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SENSITIVITY ANALYSIS OF INPUT DATA IN SURFACE WATER QUALITY MODELS

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The article is focused on analysis of input data impact on outputs of water quality models. The authors examined the impact of roughness coefficient, both boundary and initial conditions setup on changes of outputs generated by HEC-RAS model. Simulation results have shown a various response rate of input data on simulated results. The strong impact shows roughness coefficient setup that through the value of longitudinal dispersion coefficient affects pollution transport process. Changes in boundary conditions have had less influence on outputs. Relatively strong impact shows the setup of initial state of pollution concentration along the reach mainly for the case of low gradient rivers.

Keywords: sensitivity analysis, water quality modelling, open channel, HEC-RAS

With the development of economies and the improvement of living standards, our environment, especially natural water is constantly being polluted. In recent years, water pollution and water shortages in climate change conditions are two of the most serious and widespread environmental problems. Therefore, study of the analysis and management of the water quality of rivers recharged with reclaimed water has high theoretical and practical significance (Sokáč and Velísková, 2015). Mathematical models are used for approximation of various complex processes and phenomena (Ivan and Macura, 2014). The water quality modeling has the goal to provide as exactly as possible description of transport processes related to water quality changes. The determination of model parameters belongs among the most significant factors that affect the model results. The sensitivity analysis of these parameters is the crucial task in process of model validation (Hamby, 1994) and also provides support tools for decision making process in planning extent of field measurements necessary for modelling of transport processes in rivers and helps us to decide where we should focus data collection activities. The objectives of the sensitivity analysis are usually as follows: defining the model and its independent and dependent variables, identification of inputs which most influence the variability of outputs, determination of additional research of parameters for improving the knowledge base, reduction of the output uncertainty, determination of parameters which are most highly correlated with the output and in process of model use what consequence results from changing a given input parameter (Hamby, 1994). We may use several ways for conducting of sensitivity analyses. However, we may expect that for the same tasks we do not achieve identical results. We may distinguish quantitative and qualitative methods (Cariboni et al., 2007). There exist two basic approaches for sensitivity analysis (SA) – local SA and global SA. The local SA examines the local response of the outputs by varying input parameters one at a time, holding other parameters to a central value; and the global SA examines the global response averaged over the variation of all the parameters of model output by exploring a finite region (Xu et al., 2004).

Material and methods

For generating of simulated data sets for sensitivity analysis a model HEC-RAS has been used. It represents traditional numerical hydraulic model used to solve various river engineering tasks (USACE HEC, 2010). The water quality module that is a part of the HEC-RAS model, uses the QUICKEST-ULTIMATE explicit numerical scheme described by (Leonard, 1991), which solves the one-dimensional advection-dispersion equation (ADE) (Zhang and Johnson, 2014). The model includes transport and reactions that affect water quality variables that are either dissolved or in particulate form in the water column. For relatively simple transport scenarios, the ADE can be represented in the one-dimensional form (1):

$$\frac{\partial}{\partial t}(VC) = -\frac{\partial}{\partial x}(QC)\Delta x + \frac{\partial}{\partial x}\left[AD_x \frac{\partial C}{\partial x}\right]\Delta x + S_L + S_B + S_K \quad (1)$$

where:
V – volume of the water quality cell (m^3)
C – concentration of a constituent ($g.m^{-3}$)
Q – inflow ($m^3.s^{-1}$)
x – distance along channel (m)
D_x – water quality cell length (m)
A – cross-sectional flow area (m^2)
t – time (s)
D_x – dispersion coefficient ($m^2.s^{-1}$)

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S_L – source/sink term representing direct and diffuse loading rate (g.m^{-3}.s^{-1})

S_B – source/sink term representing boundary loading rate, including upstream, downstream, and benthic (g.m^{-3}.s^{-1})

S_K – source/sink term representing biogeochemical reaction rate (g.m^{-3}.s^{-1})

For sensitivity analysis we used "Measure of Local Sensitivity" approach that is, conceptually, the simplest method for sensitivity analysis which repeatedly varies one parameter at a time while holding the others (Hamby, 1994). A sensitivity ranking can be obtained quickly by increasing each parameter by a given percentage while leaving all others constant and quantifying the change in model outputs. The sensitivity assessment is based on a comparative analysis of model outputs reflecting the changes of parameters which describe model structure changes. Input parameters are represented by bed roughness coefficient, friction slope at both downstream and upstream boundaries, bed slope homogeneity and outputs are represented by maximal concentration of pollution course along the canal and travel time of pollution peak. Finally, the results were evaluated with sensitivity characteristic defined as an absolute value of ratio percentage of output change to percentage of input change.

Case study characteristics

The simulation analysis has been carried out for reference channel prototype represented by prismatic channel with bed slope S_o = 0.001, bed width w = 1.00 m, bank slope V : H = 1 : 1, channel depth d = 1.00 m, Manning´s roughness coefficient n = 0.030 and channel length L = 1,000 m. The distance of cross sections Δx = 50 m and water quality cell lengths Δx_q = 50 m.

Model inputs and loading scenarios

The analysis has been conducted for one loading scenario with initial conditions C_o = 0 mg.l^{-1} for the whole length of the canal. At the upstream boundary condition the instantaneous mass injection of 50,000 g NaCl was simulated. We simulated steady flow conditions with a constant discharge Q = 0.500 m^3.s^{-1}. Both the upstream and the downstream boundary conditions have been defined as a normal depth described by friction slope S_f = 0.001 as a reference condition. Dispersion coefficients D_x were computed by the model on the basis of hydraulic variables at each face according to Fischer equation (Fischer, 1979) (2). This approach avoids potential model instability (USACE HEC, 2010):

$$D_x = 0.011 \frac{u^2 W^2}{y u^*} \quad (2)$$

where:

u – face velocity (m.s^{-1})

W – average channel width (m)

y – depth of water in channel (m)

u^* – shear velocity (m.s^{-1})

The shear velocity is:

$$u^* = \sqrt{g d S_f} \quad (3)$$

where:

g – gravitational constant (9.81 m. s^{-2})

d – average channel depth (m)

S_L – friction slope (unitless)

Input parameter setup

The sensitivity analysis is based on input parameters changes and quantifying the change in model outputs. The comparison assumes that input parameter value ranges model structure are realistic and based on knowledge published in literature.

Results and discussion

The sensitivity analysis is based on a comparison of model outputs reflecting the changes of input parameters which are represented by channel roughness coefficient, and friction slope at both downstream and upstream boundaries. The outputs are represented by maximal concentration of pollution course in water quality cell (WQC) between river stations along the channel and travel time of pollution peak to given distance from injection point. Reference roughness state is defined with Manning's roughness coefficient n = 0.030.

Run 1

Input data – channel roughness with reference state n = 0.030

Model output – maximal concentration of pollution in particular WQC

The model output response in the first run was represented by dataset of maximal pollution concentration calculated for center of WQC. The input parameters changes are presented in Table 1. The obtained results are demonstrated in Table 2. Value ΔI (%) is percentage of input parameter change (roughness) and ΔO_m (%) is mean output change for all particular WQC.

Table 1 Channel roughness coefficients n and corresponding longitudinal dispersion coefficient D_x calculated by model and their changes to reference values (for n = 0.030)

n	**0.020**	**0.030**	**0.040**	**0.060**	**0.080**	**0.100**
Δ*n*	-33%	0%	33%	100%	167%	233%
D_x (m^2.s^{-1})	0.98	0.52	0.33	0.18	0.11	0.07
ΔD_x	-88%	0%	37%	65%	79%	87%

Table 2 Pollution concentration peak changes caused by channel roughness changes

Roughness		**Centre of WQC distance from injection point (meters)**											
		50	**150**	**250**	**350**	**450**	**550**	**650**	**750**	**850**	**950**	**1,000**	
n	±Δ*n*	$C_{max\ changes}$ (%)											
0.020	-33%	25	37	36	36	36	35	36	35	34	36	36	1.04
0.030	0%	0	0	0	0	0	0	0	0	0	0	0	0
0.040	33%	-16	-21	-19	-19	-20	-20	-19	-20	-20	-12	-14	0.50
0.060	100%	-35	-42	-41	-41	-41	-40	-41	-41	-41	-41	-41	0.40
0.080	167%	-47	-53	-60	-59	-59	-59	-59	-59	-58	-68	-68	0.35
0.100	233%	-54	-60	-60	-60	-60	-60	-60	-60	-60	-60	-60	0.25

Table 3 Travel time changes of pollution peak to a particular WQC caused by channel roughness change

Roughness		**Centre of WQC distance from injection point (m)**											
		0	**150**	**250**	**350**	**450**	**550**	**650**	**750**	**850**	**950**	**1,000**	
n	Δ*n*	travel time changes (%)											
0.020	-33%	0	0	-17	-30	-23	-25	-32	-27	-28	-30	-27	0.65
0.030	0%	0	0	0	0	0	0	0	0	0	0	0	0
0.040	33%	0	33	33	20	23	25	21	23	24	17	30	0.68
0.060	100%	0	67	67	60	62	63	68	68	68	17	30	0.52
0.080	167%	0	100	150	120	131	131	137	136	132	67	67	0.64
0.100	233%	0	133	150	130	131	138	142	136	140	143	157	0.55

Run 2

Input data – channel roughness/reference state $n = 0.030$

Model output – travel time changes of pollution peak in particular WQC

The model output response in the second run was represented by dataset of pollution peak travel time calculated to center of particular WQC. The obtained results are presented in Table 3.

The presented analyses show that model outputs reflecting the roughness change in the same order of magnitude as maximal pollution concentration and travel time of pollution concentration peak. There exist uniform changes of pollution peak concentration along the whole experimental reach where most sensitive were roughness decreasing ($n = 0.020$) and also increasing ($n = 0.040$) close to reference value ($n = 0.020$). A sensitivity characteristic was -1.04 for $n = 0.020$ and -0.50 for $n = 0.040$. Travel time outputs show higher uniformity and sensitivity characteristics reached values from 0.52 to 0.68. We may see different shape of concentration profiles presented in Fig. 1 and 2, where channel with higher values of the Manning´s coefficient has typical course with prolonged falling limb of maximal concentration connectors.

Run 3

Input data – friction slope at boundaries/reference state $S_f = 0.001$

Model output – change of pollution peak concentrations and travel time to particular WQC

The model output response in the third run was represented by data set of pollution peak changes caused by friction slope changes at upstream (US) and downstream (DS) boundaries (Table 4). The setup of friction slope S_f is

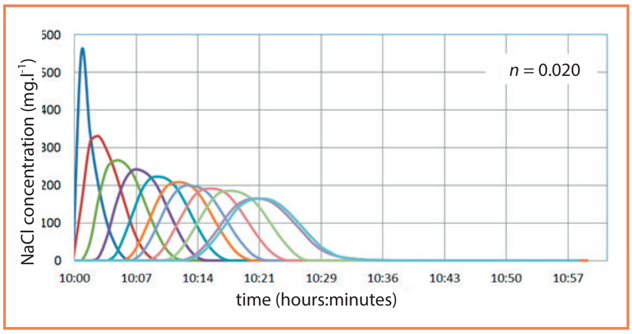

Figure 1 Concentration profiles for particular WQCs for $n = 0.020$ (from 50 to 950 m from injection point)

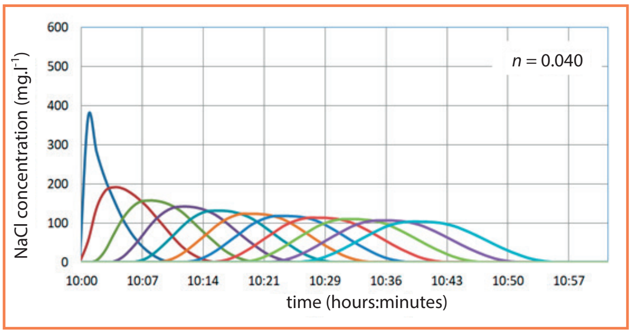

Figure 2 Concentration profiles for particular WQCs for $n = 0.040$ (from 50 to 950 m from injection point)

Table 4 Pollution concentration peak changes caused by friction slope changes at US and DS boundaries

Friction slope		**Centre of WQC distance from injection point (m)**				
		50	150	550	1,000	
S_f	Δt_f	$C_{max\ changes}$ (%)				
0.00025	-75%	0%	0%	-4%	-23%	0.31
0.00050	-50%	0%	0%	-1%	-12%	0.24
0.00100	0%	0%	0%	0%	0%	0.00
0.00200	100%	0%	0%	0%	0%	0.00
0.01000	900%	0%	0%	0%	4%	0.00

Table 5 Travel time changes of pollution peak caused by friction slope changes at US and DS boundaries (boundary conditions = normal depth)

Friction slope		**WQC distance from injection point (m)**				
		50	150	550	1,000	
S_f	$\pm\Delta_f$	travel time changes (%)				
0.00025	-75%	0%	0%	0%	13%	0.18
0.00050	-50%	0%	0%	0%	7%	0.13
0.00100	0%	0%	0%	0%	0%	0.00
0.00200	100%	0%	0%	0%	0%	0.00
0.01000	900%	0%	0%	0%	0%	0.00

necessary to setup boundary conditions defined as a normal depth. Roughness coefficient equals $n = 0.030$.

An effect of friction slope changes on outputs has not major influence (table 4 and 5). The S_f changes have been more reflected at reaches next to downstream boundary for lower values of friction slope ($S_f = 0.00025$ and 0.0005). It is due to forming of backwater curve that decreases the value of longitudinal dispersion coefficient. The higher values of n have not been projected to outputs value increases. The sensitivity characteristics reached values from 0.00 to 0.31 for pollution concentration peak changes and from 0.00 to 0.18 for travel time changes of pollution peak.

Conclusion

The sensitivity analysis represents a tool for the assessment of the input parameters with respect to their impact on model outputs. We can identify which parameters are important in the prediction of transport processes modelling. Sensitivity analysis helps us to decide where we should focus data collection activities. Our analyses have shown that most of the input parameters changes appear in the same order of magnitude as a response of outputs. The attention should be paid to exact determination of roughness coefficient where small differences from exact value sensitively affect the outputs. The results have also shown that accurate setup of boundary conditions is important for the case that normal depth is selected as a boundary condition and we have to determine the friction slope on basis of preliminary computations.

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