Application of QUAL2EU Model for the Simulation of Dissolved Oxygen Concentration in Pawtuxet River

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Abstract: A small scale river flows through heavily urbanized areas, receives effluents from 3 municipal wastewater treatment facilities (WWTFs) and one industrial WWTF. The river has summer dissolved oxygen (DO) concentrations well below 5 mg/L standard for most of its path. The QUAL2EU model was used to allocate the waste loads into the river. Biochemical oxygen demand (BOD) decay and nitrification rates were calculated by measuring instream concentrations.

The hydrologic and water quality data incorporated into the model were very close to the Qd0 flow and served as a basis for a DO/BOD waste load allocation (WLA). The WLA results were used to develop permit limits for the 3 municipal WWTFs along the river. The WLA indicated that discharge permit limits of BOD 10 mg/L, ammonia (NH3) 2 mg/L are required to attain the instream DO criteria of 5 mg/L. When simulating an advanced treatment, effluent DO concentrations were set to 6 mg/L and instream BOD decay rates were decreased from the validated rate of 0.35 to 0.23 day^{-1}. BOD decay rates were decreased to correspond to the lower effluent concentrations which would leave only refractory materials that are difficult to degrade. Flow augmentation was not found to be an acceptable alternative to advanced treatment.

Key Words: Dissolved Oxygen, Waste Load Allocation, Numerical Model, Advanced Treatment

INTRODUCTION

Waste load allocations (WLA) are frequently performed by regulatory agencies to maximize the use of a stream’s waste assimilative capacity, while protecting the ecology of stream. Dissolved oxygen (DO) concentration is often used as an indicator of a stream’s waste assimilative capacity. DO concentration of a stream is reduced as compounds present in the river system are broken down by chemical and biological oxidation. A numerical modeling of DO dynamics provides the opportunity to evaluate the effect of various point source treatment scenarios on instream DO. Therefore, the numerical model of DO is an integral part of waste load allocation and discharge permit development.

The Pawtuxet River flows through heavily urbanized areas in central Rhode Island, receives effluents from 3 municipal wastewater treatment facilities (WWTFs) and one industrial WWTF. The purpose of this study is to distribute the waste assimilative capacity of the river among the municipal and industrial dischargers in such a manner as to attain the DO concentration of 5 mg/L during critical low flow. The critical low flow is defined as the low flow which occurs over 7 consecutive days with a return period of once every 10 years (Q_d0)^1. The QUAL2EU, which was developed by the support of the U.S. Environmental Protection Agency (USEPA)^2, is a numerical model that was used in this study as the basis for discharge permit levels for the river. The ultimate goal of the modeling effort was to develop permit limits for three municipal WWTFs to attain the instream DO concentration of 5 mg/L.

METHODS

As shown in Figure 1, the Pawtuxet River watershed
is triangular in its shape and is located in central Rhode Island. The river basin encompasses 89 square kilometers (sq. km) of forest, open and urban land. The river is formed by the junction of two major branches and discharges at Pawtuxet Cove on Narragansett Bay. The north branch originates at Gainer’s Dam which impounds the Scituate Reservoir. The north branch flows southeasterly for 11 km before it joins the south branch and main stem. The south branch of the river originate at the Flat River Reservoir and flows northeasterly for 15 km to the confluence of the north branc e and main stem.

The main stem of the river flows northeasterly for 18 km to its mouth at the cove. The main stem is severely degraded and historically the summer DO level is below 5 mg/L for much of its length. At the mouth of the river, a dam was constructed to prevent salt water from intruding into the lower river and to compensate for lowering of the water level by water supply diversion. Four point source dischargers were identified for the purpose of model input. The dischargers include one industrial complex on the south branch and three WWTFs on the main stem. The industrial complex is located at the 5 km upstream from the confluence on the south branch of the river. Three WWTFs on the main stem are located 6.5 km, 8.7 km, and 13.8 km from the mouth of the river.

QUAL2EU provides two options for the determination of river velocity. The first option involves the use of Manning’s formula. The second option involves empirical formula of the form:

$$ u = a Q^b $$

(1)

where, $u$ : the average stream velocity, $Q$ : flow, $a$, $b$ : empirical coefficients.

The average velocity was derived from time of travel as determined from dye studies.

The equation (1) can be rewritten as :

$$ \ln u = \ln a + b \ln Q $$

(2)

The linear regressions using average flow and velocity data provide estimates of $a$ and $b$.

The model calibration procedure was a stepwise process. The following is a listing of the steps in the order in which they are executed.

1. Division of the river into 25 reaches.
2. Use of the conservative constituents TDS (total dissolved solids) to verify the flow profile.
3. Development of flow-velocity relationships.
4. Selection of atmospheric reaeration rate coefficient ($K_r$).
5. Calculation of deoxygenation coefficient ($K_d$) from BOD data.
6. Inclusion of ammonia and nitrite oxidation rate coefficients.
7. Plant net productivity was determined to be negligible after application of the Odum model and as a result net productivity was not modeled.
8. Separate dam reaeration studies provided estimates of reaeration rate coefficients.
9. SOD (sediment oxygen demand) rates were measured in the field, coupled with literature values provided the basis for selection of the magnitude of the rate. Field observations and dissolved oxygen profiles were used to select the locations of SOD.

As the optimum test of a water quality model, the
model is applied to a different set of input parameters under significant different flow regime. SOD rates were the last parameter input to calibrate the model and as a result was used to adjust the model predictions of DO to the field observation. Other investigators have successfully used this technique of defining all sources and sinks of DO, and then adjusting SOD rates to reproduce the observed DO profile \(^3\). The rates and locations of SOD set in the first survey were not changed in the other two surveys. The modeling procedure was confirmed by the other simulations and a validation of the model with respect to dissolved oxygen dynamics in the Pawtuxet River.

**RESULTS**

The major objective of this paper is to utilize the computer model QUAL2EU to evaluate the waste assimilative capacity of the Pawtuxet River in order to develop discharge permit limits for conventional pollutants, such as BOD and NH\(_3\). The Pawtuxet River is classified as a warm water fishery (Class C) and is subject to criteria designed to maintain this use. Discharge permit limits of BOD and NH\(_3\) was developed to ensure that the water quality of the river meet the DO criteria of 5 mg/L. The Rhode Island Water Quality Regulations do not contain the NH\(_3\) toxicity criteria, however, Federal Water Quality Criteria adopts the NH\(_3\) toxicity criteria. For a warm water fishery with pH level of 6.5–7.5, the NH\(_3\) criteria is 1.7 mg/L.

The waste load allocation (WLA) must be performed under the following worst case conditions as mandated by USEPA:

1. the \(\dot{Q}_{10}\) flow of the receiving water.
2. discharge facilities design flow.
3. the projected flow if the facility is not expected to reach its design flow.

Under this \(\dot{Q}_{10}\) flow regime, the simulations outlined below were run to assess the impact of various point source loadings on the DO profile. For each of the WLA simulations, the effluent DO concentrations were set to 6 mg/L and the BOD decay rate was set to 0.23 day\(^{-1}\) in all reaches. This BOD decay rate was chosen because a more polished effluent (lower BOD) has been almost completely biodegraded through the treatment process and the BOD which remains is resistant to further instream decay. Chapra (1997) has indicated that high levels of wastewater treatment leave only refractory materials in the effluent which are difficult to degrade, and result in lower stream oxidation rates\(^5\). A post audit of six rivers where WWTFs were upgraded to advanced treatment revealed that the BOD decay rates were reduced in three of the six rivers and remained the same in the other three\(^5\). The average decline in \(K_d\) was 60% in the literature values and in this study \(K_d\) was decreased by 34%, from 0.35 to 0.23 day\(^{-1}\).

The first set of simulations was run to assess the impact of various levels of municipal wastewater treatment facility effluent concentrations. Throughout

![Figure 2. The DO profile at various WWTF limits with calibrated SOD rates.](image-url)

Table 1. The various WWTFs effluent concentrations and their results

<table>
<thead>
<tr>
<th>Case</th>
<th>BOD(_g) (mg/L)</th>
<th>NH(_3) (mg/L)</th>
<th>Locations which violate DO 5 mg/L criteria (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>10</td>
<td>last 9.2 km</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>10</td>
<td>last 8.8 km</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>3</td>
<td>last 7.2 km</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>2</td>
<td>last 4.8 km</td>
</tr>
</tbody>
</table>

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\(^{3}\) Quinn et al., 1996

\(^{5}\) Chapra, 1997

\(^{4}\) Initial concentration of BOD (mg/L)
the WLA analysis, the effluent concentrations from the industrial complex has been set to limits of BOD 30 mg/L and NH₃ 10 mg/L. The effluent concentrations from the three WWTFs were simulated and their respective DO profiles are shown in Figure 2 and are summarized in Table 1.

The next two sets of simulations were performed to evaluate the effect of various levels of sediment oxygen demand (SOD) at four levels of WWTF effluent concentrations. As the level of BOD removal at the WWTFs increases, the occurrence of instances of poor treatment and discharge of particulate BOD to the river should decrease. Assuming that the major source of organic matter responsible for the SOD is particulate BOD present in the effluents of three WWTFs, eliminating the input of particulate BOD will reduce the SOD over time. The two sets of simulations were run with SOD rates of 0.5 g/m²/day, which was the background level measured in clean streams by Butts and Evans (1978), and also of 0.0 g/m²/day, which was an imaginary number to represent a zero SOD. The predicted DO profiles are shown in Figures 3 and 4, and are summarized in Table 2.

The sensitivity of the model to SOD at WWTF effluent levels of BOD=20 mg/L, NH₃=10 mg/L was explored by examining the predicted DO profiles at SOD

<table>
<thead>
<tr>
<th>Case</th>
<th>BOD₅ (mg/L)</th>
<th>NH₃ (mg/L)</th>
<th>SOD (g/m²/day)</th>
<th>Locations which violate the DO 5 mg/L criteria</th>
<th>Minimum DO (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>10</td>
<td>0.5</td>
<td>last 8.2 km</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>10</td>
<td>0.5</td>
<td>last 6.8 km</td>
<td>3.1</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>3</td>
<td>0.5</td>
<td>last 7.5 km</td>
<td>3.0</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>2</td>
<td>0.5</td>
<td>last 6.1 km</td>
<td>3.5</td>
</tr>
</tbody>
</table>

never violates 5.3
never violates 5.7
never violates 5.8
never violates 6.3
the nitrification rate coefficients ($K_n$) was examined at WWTF effluent levels of BOD=20 mg/L, NH$_3$=10 mg/L by reducing the coefficients 10, 30, and 50 percent (Figure 6). The study by Leo et. al. (1984) did not reveal any trends to indicate that instream nitrification rates would change with the implementation of advanced treatment.

After reviewing the predicted DO profiles the decisions were made that WWTF effluent concentrations of BOD=20 mg/L and NH$_3$=10 mg/L with reasonable variations in $K_n$, SOD and $K_a$ would not allow the river to maintain a DO concentration of 5 mg/L during the $q_{10}$ flow. In addition, NH$_3$ concentrations are well in excess of the ammonia criteria with WWTF discharges of 10 mg/L NH$_3$ and are below the criteria with WWTF discharges of 3 mg/L NH$_3$ (Figure 7). The predicted NH$_3$ profiles further support the conclusion that treatment levels of BOD 20 mg/L and NH$_3$ 10 mg/L are not acceptable based on instream ammonia concentrations.

It was concluded that if advanced treatment at the three WWTFs was deemed necessary to meet the DO criteria of 5 mg/L, it would only be required during the summer months, approximately June, July and August. This schedule of operation may be extended to May through September to allow appropriate start-up time. If seasonal advanced treatment is imposed it no longer

![DO Standard](image1)

**Figure 5.** The DO profile at WWTF limits of 20 mg/L BOD and 10 mg/L NH$_3$ with various SOD rates.

![Ammonia Nitrogen Concentration](image2)

**Figure 7.** The Ammonia Nitrogen profile with various WWTF limits of BOD and NH$_3$.

![Reduction of $K_n$](image3)

**Figure 6.** The DO profile at WWTF limits of 20 mg/L BOD and 10 mg/L NH$_3$ with background SOD rates and various $K_n$ rate.

levels of 0.0 g/m$^2$day, values used in the calibrated model, and background levels measured for clean streams by Butts and Evans (1978)$^{6}$ These DO profiles are shown in Figure 5. Even without SOD effect, the river still violates the DO criteria for 6.1 km if treatment levels of BOD 20 mg/L and NH$_3$ 10 mg/L are used.

In addition, the sensitivity of the model to changes in...
Table 3. The values of SOD (g/m²/day)

<table>
<thead>
<tr>
<th>Reach</th>
<th>Background SOD(SOD₉)</th>
<th>Calibrated SOD(SODₐ)</th>
<th>Background Weighted SOD(SOD₉wb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.50</td>
<td>0.79</td>
<td>0.72</td>
</tr>
<tr>
<td>19</td>
<td>0.50</td>
<td>1.09</td>
<td>0.94</td>
</tr>
<tr>
<td>21</td>
<td>0.50</td>
<td>2.11</td>
<td>1.71</td>
</tr>
<tr>
<td>22</td>
<td>0.50</td>
<td>1.17</td>
<td>1.00</td>
</tr>
<tr>
<td>23</td>
<td>0.50</td>
<td>2.11</td>
<td>1.71</td>
</tr>
<tr>
<td>24</td>
<td>0.50</td>
<td>3.28</td>
<td>2.59</td>
</tr>
</tbody>
</table>

seems realistic to expect that the SOD would return completely to background levels for clean streams. The following formula was used to weight the SOD reduction to coincide with seasonal treatment.

\[
SOD_{wb} = SOD_b + 0.75(SOD_c - SOD_b)
\]  

(3)

where, \( SOD_{wb} \): weighted background SOD for seasonal treatment

\( SOD_b \): background SOD (0.5 g/m²/day) measured in clean streams by Butts and Evans (1978)

\( SOD_c \): SOD rate used in the calibrated model

0.75: percentage of the year SOD reduction is not anticipated (when advanced treatment is not required)

WLA simulations were run using the background SOD (clean stream measurement by Butts and Evans, 1978) and weighted background SOD at WWTF.

Figure 8. The DO profile at WWTF limits of 15 mg/L BOD and 3 mg/L NH₃ with various SOD rates.

Figure 9. The DO profile at WWTF limits of 10 mg/L BOD and 2 mg/L NH₃ with various SOD rates.

Table 4. The various SOD rates and their results

<table>
<thead>
<tr>
<th>Case</th>
<th>BOD₅ (mg/L)</th>
<th>NH₃ (mg/L)</th>
<th>SOD (g/m²/day)</th>
<th>Locations which violate the DO 5 mg/L criteria</th>
<th>Minimum DO (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>15</td>
<td>3</td>
<td>SOD₉</td>
<td>does not violate</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SOD₉wb</td>
<td>last 6.1 km</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SOD₉c</td>
<td>last 8.1 km</td>
<td>3.8</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>2</td>
<td>SOD₉</td>
<td>does not violate</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SOD₉wb</td>
<td>last 1.2 km</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SOD₉c</td>
<td>last 5.4 km</td>
<td>4.3</td>
</tr>
</tbody>
</table>
concentrations of BOD 15 mg/L and NH₃ 3 mg/L and also BOD 10 mg/L and NH₃ 2 mg/L. Table 3 lists the values of SOD which were used. The predicted DO profiles are shown in Figures 8 and 9. The results are summarized in Table 4.

Based on this analysis, it is recommended that WWTF effluent limits of BOD 10 mg/L and NH₃ 2 mg/L are required to meet the instream DO criteria of 5 mg/L. The most conservative estimate, no change in SOD, would cause a violation of the DO criteria by less than 0.7 mg/L for the last 1 km. If the SOD is decreased to the weighted background level, the DO profile would violate the criteria by 0.3 mg/L for the last 1 km.

The rest of the simulations were run to test the conclusion that WWTF effluent limits of 10 mg/L BOD, 2 mg/L NH₃ and 6 mg/L DO would enable the main stem to reach the DO criteria of 5 mg/L. The weighted background SOD rates and Kₐ of 0.23 day⁻¹ were used under Q₉₀ flow conditions. Figure 10 indicates that increasing the WWTF effluent DO concentration from 3 to 6 mg/L provides an additional 0.8 mg/L and is necessary in order to meet the instream DO criteria.

Throughout this analysis, the Scituate Reservoir release was set to a historical minimum value of 0.4 cms (cubic meter per second). However, since the termination of hydropower generation at Gainer's Dam, this rate has occasionally been reduced to 0 cms. This extreme case was simulated using WWTF effluent concentrations of 10 mg/L BOD, 2 mg/L NH₃ and 6 mg/L DO with weighted background SOD rates and 0.23 day⁻¹ Kₐ. At these high levels of treatment, reducing Scituate's release to 0 cms causes a maximum decrease in DO of 0.3 mg/L (Figure 11). It should be noted that the negative impact of no release from the Scituate Reservoir on the main stem DO concentrations would be magnified at lower levels of treatment and higher SOD and Kₐ rates (present conditions).

The calibrated model used for the WLA simulations were also used to predict the effect of flow augmentation from Flat River Reservoir. The SOD and Kₐ rates were not changed. These rates were not changed since flow augmentation was examined as an alternative to advanced treatment. Flow augmentation was modeled at WWTF BOD concentrations of 30 mg/L with NH₃ concentrations of 20 and 10 mg/L. The BOD limit was selected since it represents a standard limit for secondary treatment facilities. The NH₃ limit of 20 mg/L was chosen since it represents levels which the
municipal WWTF indicate they can meet. The NH₃ limit of 10 mg/L was selected since it is a limit secondary treatment facilities should be able to meet during the summer months required by the USEPA.

At treatment limits of 30 mg/L BOD and 20 mg/L NH₃, the Flat River Reservoir release must be increased from 0.3 to 42 cms in order to raise the minimum DO from 0 to 4 mg/L, or 6.8 cms to raise the DO to 5 mg/L. Treatment limits of 30 mg/L BOD and 10 mg/L NH₃ require a Flat River Reservoir release of 3.1 and 5.4 cms to raise the minimum DO from 1.1 to 4 and 5 mg/L, respectively. Although flow augmentation is not a realistic alternative to advanced treatment, it does have a positive impact on DO concentrations in the main stem during low flow periods.

**CONCLUSIONS**

The QUAL2EU model was calibrated and validated to reduce unexplained variation in biochemical oxygen demand (BOD) decay and nitrification rates. As a result, one set of BOD decay, nitrification and sediment oxygen demand (SOD) rates was developed which successfully predicted the field data from 3 intensive surveys.

The main stem of the Pawtuxet River is classified as a warm water fishery and must maintain a dissolved oxygen (DO) concentration of 5 mg/L during the <sub>Q<sub>0</sub>low flow. The main objective of this paper is to develop a waste load allocation (WLA) and discharge permit limits for the 3 municipal wastewater treatment facilities (WWTFs) on the main stem of the river. The WLA was performed using the QUAL2EU model which was based on a field survey taken at a low flow profile very close to the <sub>Q<sub>0</sub>low flow. The model was adjusted to the <sub>Q<sub>0</sub>low flow profile and the WWTF flows were set to design flows.

Four levels of advanced treatment at the WWTFs were simulated and the resulting DO profiles were examined to determine if the instream DO criteria was met. When simulating advanced treatment the effluent DO concentrations were set to 6 mg/L and BOD decay rates were decreased from 0.35 to 0.23 day⁻¹. BOD decay rates were reduced since BOD discharged from advanced treatment is more resistant to instream decay than that from conventional secondary treatment. Various levels of SOD reduction were simulated along with advanced treatment. The following treatment and SOD levels were found to meet the instream DO criteria.

1. BOD 15 mg/L, ammonia (NH₃) 3 mg/L with background SOD values (values which were measured in clean streams). (2) BOD 10 mg/L, NH₃ 2 mg/L with background SOD values which were weighted for seasonal treatment. It does not seem that the reduction of SOD to background levels is reasonable if advanced treatment will only be required seasonally. For this reason, WWTF effluent limits of BOD 15 mg/L, NH₃ 3 mg/L are not considered acceptable, unless limits of BOD 10 mg/L, NH₃ 2 mg/L prove to be cost inhibiting.

Flow augmentation was modeled at the current WWTF effluent concentrations (BOD 30 mg/L, NH₃ 20 mg/L). Flow augmentation is not an acceptable solution to low instream DO, since the flow from south branch must be increased from 0.3 cubic meter per second (cms) to 6.8 cms to meet the DO criteria.

Instream reaeration was modeled as a solution to low DO levels, however, the Clean Water Act of 1987 states that best available technologies must be employed before alternative technologies (such as instream aeration), may be used. For this reason, instream aeration simulations have not been included in this paper.

Based on the simulations made in this study, the only realistic option to ensure that the main stem of the river reaches its low flow DO and NH₃ criteria is to require advanced treatment. It is recommended that the conservative option, effluent limits of BOD 10 mg/L, NH₃ 2 mg/L, is imposed at 3 WWTFs.

The cost of upgrading one existing WWTF to a regional advanced treatment facility which would accept effluent from the other 2 secondary WWTFs, should be compared with the cost of 3 separate advanced treatment facilities. Model simulation should be run to ensure that instream water quality criteria will not be violated if a single discharge point is used.

If nitrification is used to reduce the ammonia level of
the WWTF effluents to 2 mg/L, then the nitrate concentration in the effluents will rise. Nitrates are considered to be the limiting nutrients in salt water bodies and the impact of nitrate loading to the cove should be considered. There is little information to indicate the extent of nitrification which presently occurs in the river. If little nitrification takes place in the river, then the denitrification of WWTF effluents may be necessary to avoid algal blooms in the cove.

It may also be prudent to determine if phosphorus removal should be required. Although the algal productivity in the river is low, industrial pretreatment, coupled with advanced treatment at the WWTF, may remove an unknown parameter which is suppressing macrophyte growth. If the cost of phosphorus removal is minimal in comparison to the other wastewater treatment facility (WWTF) upgrades, requiring it may eliminate unforeseen algae problem.

ACKNOWLEDGEMENTS

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REFERENCES