Application of one-dimensional water quality modelling for in stream dissolved oxygen

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ABSTRACT
Located at Alor Setar the Capital City of Kedah, Raja River is a minor stream with a catchment of about 360 hectare. The stream is heavily stressed by domestic and commercial waste loads and has shown significant degradation in water quality since 1994. Currently, the stream reaches show critically low Dissolved Oxygen (DO) level through much of its length during dry weather condition with high temperature. The software package of InfoWorks RS 10.0 model was applied to simulate the DO level at dry weather condition (low flow) periods. The results were used to determine DO level according to Malaysia Water Quality Standard and to identify stream portions that indicate the worst value of DO.

Keywords: Dissolved Oxygen; urban river; water quality; InfoWorks RS model.

1 Introduction
In recent years, rapid development and urbanisation within the river catchment and along the river corridors, including Alor Setar City (ASC) have resulted in deteriorating river water quality, threatening the once pristine conditions of the upper tributaries in the river system. The Government has spent a lot of allocation and efforts to maintain and upgrade the river water quality. One of the strategies to ensure clean water as highlighted in the Sungai Kedah Basin Management Plan 2007-2012 (Department of Irrigation and Drainage Malaysia, 2007) is to reduce pollution from urban sources. The river system involved in the urban source for ASC is the Raja River System.

Raja River System (RRS) is an urban river which is located in the heart of Alor Setar City of Kedah. The main river for the system is Raja River which passes through the heart of the city and ultimately discharges into Kedah River. It was reported that the level of Dissolved Oxygen in the Kedah River was 2.6 % of saturation, hence is classified as Class V (DID, 2007).

Stream water quality study was carried out by David A. Todd and Philip B.B. (1985) for Buffalo Bayou, Texas. They found that stream conditions are important factor in stream quality, a contention that is supported by the seasonal variation of stream DO with stream flow and temperature. A study of water quality problem of RSS was conducted for 24 months, beginning in July 2009 and ending in June 2011.

The contention of the study was that Raja River is an important stream that should be protected and rehabilitated as a clean river due its location at the centre of Capital City. From evidence collected in the study, it is clear that the stream’s DO level has reached critical condition and rehabilitation programme must be planned by the related authorities to maintain cleanliness of the Capital City.

2 Study area
RRS is a tributary of Kedah River and is located at the heart of Alor Setar city. The river system consists of two main tributaries which are Alor Siam (1,475 m) and Derga River (1,813 m). These tributaries meet Raja River at 984 m upstream outlet of Kedah River (Figure 1).

In 1992, Department of Irrigation and Drainage (DID) carried out the Flood Mitigation Project to solve the flooding problems of Alor Setar City. The whole river system was converted to concrete lined channel and RRS was separated from the Kedah River by gated structure and pumping station.

Landuse of RRS catchment is made up of approximately 65% build-up areas, 30% undeveloped area (vegetated and barren lands) and 5% waterbodies. This landuse distribution may have contributed to the
poor water quality of RRS. Unfortunately, there is no
water quality data/information available at the onset of
this study to ascertain the water quality status.
RSS is enclosed system and disconnected from Kedah
River which leads to these uncertainty:

(a) Is the present pumping operation able to remove
the pollutant from RRS?
(b) Can we predict/determine how the pollutants
“move” within the system?

Figure 1   Raja River system

The original river system was a natural river that
drains out the surplus water from the city. The capacity
of the river system is insufficient to accommodate the
run off due to rapid development at the surrounding
areas. Since the current and expected future
development will result in increase in the surface run-
off of the river, The Drainage and Irrigation Department
(DID) decided to carry out the Flood Mitigation Project
in 1992 where by the river system were widened and
concrete lined. The result of this transformation may
increase pressures on the water quality of the river,
which is expected to get worst in the future.

3 Methods

With the aforementioned concept in mind, the study
focused on three major goals. The first purpose was to
establish instream water quality model for Raja River
System for DO analysis. The second purpose was to
determine current DO level according to Interim
National Water Quality Standard (INWQS) by the
Malaysian International Hydrological Programme
(2007). The last goal was to identify the location or sub
catchment that contributed the worst DO level.

Also the study followed by two basic techniques
that are sampling and analysis and another is model
setup.

3.1 Data collection and analysis

(a) Sub-catchment delineation

The area of each sub catchments were processed and
calculated using Arc-GIS software packages as
illustrated in Figure 2. The total catchment area is
about 361 hectares, consisting of various types of
developments. Generally, most of the landuse for Alor
Siam sub-catchment consists of medium-cost housing
schemes and village area. The worst expected pollution
contributions originate from the village area. Part of the
Derga River sub-catchment is covered by medium
scheme housing area and small portion of agriculture
activities.

Figure 2   Sub-catchments for entire river system

(b) Inflow hydrographs

Continues data collection was conducted from
November 2009 to February 2011 for the entire river
system. To feed data requirement for the hydraulic
model, the main pipes and drains that are connected to
the river were identified from the as-built drawing and
confirmed with GPS equipment during site visit. There
were 40 sources of outfalls of various sizes: seven into
Raja River, 20 into Alor Siam and 13 into Derga River.

The hydrographs for the 21 sub-catchments inflow
were tabulated and plotted accordingly. The site
measurement for flow in each pipe and drain was
conducted every Saturday and Sunday in the month of
January and February of 2011. The water in the river
was collected by 4 litres container and the time was
noted. The average of three flows was used to calculate
flow rate in m³/s.

According to Emre & Charles (2009), the duration
of the wet weather period that can influence in-stream
water quality varies between 2 days and 2 weeks in
similar rivers studied. They had studied the duration of
storm effect on in-stream water quality for Chicago
Waterway System.

There was no heavy rain during the sampling
period; hence these flow data can be represented as
normal dry condition and will be used for Boundary
Condition to the model. Table 1 shows an example of hydrograph for one of the sub-catchments.

Table 1 Hydrograph at Dry Weather Condition for Sub-Catchment 8

<table>
<thead>
<tr>
<th>Sub-Catchment</th>
<th>Amplitude (m)</th>
<th>Time Series (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.0012</td>
<td>0.0012</td>
</tr>
<tr>
<td>S2</td>
<td>0.0013</td>
<td>0.0013</td>
</tr>
<tr>
<td>S3</td>
<td>0.0014</td>
<td>0.0014</td>
</tr>
<tr>
<td>S4</td>
<td>0.0015</td>
<td>0.0015</td>
</tr>
<tr>
<td>S5</td>
<td>0.0016</td>
<td>0.0016</td>
</tr>
<tr>
<td>S6</td>
<td>0.0017</td>
<td>0.0017</td>
</tr>
<tr>
<td>S7</td>
<td>0.0018</td>
<td>0.0018</td>
</tr>
<tr>
<td>S8</td>
<td>0.0019</td>
<td>0.0019</td>
</tr>
</tbody>
</table>

(c) Pumping operation

Site visits were conducted with DID Kedah representatives, confirming that under normal condition (without rain) pumping operation occurs once a day with only one pump running. Site investigations were executed on February 2011 to measure the flow velocities and water surface levels at selected locations. Field measurements show that the velocity is almost zero before pumping operation and the water surface level rising slowly (about 6mm/hour). Hence, velocity profile cannot be used for calibration before pumping procedure. Instead, the recorded water surface level (WSL) as shown in Figure 3 will be used for hydraulic model calibration.

(d) Water quality sampling

Water quality sampling involved collecting samples of in-stream river water using Multi Parameter Sonde 6600v2 water quality probe to measure concentration of DO in the stream as shown in Figure 4.

The field measurement was undertaken at certain distance from the pumping station along Raja River, Derga River and Alor Siam River. The sample was collected in the container and the probe was inserted into the river for 5 to 15 minutes or till reading shown steady values.

With collaboration with Kedah DID, the samples were sent for the laboratory test for basic six index of water quality, that are Dissolved Oxygen, BioChemical Oxygen Demand, Chemical Oxygen Demand, Ammoniacal Nitrogen, Suspended Solid and pH. The result of laboratory test was illustrated in Table 2 to Table 4.
Table 4 Laboratory Test Result at middle of Derga River

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Laboratory Test Result At Sungai Derga 634 m from Junction</th>
</tr>
</thead>
<tbody>
<tr>
<td>DO</td>
<td>1.1 - - 1.7 2.2 0.3 2.1</td>
</tr>
<tr>
<td>BOD</td>
<td>16 12 &lt;2 9 13 8 7</td>
</tr>
<tr>
<td>COD</td>
<td>28 77 19 50 44 65 23</td>
</tr>
<tr>
<td>AN</td>
<td>5 - - 3 4 3 1</td>
</tr>
<tr>
<td>TSS</td>
<td>8 9 11 67 14 9 134</td>
</tr>
<tr>
<td>pH</td>
<td>7.0 7.2 6.4 7.2 6.0 7.1 7.0</td>
</tr>
<tr>
<td>Temp.</td>
<td>20.7 - - 29.0 29.0 28.5 -</td>
</tr>
<tr>
<td>WQI</td>
<td>48.9 - - 45.1 48.1 47 56.9</td>
</tr>
<tr>
<td>CLASS</td>
<td>IV - - IV IV IV III</td>
</tr>
</tbody>
</table>

The results show that the Water Quality Index (WQI) for the entire river system belong to Class IV and indicate that the contribution for the low WQI was low DO level and high BOD. Indeed the average DO level falls below Class V during the study periods. The fluctuations or trends of DO level are the main interest in this study.

Dissolved Oxygen concentration data was collected at selected river cross sections as shown in Figure 5. There were seven stations for the entire Raja River, five stations for Derga River and Alor Siam (as illustrated in Figure 6) were established.

Figure 5 Raja River observation station for DO concentration

Figure 6 Derga River and Alor Siam observation station for DO concentration

Trends of in stream DO quality before pumping operation as shown in Figure 7 indicated that the concentration of DO varies along the length of the river. The value of DO concentration for entire Raja River ranges from 1.4 mg/L and 0.4 mg/L, indicating water quality of Class IV and V during the study periods.

Figure 7 Profile of DO at Raja River

Degradation of DO concentration at upstream down to downstream indicate that DO level becomes low density in term of increasing in water volume. The concentrations measurement at selected location for the entire river system was done from February 2010 to October 2010 as shown in Figure 8. The results indicated that DO concentration varied through location that is from 0.10 mg/L to 3.0 mg/L.
3.2 Model configuration

Water Quality Modelling has evolved appreciably since its innovation in the early years of the twentieth century (Chapra, 1997). Significant improvements have been made to the original computer models, therefore, improving the quality of model outputs. Today’s computer models allow us to simulate in one, two, and even three dimensions. In addition, they enable users to model water bodies that are either in steady state or dynamic systems. Model solution techniques have also been improved and the two most commonly employed are finite differences or finite elements. As a result of these improvements, users are now applying computer models to larger and larger river systems, in order to estimate hydrodynamics and more importantly, water quality.

With regard to rivers and given specific input, such as stream flows, the hydrodynamic models can be used to predict outputs, such as water surface elevations and velocities. In addition, given hydraulic and contaminant concentration value, the water quality models also can be used to predict contaminant loading rate. The hydraulic and water quality models utilization consist of a detailed set of equations that serve to represent complex physical processes. However, as the number of required equations to describe the processes in question increases, the computational time and model complexity also increases. As a result, numerical models have been developed to aid in the solution of complex process equations.

The first step begins with hydraulic and water quality model setup or configurations. At this stage, one dimensional software packages of InfoWorks RS version 10.0 was used. This software package also has
free version up to 250 nodes (the study has less than 250 nodes) and it contains hydraulic and water quality model. The models configuration involved hydraulic model, which is need to be established in order to run water quality modelling. However, the reliability of water quality model is dependent on the accuracy of the hydraulic models, including the quality of the calibration data (Vasconcelos et al, 1997). A well-calibrated hydraulic model provides the basis for answering critical questions on facility operation, sizing, method and so forth.

Since the scope of study was dry weather condition, the configuration data setup were roughness coefficient and pump characteristic. However water quality model is more complex than hydraulic model due to more parameters that must be configured such as decay rate, diffusion coefficient, reaeration and so forth (Speight, 2008). The similar software package was used for the study of water quality Maong River, Sarawak by S.Said et al. (2009). The satisfaction decay rate of organic matter was found 0.1 per day.

There are several formulas to estimate longitudinal dispersion coefficient for streams and rivers. Fischer et al. (1979) have developed the equation with 0.43 is a coefficient of determination. For the local study, generic programming to predict longitudinal dispersion was carried out by H.M. Azamatullah and A.A. Ghani (2010). A genetic programming approach was used to derive a new expression for the prediction of the longitudinal dispersion coefficient \( K_x \) in natural rivers.

The basic equation used by the software to compute flows, depths and discharges is a method based on the equations for shallow water waves in open channels - the Saint-Venant equations as follows:

For 1-D continuity,

\[
\frac{\partial h}{\partial x} + \frac{\partial u}{\partial t} = 0, \quad \text{1-D}
\]  

And for 1-D momentum,

\[
\frac{1}{d} \frac{\partial}{\partial t} \left( \frac{h}{d} \right) + \frac{1}{d} \frac{\partial}{\partial x} \left( \frac{h^2}{d} \right) + g \left( S_o - S_f \right) = 0
\]  

Water Quality Model initial condition and boundary condition parameter was determined during data collection from February to October 2010. However, the hydraulic model initial condition was determined from the steady simulation and boundary condition as measured flow for dry weather condition.

Reaeration coefficient for dissolved oxygen can be determined by using standard formulae of Owens et al. (1964) and O‘Conner-Dobbin as follow:

For \( d \leq 2.12 \) m,

\[
k_a = 5.92 \left( \frac{u}{d} \right)^{0.67}
\]  

For \( d > 2.12 \) and \( u < \frac{1.68d^{0.6669} - 1.433}{d^2} \),

\[
k_a = 3.93 \left( \frac{u}{d} \right)^{0.6}
\]  

Where \( u \) is mean of velocity and \( d \) is the flow depth. Further, temperature factor for reaeration rate for dissolved oxygen can be calculated as follows:

\[
k_{a, T} = k_a \times 10^{7 - 20}
\]  

Equation 3 to 5 was used to determine coefficient of oxygen reaeration in the model.

4 Simulation result analysis

In this study, the boundary condition for the hydraulic model was observed flow hydrographs, calibration parameter was carried out for roughness coefficient only. Figure 9 to 13 show the bivariate plot for various roughness coefficients, \( n \) for Raja River at location distance 719 m from pumping station for the calibration date 14th February 2011.
From the results, 97.63% of the variation in water surface level at roughness coefficient of $n = 0.020$ is significant with observed WSL at location Raja River 719 m from pumping station. Hence, hydraulic model with roughness coefficient of $n = 0.020$ will be used to simulate water quality model.

Due to unavailability of automatic monitoring water quality station at the river, the type of boundary condition for water quality model used was flow-concentration. The calibration station was decided at Raja River that was 719 m from pumping station. Result of calibration shows that the parameters involved were diffusion coefficient, reaeration temperature factor, and decay rate. However, the best fit simulation result with observation was i) Diffusion Coefficient = 19.39 sq.ft/sec; ii) Reaeration temperature factor = 1.024; and iii) Decay Rate = 0.2/day. The coefficient of determination at calibration station was 0.6545 or 65.5% (Figure 14).

The simulation was carried out at 14th to 15th February 2011 for dry weather condition for the whole Raja River system. The results of DO concentration for the selected location were illustrated in Figure 15 and Figure 16.
Raja River and Alor Siam belong to Class V during the dry weather condition on 14th and 15th February 2011. However, water quality standard for Derga River at the second half of river length, indicating Class IV, is better than that in Alor Siam. Inflow from the sub catchments of Alor Siam and Derga River contributed to low concentration of DO for Raja River.

5 Model predictions

Yang et al. (2010) used calibrated model to predict future water quality conditions under two different wastewater management scenarios for the study of water quality modelling of a Hypoxic Stream. Analysis from the simulation results found that degradation of DO concentration in Raja River is due to the low DO concentration originating from Alor Siam and Derga River. The sub catchments suspected of contributing low level of DO concentration were catchments 5, 10, 11, 15 and 17. The adjustment for the model was done by adding Class II to Class IV of DO concentration at all sub catchments for Alor Siam and Derga River. This procedure was implemented to clarify the earlier judgement. The simulation results as shown in Figure 17.

Simulation result shows that DO concentration for Raja River is almost the same before and after DO alteration for sub-catchments Alor Siam and Derga River. Hence, low DO concentrations from tributaries do not significantly reduce DO in the main river that is Raja River.

6 Conclusion

The paper presents a water quality modelling study of a Raja River System (RRS) receiving effluents from urban source of Alor Setar City (ASC). Saturation of DO is about 2.6% or 0.2 mg/L was reported by DID in year 2007. The modelling framework is configured to simulate the profile of DO concentrations during dry weather condition. Unavailability of gauge station for flow and water quality in the RRS was forced us to conduct field data collection from November 2009 to February 2011 in order to fill model boundary condition. From the laboratory test results, the WQI for selected locations for RRS belong to Class III and IV. The low concentration of DO at entire RRS was contributed low WQI index. The model was well calibrated using measured data on 14th and 15th February 2011. The coefficient of determination for hydraulic model was 97.63% and water quality model 65.5%

Results of simulation show the critical low concentration of DO occur in the entire RRS unless at location up stream of Derga River and Alor Siam. Low concentration of DO at Raja River suspected has been influenced by Derga River and Alor Siam. However, model prediction simulation analysis proofs that low concentration of DO at both tributaries is not significant for low DO at Raja River and current pumping procedure inadequate to remove pollutant from RRS. Finally, some effort would need to be made to upgrade water quality in the RRS to ensure compliance with WQI standard and to provide for ongoing study to identify future river protection strategies.

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