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RIVERINE WATER OUTFLOW INTO THE GULF OF GDAŃSK

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Abstract

Drainage basin of the Gulf of Gdańsk is dominated by the river Vistula, as regards both the catchment area size and the amount of discharged water. The remaining watercourses flowing directly into the Gulf of Gdańsk or via the Vistula Lagoon (the Lagoon is a component of the Gulf of Gdańsk system) contribute slightly over 1/8 of the total water volume. The presented calculations of riverine outflow from the catchment area of the Gulf of Gdańsk were conducted based on data either published in hydrological yearbooks or purchased from the Institute of Meteorology and Water Management. Other data sources included the archives of the Physical Oceanography Department at University of Gdańsk, scientific publications and the author's expertise. Statistical characteristics of riverine outflow and water temperature were prepared as required by the model. The annual cycles of riverine outflow and water temperature at the mouth sections in the Gulf of Gdańsk are expressed by trigonometric functions in an averaged climatic scale.

INTRODUCTION

Over 250 rivers discharging water into the Baltic Sea are irregularly distributed along its coastline and they significantly differ in the outflow magnitude. Majority of the rivers flow from the western coast and the Scandinavian Peninsula, while the southern and south-eastern part of the catchment area is less abundant in watercourses. It is estimated that 102 rivers discharge over $10 \text{ m}^3 \text{ s}^{-1}$ of water from their mouth sections into the Baltic Sea (Cyberski 1995). Small water-

courses are predominant; only river Neva (flowing into the Gulf of Finland) and the Vistula (flowing into the Gulf of Gdańsk) discharge annually more than $1000 \text{ m}^3 \text{ s}^{-1}$. The Gulf of Gdańsk forms a part of the Gdańsk Basin - a hydrographic unit within the Baltic Sea (Majewski 1990) (Fig. 1).

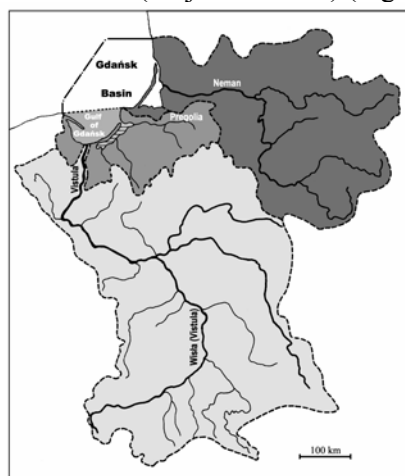


Fig. 1. Drainage basin of the Gulf of Gdańsk

In the catchment area of the Gulf of Gdańsk about 88 % of the drainage area and 85 % of water outflow is attributed to the Vistula and 8 % to Pregolia, the latter flowing into the Vistula Lagoon. The remaining, *ca.* 7 % of the outflow, is a sum of several watercourses; only six of them have an outflow in the range from 5 to $21 \text{ m}^3 \text{ s}^{-1}$ and the outflow of another two, Nogat and Pregolia, exceeds $10 \text{ m}^3 \text{ s}^{-1}$. In general, the rivers from the drainage basin of the Gulf of Gdańsk discharge *ca.* 8.5 % of the total water volume reaching the Baltic Sea.

An ecological model of the Gulf of Gdańsk developed by a team of scientists from the Institute of Oceanography at University of Gdańsk required the continuous supply of information concerning the water flow into the Gulf of Gdańsk and temperature of riverine water, as important input data. The data from the past years, collected in tables, represent one of the information sources, however, the acquisition of such data usually poses certain difficulties and increases the exploitation costs of a model.

Data, generated on line in a, for example, statistical model could become an additional information source. Such data would fulfil the requirements of an ecological model on the condition that they properly described the annual cycle of outflow and riverine water temperature changes. The requirement of a good agreement with natural fluctuations, basic from the beginning of our project of statistical analysis of data from past years, determined the choice of a method. The best agreement was achieved by the method which described annual fluctuations of the outflow and water temperature by means of trigonometric func-

tions in a climatic scale. The climatic scale incorporates the averaging time of sufficient length to eliminate high frequency fluctuations of climatic and hydrological events.

MATERIALS AND METHODS

The analysis of riverine outflow and water temperature up to 1983 was conducted using hydrometric data from the drainage basins of the rivers Oder (Hydrological ... Oder ... 1971–1983) and Vistula (Hdrological ... Vistula ... 1971–1983) collected in hydrological yearbooks and purchased from the Institute of Meteorology and Water Management (up to 1996), additional data were collected by the author from earlier publications (Cyberski 1982–1995) and materials published in the archives of the Department of Physical Oceanography at University of Gdańsk as well as from various unpublished expertise pieces of the author.

The incomplete data series, different lengths of the series, very short data series or single measurement values of the outflow presented the main problems of the project. The most complex information sets were found for the rivers: Vistula, Reda, Pasłęka, Nogat, Elbląg, Gizdepka and Kacza. Water temperature measurements were available only for four rivers: Vistula, Reda, Pasłęka and Pregolia.

The data at our disposal dictated the choice of such solutions that would generate the least erroneous information, especially in the case of watercourses for which no long-term measurements were available. To ensure the least erroneous results, the analysis of spatial differentiation of unit outflow, expressed in $\text{dm}^3 \text{s}^{-1} \text{km}^{-2}$, was carried out. Besides, the results of single measurements for watercourses without a continuous observation service were correlated with synchronised data from stations in the hydrometric network (the measurement on the same day). Information from the above mentioned analysis, supported by results of physico-geographical analysis (taking into account morphometric parameters) allowed the detection of analogies and differences between individual drainage areas. Thus, it was possible to find a mean unit outflow and determine the annual outflow cycle for catchment areas for which no hydrometric data were available.

As regards water temperature, because the original data set was very poor (data from 4 measurement stations only), the solution was based on the following rationale: small and short watercourses carry colder water in summer, longer watercourses contain warmer water. Hence, the annual cycle of water temperature and actual temperature values in river Reda were transposed to all watercourses with catchment areas smaller than 500 km^2 . Watercourses in the Vistula estuary (Szkarpawa, Wisła Królewiecka, Wisła Martwa with Motława) were

assigned temperature of the river Vistula, rivers Elbląg and Nogat were assigned temperature of river Pasłęka.

Annual fluctuations of riverine outflows and river water temperature were analysed using harmonic analysis:

$$Q(t) = Q_0 + \sum_{i=1}^N Q_i \sin(\omega t + \varphi_i), \quad (1)$$

where:

$Q(t)$, flow value on day t ; t , number of days in the year (from 1 January to 365); Q_0 , mean annual discharge; Q_i , flow amplitude or temperature amplitude corresponding to T_i , N , number of harmonic components; φ_i , phase shift; T_i , periods expressed in days;

$$\omega = \frac{2\pi}{T_i}, \text{ frequency.}$$

The mutual fitting of results from the model and empirical data was evaluated by a method proposed by Delleur, Sarma and Rao (Cyberski 1995) using correlation coefficient (R):

$$R = \frac{n \sum_{t=1}^n Y_0(t) \cdot Y_s(t) - \left[\sum_{t=1}^n Y_0(t) \right] \left[\sum_{t=1}^n Y_s(t) \right]}{\left\langle \left\{ n \sum_{t=1}^n [Y_0(t)]^2 - \left[\sum_{t=1}^n Y_0(t) \right]^2 \right\} \left\{ n \sum_{t=1}^n [Y_s(t)]^2 - \left[\sum_{t=1}^n Y_s(t) \right]^2 \right\} \right\rangle^{\frac{1}{2}}}, \quad (2)$$

and special correlation coefficient (RS):

$$RS = \sqrt{\frac{2 \cdot \sum_{t=1}^n Y_0(t) \cdot Y_s(t) - \sum_{t=1}^n [Y_s(t)]^2}{\sum_{t=1}^n [Y_0(t)]^2}}, \quad (3)$$

where:

Y_0 signifies empirical data, Y_s data calculated from the model and $n = 1 \div 365$.

The coefficient R estimates the phase agreement of model calculations with empirical data, while RS is a measure of phase and ordinate convergence of both values. An extensive discussion of the applied procedures and other methods of model convergence with the empirical data can be found in Cyberski (1995).

RESULTS AND DISCUSSION

The river Vistula, despite of its large catchment area, is susceptible to fluctuations especially to synoptic ones, occurring along with climatic periods. This is manifested by the considerable changeability of the river outflow, greatly differing as regards the monthly and particularly daily mean values but with rather stable mean annual values. The range of mean annual outflows of the Vistula and extremal annual data over 95 years (1901–1995) are presented in Fig. 2.

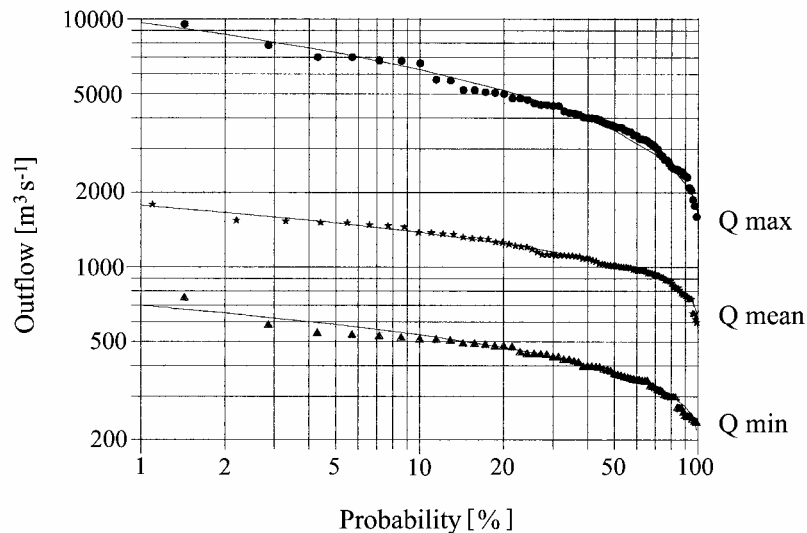


Fig. 2. The probability [%] of mean annual and extremal flows [$\text{m}^3 \text{s}^{-1}$] in the river Vistula at Tczew cross-section (1901–1995)

The annual cycle of water outflow and water temperature in all analysed watercourses were described by trigonometric equations. By substituting in equation (1) the optimised values of parameters obtained from data, a trigonometric description of the outflow (Q) or water temperature (T) was obtained in a similar climatic scale.

The equations based on long-term measurement series and tested with the series of the same time length gave results of good agreement with empirical data, which was evidenced by high values of correlation coefficient (R , calculated from equation 2, was always greater than 0.96), and particularly by special correlation coefficient (RS , calculated from equation 3, greater than 0.98).

An applicable form of the equation for calculations of the Vistula river outflow on a chosen day of a year is presented below:

$$Q_{(t)} = 1089 + 387 \sin\left(\frac{2\pi}{365}t - 0.126\right) + 190 \sin\left(\frac{2\pi}{182.5}t - 1.92\right) + 176 \sin\left(\frac{2\pi}{121.7}t + 2.93\right) + 57.6 \sin\left(\frac{2\pi}{91.25}t + 0.969\right). \quad (4)$$

Water temperature in river Reda is calculated in the following manner:

$$T_{(t)} = 8.17 + 6.42 \sin\left(\frac{2\pi}{365}t - 1.91\right) + 0.72 \sin\left(\frac{2\pi}{182.5}t + 1.02\right) + 0.22 \sin\left(\frac{2\pi}{121.7}t + 1.19\right) + 0.17 \sin\left(\frac{2\pi}{91.25}t - 1.64\right), \quad (5)$$

and in the river Vistula:

$$T_{(t)} = 9.90 + 10.64 \sin\left(\frac{2\pi}{365}t - 1.92\right) + 0.63 \sin\left(\frac{2\pi}{182.5}t + 1.67\right) + 0.57 \sin\left(\frac{2\pi}{121.7}t + 0.59\right) + 0.172 \sin\left(\frac{2\pi}{91.25}t - 0.769\right). \quad (6)$$

The values of the river Vistula outflow, calculated from equation (4), and the calculated sum of riverine outflows into the Vistula Lagoon are presented in Fig. 3. Water temperature in the Vistula and Reda (obtained from equation 5) are shown in Fig. 4.

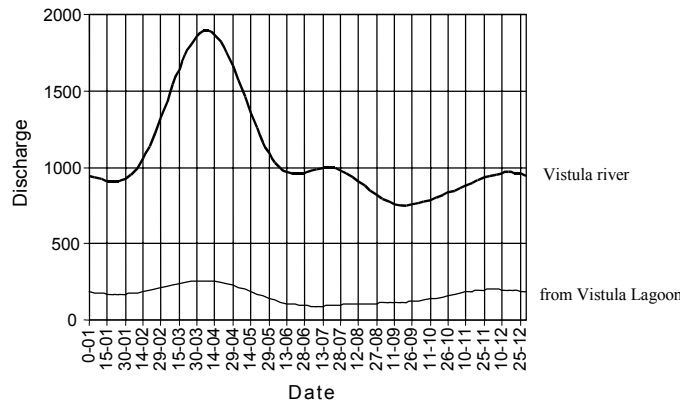


Fig. 3. Annual cycle of the Vistula river outflow and outflow from the Vistula Lagoon (total outflow) calculated from the trigonometric model (discharge [$\text{m}^3 \text{s}^{-1}$])

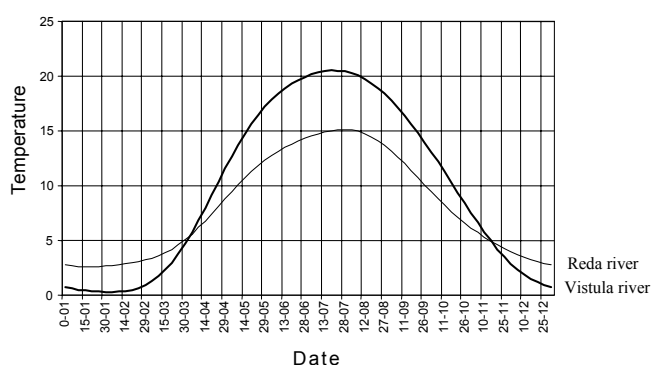


Fig. 4. Annual cycle of water temperature [°C] in rivers Reda and the Vistula calculated from the trigonometric model

The presented solution is less satisfying when calculated values are compared with empirical data within shorter time intervals, *e.g.* one year. This problem is illustrated using the same examples as above: the river Vistula outflow and water temperature in river Reda, described by equations 4 and 5. Successive illustrations, 5 a, 5 b and 5 c, show empirical data (fine line) and calculated values (thick line). In 1994 and 1995, the outflow differed considerably (Fig. 5 a, 5 b), nevertheless special correlation coefficient (RS from equation 3) took high values in both cases: $RS = 0.82$ and 0.72 , respectively. The mean value for two years reached even greater agreement with the model (Fig. 5 c, $RS = 0.86$). This observation is natural, because with the lengthening of empirical data set and the number of years approaching time series of climatic scale characteristics, both data sets become very comparable.

Particularly good agreement between data from the model and empirical results was reached in the case of water temperature (Fig. 6). Annual fluctuations of this parameter are characterised by clearly marked rhythm. Daily values of water temperature in river Reda within two years (1994 and 1995, Fig. 6) concentrate around the curve generated with the aid of equation (5), and special correlation coefficient values are close to or exceed 0.96. Mean values, calculated from daily results from 1994 and 1995, also follow the earlier presented scheme, *i.e.* lesser scattering of data and higher value of RS coefficient (0.985). Similar results were obtained for all analysed watercourses. The annual cycle of empirical water temperature and calculated from the trigonometric model was satisfactory in all analysed cases (Fig. 7). Thermal differences between large and small rivers were very obvious (Fig. 4).

The assumption applied in the analysis of outflow and water temperature, that is to relate the equations in the model to empirical data based on hydrometric results averaged for a twenty year period (1971–1990), turned out well sub-

stantiated, especially that both parameters showed significant fluctuations in this period. The calculated mean values from twenty year period are nearly identical with empirical data obtained from slightly longer measurement series and even from shorter series (Cyberski 1982).

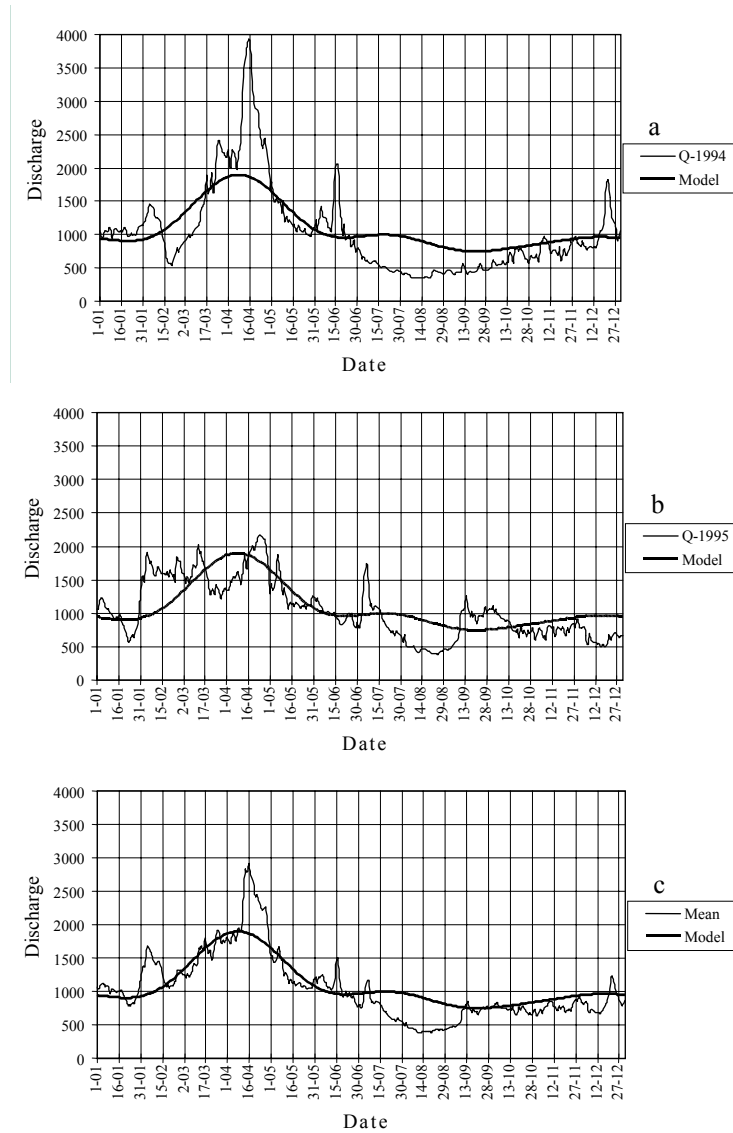


Fig. 5. Empirical daily values of the Vistula river outflow versus data calculated from the model (discharge [$\text{m}^3 \text{s}^{-1}$])

However, it is not recommended to prolong extensively the time series applied to obtain trigonometric equations. One of the objections against it is that

frequently the data include periods in the past when hydrological conditions differed significantly from today's because of much smaller anthropopressure (Ozga-Zielińska and Brzeziński 1994). The equations based on data from 20 to 30-year periods, conforming with the climatic scale, are preferred to conduct general characteristics, because they eliminate fluctuations caused by phenomena of higher frequency.

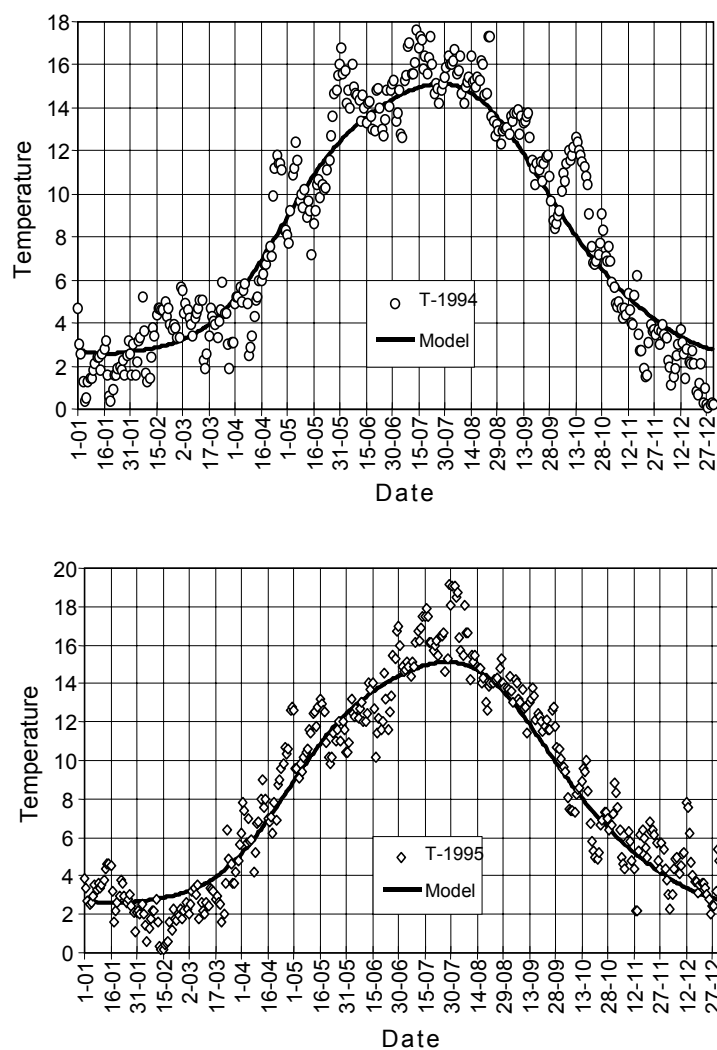


Fig. 6. Empirical daily values of water temperature [°C] in the river Reda versus data calculated from the model

It is important to mention that considerable agreement was found between the total outflow value to the Gulf of Gdańsk calculated by the author and Dr F. Wulff from Stockholm University, Sweden (personal comm.). The magnitude of the total outflow to the Gulf given in this article amounted to $1108 \text{ m}^3 \text{ s}^{-1}$ and $1138 \text{ m}^3 \text{ s}^{-1}$ according to Wulff while the outflow to Vistula Lagoon was $165 \text{ m}^3 \text{ s}^{-1}$ and $159 \text{ m}^3 \text{ s}^{-1}$, respectively. These results were obtained in independent calculations, probably by different methods and based on different original data from different time periods.

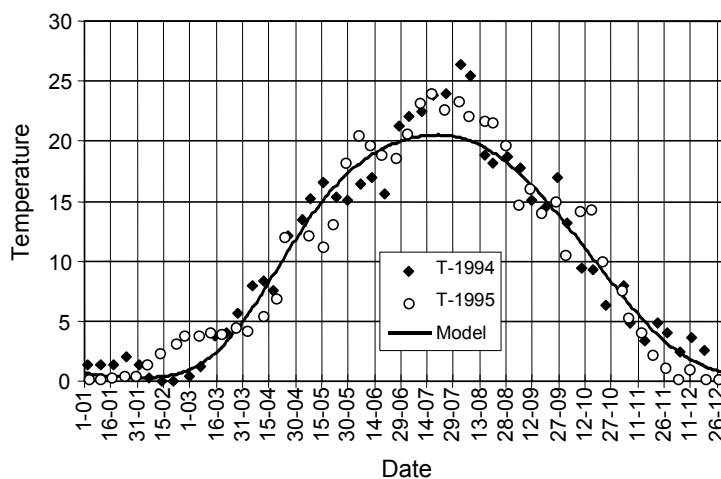


Fig. 7. Empirical daily values of water temperature [°C] in the river Vistula versus data calculated from the model

CONCLUSIONS

The obtained results demonstrate that methodological assumptions applied at the beginning of the project were correctly chosen. Thus, the obtained solutions can be considered as complying with the requirements of the ecological model regarding the source of information on riverine outflow and water temperature.

At the testing stage of any ecological model, in epignosis or prognosis concerning a large number of months or years back or in prospect, it is sufficient to apply trigonometric formulas (based on data from climatic periods) which describe annual cycle of the riverine outflow or annual fluctuations of water temperature.

The calculated values can substitute the data from past years with some limitations due to their incomplete representation of the real data. It is thus explicit

that multiyear measurement series should remain the basic source of information on riverine flow and water temperature.

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