Modelling and simulation of thermal pollution spread at Cernavodă Nuclear Power Plant (CNPP)

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1. Overview

Each unit of CNPP uses a maximum flow rate of 54 m3/s in order to cool the capacitors and coolers operating with technical water. This water is caught from Dunărea Veche branch of Danube river and it is conveyed to the nuclear power plant through the first pool of Danube-Black Sea Canal, and also to the diversion canal and distribution basin. After running through the power plant, the water is discharged into the Danube river or into the second pool of DBSC with a temperature increase by 7-103C as compared to the temperature of the source water.

The warm flow rate from CNPP is low as compared to the multi-annual monthly mean flow rates gauged along Dunărea Veche branch. However, the large breadth of the river bed does not allow a fast mixture on the entire cross section and an immediate taking-over of the additional heat amount by the whole water stream. On the river's right side, where the effluent is discharged, a thermal plum is developed. This is gradually extended along the cross section, as the water moves toward the downstream section. Knowing of the thermal plum extension rate and its temperature is a key-issue for the estimation of direct and indirect effects of the thermal pollution on the biocoenosis elements from the aquatic environment. It is also important to know the thermal plum development rate under the conditions of CNPP's operation with three or four operational units.

2. Estimation model of the thermal effect

For making a forecast of the effluent's thermal effect on the water temperature along Dunărea Veche branch, a mathematical model able to simulate the water flowing parameters and water temperature distribution on the outlet downstream section has been developed. The model consists of the equations of the free surface-water motion along Dunărea Veche branch, together with the continuity equation and with the two-dimensional heat transfer equation on a horizontal plane. This is made by means of a depth(vertical) integration of the heat transfer's main equation.

The model takes into account the main local conditions of the river bed (irregular riverbed shape) and of the mixture process, by using cross section profiles and hydrological data. The heat losses are taken into consideration by means of various phenomena and processes, but the water temperature variation at mean values of the weather parameters is low on the short flowing time, that is up to several kilometers, downstream from the outlet section. The heat's transfer equation, vertically integrated, has a structure which includes terms related to the above-mentioned processes:

$$h\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}\right)=\frac{\partial}{\partial x}\left(h\varepsilon_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(h\varepsilon_y\frac{\partial T}{\partial y}\right)+\frac{E}{\rho c_P}$$

where the notations are: h- water depth, T- water temperature, x- longitudinal coordinate, y- cross section coordinate, u- flowing longitudinal rate, ε_x- heat's longitudinal transfer equation, ε_y-heat's cross-section transfer equation, E- heat transfer from air into water by means of the surface unit, ρ- water density, C_p- specific heat coefficient.

The model is able to provide estimates of the thermal effect of the effluent along the river's right bank, under various operation condition of CNPP.

For the estimation of thermal effect of CNPP's effluent under specific circumstances, monthly values of the water levels and flow rates have been used, and also monthly and decade values of the water temperature and of the weather parameters. The values of the effluent's parameters related to various operation conditions of CNPP were also used. In case of the winter months with the monthly mean temperature of water under 5^0C, a re-running flow rate of about 50% from the total water flow rate has been considered. The values of the hydrological parameters are the ones gauged at Cernavodă Hydrological Station (CHS), located on the Dunărea Veche branch at about 2 km downstream from the intake point of DBSC, upstream from the outlet point of the warm effluent. The Danube's water temperature is daily gauged and the data collected for a period longer than 40 years may provide the characterization of the Danube water's thermal regime in the period previous to the setting into operation of The Unit 1 of CNPP, as well as during the operation of CNPP with one or two operational units. The variations of the water's mean temperature gauged at CHS have been analyzed in terms of decade, monthly or annual values. The results of the statistical processing are presented in tables 1-4. The monthly and annual temperature values frequently show significant variations each year. As an example, the figures 1 and 2 show the temporary variation of the mean water temperature gauged at CHS in April, and the temporary variation of the annual mean water temperature measured by CHS, along a 40 years period.

Table 1. The multi-annual mean values of mean monthly and annual water temperature (Cº) gauged by CHS

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I - XII
T_{med}	2,07	2,11	4,8	10,8	16,3	21,0	23,8	24,0	20,7	15,0	9,1	4,2	12,9

Table 2. Multi-annual parameters (Cº) of the mean decade water values gauged by CHS

Month	I			II			III			IV			V			VI		
Decade	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
T mean	2,7	1,9	1,6	1,6	2	2,6	3,6	4,4	6,4	9,1	10,8	12,4	14,3	16,3	18,1	19,6	21,0	22,2

Month	VII			VIII			IX			X			XI			XII		
Decade	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
T mean	23,2	23,9	24,3	24,3	24,3	23,6	22	21	19	17	15	13	11	9,3	7,2	5,5	3,9	3

Table 3. Minimum and maximum values of the mean monthly and annual water temperature (Cº)

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I - XII
$(T_{med.})_{min.}$	0	0,03	0,7	7,1	10	15	22,1	22	18,3	11	5,9	1,7	0
An	1963	1963 1964	1985	1980	1991	1991	1962 1969	1968	1996	1991	1988	1998	1963
$(T_{med.})_{max.}$	5,1	5	9,5	15	19,7	25,5	26,4	26,7	23,6	19,7	14,2	7.3	26,7
An	1991	1990 1974	1990	1989	1968	1971	1988	1994	1994 1977	1976	1962	2000	1994

Table 4. The extreme instant temperature values gauged at CHS

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I - XII
$T_{min.}$	0	0	0	1	9,1	8,3	18,3	20	15	6,4	0,5	0,2	0
An	1963 1964 1966 1972 1980 1982 1987 2000	1963 1964 1966 1972 1982 1986 1996 2000	1963 1964	1976	1991	1991	1991	1965 1987 1990 1993	1964 1996	1988	1963	1961 1963 1986	1963, 1964 1966, 1972 1980, 1982 1986 1987, 1996 2000
$T_{max.}$	7,2	8,4	13,5	20	23	26,6	29,6	28,6	25,9	23,4	17	10	29,6
An	1991	1989	1990	1977	1977	1994	1987	1994	1992	1994	1976	1977	1987

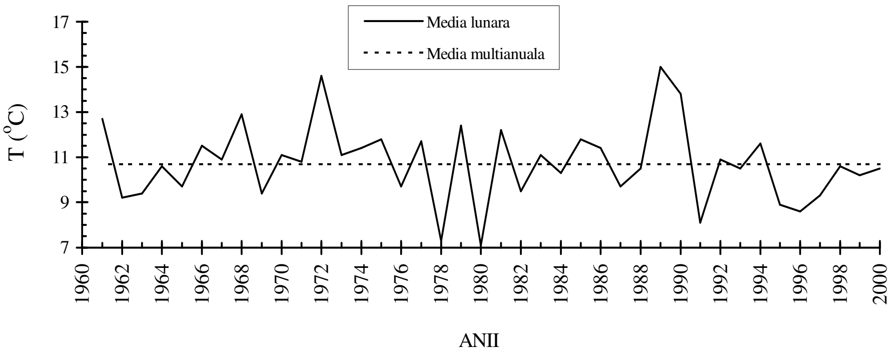

Figure 1: The temporary variation of the mean water temperature in April, gauged by CHS

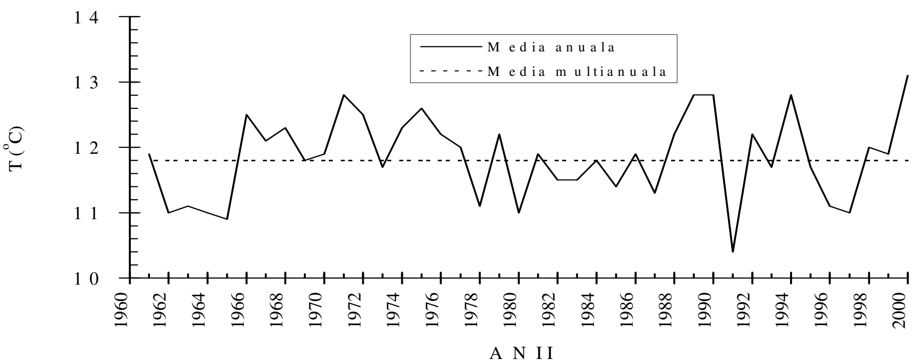

Figure 2. The temporary variation of the annual mean water temperature gauged by CHS

3. Validation of the mathematical model

For validating the mathematical model, measurements on the Danube water were performed in the impact area of the CNPP's effluent, both upstream and downstream from the outlet point. The surveys performed during various seasons of 2001, 2003, 2004, 2006 and 2009, with one and two operational units, have covered the river section between km 300 and 281. Vertical profiles of the water temperature have been gauged in points placed in successive cross sections (Figure 3). Most of the survey spots were in the cross sections (at km 295, 294, 292, 291) along a distance of 5 km downstream from the outlet section. The water temperature was also gauged in an islands area (mainly at km 288 and km 286) and in other downstream sections (at km 285, 284, 283, 281). The results validation has been carried-out by means of calculus simulation of some situations gauged during the operation of The Unit 1, under the most various hydrological and meteorological conditions. Both an average scenario and an extreme scenario have been considered. As an example, Figure 4 shows the water temperature gauged on April 2-3, 2003, as compared to the isotherms of the temperature values of 10.5° and 10ºC computed for showing hydrological monthly and decade mean conditions corresponding to April, 2003.

The water temperature along the right bank, downstream from the effluent's outlet shows a difference of few degrees on the depth section, in the initial vertical mixture area. There are also differences between the water temperature on the right bank and middle of the branch, downstream from the outlet section. The water temperature in the middle and on the left bank of Dunărea Veche branch is the natural one, very close to the values gauged by CHS.

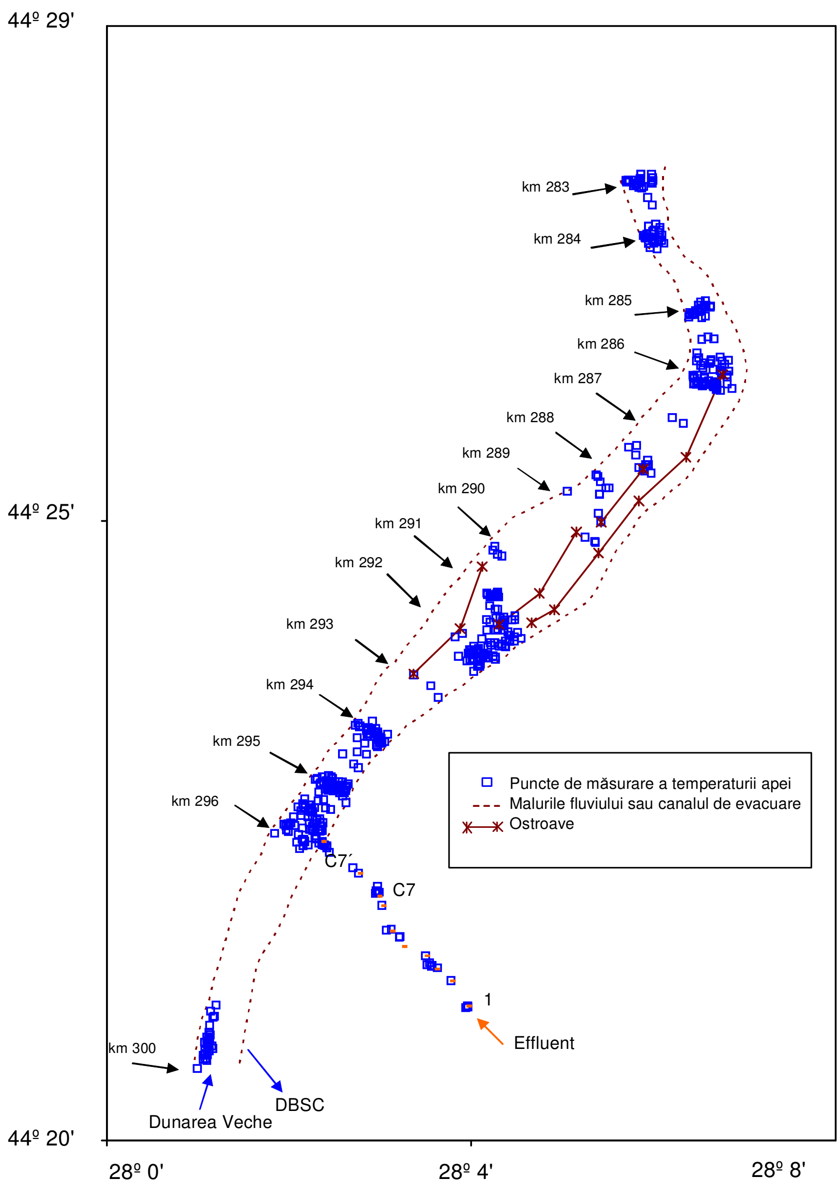

Figure 3. Gauging sections of the water temperature along Dunărea Veche branch, downstream from Cernavodă, as well as in the effluent

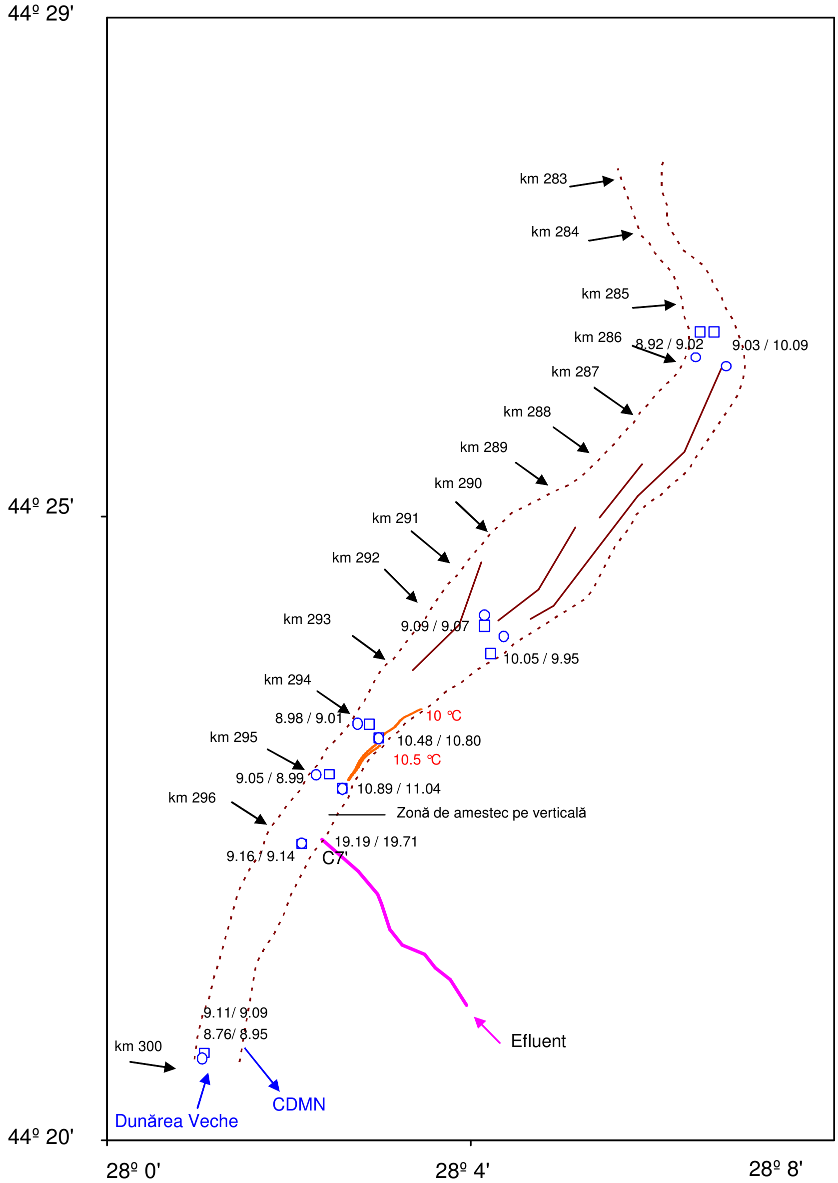

Figure 4. Water temperature along Dunărea Veche branch, due to the natural factors and to the effluent from a unit of CNPP, gauged on April 2003 (mean water levels)

The thermal plum length depends on the flow rates and levels of Danube, on the season climate variations and on the flow rate and the effluent's temperature increase. Besides the thermal plum, the natural thermal conditions of Danube water are maintained. The reduction of the temperature increase under 2ºC is produced inside the considered section, along a distance of few kilometers on the Danube river (up to 2-3 km), under monthly mean conditions. The thermal plum may be extended more, only in case of very low levels.

The mixture length into the Danube water of the effluent discharged by a unit of CNPP mainly depends on the levels and flow rates gauged on the branch, as well as on the water flowing conditions in the islands section. The mixture degree may be estimated based on the ratio between the highest temperature difference in a cross section and the difference from the effluent's outlet section. As this ratio is decreased, the mixture tends to be completed (leveling of the temperature values along the section is represented by means of a coefficient which results by subtracting the ratio value from 1). The noticed evolution of the mixture degree, presented in figures 5 and 6 shows that, under all circumstances, the mixture length does not exceed the section of kilometers 285-283.

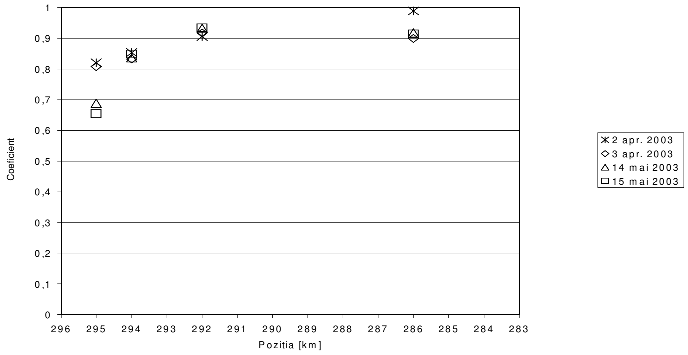

Figure 5. The noticed evolution of the mixture degree in case of medium water level

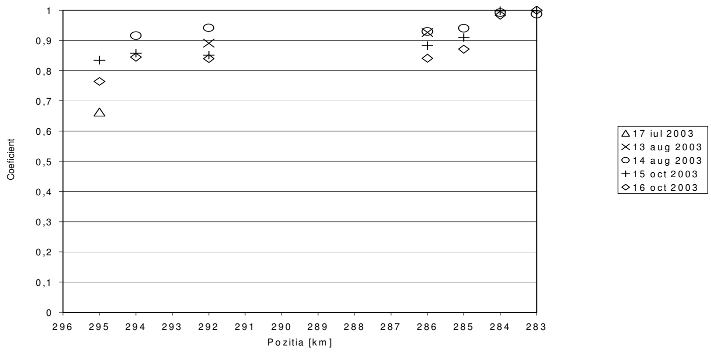

Figure 6. The noticed evolution of the mixture degree in case of shallow water level

4. Conclusions

The mathematical model was also used for the estimation of thermal effects generated by the outlet of CNPP's effluent with four operating units. The physical and chemical parameters of the water discharged by The Units 1,2,3,4 are similar as in the case of one unit, the differences coming from the increased effluent's flow rate. The total water flow rate, according to draft specifications, discharged by The Units 1,2,3,4 is 216 m3/s, as compared to a 108 m3/s flow rate, generated by two units of CNPP. In case of the winter months, with a mean monthly temperature under 5ºC, a re-running flow rate of 100 m3/s from the total cooling flow rate amount was considered. The effluent's temperature increase over the temperature of the source water is expected to be similar with the one applicable for The Unit 1 (7-10ºC).

Figures 7 and 8 show the estimated temperature distributions along Dunărea Veche branch. They display, by means of computed isotherms, (isotherms of the temperature increase by 3ºC and 2ºC), a longitudinal decrease of the temperature under thermal plum conditions, in circumstances related to the Danube's mean flow rates (gauged in July), and to the Danube's low flow rates (gauged in October). The isotherms show the longitudinal extension of the areas from the right bank with water temperature higher than the mean temperature values measured upstream of Danube. Due to the effluent's flow rate (four times higher than the flow rate value from a unit of CNPP), the thermal joint effect of the effluent from The Units 1,2,3,4 and along Dunărea Veche branch is more extended, but the temperature from the outlet section is approximately the same as in case of one unit. Along the branch, the effluent's influence is noticed on longer distances, due to the values of the effluent's flow rate. Under the current existing conditions on Danube, the expected temperature values of CNPP's effluent are within the limit of 35ºC, settled by NTPA 001 standard (in accordance with The Government's Decision 352/2005. The fraction from the cross section of the branch which is influenced by the effluent, with increase rates by 3ºC, may be in general up to a quarter, under multiannual mean monthly flow rates of Danube(flow rates higher than 1500 m3/s).

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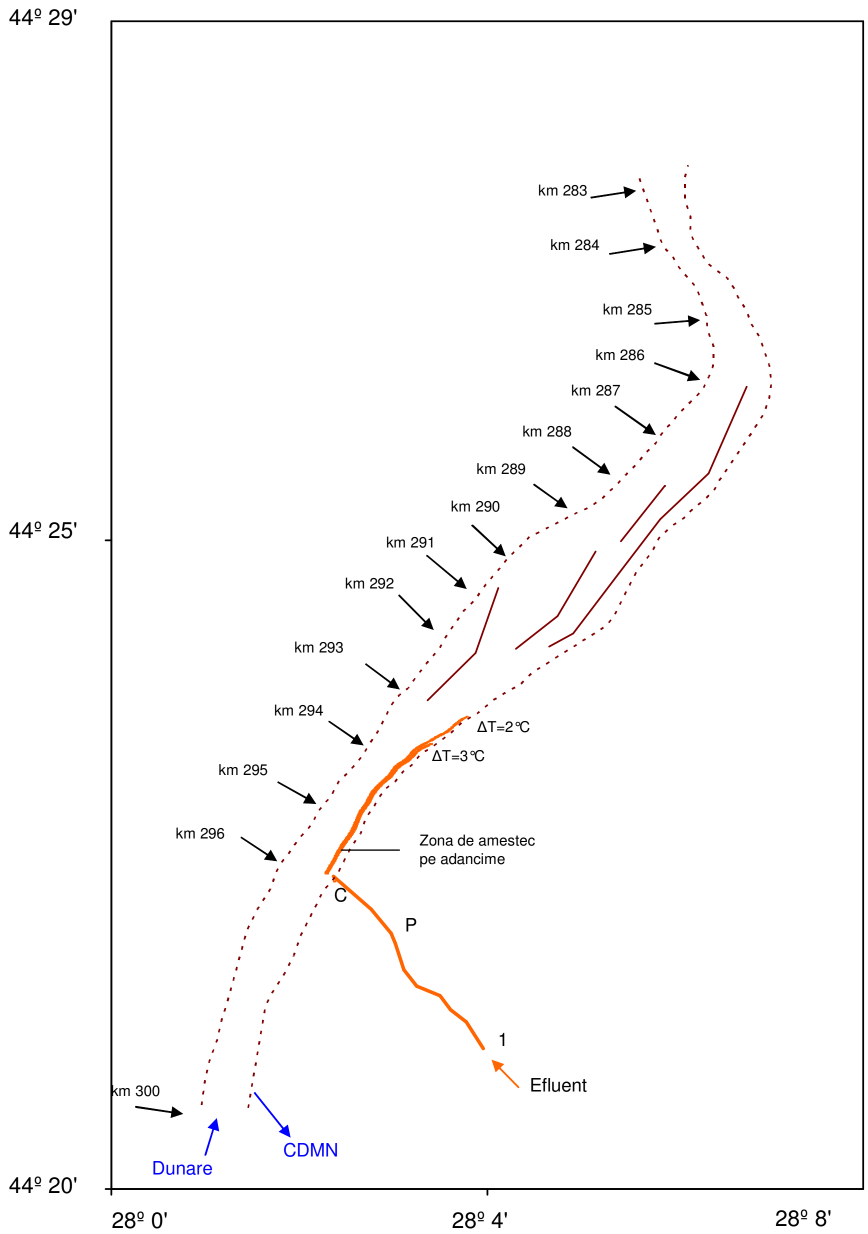

Figure 7. Computed isotherms due to the effluent generated by The Units 1,2,3,4 of CNPP, in July, under mean conditions

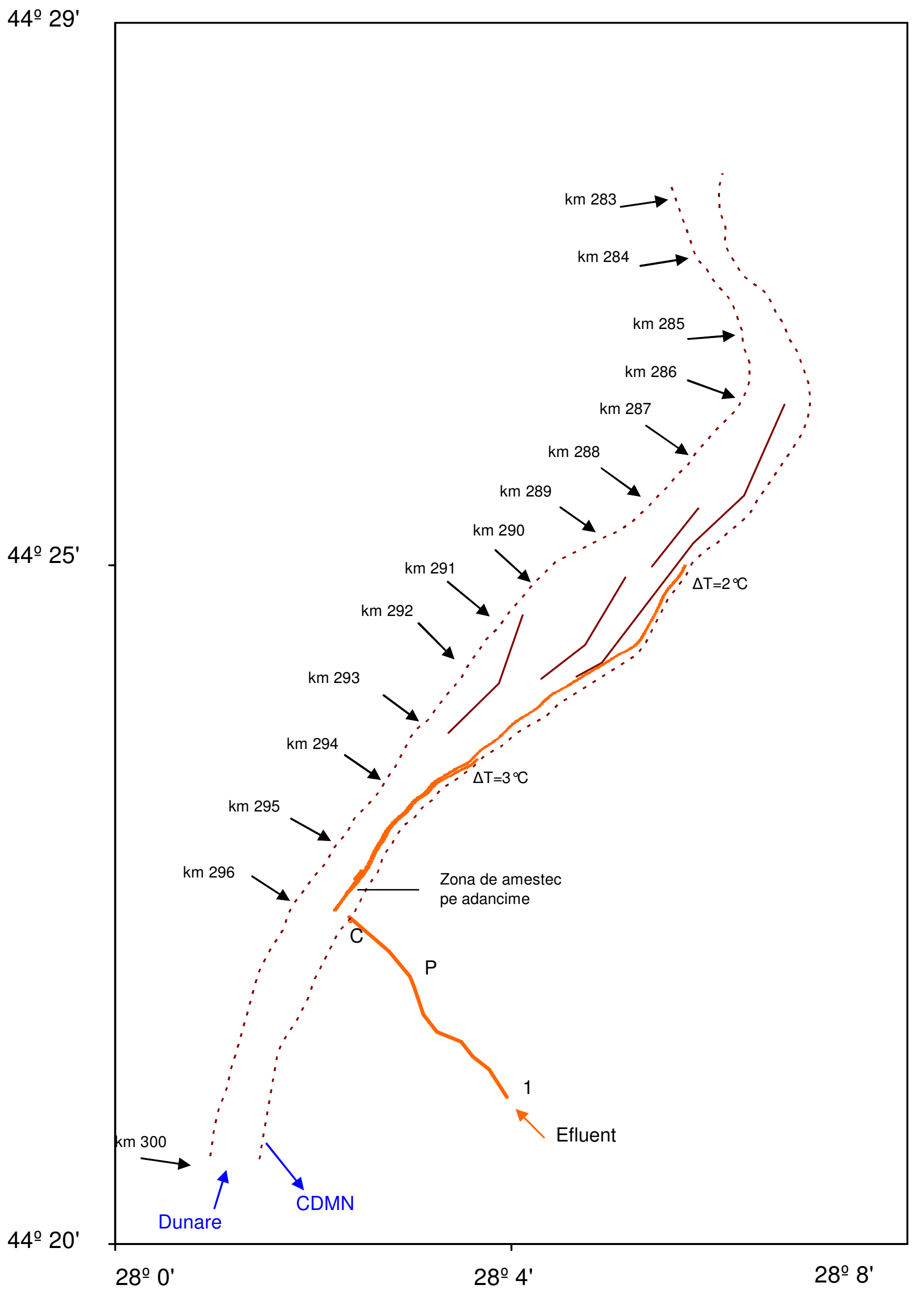

Figure 8. Computed isotherms due to the effluent generated by The Units 1,2,3,4 of CNPP, in October, under mean conditions