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Elçi, Alper; Elçi, Sebnem; Boyacioglu, Hülya

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Cooling Water Discharge Impacts to an Ephemeral Stream: a Heat Transport Modeling Study

A. Elçi
Dokuz Eylül University, Department of Environmental Engineering, Izmir, Turkey
Ş. Elçi
Izmir Institute of Technology, Department of Civil Engineering, Izmir, Turkey
H. Boyacıoğlu
Dokuz Eylül University, Department of Environmental Engineering, Izmir, Turkey

ABSTRACT: The objective of this study is to determine the effects of cooling water discharge from a small scale power plant by using a 1-D numerical heat and solute transport model WASP 7. The goal of the modeling is to determine the effects of the discharge by estimating the difference in stream water temperature before and after release. The cooling water was released to an ephemeral stream that flows through an industrial zone, receives surrounding storm water and interacts in some parts with the underlying aquifer. The release rate was unsteady during the monitoring period of the study. Average temperature of the cooling water was 23.6 °C with a maximum of 35°C.

Field work was conducted to collect data that was necessary for the modeling stage. Flow rates were measured with an acoustic Doppler velocimeter at six transects of the stream. Water temperature, dissolved oxygen concentration and electrical conductivity were determined by collecting water samples at eleven monitoring points. Modeling results indicate that the warm water release is somewhat effective in the dry period up to 600 m downstream of the release location. The estimated stream water temperature does not exceed 22 °C, thereby complying with regulations.

Keywords: Water quality modeling, Surface water, WASP, Water temperature, Cooling water, Discharge rate measurement, ADV

1 INTRODUCTION

Water temperature is an important water quality parameter that affects not only physical and chemical processes but also ecological activities and the distribution of aquatic organisms. It is known that dissolved oxygen decreases and mineral solubility increases with increasing water temperature. Chemical and biological reaction rates are proportional to water temperature. Furthermore, most organisms can live within certain temperature limits.

Power plants and other facilities use cooling water recirculation systems to transfer waste heat from their condensers. Industries using large quantities of cooling water are obliged to predict the possible thermal effects on the water bodies on which the discharge takes place to prevent damage to aquatic organisms (Maderich et al. 2008). The impact of cooling water discharge to surface water features such as streams can be estimated by using mathematical modeling. Mathematical models can be classified as empirical models that rely on statistical analysis to make predictions from weather data or information on catchment characteristics, and physically based models that involve solving the heat budget equation (Webb et al. 2008).

The objective of this study is to determine the effects of cooling water discharge from a small scale LNG conversion power plant by using a 1-D numerical heat and solute transport model WASP 7.41 (Ambrose et al. 1993). Specifically, the goal of the modeling is to determine the effects of the warm water discharge by estimating the change in stream water temperature before and after release. The cooling water is released to an ephemeral stream that flows through an industrial zone and interacts in some parts with the underlying aquifer.

1.1 *Description of Study Area*

The study area is located in the Manisa province in Western Turkey. The power plant is a liquid natural gas (LNG) combined-cycle type power plant with a total capacity of 115.26 MW and a thermal output of 238.2 MW. The LNG power plant is located 1.2 km west of the Manisa Organized Industrial Zone (Fig. 1). The area is under the influence of a typical Mediterranean climate, which is moderately cold and rainy in the winter, hot and dry in the summer season. The mean daily temperature is 17.5 °C. The highest and lowest mean temperatures occur as 28.3 °C and 6.7 °C in July and January, respectively. The mean annual precipitation is 714 mm.

The cooling water of the LNG power plant is released together with the backwash water of the demineralization system into the headwaters of the nearby Çapaçarık Stream, which is 4.91 km long and merges into the Gediz river, a major river in Western Turkey. Parts of the stream that flow through the industrial zone are improved as concrete channels. The release point is actually located on this channel and is about 300 m away from the power plant. The discharge water is conveyed via a closed concrete channel from the plant to the release point (shown as S1 in Fig. 1).

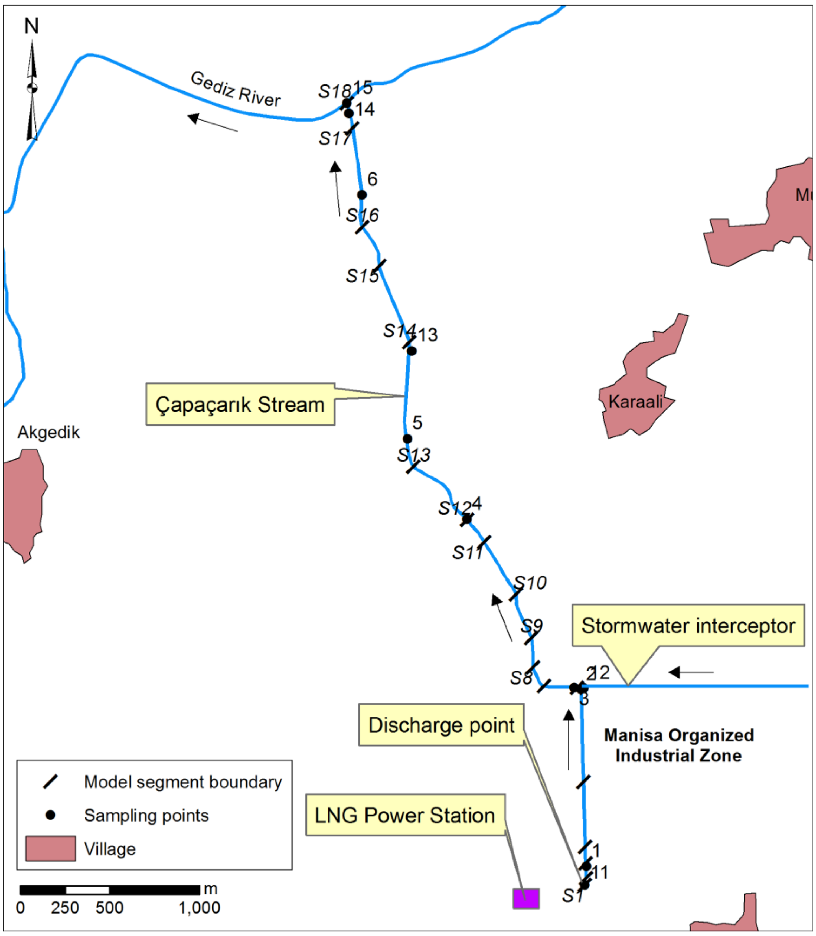

Figure 1. Map of water sampling and discharge rate measurement locations and model segment boundary markers. Water sampling and flowrate measurements were done simultaneously at sampling points 1-6, water sampling only at sampling points 11-15.

2 DATA ACQUISITION

2.1 *Cooling water discharge characterization*

Flow rate and temperature of the cooling water release was monitored during the entire period of the study, which occurred between 13.12.2010 – 15.07.2011 (214 days). Both were measured at the plant with automated devices. Measured data are shown in Figures 2 and 3. Water in the cooling tower was also continuously monitored for electrical conductivity (EC). Cooling water was released when EC exceeded the preset threshold of 1950 µS/cm, and release was stopped when EC fell below 1850 µS/cm. Due to this operational setup, the release of cooling water was intermittent. The release flowrate during the monitoring period of the study, ranged from 0 to 30 l/s with an average rate of 1.56 l/s. Release stopped also during periods of turbine and cooling tower maintenances. Average temperature of the released cooling water was 23.6 °C with a maximum and minimum of 35 °C and 10 °C, respectively.

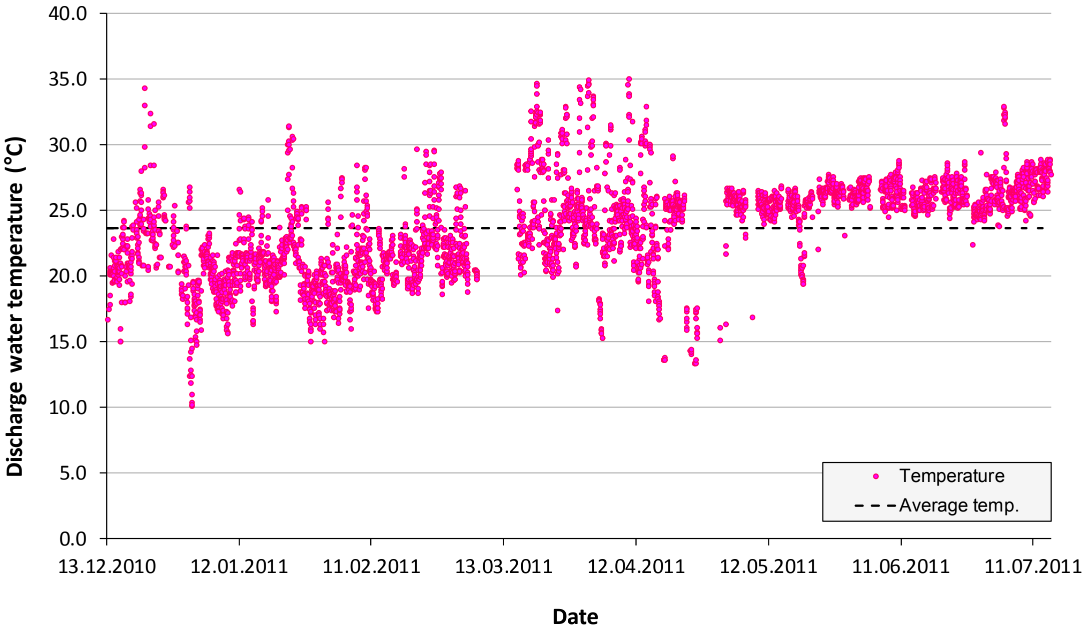

Figure 2. Temperature time series of cooling water discharge.

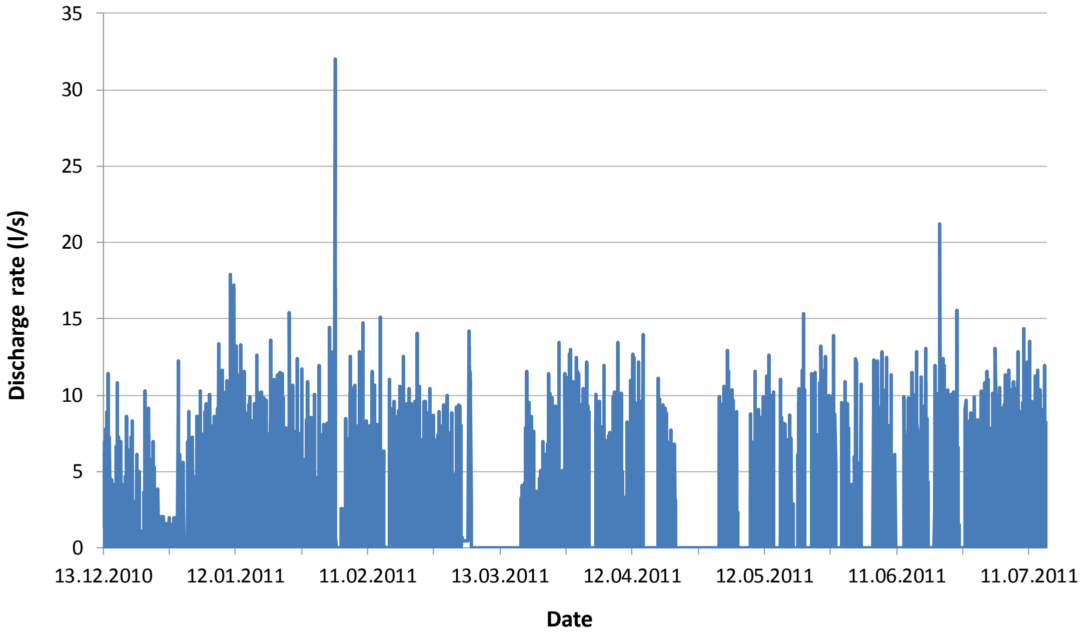

Figure 3. Release rate time series of cooling water discharge.

2.2 *Properties of receiving medium*

The receiving medium of the cooling water is the headwaters of Çapaçarık Stream, which merges with the Gediz river at the confluence point located about 4500 m north of the release location. Upstream segments of the stream are mostly improved and constructed as a trapezoidal cross-section concrete-built open channel. 1100 m downstream of the release point an interceptor channel merges with the receiving stream. Additionally, several outlets of stormwater drainage pipes are connected to the stream. These outlets contribute to the flow of the stream, in particular during rainy periods. However, their flow contribution can be considered as negligible during dry periods.

Previous records of data regarding the flow rate, water temperature and any other water quality constituents of the stream water did not exist. Therefore, field work was conducted to collect data that was necessary for the modeling. Stream discharge rates were measured with an acoustic Doppler velocimeter (ADV) at six transects of the stream. Water temperature, dissolved oxygen concentration and EC were determined on-site by collecting water samples at eleven monitoring points. Flow measurements and water sampling were done simultaneously at six of eleven monitoring points. Locations of monitoring points are shown in Fig.1.

Based on field measurement results, stream discharge could be observed during the entire study period. However, it is known that the stream is ephemeral of nature, therefore it is expected that discharge ceases late summer and during autumn. Minimum and peak discharge for the study period was 1.0 and 106.3 l/s, respectively. The mean discharge rate was recorded as 42.2 l/s. It must be noted that these discharge values are calculated for the entire length of the stream and that the discharge is very variable in the direction of flow. Temperature of stream water averaged 10.3 °C in January and 16.4 °C in May. EC and dissolved oxygen were measured as proxies for water quality. Average EC values of stream water vary between 1120-1678 μS/cm with an observed maximum of 2500 μS/cm. EC results appear to be independent of seasonal change. However, they are fluctuating with downstream distance. Similar observations apply for dissolved oxygen measurement results.

3 MODELING METHOD

3.1 *General approach*

The Water Analysis Simulation Program (WASP) was used to simulate stream temperature. WASP is a dynamic compartment modeling system that can be applied to a variety of water bodies (Ambrose et al. 1993). WASP assists users in interpreting and predicting water quality responses to natural and man-made pollution for various pollution management decisions. It permits the user to set up one, two or three-dimensional models, and allows the specification of time-variable advective flows, waste loads, exchange coefficients and water quality boundary conditions.

To evaluate the impacts of cooling water release on stream water temperature, the following approach was taken; firstly, the model was calibrated to observed stream discharge rate and water temperature data. After calibration of the model, simulations were run for scenarios representing the dry and rainy season of the year. Stream discharge rate and water temperature were calculated for a base case scenario, where there is no cooling water release, followed with an after-release scenario, where cooling water is released to the stream with a continuous release rate of 35 m^3/h. The latter scenario is basically a worst-case scenario that considers cooling water release at the highest rate possible.

The WASP model has several modules that are suitable for various modeling purposes. In this study, first the hydrodynamics (i.e. discharge rate) of the stream was determined by solving the kinematic wave equations. To determine stream water temperature, the HEAT module was implemented. Although the HEAT module allows simulation of five state variables, only water temperature was selected. The processes included in the total transformation rates for temperature are water surface and bottom sediment heat exchange. The latter process was ignored as the sediment-water column heat exchange is usually negligible compared to surface heat exchange. This assumption was tested and confirmed by running trial simulations.

Water surface heat exchange was calculated by use of equilibrium temperatures and coefficients of surface heat exchange. The governing equation for surface heat exchange is written as

$$\frac{\partial VT}{\partial t} = \frac{H_n A_s}{\rho C_p} \tag{1}$$

where V is volume, A_s surface area, T is temperature of water, t is time, ρ is density of water, C_p is its specific heat, and H_n is the net thermal energy flux. The net thermal energy flux includes the effects of a number of processes. It is the sum of incident short and long wave solar radiation, evaporative heat loss, heat conduction minus the sum of back radiation from the surface and reflected short and long wave radiation. The reader is referred to Wool et al. (2008) for further equations and coefficients used in the equilibrium temperature approach.

3.2 *Model parameters and structure*

In general, parameters that were either measured with a certain level of uncertainty or had no available data were adjusted in the calibration process of the model. The primary calibration parameter for the hydrodynamic model was the Manning friction coefficient. However, flow contributions coming from other sources such as stormwater pipe outlets along various locations along the stream and groundwater seepage from the underlying aquifer were also considered in the model. Since these flows could not be determined in the field, they were used as calibration parameters.

As for the heat transport model, temperatures of groundwater seepage and stormwater inflow were handled as calibration parameters. Other parameters used in the model were mean daily temperature, cloudiness, dew point temperature and wind velocity. Data from the nearest meteorological station were obtained and used in the model. Furthermore, the ambient background temperature of stream water was estimated from a regression equation that was written by fitting air temperature to the water temperature of the Gediz river. Here the assumption is that the cooling water release has no effect on the Gediz river water temperature because its discharge rate is much larger compared to the rate of the Çapaçarık stream.

The cooling water release point (at x = 0) and the confluence point with the Gediz river (at x=4910.9) constituted the boundaries of the model. The stream was divided into 17 model segments by considering changes in cross-section, bed slope and inflow from reaches and stormwater pipes. Model segmentation is shown in Fig. 1. Data from the first measurement campaign were used to determine initial conditions for the model.

4 RESULTS

4.1 *Model calibration results*

Before modeling the effects of cooling water release, it was ensured that the model adequately calculates all relevant processes by comparing measured and modeled discharge rate and stream water temperature. Calibration parameters were adjusted during calibration until a satisfactory fit was obtained between measured and modeled values. Fig. 4 and Fig.5 summarize calibration results for stream discharge rate and water temperature, respectively. Root mean squared errors (RMSE) after calibration of the model are shown in Table 1. RMSE values for discharge rate are 8 to 15 % of the observed range and the mean RMSE is 7.881 m^3/s. RMSE values for temperature are 9 to 16 % of the observed range and the mean RMSE is 1.8 °C. Based on these evaluations it can be concluded that calibration of the model can be considered as good. Discharge rate profiles were also consistent with field observations.

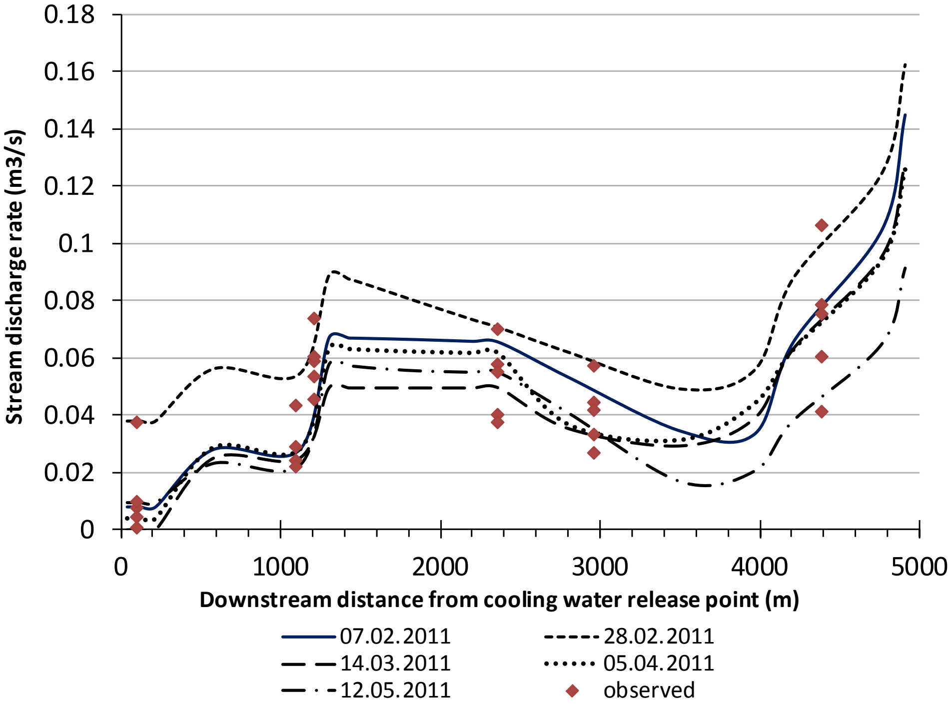

Figure 4. Comparison of simulated stream discharge rates to observed rates for the calibrated model.

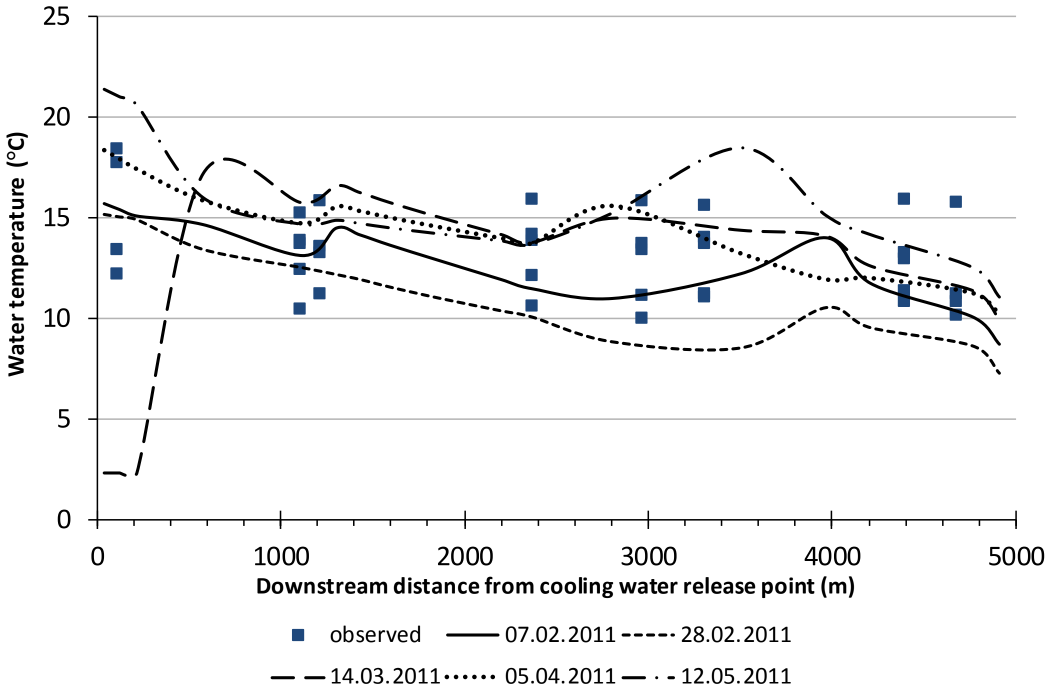

Figure 5. Comparison of simulated stream water temperature to observed temperatures for the calibrated model.

Table 1. RMSE values for stream discharge rate and water temperature for calibrated model

	Dates				
	07.02.2011	**28.02.2011**	**14.03.2011**	**05.04.2011**	**12.05.2011**
Discharge rate RMSE (m^3/s)	6.028	5.455	6.858	11.084	9.979
Temperature RMSE (°C)	1.6	2.0	2.1	1.3	1.8

4.2 *Water temperature modeling results*

The calibrated model was run for a base scenario and an after-release scenario to investigate the effects of cooling water release on the stream temperature profile. It was assumed for the after-release scenario that cooling water is released continuously at a rate of 35 m^3/h (9.72 l/s) thereby considering worst case conditions. Relevant meteorological data for dry and wet periods of the year were taken from long-term meteorological records and were used as model inputs.

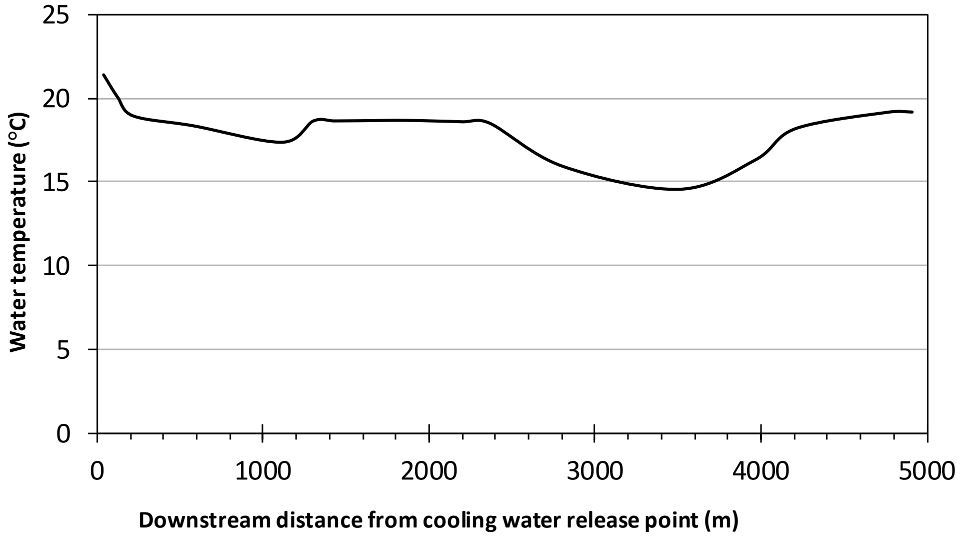

Figure 6. Simulated water temperature profile for after-release scenario (dry period).

Simulated water temperature profile of the after-release scenario for the dry period is shown in Fig. 6. Modeling results indicate that the warm water discharge is effective in the dry period up to 200 m downstream of the release location (Fig. 7). At the release point water temperature rises 8 °C. However, the simulated stream water temperature does not exceed 22 °C along the entire profile, thereby complying with regulations. The effect of cooling water release becomes significant about 600 m downstream of the release. The average water temperature change is 0.21 °C.

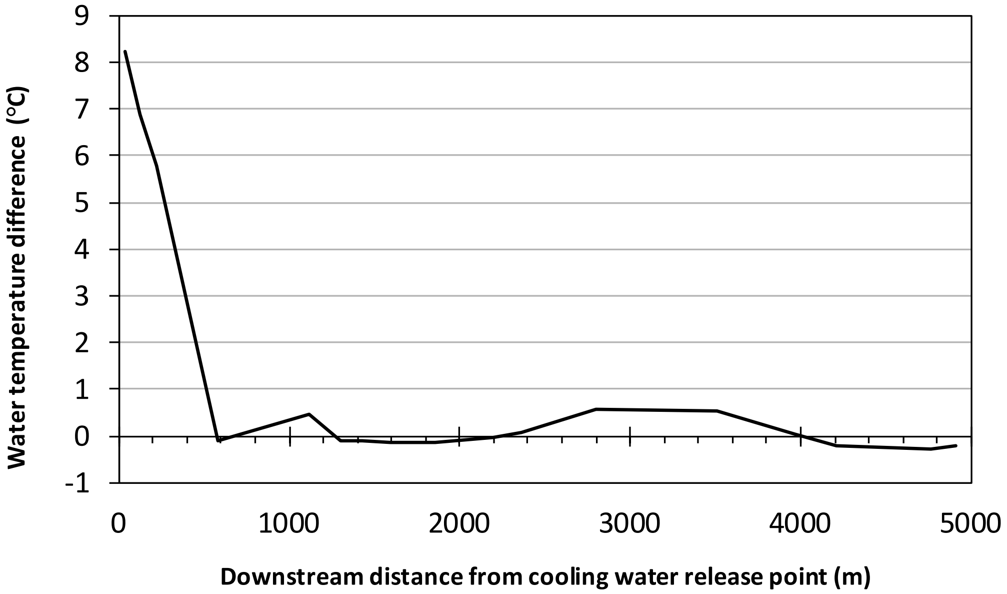

Figure 7. Change in water temperature after cooling water release occurs (dry period).

Modeling results for the wet period scenarios indicate a slightly worse outcome on stream water temperature. Simulated temperature profiles are shown in Figures 8 and 9. In this case, water temperature rises up to 19 °C at the release point (Fig. 9). Similar to dry period model scenario results, the impact of cooling water release diminishes after about 600 m downstream of the release. The average water temperature change is 0.51 °C.

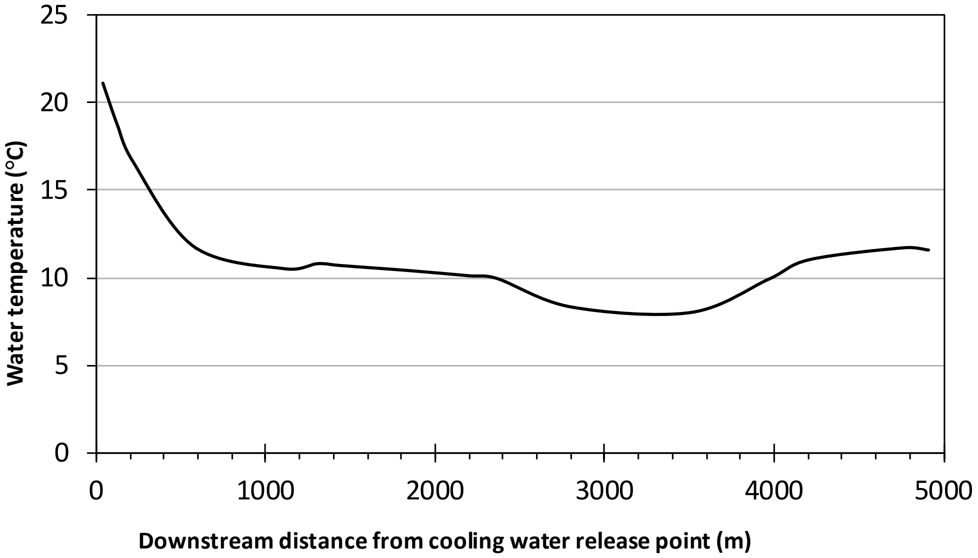

Figure 8. Simulated water temperature profile for after-release scenario (wet period).

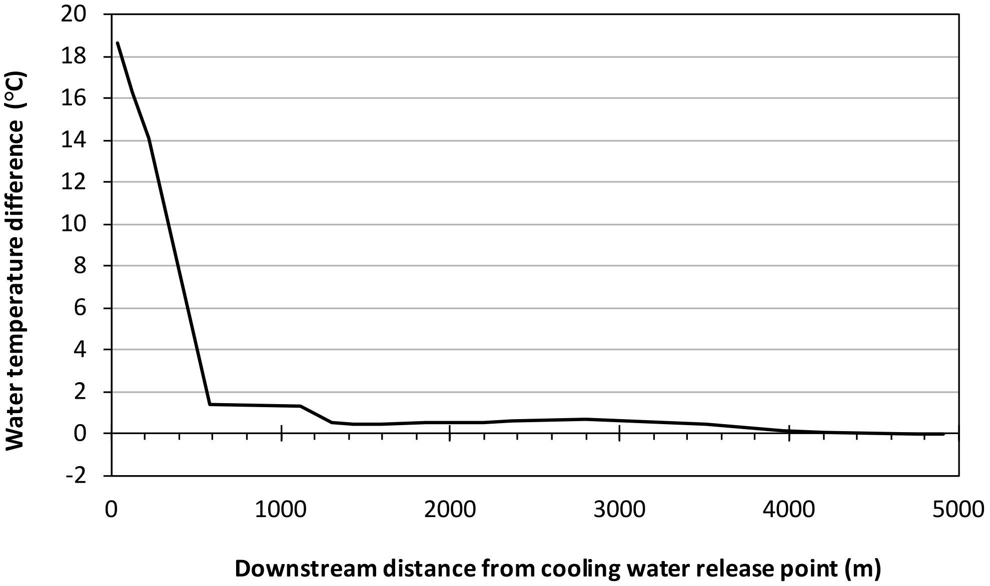

Figure 9. Change in water temperature after cooling water release occurs (wet period).

5 CONCLUSIONS

The heat transport modeling results reveal that in terms of stream water temperature even a continuous release of cooling water to the Çapaçarık stream impacts only the first 600 m of the stream. It is shown also that the impact gradually diminishes with downstream distance and becomes negligible. Following this it can be also concluded that the Gediz river as the ultimate downstream receptor is not affected by the release. An interesting aspect of the study is that unmonitored flow contributions such as groundwater seepage and stormwater inflow are effective in flow fluctuations that were observed during measurement campaigns. It is important to note that the inclusion of these flow contributions complicated the modeling process, in particular the calibration. This can in fact pose serious problems in other studies where the hydrology of the system is more complex. Additional field measurements and data would be required to more accurately include unknown flow contributions in the modeling. Development of novel scientific approaches that can handle unknown model parameters is highly recommended.

NOTATION

ρ	density of water
C_p	specific heat
H_n	net thermal energy flux
A_s	surface area
V	volume
t	time

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