Simulation of river streams: Comparison of a new technique with QUAL2E

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Abstract

Predictions and quality management issues for environmental protection in river basins rely on water-quality models. These models can be used to simulate conditions in or near the range of the calibrated or verified conditions. In this respect, estimation of parameters, which is still practiced by heuristic approaches (i.e. manually), seems to be the point where the attention needs to be focused. The authors’ research group has developed a systematic approach for dynamic simulation and parameter estimation in river water quality models, which has eliminated the cumbersome trial-end-error method. This study reports a user-interactive software named as RSDS (River Stream Dynamics and Simulation) for the implementation of the suggested technique, and provides a comparative investigation of the suggested modelling approach against a well established and worldwide known water quality software, QUAL2E. Experimental data collected in field observations along the Yesilirmak river basin in Turkey were checked against the predictions from both software programs. The results indicated that much better agreement with the experimental data could be obtained from RSDS compared with QUAL2E. Thus, the systematic procedure suggested in the present work provides an effective means for reliable estimation of the model parameters and dynamic simulation for river basins, and therefore, contributes to the efforts toward predicting the extent of the effect of possible pollutant discharges in river basins.

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1. Introduction

Water quality models generally require a relatively large number of parameters to define their functional relationships, and since prior information on parameter values is limited, they are commonly defined by fitting the model to observed data. The model can be used to simulate conditions in or near the range of the calibrated or verified conditions. In this respect, the estimation of parameters, which is still practiced by heuristic approaches (i.e. manually), seems to be the point where the attention needs to be focused.

The state of the art in river water quality modelling was summarized by Rauch et al. [3], who addressed some issues related to the practical use of river quality models. Upon comparison of 10 important software products, they...
**Nomenclature**

- $A$: Algal biomass concentration, mg-A/L
- $C$: Concentration, (mg/L)
- $C_{ORDO}$: Nitrification rate correction factor
- $d$: Mean stream depth, m
- $F_1$: Fraction of algal nitrogen uptake from ammonia pool
- $F_L$: Algal growth limitation factor for light
- $F_N$: Algal growth limitation factor for nitrogen
- $F_P$: Algal growth limitation factor for phosphorus
- $I$: Surface light intensity, Cal/m$^2$-hr
- $K_1$: BOD deoxygenation rate constant, 1/day
- $K_2$: Reaeration rate constant, 1/day
- $K_3$: Rate of loss of BOD due to settling, 1/day
- $K_4$: Benthic oxygen uptake, mg-O/m$^2$-day
- $K_5$: Coliform die-off rate, 1/day
- $K_6$: Arbitrary non-conservative decay coefficient, 1/day
- $K_L$: Half saturation coefficient for light, Cal/m$^2$-hr
- $K_N$: The Michaelis Menten half-saturation constant for nitrogen, mg-N/L
- $K_{NITRF}$: First order nitrification inhibition coefficient, mg/L
- $K_P$: The Michaelis Menten half-saturation constant for phosphorus, mg-P/L
- $L$: Concentration of ultimate carbonaceous BOD, mg/L
- $N_1$: Ammonia nitrogen concentration, mg-N/L
- $N_2$: Nitrite nitrogen concentration, mg-N/L
- $N_3$: Nitrate nitrogen concentration, mg-N/L
- $N_4$: Organic nitrogen concentration, mg-N/L
- $N_e$: The effective local concentration of available inorganic nitrogen, mg-N/L
- $O^*$: The saturation concentration of dissolved oxygen at the local temperature and pressure, mg/L
- $O$: The concentration of dissolved oxygen, mg/L
- $P_2$: The local concentration of dissolved phosphorus, mg-P/L
- $P_N$: Preference factor for ammonia nitrogen
- $P_{wv}$: Partial pressure of water vapor, atm
- $Q$: Flow rate, m$^3$/s
- $t$: Time, day
- $T$: Temperature, K
- $V$: Volume of water in each divided CSTR, m$^3$
- $\alpha_0$: Conversion factor; ratio of chlorophyll-A to algal biomass, ug-Chl a/mg-A
- $\alpha_1$: Fraction of algal biomass that is nitrogen, mg-N/mg-A
- $\alpha_2$: Fraction of algal biomass that is phosphorous, mg-P/mg-A
- $\alpha_3$: $O_2$ production per unit of algal growth, mg-O/mg-A
- $\alpha_4$: $O_2$ uptake per unit of algae respired, mg-O/mg-A
- $\alpha_5$: $O_2$ uptake per unit of NH$_3$ oxidation, mg-O/mg-N
- $\alpha_6$: $O_2$ uptake per unit of NO$_2$ oxidation, mg-O/mg-N
- $\beta_1$: Rate constant for the biological oxidation of NH$_3$ to NO$_2$, 1/day
- $\beta_2$: Rate constant for the biological oxidation of NO$_2$ to NO$_3$, 1/day
- $\beta_3$: Rate constant for the hydrolysis of organic N to ammonia, 1/day
- $\beta_4$: Rate constant for the decay of organic-P to dissolved-P, 1/day
- $\sigma_1$: Algal settling rate, m/day
- $\sigma_2$: Benthos source rate for dissolved phosphorus, mg-P/m$^2$-day
indicated that only two of them offered limited parameter estimation capability. Mulligan and Brown [4] also noted that practitioners often resorted to manual trial-and-error curve fitting for calibration. The generally accepted software product for river water quality modeling worldwide is U.S. EPA’s QUAL2E [5]. However, this software does not address a number of practical problems, such as the issue of parameter estimation. In many practical applications of water quality models, parameter values are chosen manually rather than by automated numerical techniques, or heuristic approaches are resorted to [3]. It is known that automated methods are associated with some difficulties depending on the model’s structure, optimization method, number of variables and parameters, type of measurements and so on. So far, no automated estimation of parameters for river water quality models has been reported. In a recent work, Sincock et al. [7] reported a detailed study involving the identification of model parameters. However, data were considered relatively scarce, and although temperature was predicted accurately; nitrate, BOD\textsubscript{5} and DO predictions were less so.

In a previous study [1], we have suggested a dynamic simulation and parameter estimation strategy, so that the heavy burden of finding reaction rate coefficients could be overcome. Modelling was based on the fact that the segment of river between sampling stations was assumed to be a completely stirred tank reactor (CSTR). This particular work was later extended to the series called the CSTR approach [2].

The present study provides an extension to the previous approaches, particularly in terms of automatically generating reliable estimates of water quality model parameters without resorting to trial-and-error simulations. This work extends the previous works in the sense that (a) a MATLAB-based user-interactive software product is developed for easy implementation of the developed technique. The program, named RSDS (River Stream Dynamics and Simulation) and coded in the MATLAB\textsuperscript{TM} 6.5 environment [8], is reported here, (b) a comparative study is provided to assess the capabilities and effectiveness of the suggested technique in relation to the QUAL2E software.

2. Mathematical modelling and computing methodology

In dynamic modelling, serially connected CSTRs are assumed to represent the behaviour of a river stream. Each reactor forms a computational element and is connected sequentially to similar elements upstream and downstream. The following assumptions were employed for model development:

- Well-mixed dendritic stream
- Well mixing in cross sections of the river
- Constant stream flow and channel cross section
- Constant chemical and biological reaction rates within the computational element.

Physical, chemical and biological reactions and interactions that might occur in the stream have all been considered. The modelling strategy employed in this study stems from that of QUAL2E water quality model [5]. As representative elements of water quality from the perspective of environmental pollution, the following constituents were considered: organic nitrogen, ammonia nitrogen, nitrite nitrogen, nitrate nitrogen, biological oxygen demand, dissolved oxygen, organic phosphorous, dissolved phosphorus, coliforms, chloride, phytoplanktonic algae. The mass balances for
Fig. 1. Dissolved oxygen balance and effecting parameters in QUAL2E.

these constituents were written, and additionally several algebraic equations describing various phenomena such as conversion of different forms of nitrogen (as shown in Fig. 1) were involved. The model, thus, simulates stream flow and 11 water quality constituents, i.e. state variables. Considering a volume element of the stream, descriptive equations for the properties and constituents considered were established as follows:

Ammonia nitrogen:
\[
\frac{dN_1}{dt} = \beta_3 \cdot N_4 - \beta_1 \cdot N_1 + \frac{\sigma_3}{d} - F_1 \cdot \alpha_1 \cdot \mu \cdot A + (N_1^0 - N_1) \cdot \frac{Q}{V} \tag{1}
\]

where \( F_1 \) is given by [5],
\[
F_1 = \frac{P_N \cdot N_1}{(P_N \cdot N_1 + (1 - P_N) \cdot N_3)}. \tag{2}
\]

Nitrite nitrogen:
\[
\frac{dN_2}{dt} = \beta_1 \cdot N_1 - \beta_2 \cdot N_2 + (N_2^0 - N_2) \cdot \frac{Q}{V}. \tag{3}
\]

Nitrate nitrogen:
\[
\frac{dN_3}{dt} = \beta_2 \cdot N_2 - (1 - F_1) \cdot \alpha_1 \cdot \mu \cdot A + (N_3^0 - N_3) \cdot \frac{Q}{V}. \tag{4}
\]

Organic nitrogen:
\[
\frac{dN_4}{dt} = \alpha_1 \cdot \rho \cdot A - \beta_3 \cdot N_4 - \sigma_4 \cdot N_4 + (N_4^0 - N_4) \cdot \frac{Q}{V}. \tag{5}
\]
Rate correction factors for oxidation of ammonia and nitrite [5]:

\[ \text{CORDO} = 1.0 - \exp(-K_{\text{NITRF}} \cdot \text{DO}) \]  
\[ \text{Ammonia: } (\beta_1)_{\text{inhibition}} = \text{CORDO} \cdot (\beta_1)_{\text{input}} \]
Nitrite: \((\beta_2)_{\text{inhibition}} = C_{\text{ORDO}} \cdot (\beta_2)_{\text{input}}\).

Organic phosphorus:
\[
\frac{dP_1}{dt} = \alpha_2 \cdot \rho \cdot A - \beta_4 \cdot P_1 - \sigma_5 \cdot P_1 + (P_1^0 - P_1) \cdot \frac{Q}{V}.
\]

Dissolved phosphorus:
\[
\frac{dP_2}{dt} = \beta_4 \cdot P_1 + \frac{\sigma_5}{d} - \alpha_2 \cdot \mu \cdot A + (P_2^0 - P_2) \cdot \frac{Q}{V}.
\]

Carbonaceous BOD:
\[
\frac{dL}{dt} = -K_1 \cdot L - K_3 \cdot L + (L_0 - L) \cdot \frac{Q}{V}.
\]

Dissolved oxygen:
\[
\frac{dO}{dt} = K_2 \cdot (O^* - O) + (\alpha_3 \cdot \mu - \alpha_4 \cdot \rho) \cdot A - K_1 \cdot L - \frac{K_4}{d} - \alpha_5 \cdot \beta_1 \cdot N_1 - \alpha_6 \cdot \beta_2 \cdot N_2
\]
\[
+ (O^0 - O) \cdot \frac{Q}{V}.
\]

Predictive equation for the saturation (equilibrium) concentration of dissolved oxygen, is given below [5]
\[
\ln O^* = -139.34410 + \left(\frac{1.575701 \times 10^5}{T}\right) - \left(\frac{6.642308 \times 10^7}{T^2}\right) + \left(\frac{1.243800 \times 10^{10}}{T^3}\right) - \left(\frac{8.621949 \times 10^{11}}{T^4}\right)
\]

where \(T\) is the temperature as \(K\).

For non-standard conditions of pressure, the equilibrium concentration of dissolved oxygen is corrected by the following equation [5]
\[
O_p = O^* \cdot P \cdot \left[\frac{(1 - P_{\text{wv}}/P) \cdot (1 - \theta \cdot P)}{(1 - P_{\text{wv}}) \cdot (1 - \theta)}\right]
\]

\[\ln P_{\text{wv}} = 11.8571 - (3840.70/T) - (216961/T^2)\]
\[\theta = 0.000975 - (1.426 \times 10^{-5} \cdot T) + \left(6.436 \times 10^{-8} \cdot T^2\right)\]

where \(T\) is \(\text{0}^\circ\text{C}\).

Coliforms:
\[
\frac{dE}{dt} = -K_5 \cdot E + (E^0 - E) \cdot \frac{Q}{V}.
\]

Arbitrary nonconservative constituent: As for the non-conservative constituent, we have chosen chloride
\[
\frac{dR}{dt} = -K_6 \cdot R - \sigma_6 \cdot R + \frac{\sigma_7}{d} - (R^0 - R) \cdot \frac{Q}{V}.
\]

Phytoplanktonic algae (Chlorophyll a):
\[
\frac{dA}{dt} = \mu \cdot A - \rho \cdot A - \frac{\sigma_1}{d} \cdot A + (A^0 - A) \cdot \frac{Q}{V}.
\]

Algal specific growth rate:
\[
\mu = \mu_{\text{max}}(FL) \cdot \left[\frac{2}{1/FR + 1/FP}\right].
\]
Algal-light relationships:

\[ F_L = \left( \frac{1}{\lambda \cdot d} \right) \ln \left[ \frac{K_L + I}{K_L + I \cdot e^{\lambda_d}} \right]. \]  \hfill (21)

Algal self shading:

\[ \lambda = \lambda_0 + \lambda_1 \cdot A + \lambda_2 \cdot (\alpha_0 \cdot A)^{2/3}. \]  \hfill (22)

The algal growth limitation factors for nitrogen \((F_N)\) and for phosphorus \((F_P)\) are defined by the Monod expressions

\[ F_N = \frac{N_e}{N_e + K_N}, \]  \hfill (23)

\[ F_P = \frac{P_2}{P_2 + K_P}. \]  \hfill (24)

Algae are assumed to use ammonia and/or nitrate as a source of inorganic nitrogen. The effective concentration of available nitrogen is given by:

\[ N_e = N_1 + N_3. \]  \hfill (25)

Therefore, the model was constituted from the dynamic mass balances for different forms of nitrogen and phosphorus, biological oxygen demand, dissolved oxygen, coliforms, non-conservative constituents and algae for each computational element. Model parameters conforming to those in QUAL2E water quality model were estimated by an integration based optimization algorithm by minimizing an objective function. As the QUAL2E model is almost the standard for river water quality modelling, we have chosen it for comparing the predictions from the suggested new methodology.

A nonlinear constrained parameter estimation strategy has been incorporated into the simulation so that a number of techniques (involving Gauss–Newton, Levenberg–Marquardt and Sequential Quadratic Programming SQP algorithms) can be employed. SQP, being the most effective of all, updates the Hessian matrix of the Lagrangian function, solves the quadratic programming subproblem and uses a line search and merit function calculation at each
iteration. The estimation strategy was based on minimizing an objective function defining (Eq. (26)), the difference between the predictions and observed data during the transient period of observations.

$$J = \sum_{i=1}^{n} \sum_{j=1}^{m} (x_{ij} - x_{d,ij})^2$$  \hspace{1cm} (26)

where $x$: computed value, $x_d$: observed value, $n$: total number of state variables and $m$: total number of observation points in time for the particular station.

A software and graphical user interface has been developed to implement the suggested dynamic simulation and parameter estimation technique. The program, named RSDS (River Stream Dynamics and Simulation), was coded in the MATLAB™6.5 environment. This RSDS software has the ability to make dynamic simulations using a stiff Runge–Kutta type explicit integrator along the river, and parameter estimation with different optimization methods as explained above. The program requires some input data in five main steps as follows:

- Flow rate, cross-section and length of the river to be simulated
- Initial values for state variables
- If any loading is made to river from a waste water source, properties of that loading (i.e. flow rates, value of the state variables.)
- Initial values of 33 model parameters
- Temperature and depth of the river.

After entering the inputs, the program runs and calculates the changes in each state variable along the river. The results are displayed in the graphical user interface, which includes standard file, run, view and help menus and graphic displays for monitoring the pollution constituents (Fig. 2(a) and (b)). If the parameter estimation is selected, a new menu opens and data input is made possible in four steps. These steps require the introduction of initial values, lower and upper bounds for the parameters, time intervals, and experimental values of the state variables. The program can be run after a selection of the optimization method to get the best estimates of the model parameters. In addition, the interface gives the value of the objective function reached, and the CPU time spent for the computation.

3. Experimental measurements

For both field observations and data collection, the concentrations of many water-quality constituents indicative of the level of pollution in the river were determined either on-site by portable analysis systems, or in laboratory
after careful conservation of the samples. The experimental data for parameter estimation were obtained from two sampling stations along the Yesilirmak River around the city of Amasya in Turkey. The concentrations of ten water-quality constituents, corresponding to the state variables of the model and indicative of the level of pollution in the river, were determined either on-site by portable analysis systems or in laboratory after careful conservation. For in situ measurements, four samples were taken and analysed, and the mean of these four values was used. For determination of BOD and coliform, samples were taken to the laboratory following careful conservation of the samples. Only representative algae concentrations were taken from the literature. The details about the analysis systems and methods used were presented in [1].
Water quality constituents of the river were determined at various locations along a 7 km long section of the river. The sampling location matched with the river stream such that the volume element of water whose quality was sampled at the location zero (i.e. starting point, Durucasu gauging station) was followed with the stream. This was just like dynamically keeping track of an element in the river flowing the same velocity as the main stream. The location of sampling points were determined such that available measurement and would suffice to make such a study possible. After the starting point, sampling was done at locations 0.225, 4, 5 and 7 km downstream. The industrial wastewater of a baker’s yeast production plant was being discharged right beyond the starting point. Therefore, the results of the study would indicate the extent of the pollution caused by the discharge from this industrial plant. In the simulations,
the addition of this discharge was considered as a continuous disturbance to the system, and its effect on the water quality, thus, were determined. Table 1 gives the characteristics of discharge from this local industrial plant. Table 2 reveals the properties of the Yesilirmak river just before and after mixing of the industrial discharge.

4. Results

Predictions from the RSDS and QUAL2E programs were then compared to the field data for the river reach of 7 km. Figs. 3–12 show the profiles of the ten important pollution variables, Ammonia-N, Nitrite-N, Nitrate-N, Organic-N,
Organic-P, Dissolved-P, BOD$_5$, Dissolved Oxygen (DO), Coliform and Chloride along a 7 km section of the river after point source input.

For quantitative evaluation and comparison, Absolute Average Deviation (AAD) values were calculated for both software products [6].

$$\% \text{ AAD} = \frac{1}{N} \sum_{i=1}^{N} \frac{(|y_{\text{exp}} - y_{\text{cal}}|)}{y_{\text{exp}}} \times 100$$

($N$: Number of measurements, $y_{\text{exp}}$: experimental value, $y_{\text{cal}}$: calculated value).
Table 1
Characteristics of discharge from this local industrial plant

<table>
<thead>
<tr>
<th>Variables</th>
<th>Cooling water of yeast fermentation</th>
<th>Waste water of yeast fermentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (m)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>23.4</td>
<td>24.5</td>
</tr>
<tr>
<td>Flow (m³/s)</td>
<td>0.2778</td>
<td>0.0111</td>
</tr>
<tr>
<td>Ammonia, (mg/L)</td>
<td>24.6</td>
<td>96.4</td>
</tr>
<tr>
<td>Nitrite, (mg/L)</td>
<td>4.66</td>
<td>0.181</td>
</tr>
<tr>
<td>Nitrate, (mg/L)</td>
<td>54.0</td>
<td>2.2</td>
</tr>
<tr>
<td>Org-N, (mg/L)</td>
<td>1.34</td>
<td>2.75</td>
</tr>
<tr>
<td>Org-P, (mg/L)</td>
<td>0.533</td>
<td>0.11</td>
</tr>
<tr>
<td>Dis.-P (mg/L)</td>
<td>12.8</td>
<td>2.445</td>
</tr>
<tr>
<td>BOD, (mg/L)</td>
<td>95.0</td>
<td>23.0</td>
</tr>
<tr>
<td>DO, (mg/L)</td>
<td>7.2</td>
<td>6.8</td>
</tr>
<tr>
<td>Coliform, (colonies/100 ml)</td>
<td>2000</td>
<td>1000</td>
</tr>
<tr>
<td>Chloride, (mg/L)</td>
<td>0.6</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Table 2
Properties of the Yesilirmak river just before and after the mixing of the industrial discharge

<table>
<thead>
<tr>
<th>Variables</th>
<th>Yeşilirmak—before mixing</th>
<th>Yeşilirmak—after mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (m)</td>
<td>0</td>
<td>225 4000 5000 7000</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>23</td>
<td>23.5 24.9 24.3 24.6</td>
</tr>
<tr>
<td>Flow (m³/s)</td>
<td>8.6</td>
<td>8.89 8.89 8.89 8.89</td>
</tr>
<tr>
<td>Ammonia, (mg/L)</td>
<td>0.83</td>
<td>1.2 1.15 0.97 1.11</td>
</tr>
<tr>
<td>Nitrite, (mg/L)</td>
<td>0.036</td>
<td>0.11 0.087 0.075 0.075</td>
</tr>
<tr>
<td>Nitrate, (mg/L)</td>
<td>1.6</td>
<td>2.2 2.4 2.5 2.2</td>
</tr>
<tr>
<td>Org-N, (mg/L)</td>
<td>0.045</td>
<td>0.052 0.05 0.022 0.020</td>
</tr>
<tr>
<td>Org-P, (mg/L)</td>
<td>0.07</td>
<td>0.07 0.082 0.068 0.052</td>
</tr>
<tr>
<td>Dis.-P (mg/L)</td>
<td>1.667</td>
<td>2.0 1.8 1.75 1.7</td>
</tr>
<tr>
<td>BOD, (mg/L)</td>
<td>13</td>
<td>14 14.5 13 12</td>
</tr>
<tr>
<td>DO, (mg/L)</td>
<td>7.6</td>
<td>7.4 7.65 7.9 7.8</td>
</tr>
<tr>
<td>Coliform, (colonies/100 ml)</td>
<td>4000</td>
<td>3500 4000 3500 3000</td>
</tr>
<tr>
<td>Chloride, (mg/L)</td>
<td>0.05</td>
<td>0.05 0.03 0.01 0.01</td>
</tr>
<tr>
<td>Algae, (mg/L)</td>
<td>0.05</td>
<td>0.05 0.05 0.05 0.05</td>
</tr>
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</table>

Table 3
Absolute average deviation (AAD) values for both software

<table>
<thead>
<tr>
<th>State variables</th>
<th>%AAD</th>
<th>RSDS</th>
<th>QUAL2E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia nitrogen</td>
<td>5.61</td>
<td>19.38</td>
<td></td>
</tr>
<tr>
<td>Nitrite nitrogen</td>
<td>13.50</td>
<td>76.40</td>
<td></td>
</tr>
<tr>
<td>Nitrate nitrogen</td>
<td>4.54</td>
<td>24.32</td>
<td></td>
</tr>
<tr>
<td>Organic nitrogen</td>
<td>27.24</td>
<td>11.80</td>
<td></td>
</tr>
<tr>
<td>Organic phosphorus</td>
<td>9.00</td>
<td>3.46</td>
<td></td>
</tr>
<tr>
<td>Dissolved phosphorus</td>
<td>3.74</td>
<td>6.92</td>
<td></td>
</tr>
<tr>
<td>BOD₅</td>
<td>2.37</td>
<td>3.14</td>
<td></td>
</tr>
<tr>
<td>Dissolved oxygen</td>
<td>0.83</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>Coliform</td>
<td>6.63</td>
<td>4.73</td>
<td></td>
</tr>
<tr>
<td>Chloride</td>
<td>21.47</td>
<td>23.19</td>
<td></td>
</tr>
</tbody>
</table>

The results are given in Table 3 for ten pollution variables considered. It can be seen from this table that the absolute average deviation values were much higher for QUAL2E than for RSDS for most of the state variables. The predictions from RSDS indicated a much better agreement with the experimental data compared to QUAL2E. Thus,
the dynamic simulation procedure suggested in the present, as well as previous, work of ours provides a valuable model calibration tool for easily and reliably estimating the model parameters for river basins.

5. Conclusions

The results of comparisons to extensive field data for a number of water quality constituents revealed that the predictions from the developed RSDS software are considerably better than those from QUAL2E. Besides, the proposed new software, with an interactive graphical user interface, allows the easy determination of simulation parameters, eliminating any need for trial and error runs. Therefore, the systematic procedure suggested here provides an effective means for the reliable estimation of model parameters and dynamic simulation for river basins. It has the potential to be a helpful tool for assessing the consequences of different scenarios for water resources planning.

This work contributes to the efforts toward predicting the extent of the effect of possible pollutant discharges in river basins, and therefore, holds promise for reliable ‘environmental impact assessment’ studies.

References