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

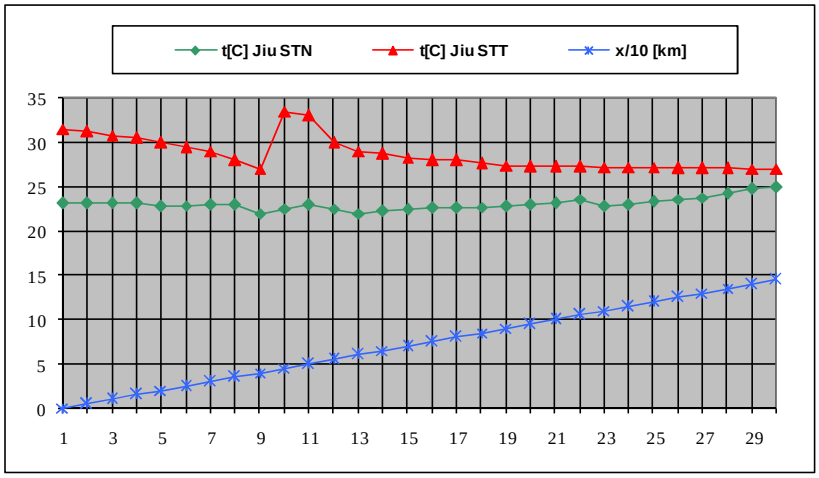
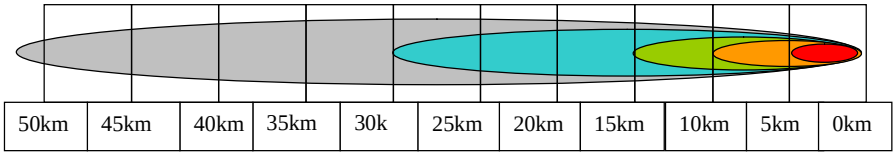


Figure 13. Isothermal curves: Iso_{33}, Iso_{30}, Iso_{29}, Iso_{28}, Iso_{27}



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}, $\Delta t_{max} = 31.5^oC$, 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}, $\Delta t_{max} = 31.5^oC$, 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}, $\Delta t_{max} = 31.5^oC$, 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 $\Delta t_{max} = 31.5^oC$, 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

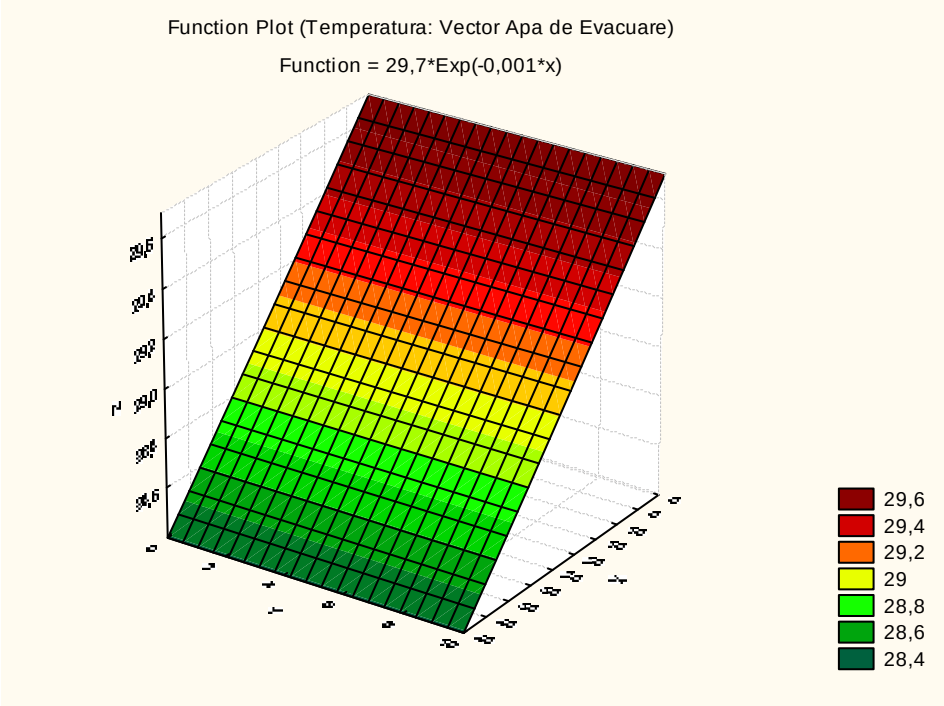
they are supplying freshwater from and discharged wastewater in the Jiu River. This case study is performed under the following conditions:

- 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

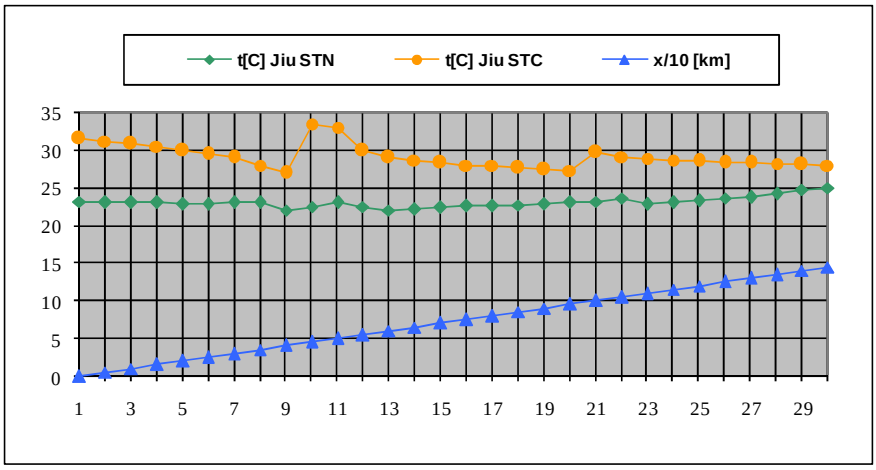
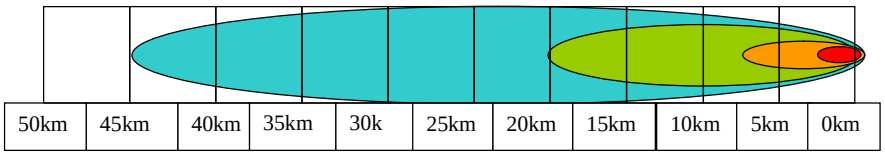


Figure 16. Isothermal curves: $Iso_{29.5}$, Iso_{29}, $Iso_{28.5}$, Iso_{28}



Accordingly, it can be observed that:

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

Consequently:

- for k = 0.001 km^{-1}, $\Delta t_{max} = 29.7^{o}C$, 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}, $\Delta t_{max} = 29.7^{o}C$, 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}, $\Delta t_{max} = 29.7^{o}C$, 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^{o}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.

References

1. El-Haggar, S. *Sustainable Industrial Design and Waste Management: Cradle to Cradle for Sustainable Development*. Elsevier Academic Press, 2007.
2. Drbal, L.F.; Borton, P.; Westra, K.L. (editors), *Power Plant Engineering*. Black & Veatch Publishing House, 1996.
3. Ehrenfeld, S. Industrial Ecology: A New Framework for Product and Process Design. *Journal of Cleaner Production*, **1997**, Vol. 5, 87-95.

4. Dincer, I; Rosen, M.A, *Exergy: Energy, Environment and Sustainable Development*, 2d ed., Elsevier: Oxford, UK, 2013.
5. Rosen, M.A.; Dincer, I. Exergy analysis of waste emissions, *Int. J Energy Research*, **1999,** 23, 1153-1163.
6. Penney, S.; Bell, J.; Balbus, J. Estimating the Health Impacts of Coal-Fired Power Plants Receiving International Financing. Report of Environmental Defence Fund, **2009**. Available at: http://www.edf.org/documents/9553_coal-plants-health-impacts.pdf, Accessed on 12 August, 2014.
7. Lockwood, A.; Welker-Hood, K.; Rauch, M.; Gottlieb, B. Cault Assault on Human Health. Physicians for Social Responsibility Report, November 2009.
8. Istrate, M.; Gusa, M. *Impactul producerii, transportului si distributiei energiei electrice asupra mediulu (Environmental Impact of Electric Energy Generation and Transportation)*, AGIR Publishing House, Bucharest, 2000.
9. Eric Shuster, *Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements.* Office of System Analyses and Planning, National Energy Technology Laboratory, DOE/NETL-400/2008/1339. 2008, Available at: http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/DOE-NETL-400-1339-2008WaterNeedsUpdate-Final-Sept08.pdf Accessed on 12 August, 2014.
10. ECOTEC, EFTEC, IEEP, Metroeconomica, TME & Candidate Country Experts. *The Benefits of Compliance with the Environmental Acquis for the Candidate Countries*. Available at: http://ec.europa.eu/environment/enlarg/pdf/benefit_short.pdf, Accessed on 12 August, 2014.
11. Termuehlen, H.; Emsperger, W. *Clean and Efficient Coal-Fired Power Plants*, ASME, 2003.
12. Kinzelbach, W.K.H. Managing the cooling capacity of the upper Rhine. A case study. *Environmental Management*, 1981, 5, 69-77.
13. Palaniappan, M.; Gleick, P.H.; Allen, L.; Cohen, M.J.; Christian-Smith, J.; Smith, C. Clearing the waters, A focus on water quality solutions. United Nations Environment Programme & Pacific Institute, 2010, Available at: www.unep.org/PDF/Clearing_the_Waters.pdf, Accessed on 14 August, 2014.
14. Hnatiuc, E. *Procedes Electriques de Mesure et de Traitment des Polluant* (*Electrical Methods for Measurement and Treatment of Pollutants*). Editions TEC&DOC, Lavoisier Publishing House: Paris, France, 2002.
15. Weil, J.C. A diagnosis of the asymmetry in top-down and bottom-up diffusion using a Lagrangian stochastic model. *Journal of the Atmospheric Sciences*, **1990**, 47(4), 501-515.
16. Brînduşa, A.; Kovacs, J. Thermoenergetic block on coal. Pollution vector: burning gas. *Annals of the University of Petrosani* (Universitas Publishing House, Petroşani, Romania), **2007**, 9, 218-221.
17. Perry, S.G.; Burns, D.J.; Adams, L.H.; Paine, R.J.; Dennis, M.G.; Mills, M.T.; Strimaitis, D.G.; Yamartino, R.J.; Insley, E.M. 1989, User's Guide to the Complex Terrain Dispersion Model PlusAlgorithms for Unstable Situations (CTDMPLUS). Volume 1: Model Description and User.110 Instructions, EPA/600/8-89/041, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1989.
18. Makinia, J. *Mathematical Modelling and Computer Simulation of Activated Sludge Systems***.** IWA Publishing House, 2010.

19. Tzolakis, G.; Papanikolaou, P.; Kolokotronis, D.; Samaras, N.; Tourlidakis, A.; Tomboulides, A. Emissions' reduction of a coal-fired power plant via reduction of consumption through simulation and optimization of its mathematical model. *Operational Research Journal*, **2010,** 10, 71-89.
20. Breuil, J.M. Input-output analysis and pollutant emissions in France. *The Energy J.*, **1992**, 13, 173-184.
21. Studiul termic al riului Jiu pe sectorul amonte CTE Rovinari , aval CTE Isalnita (Thermal study of Jiu River on the Sector between Rovinari Power Plant Upstream and Isalnita Power Plant downstream), *Institute of Power Engineering Studies ISPE Bucharest*, Project 1073/8934/94, 1994.
22. Bulucea, C.A.; Jeles, A.; Mastorakis, N.E.; Bulucea, C.A.; Brindusa, C. Managing through Pollutant Vector the Wastewater from a Chain of Coal-Fired Power Plants Discharging into Jiu River. *Recent Researches in Environment, Energy Planning and Pollution - Proc. of the 5th WSEAS Int. Conf. on Renewable Energy Sources, RES'11, EPESE'11, WWAI'11*, Iasi, Romania, July 1-3, 2011, pp. 244-251.
23. Mastorakis, N.E.; Jeles, A.; Bulucea, C.A.; Bulucea, C.A.; Brindusa, C. Evaluating the environmental impact of coal-fired power plants through wastewater pollutant vector. *Recent Researches in Geography, Geology, Energy, Environment and Biomedicine - Proc. of the 4th WSEAS Int. Conf. on EMESEG'11, 2nd Int. Conf. on WORLD-GEO'11, 5th Int. Conf. on EDEB'11*, 2011, pp. 181-187.