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Water quality modelling in river station Krasny Brod

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Abstract

Paper is aimed on prediction of concentration of selected pollutant in surface water based on dimensional analysis. This particular method of mathematical and physical modelling is based on relevant variables affecting water stream pollution. Modelling of the pollutants prediction in water stream consists in derivation of function dependency from expressed dimensionless arguments. From this function dependency is possible to obtain values of concentrations of the pollutant in water stream. Prediction of selected pollutants in water stream was performed in river station Krasny Brod (eastern Slovakia). Model was developed from statistically arranged values in time period 2003–2008 and verified for 2009–2010 for 7 pollutants – $P_{tot.}$, $N_{tot.}$, $N\text{-}NO_2^-$,$N\text{-}NO_3^-$, $N\text{-}NH_4^+$, BOD_5 and COD_{Cr}.

Keywords: dimensional analysis; Krásny Brod; pollutant concentration; water quality.

Nomenclature

A, B	regression coefficients
C_{im}	monitored pollutant concentration (kg/m^3)
C_{id}	determined pollutant concentration (kg/m^3)
F	catchment area (m^2)
N	number of values
Q_m	mass flow (kg/s)
T_w	temperature of water (K)
T_a	temperature of air (K)
υ	velocity of water in the stream (m/s)
σ	uncertainty (–)

1. Main text

The EU Water Framework Directive [1] states that all waters within the Union shall be brought to a "good status" and shall be managed in a sustainable way. According to the definition this includes both water quantity and quality aspects, and at present most water bodies, do not fulfil this goal. The common use of water as a transport medium or as a recipient for unwanted substances prevents a multiple use of the resource and is not a sustainable management strategy [2]. The new policy instruments that have been introduced to protect and improve European waters, include an ecological and holistic water status assessment approach; river basin water planning; a strategy for elimination of pollution by dangerous substances; public information and consultation and finally, new financial instruments [3].

Water quality involves a long list of individual components and physical, chemical, and biological constituents. Changes in water quality resulting from land-use activities on a watershed can make water unusable for drinking but it can still be acceptable for irrigation or other uses. In some instances, we are required by laws or regulations to prevent water-quality characteristics from being degraded from natural or background conditions defined as nondegradation, and, as a consequence, these characteristics are a key provision in the water-quality standards.

Phosphorous and nitrates in excess amounts can accelerate eutrophication, causing dramatic increases in aquatic plant growth and changes in the types of plants and animals that live in the stream. This, in turn, affects dissolved oxygen,

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temperature, and other indicators. Decomposition of the organic matter lowers the dissolved oxygen level, which in turn slows the rate at which ammonia is oxidized to nitrite (NO_2) and then to nitrate (NO_3). Under such circumstances, it might be necessary to also monitor for nitrites or ammonia, which are considerably more toxic to aquatic life than nitrate. Wastewater from sewage treatment plants often contains organic materials that are decomposed by microorganisms, which use oxygen in the process.

Water quality monitoring can be used for many purposes:

- To identify whether waters are meeting designated uses. When chemical pollutants exceed maximum or minimum allowable concentrations, waters might no longer be able to support the beneficial uses. Water quality monitoring, however, might be inadequate for determining whether aquatic life uses are being met in a stream.
- To identify specific pollutants and sources of pollution. Water quality monitoring helps link sources of pollution to a stream quality problem because it identifies specific problem pollutants. Since certain activities tend to generate certain pollutants, a tentative link might be made that would warrant further investigation or monitoring.
- To determine trends. Chemical constituents that are properly monitored (i.e., consistent time of day and on a regular basis, using consistent methods) can be analyzed for trends over time.

Monitoring of river quality is primarily done to detect the status and trends and to identify whether observed trends are due to natural or anthropogenic causes. Most important environmental problems in river water quality are eutrophication, acidification and emission dispersion where non-point source pollution has become increasingly important within the last decades [4].

Water quality models are very useful in describing the ecological state of a river system and to predict the change in this state when certain boundary or initial conditions are altered. Such changes may be due to morphological modifications to the water body, such as straightening, and discharge regulations using control structures (weirs, dams, etc.), changes in the type point or non-point), amount and location of pollutant loading into the system, and changes in meteorological inputs due to changing trends in climate [5]. The most important part is selection of appropriate variables for the model development of prediction pollutant concentration in water stream.

The paper deals with an application of the model which determines concentrations of pollutants in a water stream and which is developed based on dimensional analysis is presented. The use of dimensional analysis for water quality modelling is a new approach. The differences between the concentrations calculated from the developed model and measured concentrations are also discussed in this paper as well as the rate of uncertainty.

2. Material and methods

2.1. Methodology

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 dimensional theory has been profoundly investigated: its highest achievement is the Buckingham theorem (or pi-theorem), which states that any equation modelling a physical problem can be rearranged in terms of non-dimensional ratios, thus limiting the variables to be handled, and especially enriching the inner physical knowledge of the studied phenomenon [6–9].

The model describing pollutant concentration in a water stream is based on the following:

- Selection of appropriate variables which characterize the water stream, which may be measured and which are presented in basic dimensions (what is the condition for dimensional analysis application).
- The formation of non-dimensional arguments π_i from the stated variables influencing the pollutant concentration in the river (which in existing systems of units have no dimension).
- Derivation of functional dependence from the expressed non-dimensional variables (it has power law character) and its transformation into logarithmic coordinates.
- Model verification – comparison of measured and determined pollutant concentration in river profile.

The developed model [10–11] of the pollutant concentration in water stream based on dimensional analysis is Eqn. (1):

$$C = A^{-1} \cdot T_{\mathrm{a}}^{-\mathrm{B}} \cdot \upsilon^{-1} \cdot F^{-1} \cdot Q_{\mathrm{m}} \cdot T_{\mathrm{w}}^{\mathrm{B}} \tag{1}$$

The model is valid for each pollutant, but it is necessary for each pollutant to calculate new regression coefficients *A* and *B*.

Uncertainty – difference between the determined and monitored pollutant concentrations was calculated from equation:

$$\sigma = \frac{1}{n} \cdot \sum_{i=1}^{n} \frac{\left|C_{\mathrm{im}} - C_{\mathrm{id}}\right|}{C_{\mathrm{im}}} \cdot 100\,. \tag{2}$$

Determined concentrations in river station Krasny Brod were compared with monitored values of concentrations in river profile.

2.2. Study area

The Laborec River is adversely affected by human activities. Below the town Humenne, water pollution, construction of man-made lake Zemplinska Sirava, pollution of town Michalovce, canalization of the river bed, construction of a water reservoir at the village of Vojany and an inlet containing heated waters markerdly influenced the fish species diversity The water of the river is polluted from the town Humenne [12]. Organic pollution of domestic origin is gradually combined with high contents of ammonia, nitrates, nitrites, formaldehyde, urotropine and mineral oils. As a result, the stretch of the river below the effluent from Chemko chemical works in the town Strazske up to inlet emptying itself into the Lake Zemplinska Sirava is the most affected. Below town Michalovce, the oxygen indices of water are also very unsuitable.

The Laborec River belongs to the river system of the Tisa (the Danube River system). It drains the most eastern part of Slovakia, the drainage area being 4 522.5 km^2. The river rises in the mountain range of Nizke Beskydy at an elevation of 730 m a.s.l. The watercourse is 135 km long. In the spring area it flows through the Eastern Slovakia plain, the gradient being 0.7 per thousand, to meet the Latorica River at an elevation of 94 m a.s.l. The most important tributaries of the Laborec River are the streams Udava, Cirocha and Uh [13].

River profile Krasny Brod is situated at the north east part of Slovakia, in river Laborec at river kilometre 108.3. The area of its catchment is 158 km^2 and maximum river flow is 195 m^3/s.

2.3. Data

Determination of pollutant concentration in a water stream was performed in river profile Krasny Brod in river Laborec. Water quality in this river has been monitored in river stations over a long period. Required data of pollutant concentrations were obtained from Slovak Water Management Enterprise, state company (SWME, s.c.) in Košice. Required hydrometeorological data were obtained from Slovak Hydrometeorological Institute (SHMI) in Kosice. The input data are presented in the Table 1.

The monthly data measured during six years from 2003 to 2008 (12 values in a year) and statistically proceeded (one value monthly averaged over six years) input data were used. The model for the determination of pollutant concentrations was applied in the next two years 2009–2010 for 7 pollutants:

- nitrogen ($N_{tot.}$),
- nitrite nitrogen ($N\text{-}NO_2^-$),
- nitrate nitrogen ($N\text{-}NO_3^-$),
- ammonium nitrogen ($N\text{-}NO_4^+$),
- phosphorus ($P_{tot.}$),
- biochemical oxygen demand (BOD_5),
- chemical oxygen demand (COD_{cr}).

Table 1. Relevant parameters values of period 2009–2010

Month	Q_m (kg/s)	$F.10^6$ (m^2)	v (m/s)	T_a (K)	T_w (K)
1	2428	158	1.1709	269.6	274.2
2	1951	158	0.9927	271.9	274.3
3	4615	158	1.8184	275.1	275.9
4	2697	158	1.2691	282.7	281.9
5	4389	158	1.5539	268.5	285.7
6	3542	158	1.3979	289.9	287.5
7	1171.5	158	0.6561	292.9	292.1
8	919.5	158	0.5616	291.3	291.4
9	2565	158	1.0950	286.0	287.1
10	1888	158	0.9397	279.2	281.9
11	1846	158	0.9052	279.0	280.2
12	2226.5	158	1.0697	271.0	275.7

3. Results and discussion

The selected variables that influence the pollutant concentrations in water stream and which are required for model are presented in Table 1.

Non-dimension arguments which are base of dimensional analysis application π_1 (3) and π_2 (4) are stated as follows:

$$\pi_1 = Q_m^1 \cdot \upsilon^{-1} \cdot F^{-1} \cdot C_i^{-1}, \tag{3}$$

$$\pi_2 = T_a^1 \cdot T_w^{-1} . \tag{4}$$

The relation between independent non-dimension argument π_2 and dependent non-dimension argument π_1 can be defined by the exponential equation:

$$\pi_1 = A \cdot T_2^B . \tag{5}$$

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. From this function dependency is possible to obtain values of regression coefficients *A*, *B*.

After completing Eqn. (1) – model determining the pollutant concentration in a river profile is obtained. The model is valid for each pollutant, but it is necessary to calculate new regression coefficients *A* and *B*.

This paper presents model for determination of concentrations of P, N, $N\text{-}NH_4^+$, $N\text{-}NO_2^-$,$N\text{-}NO_3^-$, BOD_5 and COD_{cr} in Krasny Brod river station based on dimensional analysis which are compared with the monitored values obtained from SWME, s.c. Values of determined (C_{id}) and monitored (C_{im}) concentrations of pollutants in river profiles, for each month – average value for two years) are presented in Table 2.

Table 2. Values of determined and monitored concentrations of pollutants

N_{tot}		$N\text{-}NO_2^-$		$N\text{-}NO_3^-$		$N\text{-}NH_4^+$		P_{tot}		BSK_5		COD_{cr}	
C_{id} (kg/m^3)	C_{im}	C_{id}	C_{im}	C_{id}	C_{im}	C_{id}	C_{im}	C_{id}	C_{im}	C_{id}	C_{im}	C_{id}	C_{im}
0.0014	0.0019	0.000005	0.000005	0.0022	0.0013	0.000053	0.000024	0.00006	0.00009	0.0017	0.0026	0.0134	0.0284
0.0021	0.0017	0.000011	0.000006	0.0014	0.0011	0.000032	0.000029	0.00007	0.00010	0.0017	0.0028	0.0116	0.0286
0.0025	0.0020	0.000005	0.000009	0.0015	0.0014	0.000043	0.000044	0.00004	0.00014	0.0018	0.0039	0.0107	0.0391
0.0005	0.0017	0.000003	0.000009	0.0006	0.0011	0.000018	0.000044	0.00006	0.00013	0.0017	0.0035	0.0081	0.0344
0.0020	0.0017	0.000013	0.000010	0.0010	0.0011	0.000043	0.000051	0.00008	0.00015	0.0019	0.0038	0.0274	0.0371
0.0015	0.0020	0.000008	0000011	0.0008	0.0010	0.000079	0.000057	0.00006	0.00015	0.0022	0.0039	0.0113	0.0376
0.0009	0.0015	0.000009	0.000007	0.0006	0.0008	0.000024	0.000034	0.00007	0.00010	0.0019	0.0027	0.0164	0.0262
0.0012	0.0013	0.000008	0.000006	0.0006	0.0008	0.000107	0.000030	0.00004	0.00009	0.0017	0.0025	0.0113	0.0249
0.0013	0.0021	0.000010	0.000007	0.0009	0.0011	0.000056	0.000034	0.00005	0.00011	0.0018	0.0030	0.0125	0.0301
0.0011	0.0014	0.000001	0.000006	0.0010	0.0011	0.000047	0.000027	0.00003	0.00010	0.0027	0.0026	0.0143	0.0275
0.0009	0.0015	0.000017	0.000007	0.0006	0.0010	0.000070	0.000031	0.00009	0.00010	0.0026	0.0027	0.0137	0.0279
0.0017	0.0023	0.000002	0.000005	0.0009	0.0012	0.000071	0.000023	0.00002	0.00009	0.0023	0.0025	0.0057	0.0274

The difference between the determined and monitored pollutant concentrations was calculated from Eqn. (2). The values of uncertainty – error in % for each of pollutants are presented in Table 3.

Table 3. Relative error of monitored period 2009–2010 for measured pollutants

Month	N_{tot} σ (%)	$N\text{-}NO_2^-$	$N\text{-}NO_3^-$	$N\text{-}NH_4^+$	P_{tot}	BSK_5	COD_{Cr}
1	39.7	14.2	40.6	42.3	84.8	59.	191.9
2	19	52.5	20.5	36.9	75	64.6	51.3
3	17.6	77.5	23.7	60	281.7	117.3	299.2
4	207.8	178.4	92.1	152	210	152.9	328
5	36.5	23.4	19.4	37	82.3	95.6	48.3
6	29.3	61.6	23.5	205	139.7	82.4	226.6
7	62.1	21	30.9	82.5	41.5	51.4	123.5
8	7.2	33.6	63	90.8	494.8	55.8	181.6
9	61.4	25.8	39.7	110.4	110.9	72.2	148.1
10	24.8	38.9	11.5	39.1	383.5	48.5	115.3
11	145.4	57.8	97.2	94.3	222.8	5.1	139
12	34.8	272.3	36.6	65.8	381.7	27.4	503.1

The significance of uncertainty was stated based on [14] as following:

- $\sigma \in \langle 0, 20)$ – insignificant;
- $\sigma \in \langle 20, 40)$ – low;
- $\sigma \in \langle 40, 60)$ – medium;
- $\sigma \in \langle 60, 80)$ – high;
- $\sigma \in \langle 80$ and more) – undesirable.

For each pollutant and each month during the year the uncertainty has different values. We evaluate the model efficiency according to the average significance of uncertainty for period 2003–2008 for each pollutant separately (Table 4).

Table 4. Relative error of monitored period 2009–2010 for measured pollutants

Pollutant	σ (%)	Significance of uncertainty
N_{tot}	35.80	low
$N\text{-}NO_2^-$	73.35	high
$N\text{-}NO_3^-$	37.19	low
$N\text{-}NH_4^+$	76.35	high
P_{tot}	81.72	undesirable
BSK_5	56.57	medium
COD_{Cr}	76.04	high

It has been shown that the model is applicable to certain pollutants in surface water and the pollutants $N_{tot.}$, $N\text{-}NO_3^-$, where the relative error was within 40% (low). For indicators $N\text{-}NO_2^-$, $N\text{-}NO_4^+$ the model cannot be applied, according to documented calculations, since the relative error came between 60–80% (high). Pollutants in surface water are unstable to predict because it readily oxidized to a higher degree of oxidation. Model also cannot be used to predict pollutants COD_{Cr} and $P_{tot.}$ whereas the relative error according to calculations went as high as undesirable. The presence of these two substances in surface waters in large quantities can be as the result of natural processes or human activities. In the case of biological oxygen demand (BOD_5) relative error came to 60%, which seems to medium uncertainty and thus model can be used, but to increase the accuracy we recommend its use in conjunction with other methods of modeling.

4. Conclusion

The application of the model developed based on dimensional analysis that determines concentrations of pollutants in a water stream is presented in the paper. The fundamentals of modelling pollutant prediction in a water stream consist in derivation of function dependency from expressed non-dimensional arguments. Non-dimensional arguments are stated from variables which influence the occurrence of pollutants. Full selection of variables must be made in relation to assessment objectives and specific knowledge of each individual situation.

From the mentioned function dependency it is possible to obtain concentration values of a pollutant in a water stream. A model for determination of pollutant concentrations in a water stream has been developed for the river station Krasny Brod at the river Laborec in eastern Slovakia. The differences between the concentrations calculated from the developed model and measured concentrations are discussed in this paper. The use of dimensional analysis for water quality modelling is a new approach here.

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