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Research paper

Technical challenges with BOD/DO modeling of rivers in Taiwan

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Abstract

Many rivers and streams in Taiwan receive significant BOD and ammonia loads from domestic and industrial wastewaters. These loads are characterized by excessive strength (high concentrations and wastewater flows) – often with great spatial intensity. In many cases, an additional significant load enters the stream before the upstream input is fully stabilized in the receiving water. The classic DO sag and recovery curve in rivers associated with single point source BOD loads (as found in most textbooks) are therefore rare in Taiwan's rivers. As a result, a different modeling approach must be adopted to address technical challenges associated with modeling for water quality management in Taiwan. In this paper, the modeling results of two rivers in Taiwan are presented to demonstrate the associated technical issues and difficulties, as well as recommend further effort to meet these challenges.

Keywords: BOD/DO modeling; CBOD; WASP/EUTRO; Deoxygenation rate

1. Introduction and purpose

At the present time, the primary water quality problem that Taiwan faces is point source BOD and ammonia-related dissolved oxygen depression in the water column of streams and rivers. Oxygen consumption materials, such as CBOD and ammonia nitrogen from domestic wastewaters and industrial effluents, are the main source of river pollution.

Historically, the key technical challenges located within the modeling effort are two-fold: first, the sufficiency of field data and information, particularly the point source flows and pollutant loads, and second, the high intensity of CBOD and ammonia loads in terms of their spatial frequency and lack of effluent monitoring. In most practice, BOD – instead of CBOD – was measured as 5-day values. Further, water samples were not filtered, thereby accounting for the total (dissolved and sorbed) organic carbon in the water column. Long-term BOD tests were not conducted. Composite samples of effluents from domestic wastewaters (treated and untreated) and industrial effluents were estimates at best, resulting in significant uncertainty in quantifying CBOD and ammonia loading rates from these point sources.

Another challenge is the spatial intensity of the wastewater discharges. Effluent characteristics of 5-day CBOD vary significantly from one point source to another and therefore their loads cannot be compared on the same basis. Spatially variable effluent CBOD characteristics would result in different impact on DO in the receiving water. The classic DO sag curve – which results from a single point source discharged into a river (as seen in many textbooks: Thomann and Mueller, 1987; Chapra, 1997) – is rare in Taiwan.

It is essential that CBOD is simulated as ultimate values, i.e., $CBOD_u$ in the model to put all the point sources on the same basis along the river being modeled (Lung and Sobeck, 1999). If receiving water $CBOD_u$ data is lacking, then the model $CBOD_u$ results must be converted to $CBOD_5$ for comparison with measured BOD_5 data in model calibration.

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Further, the point source $CBOD_u$ loads determined by the modeling analysis must also be converted to $CBOD_5$ loads for regulatory use as wastewater discharge permits are written in terms of 5-day BOD instead of ultimate CBOD.

Overcoming these challenges requires spatially variable CBOD deoxygenation rates, resulting in spatially variable ratios of $CBOD_u$ to $CBOD_5$ along the river. The purpose of this paper is to present and document the recent modeling effort on two rivers in Taiwan. Comparing the model results of these two rivers clearly demonstrates the need for spatially variable CBOD deoxygenation rates for many rivers in Taiwan.

2. The WASP model adoption and related technical issues in Taiwan

Following a lengthy evaluation of many stream water quality models by modeling experts, the Environmental Protection Administration (EPA) in Taiwan adopted in 1994 the WASP/EUTRO code (Ambrose et al., 1993) as the agency-wide modeling framework and the primary tool in river water quality management use with following considerations:

1. The WASP/EUTRO code is capable of handling 1-D, 2-D, and 3-D configurations, as required by many site specific conditions in Taiwan.
2. Different levels of WASP applications offer flexibility and ease of use by modelers.

Lung (2001) contains a presentation of the historical development and evolution of the WASP model code. In this study, the WASP/EUTRO code was first configured to the Danshui River Estuary and its tributaries. Subsequently, it was applied to other rivers in Taiwan to support the development of water quality management plans.

The River Pollution Index (RPI) has been widely used in Taiwan to classify the degree of pollution in the following water quality constituents: 5-day BOD (BOD_5), suspended solids, ammonia, and dissolved oxygen. Two key issues are immediately raised with BOD. First, ultimate BOD in wastewaters and ambient waters is rarely measured in Taiwan. As a result, converting the ultimate values from the model results to 5-day values is needed for water quality management. In addition, BOD – not CBOD – has been measured in Taiwan. In badly polluted rivers at the present time, the ambient nitrification process is lagging behind the stabilization of CBOD in the water column of low dissolved oxygen and does not take place in the first 5 days of stabilization (usually 8 days or even longer). Therefore, 5-day CBOD is equal to 5-day BOD. However, nitrification could start sooner than 5 days once CBOD loads are significantly reduced due to water pollution control measures for badly polluted rivers, thereby creating an environment favorable to nitrifying bacteria in the future (Hall and Foxen, 1983; Lung, 2001). It is highly possible that point source CBOD load reductions followed by the nitrification process of consuming dissolved oxygen in the receiving water would minimize the benefit of CBOD load reductions, as shown in the Upper Mississippi River (Lung, 1996, 1998).

3. BOD – an old problem with a new twist

BOD is actually not a substance. Instead, it is a surrogate designed to quantify the potential of oxygen consumption by bacteria to break down organic carbon in the water and therefore is quantified using dissolved oxygen (in mg/L) as the common currency. Historically, BOD is measured and reported as 5-day value, BOD_5 for management use. In significantly polluted waters with very low dissolved oxygen levels such as raw sewage, the amount of dissolved oxygen consumed in 5 days is primarily from the deoxygenation of carbonaceous BOD (CBOD) as nitrification does not take place within the first 5 days. Therefore there is little difference between BOD_5 and $CBOD_5$ at the present time. [Continuing treatment upgrade at wastewater treatment plants would yield differences between these two values (Lung, 2001; Lung and Larson, 1995).] In addition, well over 50% of the ultimate CBOD ($CBOD_u$) is exerted within the first 5 days. The 5-day CBOD is very close to the ultimate CBOD in most domestic wastewaters lacking (or with marginal) treatment in Taiwan. The following equation gives the quantitative relationship between $CBOD_5$ and $CBOD_u$ (Leo et al., 1984; Lung, 2001):

$$\frac{CBOD_u}{CBOD_5} = \frac{1}{1 - e^{-5k}} \tag{1}$$

where k is the in-stream first-order CBOD deoxygenation rate, a coefficient closely related to the characteristics of the wastewater discharging into the receiving water. For example, Eq. (1) yields a $CBOD_u/CBOD_5$ ratio of 1.5 with a k value of 0.22 day^{-1} (equivalent to early secondary treatment of municipal wastewater using trickling filters) Continuing improvement of wastewater treatment would further decrease the k value and increase the $CBOD_u$ to $CBOD_5$ ratio.

Fig. 1 shows a family of curves of $CBOD_u/CBOD_5$ vs. k represented by Eq. (1) at different water temperature. Physical insights into Eq. (1) are summarized as follows:

(a) Marginally treated wastewater is mostly characterized by a $CBOD_u$ to $CBOD_5$ close to 1.0 and high k values well above 0.5 day^{-1}.
(b) Primarily treatment (not designed to remove dissolved CBOD) would only slightly increase the $CBOD_u$ to $CBOD_5$ ratio, yet with a wide range of k values.
(c) Secondary treatment would significantly increase the $CBOD_u$ to $CBOD_5$ ratio and lower the deoxygenation rate (to below 0.1 day^{-1}) as dissolved CBOD is much stabilized via the treatment process.
(d) Ambient waters are usually represented by very low k values (Lung, 2001) but with a range of much higher $CBOD_u$ to $CBOD_5$ ratios.

The above observations suggest that BOD laden streams could have a wide range of k values, which is the focus of this

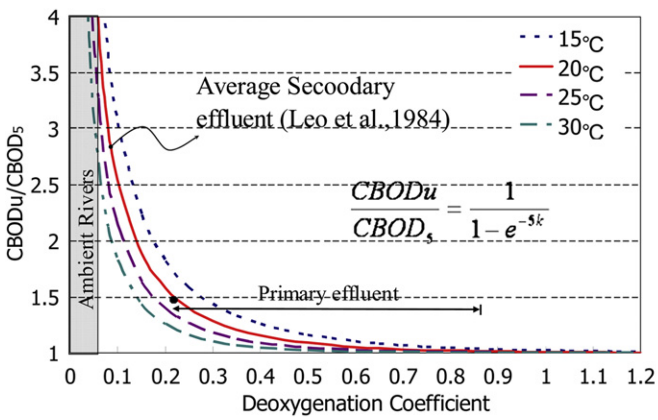

Fig. 1. CBOD to CBOD ratio vs. BOD deoxygenation rate.

work. Many rivers in Taiwan receive a significant number of point source effluents with varying strength, thereby characterized by a wide range of deoxygenation rates in the effluent.

$CBOD_u$ is modeled in WASP/EUTRO as the ultimate potency of oxygen consumption in the receiving water. Therefore, BOD loads must be input to the model as $CBOD_u$, requiring the conversion of $CBOD_5$ loads to $CBOD_u$ loads using Eq. (1). Further, the model results of $CBOD_u$ must be reconverted to $CBOD_5$ for comparison with available ambient water data using Eq. (1) again. In a river receiving multiple wastewater discharges with varying deoxygenation potency in relatively short distance, these technical issues create considerable challenges.

4. WASP/EUTRO modeling of the Dansui River and the Chungkang River

Two rivers in Taiwan were modeled with the WASP/EUTRO code. First, the Danshui River, located in northern Taiwan (Fig. 2), originates in mountains with an elevation of 3529 m above sea level. Its watershed area is approximately 2726 km^2. As the third largest river in Taiwan, the Danshui River is formed by three major tributaries: the Dahan River in the south, the Sindian River in the middle, and the Keelung River in the north. The river flows in a south-to-north direction (Fig. 2). The portion of the river modeled is the main stem formed by the Dahan River for a total distance of 42 km. Rapid urban development and industrialization in the watershed generate significant pollutant loads into the receiving water. The WASP/EUTRO code is applied to the Dansui River's main stem (formed with the Dahan River) in a 36-segment configuration (Montgomery Watson Harza, 2008).

The second river system studied is the Chungkang River in central Taiwan (Fig. 2), which originates in mountains with an elevation of 2616 m. Its watershed area is approximately 446 km^2 and is part of the Danshui River watershed. The Chungkang River is formed by a number of small tributaries (Fig. 2). The modeled section of the river is about 32.2 km in length. Major pollutant loads come from the populated towns located in the downstream portion of the river and from an industrial region called Tao Fen. The WASP model is configured for 35 segments for the Chungkang River for a total distance of 32.2 km (Montgomery Watson Harza, 2008).

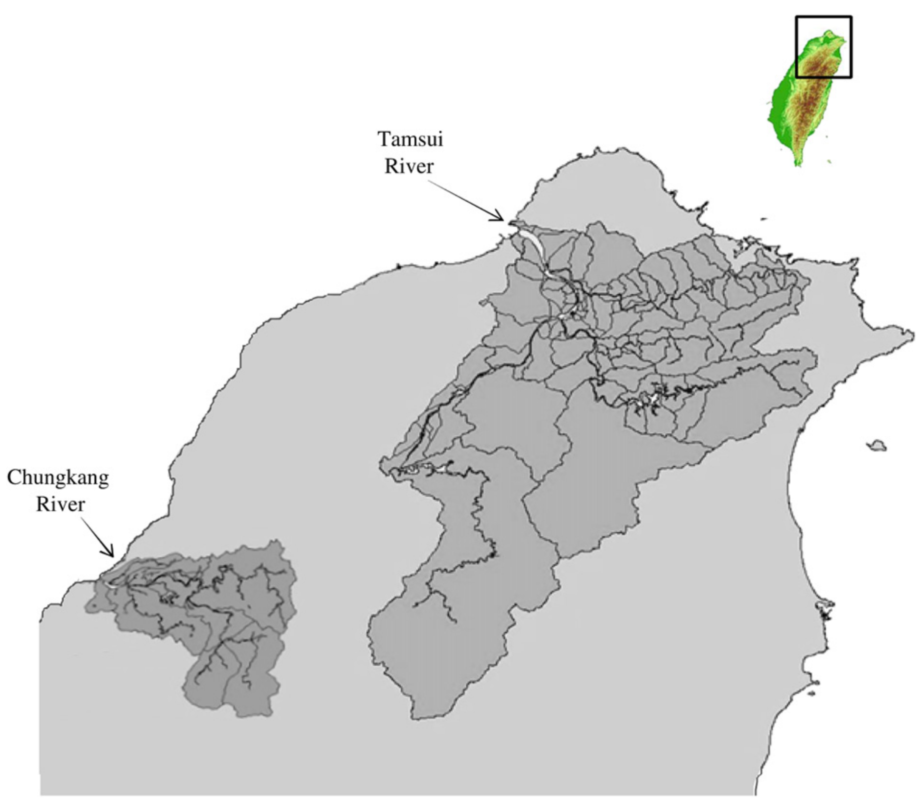

Fig. 2. The Danshui River and Chungkang River Watersheds, Taiwan.

5. Data to support the modeling analysis

Most of the ambient water quality data to support the modeling analysis is obtained from the routine monitoring program administered by Taiwan EPA. Monthly sampling of physical, chemical, and biological parameters of water quality includes: temperature, conductivity, pH, BOD_5, ammonia, suspended solids, and dissolved oxygen. In this study, data collected from two water quality surveys were used in the modeling analysis (Montgomery Watson Harza, 2008): October 2006 and November 2006 for both rivers.

The lower portion of both rivers is subject to tidal action. As such, an estuarine system is formed in these two rivers. The upstream freshwater flows in the non-tidal portion of the rivers have been monitored on a regular basis and their data were used in this study.

6. BOD and ammonia loads

Fig. 3 presents the BOD and ammonia loads along these two rivers. Loads from the three major tributaries (the Sanshia Creek, Sindian Creek, and Keelung Creek) dominate the total input to the Danshui River. In addition, there are other point source loads directly discharged into the river (Fig. 3). All these loads are primarily from domestic wastewaters with BOD_5 levels ranging from 40 mg/L to 80 mg/L entering the main stem of the Dansui River. Ammonia concentrations are typically around 16–25 mg/L. Effluents of this type are marginally stabilized with nitrification inhibited. Therefore, $CBOD_5$ may be construed as BOD_5 (Lung, 2001) and the CBOD loads needed for the model input were derived from the BOD_5 data. A recent modeling study (Montgomery Watson Harza, 2008) of the Danshui River Estuary also indicated that nitrification is insignificant in the receiving water. Industrial wastewater contributes very little to the Danshui River. On the other hand, BOD and ammonia loads to the Chungkang River are primarily generated from industries located in the downstream portion of the river (Fig. 3).

7. Model results

7.1. The Danshui River

Model results summarized from a study by Montgomery Watson Harza (2008) are presented in Fig. 4 along with field data for the Danshui River in the left-hand column. The first panel shows the longitudinal profile of river flows, increasing the downstream direction toward the river mouth. The second panel presents the pollutant loads ($CBOD_u$ and $CBOD_5$) to the Dansui River. Note that the top two BOD loads are from two tributaries: the Keelung River and Shindian River, which receive point source loads along the tributaries. Their $CBOD_u$ loads are calculated by multiplying the $CBOD_5$ loads by a factor of 1.75, an approximation characterizing the degree of stabilization of BOD loads in these two tributaries. Other less significant (in quantity) point source loads have $CBOD_u$ loads equal to $CBOD_5$ loads (a 1 to 1 ratio) due to poor water quality in the effluent. BOD loads to the Danshui River have various degrees of potency, thereby warranting the need of $CBOD_u$ as the common currency in the DO budget along the river.

The third panel of the left-hand column presents the model calculated $CBOD_u$ profiles in the Danshui River. The two curves represent model calculated $CBOD_u$ concentrations obtained from two different in-stream deoxygenation rates used in the WASP model. As expected, the lower deoxygenation rate (0.1 day^{-1}) in the Danshui River yields higher $CBOD_u$ levels in the water column than those with a higher rate (0.5 day^{-1}). Note that the difference between the $CBOD_u$ results is very insignificant in the upstream portion of the Danshui River due to strong mass transport in the riverine portion of the Danshui River. The gap between these two curves widens sharply in the downstream portion of Danshui River where tidal dispersion tends to increase the residence time, thereby creating a favorable condition for deoxygenation kinetics.

Model results of $CBOD_5$ in the next (fourth) panel in the left-hand column of Fig. 4 are quite interesting for the Danshui River. Since the $CBOD_u$ to $CBOD_5$ ratio for the high deoxygenation rate of 0.5 day^{-1} is very close to 1.0 (see Eq. (1)), the model calculated $CBOD_5$ concentration profile is almost identical to the $CBOD_u$ concentration profile (in the previous panel) in the upstream portion of the Danshui River. The lower deoxygenation rate of 0.1 day^{-1} yields a $CBOD_u$ to $CBOD_5$

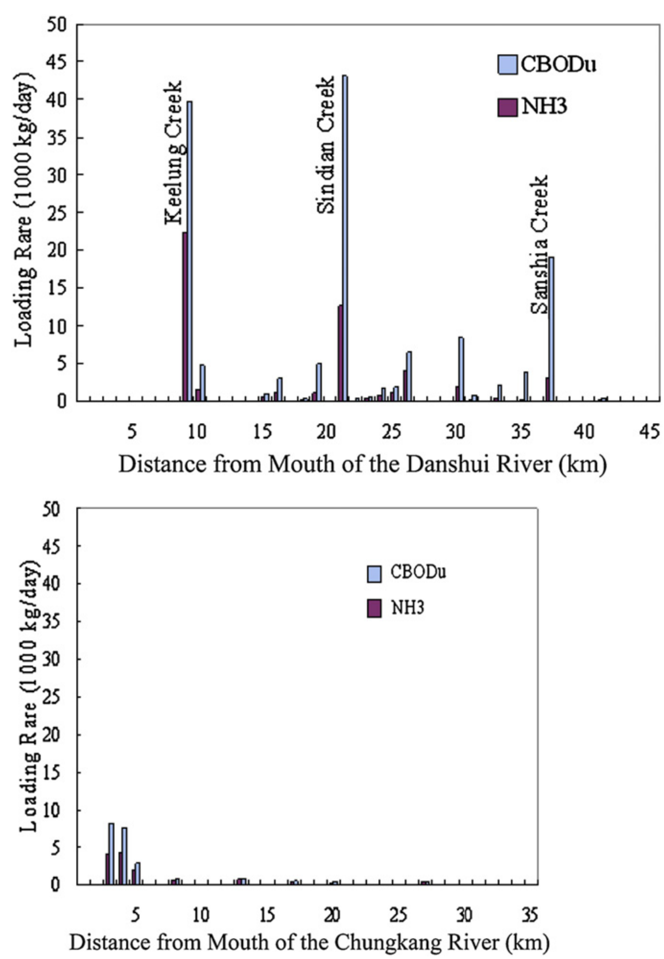

Fig. 3. BOD and ammonia loads to the Danshui River and Chungkang River.

ratio of 2.54, resulting in a $CBOD_5$ concentration profile much lower than the $CBOD_u$ concentration profile. However, such a result is reversed in the estuarine portion of the Danshui River. Note that the $CBOD_5$ concentration profile is needed for comparison with the field data of BOD_5.

The final panel of the left-hand column shows the model calculated DO concentrations with two different deoxygenation rates in the Danshui River. The model results associated with two different deoxygenation rates behave as expected as the higher deoxygenation rate yields a more depressed DO profile, particularly in the estuarine portion of the Danshui River where mass transport is significantly retarded.

7.2. The Chungkang River

Like the Danshui River, the freshwater flow increases in the downstream direction toward the mouth (see the first right-hand panel of Fig. 4). Since the BOD loads to the Chung-Kang River are primarily from industries with minimal treatment, their $CBOD_u$ loads are also the same as $CBOD_5$ loads (a ratio of 1 to 1), indicating strong potency of their waste. The second panel in the right-hand column shows very significant BOD loads in the downstream portion of the river with identical $CBOD_5$ and $CBOD_u$ loads. Model results for $CBOD_u$, $CBOD_5$, and DO concentration profiles in Chungkang River

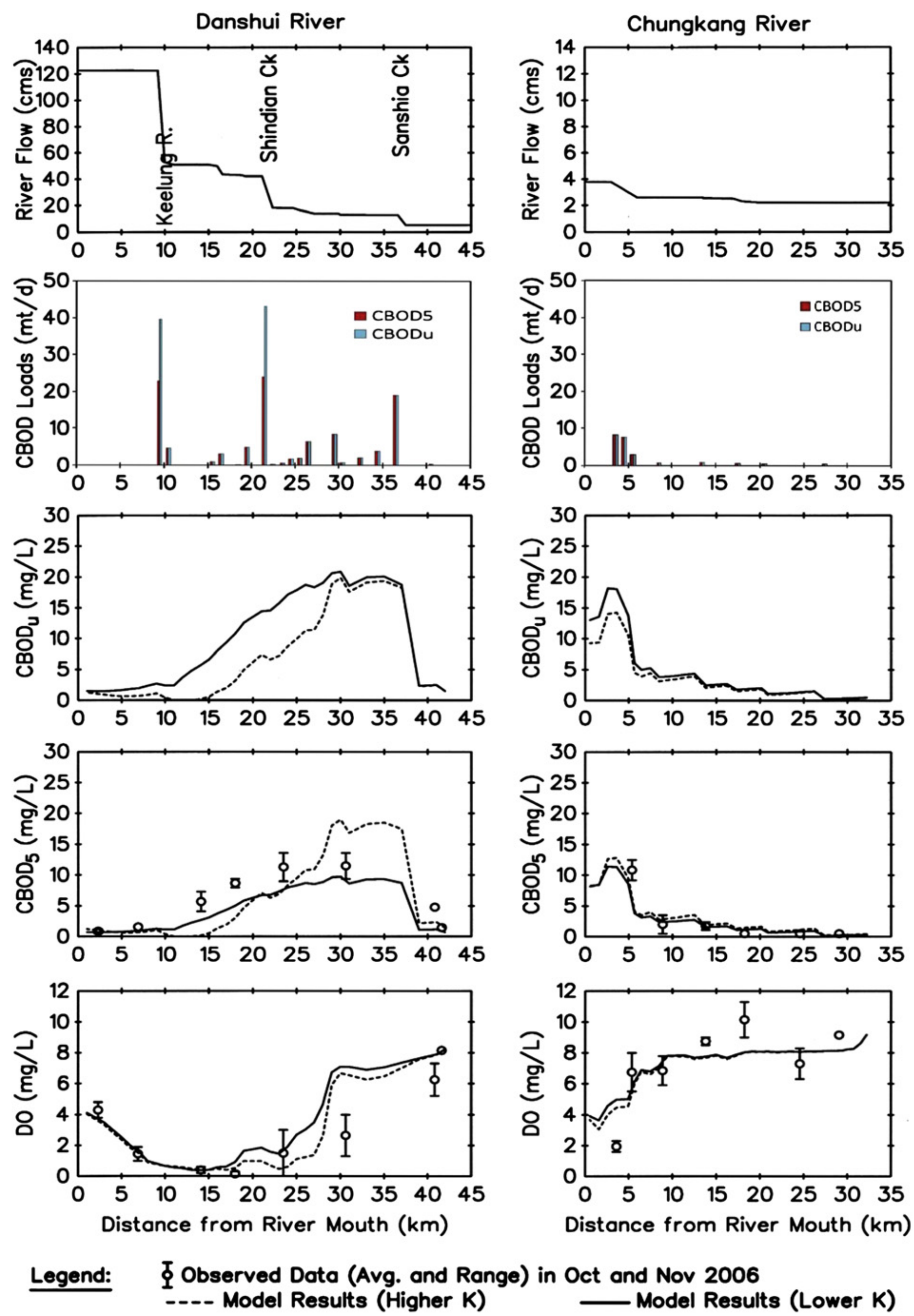

Fig. 4. WASP/EUTRO results of BOD/DO modeling of the Danshui and Chungkang Rivers.

associated with two different in-stream deoxygenation rates of 0.15 day^{-1} and 0.35 day^{-1} are shown in the right-hand column of Fig. 4. The range of the deoxygenation rates in the Chungkang River, slightly smaller than that in the Danshui River, is determined via model sensitivity analysis for the Chungkang River model.

As expected, the model calculated $CBOD_u$ concentration profile with the low deoxygenation rate of 0.15 day^{-1} is higher than the profile with the high deoxygenation rate of 0.35 day^{-1} along the entire stretch of the Chungkang River. On the other hand, the results are reversed for the $CBOD_5$ profiles due to the fact that the lower deoxygenation rate yields a higher $CBOD_u$ to $CBOD_5$ ratio all along the river. Unlike the Danshui River, the $CBOD_5$ curves do not cross each other. The resulting DO concentration profiles for the Chungkang River therefore reflect different deoxygenation rates in the water column, showing that the higher deoxygenation rate yields a slightly lower DO concentration profile along the river.

8. Discussions

Results of the modeling analysis suggest that the DO budgets in these two systems reflect a delicate balance of mass transport and kinetics in the water column. Mass transport in the upstream portion of the Danshui River dominates the mass balance of CBOD to the extent that the effect of in-stream deoxygenation of CBOD is insignificant. On the other hand, the CBOD deoxygenation process becomes a much more important mechanism in the lower Danshui River (i.e. the estuarine portion).

The Danshui River model results (i.e. $CBOD_u$, $CBOD_5$, and DO) and the field data (see the left-hand column of Fig. 4) suggest that the match between model results and data can be improved by using a higher deoxygenation rate in the upstream area and a lower deoxygenation rate in the lower portion of the Danshui River. Such an adjustment is justified by the fact that the potency of point source BOD loads is greater in the upstream portion of the Danshui River, thereby warranting a higher deoxygenation rate in the upstream area and a lower deoxygenation rate in the downstream, estuarine portion of the river system.

9. Summary and conclusions

The results of two water quality modeling studies are analyzed to demonstrate the technical challenges of river BOD/DO modeling in Taiwan. In the BOD/DO modeling analysis of the Chungkang River, the point source BOD loads to the river are potent enough that using $CBOD_u$ or $CBOD_5$ as the surrogate shows little difference in the modeling outcome for the Chungkang River. In general, model results of $CBOD_5$ match the ambient data closely along the river.

Modeling the Danshui River, however, is a different story. First, $CBOD_u$, instead of $CBOD_5$, must be used to characterize the varying degrees of potency and ultimate strength of organic carbon discharges and thereby as a surrogate of BOD loads along the river. The model calculated $CBOD_u$ concentrations in the river are then converted to $CBOD_5$ for comparison with the BOD_5 data for water quality management purpose. Model results from the Danshui River clearly show that spatially variable CBOD deoxygenation coefficients for the river water are needed to address this complicated problem.

The Danshui River receives strong and spatially intensive BOD loads from point sources with different deoxygenation characteristics. The 5-day BOD load from one source may not have the same potency as that from another source. The only means to put all the point source loads on a leveled playing field is to track the ultimate BOD, suggesting that the most accurate approach of determining the spatially variable ambient CBOD deoxygenation coefficients is direct measurement via long-term BOD analyses of river water samples. Using the long-term BOD data, Lung (1996) has demonstrated the success of this approach in a study of the Upper Mississippi River. It is recommended that this approach be adopted for the Danshui River in Taiwan to accurately quantify the CBOD deoxygenation rate as well the ambient nitrification rate, if any.

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