TRENDS IN BOD/DO MODELING FOR WASTELOAD ALLOCATIONS

By Wu-Seng Lung[1]

ABSTRACT: With higher degrees of wastewater treatment, in-stream CBOD deoxygenation rates have changed, thereby affecting the receiving response in BOD/DO modeling. An analysis of the historical water quality data from the Upper Mississippi River, supported by a modeling analysis, reveals some new information on BOD/DO modeling. Information gained from the analyses expands the data base for the practice of wasteload allocations.

INTRODUCTION AND PURPOSE

Twenty-five years ago, information and data on effluent and in-stream BOD characteristics were lacking. There were simply not sufficient data to perform comprehensive BOD/DO modeling studies. Since that time, the dissolved oxygen problems, connected intimately with primary productivity and sediment effects, have tended to be considerably more complex than generally believed (Thomann 1987). Thanks to the Clean Water Act and its amendments, we have been steadily expanding the knowledge and data base on BOD/DO modeling and making treatment upgrades at wastewater treatment plants.

Although BOD/DO modeling has been a routine practice for some time, new information continues to evolve from recent studies; furthermore, modeling technology continues to advance. One reason for this advancement is the issuance and renewal of wastewater discharge permits by regulatory agencies.

Lung (1993) outlines a number of technical issues to be addressed in modeling BOD/DO in rivers and estuaries: (1) effluent characteristics; (2) nitrification in receiving waters; (3) CBOD deoxygenation rates before and after treatment; (4) contribution of algal biomass to CBOD; (5) algal photosynthesis and respiration; and (6) reaeration. In the present paper, historical data from a case study are presented to further expand the data base for some of these categories.

IN-STREAM CBOD DEOXYGENATION RATE

The Upper Mississippi River at Minneapolis and St. Paul, MN (Fig. 1), is used to demonstrate the decrease in in-stream deoxygenation rates following wastewater treatment upgrades. The Metro Plant, located at UM835.1 (see Fig. 1), is the single largest point-source discharge (250 mgd) on the Upper Mississippi River. Originally constructed as a primary treatment plant in 1938, it was upgraded to a secondary treatment facility in 1966 and further upgraded to advanced secondary with nitrification in 1985.

To demonstrate the progressive decrease of the CBOD deoxygenation rate in the Upper Mississippi River, effluent and water quality data from three different treatment levels at the Metro Plant are used: primary treatment, secondary treatment, and secondary with nitrification. In addition, a water quality model is used to calibrate the CBOD deoxygenation rates in the river for these three different data sets. The water quality model used for this analysis, AESOP, was first developed and calibrated by Hydroscience Inc. ("Upper" 1979) using data from the river with the Metro Plant at a secondary treatment level. It was successfully postaudited with field data collected during the low-flow summer months of 1988 (Lung 1996).

Results from the model runs, for comparison of the water quality response to treatment changes, are summarized in Fig. 2. Each column of Fig. 2 displays model results associated with each treatment level at the Metro Plant. In each column, concentration profiles of $CBOD_u$, ammonium, nitrate/nitrate, viable chlorophyll *a*, and dissolved oxygen from downtown St. Paul (UM840) to Lock and Dam No. 2 (UM815) are plotted. Fig. 2 also shows the decrease in CBOD (and, particularly, filtered $CBOD_u$) levels in the river following the treatment upgrade from primary to secondary. In-stream CBOD concentrations due to the Metro Plant input are significantly minimized after the upgrade of the plant to secondary treatment. The algal biomass in the river accounts for a substantial portion of the unfiltered CBOD, reaching a peak level approaching Lock and Dam No. 2. However, the algal effect on the dissolved oxygen sag in the Upper Mississippi River is not significant (Lung 1996). The progressive reductions of ammonia nitrogen and corresponding increases in nitrate nitrogen in the river depicted in the third column reflect the impact of nitrification at the Metro Plant. It appears that the concentration profile of ammonia under the scenario of secondary treatment can easily be switched with the nitrate/nitrate concentration profile under the scenario of secondary treatment with nitrification.

A significant portion of the river from River Mile 830 to River Mile 823 is anoxic when the Metro Plant is at primary treatment (Fig. 2). The results show that the dissolved oxygen concentrations in the river improve slightly following the treatment upgrade from primary treatment to secondary treatment. Secondary treatment (Fig. 2, second column) raises the minimum DO to about 2 mg/L in August 1976. Finally, the DO sag in the receiving water is eliminated and the DO standard of 5 mg/L is met following the installation of nitrification at the Metro Plant. The model results show clear, progressive water quality improvement in raising the dissolved oxygen concentrations in the Upper Mississippi River below the Metro Plant from primary treatment to secondary treatment, and then to secondary treatment with nitrification.

Note that the model is able to match the data collected at the three water quality surveys and at each of the Metro Plant's three different treatment levels; that is, the model results confirm the water quality improvement in the river. Model coefficients are maintained at the same values for all three model runs except the in-stream CBOD deoxygenation rate, k_d. The rate is progressively reduced from 0.35 day^{-1} for primary treatment to 0.25 day^{-1} for secondary treatment, and to 0.07 day^{-1} for secondary treatment with nitrification.

EFFLUENT CHARACTERISTICS

Table 1 shows the effluent characteristics of the Metro Plant at the three different treatment levels. These values are used in the AESOP model runs. The most significant change in the

[1]Prof. of Civ. Engrg., D 209 Thornton Hall, Univ. of Virginia, Charlottesville, VA 22903.

Note. Associate Editor: Edward A. McBean. Discussion open until March 1, 1999. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this technical note was submitted for review and possible publication on February 11, 1998. This technical note is part of the ***Journal of Environmental Engineering***, Vol. 124, No. 10, October, 1998. ©ASCE, ISSN 0733-9372/98/0010-1004–1007/$8.00 + $.50 per page. Technical Note No. 17639.

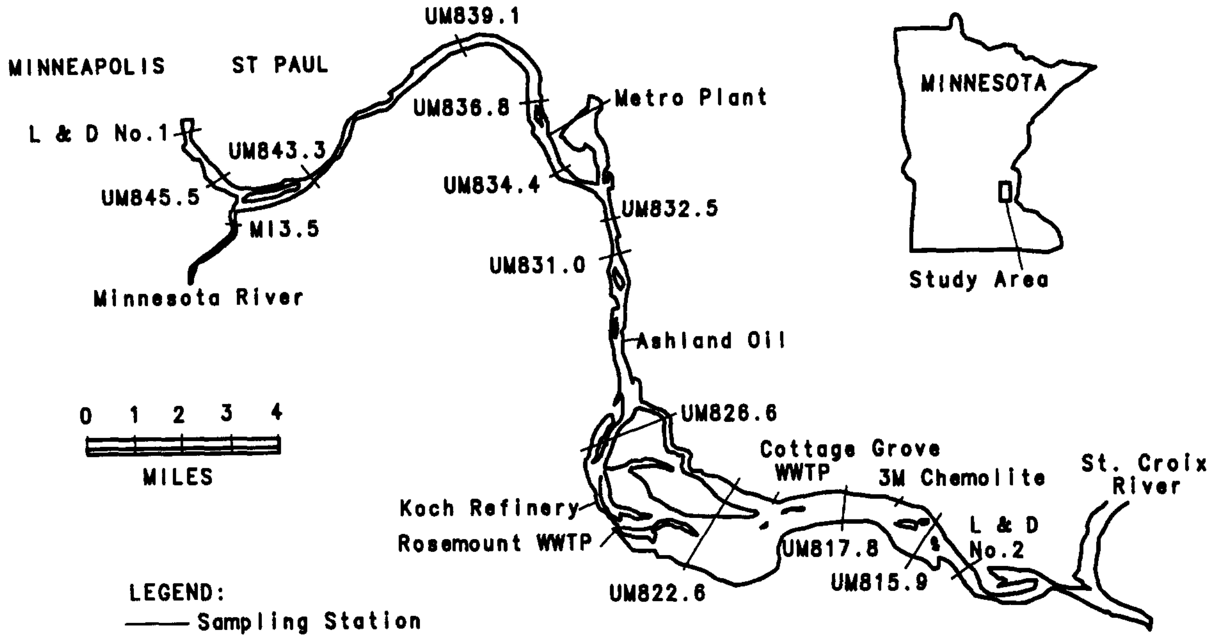

FIG. 1. Upper Mississippi River from Lock and Dam No. 1 to Lock and Dam No. 2 (Water Quality Sampling Stations and Point Source Discharges)

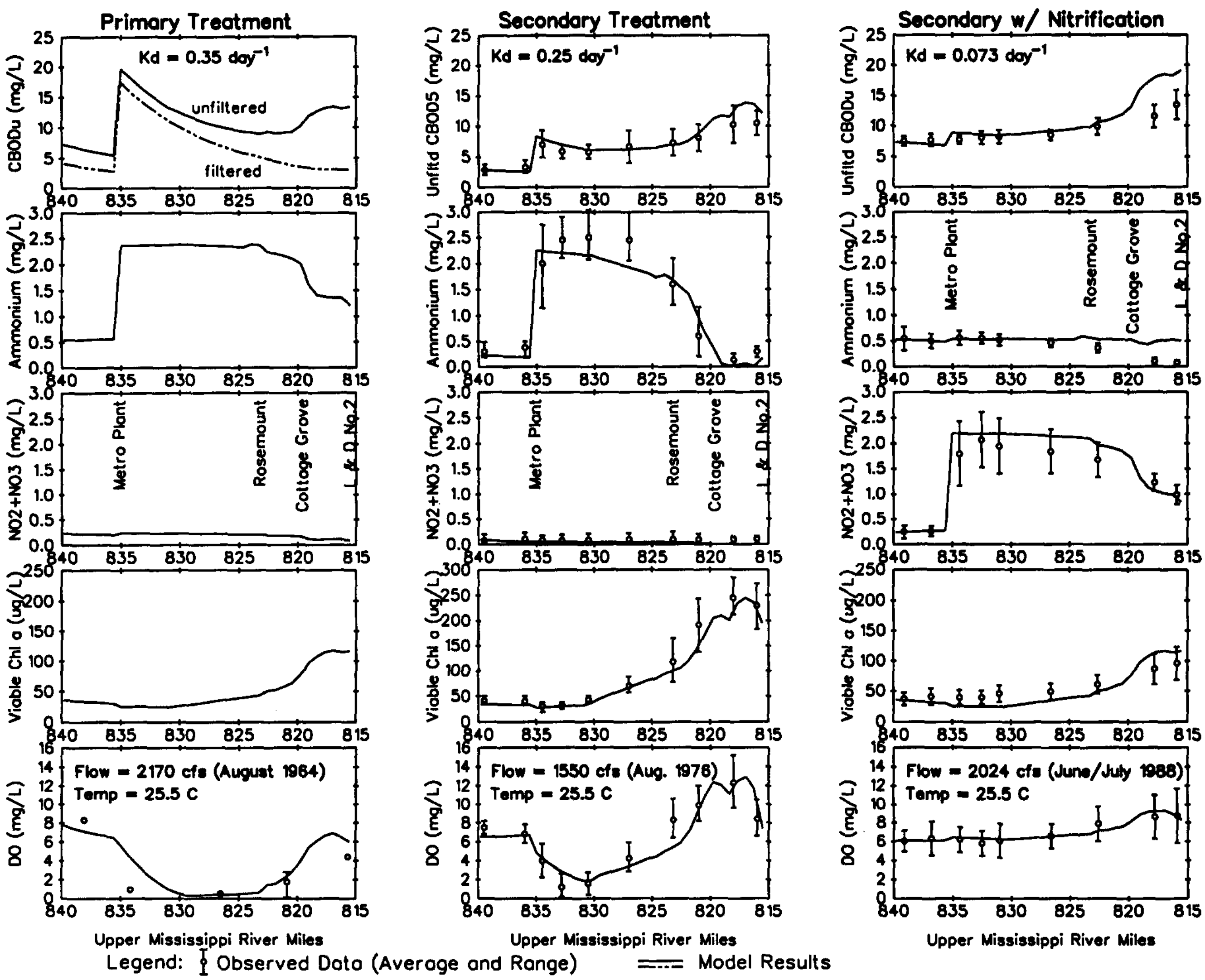

FIG. 2. Improvement of Dissolved Oxygen Levels in Upper Mississippi River Due to Treatment Upgrades

TABLE 1. Effluent Characteristics (in mg/L) at Different Treatment Levels

Parameter (1)	Metro Plant primary[a] (2)	Metro Plant secondary[b] (3)	Metro Plant with nitrification[c] (4)
CBOD	101.00[d]	40.89[d]	20.28[e]
$CBOD_u/CBOD_5$	1.0	2.50	—
Organic nitrogen	10.02	3.27	3.09
Ammonia nitrogen	11.68	14.95	0.80
Nitrite/nitrate	0.30	0.09	12.63
Total nitrogen	22.20	18.31	16.51
Organic phosphorus	5.50	0.89	0.19
Ortho-P	8.00	2.77	2.53
Total phosphorus	13.50	3.65	2.73

[a]1964–1965 data.
[b]August 1976 data.
[c]June/July 1988 data.
[d]$CBOD_5$.
[e]$CBOD_u$.

effluent characteristics is in CBOD concentration, reduced from 101 mg/L of $CBOD_5$ in the primary effluent to 20 mg/L of $CBOD_u$ in the secondary effluent with nitrification. Incidental CBOD removal has been reported with nitrification at many advanced secondary plants like the Metro Plant ("Technical" 1995). Total nitrogen and phosphorus concentrations at the Metro Plant are also reduced following treatment upgrades (Table 1).

One result of the treatment upgrade is a decrease in the $CBOD_u$ to $CBOD_5$ ratio. Assuming the in-stream CBOD deoxygenation rate, k_d, is a direct reflection of the wastewater characteristics (a reasonable assumption for highly treated effluents with k_d rates close to the bottle rates, k_1), one can relate the $CBOD_u$ to $CBOD_5$ ratio of the wastewater to k_d in the receiving water in the following fashion:

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

Thus, increased wastewater treatment (i.e., a lower k_d) tends to stabilize the wastewater, resulting in higher $CBOD_u$ to $CBOD_5$ ratios. Such a change reflects the reduced impact of the effluent CBOD on the k_d rate, but it also indicates the presence of highly refractory material in the well treated effluent (Lung 1996).

Because of the undeveloped methodology for determining $CBOD_u$ in the late 1970s, the water quality surveys used by the Minnesota Pollution Control Agency (MPCA) relied on the measurements of 5-day BOD (BOD_5). Though there is a small shift in inorganic nitrogen components from ammonia (primary treatment) to nitrite/nitrate (secondary treatment) in some activated sludge plants (Hall and Foxen 1984), nitrification is not expected to take place within 5 days. Thus, it is reasonable to assume BOD_5 equal to $CBOD_5$. A significant conversion of ammonia to nitrate is expected with the nitrification process installed (see June/July 1988 data). In recent years, the BOD methodology has been greatly improved, and long-term CBOD measurements provide reliable results (see the $CBOD_u$ reported for June/July 1988 in Table 1).

LONG-TERM CBOD ANALYSIS

The laboratory protocol to quantify the $CBOD_u$ of wastewaters has improved significantly in recent years. One of the difficulties in the laboratory analysis has been nitrification suppression. Often, anomalous results of CBOD analysis have been reported, in which $CBOD_u$ exceeds BOD_u values and CBOD versus the time curve does not follow 1st-order kinetics, as shown in (1). Haffely and Johnson (1994) suggest that

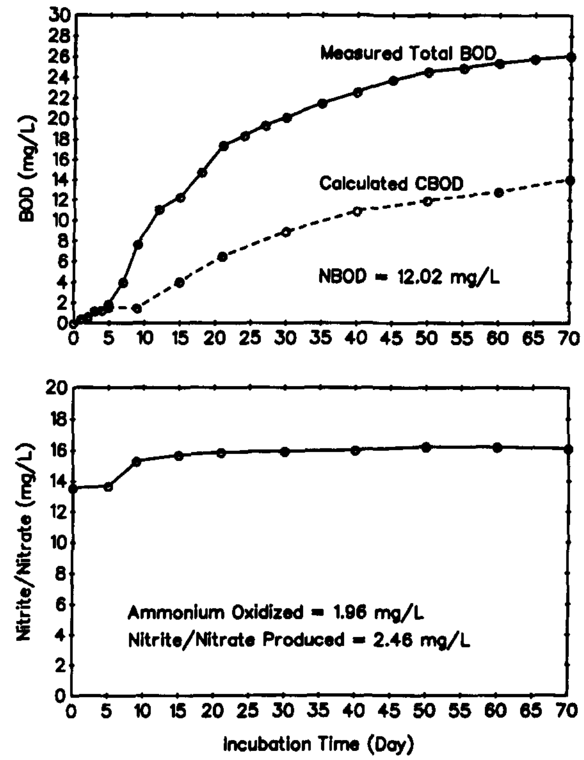

FIG. 3. Long-Term BOD Test Results for Final Effluent of Metro Plant

the source of the errors is the nitrification inhibitor, 2-chloro-6- (trichloromethyl) pyridine (TCMP), used in the laboratory analysis. In their studies, they conclude that TCMP is biodegradable and can contribute significant oxygen demand in $CBOD_u$ tests. Further, TCMP degraders (bacteria) can be transferred between BOD bottles during routine $CBOD_u$ analysis. In many cases, TCMP degraders are present in the wastewater and water samples. The high TCMP dose and long incubation period could enhance the acclimation of the microbial population to TCMP. The potential for biodegradation casts doubt on the integrity of results obtained when TCMP, or perhaps any chemical inhibitor, is used in a long-term BOD test.

The current practice of determining $CBOD_u$ does not call for the use of nitrification suppressors. Instead, the total amount of oxygen consumption is recorded along with concurrent measurements of ammonium, nitrite, and nitrate concentrations, ensuring an accurate mass balance of the nitrogen components. The CBOD is then derived by subtracting the amount of oxygen used in the nitrification process from the measured total oxygen consumption. Using this protocol, Haffely (personal communication, 1997) has obtained excellent long-term BOD test results for the Metro Plant final effluent and ambient water samples from the Upper Mississippi River (Fig. 3). Results from the Metro Plant show that the $CBOD_u$ is about 14 mg/L. The nitrogenous BOD (NBOD) is about 12 mg/L, equivalent to an ammonium concentration of 2.63 mg/L (= 12/4.57), and close to the nitrite/nitrate production of 2.46 mg/L. The test also tracks the amount of ammonium consumed and finds it to be 1.96 mg/L. It indicates that a small amount of organic nitrogen was converted to ammonium, which in turn is oxidized to form nitrate. The time series plots in Fig. 3 show that the majority of ammonium oxidation (or nitrate production) takes place between days 5 and 10. In general, the mass balance between ammonium, nitrite/nitrate, and NBOD is maintained during the long-term BOD test for the Metro Plant final effluent. Regression of the CBOD data points yields a bottle rate of 0.065 day^{-1}, close to the k_d rate of 0.07 day^{-1} in the river. Fig. 4 shows excellent laboratory test results for

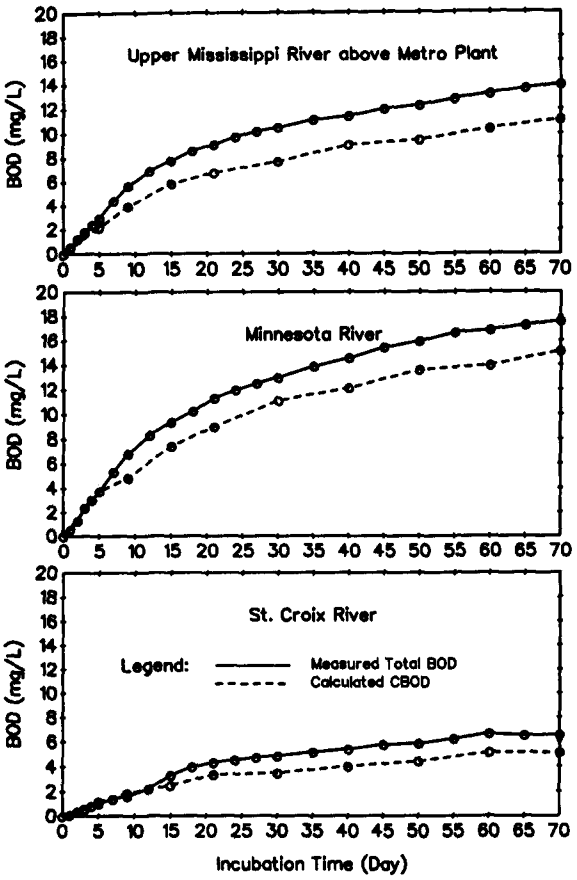

FIG. 4. Long-Term BOD Test Results for Upper Mississippi River, Minnesota River, and St. Croix River

water samples from the Upper Mississippi River and its two major tributaries (the Minnesota River and St. Croix River), further demonstrating the successful long-term BOD test.

SUMMARY AND CONCLUSIONS

Data from the Upper Mississippi River and the Metro Plant present a complete picture of the BOD/DO relationship between the plant effluent and the receiving water over the last 30 years. While the dissolved oxygen concentration profile of the 1960s is a classic example of oxygen recovery following the sag in the receiving water, successive treatment upgrades at the Metro Plant have completely removed the sag and the first half of the classic DO profile. Through treatment upgrades, the response of the receiving water has also changed, reflecting a lower in-stream deoxygenation, k_d, rate (significantly below 0.1 day^{-1}). The low k_d rates are now closely related to the $CBOD_u$ to $CBOD_5$ ratios of the treatment plant final effluent.

The techniques for long-term BOD tests have improved greatly, and CBOD concentrations in both effluent and ambient water samples can be accurately determined. It is hoped that data like these will further improve our BOD/DO modeling skills and modeling practice in wasteload allocations and total maximum daily load modeling.

ACKNOWLEDGMENTS

The writer is grateful for G. Haffely of the Metropolitan Council, Environmental Services, who provided the recent long-term BOD test data of the Metro Plant and its receiving waters.

APPENDIX. REFERENCES

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