Prediction of pollutant concentration in Laborec river station, Slovak Republic

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Abstract

A model that predicts pollutant concentrations in a river has been developed and is presented in the paper. The developed model that determines concentrations of pollutants specifically biochemical oxygen demand (BOD 5) and total nitrogen (N) in water stream is based on dimensional analysis. Fundamentals of the modeling of the pollutants prediction in water stream consist in derivation of function dependency from expressed non-dimension arguments. Non-dimension arguments are stated from variables, which influence the occurrence of pollutants. Model for prediction of biochemical oxygen demand and nitrogen concentrations in water stream has been developed for Laborec River, eastern part of Slovakia. The differences between the calculated concentrations from developed model described in this paper and measured concentrations in Laborec river stations are also discussed. The developed model might be used for prediction of any pollutant concentration in river.

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Keywords: Dimensional analysis; pollutant concentration; river station

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1. Introduction

Progressive urbanization and industrial development has also led to increasing use of rivers for waste disposal activities. The pollution arising from these and other sources, such as use of agricultural pesticides, has led to the increasing need for rigorous assessment of river water quality. The complexity and components of such assessment programs are defined by the water uses and their water quality requirements, as well as a need to protect the aquatic environment from further degradation. In recognition of the adverse impacts of pollutants and the need for integrated management, the EU has introduced a series of Directives aimed at reducing nutrient in aquatic systems [1]. The Water Framework Directive (2000/60) [2] demands new approaches for managing and improving surface and groundwater quality across the European Union, with emphasis shifting from chemical towards ecological water quality standards.

During the past decades several models which predict the concentration profiles after a discharge of pollutants in a river have been developed. Application of these models to a river leads to discrepancies between predicted and measured concentration profiles. Water quality modeling can be a valuable tool for water management since it can simulate the potential response of the aquatic system to such changes as the addition of organic pollution, the building of small hydro-electric power plants, the increase in nutrient levels or water abstraction rates and changes in sewage treatment operations [3]. The use of generally available models should be carried out with cautions and, where possible, any general model should be verified with data obtained from the water body for which its use is being considered. It is also important to verify models if they are to be used routinely in the management of water quality. River quality models seek to describe the spatial and temporal changes of constituents of concern. The paper presents possibility of pollutant concentration prediction in water stream. The developed model is based on the dimensional analysis. Dimensional analysis is a conceptual tool often applied in engineering and water management to understand physical situations involving a mix of different kinds of physical quantities. Physical scientists and engineers to check the plausibility of derived equations and computations routinely use it. It is also used to form reasonable hypotheses about complex physical situations that can be tested by experiment or by more developed theories of the phenomena [4], [5].

Dimensional analysis is a well-known methodology in physics, chemistry and other traditional engineering areas. In its simplest form, dimensional analysis is used to check the meaningfulness of a set of equations (dimensional homogeneity). In the last century, the dimensional theory has been profoundly investigated: its highest achievement is the Buckingham theorem (or π-theorem, π theorem), which states that any equation modeling a physical problem can be rearranged in terms of dimensionless ratios, thus saving variables to be handled, and especially enriching the inner physical knowledge of the studied phenomenon [6]. The Buckingham π theorem is of central importance to dimensional analysis [7]. This theorem describes how every physically meaningful equation involving \( n \) variables can be equivalently rewritten as an equation of \( n - m \) non-dimension parameters, where \( m \) is the number of fundamental dimensions used [8]. Furthermore, and most importantly, it provides a method for computing these non-dimension arguments from the given variables. This provides a method for computing sets of these parameters from the given variables, even if the form of the equation is still unknown. However, the choice of non-dimension arguments is not unique: Buckingham's theorem only provides a way of generating sets of non-dimension arguments, and will not choose the most 'physically meaningful'.

The variation of pollutant concentrations in surface waters shares broad interest by scientists and researchers in the field of water pollution control. Models are useful in defining the nature of water systems and the relation among its components. Based on the study results, it can be concluded that the coupled water quality prediction model is highly applicable to this regulated large river for water quality management. The present research has main objectives to investigate options for estimating the
parameters of the models and to develop model for concentration prediction in a stream. The paper presents model based on dimensionless arguments developed to predict concentrations of pollutant - biochemical oxygen demand (BOD$_5$) and total nitrogen (N) in water stream.

2. Variables selection

The most important part is selection of appropriate variables for the model development of prediction pollutant concentration in water stream. These variables should be selected in relation to other methods which may be appropriate, such as analysis of particulate and biological material [3]. The choice of variables will also be influenced by the ability of an organization to provide the facilities, and suitably trained operators, to enable the selected measurements to be made accurately. Full selection of variables must be made in relation to assessment objectives and specific knowledge of each individual situation. For determination of pollutant concentration in a water stream using dimensional analysis it is essential to state the parameters which characterize the water stream, and which may be measured (Bendíková et. al., 2004; Zeleňáková, Švecová, 2006):

- Mass flow $Q_m$ (kg.s$^{-1}$),
- Catchment area $F$ (m$^2$),
- Velocity of water in the stream $v$ (m.s$^{-1}$),
- Temperature of water $T_w$ (K),
- Temperature of air $T_a$ (K),
- Pollutant concentration $C_i$ (kg.m$^3$).

The variables influenced water quality is described in following [3]. The amount of suspended and dissolved matter in a water body depends on the discharge and is a product of the concentration and the discharge. Natural substances arising from erosion increase in concentration exponentially with increased discharge. If a pollutant is introduced into a river at a constant rate, the concentration in the receiving water can be estimated from the quantity input divided by the river discharge. Discharge also should be measured at the time of sampling and preferably at the same position as water samples are taken. The size of the watershed controls the fluctuations in water level, velocity and discharge. The velocity of a water body can significantly affect its ability to assimilate and transport pollutants. Thus measurement of velocity is extremely important in any modeling of water quality. It enables the prediction of movement of compounds (particularly pollutants) within water bodies. Water velocity can vary depending on hydrometeorological influences and the nature of the catchment area. It is important to measure velocity at the same sites as other water quality samples are collected. Water bodies undergo temperature variations along with normal climatic fluctuations. These variations occur seasonally and over the day. The temperature of surface waters is influenced by latitude, altitude, season, time of day, air circulation, cloud cover and the flow and depth of the water body. In turn, temperature affects physical, chemical and biological processes in water bodies and, therefore, the concentration of many variables.

3. Model development

All the given variables are presented in basic dimensions, which is the condition for dimensional analysis application. The general relation among the selected variables, which can affect the pollutant concentration, can be put down in the next form in order that each parameter is considered with the same dimension

$$\phi (Q_m, F, v, T_w, C_i, T_a) = 0$$  \hfill (1)
The following equation is valid

\[ \pi_1 = Q_m^{x_1} \cdot F^{x_2} \cdot v^{x_3} \cdot T_w^{x_4} \cdot C_i^{x_5} \cdot T_a^{x_6} \]  

(2)

The created dimensional matrix-relation (3) has the rank of matrix \( m = 4 \) and its lines are dimensionally independent from each other. From \( n = 6 \) independent variables at matrix rank \( m \), it is possible to set up \( i = n - m \) of non-dimension arguments.

\[ \begin{bmatrix} m & F & v & T_w & C & T_a \\ s & -1 & 0 & -1 & 0 & 0 \\ kg & 1 & 0 & 0 & 1 & 1 \\ K & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \]  

(3)

The matrix is modified for solution in the way that the determinant is not equal to zero.

Selection of the unknown parameter is done twice \( x_1 = 1; x_1 = 0 \). Two independent vectors – non-dimension arguments \( \pi_1 \) (5) and \( \pi_2 \) (6) are obtained by solution of the system of four linear equations in the form

\[ \pi_1 = Q_m^{x_1} \cdot F^{x_1} \cdot v^{x_1} \cdot C_i^{x_1} \]  

(5)

\[ \pi_2 = T_a^{x_1} \cdot T_w^{x_1} \]  

(6)

The dimensional homogeneous function in non-dimension form is

\[ \phi (\pi_1, \pi_2) = 0 \]  

(7)

The relation between independent non-dimension argument \( \pi_2 \) and dependent non-dimension argument \( \pi_1 \) can be defined by the exponential equation

\[ \pi_1 = A \cdot \pi_2^B \]  

(8)

From this function dependency is possible to obtain values of concentrations of the pollutant in water stream. In generally, this dependency has exponential status. Its transformation to logarithmical coordinate system is equivalent to linear status that allows working with model easier and more simply to determine parameters of linear status.

After completing the relation (8) the relation characterizing the pollutant concentration in a river is obtained. After modification the following equation for pollutant concentration is valid

\[ C_1 = A^{-1} \cdot T_a^{-B} \cdot v^{-1} \cdot F^{-1} \cdot Q_m \cdot T_w^B \]  

(9)
Relation (9) represents the model of the pollutant concentration in water stream. The model is valid for each pollutant, but it is necessary to calculate new regression coefficients $A$ and $B$. This paper presents model for prediction of biochemical oxygen demand (BOD$_5$) and total nitrogen (N) in Laborec river stations based on dimensional analysis.

4. Study area

The developed model for calculations of biochemical oxygen demand and nitrogen concentrations in the water stream is presented for the Laborec River – eastern part of Slovakia. Water quality is monitored in the Laborec River in seven river stations – which are shown in Fig. 1.

Fig. 1. Study area – river stations at Laborec River
The BOD$_5$ and N were considered as pollutants in the Laborec River because of its high concentrations in this stream. Required data were obtained from Slovak Water Management Enterprise, state company (SWME, s.c.) in Košice and Slovak Hydrometeorological Institute (SHMI) in Košice. The data measured during five years, from 2000 to 2004 (12 values in a year) were used. The developed model was verified for the next five years – 2005, 2006, 2007, 2008, 2009.

According to known relevant variables the non-dimension arguments were stated from equations (5) and (6). The real course of the dependence of non-dimension arguments $\pi_2$ and $\pi_1$ in logarithmic coordinates the regression coefficients A and B were stated as following.

Table 1. Regression coefficients calculated for BOD$_5$ and N in separate river stations

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>Regression coefficients</th>
<th>Biochemical oxygen demand</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>River stations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ižkovce</td>
<td>0.0024</td>
<td>9.0467</td>
<td>0.0039</td>
</tr>
<tr>
<td>Stretávka</td>
<td>0.0020</td>
<td>14.507</td>
<td>0.0031</td>
</tr>
<tr>
<td>Lastomír</td>
<td>0.0023</td>
<td>20.329</td>
<td>0.0039</td>
</tr>
<tr>
<td>Petrovce</td>
<td>0.0014</td>
<td>11.663</td>
<td>0.0018</td>
</tr>
<tr>
<td>Brekov</td>
<td>0.0030</td>
<td>2.055</td>
<td>0.0048</td>
</tr>
<tr>
<td>Nad Cirochou</td>
<td>0.0022</td>
<td>-1.062</td>
<td>0.0045</td>
</tr>
<tr>
<td>Krásny Brod</td>
<td>0.0041</td>
<td>-4.774</td>
<td>0.0079</td>
</tr>
</tbody>
</table>

Biochemical oxygen demand and nitrogen concentrations were calculated according to relation (9) – developed model for the prediction of pollutant concentrations in a stream; on the basis of measured input variables and determined regression coefficients.

The model verification and validation is presented in Figures 2, 3 which depict the values of measured and calculated concentrations.
Fig. 2. Comparison of measured and calculated biochemical oxygen demand concentrations in the Laborec River stations
Fig. 3. Comparison of measured and calculated nitrogen concentrations in the Laborec River stations
The differences between measured and predicted nitrogen concentrations can occur because selections of relevant parameters are not necessarily involved in all aspects, on which the pollutant concentration depends. Another reason is that measured values are not exactly stated. Negligible differences between measured and calculated biochemical oxygen demand and nitrogen concentrations are allowable. Differences occur due to a variety of reasons such as rainfall, influence of source of pollution and outflow of wastewater and so on. The major differences could occur because of an error in taking the sample or an error in the determination of the concentration in the lab. Also relevant parameters are required to be used for dimensional analysis.

There are seven river stations in the Laborec River. For each of them the separate model for the prediction of biochemical oxygen demand and nitrogen concentrations in a river profile has been developed following the above mentioned procedure. The uncertainty between measured and calculated biochemical oxygen demand and nitrogen concentrations in the Laborec River stations vary from 20 to 40 %, suitable for modeling natural processes.

Mathematic-physical model based on non-dimensionless arguments determines concentrations of pollutants in water stream and is effectively available for water quality modeling. Using of the dimensional analysis for water quality modeling is a new approach. The paper presents development of the model for pollutant concentrations in river and its verification for river stations in Laborec River (eastern Slovakia). Dimensional analysis is a useful tool for water quality modeling and determination or prediction of any pollutant concentration in any river station in any time. This method is proper basement of a new and effective approach to water quality modeling.

5. Conclusion

Rivers are dynamic systems which respond to the physical characteristics of the watershed, which in turn are controlled by the local and regional geological and climatic conditions. Extreme or rapid fluctuations are dampened as watershed size increases. The flow characteristics of a river are important to the understanding of the water mixing processes in the river channel, i.e. in association with laminar flow, helical overturn and turbulent mixing in channels with rapids and waterfalls. A basic knowledge of these processes is necessary for the correct sitting of sampling stations within the watershed. Determination of river discharge is extremely important for the measurement of the flux of material carried by the river and transported to downstream receiving waters. The changing concentrations of chemical variables relative to the changing volume and velocity of river waters can provide useful diagnostic information on the origins of contaminants. In general, with increasing discharge point sources of contaminants are diluted whereas diffuse sources show increased concentrations. Sediment related variables fluctuate with suspended solids concentrations which in turn are related to discharge.

It is obvious that input data and selection of relevant parameters are the most important factors in prediction of pollutant concentration in water stream. The choice of variables will also be influenced by the ability of an organization to provide the facilities, and suitably trained operators, to enable the selected measurements to be made accurately. Full selection of variables must be made in relation to assessment objectives and specific knowledge of each individual situation.

The obtained results proof that dimensional analysis and using of $\pi$ theorem is appropriate access to water quality modeling. This method could be used for prediction of any pollutant in water stream. The model presented in the article has a universal validity for pollutants in streams that are noted for at least approximate geometric characteristics. But for each pollutant (and particular stream of course) the parameters of linear function i.e. regression coefficients have to be determined separately.

The variation of pollutant concentrations in surface waters shares broad interest by scientists and researchers in the field of water pollution control. Models are useful in defining the nature of water
systems and the relation among its components. The models were developed, calibrated and evaluated using measured data in the Laborec River, Slovakia. Based on the study results, it can be concluded that the water quality prediction model is highly applicable to this regulated large river for water quality management.

Acknowledgements

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Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td>$Q_m$</td>
<td>mass flow (kg.s$^{-1}$)</td>
</tr>
<tr>
<td>$F$</td>
<td>catchment area (m$^2$)</td>
</tr>
<tr>
<td>$v$</td>
<td>velocity of water in the stream (m.s$^{-1}$)</td>
</tr>
<tr>
<td>$T_w$</td>
<td>temperature of water (K)</td>
</tr>
<tr>
<td>$T_a$</td>
<td>temperature of air (K)</td>
</tr>
<tr>
<td>$C_i$</td>
<td>pollutant concentration (kg.m$^{-3}$)</td>
</tr>
</tbody>
</table>

References


