EVALUATION OF SEFIDROUD RIVER’S REAERATION-RATE COEFFICIENT, IRAN

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ABSTRACT

Accurate estimation of the reaeration rate coefficient is very important for the purposes of dissolved oxygen and self-purification modelling in rivers. The main target of this paper is to evaluate 19 commonly used reaeration rate coefficient prediction equations, in Sefidroud River, North of IRAN. In this paper the river's dissolved oxygen has been modelled involving Streeter-Phelps Equation. Then the predicted reaeration rate coefficient results have been compared with four series of collected and recorded data of the river. The studied reach has a length of 110km, including 12 water quality sampling stations along the river and it is extended from downstream of Sefidroud dam to the south coast of Caspian Sea. According to the results, among all equations Parkhurst-Pomeroy equation has shown the most accurate prediction of the reaeration rate coefficient values, with the statistical criteria of Standard Error (SE), Mean Multiplicative Error (MME) and Sum of Square of Residuals (SSR) equal to 0.51, 1.05 and 2.35, respectively. Moreover, results indicate that the river has a high Biochemical Oxygen Demand (BOD) and as well a low Self-Purification capacity, during September, which is simultaneous with the seepage of non-point agricultural pollutants.

Keywords: reaeration rate coefficient, dissolved oxygen, Sefidroud River, water quality model.

1. INTRODUCTION

Three basic approaches, namely, the DO balance technique (Streeter and Phelps, 1925; Churchill et al., 1962), distributed equilibrium technique (Zogorski and Faust, 1973) and tracer techniques (Tsivoglou and Wallace, 1972) have been used, so far, in different studies for experimental evaluation of \( k_a \), reaeration rate coefficient (also see Palumbo and Brown, 2014). Bowie et al. (1985) summarized the studies that compared different reaeration coefficients. They concluded that there is no a single appropriate equation for all river cases, i.e. for any cases the best fit formula should be recognize and applied. Haider and Ali (2010) based on sensitivity analysis concluded that O’Connor–Dobbins formula has shown the least sensitivity under variable flow conditions of the Ravi River in Pakistan. Also, Haider et al. (2012) reviewed 29 reaeration rate coefficient relations and founded that in general, the group of equations containing depth and velocity as the only two variables affecting reaeration rate coefficient performed better than the equations in other groups. Omole et al. (2013) used the Akaike and Bayesian information criteria in the selection and analysis of ten models to identify the most suitable reaeration coefficient model for River Atuwara, Ogun State, Nigeria. They concluded that the used approach yield better results than empirical models developed for local conditions while it is also useful in conserving scarce resources. Kalburgi and et al. (2014) used 13 empirical reaeration equations for their applicability in Ghataprabha River system, Karnataka, India. Their results show that the predictive equation developed by Jha et al. (2001), yielded the best fit with field data. Palumbo and Brown (2014) evaluated performance of 18 reaeration rate coefficient prediction equations using statistical metrics of prediction accuracy and bias by comparing predicted reaeration coefficients to a database of values measured using gas tracer techniques. Their results show that no single reaeration equation performed well over all hydraulic conditions. Also, even the top-performing equations exhibited large prediction errors of at least 40–50% and exceeded 100% in some regions.

Jamali and Ebrahimi (2011) carried out a time-series analysis for prediction of chlorine concentration and electrical conductivity data for the period of 1991-2005 in Sefidroud River, Northern of IRAN, which has been studied in the current paper. Their study showed that the SARIMA model can be used reliably to predict chlorine concentration and electrical conductivity time series data in Sefidroud River. Although many efforts are made in developing the empirical relations, each of empirical formula is valid only over a definite range of hydraulic conditions and there is still a lack of an accurate general formula for reaeration rate coefficient. The most of \( k_a \) relationships are not applicable to all types of rivers, particularly in large and wide rivers with extreme flow variations. Due to this persisting uncertainty, there is a need to test the validity of most the equations to estimate \( k_a \).

The main objective of this paper is to evaluate the applicability of different reaeration rate coefficient empirical equations, in DO simulation models.
2. Materials and methods

2.1 Study area and database

The Sefidroud River rising in northwestern Iran and is flowing generally northeast to meet the Caspian Sea, at Rasht City. The study reach is consisted of a length of about 110 km located between Manjil Dam and Caspian Sea and has been considered for modelling and field measurements (see Figure 1, below).

![Figure 1 - Location of the selected Sefidroud River segments](image)

Figure 1 illustrates the location of 12 main sampling stations that highlighted with numbering. It worth noting that, stations 4, 6 and 8 located on Toutkabon, Tarikroud and Zilikiroud Rivers which are tributaries of Sefidroud River. Water samples were collected four times from 12 above mentioned stations. Moreover, water samples were collected only one time from 11 other points which are presented in figure 1. The selected segment of Sefidroud length was then divided to 8 reaches to model DO using Streeter-Phelps model (see figure 1).

Data sets were collected and measured along the river in two different periods during Dec 2007 to Nov 2008 and Feb 2011 to Aug 2011. The first sampling was carried out at 12 mentioned stations in Dec 2007, Jul 2008, Oct 2008 and Nov 2008. Also, Second sampling was carried out in Feb 2011, Apr 2011, Jun 2011 and Aug 2011 at five sections included; station 1, 5, 9, 11 and 12.

Minimum and maximum of average monthly discharges trough sampling months were measured equal to 10 and 88 m$^3$/s in Oct-08 and Jun-11, respectively. The measured water temperature shows that Jul-08 and Feb-11 were the warmest and coolest of the recorded water temperatures equal to 29.6°C and 7.9°C. Measured DO concentrations in lowest and largest amounts in Oct-08 and Jun-11 were with a minimum and maximum equal to 3.4 and 12.7 mg/l. Moreover, the minimum and maximum measured values of BOD were equal to 1.6 mg/l in Apr-11 and 98.0 mg/l in Oct-08.

2.2 Water Quality Model

In this paper, in order to simulate DO, along Sefidroud River under different flow conditions, the one-dimensional steady-state model, equation 1 below, was programmed for a multi-reach system (also see Thomann and Mueller, 1987).
Where \( D \) is DO deficit, \( D_0 \) is the initial value of DO, \( t \) is the travel time, \( L_0 \) is the Ultimate Biochemical Oxygen Demand (BODU), \( K_a \) is the reaeration rate coefficient, \( K_c \) is the BOD deoxygenation rate coefficient. The DO deficit \( (D) \) in Equation 1 is the difference between the DO concentration at any location \( C \) and the saturation DO concentration \( C_s \) in the river. The DO levels in the river water are related to the DO deficit by the following equation,

\[
C = C_s - D
\]

Where concentration of oxygen in water at equilibrium with water in saturated air is calculated using the equation 3 (Benson and Krause, 1984):

\[
\ln C_s = -139.34411 + \left[ 1.575701 \times 10^5 / T \right] - \left[ 6.642308 \times 10^7 / T^2 \right] + \left[ 1.243800 \times 10^{10} / T^3 \right] - \left[ 8.621949 \times 10^{11} / T^4 \right] - Chl \left[ 3.1929 \times 10^{-2} - (1.9428 \times 10 / T) + (3.8673 \times 10^3 / T^2) \right]
\]

Where \( T \) (°C) is the water temperature and Chl is chlorinity and it is related to the salinity (Chl = EC/1.80655).

### 2.3 Reaeration Rate Coefficient Prediction Equations

Many investigators have done comprehensive literature review of different empirical reaeration rate coefficients (Haider, 2010; Haider et al., 2012, Kalburgi et al., 2014). Table 1 show 19 well-known of the reaeration equations, which were evaluated in this paper and they are based on number of variables.

Table 1. Commonly used predictive reaeration coefficient equations for rivers and streams (Gualtieri C. and Gualtieri P., 2002 and Haider et al., 2012).

<table>
<thead>
<tr>
<th>No.</th>
<th>Investigator(s)</th>
<th>Abb.</th>
<th>Reaeration Eq.</th>
<th>Applicability and the used system</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>O Connor and Dobbins</td>
<td>OD</td>
<td>( K_a = 3.93U^{0.5}H^{-1.5} )</td>
<td>0.3 ≤ H ≤ 0.15 m/s, 0.01 ≤ U ≤ 0.49 m/s</td>
</tr>
<tr>
<td>2</td>
<td>Churchill et al.</td>
<td>CH</td>
<td>( K_a = 5.026U^{1-1.67} )</td>
<td>0.61 ≤ H ≤ 3.35 m, 0.55 ≤ U ≤ 1.52 m/s</td>
</tr>
<tr>
<td>3</td>
<td>Krenel and Orlob</td>
<td>KO</td>
<td>( K_a = 173SU^{0.06}H^{-0.66} )</td>
<td>0.02 ≤ H ≤ 0.06 m</td>
</tr>
<tr>
<td>4</td>
<td>Owens et al.</td>
<td>OW</td>
<td>( K_a = 5.32U^{0.67}H^{-1.85} )</td>
<td>0.12 ≤ H ≤ 0.35 m, 0.03 ≤ U ≤ 1.52 m/s</td>
</tr>
<tr>
<td>5</td>
<td>Langbein and Durum</td>
<td>LD</td>
<td>( K_a = 3.514U^{1-1.13} )</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>Issacs and Gaudy</td>
<td>IG</td>
<td>( K_a = 4.753U^{1-1.5} )</td>
<td>0.15 ≤ H ≤ 0.46 m, 0.1 ≤ H ≤ 0.50 m/s</td>
</tr>
<tr>
<td>7</td>
<td>Cadwallader and McDonnel</td>
<td>CM</td>
<td>( K_a = 186SU^{0.5}H^{-1} )</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>Negulescu and Rojanski</td>
<td>NR</td>
<td>( K_a = 10.96U^{0.85}H^{-0.85} )</td>
<td>H ≤ 0.15 m</td>
</tr>
<tr>
<td>9</td>
<td>Eloubaldy</td>
<td>EL</td>
<td>( K_a = 4.05U^{1-1.5} )</td>
<td>Recirculating flume</td>
</tr>
<tr>
<td>10</td>
<td>Issacs et al.</td>
<td>IS</td>
<td>( K_a = 3.65U^{1-1.5} )</td>
<td>Recirculating cylindrical flume</td>
</tr>
<tr>
<td>11</td>
<td>Padden and Gloyna</td>
<td>PG</td>
<td>( K_a = 4.54L/UH^{1.5} )</td>
<td>0.07 ≤ H ≤ 0.15 day-1</td>
</tr>
<tr>
<td>12</td>
<td>Bennett and Rathburn</td>
<td>BR</td>
<td>( K_a = 5.577SU^{1.607}H^{-1.689} )</td>
<td>0.12 ≤ H ≤ 3.48 m, 0.04 ≤ H ≤ 1.52 m/s</td>
</tr>
<tr>
<td>13</td>
<td>Parkhurst and Pomeroy</td>
<td>PP</td>
<td>( K_a = 23.04U^{1.17U^2}SU^{-0.375}H^{-1} )</td>
<td>Streams, Rivers</td>
</tr>
<tr>
<td>14</td>
<td>Lau</td>
<td>LA</td>
<td>( K_a = 2.5067UH[U/H]^3 )</td>
<td>Large rivers</td>
</tr>
<tr>
<td>15</td>
<td>Bansal (1973)</td>
<td>BA</td>
<td>( K_a = 4.152SU^{0.5}H^{-1.14} )</td>
<td>Numerous rivers</td>
</tr>
<tr>
<td>16</td>
<td>Smoot (1988)</td>
<td>SM</td>
<td>( K_a = 543S^{0.6264}U^{0.5325}H^{-0.7258} )</td>
<td>-</td>
</tr>
<tr>
<td>17</td>
<td>Baechler and Lazo</td>
<td>BL</td>
<td>( K_a = 1.923U^{1.325}H^{-2.006} )</td>
<td>Mountainous rivers</td>
</tr>
<tr>
<td>18</td>
<td>Melching and Flores</td>
<td>MF</td>
<td>( K_a = 596SU^{0.528}H^{-0.336} )</td>
<td>Large rivers and streams</td>
</tr>
<tr>
<td>19</td>
<td>Jha et al. (2001)</td>
<td>JH</td>
<td>( K_a = 5.792U^{0.5}H^{-0.25} )</td>
<td>River</td>
</tr>
</tbody>
</table>

Note: \( K_a \) = reaeration rate coefficient (day-1), \( U \) = mean stream velocity (m/s), \( H \) = mean stream depth (m), \( Q \) = discharge (m^3/s), \( S \) = river bed slope (m/m), \( u^\star \) = fluid shear velocity (m/s), \( g \) = acceleration due to gravity (m/s^2), \( F \) = Froude number (dimensionless), \( D \) = molecular diffusivity coefficient (m^2/s), \( R_g \) = gas-transfer Reynolds number (dimensionless), \( n \) = kinematic velocity of fluid (m^2/s). * Identified as best performer of reaeration equation in EPA (Bowie et al.1985).
The range of Ka has been calculated for all of the Sefidroud River reaches with different hydrodynamic conditions and using all equations given in Table 1. The reaeration rate coefficient equations based on the mentioned equations are presented in Equation 4:

\[
(K_a)_T = (K_a)_{20}(\theta)^{T-20} \tag{4}
\]

Where, \((K_a)_{20}\) and \((K_a)_T\) are the reaeration rate constants at 20°C and at a temperature of \(T\), respectively. In this paper for the constant “\(\theta\)”, a value of 1.024 is used, as proposed by Holley (1975).

2.4 Statistical Analysis

The performance of all the predictive equations given in Table 1 was evaluated using four statistical criteria included; Normalized Mean Error (NME), Standard Error (SE), Means Multiplicative Error (MME) and Percent Bias (PBIAS). SSR being modeled.

The SSR of equations is in parentheses.

Table 2 - Top-performing reaeration rate coefficient prediction equations

<table>
<thead>
<tr>
<th>Per.</th>
<th>Sampling date</th>
<th>Rank - Equation Abb. (SE)</th>
<th>Hydraulic Cha.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nu.</td>
<td>date</td>
<td></td>
<td>Velocity(m/s)</td>
</tr>
<tr>
<td>1</td>
<td>Dec-07</td>
<td>PP(0.87) BL(0.89) OD(1.10) IS(1.10) BA(1.14) EL(1.17) PG(1.24) IG(1.26) OW(1.28) CH(1.29)</td>
<td>0.01-1.09</td>
</tr>
<tr>
<td>2</td>
<td>Jul-08</td>
<td>KO(0.95) MF(0.96) SM(0.97) NR(0.96) CM(1.03) JH(1.04) LA(1.06) LD(1.08) PG(1.09) IG(1.09)</td>
<td>0.99-1.26</td>
</tr>
<tr>
<td>3</td>
<td>Oct-08</td>
<td>BL(3.14) IS(3.14) EL(3.14) CH(3.15) OW(3.15) IG(3.17) BA(3.18) BR(3.18) PP(3.19)</td>
<td>0.97-0.98</td>
</tr>
</tbody>
</table>

Note: SE of equations is in parentheses.

Among equations listed in table 2, BL (Baecheler and Lazo, 1999) which appear in four sampling months (Oct-08, Feb-11, Apr-11 and Jun-11) is the best Reaeration Rate Coefficient Equation (rank 1). The BL equation is covering all velocities ranging from 0.96 to 1.36 m/s and all depths ranging from 1.15 to 2.93 m. Table 2 shows that in period numbers 2 and 8 (Jul-08 and Aug-11) KO and MF equations could be selected as the best performing equations, their velocities and their depths have been the same ranging (Double underlined) from 0.97 to 2.36 m and 2.30 to 2.35 m. Table 2 also highlights that overall water quality model uncertainty due to error introduced from reaeration can likely be minimized by selecting appropriate reaeration rate coefficient prediction equations based upon the anticipated depth and velocity of the stream being modeled.
General speaking, ten equations including; BL, PP, IS, KO, MF, EL, OD, OW, BA and CH are selected in the initial step in identifying the best performing equations with the lowest SE, correspondingly. The second step in identifying the best performing equations was to select the equation with the lowest MME and PBIAS in sampling months. However, it soon became clear that the equations have very similar MMEs ranging from 1.04 to 1.78. PBIAS value of zero is optimal and indicates accuracy of model simulation. However, negative and positive PBIAS values indicate overestimation and underestimation in simulation, respectively. The largest error metric values (SE, MME and PBIAS) are belonging to DO modeling in third period sampling, Oct-08. Also, all of ten selected equations except PP and BL equations have overestimate the DO in Oct-08 with more than 40%. However, KO and MF equations have the largest PBIASs in Oct-08, but they have the lowest Error in Jul-08 and Aug-11. The modeled results using Streeter-Phelps model show reasonable agreement between the predicted values and field measurements in all months. The NME values are found to be uniform for all of the predictive equations and so do not indicate any equation to be suitable for all of sampling months. The NME values vary for different predictive equations and indicate that some of the equations are suitable to simulate the DO in the Sefidroud River.

Covar (1976) recommended the Owens et al. (1964) equation for stream depths less than 0.6 m and all velocities and for depths greater than 0.6 m, he recommended either the O’Connor-Dobbins (1958) or Churchill et al. (1962) equations, which could be used depending upon stream velocity. Zison et al. (1978) evaluated Covar method (1976) and found that the O’Connor-Dobbins (1958), Churchill et al. (1962) and Owens et al. (1964) equations could be applicable in a different depth and velocity regimes. Also, the results show that OD (O’Connor and Dobbins, 1958) and CH (Churchill et al., 1962) equations have not suitable performing for depths greater than 0.6 m. Palumbo and Brown (2014) concluded that the overall performance of the Covar (1976) guidance is poor with many MME values greater than 2.0 and the Bias Factor values indicate significant overestimation at low depths and underestimation at greater depths.

4. Conclusions

The main conclusion of the evaluation of the equations is that appropriate equation for predicting reaeration rate coefficient of any river is dependent on the hydraulic condition of the stream reach. Results of this research showed that for Sefidroud River BL (Baecheler and Lazo, 1999) and PP (Parkhurst and Pomeroy, 1972) equations are the most appropriate formula for all depths are ranging from 1.15-2.93 m and all velocities ranging from 0.96-1.36 m/s, respectively. Whereas MF (Melching and Flores, 1999) and KO (Krenkli and Orlob, 1963) equations are appropriate for depths greater than 2.30 m and velocities ranging from 0.97-1.26 m/s. Sensitivity analyses of top-performed, in reaeration rate equations show that the PP (Parkhurst and Pomeroy, 1972) and BL (Baecheler and Lazo, 1999) are least sensitive to variations in Sefidroud River flows, but MF, KO and EL have a high sensitivity to the variation of flow.

ACKNOWLEDGMENTS

The Sefidroud River water quality data, used in this paper, were collected by IRAN’s Environment Protection Organization and the study has been supported by the University of Tehran. The authors are grateful to the University of Tehran and would like to also express their sincere appreciation and gratitude to the, IRAN’s Environment Protection Organization.

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