Impact of initial conditions on the prediction of the spread of thermal pollution in rivers

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Abstract. The influence of initial conditions on the prediction of the increase of river temperature below the point of release of heated water for a designed power plant has been analysed in this study. The results for different assumed values of river flow and different temperatures of the discharged heated water have been presented. The results have been analysed taking into account existing legal frames. The two-dimensional in-house RivMix model has been used to simulate the temperature distribution whereas the two-dimensional depth-averaged turbulent open channel flow model CCHE2D has been used to simulate the velocity fields and the water depths for the selected flows of the river.

1. Introduction

Intuitively, river temperature results from environmental conditions, its topography, and stream discharge. In the case when the release of thermal plume into a river stream is considered water temperature depends also on the amount of the discharged warm water, its temperature, the site and way of its release etc. Conservation of heat in open channels yields the transport equation for heat, or rather, for the change of temperature. The nature of boundary value problems is that the results depend on the initial conditions. Therefore studies of the influence of initial conditions on the fate of the thermal plume may be carried out by studying the behaviour of a relevant model. In other words, we may model the spread of thermal plume by supposing that at some initial instant $t = 0$, there are given distribution of temperature, water depths and velocity vector in space. We then would like to trace the subsequent development of temperature for $t > 0$.

Thermal pollution is a result of any unnatural process that changes ambient water temperature. In rivers, it is often caused by discharged heated water used for cooling purposes by industrial facilities, such as steam electric power plants, chemical plants, etc. Since the increase of water temperature may be dangerous for the environment, for example by affecting fish population, in many countries it is required to prepare an Environmental Impact Assessment (EIA) before such facilities are constructed. Besides many other aspects of EIA, prediction of possible increase of water temperature caused by an artificial heat source is of crucial importance. Such predictions are usually made using numerical models. The choice of a relevant model, and all the more, the collection of data used as model input, are often

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difficult tasks. At the same time the choice of initial conditions for which the prediction is made constitutes a key problem. In principle such predictive computations should be performed for the most severe situations from the environmental point of view. But the choice of such conditions usually requires an in-depth analysis of the historical data for a particular case. Also, many coefficients and model parameters have to be anticipated, since real calibration based on the measured data is frequently not feasible.

In this study, we consider a particular case in which an anticipated heated water jet was planned to be continuously released in the lowland, urban part of the Vistula River in Poland after an existing thermal-electric power plant is reconstructed. We analyse the influence of the chosen initial conditions on the prediction of river temperature increase, namely different values of the river flow and different values of the discharged heated water temperature. Note, however, that other input coefficients and parameters in the heat transfer equation may also be important and may influence the obtained results to a large extent (see [1, 2, 3]).

The presented results are analysed taking into account existing legal regulations with respect to admissible discharged heated water temperature in Polish rivers [4, 5]. The two-dimensional (2D) RivMix model has been used to simulate the temperature distribution. This model is based upon the depth-averaged heat transport equation in which a non-diagonal dispersion tensor with four dispersion coefficients is taken into account (see details in [1, 2, 3, 6, 7, 8]. Crucial input values, namely the depth-averaged velocities and the water depths distributions for the given river flow, are obtained using the 2D depth-averaged turbulent open channel flow model CCHE2D [9, 10, 11].

Some piecemeal results related to the considered herein case of heated water discharges were mentioned in [3, 12].

2. Study area

The study area is located in Poland in the lowland, urban part of the Vistula River. The given river reach has semi-natural braided channel geometry and is protected by Natura 2000 protocol. Calculations of the increase of water temperature below the anticipated discharges of heated water from the designed power plant have been made for the river reach presented in Fig. 1.
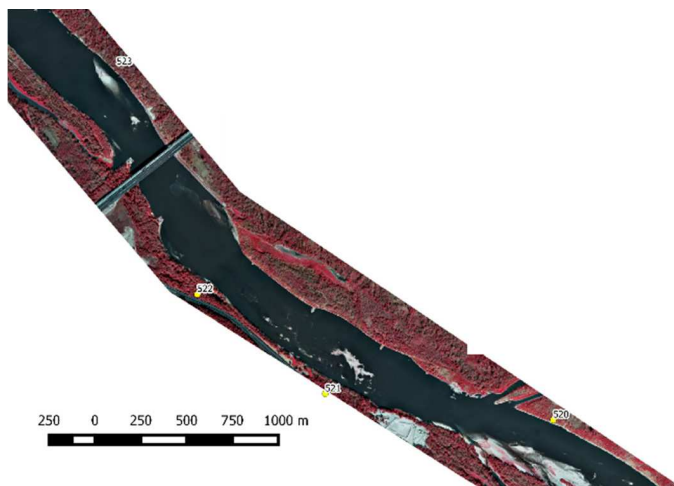

Fig. 1. Aerial photograph in IR showing the study area during the extremely low flow in August 2015 recorded by the MGGP Aero and provided by Warsaw Conservation Office of the Warsaw City Hall.

3. Initial conditions

The possibly most severe situations from the environmental viewpoint that may occur within the study area were chosen for calculations. To capture such unfavourable low flow conditions (lowest water levels), it is necessary to analyse relevant historical data. Average long-term (1951-2010) discharge of the considered reach of Vistula River is $MQ = 574$ m^3/s. According to [13, 14] long-term average low flow is equal to $MLQ = 192$ m^3/s. The newest study (1965-2010) shows $MLQ = 242$ m^3/s [15]. Calculated by the probability method, using data from 1921 to 1970 and Gumbel distribution, low flow with a recurrence of 100 years is equal $LQ1\% = 110$ m^3/s [14, 16]. Using the data from 1951 to 1970, $LQ1\% = 91.3$ m^3/s [14, 16]. The extreme low flows of the analysed reach of Vistula River that have occurred within last 100 years are collected in Table 1. Note that the lowest flow occurred in January 1947 and it was equal to 68.2 m^3/s.

Based on the longstanding historical data observation and the analysis mentioned above, calculations of possible water temperature increase have been done for the flow close to the mean low-flow $Q = 200$ m^3/s. Additionally, calculations for flow approximate to low flow with a recurrence of 100 years, $Q = 100$ m^3/s, and for the lowest possible value of the flow recorded within 100 years, $Q = 68$ m^3/s, have been done. The value of the assumed water flow conditions not only influence the velocity distribution in the channel, but also water depth, shear velocity and consequently the values of dispersion coefficients. An example with distributions of water depth and velocities for the analysed case (for Q = 200 m^3/s) calculated with use of CCHE2D model is shown in [3].

In the present calculations, temperature of the discharged heated water (T_Z) is set 8°C higher than ambient water temperature (T_W). Additionally, scenarios with heated water temperature equal to 35°C (the upper limit imposed by Polish law) have been computed. All computation variants presented in the paper are summarised in Table 2. In all scenarios, the heated water has been released with a constant intensity of 9 m^3/s.

The initial water temperature for all scenarios, has been estimated based on historical data as equal to the average natural summer temperature of the river water in the considered region, i.e. $T_W = 22.7$ °C.

Table 1. Extremely low flows of the analysed reach of Vistula River;
* – flow disturbed by the ice jams. Based on [13 and 14], supplemented with the latest data.

Date	Flow discharge Q [m^3/s]	Date	Flow discharge Q [m^3/s]
July 24, 1921	113	October 5, 1946	146
May 23, 1925	139	January 15, 1946	68.2*
July 17, 1928	131	August 2, 1950	145
February 4, 1929	150*	September 15, 1951	158
June 23, 1930	128	August 12, 1952	153
September 11, 1932	166	January 19, 1964	152*
January l, 1933	120*	September 5, 1992	184
November 11, 1943	122	September 12, 2012	172
		August 28, 2015	157

<div align="center">**Table 2.** Simulation scenarios.</div>

| Scenario	Flow discharge Q [m³/s]	Natural (ambient) water temperature T_W [°C]	Temperature of discharged heated water T_Z [°C]	(T_Z-T_W) [°C]
1	200	22.7	35	12.3
2		22.7	30.7	8
4	100	22.7	35	12.3
5		22.7	30.7	8
7	68	22.7	35	12.3

4. Results

The computed temperature distributions for the continuous point-like discharges for the scenarios mentioned in Table 2 are presented below. Figure 2 presents the predicted 2D temperature distributions within the whole analysed area for two selected scenarios, namely the environmentally worst and best results. Figure 3 presents the temperature distributions in the vicinity of the discharge point calculated for all considered scenarios. Although far away from the discharge point, the differences between variants are very small, close to the discharge point the differences are easily noticeable. This statement is supported also by figures 4 and 5. Figure 4 indicates the maximum water temperature that might occur within a distance r from the discharge point. Figure 5 shows the temperature distributions at cross-sections located approximately at distances 100, 250 and 500 m from the discharge point. Those cross-sections are also marked for all variants in Fig. 2. Figure 2 reveals that water level is different in case of different assumed flows. For the lower flows (100 and 68 m³/s) a few islands are visible, but they are not present in case of flow equal to 200 m³/s.
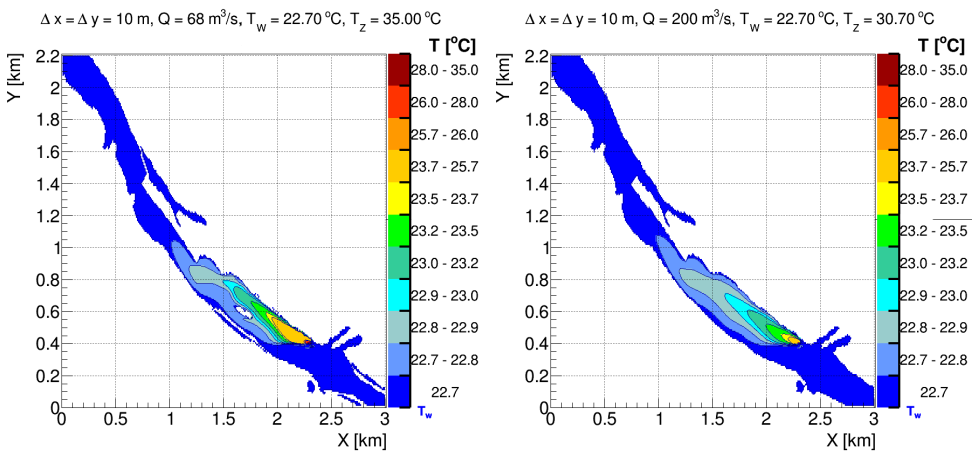
Fig. 2. Predicted 2D temperature distributions within considered river reach – the worst (**left**) and the best (**right**) scenarios.
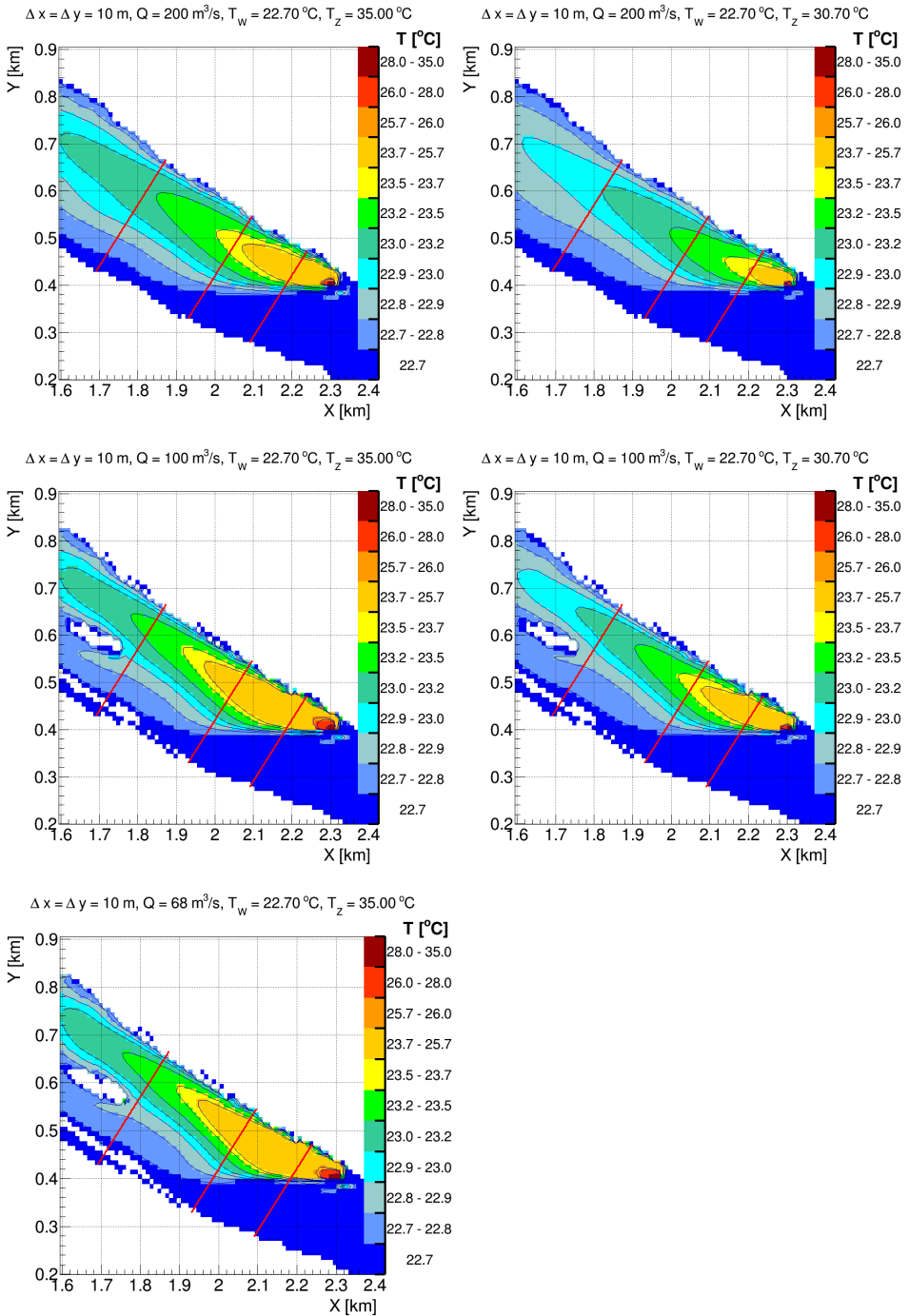
Fig. 3. Predicted 2D temperature distributions near the discharge point for flows: Q = 200 m³/s (**top** subfigures), Q = 100 m³/s (**middle** subfigures), Q = 68 m³/s (**bottom** subfigure) and for two assumed values of the temperature of discharged heated water: T_Z = 35.0°C (**left** subfigures) T_Z = 30.7°C (**right** subfigures).
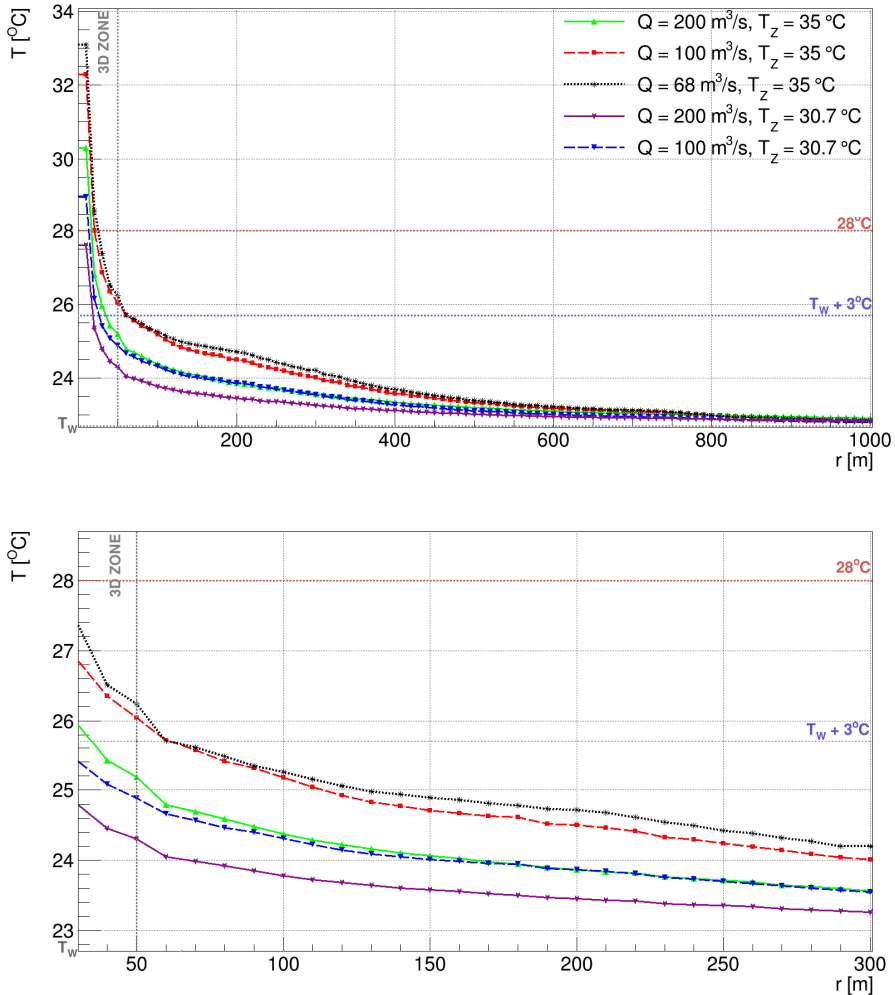
Fig. 4. The maximum temperature that might occur within a distance *r* ranging from 0 to 1000 meters from the discharge point (**top** subfigure) and from 40 to 300 meters (**bottom** subfigure). Initial water temperature *Tw* and two threshold values of water temperature: *Tw* + 3°C and 28°C have been marked.

The initial conditions assumed in the present study were selected in the way allowing to judge whether the standards applicable in Poland for the environmental safety of surface waters would be met after construction of the designed thermal power plant. Note that the river in the considered area is a habitat for fish from Cyprinidae family and to protect them two threshold values are set: the heated water temperature should not exceed the temperature of ambient water by more than 3°C, and moreover, the temperature of water should not exceed the value of 28°C. Both values should not be exceeded below the warm water discharge point on the boundary of the so-called mixing zone. As can be seen from temperature distributions above, the planned construction project does not pose a threat for the environment from this viewpoint but calculations performed for various initial conditions constitute an excellent exercise allowing to determine threshold values that should not be exceeded in reality. One can easily imagine that at larger discharges of heated water under

low water levels those environmental requirements could not be met. Under the conditions of low water flows and maximum admissible temperatures of the released water, the results reach the environmental standards.
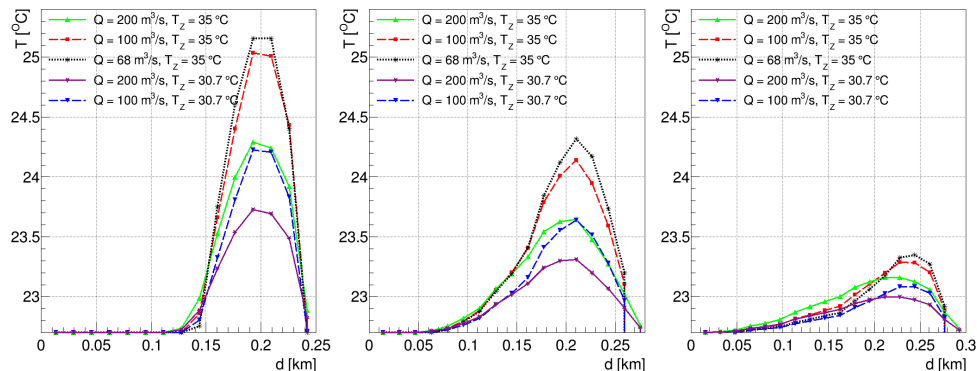
Fig. 5. Temperature distribution in the cross-sections located approximately 100, 250 and 500 m downstream from the discharge point for all scenarios ; *d* [km] denotes the distance from the left bank along the cross-section line. The relevant cross-sections have been marked in all subfigures in Fig. 2.

5. Conclusions

We fully realize that the influence of initial conditions on final results in boundary value problems dissipates and the temperatures of water tend to the same values no matter what initial conditions we set. However, the speed at which this influence dissipates reflects different patterns of the transport of the heated water plume. This pattern is crucial since we are extremely interested in determining in which area the temperature of heated water may pose a threat to the biological life in the stream. The study is based upon Environmental Impact Assessment exercise carried out with use of a 2D model of heat transfer in rivers with respect to real data related to a designed hydro-engineering construction in a lowland river. The focus of this study was on the choice of initial conditions, such as river flow and temperatures of ambient and released water. Those conditions influence the detailed velocity field, water depths, bed shear stresses and consequently dispersion coefficients which in turn influence the solutions of heat transfer equations and thus the temperature distributions.

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