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ABSTRACT

While solving practical problems concerning thermal pollution spreading in rivers we usually deal with limited data. At the same time we are interested in evaluating the increase of water temperature accurately enough to assess the anticipated threats to the environment. We face the problem of what level of accuracy is acceptable and which processes influencing the change of water temperature in rivers need to be taken into account. This problem, with a special emphasis on heat exchange between water and atmosphere in practical applications in the mid-field zone, which is crucial for the environmental impact assessment, constitute the main subject of the present study.

KEY WORDS: thermal pollution, heat exchange, heat budget, heat transport, water temperature, RivMix model.

INTRODUCTION

Heat transport in rivers in general case should be described by three-dimensional (3D) differential equation (see e.g. Szymkiewicz, 2010). But solution of such equation requires huge amount of data that are usually difficult to obtain. The computational costs of the solution of such 3D equation are also very high, so different simplifications are considered in practice. The most obvious simplifications pertain to the reduction of the problem to two (2D) or even one dimension (1D). In rivers we can distinguish three characteristic mixing zones (Kalinowska and Rowiński, 2015): a near field zone – starting at the discharge point and continuing to the point of complete vertical mixing; a mid field zone – stretching down the river until complete lateral mixing occurs and a far field zone – starting after the complete mixing along the depth and width of the channel. Mixing in each zone may be described, respectively in three-, two-, and one-dimension. While the mixing along the depth is relatively fast, the mixing along the width may take long distance, so the mid field zone is crucial from the environmental point of view in thermal pollution spreading modelling. The equation describing the process in the 2D case (in the mid field zone) is obtained by the averaging of the 3D equation along the depth (see e.g.: Kalinowska and Rowiński, 2008; Rutherford, 1994; Szymkiewicz, 2010). Additional simplifications of heat transport equation are related to the particular terms of the equation that have to be estimated i.e.: the dispersion tensor components (see: Rowiński and Kalinowska, 2006) and the sources function describing additional heating or cooling processes. The decision which of processes should be included in the model to be accurate enough in particular case is not easy. One may obviously try to include all known processes (like e.g.: heat exchange with the atmosphere, bed, banks, sediment, groundwater and rainfall or heat production from biological and chemical processes, etc.) but it is feasible only if enough data are available and they are sufficiently accurate. In practical applications, however, such convenient situation does not occur too often. Contrary to scientific applications, when the data are measured and experiments are prepared specially for the particular case, in practical applications we usually have only historical and incomplete data at our disposal. At the same time the description of the heat exchange processes between river and surrounding is usually very complex and depend on many local and temporal factors. Therefore it is difficult to assess them reliably. While most of additional processes are usually neglected in the mid field zone, the inclusion of heat exchange between water and atmosphere, which is the most significant comparing to the others, is a subject of discussion. That process is included in some 2D models since usually users expect it. The role of heat exchange between water and atmosphere in models of thermal pollution spreading in rivers in the mid field zone will be then the subject of the presented study.

HEAT EXCHANGE BETWEEN WATER AND ATMOSPHERE

The heat exchange between water and atmosphere is the most significant compared to other processes concerning the heat exchange between the river and its environment (see e.g.: Evans et al. 1998; Webb and Zhang 1999). The net heat flux results from the energy balance at the water-air interface, and it includes several terms like: short-wave solar radiation, long-wave atmospheric radiation, long-wave water back radiation, evaporation and condensation, conduction and convection. These terms may be calculated based on water temperature and meteorological data such as: wind speed, air temperature, cloud cover, bathymetric pressure, solar radiation, humidity and emissivity of water. Different more or less complicated formulae that can be used to compute particular terms are available in literature. Fig. 1 presents the values of calculated heat flux terms for exemplary case. But choosing the type of formula is not simple. For example, long-wave atmospheric radiation is proportional to the fourth power of the air temperature and it depends on the atmospheric emissivity, for which many formulae: empirically (e.g. Brunt, 1932) or physically based (e.g. Brutsaert, 1975) have been obtained. All of them may give different values for the final long-wave atmospheric radiation heat flux (see Fig. 2). Additionally they may be corrected by the cloud cover factor (see e.g.: Flerchinger et al. 2009) which makes the calculation even harder. However the study performed by Abramowitz and Ajami (2012) shows that such factor may be redundant since it does not really improve the results. They also

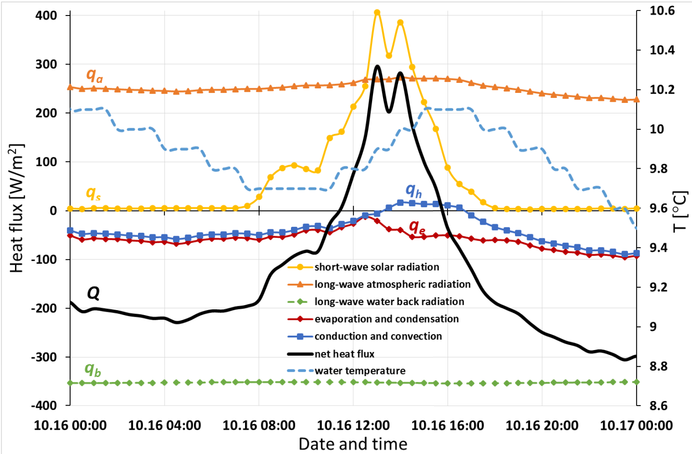


Fig. 1 Heat flux terms calculated for the Narew River case study on 16th of October 2013 (see details in Rajwa et al., 2014 and Rajwa-Kuligiewicz et al., 2015). The meteorological data used for calculation have been obtained from the nearest meteorological station: Narew National Park Weather Station (http://meteo.npn.pl/).

proposed a new formula which clearly differs from the other (see Fig. 2). Some authors also suggest to take into account additional information like e.g. elevation or greenhouse gases. The long-wave atmospheric radiation heat flux may also be measured directly, but while the measurements of short-wave solar radiation are easily accessible from many meteorological stations, the measurements of long-wave atmospheric radiation are rare. In case of experiment conducted in the Narew River, we have found the nearest weather station with long-wave atmospheric radiation measurements about 160 km away from the case study area. Of course recalculation of heat flux terms with the meteorological data from this far away station gives different results comparing to those obtained with the data from the nearest meteorological station. Note the difference between Figs. 2a and 2b for long-wave atmospheric radiation for different atmospheric emissivity formulae and measured value of heat flux in Fig. 2b.

In case of the long-wave water back radiation term, the only question is about the water emissivity coefficient. This coefficient depends on water surface smoothness and transparency. Usually it is set to 0.97 (e.g. Chapra, 2008), but in literature the values between 0.9-0.99 may be found.

Although the long-wave water back radiation is easy to calculate we encounter the problem how to calculate the evaporation and condensation terms. It is especially not clear how the so-called wind speed function should look like. There are many formulae available in literature for lakes and reservoirs, but unfortunately it is difficult to find such formulae for rivers. Therefore in practical applications formulae designed for lakes are usually adopted to rivers. In Fig. 3 the evaporation heat flux term computed with use of a selected wind speed function is shown. Note that one of the presented formulae assume that evaporation does not occur in absence of wind. The difference in results are clearly visible and the highest difference that may be noticed is almost 100 W/m². We will face the same problem with the wind speed function computing the conduction and convention term.

Finally, the calculation of each heat flux term increases the uncertainty of the final outcome. Additionally it is necessary to note the serious

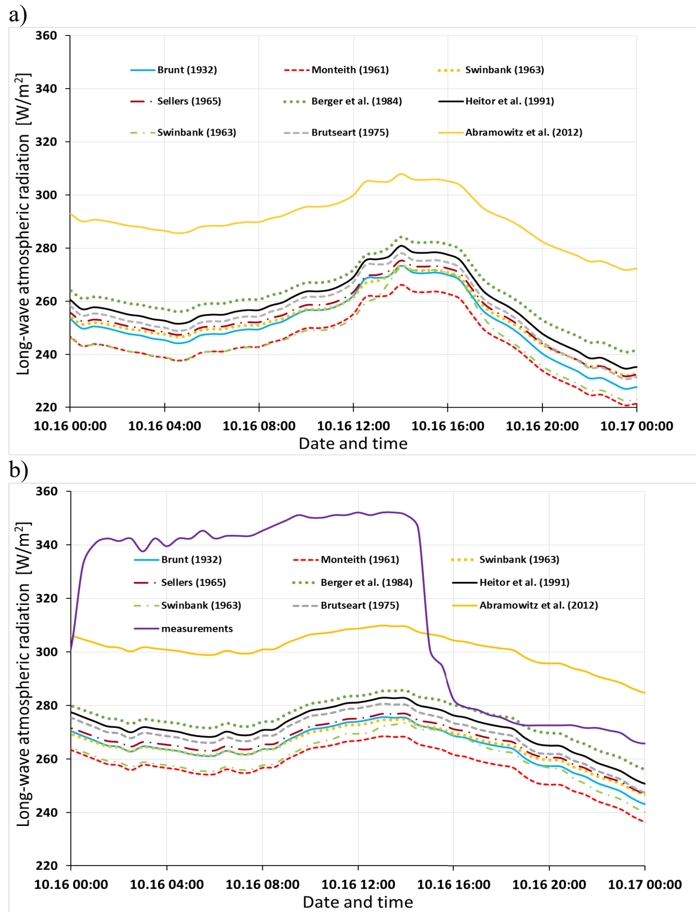


Fig. 2 Long-wave atmospheric radiation heat flux for case study on the Narew River on 16th of October 2013 with different formula for atmospheric emissivity. The meteorological data used for calculation have been obtained from a) Narew National Park Weather Station; b) IGF UW Meteorological observatory (http://metobs.igf.fuw.edu.pl/); 2 and 160 km from the case study area respectively.

input data problem occurring in practical applications. As mentioned before the data are often taken from the nearest meteorological and hydrological stations, eventually located far away from the study area, where the conditions may be totally different. But even the stations located closely to the study area do not guarantee accurate data. For example the wind velocity should be measured at a specific height above water surface (usually 2 meters) depending on the selected wind speed formula. Data obtained from the nearest weather station (the wind gauges are often located on the hill) may not represent the condition in the vicinity of the river. In addition, the conditions can vary along the river reach and this factor is practically not considered in calculations. For example Johnson (2004) preceded experiment and measured the heat fluxes in the full sun and under the shade at the same time in the same stream. The results show that final sum of heat fluxes was 580 W/m² towards the stream in full sun and 149 W/m² away from the stream under the shade. So the results differ significantly. There are some works that try to include such factor but then we require additional, hard to measure input parameters. So proper computation of the net heat flux is not easy, and one should bear in mind that inaccurate calculations of heat flux terms may introduce larger error in the final results than their omission.

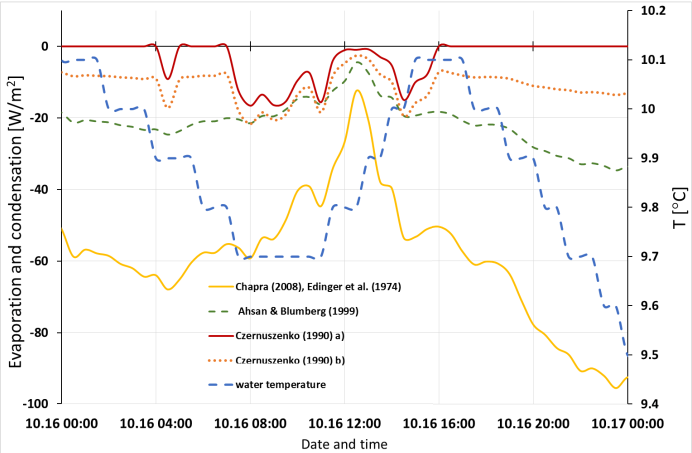


Fig. 3 Evaporation and condensation heat flux for the Narew River case study calculated based on different formulae for the wind speed function.

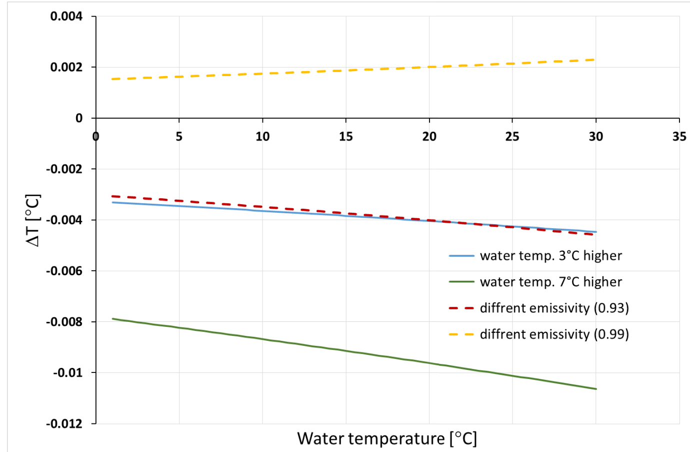


Fig. 4 Difference in temperature change caused by long-wave back water radiation when the water temperate is 3 or 7°C higher than natural water temperature (solid lines) or when different water emissivity coefficients: 0.93 or 0.99 are used (dashed line).

MODELING OF THERMAL POLLUTION

As it was already mentioned the spread of thermal pollution in rivers in the mid-field zone should be modeled by means of 2D equations. The most convenient are the models in which the unknown variable is the temperature change (compared to the ambient water temperature) and not the temperature itself. Such approach (with the temperature change) simplifies determination of additional possible heat fluxes concerning the heat exchange between water and its surrounding environment. All non-water temperature related terms counterbalance one another in such models in which the water temperature difference is calculated and therefore may be omitted. In case of heat exchange between river water and atmosphere, the short-wave and long-wave atmospheric radiation terms may be disregarded. They are not related to water temperature and they do not influence the temperature change. This makes the situation much easier and one may avoid the problems of acquiring various meteorological input data and of computational difficulties to obtain e.g. long-wave atmospheric radiation. When it comes to other heat flux terms, if the temperature of introduced heated water is not very high compared to the natural water temperature, we may assume that those terms influence more or less in the same way both natural and the heated water. Therefore when the temperature difference is our unknown variable, those terms practically disappear. Due to legal restrictions the temperature of discharged heated water from industrial objects in the discharge point usually does not exceed the natural water temperature by more than 7°C. After short initial distance, in the mid-field zone, it is not higher than 3°C. For instance Fig. 4 shows the difference in temperature change caused by long-wave back water radiation (usually the largest term at the water-atmosphere interface). That difference computed for ambient water temperature, and for temperature 3°C higher than ambient water temperature is similar to the difference when we compute the long-wave back water radiation for ambient water temperature with emissivity coefficient equal to 0.93 (by default 0.97 value has been used). The difference, as may be expected, increases with the water temperature, but it is of the order of 0.001°C. For the extreme case when the ambient water is cooler than the heated water by 7°C the difference reaches only 0.01°C. Additionally, the results from real case study with heated water discharged from a designed gas-steam power plant located near Włocławek town on the Vistula River (Poland) have been analyzed (see Kalinowska et al., 2012). To predict the possible temperature increase River Mixing Model (RivMix), developed by authors, has been used (Kalinowska and Rowiński, 2008). This is the 2D numerical model that calculates the temperature change and can be used in the mid-field zone. Computations have been done in two ways - including the exemplary heat flux (see. Fig. 5a) caused by the heat exchange between the water and atmosphere as well as without heat flux. The difference in the obtained results (after one hour) is of order of 10^{-2} (see fig. 5b). At the same time other unavoidable errors committed during the computation are much higher (see Kalinowska and Rowiński, 2012). For example, usually we have no information about the dispersion coefficients in the 2D transport equation. We have to estimate them and usually we perform several simulations for different (possibly extreme) values of dispersion coefficients. But the difference between the results appears then to be huge - up to 1°C (see Kalinowska and Rowiński, 2012).

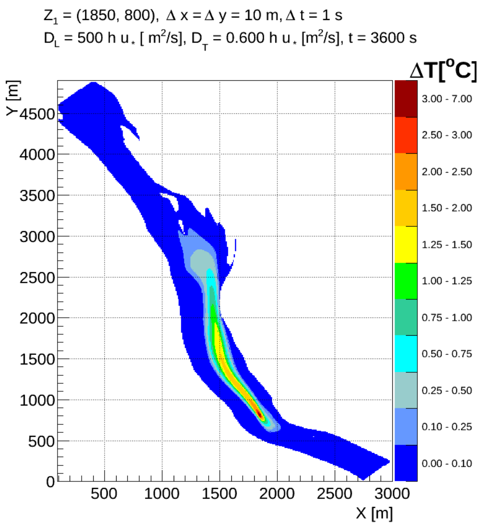
CONCLUSIONS

In mathematical modeling of environmental processes a natural temptation is to evaluate each term that can influence the final result with the best possible accuracy. In modeling of heat transfer in rivers researchers put much effort to gain necessary data and to evaluate the source terms in the relevant equations but it turns out to be unnecessary undertaking in the problems in which we are interested in the temperature difference between ambient and the heated water. In fact it is the main task in environmental impact assessment when thermal pollution discharges are considered and the good message is that we may avoid evaluating the heat exchange between water and the atmosphere in such cases.

ACKNOWLEDGEMENTS

The study has been supported by the grant IP2012 028772 from the Polish Ministry of Science and Higher Education and the publication has been partially financed from the funds of the Leading National Research Centre (KNOW) received by the Centre for Polar Studies for the period 2014-2018. The authors would like to thank Krzysztof Markowicz for sharing data from IGF UW Meteorological observatory and Narew National Park for sharing data from Narew National Park Weather Station.

a)



b)

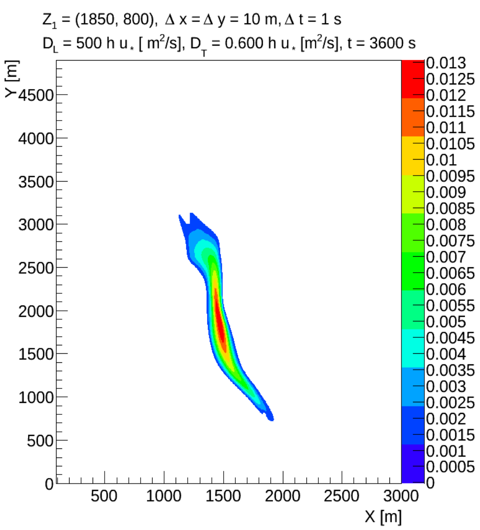


Fig. 5 Real case study with heated water discharged from a designed gas-steam power plant in the Vistula River a) predicted temperature increase (ΔT) with the exemplary heat flux include in the calculation; b) the difference in temperature increase with and without exemplary heat flux included in the calculation.

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