Model based analysis of effectiveness of the engineering solutions designed to increase cooling capacity of Tashlyk water reservoir of South-Ukrainian Nuclear Power Plant

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Three-dimensional numerical hydrothermodynamical model THREETOX was used to calculate the thermal regime of the cooling pond of the South-Ukrainian NPP under adverse weather conditions. The reliability of simulation results confirmed the coincidence of the calculated values of water temperature in the reservoir and measurements. It is shown that the calculation of the thermal regime of the cooling pond can be performed using both preassigned and forecasted weather conditions. Modeling of the hydrothermodynamics of the cooling pond for different engineering solutions allowed to choose the most effective solutions to increase its cooling capacity.

Keywords: numerical modelling, cooling pond, hydrothermodynamic.

Introduction

Tashlyk Reservoir (TR), which surface area is at 7.28 km^2 and volume at 73 300 000 m^3 is an artificial water body constructed in the valley at South Boog River as a Cooling Pond (CP) of the South-Ukrainian Nuclear Power Plant (SU NPP). Initially CP included whole Tashluk reservoir, however later the dike was constructed to cut neighboring to South Boog River part of TR as a water storage for the Hydro Pumped Storage Power Plant (HPSPP). The bottom water intake in the central part of the CP pumping water that is transported for the cooling of 3 reactors of VVER type and then the hot water is discharged from the channel at central part of the east coast of CP. In summer when air temperature at SUNPP area is at 30ºC the water temperature at the bottom intake can be higher then the threshold value of 33ºC. The exceeding of this threshold temperature means that the water can not be used for the reactor's cooling and before water temperature reaches this value one of the reactor should be shut down to diminish the amount of the hot water discharged into the CP. Such situation each year in summer months decreases the NPP's energy production. The shut down periods could be longer after planning increasing of the volume of Hydro Pump Storage by the construction of new dam in Tashlyk Reservoir that will decrease the volume of the cooling pond. The goal of the study was the model based analyses of the thermohydrodynamics of CP and temperature at the bottom water intake in dependence of the different engineering reconstructions of Tashklyk reservoir to provide the recommendation on the choice of the most effective project for better water cooling in the Cooling pond.

In this paper the impact of the project and other possible technical solutions to the hydro-thermal regimes of the cooling pond of SU NPP is predicted by using modeling techniques.

Prediction of the thermal regime of the cooling pond is only possible when certain meteorological conditions are set down. For this purpose one can use the predifined meteorological conditions as well as the conditions obtained from the Numerical Weather Prediction (NWP) models. In the first case we obtain a state of the cooling pond under the specific meteorological conditions (for example for extremely hot summer or for the average summer). In the second case we obtain the actual state and its forecast for the next few days. In this paper we present both cases.

THREETOX model

THREETOX has been developed in 90-th as 3D modeling system, coupling the models of hydrothermodynamics and radionuclide transport (Margvelashvili et. al. 1997). THREETOX describes the motion of an incompressible fluid by a system of Reynolds-averaged equations of motion and continuity under the Boussinesq and hydrostatic approximations. The system also includes the heat transfer equation and the equation of state, describing the dependence of the density of water on its temperature and pressure. The system of equations is closed by the equations of the k-ε turbulence model which describes the coefficients of vertical turbulent viscosity and diffusion. The coefficients of horizontal viscosity and diffusion are determined by the formula of Smagorinsky. Also, the model includes the boundary conditions for each variable on the surface and at the bottom of the reservoir, as well as at the solid and open boundaries, which are necessary for the uniqueness of the solution. From the begining of 2000th the model were modified for more accurate description of the thermal processes in water bodies (Koshebutsky et. al. 2004, Maderich et.al. 2008, Bezhenar and Maderich 2008).

Correct description of heat fluxes in the atmosphere – water – bottom system are very important for simulation of the thermal regime. Modern approaches are used in THREETOX to describe those flows. Moreover, there is a choice of parameterization of the heat flux through the surface of the reservoir, depending on environmental conditions. As it will be shown in this study a special microclimate is formed over cooling ponds. So if we will use parameterization of heat fluxes adopted for natural rivers or lakes, we obtain much underestimated temperature in comparison with observations. The total heat flux through the surface of the reservoir, which was used to simulate the thermal regime of the SU NPP cooling pond consist of the following components: the flux of solar radiation (Zillmann 1972), which is absorbed by the surface, the balance of longwave radiation (Zapadka et. al. 2001), as well as the turbulent heat flux and heat losses by evaporation (Rosati and Miyakoda 1988). Also, the model takes into account the absorption of light by water according to the law of Lambert-Beer: $I(z) = I_0 e^{-K_d z}$ where I_0 is the part of the flux of solar radiation which has passed through the surface; K_d - coefficient of vertical attenuation of light in water. For a correct description of the heat exchange between water and the bottom, the temperature of the bottom surface is to be known. For this purpose the model solves heat equation in sediments (Bezhenar and Maderich 2008).

WRF-Ukraine – meteorological driver for THREETOX simulations

THREETOX was connected with numerical weather forecasting of three-dimensional mesoscale meteorological model WRF (Skamarock et. al. 2008) adapted to the territory of Ukraine (Guziy et. al. 2008) WRF-Ukraine. WRF model numerically solves the complete system of equations of hydrothermodynamics of the atmosphere, including the continuity equation, conservation of momentum, moisture transport and energy. The user model offers a library of different parametrizations of turbulent heat and mass transfer in the atmospheric boundary layer, transport of short-and long-wave radiation in the atmosphere, as well as submodels describing the formation processes of clouds and precipitation.

The WRF-Ukraine system uses two nested domains. A large domain has a size of 37 by 37 nodes with horizontal grid resolution of 81 km, the second domain has a size of 73 by 73 nodes with a horizontal resolution of 27 km. Both domains fully cover the territory of

Ukraine. Nevertheless, the results obtained in the first domain has a low predictive accuracy, and they are used only to improve boundary conditions in the second domain. The system uses 31 σ levels in the vertical, which correspond to the geometric heights from 30 meters above the ground up to about 15 km above sea level.

The initial and boundary conditions are specified using data of operational weather forecasts of the GFS model operated by the National Center for Atmospheric Prediction (NCEP, USA), presented on NOMADS servers (Rutledge et. al. 2006). Those forecasts are calculated with a horizontal spatial resolution of 1 degree. The maximum leading time of the forecast is 168 hours. The bottom boundary conditions depend on the following properties of the underlying surface: the height above sea level, land-use category (forest, water, etc.), vegetation type, soil type. The corresponding data are available at WRF model site and are based on data of the US Geological Service.

The model was tested for the extremely hot period starting from July 1 to August 8. The calculated atmospheric temperatures were compared with corresponding measurements of the weather station of SU NPP (Fig. 1). The quality of the forecast for the whole period is evaluated by comparing each measurement with the forecast which starting date is by 48 hours ahead of measurement time. Standard deviation of the calculated and measured values of temperature was 2.4°C, and the average absolute error was 1.8 °C.

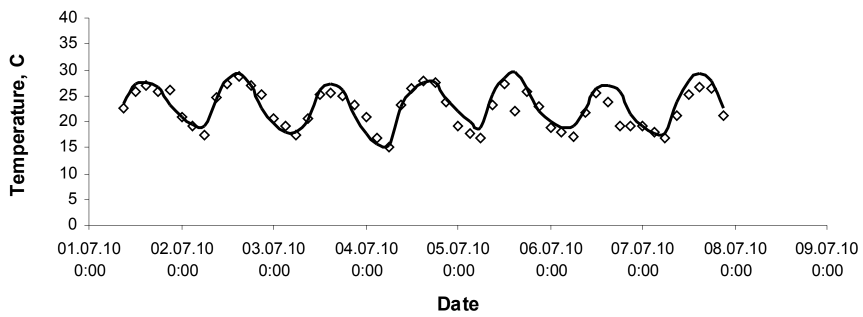

Fig. 1. Comparison of the 2 m atmospheric temperatures forecasted by WRF-Ukraine model (line) and measured at the weather station of SU NPP (points).

Model testing

The depths of the cooling pond had been measured (Fig. 2) to provide THREETOX with bottom topography. The coordinate system used by THREETOX is curvilinear orthogonal in horizontal plain (Fig. 3), and in vertical direction $\sigma - z$ coordinate system is used. This allows to describe the fluctuations of the free surface and to avoid numerical errors in regions of large slopes of the bottom. The horizontal resolution of the constructed grid varied from 50 m near the power plant up to 250 meters in remote areas. The total length of the cooling pond is 8 km, its average width is 1 km, its maximum depth is 40 m. The special feature of the cooling pond is a small distance between the position of effluence of the hot water from the cooling system of the power plat stations and deep water intake (Fig. 2).

Calculation was performed using real flow rates and water temperature at the station, flow rate to the Boog River and inflow rate from gully Tashlik. Also, the weather station of

SU NPP provided meteorological conditions for the August-September 2007. We used a considerable spin-up period associated with the need to reduce the effect of unknown initial conditions on the simulation results.

To test the THREETOX model during September 12, 2007 survey was carried out and water temperatures in the pond were measured. The simulation results showed good agreement with measurements (Fig. 4). Comparison was carried out in 52 points, and at each point the temperature was compared at different depths. The average deviation of calculated values from the measured temperatures was 0.1°C, the standard deviation was 0.75°C.

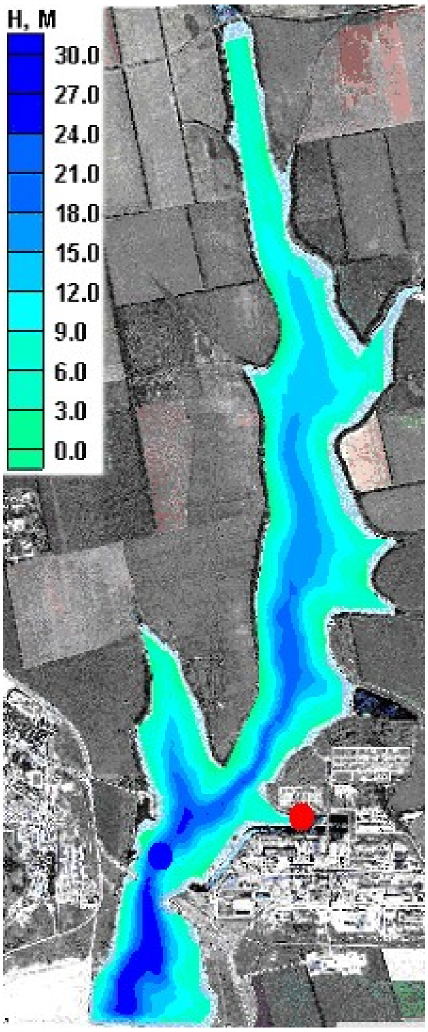

Fig. 2. Topography of the cooling pond of SU NPP. Effluence of hot water is marked with a red circle, and blue is a deep water bottom intake.

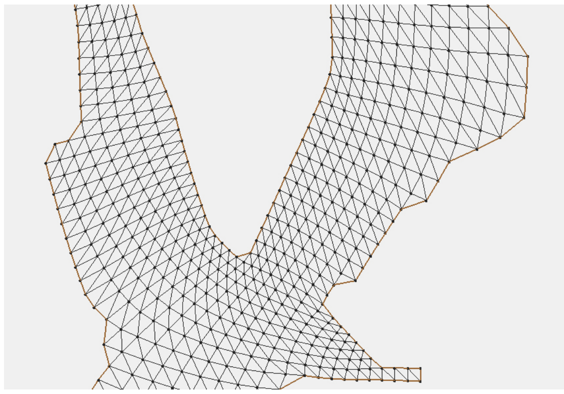

Fig. 3. Part of the computational grid

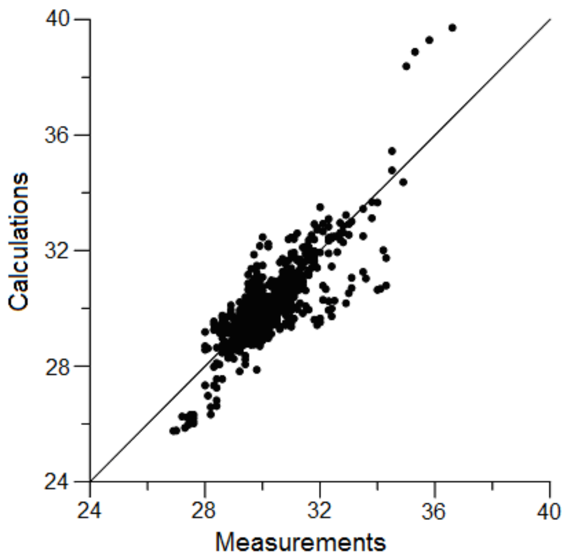

Fig. 4. Correlation of measurements and calculations on 09/12/2007

In other case the comparison of modeled water temperature at the surface of CP and satelite image was made for model testing. The satelite image (Fig. 5) corresponds for 21st of April 2001. Real meteorological data for April 2001 provided by Yuzhnoukrainsk weather station were used for mathematical modeling of thermohydrodynamic conditions of CP. Obtained surface temperature for 21st of April 2001 is presented on fig. 6. It is complicated to make a quantitative comparison but in workmanlike manner two temperature fields are similar.

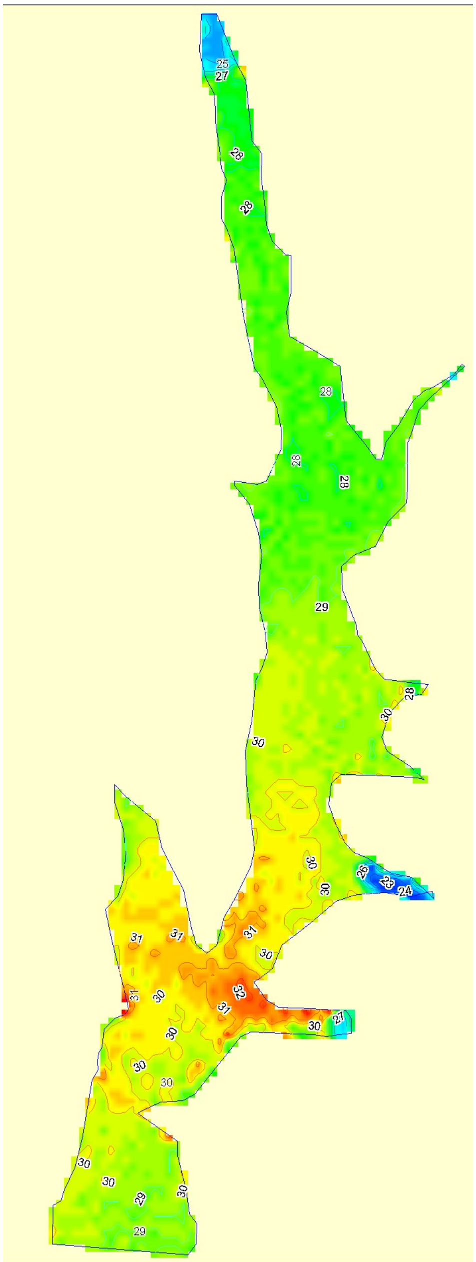

Fig. 5. Results of satelite image processing

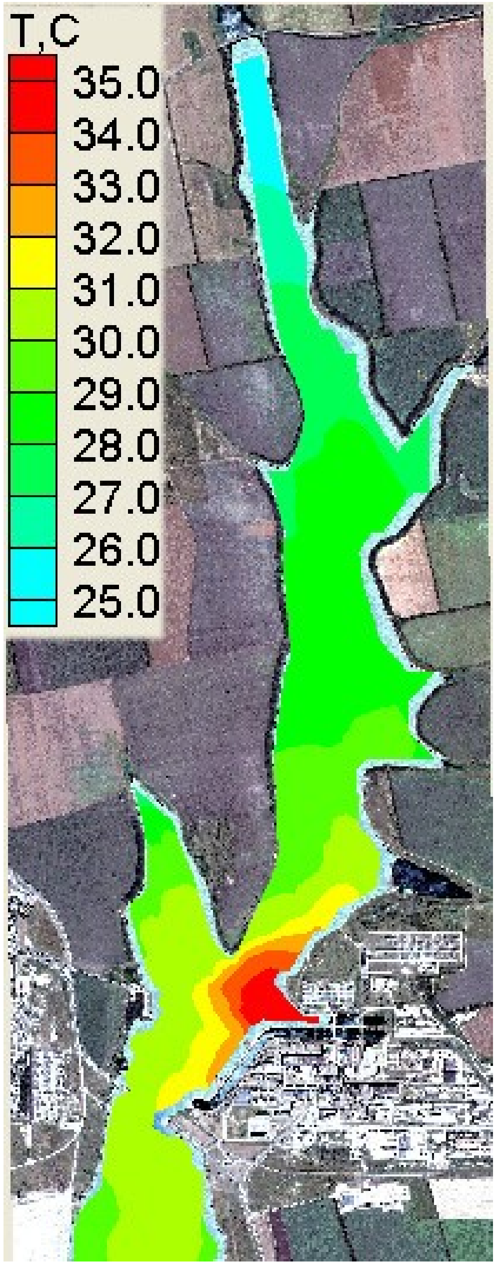

Fig. 6. Modeled surface temperature

Calculation of thermal conditions in the cooling pond for different engineering solutions proposed to increase its cooling capacity

Currently SU NPP cannot operate at full capacity during summer, since the current limit on the temperature of water used for cooling reactors is violated (T<33˚C). Simulation show that in case of the station working at full capacity during average summer, the average temperature of water at water intake is 36.9˚C, which is about 4 degrees above the limit. The distribution of surface temperature for this case is shown in Fig. 7. The periodic meteorological conditions have been used in this and in other cases: the temperature had been variable during the day an average value of 22.4˚C, the wind speed had been equal to 4.1 m/s and had variable direction, the cloudness and relative humidity had been constant and equal to 0.49 and 0.62 while the air pressure had been equal to 0.1 MPa. The water flow from Tashlyk had been constant with the values of water discharge 0.005 m^3/s and temperature 24 °C. The corresponding values of the recharge flow were 1.96 m^3/s and 24°C while the value of flow rate to the Boog River was 0.33 m^3/s. Consumption of water required for cooling of the station while working at full capacity is 155 m^3/s. Under such conditions water is heated up to 9°C.

In case of cutting off the part of the cooling pond for the needs of HPSPS the calculated water temperature at the point of water intake of NPP was 39.1°C. The distribution of surface temperature for this case is shown in Fig. 8. The task was to find solutions that would lead to a lowering of water temperature at water intake down to at least 6°C.

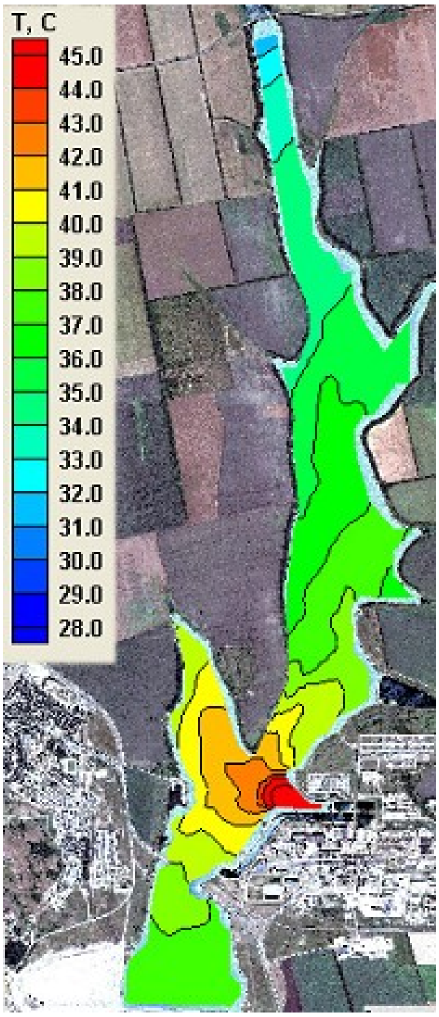

Fig. 7. The distribution of surface temperature during work of 3 units of SU NPP with full capacity at the existing configuration of the cooling pond

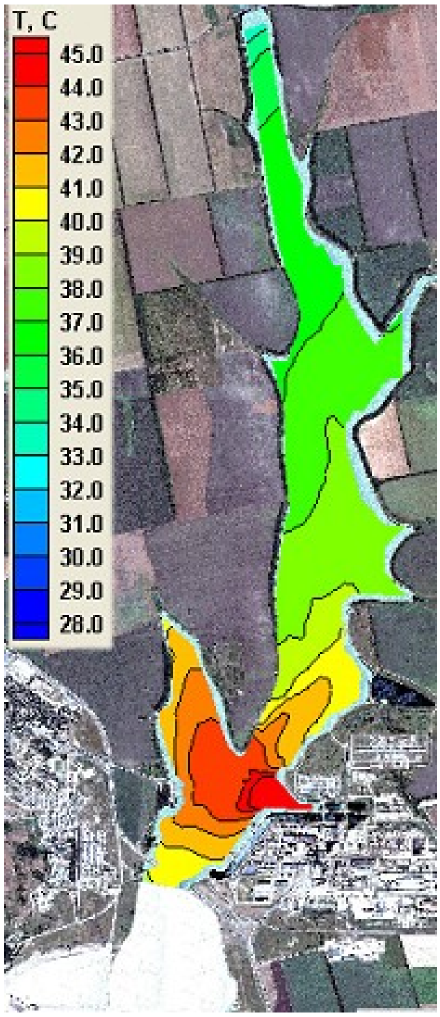

Fig. 8. The distribution of surface temperature during the work of 3 units of SU NPP to full capacity after the construction of the dam for the needs of HPSPS

One of the solutions that increase the cooling capacity of the cooling pond is the use of spray ponds. According to the draft plan the construction of spray ponds is planned approximately 2.2 km north from water discharge of cooling station. Cooling of water in the spray pond was calculated by the method of "Energoprojekt" [10]. In total 5 spray ponds were considered with a total water consumption of 79.5 m^3/s. The results of calculations had shown that for this configuration of the system water temperature at the water intake station was

32.6°C. Fig. 9 shows the distribution of surface temperature for this case. But it should be clear that small errors in the method of calculation of the cooling of water by the spray ponds or decrease in wind speed, which is one of the main parameters of their cooling capacity, can lead to an increase in temperature in the cooling pond. This in turn may lead to rising of the water temperature at the water intake station above 33°C. Therefore it is desirable to achieve some reserve cooling capacity of the cooling pond. Therefore a further 2 options were considered which will lead to redistribution of circulation in the cooling pond and to a lowering of water temperature at water intake station. In the first case a bypass channel on the opposite bank of the cooling pond (as compared to the location of the spray ponds) was considered. The second option was the construction of training dike along the Eastern coat of CP. In both cases the aim was to direct the heated cooling water to the northern part of the reservoir, where it is rapidly cooled by heat exchange with the atmosphere. The distribution of surface temperature for these cases is shown on Figures 10 and 11.

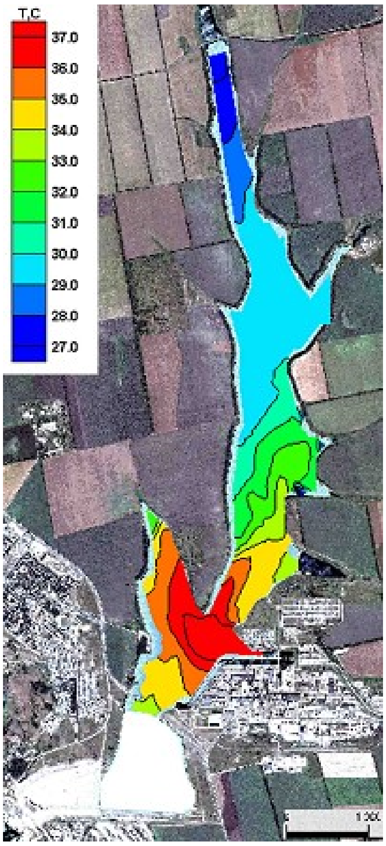

Fig. 9. The distribution of surface temperature for the same configuration as in Fig. 8, but with the existing spray pond

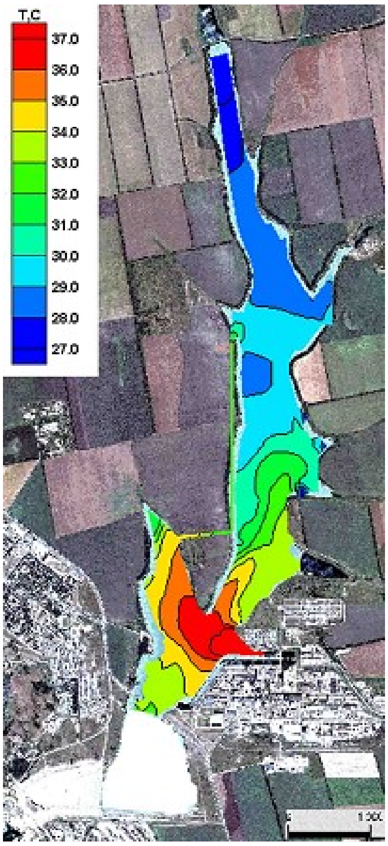

Fig. 10. The distribution of surface temperature for the same configuration as in Fig. 9, but with a bypass channel

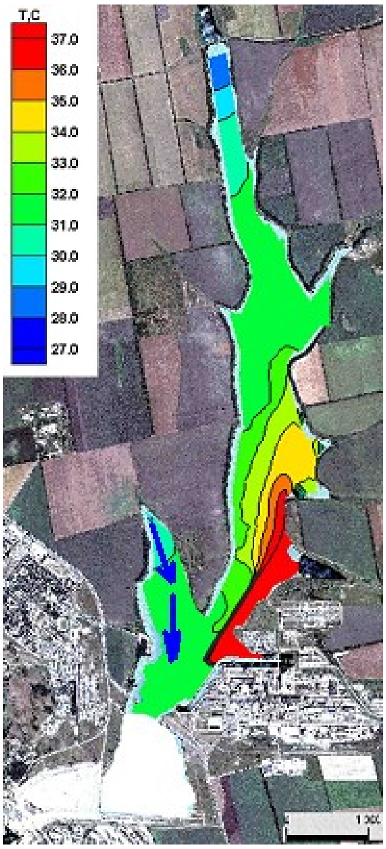

Fig. 11. The distribution of surface temperature for the same configuration as in Fig. 9, but with training dike

Simulation results showed that the configuration of training dike (the temperature at the water intake station was 31.1°C) is more effective than a bypass channel (the temperature at the water intake station was 31.8°C). This is due to the fact that water heated by the cooling system is sent directly to the water intake point of the spray ponds, which increases their cooling capacity. In addition, much of the heated water enters the shallow northern part of the cooling pond, where it quickly cools. Cooled water flows along the bottom of the reservoir into the deep part and it does not influence the temperature of water at the water intake. The importance of the shallow part of the cooling pond in water cooling can be seen in Fig. 10, which shows a three-layer circulation in the cooling pond. Reproduction of this circulation is possible only with the help of three-dimensional modeling. In the case of training dike another source of cooled water is formed, which is located in shallow bay against the place of discharge of the hot water. But it is much closer to the deep water intake than the northern shallow part of the cooling pond, and therefore it determines the temperature at water intake. The arrows in Fig. 12 show the movement of cooled water at the bottom of the cooling pond.

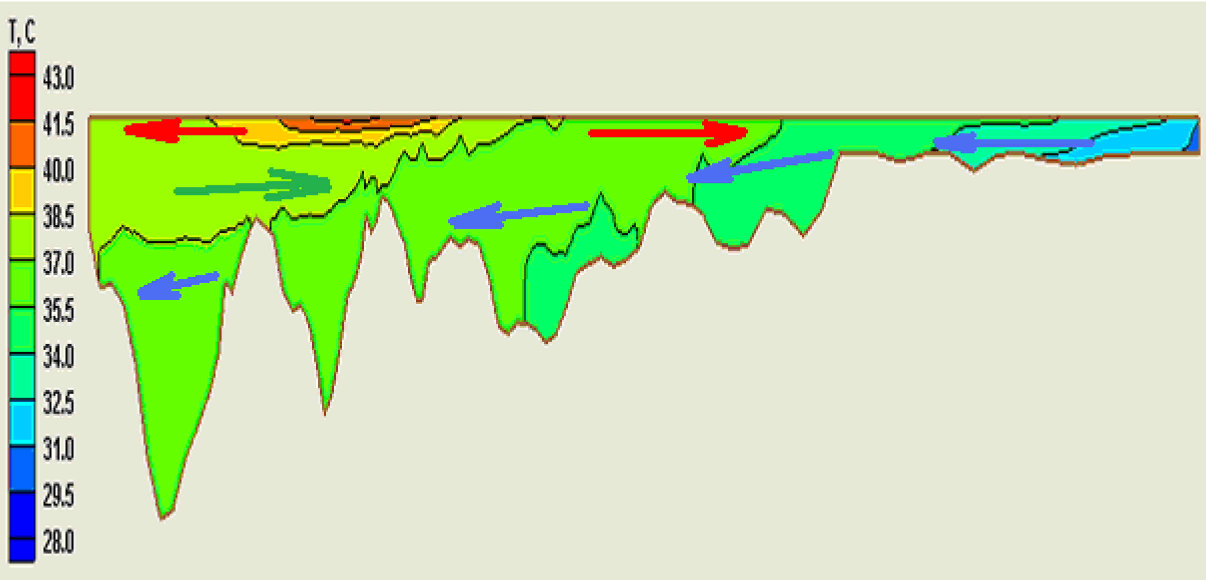

Fig. 12. The circulation in the vertical section of the cooling pond in the direction from south to north. The red arrows show the flow of warm water, blue - return flow of cooled water. Green - the water flow at the intermediate level.

Simulations show that the training dike effectively improves treatment of the cooling pond, even without the use of spray ponds and the bypass channel, only through the redirection of flows of warm water in the shallow northern part. Currently, the cooling capacity of the cooling pond of SU NPP is not even enough for 2 units at full capacity during the summer. Heating of the water by the cooling system of the station is by 8°C at a flow rate of water 104 m^3/s. This allows not to violate the restriction on the temperature of water at water stations, which is equal to 33.0°C. The distribution of surface temperature for this case is shown in Fig. 13.

Construction of training dike allows to use two units at full capacity with the existing configuration of the cooling pond. In this case, the temperature of at water intake will be 31.5°C, suggesting that there is sufficient reserve cooling capacity of the cooling pond required for the work of energy generating units at extremely high air temperatures.

In the case of construction of the dam training dike will preserve the existing mode of operation of the two units at a reduced size of the cooling pond. The distribution of surface temperatures for the cases with training dike with the existing configuration of the cooling pond and with the construction of the dam is shown in Figures 14 and 15.

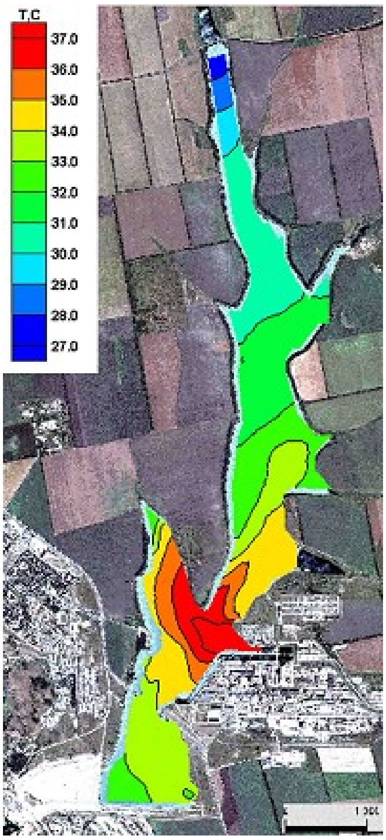

Fig. 13. The distribution of surface temperature when working with 2 units of SU NPP (water heating is by 8°C) with the existing configuration of the cooling pond

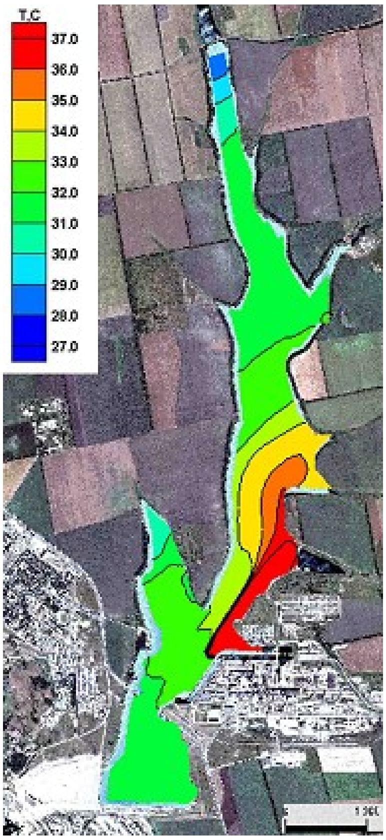

Fig. 14. The distribution of surface temperature when working with 2 units of SU NPP units at full power (water heating is by 9°C) with the existing configuration of the cooling pond and construction of the training dike.

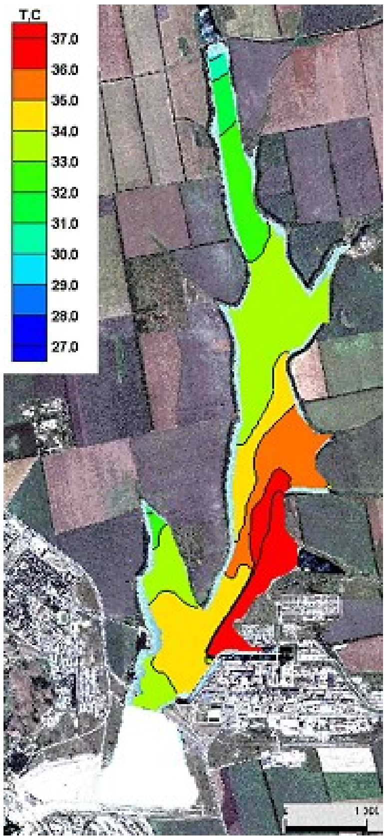

Fig. 15. The distribution of surface temperature when working with 2 units of SU NPP units at full power (water heating is by 8°C) with the existing configuration of the cooling pond and construction of the dam for HPSPS and training dike.

Conclusions

The hydrothermodynamic model of cooling pond of SU NPP is created. The results of calculations agree well with the corresponding measurements of water temperature in the pond. The analysis of the effectiveness of engineering solutions to increase the cooling capacity of the cooling pond was performed.

It is shown that the most efficient diminishing of the temperatute near deep water intake can be achieved under the construction of training dike. If the dam for the needs of hydroelectric is constructed then for the operation of 3 energy generating units spray ponds must be used.

The possibility of creating of the on-line prediction system of the temperature regime of the cooling pond is shown which consists of a numerical weather prediction model WRF and 3-D hydrothermodynamic model of the cooling pond.

Figures

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