UNITED STATES

DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

A ONE-DIMENSIONAL, STEADY-STATE, DISSOLVED-OXYGEN MODEL AND WASTE-LOAD ASSIMILATION STUDY FOR LITTLE LAUGHERY CREEK, RIPLEY AND FRANKLIN COUNTIES, INDIANA

Open-File Report 80-74

Prepared in cooperation with
Indiana State Board of Health

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METRIC CONVERSION FACTORS

The inch-pound units used in this report can be converted to the metric system of units as follows:

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	2.540	centimeter (cm)
foot (ft)	0.3048	meter (m)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
foot per second (ft/s)	0.3048	meter per second (m/s)
square foot (ft^2)	0.0929	square meter (m^2)
cubic foot per second (ft^3/s)	0.0283	cubic meter per second (m^3/s)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
million gallon per day (Mgal/d)	3,785	cubic meter per day (m^3/d)
pound (lb)	0.454	kilogram (km)

ABBREVIATIONS

Abbreviation	Description
BOD	Biochemical-oxygen demand.
CBOD	Carbonaceous biochemical-oxygen demand.
°C	Degree Celsius.
DO	Dissolved oxygen.
e	Base of the natural logarithm, 2.71828.
ft	Foot.
ft/mi	Foot per mile.
ft^3/s	Cubic foot per second.
$(g/m^2)/d$	Gram per square meter per day.
in.	Inch.
ISBH	Indiana State Board of Health.
K_a	Atmospheric reaeration rate.
K_d	Deoxygenation rate for CBOD.
K_n	First-order kinetics deoxygenation rate for NBOD.
$K_{n,zero}$	Zero-order kinetics deoxygenation rate for NBOD.
K_r	Stream decay rate for CBOD.
(lb/d)/d	Pound per day per day.
ln	The natural logarithm, base e.
Mgal/d	Million gallon per day.
mg/L	Milligram per liter.
(mg/L)/d	Milligram per liter per day.
mi	Mile.
mL	Milliliter.
NBOD	Nitrogenous biochemical-oxygen demand.
NPDES	National Pollution Discharge Elimination System.
$Q_{7,10}$	Average low flow over a 7-day period with a recurrence interval of 10 years.
RM	River mile.
Sta. no.	Station number.
t	Traveltime down the stream.
µmho/cm	Micromho per centimeter.

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ABSTRACT

The Indiana State Board of Health is developing a State water-quality-management plan that includes establishing limits for wastewater effluents discharged into Indiana streams. A digital model calibrated to conditions in Little Laughery Creek tributary and Little Laughery Creek was used to predict alternatives for future waste loadings that would be compatible with Indiana stream water-quality standards defined for two critical hydrologic conditions, summer and winter low flows.

Natural streamflow during the summer and annual 7-day, 10-year low flow is zero. Headwater flow upstream from the wastewater-treatment facilities consists solely of process cooling water from an industrial discharger. This flow is usually less than 0.5 cubic foot per second. Consequently, benefits from dilution are minimal. As a result, current and projected ammonia-nitrogen concentrations from the municipal discharges will result in in-stream ammonia-nitrogen concentrations that exceed the Indiana ammonia-nitrogen toxicity standards (maximum stream ammonia-nitrogen concentrations of 2.5 and 4.0 milligrams per liter during summer and winter low flows, respectively).

This waste-load assimilation study is not based on a verified model. The changes in stream water quality predicted by the model represent only possible stream responses to differing effluent conditions.

Benthic-oxygen demand is probably the most significant factor affecting Little Laughery Creek and is probably responsible for the in-stream dissolved-oxygen concentration being less than the Indiana stream dissolved-oxygen standard (5.0 milligrams per liter) during two water-quality surveys. After municipal dischargers complete advanced waste-treatment facilities, benthic-oxygen demand should be less significant in the strean dissolved-oxygen dynamics.

INTRODUCTION

To meet the goals of section 208 of the Federal Water Pollution Control Act, Amendments of 1972, Public Law 92-500, the ISBH (Indiana State Board of Health) is developing a State water-quality-management plan. A key element of the plan is establishing effluent-discharge limits under NPDES (National Pollution Discharge Elimination System). These limits for Indiana are designed to maintain the following in-stream water-quality standards:

1. Average DO (dissolved-oxygen) concentrations of at least 5.0 mg/L (milligrams per liter) per calendar day and not less than 4.0 mg/L at any time.

2. Maximum ammonia-nitrogen concentrations of 2.5 mg/L for June-August (based on a 96-hour median lethal concentration of 0.05 mg/L unionized ammonia nitrogen) and 4.0 mg/L for November through March.

3. A maximum concentration for toxic substances of one-tenth the 96-hour median lethal concentration for important indigenous aquatic species (Indiana State Board of Health, 1977, p. 6).

In the past, point-source discharge limitations were based on arbitrary assumptions and "best engineering estimates." In the current approach, a digital model is used to link a stream's water quality and effluent discharges. Once calibrated to the specific stream conditions, the model can be used to predict the effect of varying waste load, streamflow, and stream temperature. This capability is essential to proper waste-load allocation.

The objectives of this study were to (1) use data provided by ISBH for calibrating and verifying a one-dimensional, steady-state, dissolved-oxygen model for Little Laughery Creek in Ripley and Franklin Counties, Ind., and (2) use the verified model for determining alternatives for future waste loadings that will ensure that the stream meets Indiana water-quality standards defined for two critical hydrologic conditions, summer and winter low flows. The critical-condition rationale is useful for water-quality planning and management (Hines and others, 1975, p. B5-B6).

BASIN DESCRIPTION

Little Laughery Creek drains a 27.4-mi^2 area in Ripley and Franklin Counties in southeastern Indiana and flows south to its confluence with Laughery Creek near Ballstown (fig. 1). The basin, which lies in the Muscatatuck Regional Slope area of Indiana (Schneider, 1966, p. 43), is underlain by shales and limestones of Ordovician age (Gray and others, 1972). Thickness of unconsolidated deposits ranges from only a few ft to 50 ft (Reeves, 1922, p. 979).

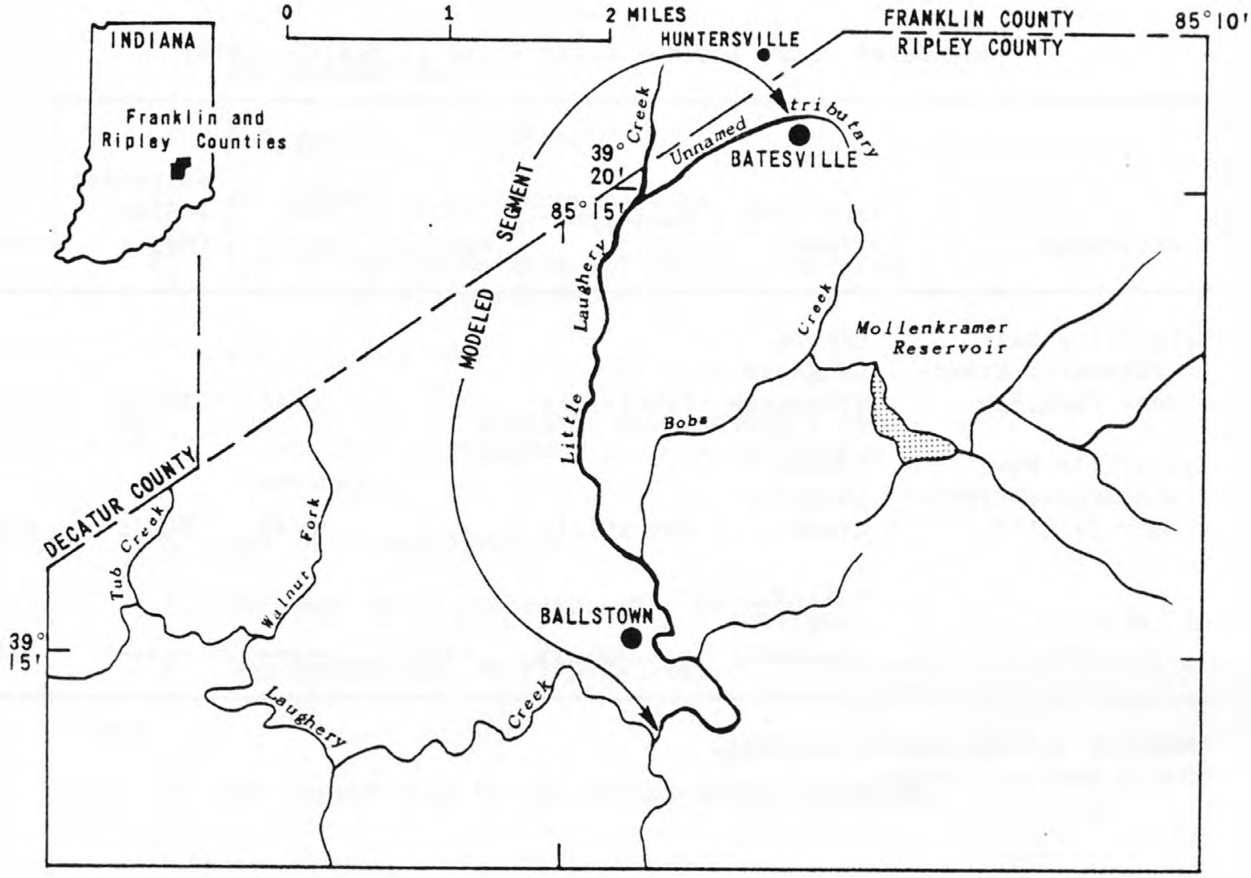

Figure 1.-- Location of modeled segment on Little Laughery Creek, Ripley and Franklin Counties, Ind.

Land use in Ripley County is primarily agricultural, except for several small towns.

Annual rainfall in the county averages 30 inches (Schaal, 1966, p. 157). The mean daily air temperature in January is -4°C and in July is 18°C (Schaal, 1966, p. 162). Runoff averages 14 inches (Hoggatt, 1962, p. 9).

The two major point-source waste dischargers affecting Little Laughery Creek are two wastewater-treatment facilities operated by the city of Batesville, Ind. In addition, Hillenbrand Industries, Inc., also discharges its effluent into the Little Laughery Creek tributary. (See table 1.) The Batesville East wastewater-treatment facility uses an intermediate rate trickling filter for wastewater treatment; the Batesville West facility uses the activated-sludge process. At present, flow at each facility averages 0.37 Mgal/d (million gallon per day) according to Vince Sommers (ISBH, written commun., 1979). Current plans call for expansion of the West facility and elimination of the East. Also under consideration is a plan to treat wastewater from several smaller nearby communities at the Batesvilles West wastewater-treatment facility (D. S. Patell, ISBH, oral commun., 1979).

Table 1.--NPDES restrictions for municipalities and industries in the Little Laughery Creek basin, Ripley and Franklin Counties, Ind.

[Source of data, Indiana State Board of Health, 1978]

Discharger	Receiving stream	Municipal-ity	Flow (Mgal/d)	Five-day BOD[1] (mg/L)	Suspended solids (mg/L)	pH[2]
Batesville East wastewater-treatment facility	Little Laughery tributary	Batesville	0.4	30/45	30/45	6/9
Batesville West wastewater-treatment facility	Little Laughery Creek	Batesville	.13	30/45	30/45	6/9
Hillenbrand Industries, Inc.	Little Laughery tributary	Batesville	----	-----	-----	6/9

[1]Monthly average/weekly average.
[2]Daily low/daily high.

MODEL DESCRIPTION

A steady-state, one-dimensional, segmented water-quality model developed by Bauer and others (1979) was used in this study. One of the objectives of the study was to determine the waste-load assimilation capacity of Little Laughery Creek at the critical low-flow condition. The use of a steady-state, one-dimensional model is consistent with this objective. The modeling approach assumes that the various flows, loads, and other factors used do not vary significantly with time for a given simulation. The model uses a modified Streeter-Phelps equation that also incorporates nitrogenous, benthic, photosynthetic, and plant-respiratory effects on the DO balance. The DO balance is represented in the model by the following equation:

$$\text{Zero} = -\frac{1}{A}\,\partial\,\frac{(QD)}{dx} - K_a D + K_d L + K_n N - P + R + B \qquad (1)$$

where

A is stream cross-sectional area,

D the DO deficit defined as the difference between saturated DO concentration (C_s) and the observed DO concentration, (C),

Q the streamflow,

x the downstream distance,

K_a the atmospheric reaeration rate,

K_d the deoxygenation rate for CBOD (carbonaceous biochemical-oxygen demand),

L the ultimate CBOD,

K_n the first-order kinetics deoxygenation rate for NBOD (nitrogenous biochemical-oxygen demand),

N the NBOD concentration,

P the mean daily photosynthetic DO production,

R the oxygen used by respiration,

and

B the oxygen used by the stream-bottom deposits.

By integration, the dissolved-oxygen deficit becomes the sum of the following components:

$D_o e^{-K_a t}$ the initial DO deficit, (2)

$\frac{K_d L_o}{K_a - K_r} (e^{-K_r t} - e^{-K_a t})$ the deficit due to CBOD, (3)

$\frac{K_n N_o}{K_a - K_n} (e^{-K_n t} - e^{-K_a t})$ the deficit due to NBOD, (4)

$\frac{R}{K_a} (1 - e^{-K_a t})$ the deficit due to plant respiration, (5)

$\frac{B}{K_a} (1 - e^{-K_a t})$ the deficit due to stream-bottom deposits, and (6)

$\frac{-P}{K_a}$ $(1 - e^{-K_a t})$ the deficit due to mean daily photosynthetic production, (7)

where

D_o is the DO deficit at some initial time, t_o,

t the traveltime down the stream,

L_o the ultimate CBOD concentration at some initial time, t_o,

K_r the stream decay rate for CBOD,

N_o the ultimate NBOD concentration at some initial time, t_o,

and

e the base of the natural logarithm, 2.71828.

If the deoxygenation rate for NBOD is assumed to follow $K_{n,\ zero}$ (zero-order kinetics), equation 1 becomes:

$$\text{Zero} = -\frac{1}{A}\,\partial\,\frac{(QD)}{dx} - K_a D + K_d L + K_{n,\ zero} - P + R + B \qquad (8)$$

and component 4 becomes

$$\frac{K_{n,\ zero}}{K_a}\ (1 - e^{-K_a T}),\ \text{the deficit due to NBOD,} \qquad (9)$$

where

$K_{n,\ zero}$ is the zero-order kinetics deoxygenation rate for NBOD.

DATA COLLECTION

The modeled stream segment extends from Batesville to the stream's confluence with Laughery Creek (fig. 2). Five sampling stations were selected for the initial survey in June 1977. This number was increased to 16 for the survey in September 1978.

Water-quality data were collected every 4 to 6 hours for 24 hours at each main-stem site and once for tributary sites by the ISBH Water-Quality Surveillance Section. Field measurements included dissolved-oxygen concentration, stream temperature, and pH. Composite samples were analyzed by the Indiana State Board of Health Laboratory for 5-day BOD (biochemical-oxygen demand), ammonia nitrogen, and nitrite nitrogen plus nitrate nitrogen. Additionally, several long-term carbonaceous biochemical-oxygen demand (ultimate CBOD) concentrations were determined for samples collected during the second survey by periodic observations throughout a 20-day incubation period. Water-quality data used in the waste assimilation study are presented in tables 2 and 3.

Ultimate CBOD was measured by the Elmore method (Ludzack, 1966). In this procedure, the ultimate CBOD is estimated initially by assuming it to be 30 percent of the chemical oxygen demand. On the basis of this calculation, the sample is diluted to an estimated ultimate CBOD concentration of not more than 4 mg/L. The diluted samples are analyzed by standard methods in American Public Health Association and others (1976). (See Results and Discussion.)

The annual laboratory-performance evaluation by the U.S. Environmental Protection Agency in 1978 indicated that water-quality analyses done by the ISBH Laboratory were accurate to within 1 percent. (S. R. Kin, ISBH, written commun., 1979).

Stream discharge was measured by the U.S. Geological Survey, during both sampling periods.

Time of travel was measured by instantaneously injecting a slug of fluorescent dye into the stream at a bridge or other easily identifiable location and timing the movement of the resulting dye cloud as it passed one or more locations downstream. The times of travel at different flows are plotted against the instantaneous discharge measured during the study in figures 3-10. Time of travel for reaches for which time-of-travel data were not available were estimated from data collected for hydrologically similar reaches. Time of travel for Little Laughery Creek tributary from RM 1.60 to 1.49 (fig. 3) was estimated from data collected between RM 1.49 and 1.13. Time of travel for Little Laughery Creek from RM 1.78 to 0.00 (fig. 10) was estimated from data collected between RM 2.66 and 1.78.

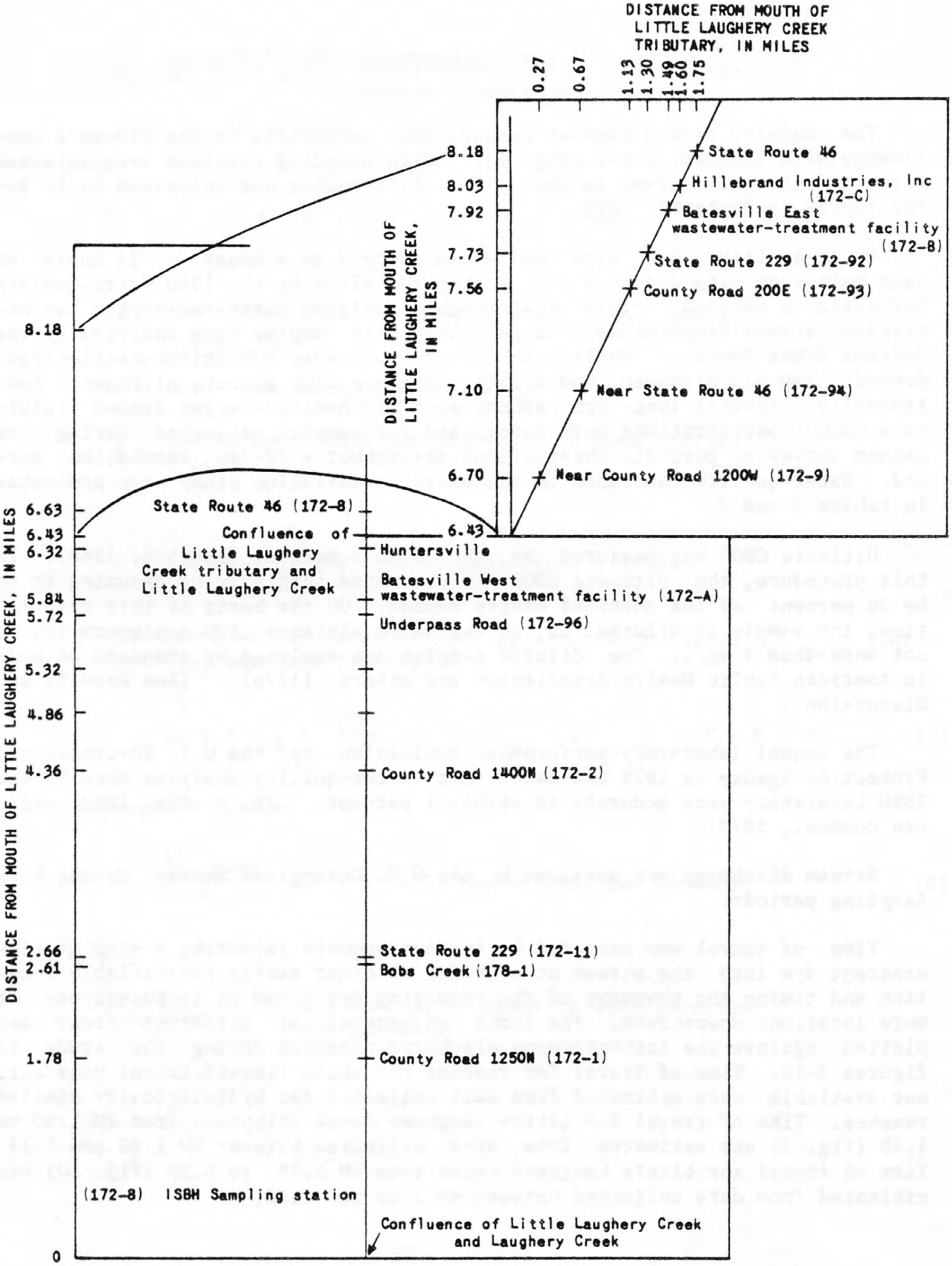

Figure 2.-- Locations of sampling stations in the Little Laughery Creek basin, Ripley and Franklin Counties, Ind.

Table 2.--Water-quality analyses and discharge measurements for sampling stations on Little Laughery Creek tributary and Little Laughery Creek, Ripley and Franklin Counties, Ind., June 3, 1977

[Water-quality data collected by Indiana State Board of Health; discharge measured by U.S. Geological Survey]

Location and station (ISBH sta. no. in parens)	River mile	Discharge (ft^3/s)	Field pH range	Average[1] temp. (°C)	Suspended solids (mg/L)	Average[1] DO (mg/L)	Five-day BOD (mg/L)	Twenty-day CBOD (mg/L)	Ammonia nitrogen (mg/L)	Total Kjeldahl nitrogen (mg/L)	Nitrite plus nitrate nitrogen (mg/L)
Hillenbrand Industries, Inc. (172-C)	8.03	0.27	6.8-7.3	25	4	4.4	2.6	--	0.2	--	<0.1
Batesville East wastewater-treatment facility (172-B)	7.92	.77	6.8-7.5	23	48	2.4	46	--	8.7	--	1
Batesville West wastewater-treatment facility (172-A)	5.84	.52	6.7-7.2	21	100	2.0	73	--	12.0	--	6
Little Laughery Creek at County Road 1400N (172-2)	4.36	1.67	6.7-7.2	21	18	5.1	7.3	--	4.4	--	9
Little Laughery Creek at County Road 1250N (172-1)	1.78	2.27	7.0-7.2	23	36	3.5	5.8	--	3.1	--	1.5

[1]Average based on data collected every 4 to 6 hours for 24 hours.

Table 3.--Water-quality analyses and discharge measurements for sampling stations on Little Laughery Creek tributary and Little Laughery Creek, Ripley and Franklin Counties, Ind., September 20, 1978

[Water-quality data collected by Indiana State Board of Health; discharge measured by U.S. Geological Survey]

Location and station (ISBH sta. no. in parens)	River mile	Discharge (ft^3/s)	Field pH range	Average[1] temp. (°C)	Suspended solids (mg/L)	Average[1] DO (mg/L)	Five-day BOD (mg/L)	Twenty-day CBOD (mg/L)	Ammonia nitrogen (mg/L)	Total Kjeldahl nitrogen (mg/L)	Nitrite plus nitrate nitrogen (mg/L)
Little Laughery Creek tributary at State Route 46 (172-91)	----	<0.1	----	28	15	6.5	12.4	----	<0.1	0.9	<0.1
Hillenbrand Industries, Inc. (172-C)	8.03	----	----	30	9	3.0	----	7.8	.1	2.2	<.1
Batesville East wastewater-treatment facility (172-B)	7.92	.63	----	--	36	---	----	21.8	5.6	9.3	1.7
Little Laughery Creek tributary at State Route 229 (172-92)	7.73	-----	6.7-7.3	27	8	3.1	----	13.7	3.1	5.2	8
Little Laughery Creek tributary at County Road 200E (172-93)	7.56	-----	6.8-7.5	26	13	3.5	6.9	----	3.0	5.2	.6
Little Laughery Creek tributary at State Route 46 (172-94)	7.10	-----	6.9-7.2	24	11	3.4	6.2	----	2.6	4.6	.5
Little Laughery Creek at County Road 1200W (172-9)	6.70	-----	6.8-7.5	24	10	3.2	----	9.8	2.0	4.0	.9
Little Laughery Creek at RM 6.43 (172-8)	6.43	-----	6.1-8.0	26	8	6.3	1.6	----	<.1	.8	<.1

Table 3.--Water-quality analyses and discharge measurements for sampling stations on Little Laughery Creek tributary and Little Laughery Creek, Ripley and Franklin Counties, Ind., September 20, 1978--Continued

Location and station (ISBH sta. no. in parens)	River mile	Dis-charge (ft^3/s)	Field pH range	Aver-[1] age temp. (°C)	Sus-pended solids (mg/L)	Aver-[1] age DO (mg/L)	Five-day BOD (mg/L)	Twenty-day CBOD (mg/L)	Ammonia nitrogen (mg/L)	Total Kjeldahl nitrogen (mg/L)	Nitrite plus nitrate nitrogen (mg/L)
Little Laughery Creek at Huntersville (172-95)	6.23	---	6.6-7.5	25	13	4.0	---	8.1	1.4	3.1	1.1
Batesville West wastewater-treatment facility (172-A)	5.84	.75	----	--	110	---	---	81.5	12.0	21	<.1
Little Laughery Creek at Underpass Road (172-96)	5.72	----	6.7-7.6	25	16	1.5	---	16.7	5.1	7.6	.2
Little Laughery Creek at RM 5.32 (172-97)	5.32	----	----	--	10	---	6.0	----	3.5	5.2	<.1
Little Laughery Creek at RM 4.86 (172-98)	4.86	----	6.7-7.6	25	16	2.1	6.7	----	5.5	7.4	<.1
Little Laughery Creek at County Road 1400N (172-2)	4.36	1.9	6.7-6.9	26	30	4.4	6.0	----	5.3	7.5	1
Little Laughery Creek at State Route 229 (172-11)	2.66	1.9	6.7-7.1	26	35	5.2	---	11.7	4.8	7.1	.5
Bobs Creek (178-1)	2.61	<.1	----	--	23	---	1.8	----	<.1	.8	.3

[1]Average based on data collected every 4 to 6 hours for 24 hours.

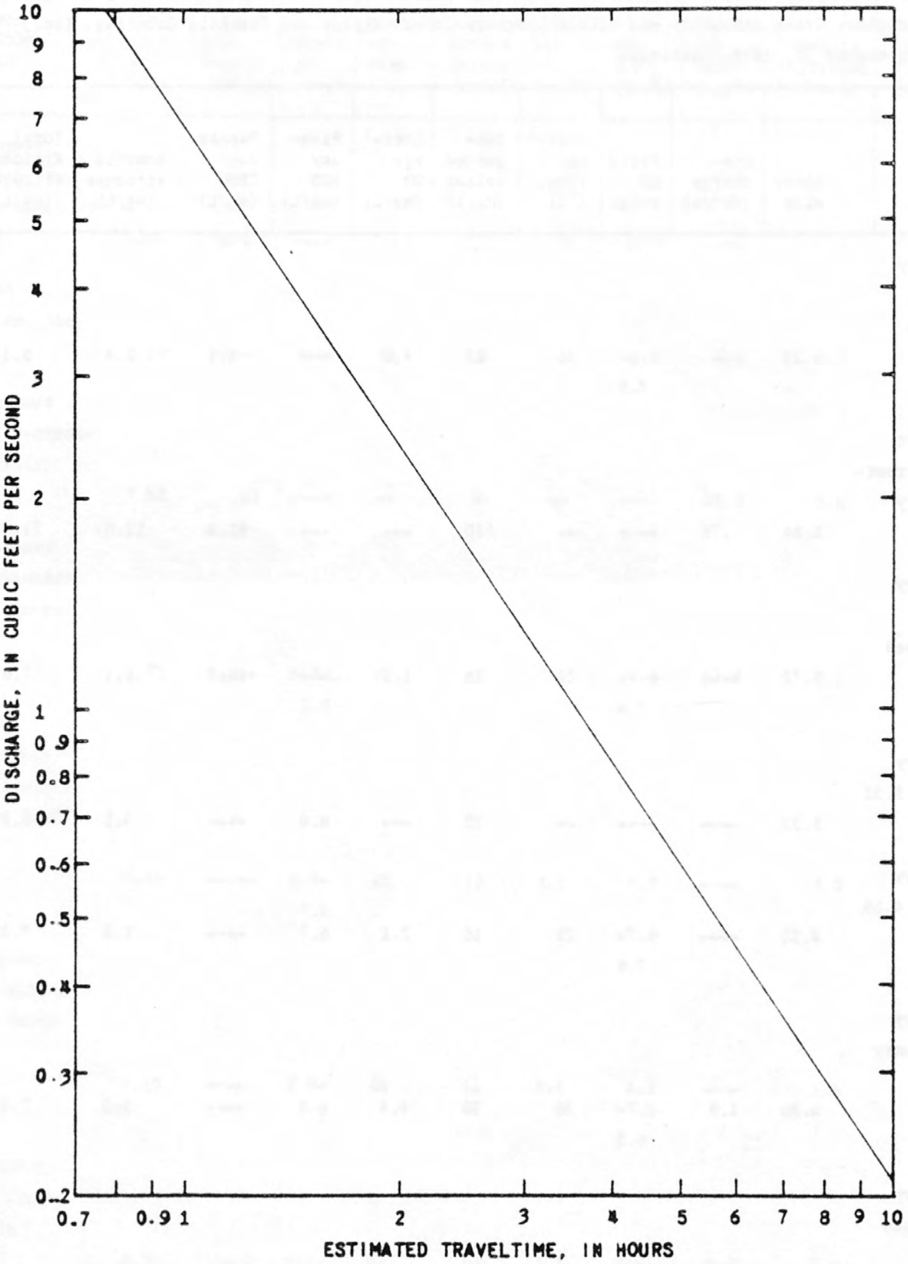

Figure 3.-- Relation of discharge to estimated traveltime of the peak dye concentration for Little Laughery Creek tributary, river miles 1.60 to 1.49.

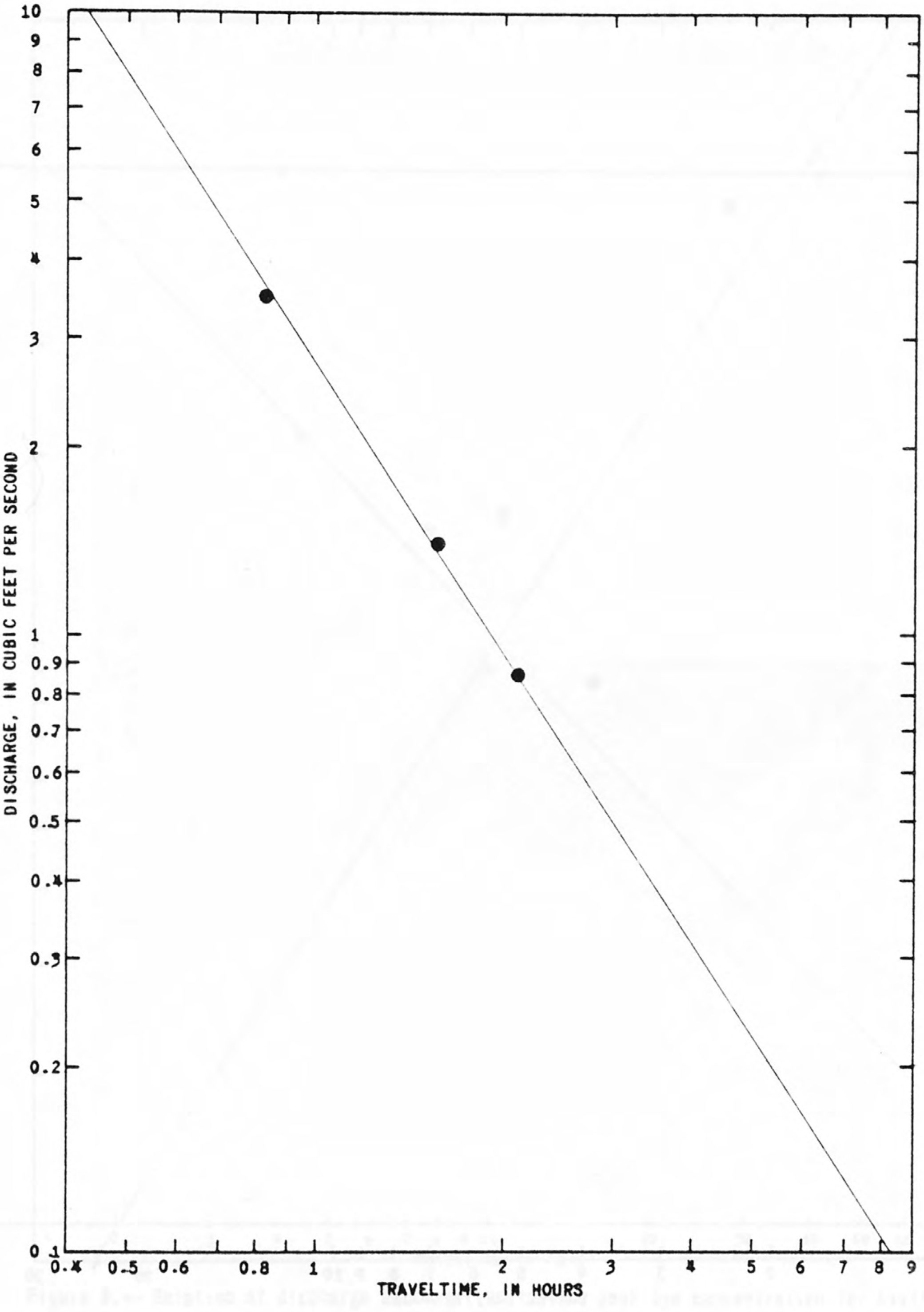

Figure 4.-- Relation of discharge to traveltime of the peak dye concentration for Little Laughery Creek tributary, river miles 1.49 to 1.13.

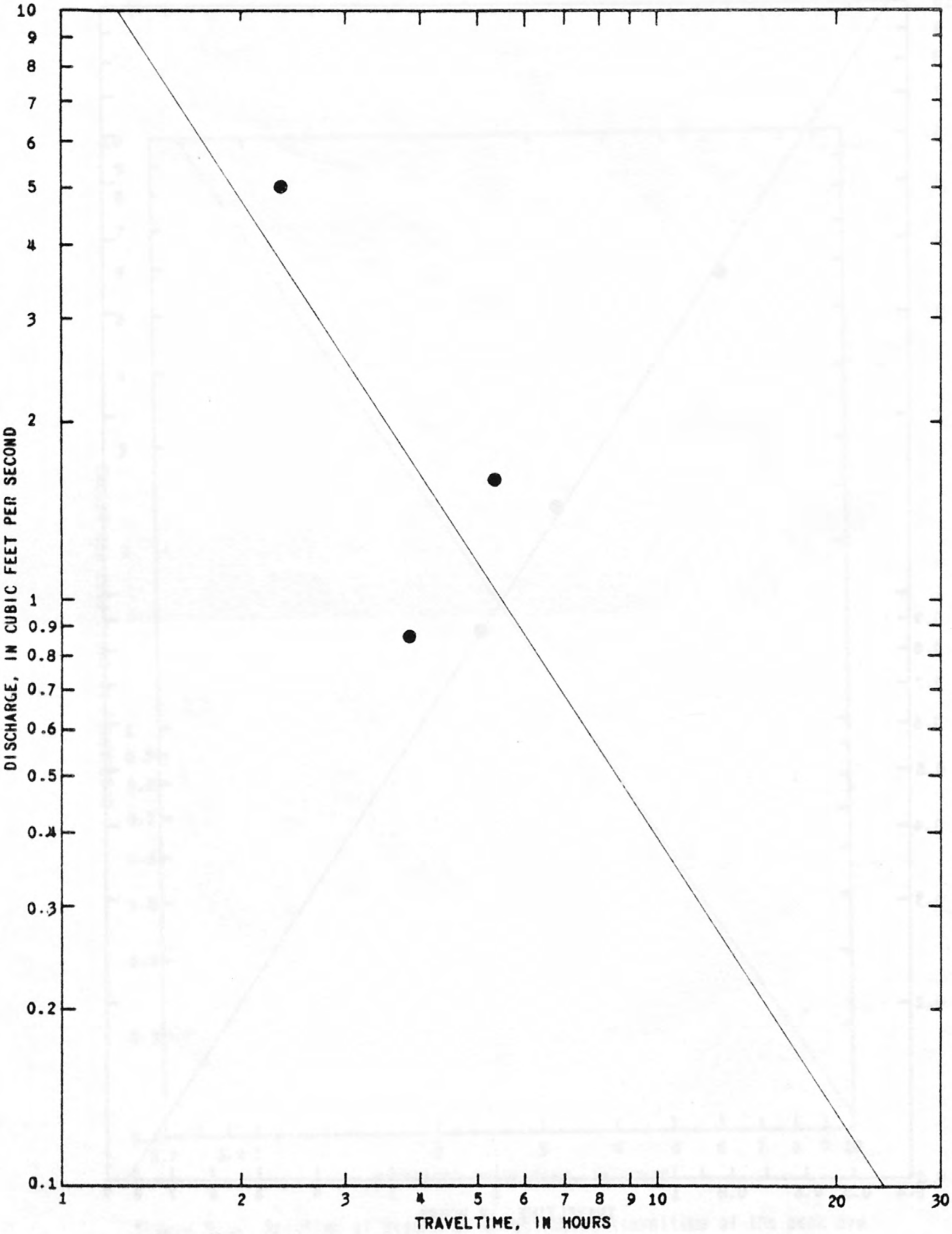

Figure 5.-- Relation of discharge to traveltime of the peak dye concentration for Little Laughery Creek tributary, river miles 1.13 to 0.27.

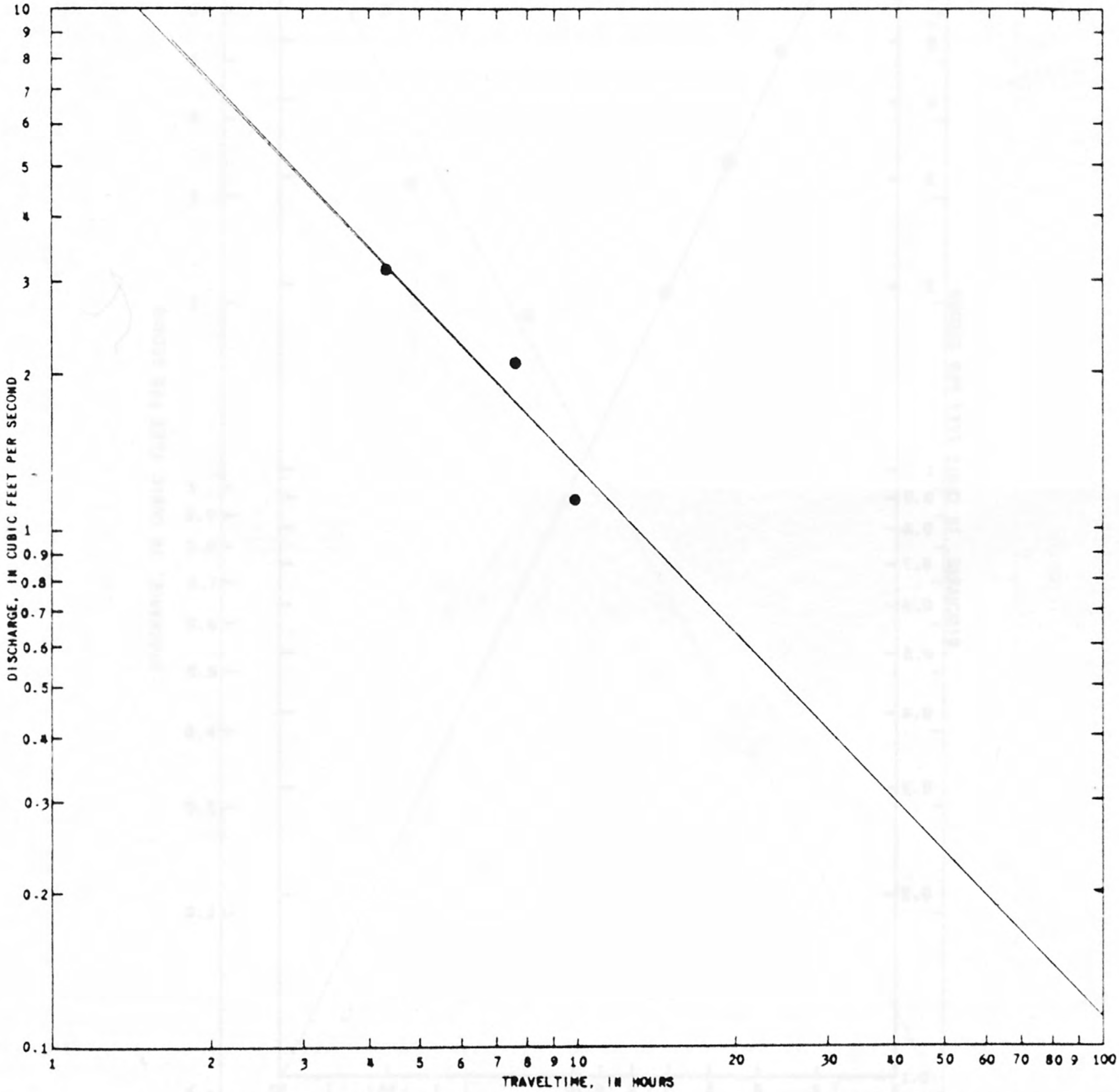

Figure 6.-- Relation of discharge to traveltime of the peak dye concentration for Little Laughery Creek tributary, river mile 0.27, to Little Laughery Creek, river mile 5.84.

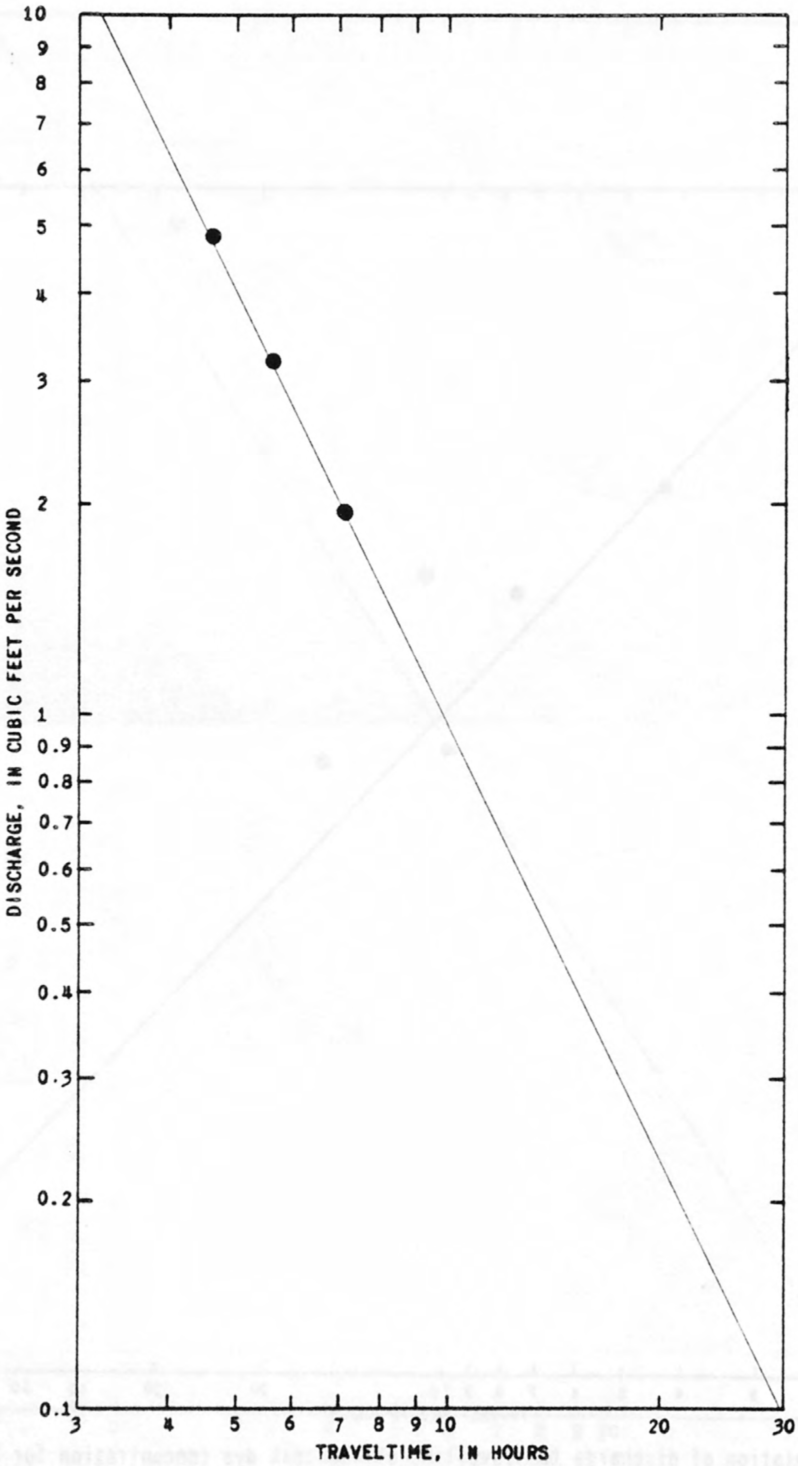

Figure 7.-- Relation of discharge to traveltime of the peak dye concentration for Little Laughery Creek, river miles 5.84 to 4.36.

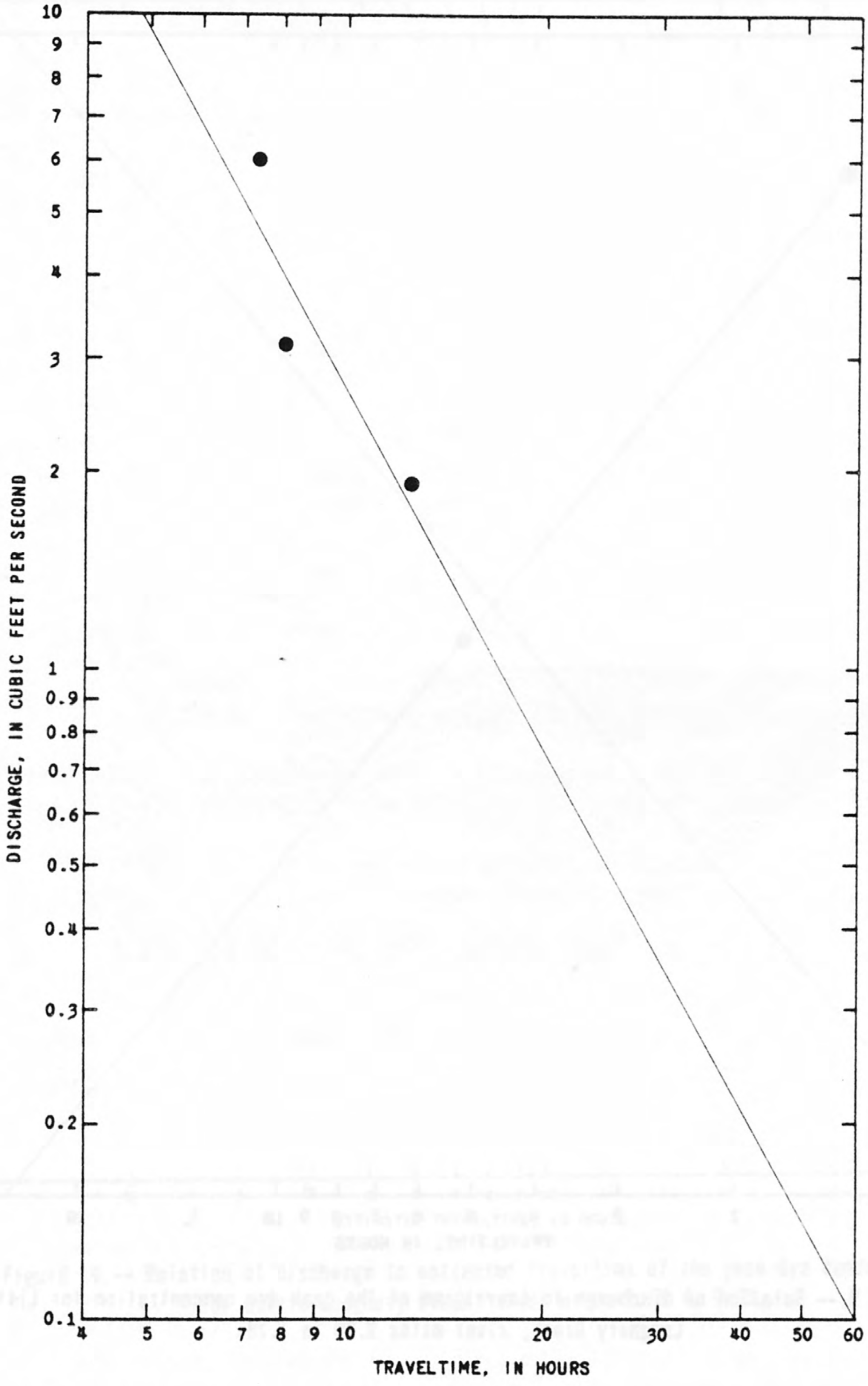

Figure 8.-- Relation of discharge to traveltime of the peak dye concentration for Little Laughery Creek, river miles 4.36 to 2.66.

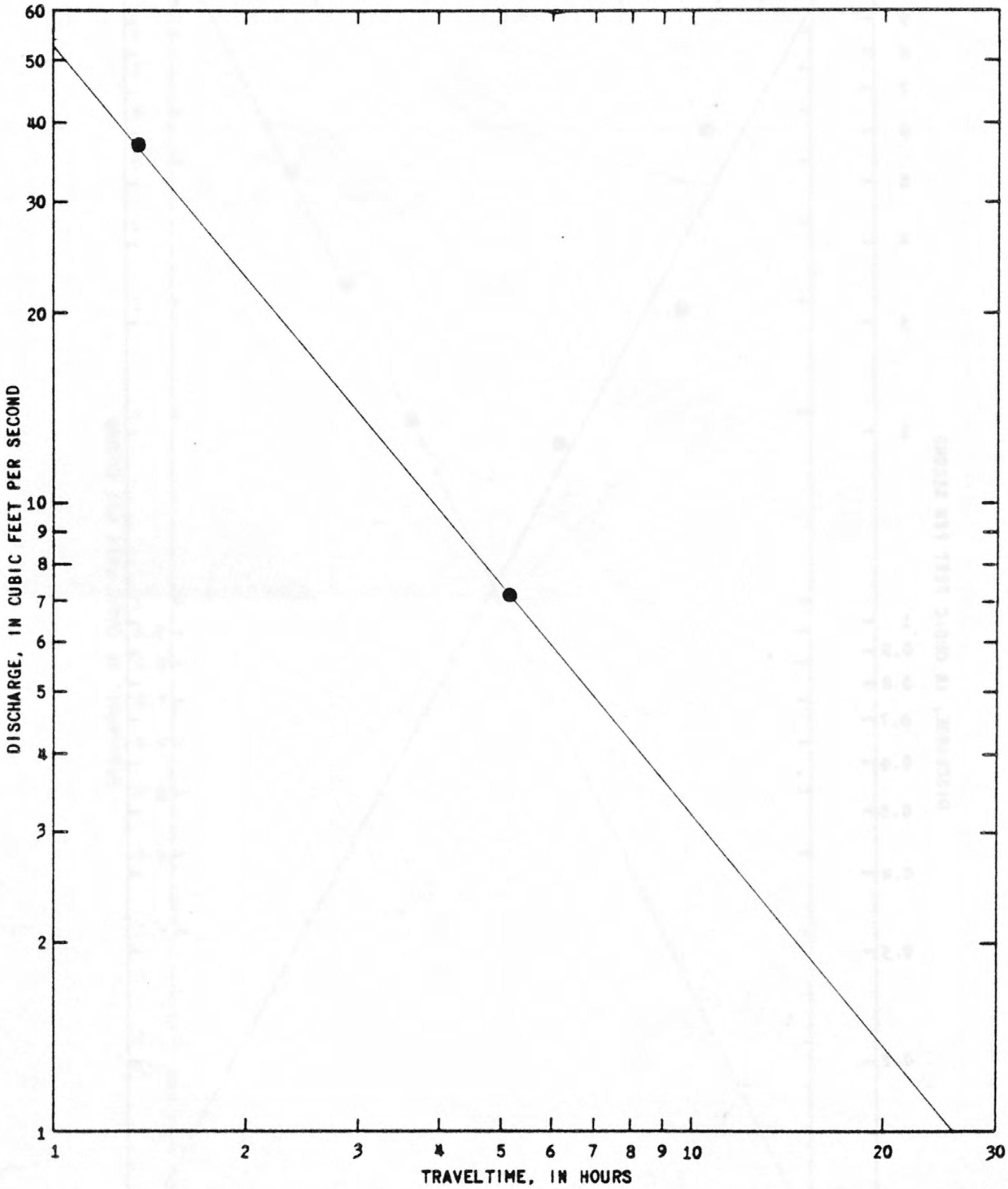

Figure 9.-- Relation of discharge to traveltime of the peak dye concentration for Little Laughery Creek, river miles 2.66 to 1.78.

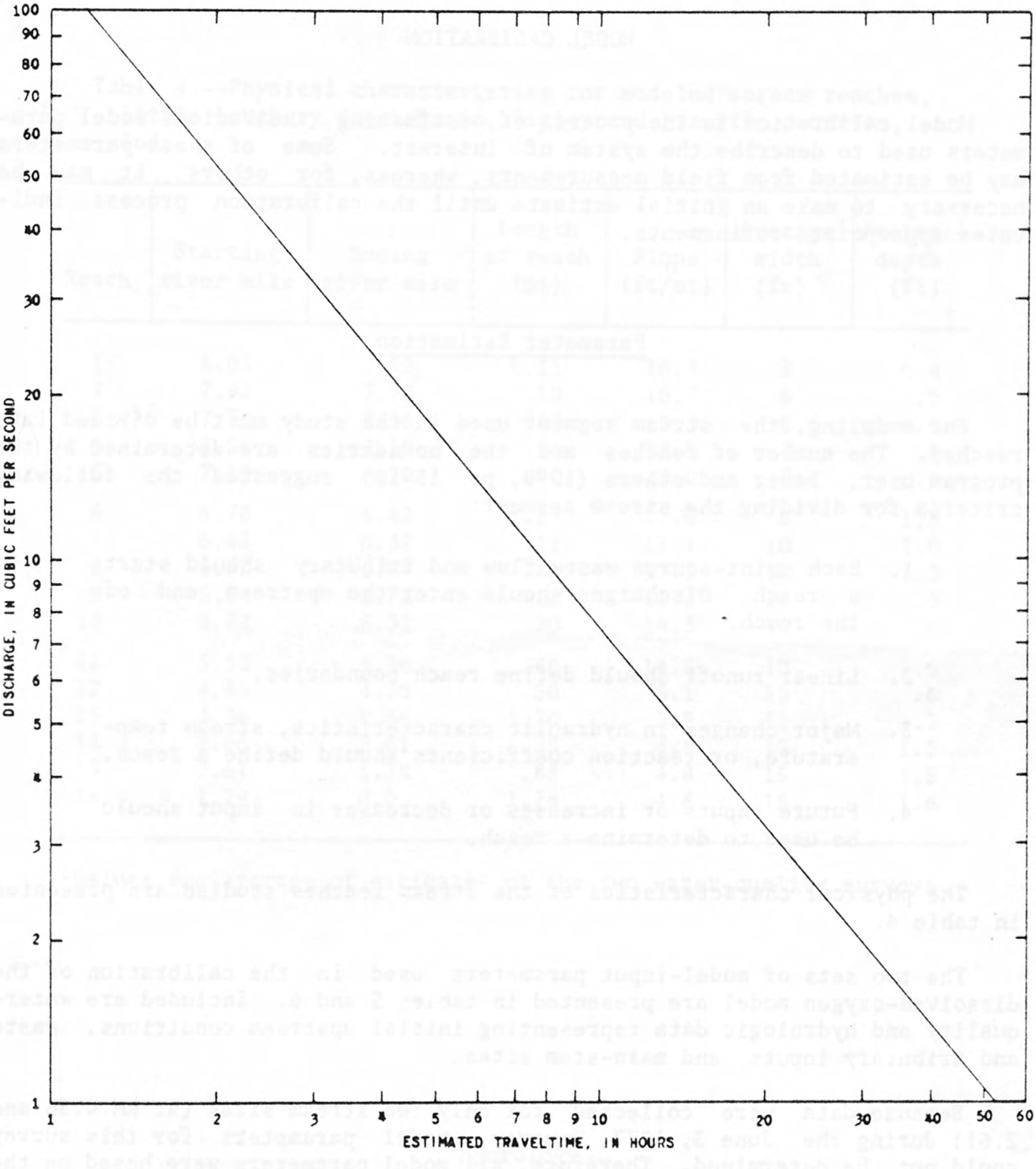

Figure 10.-- Relation of discharge to estimated traveltime of the peak dye concentration for Little Laughery Creek, river miles 1.78 to 0.00.

MODEL CALIBRATION

Model calibration is the process of estimating the various model parameters used to describe the system of interest. Some of these parameters may be estimated from field measurements, whereas, for others, it may be necessary to make an initial estimate until the calibration process indicates appropriate refinements.

Parameter Estimation

For modeling, the stream segment used in the study must be divided into reaches. The number of reaches and the boundaries are determined by the program user. Bauer and others (1979, p. 15-16) suggested the following criteria for dividing the stream segment:

1. Each point-source waste flow and tributary should start a reach. Discharges should enter the upstream end of the reach.

2. Linear runoff should define reach boundaries.

3. Major changes in hydraulic characteristics, stream temperature, or reaction coefficients should define a reach.

4. Future inputs or increases or decreases in input should be used to determine a reach.

The physical characteristics of the stream reaches studied are presented in table 4.

The two sets of model-input parameters used in the calibration of the dissolved-oxygen model are presented in tables 5 and 6. Included are water-quality and hydrologic data representing initial upstream conditions, waste and tributary inputs, and main-stem sites.

Because data were collected for only two stream sites (at RM 4.36 and 2.61) during the June 3, 1977, survey, model parameters for this survey could not be determined. Therefore, all model parameters were based on the September 20, 1978, survey data. In addition, neither dissolved-oxygen nor temperature data were collected at either of the Batesville wastewater-treatment facilities during the September 20, 1978, survey. The DO and temperature of these effluents were assumed to be the same as the values observed during the June 3, 1977, survey.

Table 4.--Physical characteristics for modeled stream reaches, Little Laughery Creek basin, Ripley and Franklin Counties, Ind.

Reach	Starting river mile	Ending river mile	Length of reach (mi)	Slope (ft/mi)	Average[1] width (ft)	Average[1] depth (ft)
1	8.03	7.92	0.11	16.7	5	0.4
2	7.92	7.73	.19	16.7	6	.6
3	7.73	7.56	.17	12.5	6	.6
4	7.56	7.10	.46	12.5	7	.6
5	7.10	6.70	.40	17.0	7	.6
6	6.70	6.43	.27	17.0	8	1.3
7	6.43	6.32	.11	11.1	10	1.0
8	6.32	5.84	.48	11.1	10	1.0
9	5.84	5.72	.12	11.1	10	.6
10	5.72	5.32	.20	14.3	10	.6
11	5.32	4.86	.46	14.5	10	.6
12	4.86	4.36	.50	6.1	10	.6
13	4.36	2.66	1.70	5.5	12	.7
14	2.66	2.61	.05	4.8	15	1.5
15	2.61	1.78	.83	4.8	15	1.5
16	1.78	0.0	1.78	4.8	15	1.6

[1]Values are average of estimates of the two water-quality surveys.

Hydrology

Both water-quality surveys were done during steady-state low flow. No natural flow was reported in the Little Laughery tributary upstream from Hillenbrand Industries, Inc., during either the June 3, 1977, or the September 20, 1978 surveys. Flow in Little Laughery Creek upstream from its confluence with Little Laughery Creek tributary was estimated to be less than 0.3 ft^3/s during both surveys. During the two surveys, most of the flow in the creek was effluent from the two wastewater-treatment facilities and Hillenbrand Industries, Inc.

Table 5.--Model input for Little Laughery Creek tributary and Little Laughery Creek, Ripley and Franklin Counties, Ind., June 3, 1977

[All rates corrected to observed stream temperatures; water-quality data collected by Indiana State Board of Health; discharge measured by U.S. Geological Survey]

Reach	Upstream boundary of modeled reach (ISBH sta. no. in parens)	River mile	Depth (ft)	Dis-charge (ft^3/s)	Linear runoff (ft^3/s)	Time of travel to next site (hours)	Ulti-mate CBOD (mg/L)	NBOD (mg/L)	DO (mg/L)	DO deficit (mg/L)	Temp. (°C)	Mean daily photosyn-thetic DO pro-duction [(mg/L)/d]	K_r (day^{-1})	K_d (day^{-1})	K_a (day^{-1})	$K_{n, zero}$ [(lb/d)/d]
1	Hillenbrand Industries, Inc. (172-C)	8.03	0.5	0.27	0.0	1.13	5.5	0.9	4.4	3.4	25	-3.6	0.243	0.243	3.95	0.0
2	Batesville East wastewater-treat-ment facility (172-B)	7.92	.6	.77	0	.98	95.5	37.7	2.4	5.9	23	-18.6	1.40	.148	9.09	13.0
3	Little Laughery Creek tributary at State Route 229, river mile 1.30 (172-92)	7.73	.6	----	0	.88	----	----	---	---	23	-3.0	1.40	.169	8.90	13.0
4	Little Laughery Creek tributary at County Road 200E river mile 1.13 (172-93)	7.56	.6	----	0	2.85	----	----	---	---	23	-6.9	1.47	.169	5.55	13.0
5	Little Laughery Creek tributary near State Route 46, river mile 0.67 (172-94)	7.10	.6	----	0	2.48	----	----	---	---	23	-10.3	1.61	.169	5.55	13.0
6	Little Laughery Creek tributary near County Road 1200W, river mile 0.27 (172-9)	6.70	1.3	----	0	3.98	----	----	---	---	22	-3.0	1.55	.151	3.18	11.9
7	Little Laughery Creek at river mile 6.43 (172-8)	6.43	1.1	.11	0	1.47	3.5	.4	6.8	1.8	22	-3.0	1.07	.151	3.49	11.9
8	Little Laughery Creek at Huntersville (172-95)	6.32	1.1	----	0	6.43	----	----	---	---	22	-3.0	1.07	.176	2.28	11.9
9	Batesville West wastewater-treat-ment facility (172-A)	5.84	.6	.52	0	.61	154.8	52.0	2.0	6.6	22	-3.6	28.1	.132	6.04	11.9
10	Little Laughery Creek at Under-pass Road (172-96)	5.72	.6	----	0	2.02	----	----	---	---	21	-3.6	2.83	.126	6.04	10.9
11	Little Laughery Creek at river mile 5.32 (172-97)	5.32	.6	----	0	2.33	----	----	---	---	21	-3.6	.126	.126	7.78	10.9
12	Little Laughery Creek at river mile 4.86 (172-98)	4.86	.6	----	0	2.53	----	----	---	---	21	-.3	.126	.126	6.25	10.9
13	Little Laughery Creek at County Road 1400N (172-2)	4.36	.7	----	.40	13.02	----	----	---	---	21	-.3	.126	.126	2.19	10.9
14	Little Laughery Creek at State Route 229 (172-11)	2.66	1.5	----	.01	.80	----	----	---	---	22	-.3	.197	.197	.95	11.9
15	Bobs Creek (178-1)	2.61	1.5	----	.19	13.20	----	----	---	---	22	-.3	.197	.197	.83	11.9
16	Little Laughery Creek at County Road 1250N (172-1)	1.78	1.7	----	.41	28.29	----	----	---	---	22	-.3	.197	.197	.83	11.9

Table 6.--Model input for Little Laughery Creek tributary and Little Laughery Creek, Ripley and Franklin Counties, Ind., September 20, 1978

[All rates corrected to observed stream temperatures; water-quality data collected by Indiana State Board of Health; discharge measured by U.S. Geological Survey]

Reach	Upstream boundary of modeled reach (ISBH sta. no. in parens)	River mile	Depth (ft)	Discharge (ft^3/s)	Linear runoff (ft^3/s)	Time of travel to next site (hours)	Ultimate CBOD (mg/L)	NBOD (mg/L)	DO (mg/L)	DO deficit (mg/L)	Temp. (°C)	Mean daily photosynthetic DO production [(mg/L)/d]	K_r (day^{-1})	K_d (day^{-1})	K_a (day^{-1})	$K_{n, zero}$ [(lb/d)/d]
1	Hillenbrand Industries, Inc. (172-C)	8.03	0.4	0.23	0.0	1.5	8.2	0.4	3.0	4.2	28	-3.6	0.279	0.279	3.8	0.0
2	Batesville East wastewater-treatment facility (172-B)	7.92	.6	.63	0	1.1	22.0	24.2	2.4	5.4	27	-18.6	1.68	.178	8.7	18.3
3	Little Laughery Creek tributary at State Route 229, river mile 1.30 (172-92)	7.73	.6	----	0	1.0	----	----	---	---	27	-3.0	1.68	.203	6.5	18.3
4	Little Laughery Creek tributary at County Road 200E river mile 1.13 (172-93)	7.56	.6	----	0	3.2	----	----	---	---	26	-6.9	1.68	.194	5.3	16.8
5	Little Laughery Creek tributary near State Route 46, river mile. 67 (172-94)	7.10	.6	----	0	2.8	----	----	---	---	24	-10.3	1.68	.177	7.0	14.1
6	Little Laughery Creek tributary near County Road 1200W, river mile .27 (172-9)	6.70	1.3	----	0	4.8	----	----	---	---	24	-3.0	1.68	.166	2.8	14.1
7	Little Laughery Creek at river mile 6.43 (172-8)	6.43	1.0	.29	0	1.5	3.5	.4	6.8	1.1	25	-3.0	1.23	.174	2.4	15.4
8	Little Laughery Creek at Huntersville (172-95)	6.32	1.1	----	0	6.4	----	----	---	---	25	-3.0	1.23	.203	2.5	15.4
9	Batesville West wastewater-treatment facility (172-A)	5.84	.7	.75	0	.6	84.0	52.0	2.0	5.8	25	-3.6	32.2	.151	6.8	15.4
10	Little Laughery Creek at Underpass Road (172-96)	5.72	.7	----	0	1.9	----	----	---	---	25	-3.6	3.40	.151	8.8	15.4
11	Little Laughery Creek at river mile 5.32 (172-97)	5.32	.7	----	0	2.2	----	----	---	---	25	-3.6	.151	.151	8.9	15.4
12	Little Laughery Creek at river mile 4.86 (172-98)	4.86	.7	----	0	2.4	----	----	---	---	26	-.3	.158	.158	3.7	16.8
13	Little Laughery Creek at County Road 1400N (172-2)	4.36	.8	----	0	12.0	----	----	---	---	26	-.3	.158	.158	2.3	16.8
14	Little Laughery Creek at State Route 229 (172-11)	2.66	1.5	----	0	.9	----	----	---	---	26	-.3	.237	.237	.33	16.8
15	Bobs Creek (178-1)	2.61	1.5	----	0	14.1	----	----	---	---	26	-.3	.237	.237	.33	16.8
16	Little Laughery Creek at County Road 1250N (172-1)	1.78	1.5	----	0	30.2	----	----	---	---	26	-.3	.237	.237	.83	16.8

Increases in flow, unaccounted for by wastewater effluents or tributary flow, was added linearly along the modeled reaches involved. Flow of this type was attributed to ground water. Ground-water contributions to stream discharge during the June 3, 1977, survey seemed to be negligible during the two surveys except in the downstream reaches (RM 4.36-0.00).

Average depth of reach, D, was estimated by the following equation:

$$D = \frac{Q}{WV} \tag{10}$$

Where

D is the average depth of reach, in feet,

Q the average discharge, in cubic feet per second,

W the average width, in feet,

and

V the average velocity, in feet per second.

Carbonaceous Biochemical-Oxygen Demand

The relation between 5-day BOD and ultimate CBOD was estimated from the long-term CBOD concentrations for the September 1978 survey. (See fig. 11 and table 7.) This method gives reliable estimates of ultimate CBOD concentrations (Stamer and others, 1979). The average ratio of ultimate CBOD to 5-day BOD for the September 20, 1978, survey determined by this method, 2.16, was also used for the June 3, 1977, survey.

The deoxygenation rate for CBOD, K_d, was determined from a plot of the percentage of long-term CBOD remaining against time. The least-squares method was then used to provide the best estimate of K_d (Nemerow, 1974, p. 93). K_d ranged from 0.12 to 0.19 day^{-1}.

The stream decay rate for CBOD, K_r, was calculated on the basis of CBOD load, so that changes in concentration due to dilution would be included (Thomann, 1972, p. 96).

$$K_r = \ln \left[\frac{C_d}{C_u}\right] t^{-1} \tag{11}$$

where

K_r is the stream decay rate for CBOD, in day^{-1},

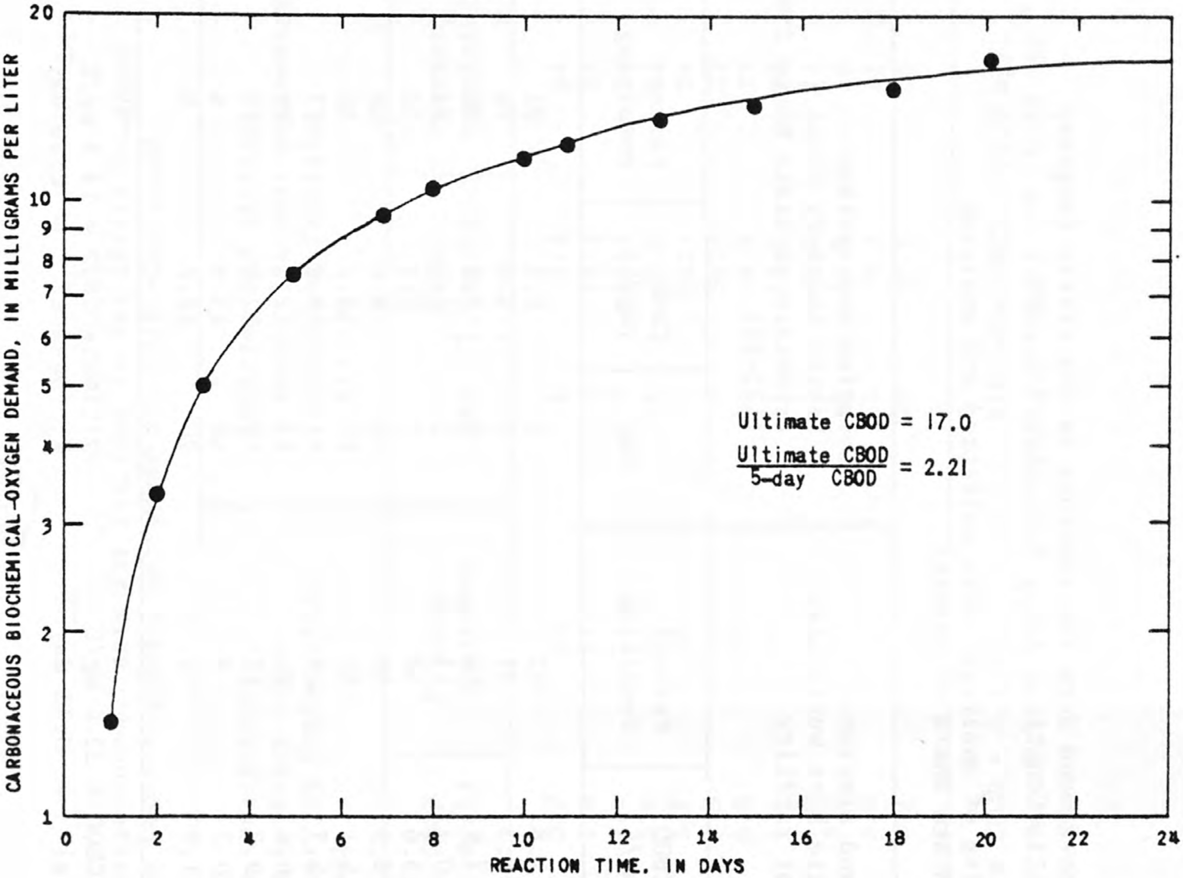

Figure 11.-- Relation of carbonaceous biochemical-oxygen demand to time at river mile 5.72, Little Laughery Creek, September 20, 1978.

C_d and C_u the loads of CBOD, at downstream and upstream sites, respectively, in pounds per day,

t the time of travel between the two sites, in days,

and

ln the natural logarithm, base e.

K_r ranges from 25 day^{-1}, downstream from the Batesville West wastewater-treatment facility, to 0.12 day^{-1}, near the confluence of Little Laughery and Laughery Creeks. This range suggests that a significant part of CBOD is removed by some process other than biochemical degradation; for example, settling or biological extraction.

Table 7.--Carbonaceous biochemical-oxygen-demand data for stations in the Little Laughery Creek basin, Ripley and Franklin Counties, Ind., September 20, 1978

[Day, number of days after beginning of analysis; data collected and analyzed by Indiana State Board of Health]

Location and station: Hillenbrand Industries, Inc. (172-C)			Location and station: Batesville East wastewater-treatment facility (172-B)			Location and station: Little Laughery Creek tributary at State Route 229 (172-92)		
Day	CBOD (mg/L)	Percent remaining	Day	CBOD (mg/L)	Percent remaining	Day	CBOD (mg/L)	Percent remaining
1	2.2	73	1	1.8	92	1	1.3	91
2	3.3	60	2	6.3	71	2	3.0	79
3	4.3	48	3	7.6	66	3	4.4	70
5	5.5	33	5	10.4	53	5	6.7	54
7	5.3	35	7	13.6	38	7	8.2	43
8	6.2	24	8	13.5	39	8	9.0	38
10	6.8	17	10	15.1	31	10	10.1	30
11	6.7	18	11	15.7	29	11	10.6	27
13	7.9	4	13	16.6	25	13	11.7	19
15	6.7	18	15	19.2	13	15	12.5	14
18	8.2	0	18	20.2	8	18	13.4	8
20	7.8	4	20	21.8	1	20	13.8	5
Ultimate CBOD = 8.2 mg/L K_d (base e) = 0.19 day^{-1}			Ultimate CBOD = 22.0 mg/L K_d (base e) = 0.13 day^{-1}			Ultimate CBOD = 14.5 mg/L K_d (base e) = 0.15 day^{-1}		

Table 7.--Carbonaceous biochemical-oxygen-demand data for stations in the Little Laughery Creek basin, Ripley and Franklin Counties, Ind., September 20, 1978--Continued

Location and station: Little Laughery Creek tributary at County Road 1200W (172-9)			Location and station: Little Laughery Creek tributary at Huntersville (172-95)			Location and station: Batesville West wastewater-treatment facility (172-A)		
Day	CBOD (mg/L)	Percent remaining	Day	CBOD (mg/L)	Percent remaining	Day	CBOD (mg/L)	Percent remaining
1	1.3	88	1	0.7	92	1	5.4	94
2	2.5	76	2	1.6	81	2	14.2	83
3	3.0	71	3	2.4	71	3	25.2	70
5	4.4	58	5	4.1	50	5	39.6	53
7	5.1	51	7	5.1	38	7	52.2	38
8	5.9	43	8	5.8	29	8	57.3	32
10	6.8	35	10	6.4	22	10	65.1	23
11	7.7	26	11	6.6	20	11	67.6	20
13	8.3	20	13	6.9	16	13	72.4	14
15	8.9	14	15	7.5	9	15	75.6	10
18	9.4	10	18	8.2	0	18	75.2	11
20	9.8	6	20	8.1	0	20	81.5	3
Ultimate CBOD = 10.4 mg/L; K_d (base e) = 0.14 day^{-1}			Ultimate CBOD = 8.2 mg/L; K_d (base e) = 0.16 day^{-1}			Ultimate CBOD = 84.0 mg/L; K_d (base e) = 0.16 day^{-1}		

Table 7.--Carbonaceous biochemical-oxygen-demand data for stations in the Little Laughery Creek basin, Ripley and Franklin Counties, Ind., September 20, 1978--Continued

Location and station: Little Laughery Creek at Underpass Road (172-96)			Location and station: Little Laughery Creek at State Route 229 (172-11)		
Day	CBOD (mg/L)	Percent remaining	Day	CBOD (mg/L)	Percent remaining
1	1.4	92	1	1.0	92
2	3.6	79	2	2.1	83
3	5.0	71	3	3.0	75
5	7.7	55	5	5.8	52
7	9.5	44	7	6.9	43
8	10.5	38	8	8.2	32
10	11.8	31	10	9.1	24
11	12.3	28	11	9.4	22
13	13.3	22	13	10.4	13
15	14.1	17	15	10.8	10
18	15.0	12	18	11.3	6
20	16.7	2	20	11.7	3
Ultimate CBOD = 17.0 mg/L K_d (base e) = 0.12 day^{-1}			Ultimate CBOD = 12.0 mg/L K_d (base e) = 0.18 day^{-1}		

The deoxygenation rate for CBOD, K_d, and the stream decay rate for CBOD, K_r, were adjusted for temperature by the following equation:

$$(K)_T \text{ Carbonaceous} = (K)_{20^\circ C}(1.047^{T-20^\circ C}) \quad (12)$$

where

(K) is the base-e reaction constant, in day^{-1},

1.047 the constant applicable over a typical field-temperature range,

and

T the stream temperature, in degrees Celsius.

Nitrogenous Biochemical-Oxygen Demand

Because of the complex nature of nitrification and its application to Little Laughery Creek, a brief description of the process is appropriate. In the broadest sense, nitrification is the biologically mediated increase in the oxidation state of reduced organic or inorganic forms of nitrogen. A narrower definition restricts nitrification to the autotrophic oxidation of ammonia to nitrate; nitrite is an intermediate compound. The two-step oxidation by nitrifying bacteria is as follows:

Ammonia oxidation

$$NH_4^+ + {}^3/_2\, O_2 = NO_2^- + 2H^+ + H_2O + \text{energy} \quad (13)$$

Nitrite oxidation

$$NO_2^- + {}^1/_2\, O_2 = NO_3^- + \text{energy} \quad (14)$$

The amounts of dissolved oxygen consumed by this process can be significant. Wezernak and Gannon (1967) found experimentally that 3.22 mg of molecular oxygen is needed to convert 1 mg of ammonia nitrogen (NH_4 - N) to nitrite nitrogen (NO_2 - N) and that 1.11 mg is needed to convert 1 mg of nitrite nitrogen to nitrate nitrogen (NO_2 - N to NO_3 - N). In a typical non-nitrified secondary effluent, the ammonia-nitrogen concentration may range from 12 to 50 mg/L (Metcalf and Eddy, Inc., 1972, p. 231). The potential oxygen demand placed on the receiving stream in this example would range from 53 to 217 mg of oxygen per liter of effluent.

The factors that should be evaluated in determining the significance of nitrification in an aquatic environment are habitat suitability, changes in nitrogen flux, species loads, and nitrifier populations. According to Tuffey and others (1974) and Finstein and others (1978), nitrification in shallow, surface-active streams is due to a population of nitrifying bacteria attached to the streambed. Other environmental factors necessary for nitrification are sufficient ammonia loads, water temperatures greater than 20°C, and near neutral or slightly alkaline pH.

The environmental conditions necessary for nitrification were favorable during the two water-quality surveys. Little Laughery Creek ranges in depth from 0.5 to 1.7 ft. Temperature in the creek ranged from 21° to 25°C during the first survey and from 24° to 28°C during the second. Ammonia-nitrogen concentration of the creek ranged from 3.1 to 4.4 mg/L during the June 1977 survey and from 2.0 to 5.5 mg/L during the September 1978 survey.

The nitrification process in streams is difficult to model. One reason for this is that the rate of change of nitrogen compounds is dependent not only on nitrification but also on other processes in the nitrogen cycle. For example, nitrification causes a decrease in the ammonia-nitrogen concentration and an increase in the nitrate-nitrogen concentration. However, the hydrolysis of organic nitrogen or the reduction of nitrate nitrogen for cell synthesis by heterotrophic bacteria also may cause an increase in the ammonia-nitrogen concentration. Additional factors effecting a change in nitrate-nitrogen concentration in a stream include denitrification and plant respiratory reduction and assimilatory reduction (Ruane and Krenkel, 1977). Because of the difficulty in estimating the significance of these processes, a mass balance for nitrogen species from upstream to downstream locations is not always achieved.

Nitrification rates downstream from wastewater-treatment facilities are usually determined on the basis of the rate of change in ammonia-nitrogen and (or) nitrate-nitrogen load and first-order kinetics. However, in small surface-active streams, where the responsible organisms are nonplanktonic (stationary relative to streamflow, as cells fixed to streambed surfaces or associated with the sediment), a BOD equivalent model based on zero-order kinetics would better describe the process of nitrification under these circumstances (Finstein and others, 1978; Huang and Hopson, 1974). The rate of nitrification would be controlled by the factors affecting the population density of the nitrifying bacteria on the streambed. In this circumstance, nitrification would begin immediately downstream from the outfall and would be independent of the ammonia-nitrogen concentration in the water column, whereas, if the responsible organisms were planktonic, nitrification would be delayed until the nitrifying population had expanded in response to the ammonia enrichment. Under zero-order kinetics, nitrification would result from the action of pregrown cells and would be independent of growth, except in the historical sense. In some circumstances, both planktonic and nonplanktonic cells could contribute to the nitrification. However, Strom and others (1976) determined that the number of nitrifiers released from wastewater effluents is insufficient to exert an appreciable oxygen demand.

The decision to include nitrification in the model was based on the rapid decrease in ammonia-nitrogen concentration observed downstream from the wastewater-treatment facility (fig. 12). Nitrification rates were estimated on the basis of ammonia-nitrogen load removal rate and zero-order kinetics.

$$K_{n,\ zero} = \frac{C_u - C_d}{t} \tag{15}$$

where

C_u and C_d are the loads of ammonia nitrogen per day, at upstream and downstream sites, respectively, in pounds per day,

and

t the time of travel between the two sites, in days.

The removal rate of NBOD for stream reaches downstream from the Batesville East wastewater-treatment facility (RM 7.92 to 6.32) was 41 (lb/d)/d at 20°C. The removal rate for NBOD for stream reaches downstream from the Batesville West wastewater-treatment facility (RM 5.72 to 2.66) was 10 (lb/d)/d at 20°C. Corresponding rates based on nitrite-nitrogen plus nitrate-nitrogen loads were 20 (lb/d)/d at 20°C, downstream from the East wastewater-treatment facility, and 8 (lb/d)/d at 20°C, downstream from the West wastewater-treatment facility. The nitrification rates estimated from ammonia-nitrogen and nitrate-nitrogen load downstream from the Batesville West wastewater-treatment facility approximate a mass balance of nitrogen. Therefore, 10 (lb/d)/d was assumed for all stream reaches.

Equivalent first-order rates of nitrification based on changes in ammonia-nitrogen load were estimated by the following equation:

$$K_n = \frac{1}{t} \ln \frac{C_u}{C_d} \tag{16}$$

where

C_u and C_d are the loads of ammonia nitrogen, at upstream and downstream sites, respectively, in pounds per day,

t the time of travel between the two sites, in days,

and

ln the natural logarithm, base e.

First-order kinetics rates of nitrification ranged from 0.1 to 1.4 day^{-1} at 20°C.

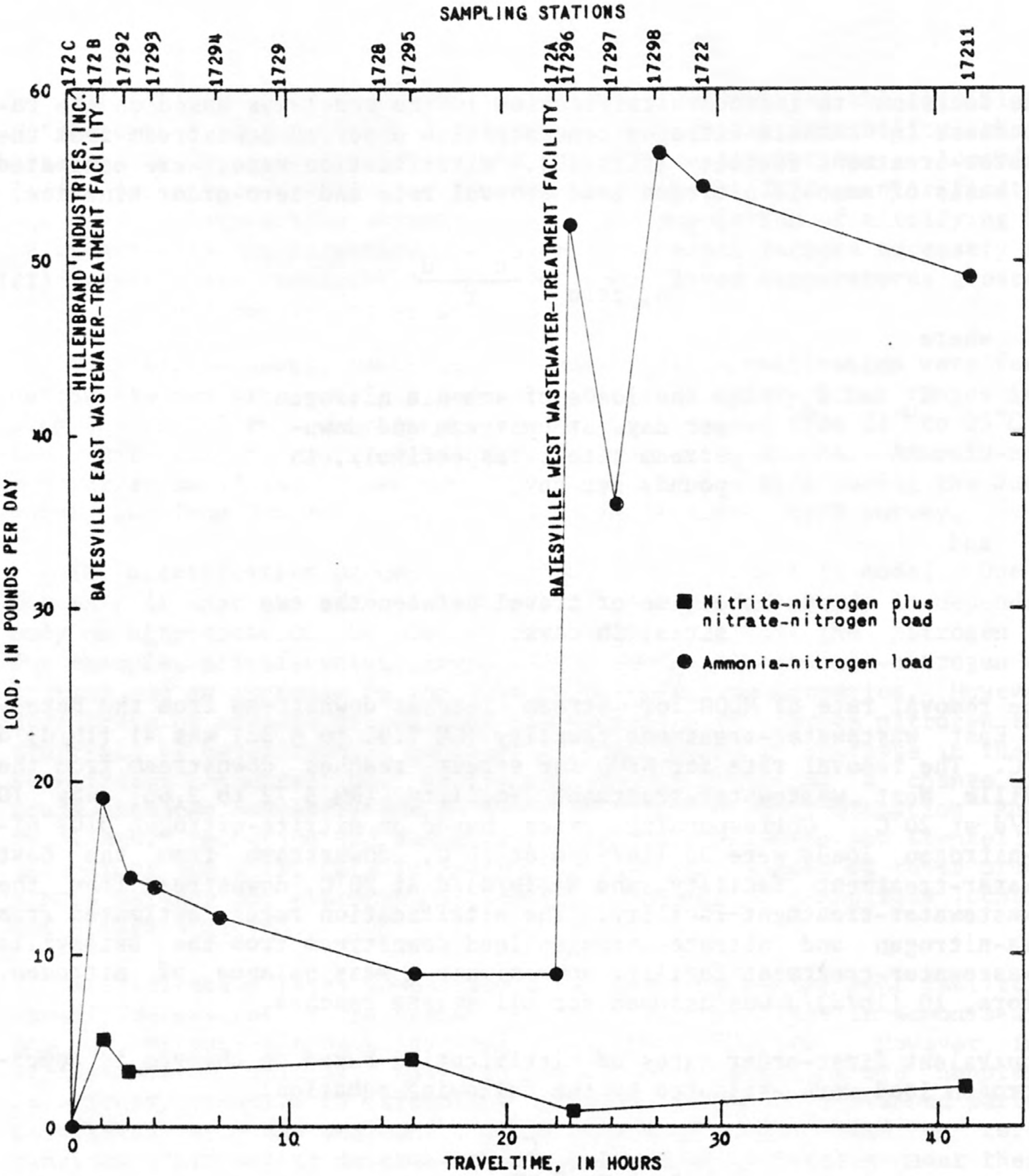

Figure 12.-- Relation of ammonia-nitrogen and nitrite-nitrogen plus nitrate-nitrogen loads to traveltime from Little Laughery Creek tributary at river mile 1.60 to Little Laughery Creek at river mile 2.66, September 20, 1978.

The rate of nitrification in Little Laughery Creek is much lower than the authors had expected it to be. A possible explanation for this lower rate is the low dissolved-oxygen concentrations observed during the September 1978 survey. The minimum average dissolved-oxygen concentration downstream from the East wastewater-treatment facility was 3.1 mg/L. Downstream from the West wastewater-treatment facility, the minimum average dissolved-oxygen concentration was 1.5 mg/L. Minimum daily dissolved-oxygen concentrations of less than 2 mg/L were observed at all but one stream station where diel dissolved-oxygen concentration was measured. Several investigators (Knowles, Downing, and Barrett, 1965; Wuhrmann, 1968; and Metcalf and Eddy, Inc., 1973) reported that low dissolved-oxygen concentrations may limit both the rate of nitrification and the rate of growth of the responsible bacteria. The rate of nitrification may increase after installation of advanced waste treatment at Batesville and an increase in the stream dissolved-oxygen concentration so that the low DO concentration is no longer a factor limiting nitrification.

Nitrogenous decay coefficients were adjusted for temperature by the following equation:

$$(K)_T \text{ nitrogenous} = K_{20°C}(1.09^{T-20°C}) \qquad (17)$$

where

(K) is the reaction constant, in day^{-1},

1.09 a constant applicable over a typical field-temperature range,

and

T the temperature, in degrees Celsius.

Photosynthesis

Mean-daily, net-photosynthetic dissolved-oxygen production was evaluated by the two-station (upstream-downstream) method of Odum (1956), as modified by Stephens and Jennings (1976). The two-station method generates a relationship describing the rate of change of dissolved-oxygen concentration between two stations at discrete sampling intervals. The model assumes that oxygen is produced only during daylight hours and that any change in dissolved-oxygen concentration during this period, after corrections have been made for diffusion, is due to photosynthetic oxygen production. Any change in dissolved-oxygen concentration during hours of darkness, after corrections for diffusion have been made, is attributed to respiration.

Diel dissolved-oxygen fluctuations ranged from 1.5 to 7.5 mg/L. Calculated mean-daily net-photosynthetic, oxygen-production values for Little Laughery Creek are presented in table 8. These values fall within the range

Table 8.--Calculated mean-daily, net-photosynthetic oxygen-production values for Little Laughery Creek tributary and Little Laughery Creek, Ripley and Franklin Counties, Ind., September 20, 1978

Reach	Calculated net-photosynthetic oxygen production [(g/m²)/d]
1	([1])
2	([1])
3	-6.1
4	-1.2
5	-1.9
6-8	-.6
9	([1])
10-11	-.7
12	-1.5
13	-.1
14	([1])
15	([1])
16	([1])

[1] Data unavailable to determine oxygen production for these stream reaches.

of values reported by Hoskin (1959) for small streams in North Carolina. All net-photosynthetic, oxygen-production values calculated for Little Laughery Creek are less than zero and, therefore, are a liability to the stream dissolved oxygen. O'Connell and Thomas (1965) reported that this liability is common, for streams such as Little Laughery, where benthic algae seems to be the dominant algal type.

Benthic-Oxygen Demand

The in-stream CBOD decay coefficient, K_r, determined for the two water-quality surveys, suggests that in some reaches CBOD is being removed by processes such as settling from the water column or biological extraction in addition to being removed by biochemical oxidation. Although this condition suggests a benthic-oxygen demand, no attempt was made to measure it in the field during the surveys.

In some large deep rivers, benthic-oxygen demand can be omitted as a significant oxygen demand. However, in shallow rivers and streams, it can become one of the most important factors affecting the dissolved-oxygen dynamics. According to Thomann (1972, p. 104), an average benthic-oxygen demand for a sludge deposit is 4 $(g/m^2)/d$ (grams per square meter per day). This demand in a river 10 ft deep consumes 1.3 (mg/L)/d dissolved oxygen. The same benthic-oxygen demand in a shallow stream 1 ft deep consumes 13.1 (mg/L)/d dissolved oxygen.

Benthic-oxygen demand is generally assumed to be dependent on the relation between accumulated deposits and the oxygen demand exerted by the deposits. The accumulation of CBOD on the stream bottom is related to the period of stable hydrologic conditions during which CBOD may settle. A velocity of 0.6 ft/s is generally assumed to be the critical velocity at which organic solids may deposit (Velz, 1970, p. 162). The oxygen demand of the deposit is a function of accumulation and the rate of consumption. For short periods of time after a scour, the total accumulation would be low.

If the rate of settling is greater than the rate of consumption, CBOD will accumulate much faster than it is used. Probably only the upper 1 to 2 inches of the benthic deposit is active in the stream-deoxygenation process. CBOD underlying this upper layer is decomposed by anaerobic organisms (Phelps, 1944, p. 122), which means that CBOD can be removed from the water without exerting an oxygen demand until it is resuspended during a scour.

Phelps (1944, p. 125) reported a method for estimating the effect of deoxygenation of benthic deposits on stream dissolved oxygen. The method estimates the amount of CBOD accumulation on the stream bottom as follows:

$$L_d = \frac{P}{K^1}\left(1 - e^{-K^1 t}\right) \qquad (18)$$

Where

L_d is the accumulated deposit of CBOD in a given reach, in pounds,

P the daily deposit of CBOD in a given reach, in pounds per day,

K^1 the base-e, reaction-rate coefficient for benthic-oxygen demand, in day^{-1},

and

t the elapsed time of accumulation, in days.

The authors assumed that the daily deposit of CBOD, P, was the difference between the CBOD removed from the stream and the CBOD estimated to have been oxidized. The elapsed time of accumulation, t, was estimated from rainfall records (National Oceanic and Atmospheric Administration, 1977 and 1978).

The oxygen demand of the accumulated CBOD deposit can be estimated by:

$$D = K^1 L_d \tag{19}$$

where

D is the oxygen demand, in pounds per day.

Benthic-oxygen demand, D, is customarily reported in grams per square meter per day. To convert D to this unit the following conversion is used:

$$B = 454(D/A) \tag{20}$$

where

B is the benthic-oxygen demand, in grams per square meter per day,

and

A the area over which D is exerted, in square meters.

The reaction-rate coefficient for benthic-oxygen demand, K^1, is approximately equivalent to the deoxygenation rate for CBOD, K_d (Streeter, 1935). Estimated values of benthic-oxygen demand ranged from 0 to 16.2 $(g/m^2)/d$. The method does not compensate for the layering of the CBOD deposits and consequent zones of aerobic and anaerobic decomposition. By not compensating for this layering effect, values in excess of the average range of values may be calculated. Therefore, the authors used 10 $(g/m^2)/d$ at 20°C as the upper limit of benthic-oxygen demand in the model.

A drawback of the preceding method is that it only estimates oxygen demand attributed to microbial activity. Other processes by which benthic deposits remove oxygen from the overlying water are (1) oxygen consumption by the soluble end products of aerobic benthic decomposition (Fair and others, 1941), (2) oxygen consumption by gases that are produced during anaerobic decomposition (Baity, 1938), and (3) CBOD added to the water column by bottom scour (Streeter, 1935; Edwards and Rolley, 1965). Bottom scour can also suspend particles that, after being redoposited downstream, can again exert an oxygen demand.

Several investigators have indicated that the type of the biological population also influences the nature and magnitude of benthic-oxygen demand. Edwards and Rolley (1965), working with river muds, found that 40 percent of the total oxygen demand of the muds can be attributed to macroinvertebrates, primarily tubificids. McDonnell and Hall (1969), working with benthal deposits from an eutrophic stream and obtaining results similar to those of Edwards and Rolley attributed more than 50 percent of the total oxygen demand to invertebrate respiration.

Further complicating the estimating of benthic-oxygen demand is the dependence of invertebrate respiration on the stream-oxygen concentration (Knowles, Edwards, and Briggs, 1962; Edwards and Rolley, 1965; Hargrave, 1969; McDonnell and Hall, 1969). Microbial respiration does not seem to be inhibited if the dissolved-oxygen concentration of the overlying water is more than 1.5 mg/L (Baity, 1938; Hanes and Irvine, 1968).

Ranges of benthic-oxygen uptake by various sediments are given in table 9. The wide variation in these values represent the influence of differing environmental conditions, such as the nature and magnitude of invertebrate populations, dissolved-oxygen concentration, and sediment depths. Butts and Evans (1978), in a study of very clean to degraded northeastern Illinois streams, reported that benthic-oxygen demand ranged from 0.38 to 9.32 (g/m^2)/day at 20°C. They also reported a benthic-oxygen demand of at least 0.7 to 1.5 (g/m^2)/day at 20°C in 95 percent of the sites studied. Values of benthic-oxygen demand used in the model calibrations ranged from 0.0 to 10 (g/m^2)/d at 20°C.

Benthic-oxygen demand was adjusted for temperature by the following equation:

$$B_T = B_{20^\circ C}(1.065)^{T-20^\circ C} \qquad (21)$$

where

B is the benthic-oxygen demand, in day^{-1},

1.065 a constant, applicable over a typical field-temperature range,

and

T the temperature, in degrees Celsius.

Table 9.--Values of benthic-oxygen uptake by various sediments

Sediment type	Range of benthic-oxygen uptake $[(g/m^2)/d$ at 20°C]	References
Sewage sludge	0.5-4.6	Baity (1938).
Paperwaste sludge	.2-3.3	Hanes and Irvine (1968).
River mud	1-24	Edwards and Rolley (1965).
Stream mud	1.4-6.1	McDonnell and Hall (1969).
Lake mud	.3-1.1	Brewer and others (1977).
Sand	.2-1.0	Thomann (1972, p. 104).

Reaeration

Reaeration is generally the most important single parameter used in describing a stream's ability to assimilate biodegradable material. Many of the common empirical or semi-empirical equations used to predict reaeration, including those developed by O'Connor and Dobbins (1958), Owens and others (1964), Thackston and Krenkel (1969), and Parkhurst and Pomeroy (1972), assume that gaseous exchange varies directly with stream velocity and inversely with stream depth and that reaeration increases with decreasing flow. However, channel morphology should also be considered in the determination of reaeration. Langbein and Durum (1967) indicated that gaseous-exchange rates increase with decreasing flow in riffles but decrease in pools. The low slopes of most Indiana streams usually cause the pooled condition to predominate. In addition, several investigators using the radioactive-tracer technique for direct determination of reaeration reported a strong correlation between reaeration and channel slope (Tsivoglou and Neal, 1976; Foree, 1976). Foree (1976), in his study on small streams in Kentucky, also reported a general tendency for reaeration to decrease with decreasing specific discharge (discharge per unit drainage area).

The equation used to predict reaeration in this study is the energy-dissipation model developed by Tsivoglou and Neal (1976).

$$K_a = 0.110SV \quad \text{when } 1 \leq Q \leq 10 \text{ ft}^3/\text{s} \tag{22}$$

$$K_a = 0.054SV \quad \text{when } 25 \leq Q \leq 3{,}000 \text{ ft}^3/\text{s} \tag{23}$$

where

K_a is the base-e reaeration rate, at 20°C, in day^{-1},

S the stream slope, in feet per mile,

V the stream velocity, in miles per day,

and

Q the stream discharge, in cubic feet per second.

From a statistical evaluation of predictive reaeration equations, Wilson and MacLeod (1974) concluded that equations containing slope give better results than equations based on velocity and depth. In a recent study, Rathbun (1977) found Tsivoglou's energy-dissipation model to be the best overall equation when compared to data obtained by the tracer method for direct determination of reaeration.

Reaeration coefficients were adjusted for temperature by the following equation:

$$(K)_T \text{ reaeration} = (K)_{20°C}(1.021^{T-20°C}), \tag{24}$$

where

(K) is the base-e reaction constant, in day^{-1},

1.021 a constant applicable over a typical field-temperature range,

and

T the stream temperature, in degrees Celsius.

Model-Calibration Results

The calculated and observed CBOD, NBOD, and dissolved-oxygen concentrations and calculated flows are illustrated in figures 13 to 20. Several observations of the results follow.

The normalized-mean error, defined by Wilson and MacLeod (1974) as follows, was used as the criterion for comparison:

$$\text{Normalized-mean error} = \left[\sum_{i=1}^{N} \frac{(A_{calc} - A_{obs})}{A_{obs} N} \right] 100 \text{ percent} \tag{25}$$

where

A_{calc} and A_{obs} are the calculated and observed values, respectively,

and

N the number of observations.

The normalized-mean error for DO, CBOD, and NBOD concentrations were 3.6, 5.8, and 46 percent, respectively, for the September 20, 1978, model calibration. Normalized-mean errors were not calculated for the June 3, 1977, model calibration because of the small number of sampling sites. The high normalized-mean error for NBOD may be explained by the fact that the model assumes that the only removal process for ammonia (NBOD) is nitrification. Factors other than nitrification, discussed previously, may also account for the loss of ammonia nitrogen in the stream.

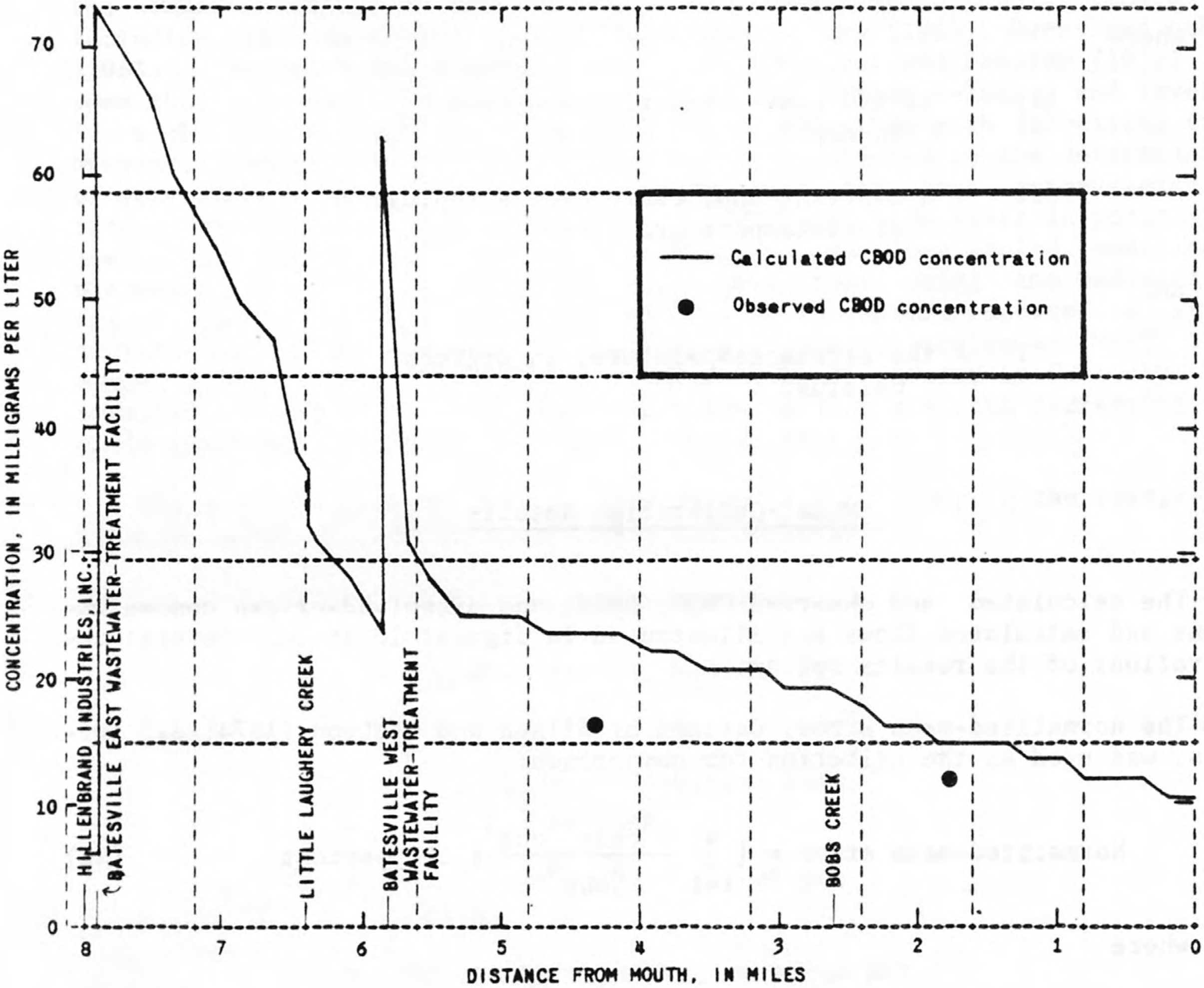

Figure 13.-- Calculated and observed carbonaceous biochemical-oxygen-demand concentrations in Little Laughery Creek tributary and Little Laughery Creek, June 3, 1977.

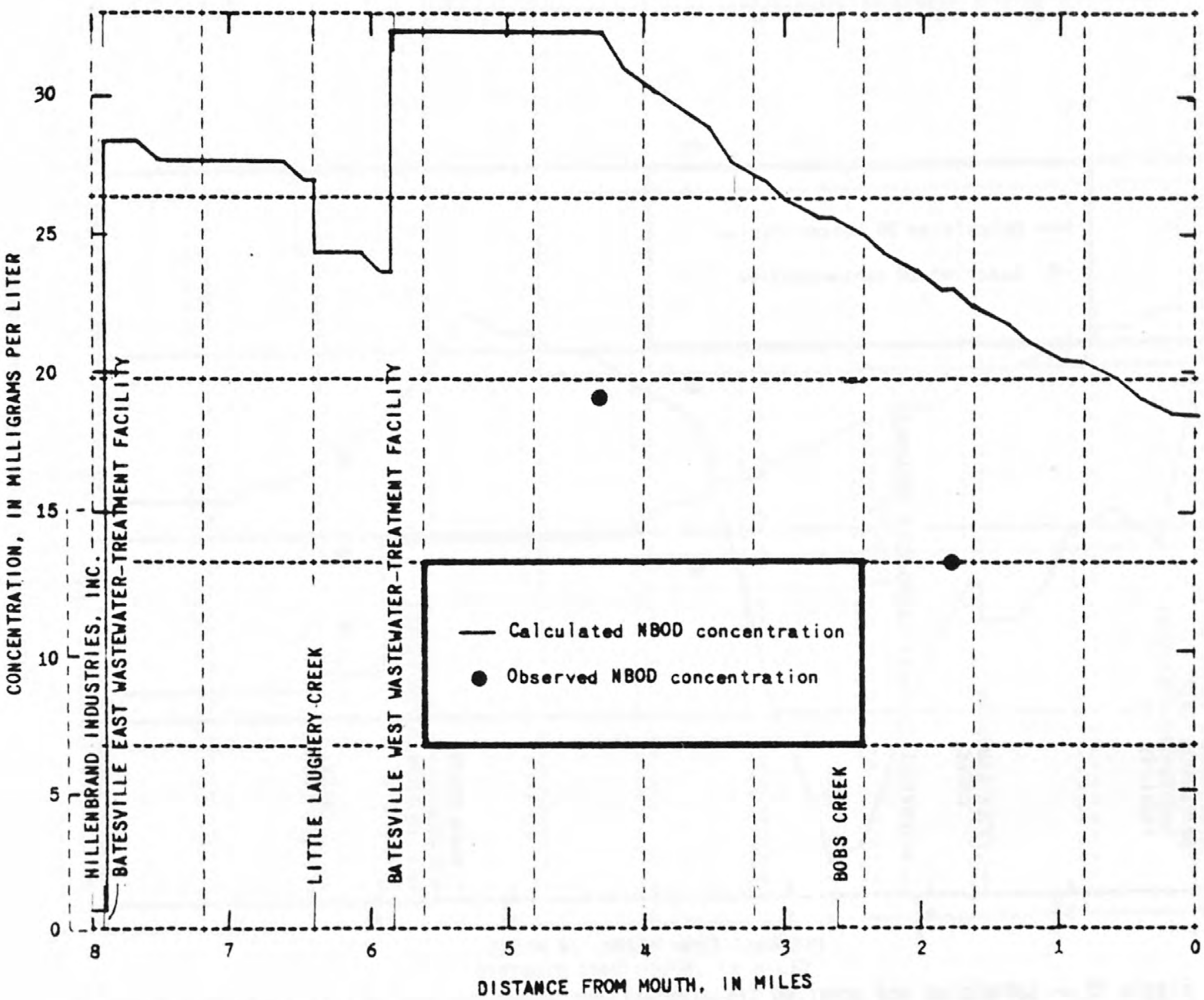

Figure 14.-- Calculated and observed nitrogenous biochemical-oxygen-demand concentrations in Little Laughery Creek tributary and Little Laughery Creek, June 3, 1977.

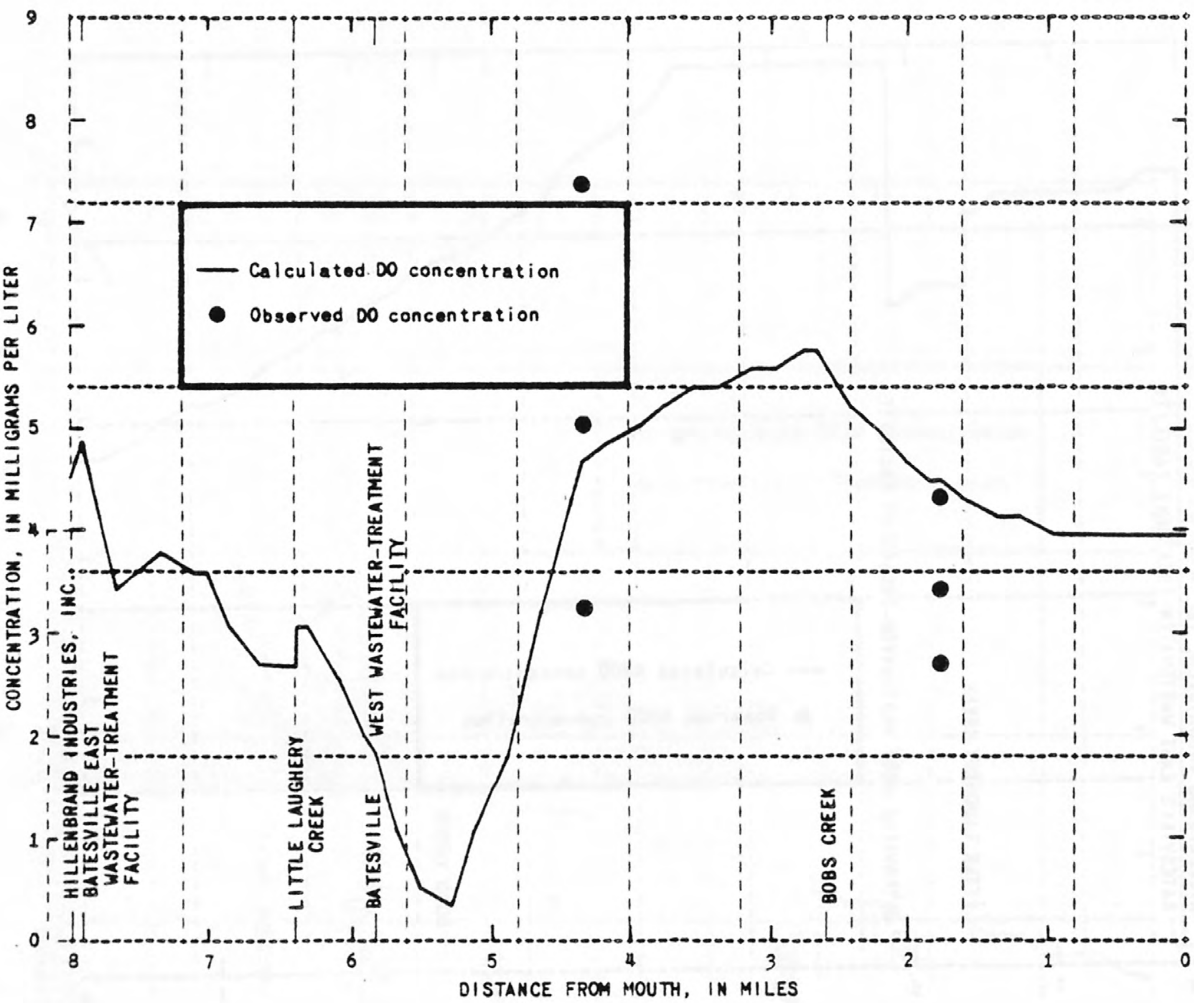

Figure 15.-- Calculated and observed dissolved-oxygen concentrations in Little Laughery Creek tributary and Little Laughery Creek, June 3, 1977.

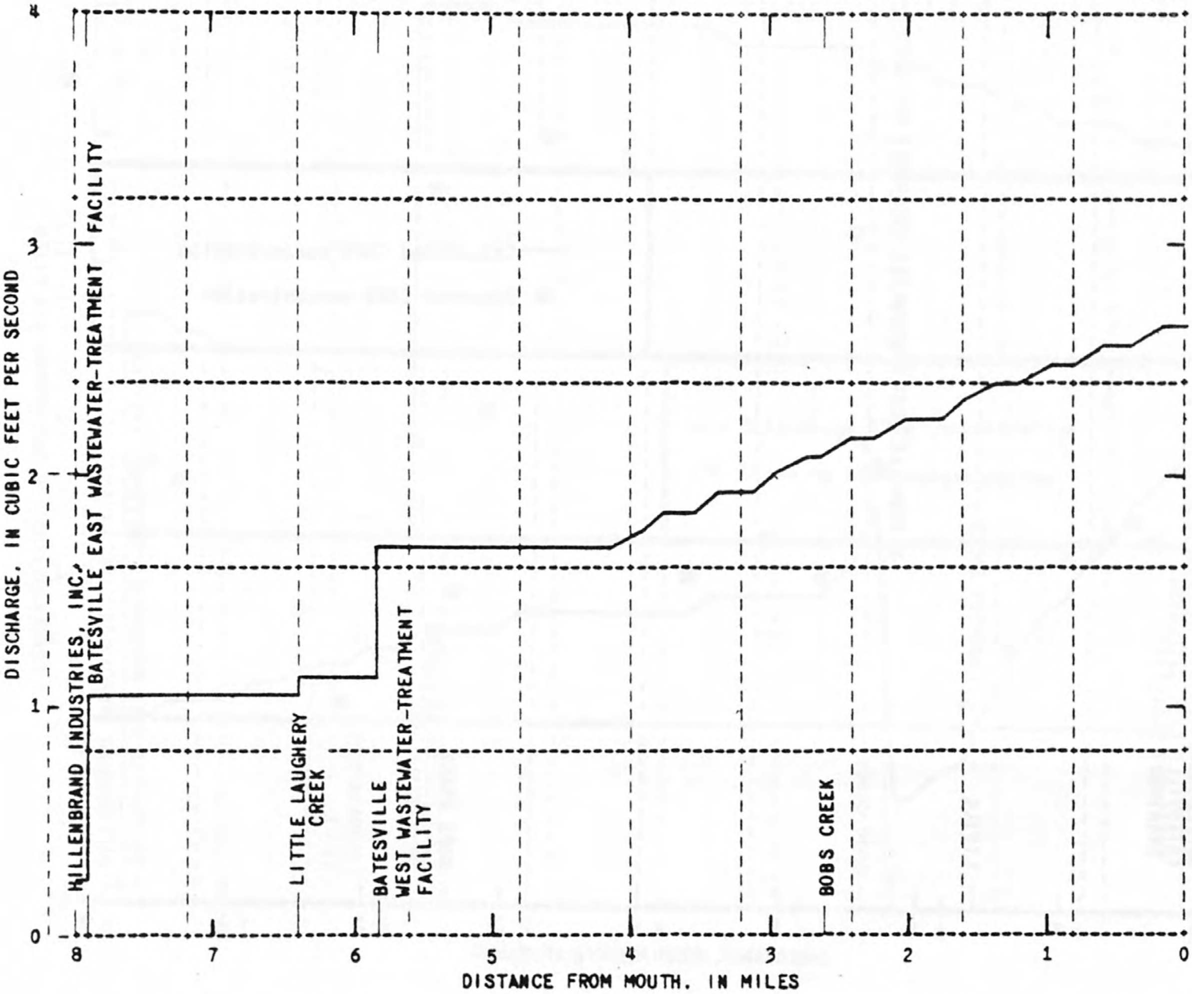

Figure 16.-- Discharge in Little Laughery Creek tributary and Little Laughery Creek, June 3, 1977.

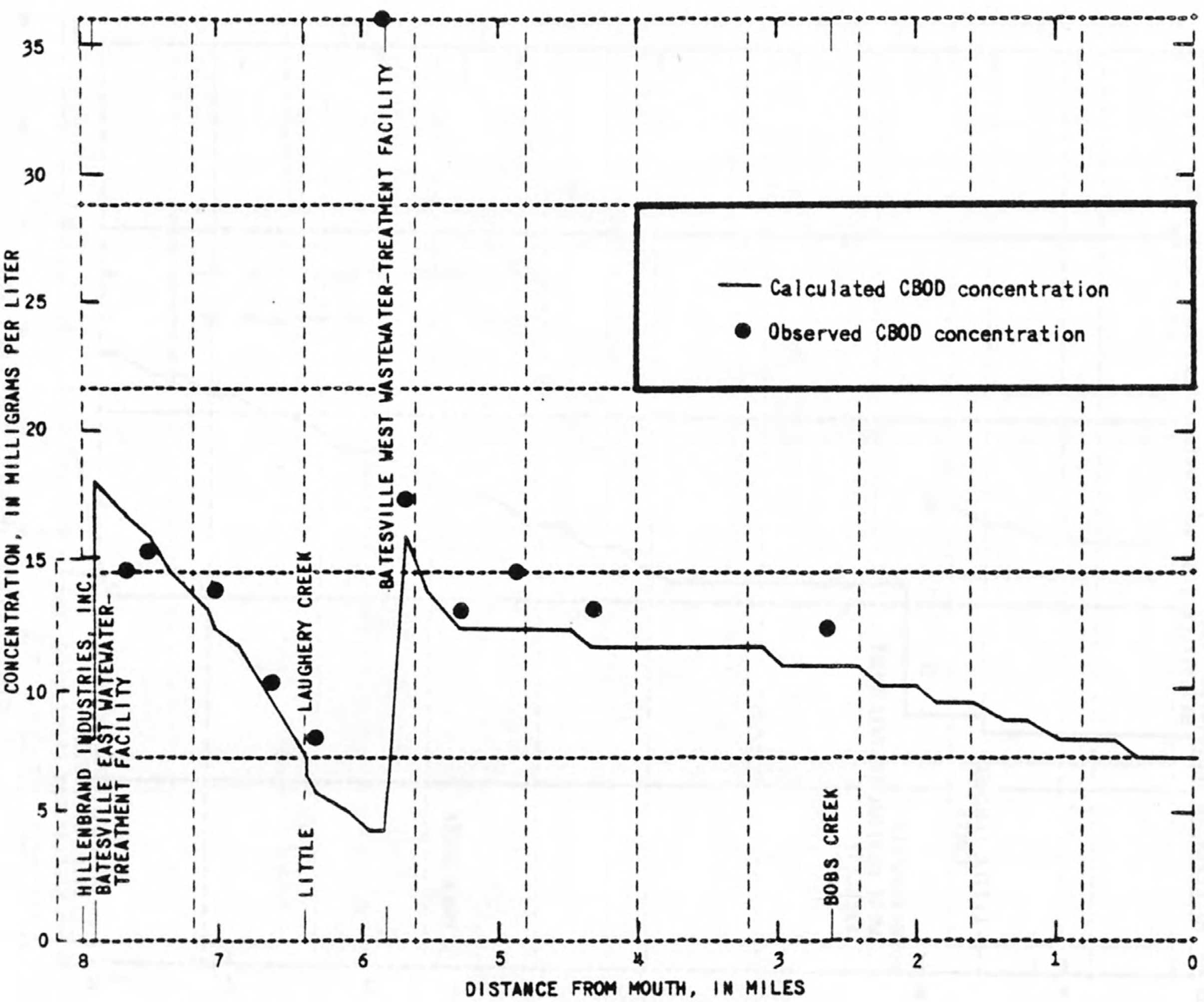

Figure 17.-- Calculated and observed carbonaceous biochemical-oxygen-demand concentrations in Little Laughery Creek tributary and Little Laughery Creek, September 20, 1978.

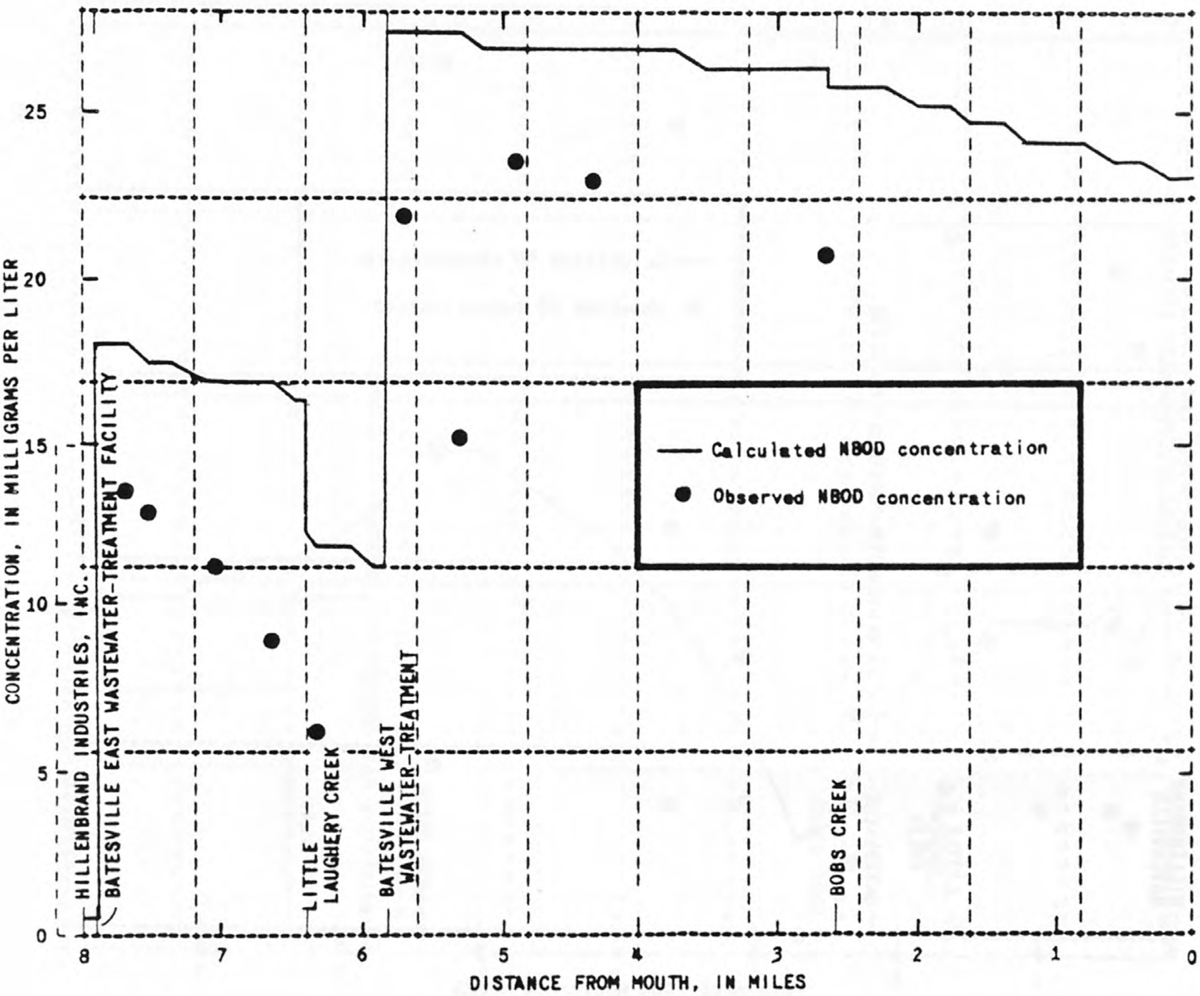

Figure 18.-- Calculated and observed nitrogenous biochemical-oxygen-demand concentrations in Little Laughery Creek tributary and Little Laughery Creek, September 20, 1978.

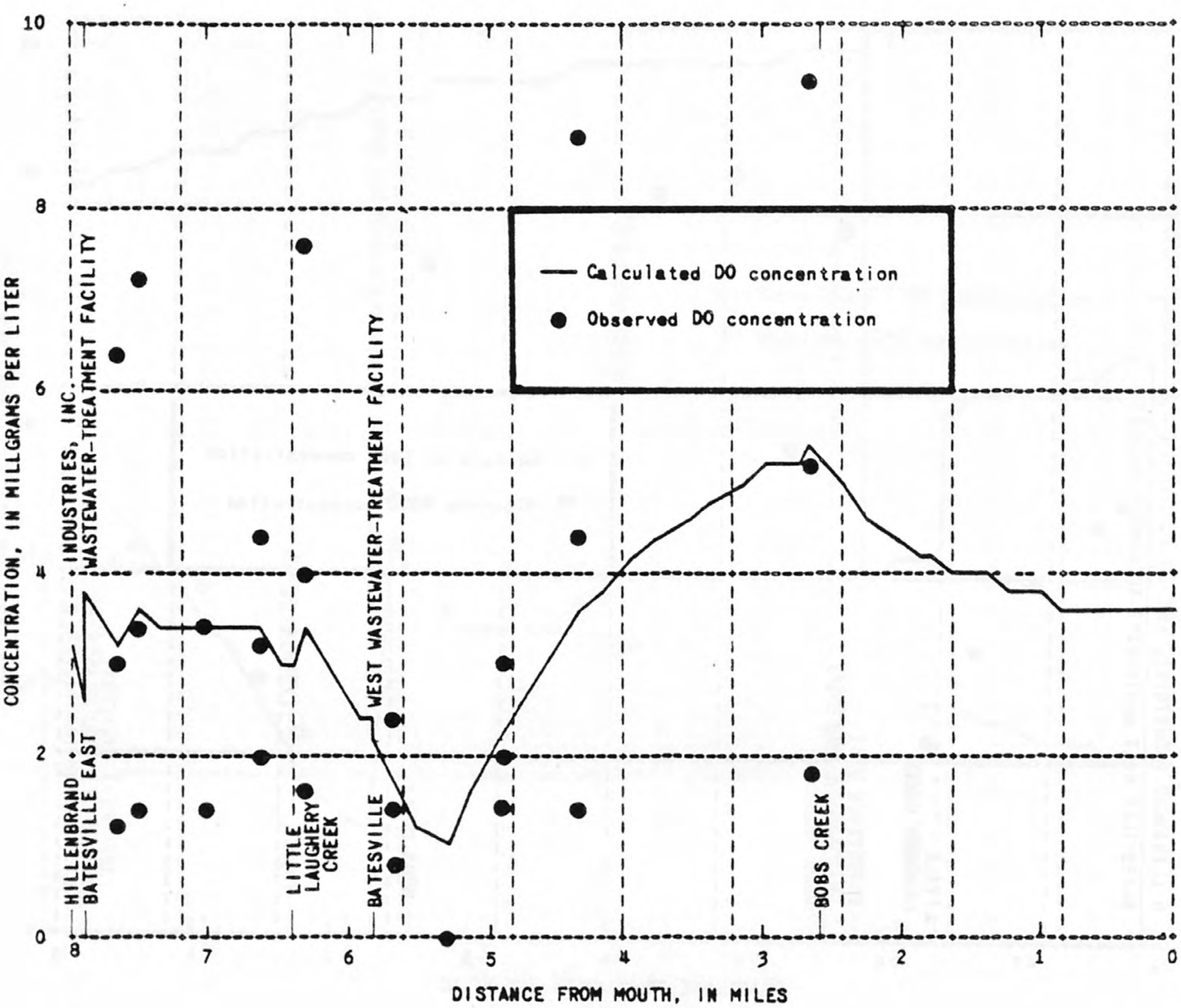

Figure 19.-- Calculated and observed dissolved-oxygen concentrations in Little Laughery Creek tributary and Little Laughery Creek, September 20, 1978.

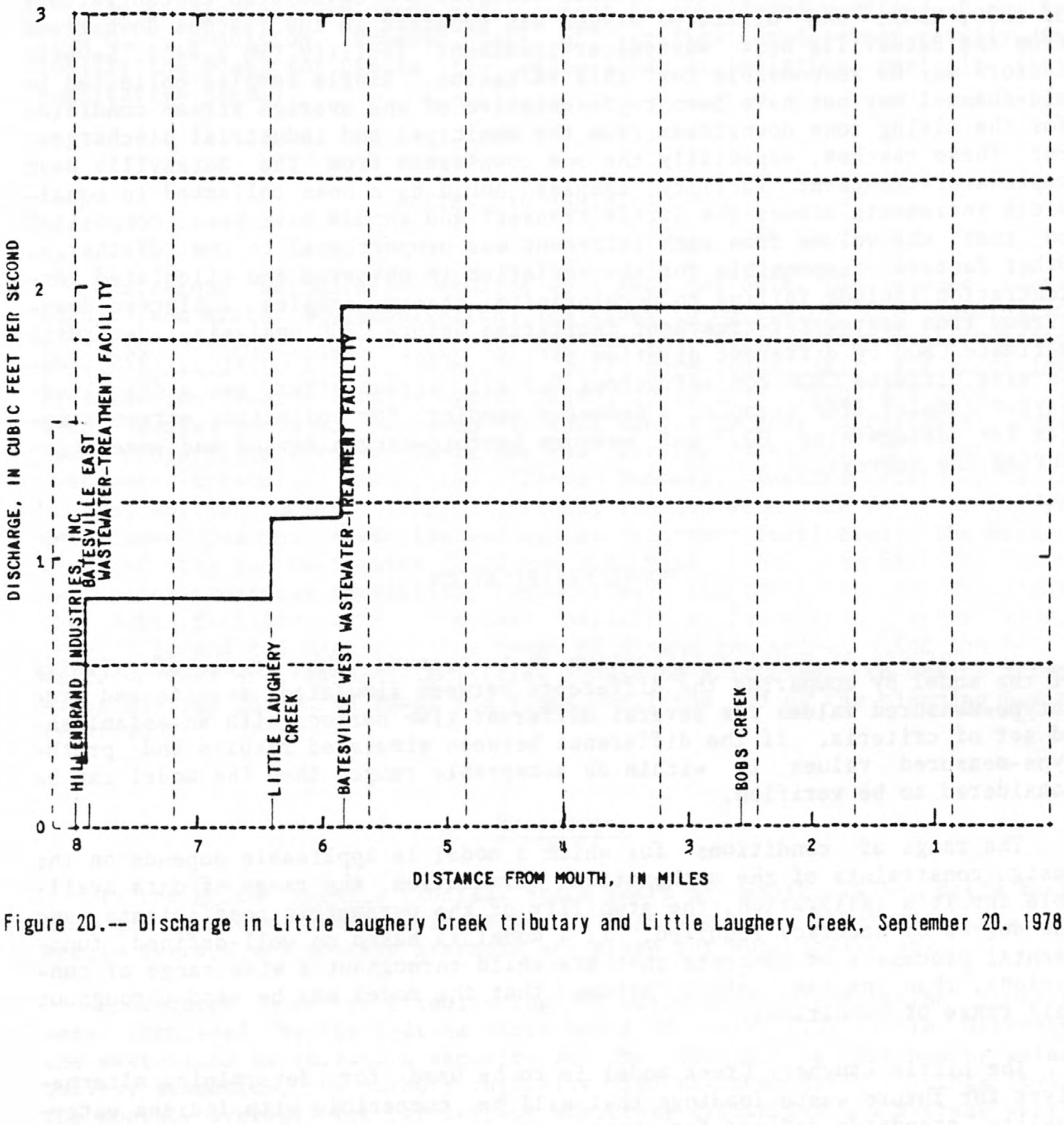

Figure 20.-- Discharge in Little Laughery Creek tributary and Little Laughery Creek, September 20. 1978.

In general, the variation between observed and calculated concentrations of CBOD, NBOD, and dissolved oxygen was greatest in the reaches downstream from the Batesville West wastewater-treatment facility (RM 5.84). Several factors may be responsible for this variation. Single samples collected in mid-channel may not have been representative of the average stream condition for the mixing zone downstream from the municipal and industrial discharges. For these reaches, especially the one downstream from the Batesville West wastewater-treatment facility, samples should have been collected in equal-width increments across the stream transect and should have been composited so that the volume from each increment was proportional to the discharge. Other factors responsible for the variation in observed and calculated concentration include failing to dechlorinate stream samples collected downstream from wastewater-treatment facilities before CBOD analysis, determine ultimate CBOD by different dilution ratios (Grant, 1976; Colston, 1975), determine ultimate CBOD concentrations for all stream sites, use a dissolved-oxygen sampler (for example, a Kemmerer sampler) for collecting stream samples for determining DO, and measure benthic-oxygen demand and reaeration during the surveys.

MODEL VERIFICATION

The purpose of model verification is to measure the degree of validity of the model by comparing the difference between simulated results and prototype-measured values for several different time periods with an established set of criteria. If the difference between simulated results and prototype-measured values is within an acceptable range, then the model can be considered to be verified.

The range of conditions for which a model is applicable depends on the design constraints of the mathematical formulation, the range of data available for it's calibration, the stability of the parametric coefficients, and the degree of accuracy required. If a model is based on well-defined, fundamental processes or concepts that are valid throughout a wide range of conditions, then one can safely assume that the model may be used throughout this range of conditions.

The Little Laughery Creek model is to be used for determining alternatives for future waste loadings that will be compatible with Indiana water-quality standards defined for summer and winter low flows. However, time and budgetary constraints for this study prohibited adequate data collection for model calibration.

For the Little Laughery Creek study, two sets of water-quality data were collected at steady-state, low flows. However, for the June 1977 survey, only two stream sites were sampled. Both of these sites were downstream from the Batesville West wastewater-treatment facility. Dissolved-oxygen concentration and water temperature at the Batesville East and West wastewater-treatment facilities were not measured during the September 1978 survey. Because benthic-oxygen demand was not measured directly during the water-quality surveys, independent data for verifying the model at the $Q_{7,10}$ flow were not available.

The Little Laughery Creek model cannot be considered verified at the low flow $Q_{7,10}$ condition. However, lack of verification does not totally disqualify the model for use in the waste-load assimilation analysis (in a qualitative sense).

WASTE-LOAD ASSIMILATION

Waste-load assimilation studies were made for both the summer (June-August) and winter (November-March) low flows to determine the combination of waste loadings that would meet the current Indiana water-quality standards. Indiana State Board of Health (1977) guidelines call for waste-load assimilation studies for the years 1980, 1983, 1985, 1990, and 2000. However, studies could not be done in this manner because no reliable population projections were available for the service area of the Batesville wastewater-treatment facilities (Vince Sommers, Indiana State Board of Health, written commun., 1979). Instead, studies were done for four different flows for the Batesville wastewater-treatment facilities: The present flow of the two facilities (0.37 and 0.36 Mgal/d for the East and West wastewater-treatment facilities, respectively) and three different flows for the West facility after the East facility is closed in the early 1980's (0.9, 1.1, and 1.3 Mgal/d). The range of discharges selected for the Batesville wastewater-treatment facilities should be sufficient to define stream water quality for waste loads and flows until the end of the planning period (year 2000).

Procedures

In the NPDES permits (Indiana State Board of Health, 1978), daily maximum and monthly average discharge loadings are given for industries, and weekly average and monthly averages are given for municipalities.

Procedures used in establishing the waste-load assimilation capacity were furnished by the Indiana State Board of Health (1977). To determine the waste-load assimilative capacity of the stream, as defined by water-quality standards, the authors initially used maximum daily loadings (twice the monthly average) for the largest municipal discharger and average weekly loadings for the remainder of the municipal dischargers. For industries, the maximum daily loadings were used (Indiana State Board of Health, (1977). Where no limits for dissolved-oxygen, CBOD and ammonia concentrations had been established by ISBH, the combined data from the Monthly Report of Operations for 1978 and data from the ISBH Water Quality Surveillance Section were used to determine an appropriate limit.

The observed ammonia-nitrogen concentration of wastewater effluents during the two water-quality surveys ranged from 5.6 to 12 mg/L. According to Metcalf and Eddy, Inc. (1972), the ammonia-nitrogen concentration for untreated domestic sewage ranges from 12 to 50 mg/L. The amount of ammonia removal in conventional secondary treatment is usually small. Nitrification in the activated-sludge process is usually insignificant because the detention times required for nitrifiers to proliferate are usually too short. Jenkins and Garrison (1968) found that, for a domestic wastewater treated by the activated-sludge process at a temperature of 21° to 22°C, a mean cell residence time of at least 10 days is needed to ensure nitrification. As a result, the ammonia-nitrogen concentration of effluent from the wastewater-treatment facilities was assumed to be 15 mg/L, which is equal to an NBOD concentration of 65 mg/L (Aolad Hossain, Indiana State Board of Health, oral commun., 1978). The determination of a representative ammonia-nitrogen concentration for each wastewater-treatment facility is important to the waste-load assimilation study of Little Laughery Creek.

The observed dissolved-oxygen concentrations at the Hillenbrand Industries, Inc., and the two wastewater-treatment facilities were low during the two water-quality surveys and averaged 37 percent of saturation. If the dissolved-oxygen concentrations of the wastewater effluents had been assumed to have been this low for the waste-load assimilation study, the amount of wastes that could have been discharged without violating the stream water-quality standards would have been severely limited. The aeration of wastewater before discharge would be inexpensive compared to additional waste treatment. Consequently, the initial dissolved-oxygen concentration of the wastewater effluents was assumed to be 80 percent of saturation or 6.5 mg/L during summer low flows and 9.3 mg/L during winter low flows (Aolad Hossain, Indiana State Board of Health, oral commun., 1978).

Where the water-quality standards were exceeded, the CBOD and NBOD loads for the wastewater-treatment facilities were reduced until the appropriate standards were met. The determination of alternative combinations of CBOD and NBOD loads that would just meet the Indiana water-quality standards defined the assimilative capacity of the stream.

Summer and annual $Q_{7,10}$ flows are not available for Little Laughery Creek. Because of the small drainage area of the stream and the low flow observed during the two water-quality surveys, natural flow at the $Q_{7,10}$ condition was assumed to be zero. Flow upstream from the two wastewater-treatment facilities is cooling process water from an industrial discharger. This flow is usually less than 0.5 ft^3/s. Therefore, flow at the $Q_{7,10}$ condition consisted of only effluents from the municipal and industrial dischargers. Gains or losses in flow due to surface-water and ground-water interactions were assumed to be negligible.

Temperatures for Little Laughery Creek were estimated by the following equation:

$$T = M + A\,[\sin(0.0172\underline{d} + C)] \quad \text{Shampine (1977, p. 13)} \qquad (26)$$

where

T is the temperature at a given site on a specific day, in degrees Celsius,

M is 12.91, the mean annual stream temperature, in degrees Celsius, A is 11.89, the stream temperature amplitude, in degrees Celsius,

d the Julian date,

and

C is 4.39, the angle-phase coefficient, in radians.

Historical temperature data are not available for Little Laughery Creek. Therefore, the coefficients M, A, and C were assumed to be the same as those determined for Laughery Creek (Shampine, 1977, p. 44).

A mean daily stream temperature of 25°C was used in the summer waste-assimilation study. This temperature was based on the mean daily stream water temperature, which is exceeded 10-20 percent of the time for the months June-August. A temperature of 7.7°C was used in the winter $Q_{7,10}$ model. This temperature was the average of the daily mean water temperature for November, the winter month assumed to have the lowest flow. This assumption is based on flow records for Laughery Creek, the nearest gaged stream (Horner, 1976, p. 35).

Reaction rates used, K_d for CBOD and $K_{n,\ zero}$ for NBOD deoxygenation, were the same as those used in the model calibration. For the winter waste-assimilation study based on zero-order kinetics, nitrification due to bacterial populations would not be prevented by the low stream temperatures but would proceed at a reduced rate as predicted by the temperature conversion for the nitrification process (Melvin Finstein, Rutgers University, oral commun., 1978). Thomann and others (1971) reported that, at stream temperatures below 10°C, concentrations of almost all forms of nitrogen remain unchanged in a large river where nitrification is attributed to first-order kinetics. Therefore, the nitrification estimate based on first-order kinetics was assumed to be negligible during the winter waste-assimilation study.

The stream decay rate for CBOD, K_r, was assumed to be the same as that used for the two model calibrations, except for the high value observed downstream from the Batesville West wastewater-treatment facility. The suspended-solids concentration of the wastewater effluent was assumed to be within the restrictions of the facility's current NPDES permit. Therefore, the high values of K_r downstream from the wastewater-treatment facility during the two water-quality surveys were assumed to be inapplicable for the waste-load assimilation study. Values of K_r determined for reaches downstream from the East wastewater-treatment facility (reaches 2 and 3) were also used in reaches immediately downstream from the West wastewater-treatment facility (reaches 9 and 10). See tables 5 and 6.

Advanced wastewater treatment is scheduled to be completed for Batesville in the early 1980's (D. S. Patell, Indiana State Board of Health, oral commun., 1979). The suspended-solids concentration of the wastewater effluent should be greatly reduced on completion of this project. Therefore, the value of K_r used in the waste-assimilation study for these sets of conditions was assumed to be the same as the value of K_d.

Reaeration rates were computed by the energy-dissipation equation of Tsivoglou and Neal (1976) as discussed in the section "Reaeration."

All rate coefficients were corrected for temperature as discussed in the appropriate sections of "Model Parameter Estimation."

Algae effects were not considered in the waste-assimilation study because the effect of algal productivity under various environmental conditions at future times cannot be predicted.

The waste assimilation study for the current average flow at both the East and West wastewater-treatment facilities was done with and without the benthic-oxygen demand determined in the model calibration. As with K_r, the high benthic-oxygen demand attributable to the high concentration of suspended solids in the effluent was not used. Benthic-oxygen demand used in reaches 9 and 10 was the same as that used in reaches 2 and 3 for the model calibration. After completion of advanced waste treatment at the Batesville West wastewater-treatment facility, the current sludge deposits that create a significant benthic-oxygen demand should no longer accumulate. Therefore, the waste-load assimilation study for the other three flow conditions simulated did not include benthic-oxygen demand. After completion of the new wastewater-treatment facility, measurement of benthic-oxygen demand to test the assumption that the new facility will eliminate the benthic-oxygen demand attributed to the sludge deposits would be useful.

Results and Discussion

The model used in the waste-load assimilation study has not been verified. Therefore, interpretations of the results should be limited to qualitative uses only. A quantitative model would require calibration and verification with data collected after completion of changes to effluent discharges have been made.

According to the Indiana State Board of Health (1977), a part of the assimilative capacity of a stream reach should be reserved for future growth and development. Two modeling techniques are acceptable in this regard. First, a percentage of the assimilative capacity of the stream can be left as a reserve. This capacity should be no greater than 30 percent of the assimilative capacity and, ideally, should be the capacity required to assimilate probable future growth for the planning period. The size of the reserve is dependent on the rate of growth and the length of time of the planning period. Second, the waste loads and flows for the existing dischargers (except industries) may be projected for 5-year intervals to the end of the planning period (year 2000) and used as input into the calibrated waste-load allocation model.

For this study, a modification of the second modeling technique was used. Accordingly, increased waste loads and flows for the wastewater-treatment facility were used. These flows were used in the calibrated model, and the necessary concentrations for the discharges to meet current water-quality standards were determined. (See figures 21-24 and tables 10 and 11.) The goals were an average dissolved-oxygen concentration of 5.0 mg/L and maximum ammonia-nitrogen concentrations of 2.5 mg/L and 4.0 mg/L during summer and winter low flows, respectively.

Several observations on the estimates of waste-load, assimilative capacity of streams follow.

The model indicates that benthic-oxygen demand is probably the most important factor affecting the dissolved-oxygen concentration of Little Laughery Creek during summer low flows. Because of this benthic-oxygen demand, the model indicates that the dissolved-oxygen standard of the stream will not be met during summer low flows under current (1979) basin conditions. Figures 21 and 22 show the results of model simulations for the present basin conditions without incorporating benthic-oxygen demand. However, since K_r is greater than K_d in most of the reaches, most of the CBOD is removed from the stream without exerting an oxygen demand in these simulations. Because the dissolved-oxygen sag from the two wastewater-treatment facilities overlap, the same alternative waste loads should be applied equally to both facilities.

The model also indicates that the minimum dissolved-oxygen concentration during summer and winter low flows occurs at the confluence of Little Laughery and Laughery Creeks. This condition can be attributed to two factors. First, a high value of K_d (0.18 day^{-1} at 20°C) was determined for model reaches 14, 15, and 16 during the model calibration. Only one long-term CBOD determination was made for these stream reaches during the two surveys. Consequently, the validity of the high value of K_d is uncertain. Secondly, and more importantly, the predicted reaeration rate is lower in the last three reaches than elsewhere in the stream. Insufficient data were collected during the two water-quality surveys to determine adequately if a DO sag occurs in these reaches. However, the one sample collected during the two surveys indicates a DO sag. During the June 1977 water-quality survey, the dissolved-oxygen concentration decreased from 5.1 mg/L at RM 4.36 to 3.5 mg/L at RM 1.78.

Ammonia-nitrogen toxicity is a significant factor affecting stream water quality. Current ammonia-nitrogen concentrations in the wastewater effluent from the Batesville wastewater-treatment facilities will result in stream ammonia-nitrogen concentrations that exceed the maximum ammonia-nitrogen toxicity standard during summer and winter low flows. Nitrification should not be a problem when the ammonia-nitrogen toxicity standard is not exceeded if the nitrification rates do not increase in response to higher stream DO concentrations after installation of advanced waste treatment.

The model indicates that Little Laughery Creek will not recover from the impact of the Batesville wastewater-treatment facility at the $Q_{7,10}$ flow upstream from its confluence with Laughery Creek. Consequently, additional

NOTE: The information presented in this figure is not based on a verified model and should be used only for qualitative interpretation.

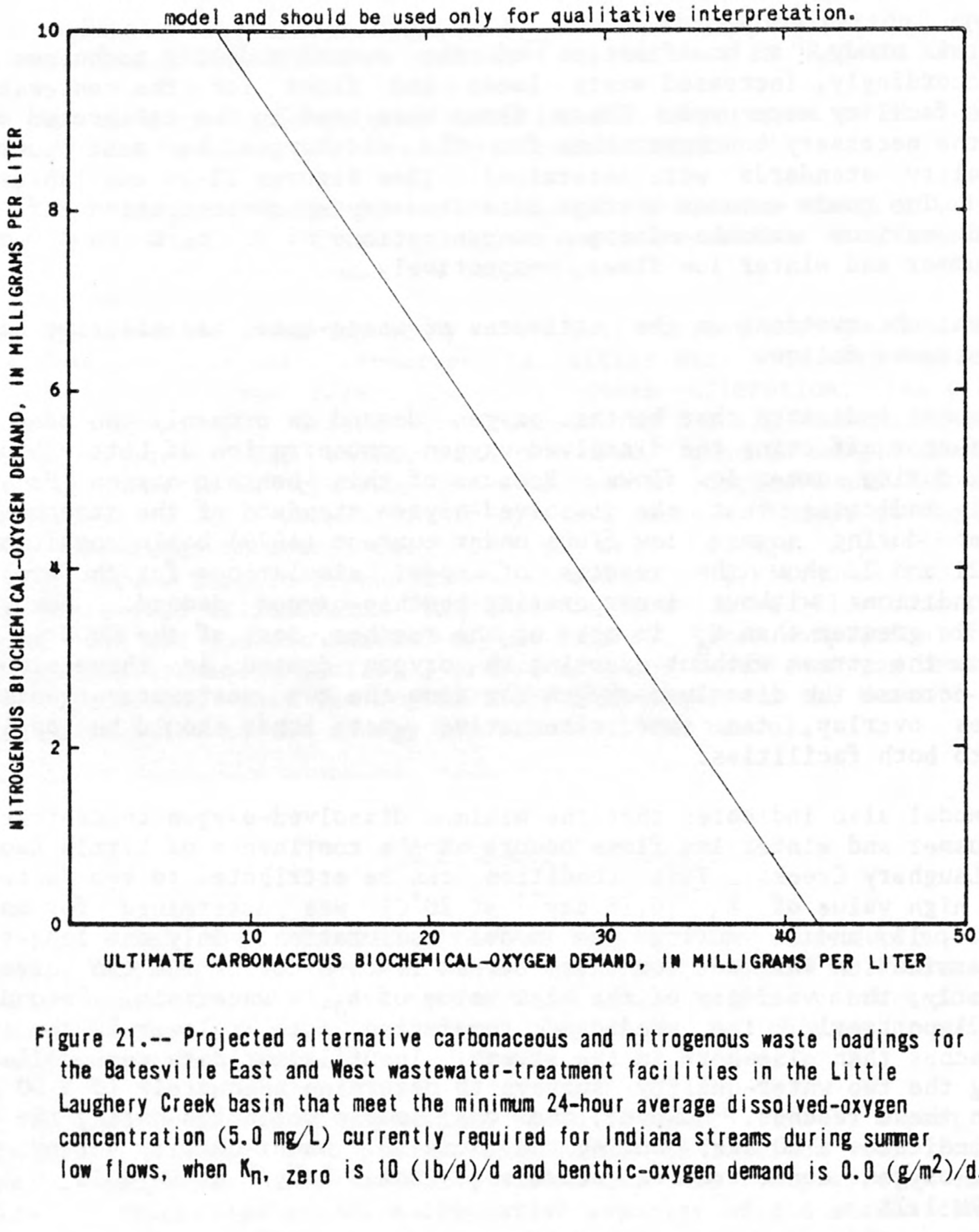

Figure 21.-- Projected alternative carbonaceous and nitrogenous waste loadings for the Batesville East and West wastewater-treatment facilities in the Little Laughery Creek basin that meet the minimum 24-hour average dissolved-oxygen concentration (5.0 mg/L) currently required for Indiana streams during summer low flows, when $K_{n,\ zero}$ is 10 (lb/d)/d and benthic-oxygen demand is 0.0 (g/m^2)/d.

waste loads will have the least impact on stream water quality downstream from this confluence. Because adequate water-quality data were not collected on Laughery Creek downstream from it's confluence with Little Laughery Creek, the effect of the Batesville wastewater-treatment facilities on this stream could not be determined.

NOTE: The information presented in this figure is not based on a verified model and should be used only for qualitative interpretation.

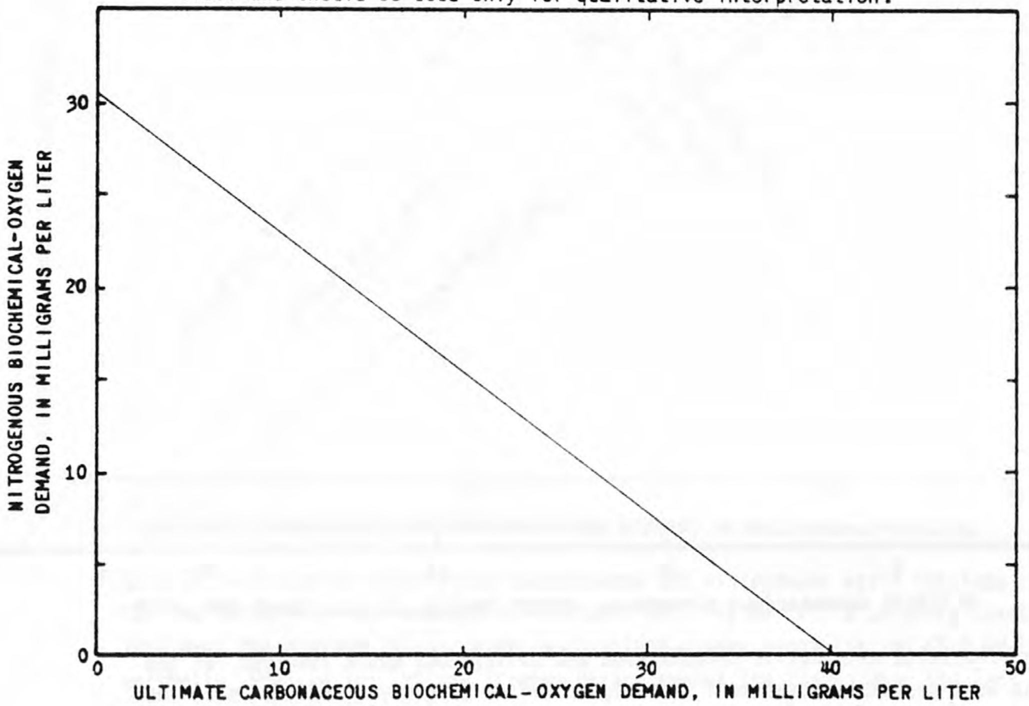

Figure 22.-- Projected alternative carbonaceous and nitrogenous waste loadings for the Batesville East and West wastewater-treatment facilities in the Little Laughery Creek basin that meet the minimum 24-hour average dissolved-oxygen concentration (5.0 mg/L) currently required for Indiana streams during summer low flows, when K_n is 0.1 day^{-1} and benthic-oxygen demand is 0.0 $(g/m^2)/d$.

Future water-quality studies that could help verify the model and clarify the effect of various factors on the dissolved-oxygen dynamics include: (1) Additional water-quality surveys at steady-state, low-flow conditions emphasizing the collecting of more samples immediately downstream from the Batesville wastewater-treatment facility and RM 4.6 and including samples collected on Laughery Creek downstream from the confluence; (2) samples collected in equal-width increments across the stream transect and composited so that the volume from each increment is proportional to the discharge; (This type of sampling is preferable to collecting grab samples at sites, such as a mixing zone, where a sample collected in mid-channel may not be representative of the average stream condition.) (3) a study of the fate of

NOTE: The information presented in this figure is not based on a verified model and should be used only for qualitative interpretation.

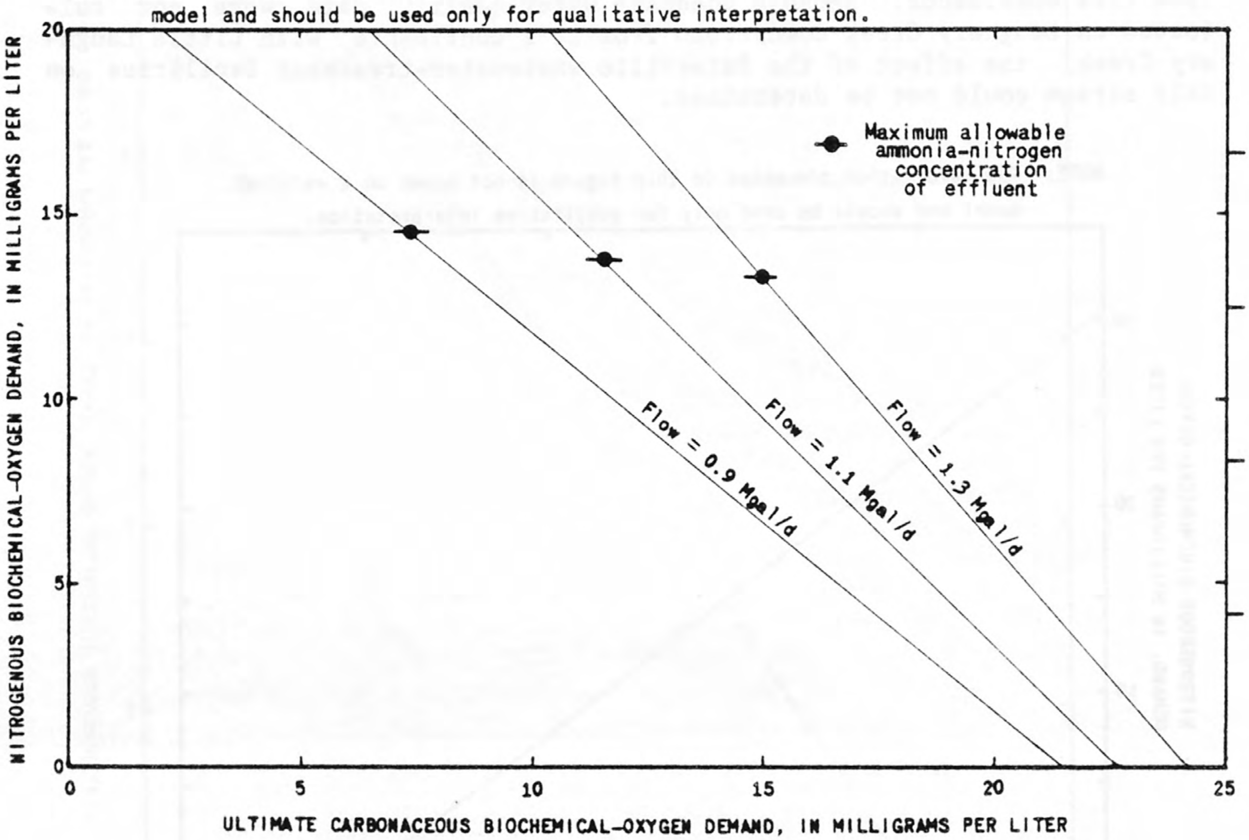

Figure 23.-- Projected alternative carbonaceous and nitrogenous waste loadings for the Batesville West wastewater-treatment facility on Little Laughery Creek that meet the minimum 24-hour average dissolved-oxygen concentration (5.0 mg/L) currently required for Indiana streams during summer low flows, when the East wastewater-treatment facility is no longer in operation, $K_{n,\ zero}$ is 10 (lb/d)/d, and the benthic-oxygen demand is 0.0 $(g/m^2)/d$.

NOTE: The information presented in this figure is not based on a verified model and should be used only for qualitative interpretation.

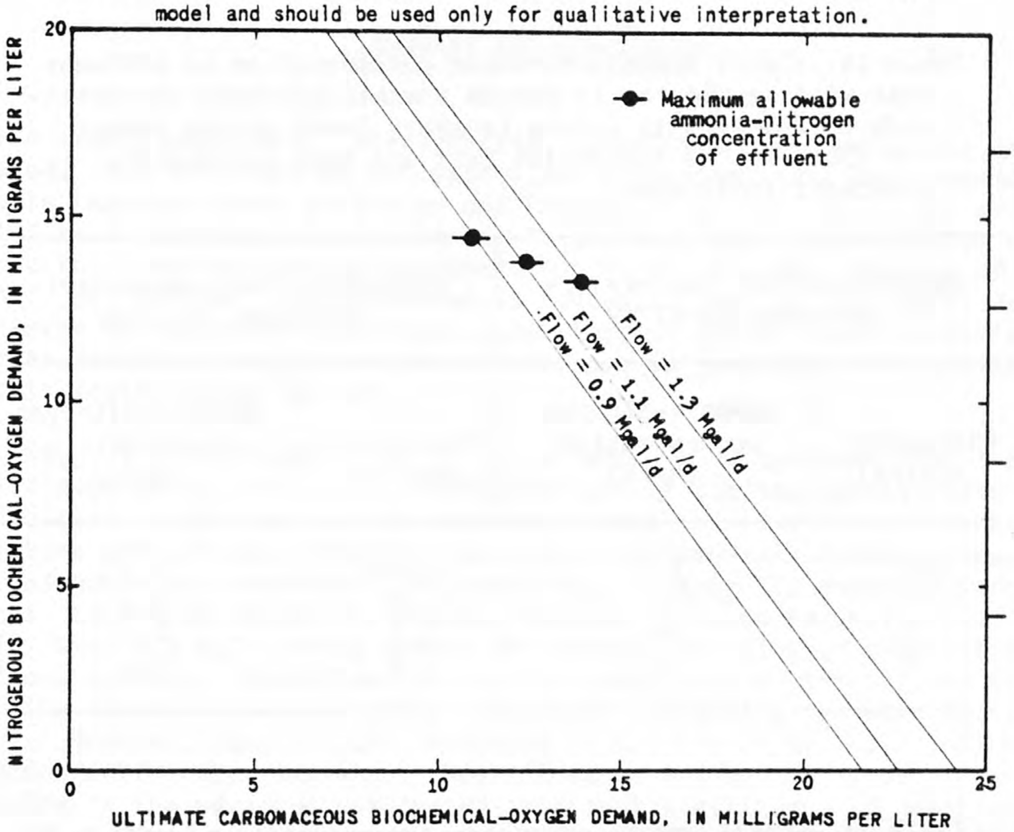

Figure 24.-- Projected alternative carbonaceous and nitrogenous waste loadings for the Batesville West wastewater-treatment facility on Little Laughery Creek that meet the minimum 24-hour average dissolved-oxygen concentration (5.0 mg/L) currently required for Indiana streams during summer low flows, when the East wastewater-treatment facility is no longer in operation, K_n is 0.1 day^{-1}, and the benthic-oxygen demand is 0.0 $(g/m^2)/d$.

nitrogen species and their effect on dissolved oxygen where sufficient data are collected to enable use of a more sophisticated model for estimating nitrification, such as a sequential reaction model; (A model of this type may better describe the process of nitrification in Little Laughery Creek than the BOD-equivalent model that was used in this study.) (4) enumerations of nitrifying bacterial populations of both the stream-bottom materials and the water column downstream from the wastewater-treatment facility to determine if significant populations of nitrifying bacteria are available to exert an oxygen demand; (5) direct determination of benthic-oxygen demand because of its apparent significant impact on dissolved-oxygen concentration in Little Laughery Creek and the uncertainty in estimating it; (6) additional direct determinations of reaeration for verification of the predictive-reaeration equation used in this study; and (7) collecting additional hydrologic data during the $Q_{7,10}$ for better definition of stream-discharge relations and width and depth of stream.

Table 10.--Total ammonia-nitrogen concentration of effluent that will provide an in-stream ammonia-nitrogen concentration of 2.5 mg/L in Little Laughery Creek during summer low flows at the Batesville East and West wastewater-treatment facilities

Batesville East wastewater-treatment facility		Batesville West wastewater-treatment facility	
Discharge (Mgal/d)	Ammonia-nitrogen concentration (mg/L)	Discharge (Mgal/d)	Ammonia-nitrogen concentration (mg/L)
0.37	4.5	0.36	3.5
.0	---	.9	3.4
.0	---	1.1	3.2
.0	---	1.3	3.0

Table 11.--Total ammonia-nitrogen concentration of effluent that will provide an in-stream ammonia-nitrogen concentration of 4.0 mg/L in Little Laughery Creek during summer low flows at the Batesville East and West wastewater-treatment facilities

Batesville East wastewater-treatment facility		Batesville West wastewater-treatment facility	
Discharge (Mgal/d)	Ammonia-nitrogen concentration (mg/L)	Discharge (Mgal/d)	Ammonia-nitrogen concentration (mg/L)
0.37	6.8	0.36	4.4
.0	---	.9	5.4
.0	---	1.1	5.1
.0	---	1.3	4.9

SUMMARY AND CONCLUSIONS

A one-dimensional, steady-state, dissolved-oxygen model has been calibrated, and alternatives for waste-load allocation have been developed for Little Laughery Creek in Ripley and Franklin Counties, Ind. The model indicates that benthic-oxygen demand is the most significant factor currently affecting dissolved-oxygen concentration of the stream. Because of this demand, an average dissolved-oxygen concentration of 5.0 mg/L cannot be achieved during summer low flows under current (1979) basin conditions. The stream dissolved-oxygen standard should not be exceeded if present NPDES permit restrictions are met.

Natural streamflow at the $Q_{7,10}$ is zero. Flow upstream from the municipal discharge at the $Q_{7,10}$ consists only of cooling process water from an industrial discharger and is generally less than 0.5 ft^3/s. Benefits from dilution are minimal. Current and projected ammonia-nitrogen concentrations of the municipal wastewater effluents will result in ammonia-nitrogen concentrations that exceed the Indiana ammonia-nitrogen toxicity standard (2.5 mg/L and 4.0 mg/L during summer and winter low flows, respectively) for Indiana streams. Nitrification did not seem to be a significant factor affecting stream dissolved-oxygen concentration during the water-quality surveys. However, the degraded condition of the stream may have inhibited this process during the surveys. Nitrification may become important after completion of the advanced wastewater-treatment facilities if ammonia nitrogen is not removed from the wastewater effluent and the stream condition is not improved.

The model indicates that future growth in the Little Laughery Creek basin will be limited unless waste loads in the Batesville wastewater-treatment facility are reduced.

This wasteload-assimilation study is not based on a verified model. The changes in stream water quality predicted by the model represent only possible stream responses to different effluent conditions.

REFERENCES

American Public Health Association and others, 1976, Standard methods for the examination of water and wastewater, 14th ed.: New York, American Public Health Association and others, 1193 p.

Baity, H. G., 1938, Some factors affecting the aerobic decomposition of sewage sludge deposits: Sewage Works Journal, v. 10, no. 3, p. 539-568.

Bauer, D. P., Jennings, M. E., and Miller, J. E., 1979, One-dimensional, steady-state, stream-water-quality model: U.S. Geological Survey Water-Resources Investigations 79-45, 215 p.

Brewer, W. S., Abernathy, A. R., and Paynter, M. J. B., 1977, Oxygen consumption by freshwater sediments: Water Research, v. 44, p. 471-473.

Butts, T. D., and Evans, R. L., 1978, Sediment oxygen demand studies of selected northeastern Illinois streams: Urbana, Illinois State Water Survey, 177 p.

Colston, N. V., Jr., 1975, Characterization of urban land runoff, in Ashton, P. M., and Underwood, R. C., eds., Nonpoint sources of water pollution: Blacksburg, Virginia Water Resources Research Center, 314 p.

Edwards, R. W., and Rolley, H. L. J., 1965, Oxygen consumption of river muds: Journal of Ecology, v. 53, no. 1, p. 1-19.

Fair, G. M., Moore, E. W., and Thomas, H. A. Jr., 1941, The natural purification of river muds and pollutional sediments: Sewage Works Journal, v. 13, no. 2, p. 270-305.

Finstein, M. S., Strom, P. F., and Matulewich, V. A., 1978, Discussion of Significance of nitrification in stream analysis--effects on the oxygen balance, by R. J. Courchaine, 1968, (in Water Pollution Control Federation Journal, v. 40, p. 835): Water Pollution Control Federation Journal, v. 50, no. 8, p. 2055-2057.

Foree, E. G., 1976, Reaeration and velocity prediction for small streams: American Society of Civil Engineers Proceedings, Journal of the Sanitary Engineering Division, v. 102, no. EE5, p. 937-952.

Grant, R. S., 1976, Waste-assimilation study of Koshkonong Creek below sewage-treatment plant at Sun Prairie, Wisconsin: U.S. Geological Survey Open-File Report 76-655, 44 p.

Gray, H. H., Forsyth, J. L., Schneider, A. F., and Gooding, A. M., 1972, Geologic Map of the 1° X 2° Cincinnati quadrangle, Indiana and Ohio, showing bedrock and unconsolidated deposits: Indiana Department of Natural Resources, Geological Survey Division.

Hanes, N. B., and Irvine, R. L., 1968, New technique for measuring oxygen uptake rates of benthal systems: Water Pollution Control Federation, Journal, v. 40, no. 2, p. 223-232.

Hargrave, B. T., 1969, Similarity of oxygen uptake by benthic communities: Limnology and Oceanography, v. 14, p. 801-805.

Hines, W. G., Rickert, D. A., McKenzie, S. W., and Bennett, J. P., 1975, Formulation and use of practical models for river-quality assessment: U.S. Geological Survey Circular 715-B, p. B1-B13.

Hoggatt, R. E., 1962, Low-flow characteristics of Indiana streams: Indiana Stream Pollution Control Board, 171 p.

Horner, R. G., 1976, Statistical summaries of Indiana streamflow data: U.S. Geological Survey Water-Resources Investigations Open-File Report 35-75, 526 p.

Hoskin, C. M., 1959, Studies of oxygen metabolism of streams of North Carolina: Austin, Tex., Institute of Marine Science, University of Texas, v. 6, p. 186-192.

Huang, Ching-San, and Hopson, N. E., 1974, Nitrification rate in biological processes: American Society of Civil Engineers Proceedings, Journal of the Environmental Engineering Division, v. 100, no. EE2, p. 409-422.

Indiana State Board of Health, 1977, Guidelines for waste load allocation and total maximum daily loads: Indiana State Board of Health, Water Pollution Control Division, 27 p.

______ 1978, National pollution discharge elimination system permits: Indiana State Board of Health, Water Pollution Control Division.

Jenkins, D., and Garrison, W. E., 1968, Control of activated sludge by mean cell residence time: Water Pollution Control Federation Journal, v. 40, no. 11, p. 1905-1919.

Knowles, G., Downing, A. L., and Barrett, M. J., 1965, Determination of kinetic constants for nitrifying bacteria in mixed culture, with the aid of an electric computer: Journal of General Microbiology, v. 38, p. 263-278.

Knowles, G., Edwards, R. W., and Briggs, R., 1962, Polarographic measurement of the rate of respiration of natural sediments: Limnology and Oceanography, v. 7, p. 481-484.

Langbein, W. B., and Durum, W. H., 1967, The aeration capacity of streams: U.S. Geological Survey Circular 542, 6 p.

Ludzack, F. J., 1966, Chemical analysis for water quality: U.S. Department of the Interior, Federal Water Pollution Control Administration, p. 8-1 to 8-14.

McDonnell, A. J., and Hall, S. D., 1969, Effect of environmental factors on benthic oxygen uptake: Water Pollution Control Federation Journal, v. 41, no. 8, p. R353-R363.

Metcalf and Eddy, Inc., 1972, Wastewater engineering: Collection, treatment, disposal: New York, McGraw-Hill, 782 p.

______ 1973, Nitrification and denitrification facilities. Waste water treatment: U.S. Environmental Protection Agency, 33 p.

National Oceanic and Atmospheric Administration, 1977, Climatological data, Indiana: Asheville, N.C., National Oceanic and Atmospheric Administration, Environmental Data Service, v. 82, no. 5, 14 p.

______ 1978, Climatological data, Indiana: Asheville, N.C., National Oceanic and Atmospheric Administration, Environmental Data Service, v. 83, no. 9, 14 p.

Nemerow, N. L., 1974, Scientific stream pollution analysis: Washington, D.C., Scripta Book Co., 358 p.

O'Connell, R. L., and Thomas, N. A., 1965, Effect of benthic algae on stream dissolved oxygen: American Society of Civil Engineers Proceedings, Journal of the Sanitary Engineering Division, v. 91, no. SA3, p. 1-16.

O'Connor, D. J., and Dobbins, W. E., 1958, Mechanisms of reaeration in natural streams: Transactions of the American Society of Civil Engineers, v. 123, p. 641-684.

Odum, H. T., 1956, Primary production in flowing waters: Limnology and Oceanography, v. 1, no. 2, p. 102-117.

Owens, M., Edwards, R. W., and Gibbs, J. W., 1964, Some reaeration studies in streams: International Journal of Air and Water Pollution, v. 8, no. 819, p. 469-486.

Parkhurst, J. D., and Pomeroy, R. D., 1972, Oxygen absorption in streams: American Society of Civil Engineers Proceedings, Journal of the Sanitary Engineering Division, v. 98, no. SA1, p. 101-124.

Phelps, E. B., 1944, Stream sanitation: New York, John Wiley, 276 p.

Rathbun, R. E., 1977, Reaeration coefficients of streams--state of the art: American Society of Civil Engineers Proceedings, Journal of the Hydraulics Division, v. 103, no. HY4, p. 409-424.

Reeves, J. R., 1922, Economic Geology, in Logan, W. N. and others, Handbook of Indiana Geology: Indiana Department of Conservation, Division of Geology, p. 571-1058.

Ruane, R. J., and Krenkel, P. A., 1977, Nitrification, and other factors affecting nitrogen in the Holston River: Progress in Water Technology, v. 8, no. 4-5, p. 209-224.

Schaal, L. A., 1966, Climate, in Lindsey, A. A., ed., Natural features of Indiana: Indianapolis, Indiana Academy of Science, p. 156-170.

Schneider, A. F., 1966, Physiography, in Lindsey, A. A., ed., Natural features of Indiana: Indianapolis, Indiana Academy of Science, p. 40-56.

Shampine, W. J., 1977, Indiana stream-temperature characteristics: U.S. Geological Survey Water-Resources Investigations 77-6, 55 p.

Stamer, J. K., McKenzie, S. W., Cherry, R. N., Scott, C. T., and Stamer, S. L., 1979, Methods of ultimate carbonaceous BOD determination: Water Pollution Control Federation Journal, v. 51, no. 5, p. 918-925.

Stephens, D. W., and Jennings, M. E., 1976, Determination of primary productivity and community metabolism in streams and lakes using diel oxygen measurements: U.S. Geological Survey Computer Contributions User's Manual, 94 p.

Streeter, H. W., 1935, Measures of natural oxidation in polluted streams. I. The oxygen demand factor: Sewage Works Journal, v. 7, no. 2, p. 251-279.

Strom, P. F., Finstein, M.S., and Matulewich, V. A., 1976, Concentrations of nitrifying bacteria in sewages, effluents, and a receiving stream and resistance of these organisms to chlorination: Applied Environmental Microbiology, v. 31, no. 5, p. 731.

Thackston, E. L., and Krenkel, P. A., 1969, Reaeration predictions in natural streams: American Society of Civil Engineers Proceedings, Journal of the Sanitary Engineering Division, v. 95, no. SA1, Paper 7407, p. 65-94.

Thomann, R. V., 1972, Systems analysis and water quality management: New York, Environmental Research and Applications, Inc., 286 p.

Thomann, R. V., O'Connor, D. J., and DiToro, D. M., 1971, The effect of nitrification on the dissolved oxygen of streams and estuaries--technical report: Bronx, N.Y., Manhattan College, Environmental engineering and science program, 55 p.

Tsivoglou, E. C., and Neal, L. A., 1976, Tracer measurement of reaeration. III. Predicting the reaeration capacity of inland streams: Water Pollution Control Federation Journal, v. 48, no. 12, p. 2669-2689.

Tuffey, T. J., Hunter, J. V., and Matulewich, V. A., 1974, Zones of nitrification: Water Resources Bulletin v. 10, no. 3, p. 555-564.

Velz, C. J., 1970, Applied stream sanitation: New York, Wiley-Interscience, 619 p.

Wezernak, C. T., and Gannon, J. J., 1967, Oxygen nitrogen relationship in autotrophic nitrification: Applied Microbiology, v. 15, p. 1211-1215.

Wilson, G. T., and MacLeod, N., 1974, A critical appraisal of empirical equations and models for the prediction of the coefficient of re-aeration of deoxygenated water: Water Research, v. 8, no. 6, p. 341-366.

Wuhrmann, K., 1968, Objectives, technology, and results of nitrogen and phosphorus removal processes, in Alyona, L., and W. W. Eckenfelder, eds., Advances in water quality improvement: Austin, Tex., University of Texas Press, p. 21-48.