the maximum heating of river water after mixing with the warm water outlet.

3.5. Experimental Validation of EDF Methodology Results on Thermoelectric Units of 330 MW of Rovinari Power Stations

Under the above mentioned conditions, for an acceptable evaluation of the mathematical pattern described by the EDF formula, it is necessary to join the simulations with experimental tests. For the experimental validation of the EDF model, on Jiu River have been performed recordings both for natural thermal load (JIU STN) on the upstream river and for the Rovinari thermal load (JIU STR) on river downstream. These data were obtained with the support of the Rovinari Power Plant staff.Table 2 and Figure 9 show the temperature evolution along the river length.

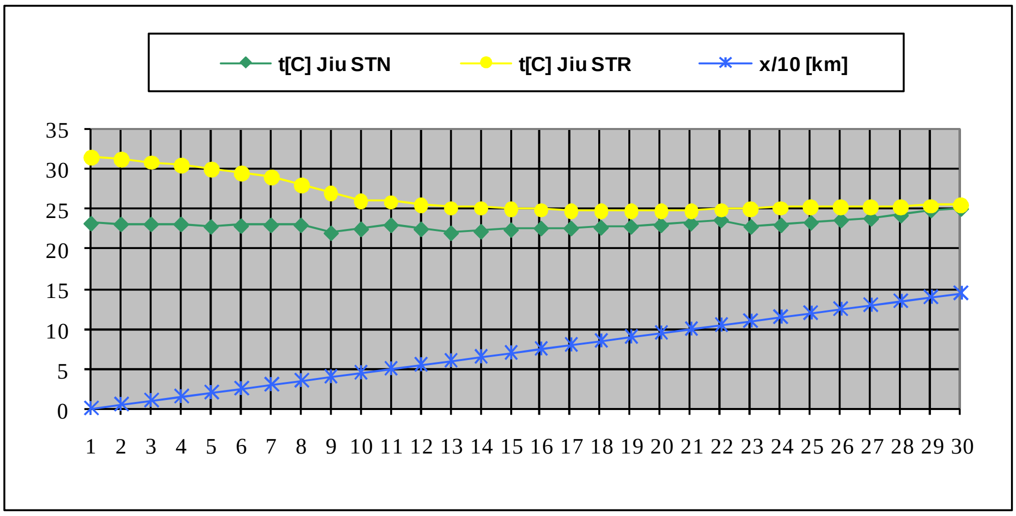
Normally, the medium river flow rate at the Rovinari site is roughly 47 m^3/s [25-27]. The operation of three thermoelectric blocks in open circuit of the Rovinari power plant relies on this river flow, under the stability conditions for the relevant environmental parameters

Table 2. Temperature t and distance x data series for Jiu River STN and Jiu River STR

t [C] Jiu River STN	t [C] Jiu River STR	x [km]	Reading: number
23.2	31.5	0.0	1
23.1	31.2	0.5	2
23.1	30.8	1.0	3
23.1	30.5	1.5	4
22.8	30.0	2.0	5
22.9	29.5	2.5	6
23.0	29.0	3.0	7
23.0	28.0	3.5	8
22.0	27.0	4.0	9
22.5	26.0	4.5	10
23.0	25.9	5.0	11
22.5	25.5	5.5	12
22.0	25.1	6.0	13
22.2	25.1	6.5	14
22.4	25.0	7.0	15
22.6	24.9	7.5	16
22.6	24.8	8.0	17
22.7	24.8	8.5	18

22.8	24.7	9.0	19
23.0	24.7	9.5	20
23.2	24.8	10.0	21
23.6	24.9	10.5	22
22.8	25.0	11.0	23
23.0	25.1	11.5	24
23.3	25.2	12.0	25
23.6	25.2	12.5	26
23.8	25.3	13.0	27
24.2	25.3	13.5	28
24.8	25.4	14.0	29
25.0	25.5	14.5	30

Figure 9. Diagram of t and x data series for Jiu River STN and Jiu River STR



The measurement conditions assume the following:

1. Maintaining in operation three thermoelectric units of 330 MW in Rovinari for 5 hours (4 hours before measurement and 1 hour during measuring).
2. Positioning a human observer with a measuring instrument (precision digital thermometer) along the riverbed and in the mainstream of the river, at intervals of 5 km.
3. Establishing the trigger timing of the readings, chosen to be 10 AM, since according to legislation [21] this is the most appropriate time from the viewpoint of heat exchange between Jiu River and the environmental surroundings.
4. Performing the 11 temperature readings, over a period of 50 minutes, at intervals of 5 minutes.

An AMD multiprocessor computer system with Microsoft Office - Version 7.0 software is used for data acquisition and processing.

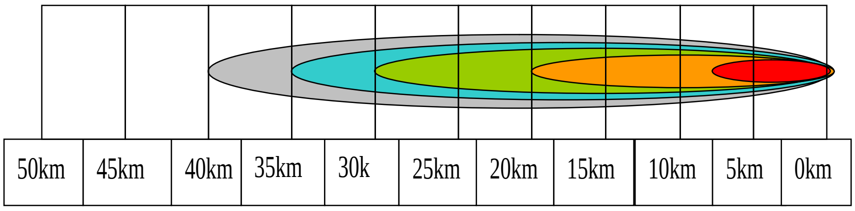
The experimental validation of the EDF pattern for the wastewater pollutant vector in this case study is shown in Fig. 9, which shows data for temperature t [^{0}C] and distance x [km] on River Jiu, for the natural thermal load (Jiu River STN) and for the Rovinari thermal load (Jiu River STR).

In Table 3 and Fig. 10 the isothermal curves Iso_{31}, Iso_{30}, Iso_{29}, Iso_{28}, Iso_{27} are depicted.

Table 3. Data of isothermal curves Iso_{31}, Iso_{30}, Iso_{29}, Iso_{28}, Iso_{27}

No	Isothermal curve	Iso = Isothermal indicator	Δt_m[°C] = Outlet water temperature	k[km^{-1}]= correction factor
1	Iso_{31}	31	31.5	0.004
2	Iso_{30}	30	31.5	0.004
3	Iso_{29}	29	31.5	0.004
4	Iso_{28}	28	31.5	0.004
5	Iso_{27}	27	31.5	0.004

Figure 10. Isothermal curves: Iso_{31}, Iso_{30}, Iso_{29}, Iso_{28}, Iso_{27}



Accordingly, it can be observed that:

- the limit x = 7.5 km for the isothermal curve $Iso_{31} = 31^oC$;
- the limit x = 20 km for the isothermal curve $Iso_{30} = 30^oC$;
- the limit x = 30 km for the isothermal curve $Iso_{29} = 29^oC$;
- the limit x = 35 km for the isothermal curve $Iso_{28} = 28^oC$;
- the limit x = 40 km for the isothermal curve $Iso_{27} = 27^oC$.

Consequently:

- for k = 0.003 km^{-1}, Δt_{max}= 31.5°C, n = 3, P_{inst}/unit = 330 MW, P_{inst} = 990 MW, the maximum relative error is $\varepsilon_{rel} \leq 5.85\%$;
- for k = 0.004 km^{-1}, Δt_{max}= 31.5°C, n = 3, P_{inst}/unit = 330 MW, P_{inst} = 990 MW, the maximum relative error is $\varepsilon_{rel} \leq 3.66\%$;
- for k = 0.005 km^{-1}, Δt_{max}= 31.5°C, n = 3, P_{inst}/unit = 330 MW, P_{inst} = 990 MW, the maximum relative error is $\varepsilon_{rel} \leq 6.51\%$;
- the optimum of the mathematical model according to relative error, under the conditions Δt_{max}= 31.5°C, n = 3, P_{inst}/unit = 330MW and P_{inst} = 990 MW, is given by k = 0.004 km^{-1}.

3.6. EDF Methodology Applied to Thermoelectric Units of 330 MW of Rovinari and Turceni Power Stations in Simultaneous Operation

Now this case study takes into consideration the continuous operation of the thermoelectric power plant of Rovinari with a power corresponding to three energetic units (n=3) of 330 MW (resulting in a total power of 990 MW, which represents 75% of the total installed power) plus the continuous operation of the coal-fired power plant of Turceni with a power corresponding to three energetic units (n=3) of 330 MW (resulting the total power of 990 MW, which represents 50% of the total installed power) [17,26].

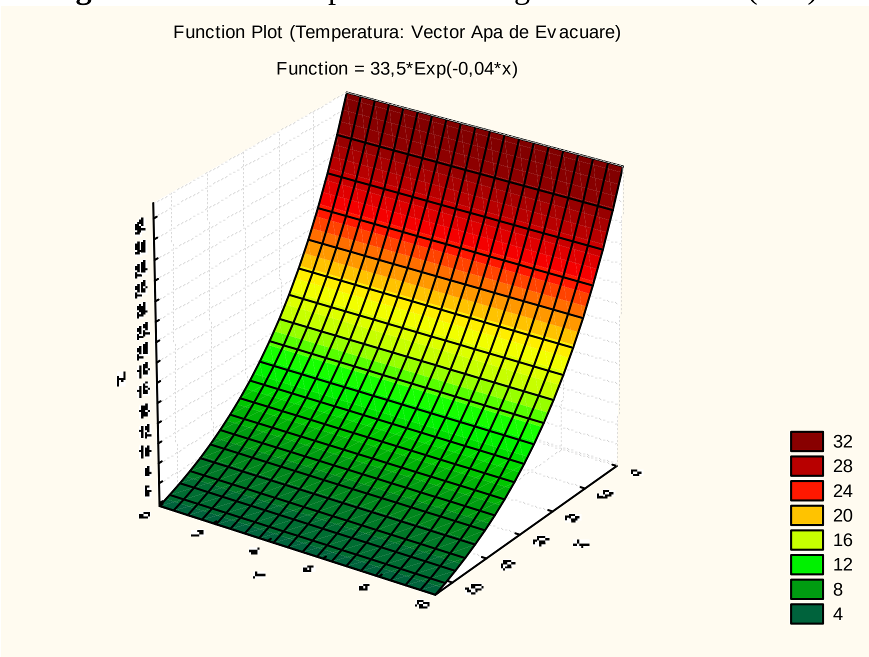
The wastewater pollutant vector investigation aims to assess the correct evolution of temperature, on the basis of the EDF Methodology.

Note in this case that the outlets allow the discharge of wastewater provided by three thermoelectric units of 330 MW from the Rovinari power plant and three thermoelectric units of 330 MW from the Turceni power plant.

Following the same procedure as before, the simulation process of the EDF pattern for the wastewater pollution vector involves four types of recording on a 45 km river length, namely:

- temperature nomogram, k =0.004 (n=6), depicted by Fig. 11, as an example;
- temperature nomogram, k =0.0054 (n=6);
- temperature nomogram, k =0.006 (n=6).

Figure 11. Water temperature nomogram for k=0.004 (n=6)



3.7. Experimental Validation of EDF Methodology Results on Thermoelectric Units of 330 MW of Rovinari and Turceni Power Stations in Simultaneous Operation

To provide experimental validation of the EDF model, on Jiu River readings are taken [15,22,23] both for natural thermal load (JIU STN) in the upstream river and for the Rovinari and Turceni thermal loads (JIU STRT) in the downstream river for Turceni.

Normally, the medium river flow rate at the Rovinari site is roughly 47 m^3/s, and at the Turceni site is roughly 54.5 m^3/s. Operation of three thermoelectric units, in open circuit of the Rovinari and Turceni power plants relies on these river flow rates, under the stability conditions for the relevant environmental parameters.

Under the same measurement conditions as before, the experimental validation of the EDF pattern for the wastewater pollutant vector in this case study is shown in Table 4 and Fig. 12, which depict the temperature t [^{0}C] and distance x [km] on River Jiu for natural thermal load (Jiu River STN) and for the Rovinari and Turceni thermal loads (Jiu River STRT). In Fig. 13 the isothermal curves Iso_{33}, Iso_{30}, Iso_{29}, Iso_{28}, Iso_{27} are depicted.

Table 4. Temperature t and distance x data series for Jiu River STN and Jiu River STRT

t[C] Jiu STN	t[C] Jiu STRT	x/10 [km]	Reading number
23.2	31.5	0.0	1
23.1	31.2	0.5	2
23.1	30.8	1.0	3
23.1	30.5	1.5	4
22.8	30.0	2.0	5
22.9	29.5	2.5	6
23.0	29.0	3.0	7
23.0	28.0	3.5	8
22.0	27.0	4.0	9
22.5	33.5	4.5	10
23.0	33.0	5.0	11
22.5	30.0	5.5	12
22.0	29.0	6.0	13
22.2	28.7	6.5	14
22.4	28.3	7.0	15
22.6	28.0	7.5	16
22.6	28.0	8.0	17
22.7	27.7	8.5	18
22.8	27.4	9,0	19
23.0	27.3	9.5	20
23.2	27.3	10.0	21
23.6	27.3	10.5	22
22.8	27.2	11.0	23
23.0	27.2	11.5	24
23.3	27.2	12.0	25
23.6	27.1	12.5	26
23.8	27.1	13.0	27
24.2	27.1	13.5	28
24.8	27.0	14.0	29
25.0	27.0	14.5	30

Figure 12. Diagram of t and x data series for Jiu River STN and Jiu River STRT

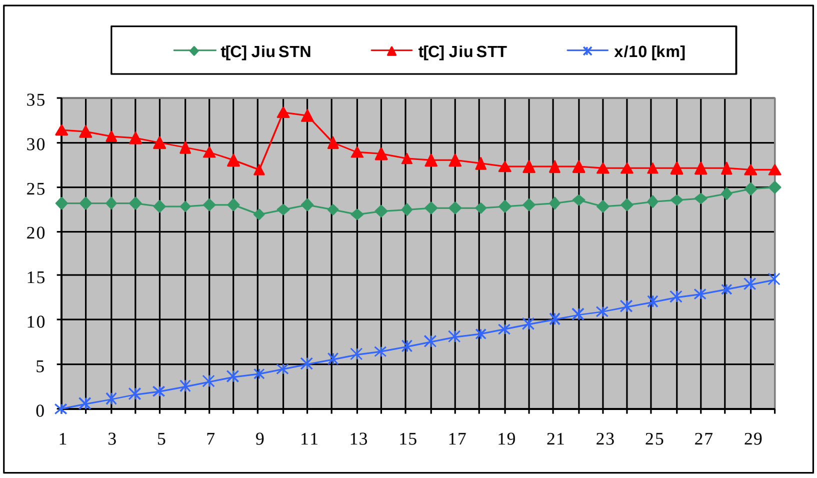
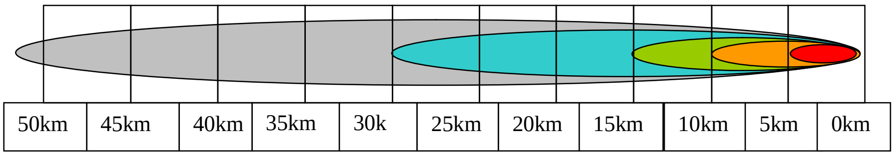


Figure 13. Isothermal curves: Iso_{33}, Iso_{30}, Iso_{29}, Iso_{28}, Iso_{27}



According to the data depicted above, it can be observed that:

- the limit x = 5 km for the isothermal curve $Iso_{33} = 33^oC$;
- the limit x = 10 km for the isothermal curve $Iso_{30} = 30^oC$;
- the limit x = 15 km for the isothermal curve $Iso_{29} = 29^oC$;
- the limit x = 30 km for the isothermal curve $Iso_{28} = 28^oC$;
- the limit x = 52.5 km for the isothermal curve $Iso_{27} = 27^oC$.

Consequently:

- for k = 0.004 km^{-1}, Δt_{max}= 31.5^oC, n = 6, P_{inst}/unit = 330 MW, P_{inst} = 1980 MW, the maximum relative error is $\varepsilon_{rel} \leq 8.79\%$;
- for k = 0.0054 km^{-1}, Δt_{max}= 31.5^oC, n = 6, P_{inst}/unit = 330 MW, P_{inst} = 1980 MW, the maximum relative error is $\varepsilon_{rel} \leq 6.53\%$;
- for k = 0.006 km^{-1}, Δt_{max}= 31.5^oC, n = 6, P_{inst}/unit = 330 MW, P_{inst} = 1980 MW, the maximum relative error is $\varepsilon_{rel} \leq 9.09\%$.
- fhe optimum of the mathematical model according to relative error, under the conditions Δt_{max}= 31.5^oC, n = 6, P_{inst}/unit = 330MW, P_{inst} = 1980 MW, is given by k = 0.0054 km^{-1}.

3.8. EDF Methodology Applied to Thermoelectric Units of 330 MW of Rovinari, Turceni and Craiova Power Stations in Simultaneous Operation

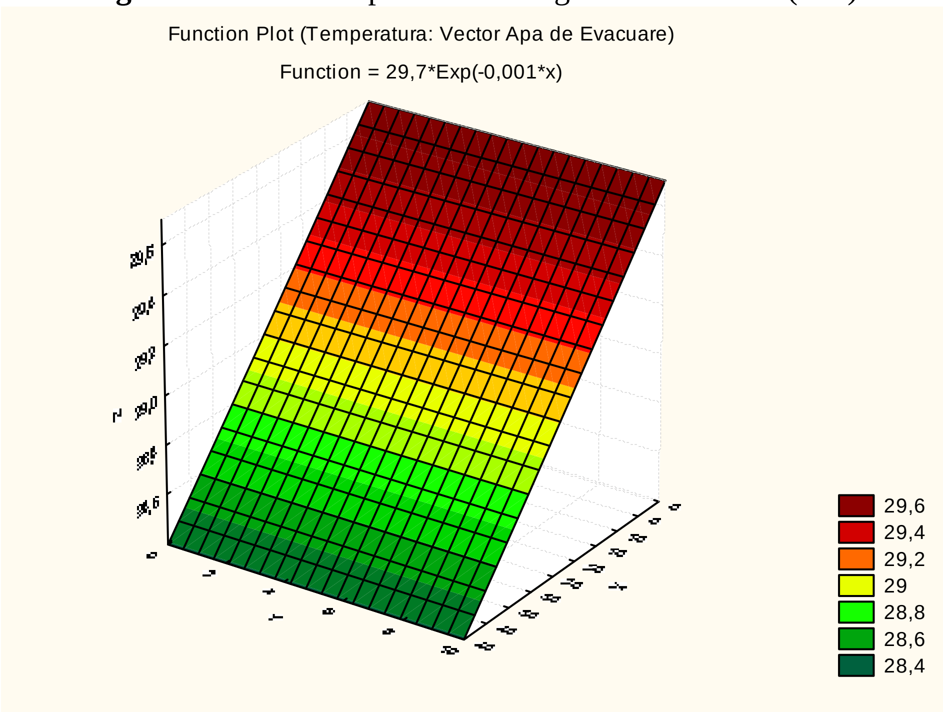
The third situation in this case study considers the continuous, simultaneous operation of three coal-fired power plants which are connected in a cascade manner, from the cooling system viewpoint, since they are supplying freshwater from and discharged wastewater in the Jiu River. This case study is performed under the following conditions:

- the Rovinari power plant operates with three units of 330 MW (capacity utilization of 75% of the installed power);
- the Turceni power plant operates with three units of 330 MW (capacity utilization of 50% of the installed power);
- the Craiova power plant operates with three units of 330 MW (capacity utilization of 100% of the installed power);
- the total installed power is 2970 MW;
- the outlets of these power plants allow the discharge of wastewater provided by the nine thermoelectric blocks of 330 MW, comprised of three units from each power plant;
- temperature assessment is based on the EDF methodology.

Following the same procedure, the simulation process of the EDF pattern for the wastewater pollution vector involves four types of recordings on a 45 km river length, namely:

- temperature nomogram, k =0.001 (n=9), depicted by Fig. 14, as an example;
- temperature nomogram, k =0.002 (n=9);
- temperature nomogram, k =0.003 (n=9).

Figure 14. Water temperature nomogram for k=0.001 (n=9)



3.9. Experimental Validation of EDF Methodology Results of Thermoelectric Units of 330 MW of Rovinari, Turceni and Craiova Power Stations in Simultaneous Operation

To provide experimental validation of the EDF model, on Jiu River readings are taken both for the natural thermal load (JIU STN) on the river upstream, and for the Rovinari and Turceni and Craiova thermal loads (JIU STRTC) on the downstream river in Craiova [23-25].

Normally, the medium river flow at the Rovinari site is roughly 47 m^3/s, while at the Turceni site it is roughly 54.5 m^3/s and at the Craiova site it is roughly 80 m^3/s.

The experimental validation of the EDF pattern for the wastewater pollutant vector in this case study is illustrated in Table 5 and Fig. 15. That diagram depicts the temperature t [^{0}C] and distance x [km] on River Jiu, for the natural thermal load (Jiu River STN) and for the Rovinari + Turceni + Craiova thermal loads (Jiu River STRTC). In Fig. 16 the isothermal curves $Iso_{29.5}$, Iso_{29}, $Iso_{28.5}$, Iso_{28} are shown.

Table 5. Temperature t and distance x data series for Jiu River STN and Jiu River STRTC

t[C] Jiu STN	t[C] Jiu STRTC	x/10 [km]	Reading number
23.2	31.5	0.0	1
23.1	31.2	0.5	2
23.1	30.8	1.0	3
23.1	30.5	1.5	4
22.8	30.0	2.0	5
22.9	29.5	2.5	6
23.0	29.0	3.0	7
23.0	28.0	3.5	8
22.0	27.0	4.0	9
22.5	33.5	4.5	10
23.0	33.0	5.0	11
22.5	30.0	5.5	12
22.0	29.0	6.0	13
22.2	28.7	6.5	14
22.4	28.3	7.0	15
22.6	28.0	7,5	16
22.6	28.0	8.0	17
22.7	27.7	8.5	18
t[C]	t[C]	x/10	Reading
Jiu STN	Jiu STRTC	[km]	Number
22.8	27.4	9.0	19
23.0	27.3	9.5	20
23.2	29.7	10.0	21
23.6	29.1	10.5	22
22.8	28.9	11.0	23
23.0	28.7	11,5	24
23.3	28,5	12.0	25
23,6	28.4	12.5	26
23.8	28.3	13.0	27

24.2	28.2	13.5	28
24,8	28,1	14.0	29
25.0	28.0	14.5	30

Figure 15. Diagram of t and x data series for Jiu River STN and Jiu River STRTC

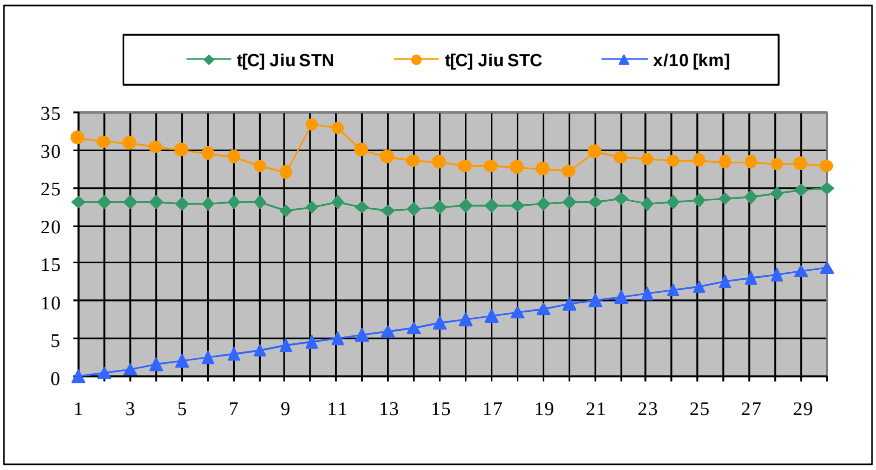
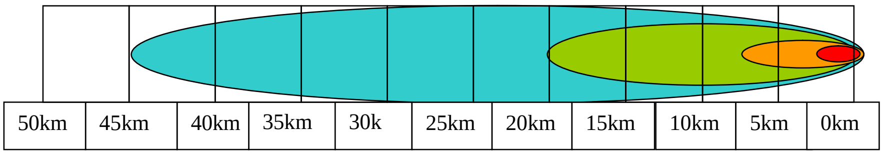


Figure 16. Isothermal curves: $Iso_{29.5}$, Iso_{29}, $Iso_{28.5}$, Iso_{28}



Accordingly, it can be observed that:

- the limit x = 2.5 km for the isothermal curve $Iso_{29.5} = 29.5^oC$;
- the limit x = 7.5 km for the isothermal curve $Iso_{29} = 29^oC$;
- the limit x = 20 km for the isothermal curve $Iso_{28.5} = 28.5^oC$;
- the limit x = 45 km for the isothermal curve $Iso_{28} = 28^oC$.

Consequently:

- for k = 0.001 km^{-1}, Δt_{max}= 29.7^{o}C, n = 9, P_{inst}/unit = 330 MW, P_{inst} = 2970 MW, the maximum relative error is $\varepsilon_{rel} \leq 2.15\%$;
- for k = 0.002 km^{-1}, Δt_{max}= 29.7^{o}C, n = 9, P_{inst}/unit = 330 MW, P_{inst} = 2970 MW, the maximum relative error is $\varepsilon_{rel} \leq 3.06\%$;
- for k = 0.003 km^{-1}, Δt_{max}= 29.7^{o}C, n = 9, P_{inst}/unit = 330 MW, P_{inst} = 2970 MW, the maximum relative error is $\varepsilon_{rel} \leq 7.32\%$;

- the optimum of the mathematical model according to relative error, under the conditions Δt_{max}= 31.5°C, n = 9, P_{inst}/unit = 330MW, P_{inst} = 2970 MW, is given by k = 0.001 km^{-1}.

4. Conclusions

In terms of technical analysis, with three thermoelectric units of 330 MW operating in each of the Rovinari and Turceni power plants, and assuming an average river flow rate of 47 m^3/s at the Rovinari site and 54.5 m^3/s at the Turceni site, the effect of wastewater discharging in the Jiu River is marginally acceptable.

Simultaneous operation of the thermoelectric units, in open circuit, (meaning, supplying fresh water from the river and discharging wastewater in the river, without using the cooling towers of the power plant) of the Rovinari, Turceni and Craiova power stations relies on the Jiu River flow, under the stability conditions for relevant environmental parameters. In an undeveloped regime of the river system, the flow of the Jiu River does not ensure the functioning in open circuit at the installed power of this chain of three coal-fired power plants connected in a cascade manner (from the cooling system viewpoint) along the Jiu River. If the coal-fired power plants of Rovinari and Turceni operate in open circuit (meaning without recirculation of the water in the cooling system of the power plant) at full capacity (with four and six thermoelectric units, respectively) then the environmental impact, concerning aquatic ecosystems, would be devastating. In these conditions the operation of tower cooling systems in these power stations is necessary.

The EDF mathematic model of temperature evolution within the water of the Jiu River downstream from the outlet of the warm water pollutant vector allows an acceptable evaluation in terms of errors, for river lengths of 10 km to 50 km.

For an acceptable evaluation, it is necessary to combine the simulation results (based on EDF mathematical pattern) with experimental tests for wastewater pollutant vector.

It would be useful to assess overall projections of the wastewater pollutant vector, for both small and large distances.

Another environmental concern is related to abnormal weather conditions, such as arid summer or strong winter frost. Then either the electrical capability of the coal-fired power plant would be decreased, or the aquatic ecosystems would be affected by the operation of the thermoelectric units.

Conflict of Interest

The authors declare no conflict of interest.

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