UNITED STATES

DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

A ONE-DIMENSIONAL, STEADY-STATE, DISSOLVED-OXYGEN MODEL AND WASTE-LOAD ASSIMILATION STUDY FOR LITTLE LICK AND BIG LICK CREEKS, BLACKFORD AND DELAWARE COUNTIES, INDIANA

Open-File Report 80-73

Prepared in cooperation with
Indiana State Board of Health

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By James G. Peters, Charles G. Crawford,
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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 second (ft/s)	0.3048	meter per second (m/s)
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)

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/s	Foot per second.
ft^3/s	Cubic foot per second.
$(g/m^2)/d$	Gram per square meter per day.
h	Hour.
in.	Inch.
ISBH	Indiana State Board of Health.
K^1	Benthic-oxygen demand rate.
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.
L_d	Accumulated benthic deposit.
L_i	Initial CBOD load.
(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.
mi^2	Square mile.
mL	Milliliter.
NBOD	Nitrogenous biochemical-oxygen demand.
NPDES	National Pollution Discharge Elimination System.
P	Mean daily photosynthetic DO production.
$Q_{7,10}$	Average low flow over a 7-day period with a recurrence interval of 10 years.
R	Daily deposit of CBOD.
RM	River mile.
T	Elapsed time of benthic accumulation.
t	Traveltime down the stream.
temp.	Temperature.
μmho/cm	Micromho per centimeter.
USGS	U.S. Geological Survey.

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ABSTRACT

The Indiana State Board of Health is developing a State water-quality management plan that includes establishing limits for liquid wastes discharged into Indiana streams. A digital computer model was used to predict alternatives for future waste loadings on Little Lick and Big Lick Creeks that would be compatible with Indiana stream water-quality standards defined for two critical hydrologic conditions, summer and winter low flows.

The model parameters included atmospheric reaeration, carbonaceous and nitrogenous biochemical-oxygen demand, and benthic-oxygen demand. The model was calibrated with data collected during three water-quality surveys at low flow. Verification of the model was not possible owing to varied effluent discharge during sampling. During these surveys, in-stream dissolved-oxygen concentration averaged less than 3 milligrams per liter, well below the State minimum requirement of 5.0 milligrams per liter. The model indicated that these low concentrations were caused by high waste loadings, lack of dilution, low reaeration, and benthic-oxygen demand.

The hypothetical summer waste-assimilation study assumed that future reductions in discharge loadings would decrease carbonaceous and benthic decay and increase nitrogenous decay. This hypothetical study indicated that projected effluent waste loads that would provide acceptable in-stream dissolved-oxygen concentrations are highly dependent on rates of nitrification. Ammonia toxicity became the limiting water-quality criterion at low nitrification rates.

The hypothetical winter waste-assimilation study indicated that projected dissolved-oxygen concentrations in Little Lick and Big Lick Creeks did not fall below the State standard. Owing to a lack of dilution, however, ammonia-nitrogen concentrations would violate in-stream toxicity standards in both Little Lick and Big Lick Creeks. In order to quantify the results of the waste-assimilation study, it would be necessary to collect additional stream data.

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 the 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 un-ionized 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) develop a one-dimensional, steady-state, dissolved-oxygen model for Little Lick and Big Lick Creeks, Blackford and Delaware Counties, Ind., with data provided by the Indiana State Board of Health and (2) use the model for determining alternatives for future waste loadings that would be compatible with Indiana water-quality standards defined for two critical hydrologic conditions, summer and winter low flows.

Owing to the varied effluent discharge during sampling, verification of the model was not possible. Thus, the waste-assimilation study represents hypothetical examples of possible changes in stream water quality. A verification of the model would require that additional data be collected after proposed changes to effluent discharge.

BASIN DESCRIPTION

Little Lick and Big Lick Creeks flow generally southwest to the Mississinewa River and drain about 76 mi^2 of Blackford and Delaware Counties (fig. 1). These streams have formed in Atherton and Martinsville glacial formations, which consist of lacustrine, clay, gravel, and recent alluvium deposits. These deposits overlie limestone, dolomite, and shale of Silurian age (Blackford County Area Planning Commission, 1973, p. 1-15 to 1-19).

Soils close to the streambed are derived primarily from medium-textured Fox-Martinsville alluvium, which is deep and well- to very-poorly drained. The nearly level upland area comprises the Morley-Blout Association soils, which are deep, medium textured, and poorly drained. (See Blackford County Area Planning Commission, 1973, p. 44-49.)

Land use in the Big Lick Creek basin is primarily agricultural. Excluding urban centers, 83 percent of the area is cropland, 8 percent is forest, 7 percent is pasture, and 2 percent is roads and farmsteads.

Hartford City and Dunkirk are the only two incorporated municipalities within the Big Lick Creek drainage. Their populations during the 1970 census were 8,200 and 3,200, respectively. Virtually all point-source discharge to Little Lick and Big Lick Creeks is in these two communities (table 1). Both communities are served by combined storm and sanitary sewers and secondary sewage treatment. Several unincorporated communities and the rural population are served by septic systems.

MODEL DESCRIPTION

A steady-state, one-dimensional, segmented water-quality model developed by Bauer and others (1979) was used in this study. The modeling approach assumes that the various flows, loads, and other factors used do not vary significantly with time. The model uses a modified Streeter-Phelps equation that incorporates nitrogenous, benthic, photosynthetic, and respiratory effects on the DO balance. The model is represented by the following equation:

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

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,

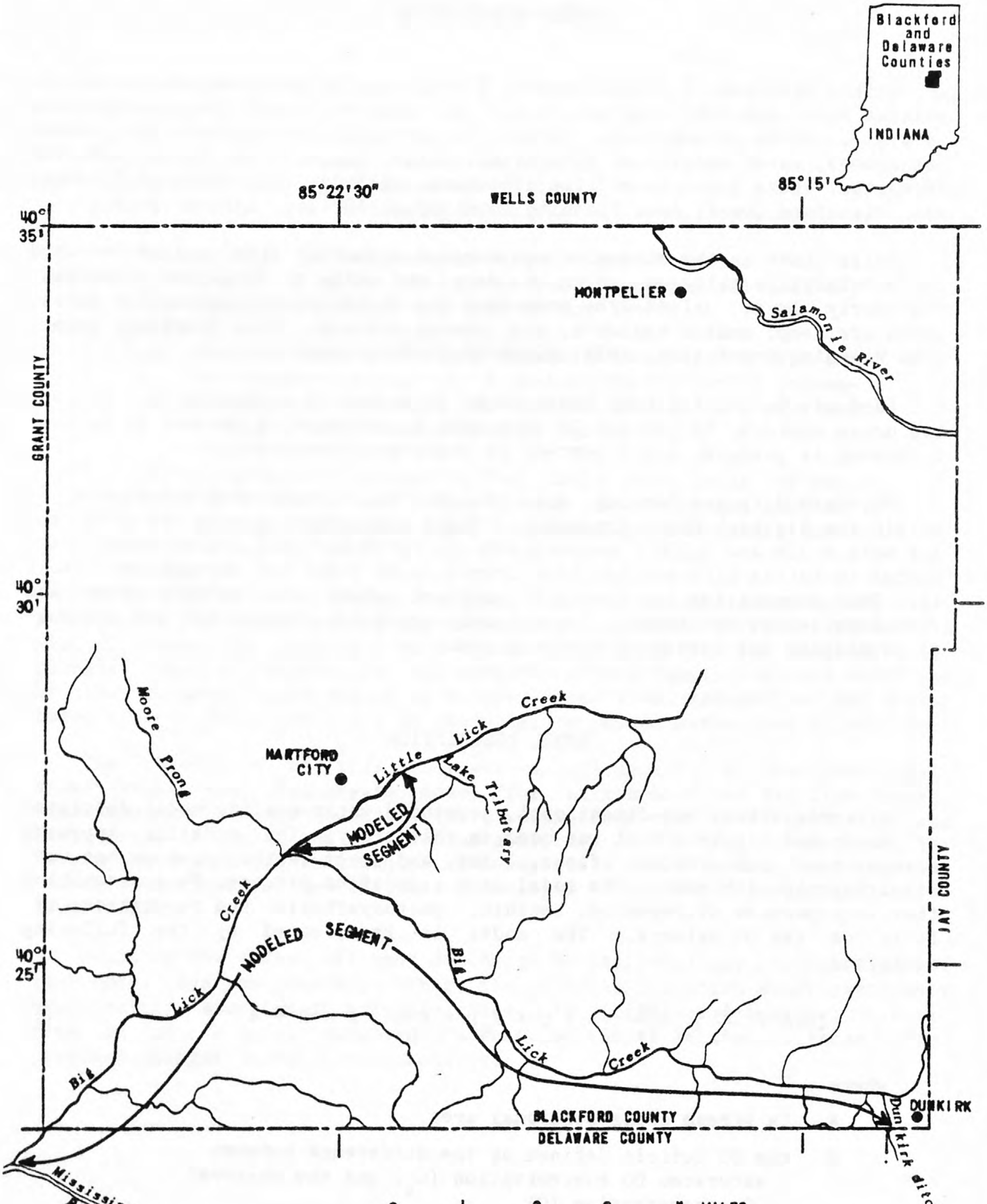

Figure 1.-- Location of modeled segments on Little Lick and Big Lick Creeks, Blackford and Delaware Counties, Ind.

Table 1.--NPDES restrictions for municipalities and industries in the Big Lick Creek basin, Blackford and Delaware Counties, Ind.

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

Discharger	Municipality	Receiving stream	Flow (Mgal/d)	Five-day BOD (mg/L)	Suspended solids (mg/L)	Total ammonia (mg/L)	pH[1]
Dunkirk waste-water treat-ment facility	Dunkirk	Dunkirk ditch	0.89	[2]10/15	[2]10/15	------	6/9
Lake Placid Camp	Hartford City	Lake tributary	----	[2]30/45	[2]30/45	------	6/9
Hartford Packing Co.	do.	Little Lick Creek	----	------	------	------	6/9
3M Co. cooling water outfall No. 002	do.	do.	----	------	------	------	6/9
3M Co. discharge outfall No. 101 and 001	do.	do.	----	[3]30/40	[3]20/30	[3]10/20	6/9
Hartford City East waste-water-treat-ment facility	do.	do.	1.1	[2]30/45	[2]30/45	------	6/9
Hartford City West waste-water-treat-ment facility	do.	Moore Prong	.8	[2]30/45	[2]30/45	------	6/9

[1]Daily low/daily high.
[2]Monthly average/weekly average.
[3]Daily average/daily maximum (interim limits, November 1, 1978 to July 1, 1983).

K_a the atmospheric reaeration rate,

K_d the deoxygenation rate for CBOD,

L the ultimate CBOD,

K_n the deoxygenation rate for NBOD,

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 carbonaceous BOD, (3)

$\frac{K_n N_o}{K_a - K_n} (e^{-K_n t} - e^{-K_a t})$ the deficit due to nitrogenous BOD, (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 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 downstream,

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 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:

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

DATA COLLECTION

Point discharges impacting Little Lick and Big Lick Creeks were restricted to Dunkirk and Hartford City (fig. 2). Thus the modeled segments included 0.33 river mile of Dunkirk ditch from the Dunkirk wastewater-treatment facility outfall to the confluence with Big Lick Creek; 1.52 river miles of Little Lick Creek from the 3M Company outfall No. 002 to the confluence with Big Lick Creek; and 17.03 river miles of Big Lick Creek from the confluence with Dunkirk ditch to the mouth. The total area drained by the Big Lick basin is 76.30 mi^2.

Water-quality surveys in August and October 1977 and a third survey in September 1978 were done by the Water-Quality Surveillance Section of the Indiana State Board of Health. The streamflow measurements made by the U.S. Geological Survey during the first two surveys did not adequately describe the hydrology of the basin. The measurements indicated an interaction between ground and surface water, but the extent and magnitude of this interaction could not be defined. The number of stream-measuring sites for the third survey was more than doubled to alleviate this problem. The stream measurements and the outfall discharges, were used to calculate seepage losses and gains for each reach on Big Lick and Little Lick Creeks. Linear adjustments of these seepage calculations, based on Geological Survey gaging records and outfall discharge, provided estimates of seepage for the first two surveys (fig. 2). All flows for the three surveys and the method of determining them are listed in table 2.

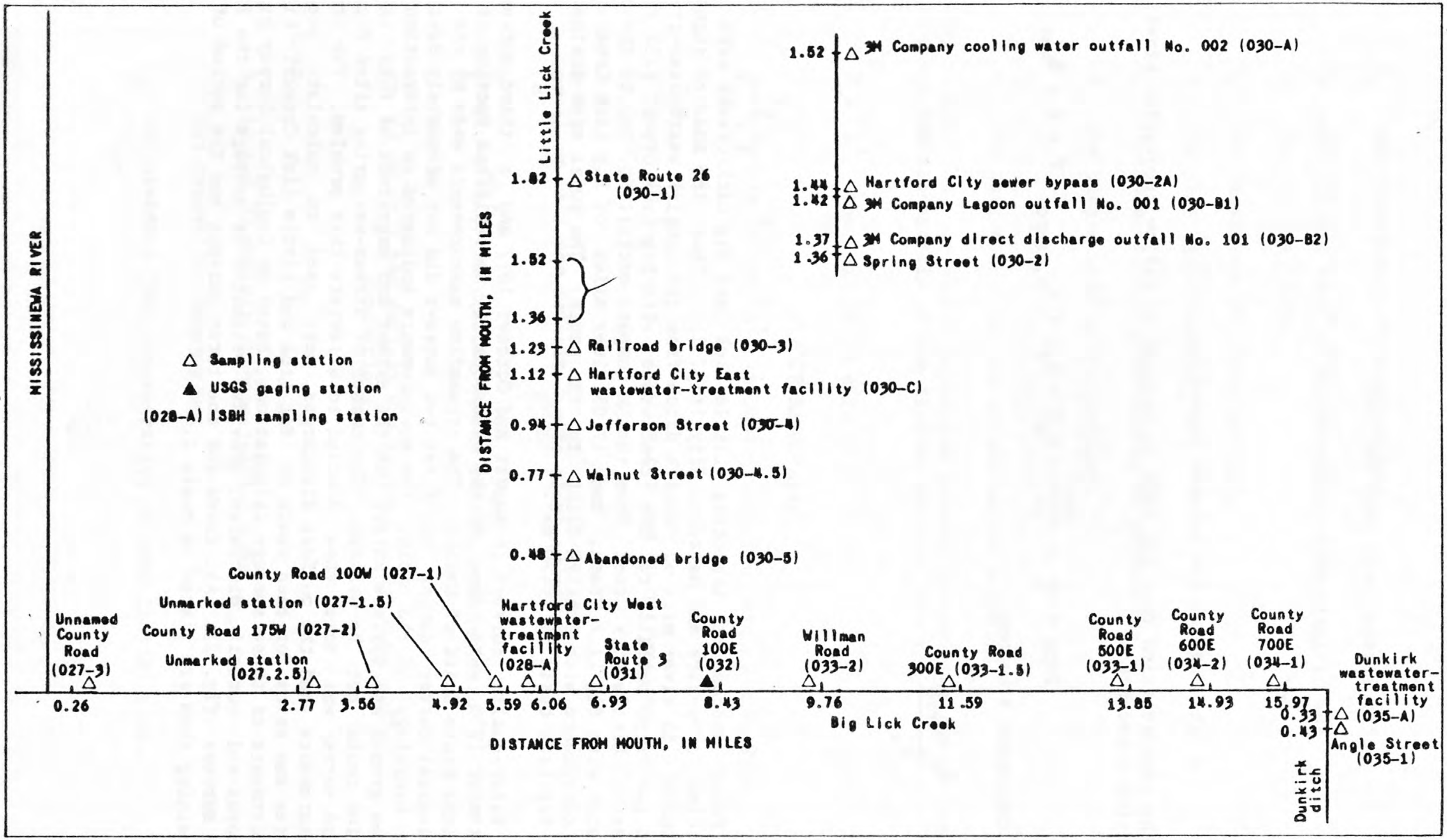

Figure 2.-- Locations of sampling stations, Big Lick Creek basin, Blackford and Delaware Counties, Ind.

During the two 1977 surveys, water-quality data were collected every 3 to 4 hours during a 24-hour period. Diel variation of outfall discharge measurements and field data collected was insignificant. During the third survey, grab samples were collected at each sampling station.

Field measurements included dissolved-oxygen concentration, temperature, specific conductance, and pH. Composite and grab samples were analyzed by the Indiana State Board of Health Laboratory for 5-day CBOD (carbonaceous biochemical-oxygen demand), ammonia nitrogen, and nitrite nitrogen plus nitrate nitrogen concentrations (tables 3-8). Additionally, several long-term CBOD determinations were observed, periodically, throughout the incubation period. (See section "Carbonaceous Biochemical-Oxygen Demand.")

Ultimate CBOD concentration was determined by the Elmore method (Ludzack, 1966). In this method, 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 give an estimated ultimate CBOD of not more than 4 mg/L. The diluted samples are analyzed by standard methods in American Public Health Association and others (1976).

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

Stream discharge was measured by the U.S. Geological Survey during the 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 time of travel at several different flow conditions are plotted against the concurrent discharge at the nearest gaging station in figures 3-13 (unpublished U.S. Geological Survey data).

MODEL CALIBRATION

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

Table 2.--Measured and estimated streamflow, waste and tributary discharges, and linear runoff for the water-quality surveys on Little Lick and Big Lick Creeks, Blackford and Delaware Counties, Ind.

Location and station (ISBH sta. no. in parens)	Date of survey								
	August 3, 1977			October 20, 1977			September 21, 1978		
	Streamflow at station[1] (ft^3/s)	Waste or tributary discharge[2] (ft^3/s)	Linear runoff[3] (ft^3/s)	Streamflow at station[1] (ft^3/s)	Waste or tributary discharge[2] (ft^3/s)	Linear runoff[3] (ft^3/s)	Streamflow at station (ft^3/s)	Waste or tributary discharge (ft^3/s)	Linear runoff[3] (ft^3/s)
LITTLE LICK CREEK									
Little Lick Creek at State Route 26 (030-1)	0.0	----	0.0	0.0	----	0.0	[4]0.21	-----	0.0
3M Co. cooling water outfall No. 002 (030-A)	.78	0.78	.0	.0	----	.0	[1]1.45	[2]1.24	.0
Hartford City sewer bypass (030-2A)	.78	.0	.0	.0	----	.0	[1]2.13	[1].68	.0
3M Co. lagoon outfall No. 001 (030-B1)	.78	.0	.0	.71	0.71	.0	[1]2.13	[5].00	.0
3M Co. direct discharge outfall No. 101 (030-B2)	1.71	.93	.0	----	----	.0	[1]3.18	[5]1.05	.0
Little Lick Creek at Spring Street (030-2)	1.71	----	.0	.71	----	.0	[4]3.18	-----	-.03
Little Lick Creek at railroad bridge (030-3)	1.71	----	.0	.71	----	.0	[1]3.15	-----	-.02
Hartford City East wastewater-treatment facility (030-C)	3.22	1.51	.0	1.91	1.20	.0	[1]4.35	[5]1.22	-.04
Little Lick Creek at Jefferson Street (030-4)	3.22	----	.0	1.91	----	.0	[1]4.31	-----	-.03
Little Lick Creek at Walnut Street (030-4.5)	3.22	----	.0	1.91	----	.0	[4]4.28	-----	----
Little Lick Creek at abandoned bridge (030-5)	3.22	----	.0	1.91	----	.0	[1]4.28	-----	----
Little Lick Creek at mouth	3.22	----	.0	1.91	----	.0	[1]4.28	-----	----

Table 2.--Measured and estimated streamflow, waste and tributary discharges, and linear runoff for the water-quality surveys on Little Lick and Big Lick Creeks, Blackford and Delaware Counties, Ind.--Continued

Location and station (ISBH sta. no. in parens)	Date of survey								
	August 3, 1977			October 20, 1977			September 21, 1978		
	Streamflow at station[1] (ft^3/s)	Waste or tributary discharge[2] (ft^3/s)	Linear runoff[3] (ft^3/s)	Streamflow at station[1] (ft^3/s)	Waste or tributary discharge[2] (ft^3/s)	Linear runoff[3] (ft^3/s)	Streamflow at station (ft^3/s)	Waste or tributary discharge (ft^3/s)	Linear runoff[3] (ft^3/s)
BIG LICK CREEK									
Dunkirk ditch (035-1)	0.0	----	-----	----	----	-----	[4]0.09	-----	-----
Dunkirk wastewater-treatment facility (035-A)	1.44	1.44	-0.79	1.83	1.83	-0.83	[1]1.49	[5]1.40	-0.76
Big Lick Creek at County Road 700E (034-1)	.65	----	.0	1.00	----	.0	[4].73	-----	-.01
Big Lick Creek at County Road 600E (034-2)	.65	----	.0	1.00	----	.0	[1].72	-----	-.01
Big Lick Creek at County Road 500E (033-1)	.65	----	.50	1.00	----	1.0	[4].71	-----	.66
Big Lick Creek at County Road 300E (033-1.5)	----	----	-----	----	----	----	[4]1.37	-----	.37
Big Lick Creek at Willman Road (033-2)	1.15	----	-.27	2.00	----	.0	[4]1.74	-----	-.04
Big Lick Creek at County Road 100E (032)	.88	----	.42	2.00	----	.4	[4]1.70	-----	.46
Big Lick Creek at State Route 3 (031)	1.30	----	.0	2.40	----	.0	[4]2.16	-----	.0
Big Lick Creek at confluence with Little Lick Creek	4.52	3.22	-.18	4.31	1.91	-.15	[1]6.44	-----	-.19
Hartford City West wastewater-treatment facility (028-A)	5.02	.68	-.70	4.70	.54	-.49	[1]6.80	[5].55	-.58
Big Lick Creek at County Road 100W (027-1)	4.32	----	1.00	4.21	----	1.10	[1]6.22	-----	.34
Big Lick Creek at river mile 4.92 (027-1.5)	----	----	-----	----	----	----	[4]6.56	-----	.69
Big Lick Creek at County Road 175W (027-2)	5.32	----	2.90	5.31	----	2.90	[1]7.25	-----	.68
Big Lick Creek at river mile 2.77 (027-2.5)	----	----	-----	----	----	----	[4]7.93	-----	2.17
Big Lick Creek at unnamed county road (027-3)	8.22	----	.0	8.21	----	----	[1]10.10	-----	.0
Big Lick Creek at mouth	8.22	----	----	8.21	----	----	[1]10.10	-----	----

[1]Flow estimated by summing waste or tributary discharge and linear runoff.
[2]Flow measured by Indiana State Board of Health.
[3]Flow estimated by linear interpolation.
[4]Flow measured by U.S. Geological Survey.
[5]Flow averaged from Monthly Report of Operations, Indiana State Board of Health.

Table 3.--Water-quality analyses for sampling stations on Little Lick Creek, Blackford County, Ind., August 3, 1977

[Water-quality data collected by Indiana State Board of Health]

Location and station (ISBH sta. no. in parens)	River mile	Average temp.[1] (°C)	Specific cond. (µmho/cm at 25°C)	Average DO[1] (mg/L)	Five-day BOD (mg/L)	Ammonia nitrogen (mg/L)	Total Kjeldahl nitrogen (mg/L)	Nitrite plus nitrate nitrogen (mg/L)	Suspended solids (mg/L)
3M Co. cooling water outfall No. 002 (030-A)	1.52	20	923	8.8	1.8	<0.1	---	0.5	<1
3M Co. direct discharge outfall 101 (030-B2)	1.37	24	1,429	6.3	70	<.1	---	<.1	10
Little Lick Creek at Spring Street (030-2)	1.36	22	1,209	4.7	45	<.1	8.6	.1	7
Little Lick Creek at railroad bridge (030-3)	1.23	22	1,274	.2	38	.6	7.6	<.1	10
Hartford City East wastewater-treatment facility (030-C)	1.12	22	2,423	2.6	48	2.1	---	8.9	2
Little Lick Creek at Jefferson Street (030-4)	.94	22	1,887	2.8	17	1.8	5.2	2.3	5
Little Lick Creek at abandoned bridge (030-5)	.48	22	1,925	1.4	11	2.0	---	1.0	4

[1]Average based on water-quality data collected every 3 to 4 hours for 24 hours.

Table 4.--Water-quality analyses for sampling stations on Big Lick Creek, Blackford and Delaware Counties, Ind., August 3, 1977

[Water-quality data collected by Indiana State Board of Health]

Location and station (ISBH sta. no. in parens)	River mile	Average temp.[1] (°C)	Specific cond. (µmho/cm at 25°C)	Average DO[1] (mg/L)	Five-day BOD (mg/L)	Ammonia nitrogen (mg/L)	Total Kjeldahl nitrogen (mg/L)	Nitrite plus nitrate nitrogen (mg/L)	Suspended solids (mg/L)
Dunkirk wastewater-treatment facility (035-A)	[2]17.36	22	1,400	3.7	42	18	22	0.2	46
Big Lick Creek at County Road 700E (034-1)	15.97	23	1,722	2.1	21	18	22	<.1	26
Big Lick Creek at County Road 600E (034-2)	14.93	23	1,825	2.0	20	15	----	1.0	20
Big Lick Creek at County Road 500E (033-1)	13.85	22	1,122	3.7	7.6	5.9	----	1.2	8
Big Lick Creek at Willman Road (033-2)	9.76	23	1,312	3.5	10	6.1	----	2.1	32
Big Lick Creek at State Route 3 (031)	6.93	22	1,192	5.5	4.2	.4	----	2.8	28
Hartford City West wastewater-treatment facility (028-A)	6.06	21	1,308	3.6	4.1	.1	----	14	6
Big Lick Creek at County Road 100W (027-1)	5.59	22	1,723	1.8	5.3	1.2	3.5	1.9	6
Big Lick Creek at County Road 175W (027-2)	3.56	22	1,820	3.0	4.3	.2	----	2.0	3
Big Lick Creek at unnamed county road (027-3)	.26	21	-----	3.3	3.2	.5	----	.7	.7

[1]Average based on water-quality data collected every 3 to 4 hours for 24 hours.
[2]Actually on Dunkirk ditch upstream from confluence with Big Lick Creek.

Table 5.--Water-quality analyses for sampling stations on Little Lick Creek, Blackford County, Ind., October 20, 1977

[Water-quality data collected by Indiana State Board of Health]

Location and station (ISBH sta. no. in parens)	River mile	Average temp.[1] (°C)	Specific cond. (µmho/cm at 25°C)	Average DO[1] (mg/L)	Five-day BOD (mg/L)	Ammonia nitrogen (mg/L)	Total Kjeldahl nitrogen (mg/L)	Nitrite plus nitrate nitrogen (mg/L)	Suspended solids (mg/L)
3M Company lagoon outfall No. 001 (030-B1)	1.42	19	2,050	<0.1	80	---	24	<0.1	24
Little Lick Creek at railroad bridge (030-3)	1.23	16	1,575	.5	41	---	16	.1	8
Hartford City East wastewater-treatment facility (030-C)	1.12	18	3,375	2.9	2.4	0.6	.6	8.2	5
Little Lick Creek at Jefferson Street (030-4)	.94	14	2,350	.98	18	---	9.8	1.6	5
Little Lick Creek at Walnut Street (030-4.5)	.77	12	2,500	.93	22	---	9.1	1.0	8
Little Lick Creek at abandoned bridge (030-5)	.48	15	2,150	.65	15	---	9.6	.3	7

[1]Average based on water-quality data collected every 3 to 4 hours for 24 hours.

Table 6.--Water-quality analyses for sampling stations on Big Lick Creek, Blackford and Delaware Counties, Ind., October 20, 1977

[Water-quality data collected by Indiana State Board of Health]

Location and station (ISBH sta. no. in parens)	River mile	Average temp.[1] (°C)	Specific cond. (µmho/cm at 25°C)	Average DO[1] (mg/L)	Five-day BOD (mg/L)	Twenty-day BOD (mg/L)	Ammonia nitrogen (mg/L)	Total Kjeldahl nitrogen (mg/L)	Nitrite plus nitrate nitrogen (mg/L)	Suspended solids (mg/L)
Dunkirk wastewater-treatment facility (035-A)	[2]17.36	14	1,500	5.4	90	----	16	17	0.2	38
Big Lick Creek at County Road 700E (034-1)	15.97	11	1,475	1.2	48	----	13	----	<.1	9
Big Lick Creek at County Road 600E (034-2)	14.93	13	1,600	1.5	37	----	13	----	<.1	11
Big Lick Creek at County Road 500E (033-1)	13.85	13	1,375	1.8	9	----	9.5	----	<.1	8
Big Lick Creek at Willman Road (033-2)	9.76	11	1,463	4.6	7.3	----	4.5	----	.8	13
Big Lick Creek at State Route 3 (031)	6.93	11	1,138	5.7	3.1	----	1.2	----	1.8	3
Hartford City West wastewater-treatment facility (028A)	6.06	17	1,500	2.5	3.6	----	2.5	4.0	8.4	10
Big Lick Creek at County Road 100W (027-1)	5.59	12	1,600	3.1	3.3	10.3	4.5	6.9	1.9	5
Big Lick Creek at County Road 175W (027-2)	3.56	12	1,525	3.4	8.1	----	3.9	----	1.4	6
Big Lick Creek at unnamed county road (027-3)	.26	11	1,375	4.3	6.6	----	2.9	----	1.8	5

[1]Average based on water-quality data collected every 3 to 4 hours for 24 hours.
[2]Actually on Dunkirk ditch upstream from confluence with Big Lick Creek.

Table 7.--Water-quality analyses for sampling stations on Little Lick Creek, Blackford County Ind., September 21, 1978

[Water-quality data collected by Indiana State Board of Health]

Location and station (ISBH sta. no. in parens)	River mile	Average temp.[1] (°C)	Average DO[1] (mg/L)	Five-day BOD (mg/L)	Twenty-day BOD (mg/L)	Ammonia nitrogen (mg/L)	Total Kjeldahl nitrogen (mg/L)	Nitrite plus nitrate nitrogen (mg/L)	Suspended solids (mg/L)
Little Lick Creek at State Route 26 (030-1)	1.82	22	1.7	3.0	-----	0.6	2.5	<0.1	16
3M Co. cooling water outfall no. 002 (030-A)	1.52	18	9.2	1.1	1.9	<.1	.2	.4	2
Hartford City sewer bypass (030-2A)	1.44	21	.0	135.4	207.0	25	36	<.1	56
3M Co. lagoon outfall no. 001 (030-B1)	1.42	24	6.8	5.4	12	.1	6.5	<.1	5
3M Co. direct discharge outfall no. 101 (030-B2)	1.37	24	7.1	5.4	12	3.2	35	<.1	19
Little Lick Creek at Spring Street (030-2)	1.36	22	1.5	140.3	220	6.6	26	<.1	19
Little Lick Creek at railroad bridge (030-3)	1.23	22	1.5	67	-----	6.2	25	<.1	20
Hartford City East wastewater-treatment facility (030-C)	1.12	22	7.0	3.9	9.4	.2	1.4	8.3	14
Little Lick Creek at Jefferson Street (030-4)	.94	21	1.0	8.0	-----	2.3	3.8	1.2	5
Little Lick Creek at Walnut Street (030-4.5)	.77	22	1.1	7.4	13.2	2.3	3.8	1.2	12
Little Lick Creek at abandoned bridge (030-5)	.48	21	.8	7.3	-----	2.9	4.5	.4	3

[1]Average based on water-quality data collected every 3 to 4 hours for 24 hours.

Table 8.--Water-quality analyses for sampling stations on Big Lick Creek, Blackford and Delaware Counties, Ind., September 21, 1978

[Water-quality data collected by Indiana State Board of Health]

Location and station (ISBH sta. no. in parens)	River mile	Average temp.[1] (°C)	Average DO[1] (mg/L)	Five-day BOD (mg/L)	Twenty-day BOD (mg/L)	Ammonia nitrogen (mg/L)	Total Kjeldahl nitrogen (mg/L)	Nitrite plus nitrate nitrogen (mg/L)	Suspended solids (mg/L)
Dunkirk ditch at Angle Street (035-1)	[2]17.46	24	0.0	19	----	6	8.4	<0.1	18
Dunkirk wastewater-treatment facility (035-A)	[3]17.36	26	4.5	25.6	48.2	9	12	.1	14
Big Lick Creek at County Road 700E (034-1)	15.97	23	2.8	15.5	30.0	8.8	10	<.1	19
Big Lick Creek at County Road 600E (034-2)	14.93	23	3.4	8.6	----	8.7	10	<.1	5
Big Lick Creek at County Road 500E (033-1)	13.85	23	2.0	5.0	----	5.5	6.4	.1	6
Big Lick Creek at County Road 300E (033-1.5)	11.59	23	2.9	3.0	8.2	2.6	3.4	.8	9
Big Lick Creek at Willman Road (033-2)	9.76	23	3.0	3.4	----	.5	1.3	1.1	28
Big Lick Creek at County Road 100E (032)	8.43	24	4.0	1.4	----	.1	.8	1.1	22
Big Lick Creek at State Route 3 (031)	6.93	24	4.7	1.4	----	.2	.9	.9	20
Hartford City West wastewater-treatment facility (028-A)	6.06	19	4.9	1.5	3.7	.1	.9	23	11
Big Lick Creek at County Road 100W (027-1)	5.59	22	1.1	5.0	8.4	2.6	3.9	.9	6
Big Lick Creek at river mile 4.92 (027-1.5)	4.92	23	1.4	----	----	3.1	4.9	.5	5
Big Lick Creek at County Road 175W (027-2)	3.56	22	1.0	9.3	17.3	2.6	8.4	.2	6
Big Lick Creek at river mile 2.77 (027-2.5)	2.77	--	.9	----	----	2.7	8.4	.1	36
Big Lick Creek at unnamed county road (027-3)	.26	22	3.0	2.5	----	1.3	3.3	.8	7

[1]Average based on water-quality data collected every 3 to 4 hours for 24 hours.
[2]Actually on Dunkirk ditch (RM 0.33) upstream from confluence with Big Lick Creek.
[3]Actually on Dunkirk ditch (RM 0.43) upstream from confluence with Big Lick Creek.

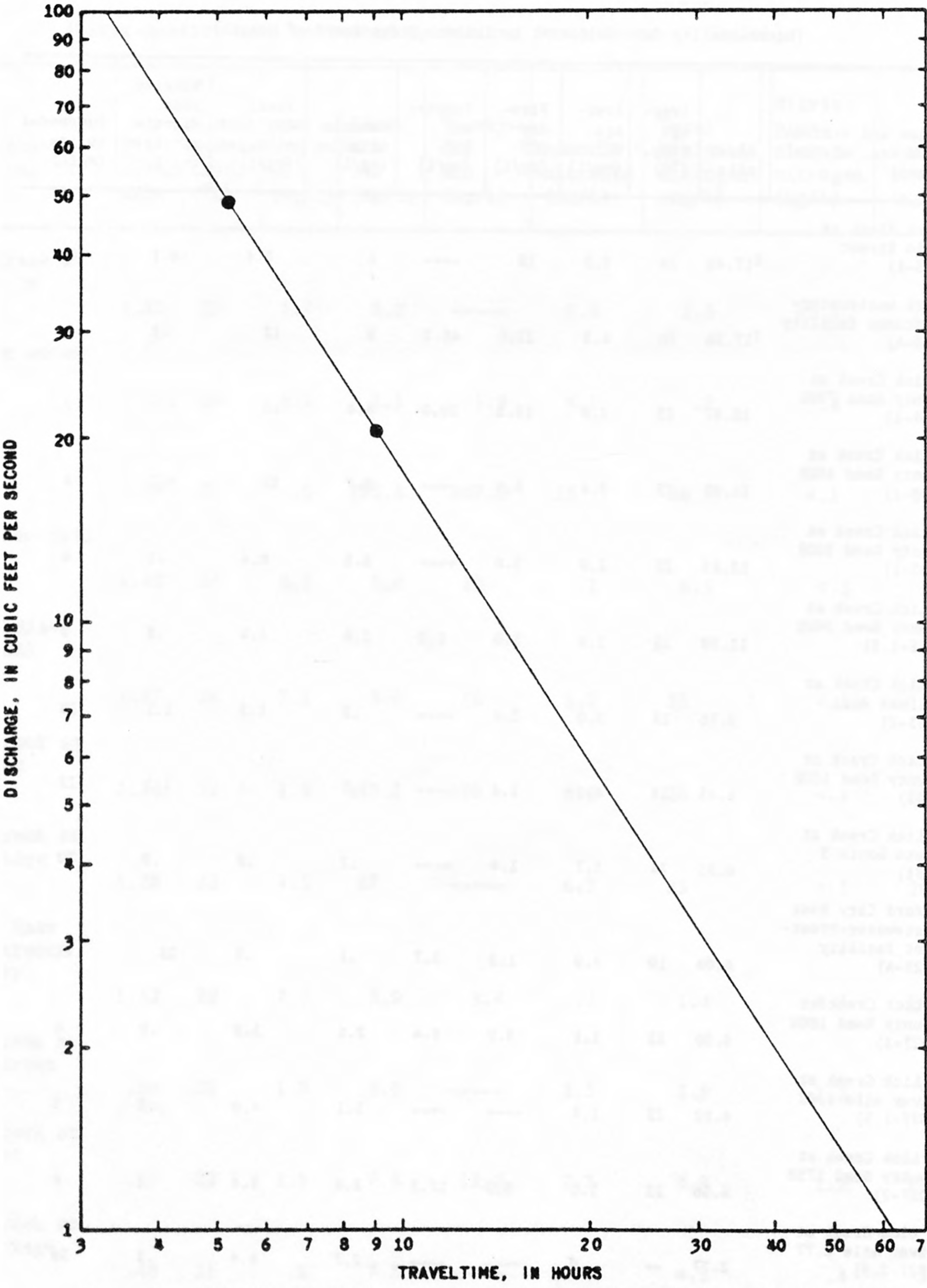

Figure 3.-- Relation of discharge to traveltime of the peak dye concentration for Little Lick Creek, river miles 1.59 to 1.36.

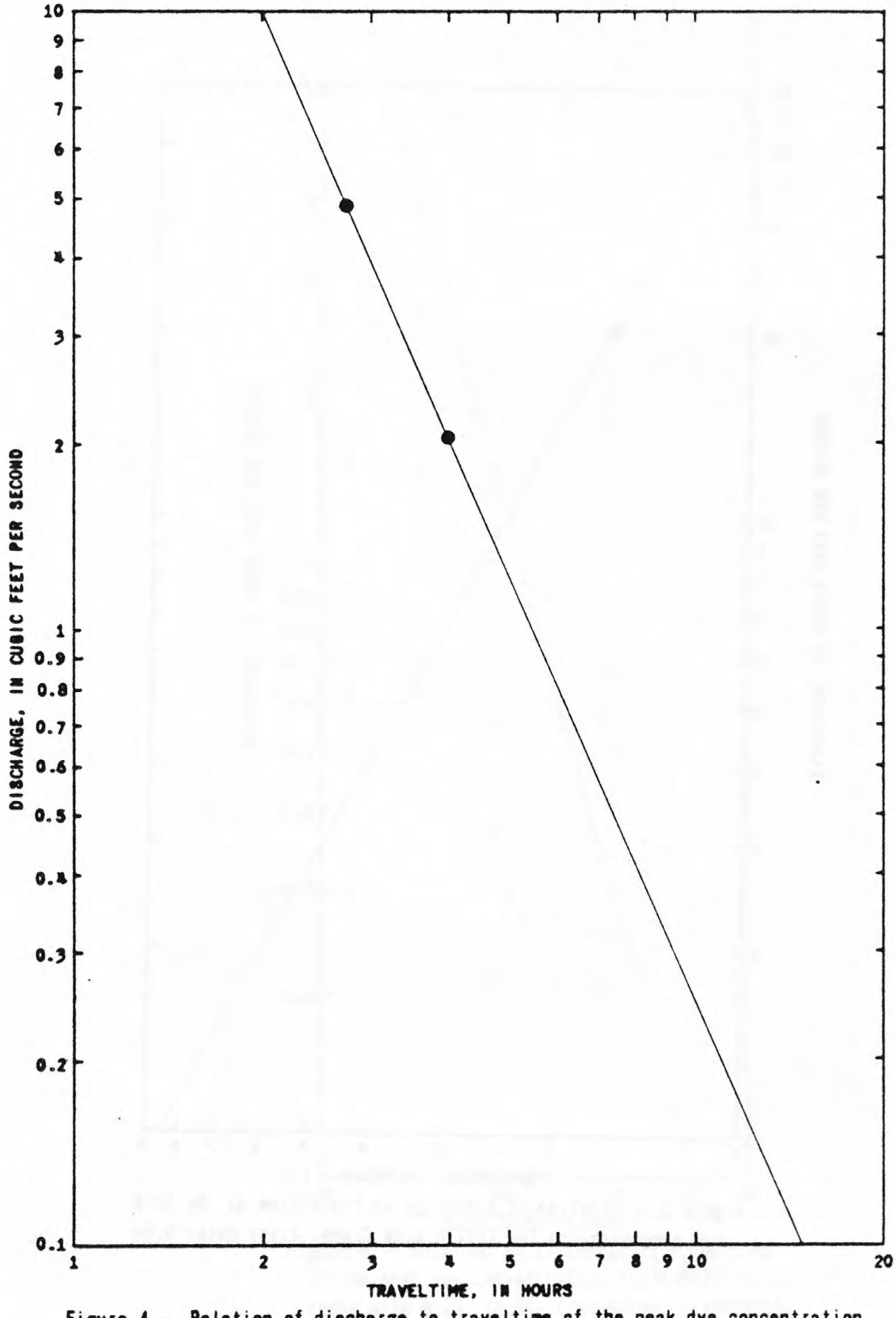

Figure 4.-- Relation of discharge to traveltime of the peak dye concentration for Little Lick Creek, river miles 1.36 to 0.94.

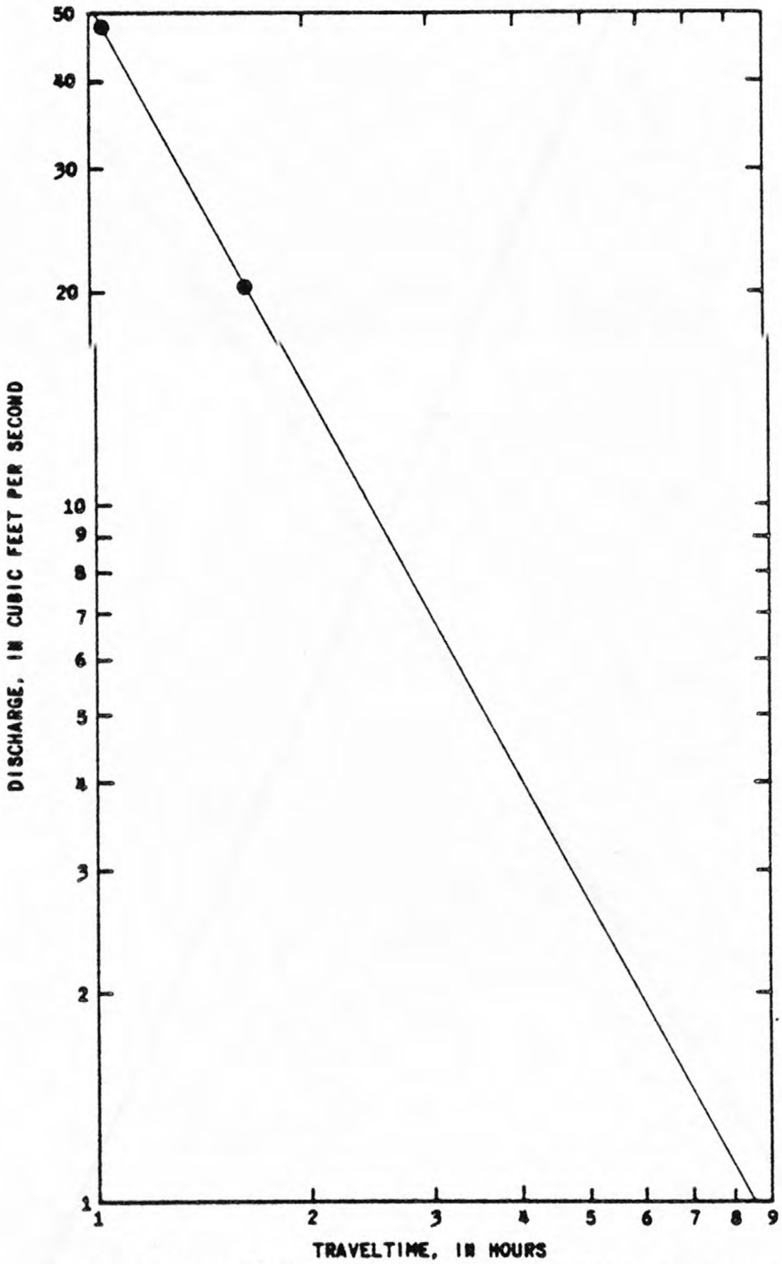

Figure 5.-- Relation of discharge to traveltime of the peak dye concentration for Little Lick Creek, river miles 0.94 to 0.77.

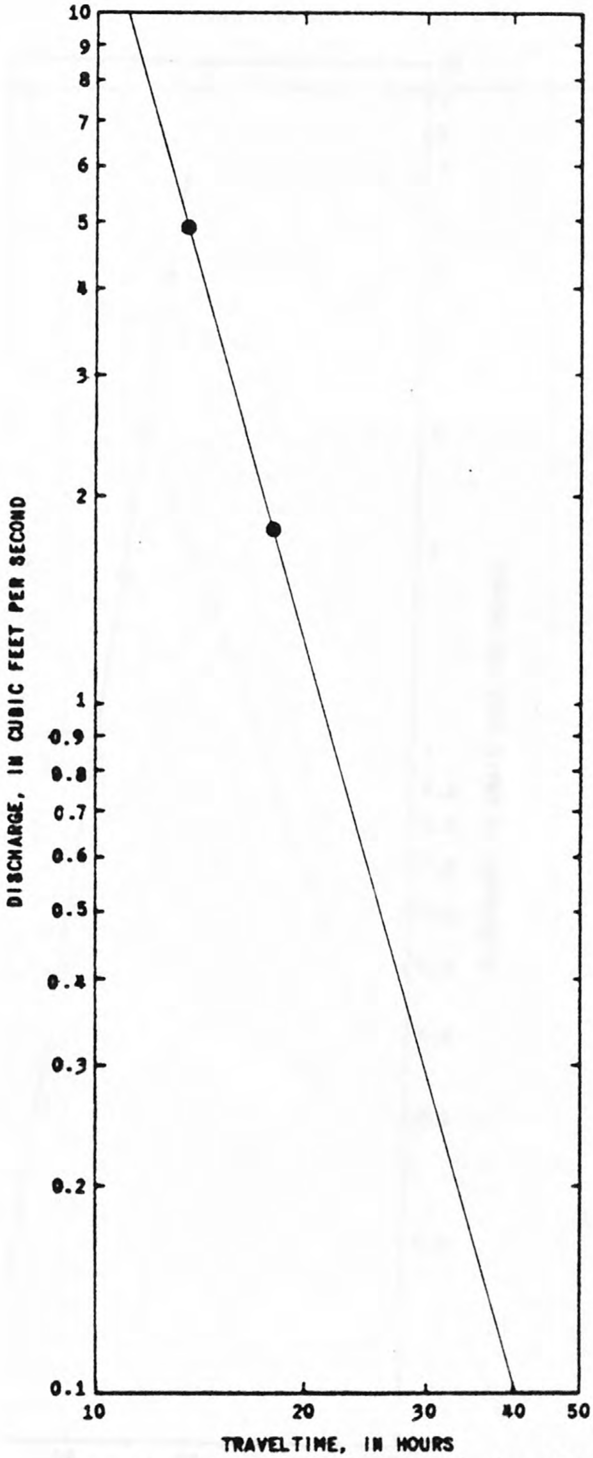

Figure 6.-- Relation of discharge to traveltime of the peak dye concentration for Dunkirk ditch, river mile 0.33, to Big Lick Creek, river mile 14.93.

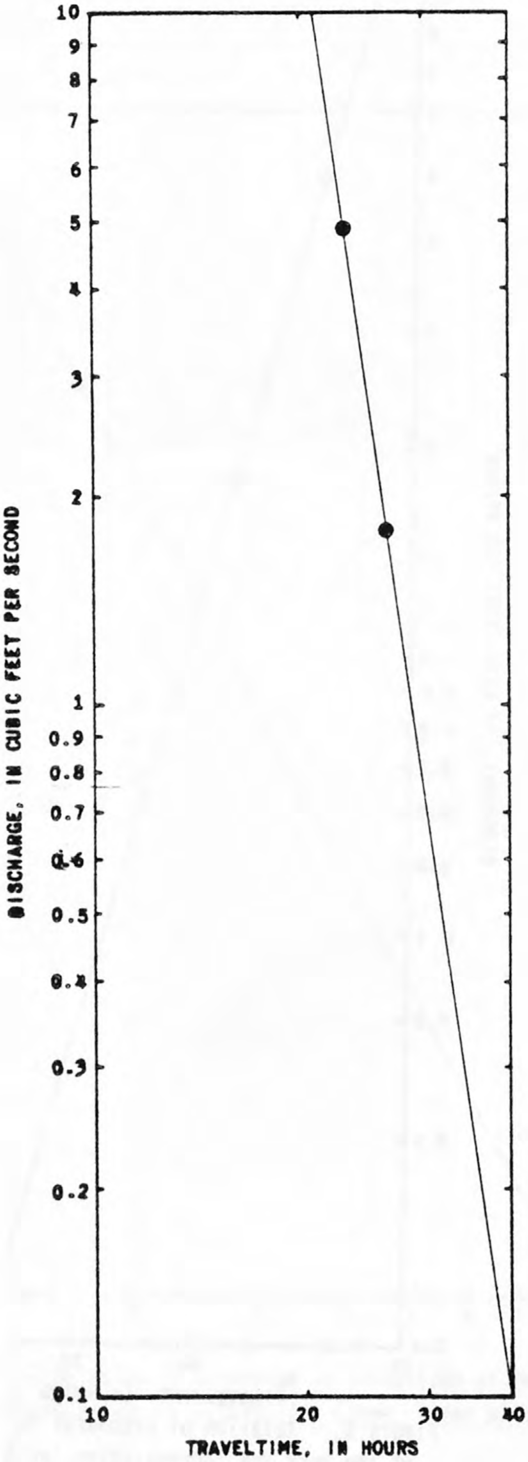

Figure 7.-- Relation of discharge to traveltime of the peak dye concentration for Big Lick Creek, river miles 14.93 to 12.63.

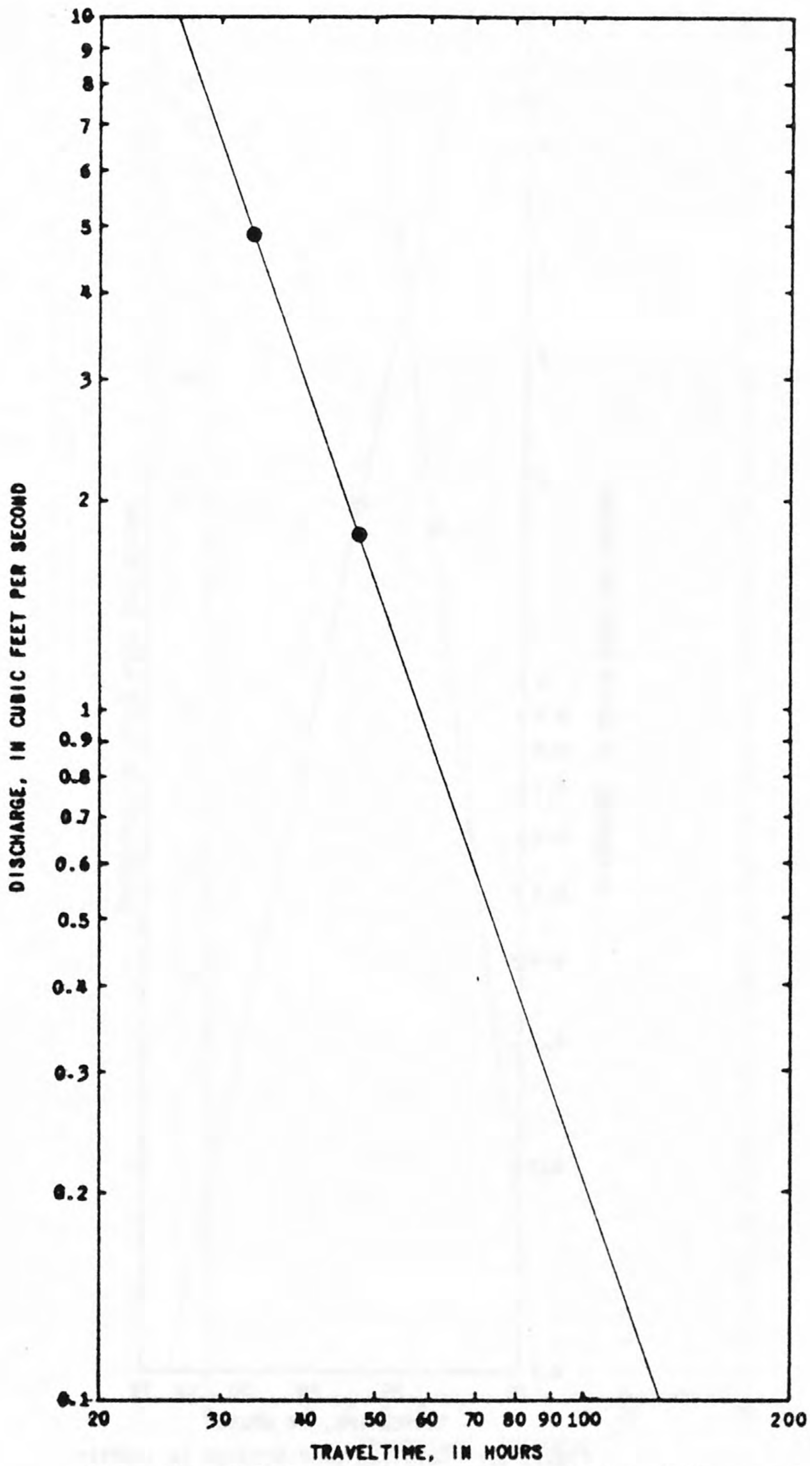

Figure 8.-- Relation of discharge to traveltime of the peak dye concentration for Big Lick Creek, river miles 12.63 to 9.76.

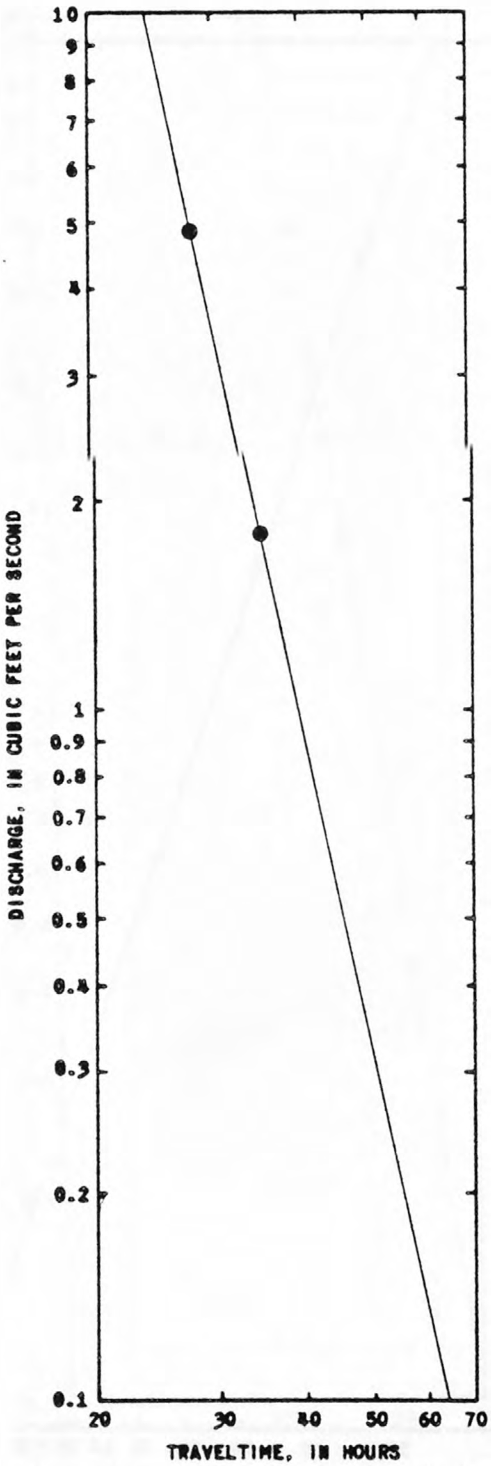

Figure 9.-- Relation of discharge to travel-time of the peak dye concentration for Big Lick Creek, river miles 9.76 to 6.93.

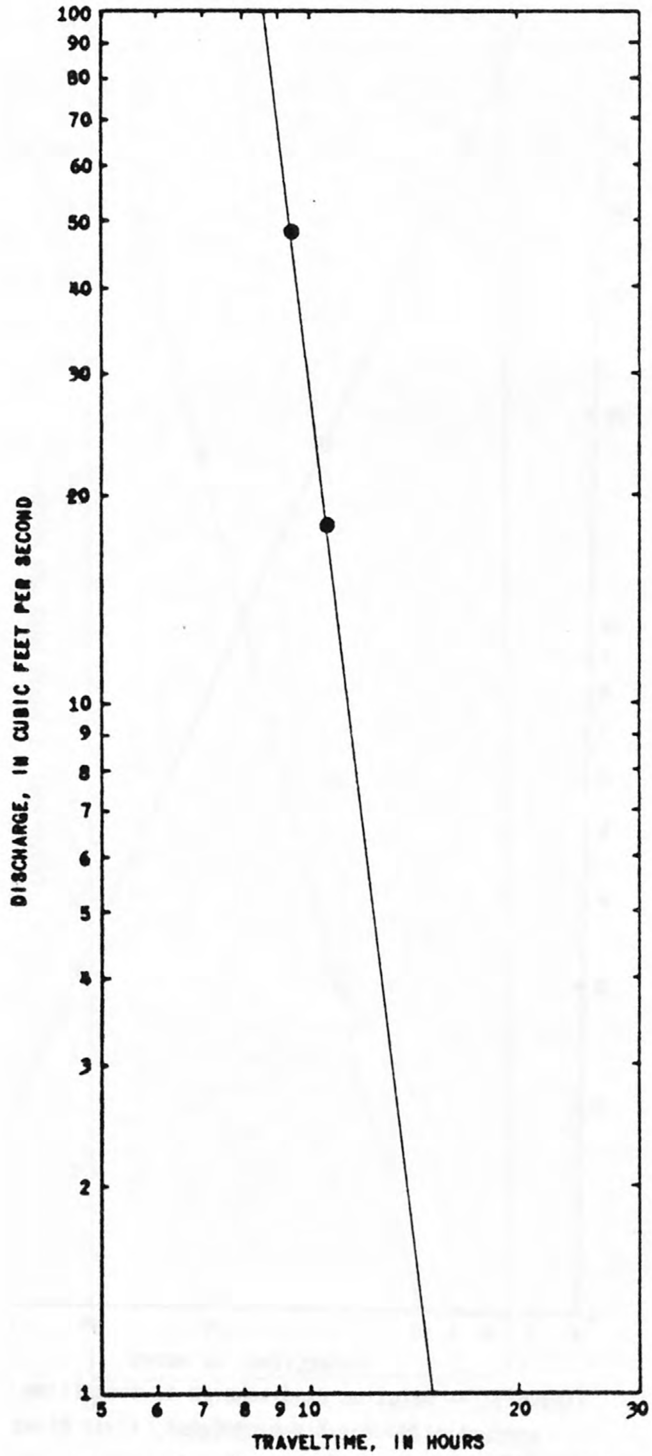

Figure 10.-- Relation of discharge to traveltime of the peak dye concentration for Big Lick Creek, river miles 6.93 to 5.59.

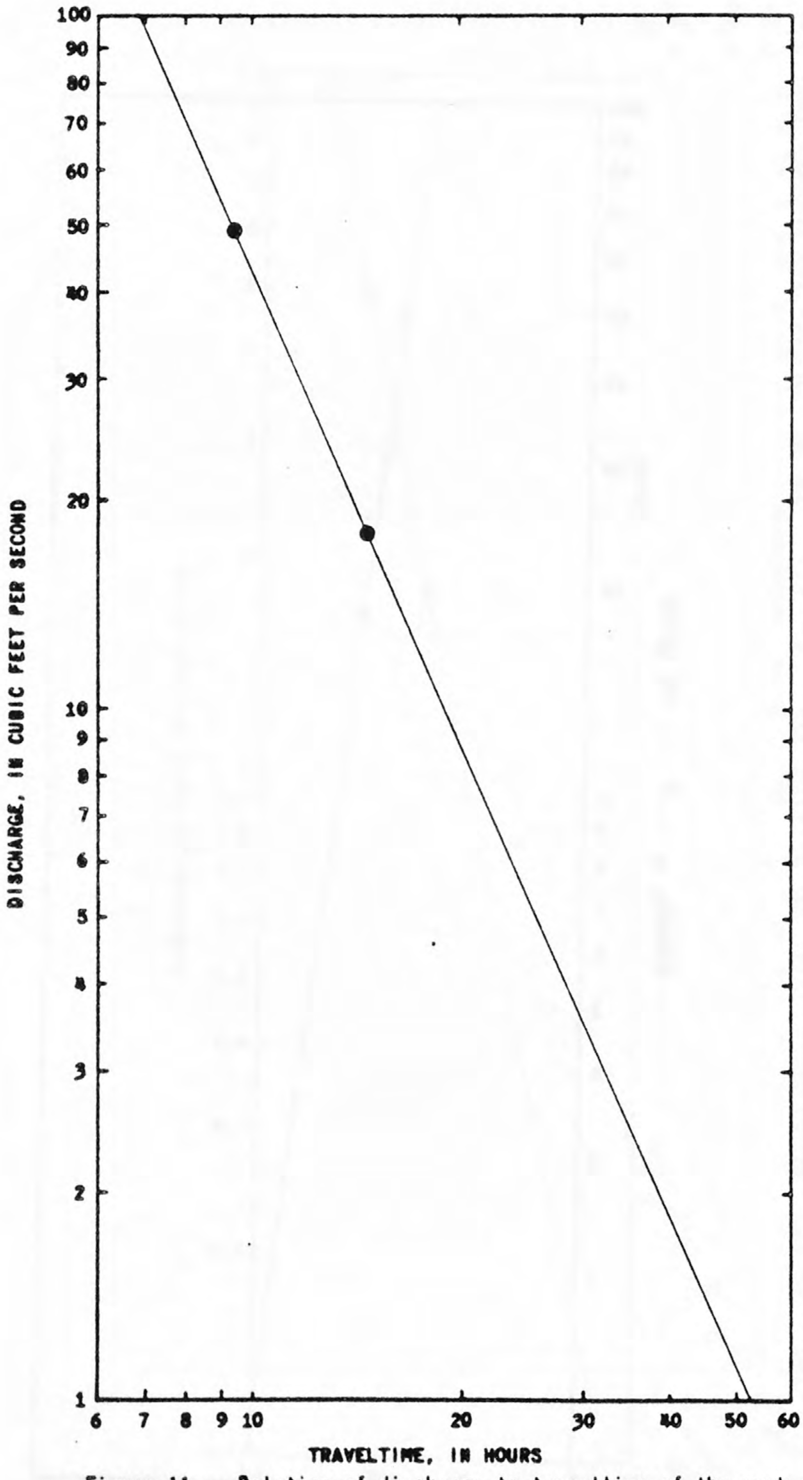

Figure 11.-- Relation of discharge to traveltime of the peak dye concentration for Big Lick Creek, river miles 5.59 to 3.56.

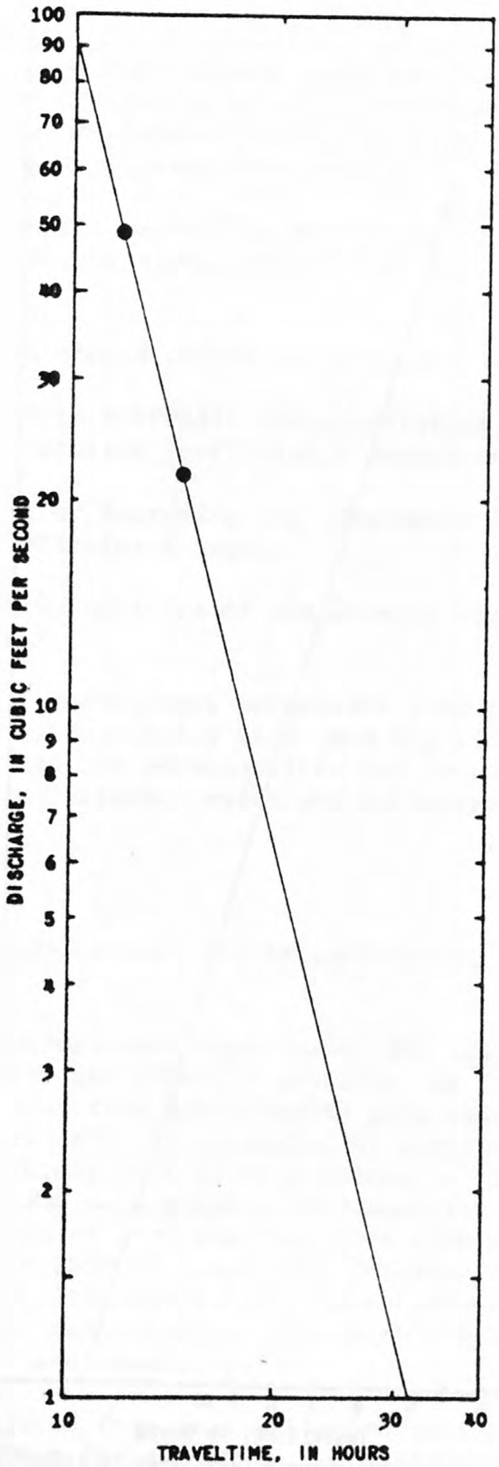

Figure 12.-- Relation of discharge to traveltime of the peak dye concentration for Big Lick Creek, river miles 3.56 to 1.13.

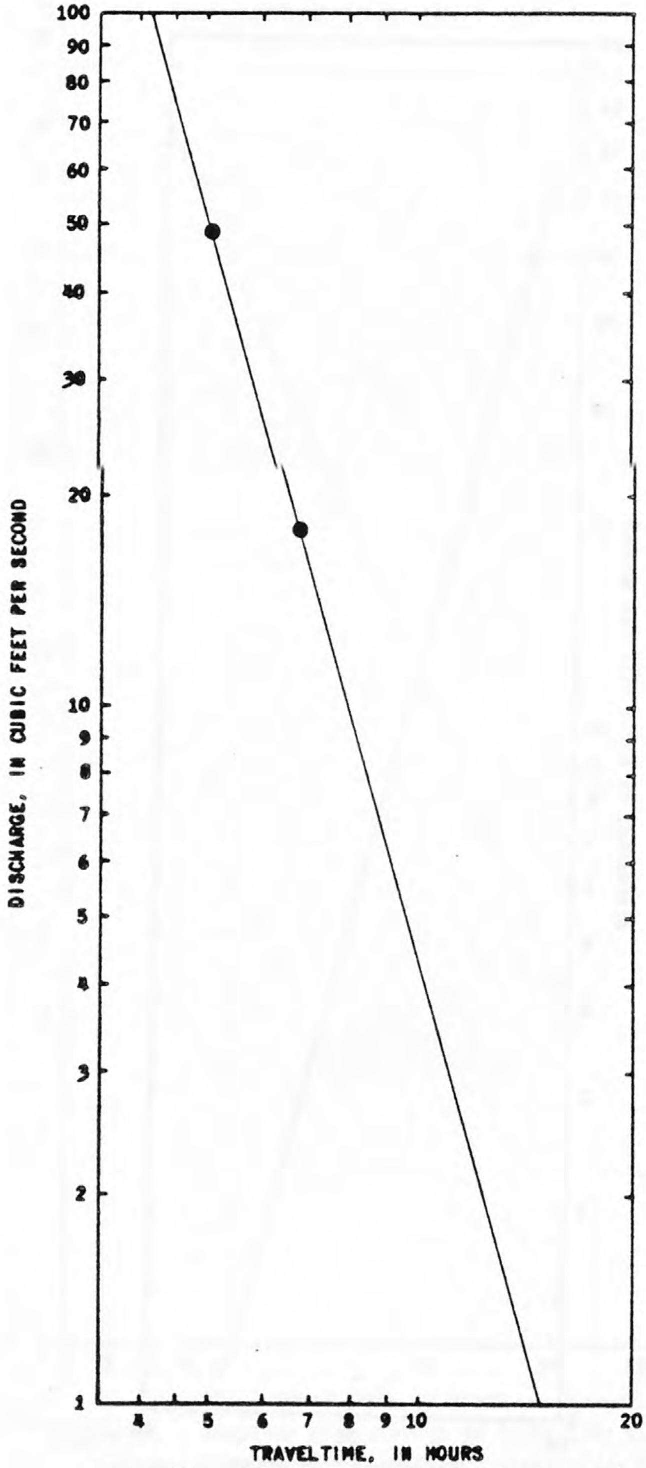

Figure 13.-- Relation of discharge to traveltime of the peak dye concentration for Big Lick Creek, river miles 1.13 to 0.26.

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 modeled stream reaches are presented in table 9.

The three sets of model-input parameters used in the calibration of the dissolved-oxygen model for Little Lick and Big Lick Creeks are presented in tables 10-15. Included are water-quality and hydrologic data representing initial upstream conditions, waste and tributary inputs, and main-stem sites.

Carbonaceous Biochemical-Oxygen Demand

Long-term CBOD measurements were made for samples from two stations in the October 1977 survey and from 13 stations in the September 1978 survey (tables 16-18). No long-term measurements were made on samples collected in August 1977. Ultimate CBOD was estimated by plotting CBOD against time and extending the curve through the plotted points to a maximum value. (See fig. 14.) Five-day CBOD measurements were made for samples from the remaining stations. The authors used the long-term CBOD measurements to calculate the ratios of ultimate CBOD to 5-day CBOD (tables 16-18). These ratios were then used to estimate ultimate CBOD for those samples in which only a 5-day BOD determination had been made. This method gives reliable estimates of ultimate CBOD (Stamer and others, 1979).

The ratios calculated from data collected in September 1978 were used to estimate ultimate CBOD's for the other two surveys. Exceptions were the two samples from the October 1977 survey for which 20-day CBOD was measured.

Table 9.--Physical characteristics for modeled stream reaches, Big Lick Creek basin, Blackford and Delaware Counties, Ind.

[Data compiled by U.S. Geological Survey]

Reach	Starting river mile	Ending river mile	Distance (mi)	Drainage[1] area (mi^2)	Average slope (ft/mi)	Average[2] depth (ft)	Average[2] width (ft)
			Little Lick Creek				
1	1.52	1.44	0.08	-----	2.41	2.1	7.0
2	1.44	1.42	.02	-----	2.41	2.3	9.0
3	1.42	1.37	.05	-----	2.41	1.9	11.0
4	1.37	1.36	.01	-----	2.41	2.6	12.0
5	1.36	1.23	.13	12.54	2.41	1.4	12.0
6	1.23	1.12	.11	-----	2.41	1.6	11.0
7	1.12	.94	.18	12.74	2.41	2.5	9.0
8	.94	.77	.17	12.85	2.41	2.8	8.0
9	.77	.48	.29	13.04	2.41	2.8	8.0
10	.48	.00	.48	13.50	2.41	2.8	8.0
			Big Lick Creek				
[3]1	17.36	17.03	.33	-----	17.0	0.6	3.5
2	17.03	15.97	1.06	7.9	5.0	1.2	4.5
3	15.97	13.93	1.04	-----	3.9	.6	6.5
4	14.93	13.85	1.08	12.5	3.9	.6	9.5
5	13.85	11.59	2.26	23.0	3.6	.9	11.5
6	11.59	9.76	1.83	26.5	3.6	1.0	10.5
7	9.76	8.43	1.33	29.2	4.9	1.7	8.5
8	8.43	6.93	1.50	32.3	4.9	2.0	8.0
9	6.93	6.18	.75	46.5	4.9	1.0	12.0
10	6.18	6.06	.12	-----	3.6	2.5	16.0
11	6.06	5.59	.47	52.3	3.6	2.2	16.0
12	5.59	4.92	.67	54.0	3.7	1.9	16.5
13	4.92	3.56	1.36	59.5	3.7	2.0	17.5
14	3.56	2.77	.79	60.5	4.0	2.3	17.5
15	2.77	.26	2.51	75.0	4.0	2.9	16.5
16	.26	.00	.26	76.3	4.0	3.4	16.0

[1]Given for ending river mile.
[2]Values correspond to a flow of 1.70 ft^3/s at the U.S. Geological Survey gage near Hartford City, Ind.
[3]This reach is actually the initial 0.33 mile of Dunkirk ditch but was modeled as if it were Big Lick Creek.

Table 10.--Model input for Little Lick Creek, Blackford County, Ind., August 3, 1977

[h, hour; all rates corrected to observed stream temperatures; water-quality and discharge data collected by Indiana State Board of Health]

Reach	Upstream boundary of modeled reach (ISBH sta. no. in parens)	River mile	Discharge (ft^3/s)	Linear runoff (ft^3/s)	Time of travel to next site (h)	Ultimate CBOD (mg/L)	NBOD (mg/L)	Benthic oxygen demand [($g/m^2/d$)]	DO (mg/L)	In-stream temp. (°C)	K_r (day^{-1})	K_d (day^{-1})	K_n (day^{-1})	K_a (day^{-1})
1	3M Co. cooling water outfall No. 002 (030-A)	1.52	0.78	0.0	2.88	3.0	0.4	10.0	8.8	22	3.26	0.16	0.12	0.50
2	3M Co. direct discharge outfall No. 101 (030-B2)	1.37	.93	.0	.24	110.0	[1]11.1	10.0	6.3	22	3.26	.16	[2]215.8	.41
3	Little Lick Creek at Spring Street (030-2)	1.36	----	.0	1.28	-----	-----	10.0	---	22	3.26	.16	[2]629.1	1.03
4	Little Lick Creek at railroad bridge (030-3)	1.23	----	.0	1.08	-----	-----	.0	---	22	3.26	.16	.12	.92
5	Hartford City East waste-water-treatment facility (030-C)	1.12	3.22	.0	1.77	[3]22.0	9.1	.0	2.6	22	2.28	.16	.12	.56
6	Little Lick Creek at Jefferson Street (030-4)	.94	----	.0	4.56	-----	-----	.0	---	22	2.28	.16	.12	.56
7	Little Lick Creek at abandoned bridge (030-5)	.48	----	.0	4.80	-----	-----	.0	---	22	2.28	.16	.12	.50

[1]Includes 0.4 mg/L from 3M Co. and 10.7 mg/L estimated from ammonification.
[2]Zero-order nitrification rate, in pounds per day per day.
[3]Taken from Monthly Report of Operations, Indiana State Board of Health.

Table 11.--Model input for Big Lick Creek, Blackford and Delaware Counties, Ind. August 3, 1977

[h, hour; all rates corrected to observed stream temperatures; water-quality and discharge data collected by Indiana State Board of Health]

Reach	Upstream boundary of modeled reach (ISBH sta. no. in parens)	River mile	Dis-charge (ft^3/s)	Linear runoff (ft^3/s)	Time of travel to next site (h)	Ultimate CBOD (mg/L)	NBOD (mg/L)	Benthic oxygen demand $[(g/m^2)/d]$	DO (mg/L)	In-stream temp. (°C)	K_r (day^{-1})	K_d (day^{-1})	K_n (day^{-1})	K_a (day^{-1})
1	Dunkirk waste-water-treat-ment facility (035-A)	17.36	1.44	-0.19	0.96	79.0	77.9	0.0	5.4	23	0.34	0.12	0.13	7.70
2	Big Lick Creek at confluence with Dunkirk ditch	17.03	----	-.60	10.56	----	----	.0	---	23	.34	.13	.13	[1]2.44
3	Big Lick Creek at County Road 700E (034-1)	15.97	----	.0	10.40	----	----	.0	---	23	.34	.12	.13	[1]2.44
4	Big Lick Creek at County Road 600E (034-2)	14.93	----	.0	13.61	----	----	.0	---	23	.34	.12	.13	[1]2.44
5	Big Lick Creek at County Road 500E (033-1)	13.85	----	.50	75.84	----	----	1.30	---	22	.33	.11	.12	1.80
6	Big Lick Creek at Willman Road (033-2)	9.76	----	-.27	40.00	----	----	.35	---	22	.33	.11	.12	1.20
7	Big Lick Creek at State Route 3 (031)	6.93	----	.42	6.48	----	----	2.85	---	22	.33	.11	.12	1.93
8	Big Lick Creek at confluence with Little Lick Creek	6.18	----	.0	.96	----	----	2.85	---	22	.44	.33	.12	.70
9	Hartford City West wastewater-treat-ment facility (028-A)	6.06	.68	-.18	4.08	17.0	.4	2.85	2.6	22	.44	.33	.12	.78
10	Big Lick Creek at County Road 100W (027-1)	5.59	----	-.70	19.90	----	----	.0	---	22	.44	.33	.12	.87
11	Big Lick Creek at County Road 175W (027-2)	3.56	----	1.00	26.16	----	----	1.0	---	22	.44	.33	.12	.74
12	Big Lick Creek at unnamed county road (027-3)	.26	----	2.90	2.06	----	----	.0	---	21	.42	.31	.11	.74

[1]Average for three reaches.

Table 12.--Model input for Little Lick Creek, Blackford County, Ind., October 20, 1977

[h, hour; all rates corrected to observed stream temperatures; water-quality and discharge data collected by Indiana State Board of Health]

Reach	Upstream boundary of modeled reach (ISBH sta. no. in parens)	River mile	Dis-charge (ft^3/s)	Linear runoff (ft^3/s)	Time of travel to next site (h)	Ultimate CBOD (mg/L)	NBOD (mg/L)	Benthic oxygen demand [$(g/m^2)/d$]	DO (mg/L)	In-stream temp. (°C)	K_r (day^{-1})	K_d (day^{-1})	K_n (day^{-1})	K_a (day^{-1})
1	3M Co. lagoon outfall no. 001 (030-B1)	1.42	0.71	0.0	2.39	181.0	103.9	0.0	0.0	11	1.52	0.07	0.05	0.70
2	Little Lick Creek at Spring Street (030-2)	1.36	---	.0	1.05	-----	-----	.0	---	16	1.91	.08	.07	.92
3	Hartford City East wastewater-treatment facility (030-C)	1.12	1.20	.0	1.71	6.0	2.9	10.0	2.9	16	1.75	.11	.06	.56
4	Little Lick Creek at Jefferson Street	.94	----	.0	2.23	-----	-----	.0	---	14	1.75	.11	.06	.50
5	Little Lick Creek at State Route 3 (030-4.5)	.77	----	.0	2.23	-----	-----	.0	---	14	1.75	.11	.06	.50
6	Little Lick Creek at abandoned bridge (030-5)	.48	----	.0	4.66	-----	-----	.0	---	14	1.75	.11	.06	.50

Table 13.--Model input for Big Lick Creek, Blackford and Delaware Counties, Ind., October 20, 1977

[h, hour; all rates corrected to observed stream temperatures; water-quality and discharge data collected by Indiana State Board of Health]

Reach	Upstream boundary of modeled reach (ISBH sta. no. in parens)	River mile	Discharge (ft^3/s)	Linear runoff (ft^3/s)	Time of travel to next site (h)	Ultimate CBOD (mg/L)	NBOD (mg/L)	Benthic oxygen demand [(g/m^2)/d]	DO (mg/L)	Instream temp. (°C)	K_r (day^{-1})	K_d (day^{-1})	K_n (day^{-1})	K_a (day^{-1})
1	Dunkirk wastewater-treatment facility (035-A)	17.36	1.83	-0.20	0.80	169.0	69.3	-0.20	5.4	11	1.05	0.20	0.05	8.20
2	Big Lick Creek at confluence with Dunkirk ditch	17.03	----	-.63	8.83	-----	----	-.63	---	11	1.05	.20	.05	1.65
3	Big Lick Creek at County Road 700E (034-1)	15.97	----	.0	8.67	-----	----	.0	---	12	1.10	.21	.05	3.02
4	Big Lick Creek at County Road 600E (034-2)	14.93	----	.0	12.19	-----	----	2.50	---	13	1.15	.22	.06	2.67
5	Big Lick Creek at County Road 500E (033-1)	13.85	----	1.00	61.12	-----	----	2.50	---	11	.29	.20	.05	1.56
6	Big Lick Creek at Willman Road (033-2)	9.76	----	.0	34.87	-----	----	1.30	---	11	.29	.20	.05	.94
7	Big Lick Creek at State Route 3 (031)	6.93	----	.40	5.90	-----	----	3.4	---	11	.29	.20	.05	2.01
8	Big Lick Creek at confluence with Little Lick Creek	6.18	----	.0	.94	-----	----	3.4	---	11	.29	.20	.05	.72
9	Hartford City West wastewater-treatment facility (028-A)	6.06	.54	-.15	3.70	9.0	10.8	3.4	2.5	12	.29	.21	.05	.81
10	Big Lick Creek at County Road 100W (027-1)	5.58	----	-.49	14.86	-----	----	2.6	---	12	.29	.21	.05	.97
11	Big Lick Creek at County Road 175W (027-2)	3.56	----	1.10	26.65	-----	----	1.0	---	12	.29	.21	.05	.74
12	Big Lick Creek at unnamed county road (027-3)	.26	----	2.90	2.05	-----	----	.0	---	11	.28	.20	.05	.74

Table 14.--Model input for Little Lick Creek, Blackford County, Ind., September 21, 1978

[h, hour; all rates corrected to observed stream temperatures; water-quality and discharge data collected by Indiana State Board of Health]

Reach	Upstream boundary of modeled reach (ISBH sta. no. in parens)	River mile	Discharge (ft^3/s)	Linear runoff (ft^3/s)	Time of travel to next site (h)	Ultimate CBOD (mg/L)	NBOD (mg/L)	Benthic oxygen demand [$(g/m^2)/d$]	DO (mg/L)	In-stream temp. (°C)	K_r (day^{-1})	K_d (day^{-1})	K_n (day^{-1})	K_a (day^{-1})
	[1]Little Lick Creek at State Route 26 (030-1)	1.82	0.21	0.0	----	5.3	2.6	10.00	1.7	22	-----	----	----	----
1	3M Co. cooling water outfall No. 002 (030-A)	1.52	1.24	.0	1.18	1.9	.4	10.00	9.2	22	10.96	0.43	0.12	2.80
2	City sewer bypass (030-2A)	1.44	.68	.0	.30	207.0	108.2	10.00	.0	22	10.96	.43	.12	.50
3	3M Co. lagoon outfall No. 001 (030-B1)	1.42	.00	.0	.74	-----	-----	10.00	---	22	10.96	.43	.12	.50
4	3M Co. direct discharge outfall No. 101 (030-B2)	1.37	1.05	.0	.15	220.0	13.9	10.00	7.1	22	10.96	.43	.12	.60
5	Little Lick Creek at Spring Street (030-2)	1.36	----	-.03	1.02	-----	-----	10.00	---	22	10.96	.43	.12	.40
6	Little Lick Creek at railroad bridge (030-3)	1.23	----	-.02	.86	-----	-----	8.00	---	22	10.96	.43	.12	1.00
7	Hartford City East wastewater-treatment facility (030-C)	1.12	1.22	-.04	1.41	9.4	1.0	2.00	7.0	21	10.96	.46	.11	.90
8	Little Lick Creek at Jefferson Street (030-4)	.94	----	-.03	1.30	-----	-----	.00	---	21	.46	.46	.11	.60
9	Little Lick Creek at State Route 3 (030-4.5)	.77	----	.0	2.21	-----	-----	.0	---	22	.48	.48	.12	.50
10	Little Lick Creek at abandoned bridge (030-5)	.48	----	.0	3.66	-----	-----	.0	---	21	.46	.46	.11	.50

[1]These data used to describe upstream background conditions.

Table 15.--Model input for Big Lick Creek, Blackford and Delaware Counties, Ind., September 21, 1978

[h, hour; all rates corrected to observed stream temperatures; water-quality and discharge data collected by Indiana State Board of Health]

Reach	Upstream boundary of modeled reach (ISBH sta. no. in parens)	River mile	Discharge (ft^3/s)	Linear runoff (ft^3/s)	Time of travel to next site (h)	Ultimate CBOD (mg/L)	NBOD (mg/L)	Benthic oxygen demand [$(g/m^2)/d$]	DO (mg/L)	In-stream temp. (°C)	K_r (day^{-1})	K_d (day^{-1})	K_n (day^{-1})	K_a (day^{-1})
	Dunkirk ditch at at Angle Street (035-1)[1]	17.46	0.09	----	-----	----	----	---	4.5	24	----	----	----	----
1	Dunkirk waste-water-treatment facility (035-A)	17.33	1.40	-0.18	0.80	48.2	39.0	0.0	---	25	0.49	0.05	0.15	8.90
2	Big Lick Creek at confluence with Dunkirk ditch	17.03	----	-.58	8.83	----	----	.0	---	24	.94	.24	.14	1.60
3	Big Lick Creek at County Road 700E (034-1)	15.97	----	-.01	8.67	----	----	.3	---	23	.90	.23	.13	3.00
4	Big Lick Creek at County Road 600E (034-2)	14.93	----	.66	12.19	----	----	.5	---	23	.90	.23	.13	2.70
5	Big Lick Creek at County Road 500E (033-1)	13.85	----	.66	33.77	----	----	.8	---	23	.23	.23	.13	1.50
6	Big Lick Creek at County Road 300E (033-1.5)	11.59	----	.37	27.35	----	----	1.2	---	23	.23	.23	.13	1.40
7	Big Lick Creek at Willman Road (033-2)	9.76	----	-.04	16.39	----	----	.4	---	23	.23	.23	.13	1.00
8	Big Lick Creek at County Road 100E (032)	8.43	----	.46	18.48	----	----	.0	---	23	.24	.24	.14	.90
9	Big Lick Creek at State Route 3 (031)	6.93	----	.0	5.90	----	----	.7	---	24	.24	.24	.14	2.10
10	Big Lick Creek at confluence with Little Lick Creek	6.18	----	-.19	.94	----	----	1.2	---	24	.54	.53	.13	.60
11	Hartford City West wastewater-treatment facility (028-A)	6.06	.55	-.58	3.70	3.7	.4	1.2	4.9	23	.54	.53	.13	.80
12	Big Lick Creek at County Road 100W (027-1)	5.59	----	.34	4.90	----	----	.0	---	23	.54	.53	.13	1.00
13	Big Lick Creek at river mile 4.92 (027-1.5)	4.92	----	.69	9.96	----	----	1.7	---	23	.54	.53	.13	1.00
14	Big Lick Creek at County Road 175W (027-2)	3.56	----	.68	6.24	----	----	1.8	---	22	.52	.43	.12	.80
15	Big Lick Creek at river mile 2.77 (027-2.5)	2.77	----	2.17	19.81	----	----	.0	---	22	.52	.43	.12	.60
16	Big Lick Creek at unnamed county road (027-3)	.26	----	.0	2.05	----	----	.0	---	22	.52	.43	.12	.50

[1]These data used to describe upstream background conditions.

Table 16.--Carbonaceous biochemical-oxygen-demand data for sampling stations on Little Lick and Big Lick Creeks, Blackford and Delaware Counties, Ind., October 20, 1977

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

Location and station: Hartford City East waste-water-treatment facility (030-C)			Location and station: Big Lick Creek at County Road 100W (027-1)		
Day	CBOD (mg/L)	Percent remaining	Day	CBOD (mg/L)	Percent remaining
1	0.6	90	1	1.3	87
3	1.1	82	3	2.5	76
5	2.4	60	5	3.3	68
8	2.7	55	8	4.0	61
10	2.8	53	10	4.3	58
14	4.7	22	14	7.3	29
15	5.1	15	15	7.5	27
17	5.4	10	17	9.5	8
20	5.5	8	20	10.3	0
Ultimate CBOD = 6.0 mg/L K_d (base e) = 0.31 day^{-1}			Ultimate CBOD = 10.3 mg/L K_d (base e) = 0.28 day^{-1}		

Table 17.--Carbonaceous biochemical-oxygen-demand data for sampling stations on Little Lick Creek, Blackford County, Ind., September 21, 1978

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

Location and station: 3M Co. cooling water outfall No. 002 at RM 1.52 (030-A)			Location and station: Sewer bypass at RM 1.44 (030-2A)			Location and station: 3M Co. lagoon discharge, outfall No. 001 at RM 1.42 (030-B1)		
Day	CBOD (mg/L)	Percent remaining	Day	CBOD (mg/L)	Percent remaining	Day	CBOD (mg/L)	Percent remaining
1	0.5	68	1	48.9	76	1	2.9	76
2	.8	56	2	85.8	59	2	5.2	58
3	1.1	42	3	112.5	46	3	5.4	56
4	1.1	42	4	125.4	39	4	5.6	54
5	1.1	42	5	135.4	35	5	5.4	56
6	1.2	37	6	145.4	30	6	6.7	45
8	1.3	32	8	515.1	27	8	7.5	39
9	1.3	32	9	151.6	27	9	7.3	40
10	1.5	21	10	165.8	20	10	9.1	25
12	1.5	21	12	177.4	14	12	10.0	18
13	1.6	16	13	186.1	10	13	10.4	15
15	1.9	0	15	193.1	7	15	11.3	7
16	1.9	--	16	197.1	5	16	10.8	11
18	1.8	--	18	203.4	2	18	12.2	0
20	1.9	--	20	207.0	0	20	12.0	--
Ultimate CBOD = 1.9 mg/L; K_d (base e) = 0.23 day^{-1}			Ultimate CBOD = 207.0 mg/L; K_d (base e) = 0.41 day^{-1}			Ultimate CBOD = 12.2 mg/L; K_d (base e) = 0.32 day^{-1}		

Table 17.--Carbonaceous biochemical-oxygen-demand data for sampling stations on Little Lick Creek, Blackford County, Ind., September 21, 1978--Continued

Location and station: 3M Co. direct discharge outfall No. 101 at RM 1.37 (030-B2)			Location and station: Hartford City East waste-water-treatment facility at RM 1.12 (030-C)			Location and station: Walnut Street, Hartford City at RM 0.77 (030-4.5)		
Day	(mg/L)	remaining	Day	(mg/L)	remaining	Day	(mg/L)	remaining
1	29.2	87	1	0.23	98	1	1.8	86
2	51.7	76	2	1.8	81	2	4.5	66
3	96.3	56	3	3.2	66	3	5.7	57
4	117.8	46	4	3.0	68	4	6.8	49
5	140.3	36	5	3.9	57	5	7.4	44
6	152.3	31	6	4.8	49	6	8.4	36
8	164.1	25	8	6.0	36	8	9.2	30
9	166.1	24	9	6.2	34	9	9.6	27
10	178.5	19	10	7.1	24	10	10.5	20
12	187.9	15	12	7.4	21	12	11.0	17
13	197.0	10	13	7.9	16	13	11.5	13
15	199.7	9	15	8.5	10	15	12.1	8
16	203.0	8	16	8.5	10	16	12.3	7
18	209.1	5	18	9.1	3	18	12.7	4
20	214.4	3	20	9.3	1	20	13.1	1
Ultimate CBOD = 220 mg/L K_d (base e) = 0.37 day^{-1}			Ultimate CBOD = 9.4 mg/L K_d (base e) = 0.46 day^{-1}			Ultimate CBOD = 13.2 mg/L K_d (base e) = 0.44 day^{-1}		

Table 18.--Carbonaceous biochemical-oxygen-demand data for sampling stations on Big Lick Creek, Blackford and Delaware Counties, Ind., September 21, 1978

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

Location and station: Dunkirk wastewater-treatment facility at RM 17.36 (035-A)			Location and station: County Road 700E at RM 15.97 (034-1)			Location and station: County Road 300E at RM 11.59 (033-1.5)		
Day	CBOD (mg/L)	Percent remaining	Day	CBOD (mg/L)	Percent remaining	Day	CBOD (mg/L)	Percent remaining
1	4.5	91	1	3.9	87	1	0.9	89
2	15.4	68	2	9.5	68	2	1.7	79
3	18.0	61	3	12.4	58	3	2.3	72
4	21.9	55	4	14.3	52	4	2.5	69
5	25.6	46	5	15.5	45	5	3.0	63
6	29.5	39	6	18.9	37	6	3.6	56
8	33.2	36	8	20.5	28	8	4.1	50
9	34.5	35	9	20.7	28	9	4.4	46
10	38.8	21	10	23.7	21	10	4.8	41
12	39.2	18	12	25.4	15	12	5.4	34
13	42.8	12	13	26.6	11	13	5.8	29
15	44.2	8	15	27.9	7	15	6.3	23
17	46.0	6	17	29.2	2	16	6.5	21
18	48.2	0	18	29.1	3	18	6.7	18
20	47.6	--	20	30.0	0	20	7.2	12
Ultimate CBOD = 48.2 mg/L K_d (base e) = 0.39 day^{-1}			Ultimate CBOD = 30.0 mg/L K_d (base e) = 0.46 day^{-1}			Ultimate CBOD = 8.2 mg/L K_d (base e) = 0.23 day^{-1}		

Table 18.--Carbonaceous biochemical-oxygen-demand data for sampling stations on Big Lick Creek, Blackford and Delaware Counties, Ind., September 21, 1978--Continued

Location and station: Hartford City West wastewater-treatment facility (028-A)			Location and station: County Road 100W at RM 5.59 (02701)			Location and station: County Road 175W at RM 3.56 (027-2)		
Day	CBOD (mg/L)	Percent remaining	Day	CBOD (mg/L)	Percent remaining	Day	CBOD (mg/L)	Percent remaining
1	0.3	92	1	1.4	83	1	2.6	85
2	1.1	70	2	3.2	62	2	5.2	70
3	1.5	59	3	3.7	56	3	7.2	58
4	1.6	57	4	4.3	49	4	8.5	51
5	1.5	59	5	5.0	40	5	9.3	46
6	2.0	46	6	5.5	35	6	10.5	39
8	2.3	38	8	6.4	24	8	11.1	36
9	2.2	41	9	6.7	20	9	11.4	34
10	2.5	32	10	6.9	18	10	13.5	22
12	2.8	24	12	7.3	13	12	14.2	18
13	2.9	22	13	7.6	10	13	14.5	16
15	3.4	8	15	8.0	5	15	15.2	12
16	3.4	8	16	8.0	5	16	15.8	9
18	3.7	0	18	8.1	4	18	16.6	4
20	3.6	--	20	8.3	1	20	17.0	2
Ultimate CBOD = 3.7 mg/L K_d (base e) = 0.34 day^{-1}			Ultimate CBOD = 8.4 mg/L K_d (base e) = 0.46 day^{-1}			Ultimate CBOD = 17.3 mg/L K_d (base e) = 0.39 day^{-1}		

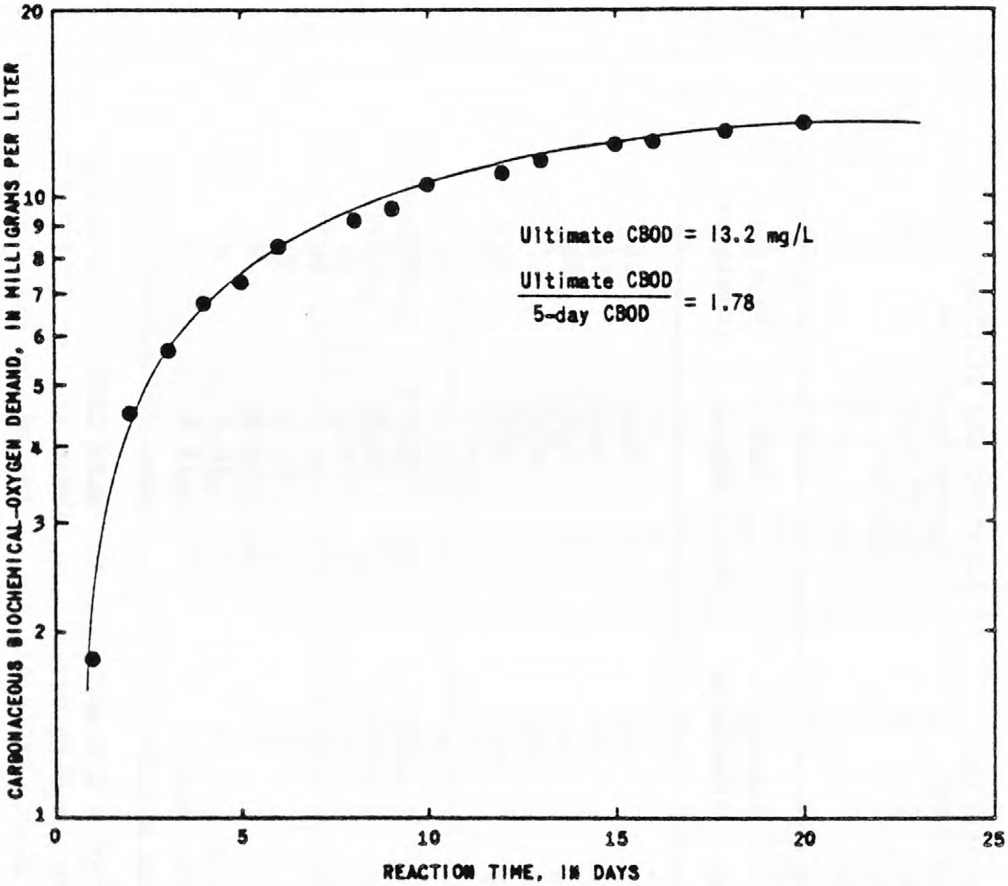

Figure 14.-- Relation of carbonaceous biochemical-oxygen demand to time at river mile 0.77, Little Lick Creek, September 21, 1978.

When used in the model, the 5-day BOD value, 48 mg/L (ultimate CBOD = 117.3 mg/L), measured at the Hartford City East wastewater-treatment facility (table 3), produced an unrealistically high in-stream CBOD load. The 48 mg/L might have been due to unrepresentative sampling and contamination. The value did not conform to observed in-stream conditions or to values measured from the same outfall at other times. Therefore, a more representative 5-day BOD value, 9.0 mg/L (ultimate CBOD = 22.0 mg/L), determined from Indiana State Board of Health's Monthly Report of Operations data was used in the calibration model.

The deoxygenation rate for CBOD, K_d, was estimated from 20-day CBOD data by a least-squares method attributed to Reed and Theriault (1931) and described in Metcalf and Eddy, Inc. (1972, p. 246). The percentage of CBOD remaining and time were the dependent and independent variables, respectively. Calculated values for K_d are listed in tables 16-18.

Values of K_d for Little Lick Creek could not be calculated from data collected in August and October 1977 because no long-term CBOD measurements were made of samples collected at these times. Water samples collected during the September 1978 survey produced high K_d values (0.23-0.46 day^{-1}) because of the raw sewage discharged at that time. These high values were not considered reasonable for the other two surveys. Therefore, average K_d values of 0.10 to 0.15 day^{-1} were used for the models calibrated with August and October 1977 data. These values compare favorably with K_d values calculated by the authors for other small streams in Indiana.

The stream decay rate for CBOD, K_r, was calculated at 20°C on the basis of CBOD load by the equation:

$$K_r = \ln \left[\frac{Cd}{C\mu}\right] t^{-1} \tag{10}$$

where

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

C_d and C_μ 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 for Little Lick ranged from 2.3 day^{-1} (October 1977 survey) to 10.0 day^{-1} (September 1978 survey) and for Big Lick Creek, ranged from 0.3 day^{-1} (October 1977 survey) to 0.8 day^{-1} (September 1978 survey). These values, especially those for Little Lick Creek, are high and suggest that most CBOD was removed by processes other than oxidation; for example sedimentation, volatilization, biological extraction, and adsorption (Wright and McDonnell, 1979). No data were available to isolate these processes, though sedimentation was probably the dominant removal mechanism. (See "Benthic-Oxygen Demand.")

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

$$(K)_T \quad \text{Carbonaceous} = (K)_{20°C}(1.047^{T-20°C}) \tag{11}$$

where

T is the stream temperature, in degrees Celsius,

$(K)_T$ the base-e reaction constant at temperature T, in day^{-1},

$K_{20°C}$ the base-e reaction constant at 20° Celsius,

and 1.047 a constant applicable over a typical field-temperature range (Shindala, 1972).

Nitrogenous Biochemical-Oxygen Demand

Because of the complex nature of nitrification and its application to Little Lick and Big Lick Creeks, 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 more precise 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

$$NH_4^+ + {}^3/_2\, O_2 = NO_2^- + 2H^+ + H_2O + \text{energy} \tag{12}$$

Nitrite oxidation

$$NO_2^- + {}^1/_2\, O_2 = NO_3^- + \text{energy} \tag{13}$$

The amount 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 ranges from 43 to 130 mg of oxygen per liter of effluent.

The nitrification process in streams is difficult to model. One of the reasons for this is that the rate of change of nitrogen compounds is dependent not only on nitrification but also on other processes that are involved 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 ammonia-nitrogen concentration may increase in the stream owing to the hydrolysis of organic nitrogen or the reduction of nitrate nitrogen or may decrease owing to aquatic plant consumption or conversion to organic nitrogen for cell synthesis by heterotrophic bacteria. Factors other than nitrification affecting nitrate-nitrogen concentration in a stream include denitrification, respiratory reduction, and assimilatory reduction. Consequently, a mass-balance for nitrogen species is not always achieved.

The factors that should be evaluated in determining the significance of nitrification in an aquatic environment are habitat suitability, nitrogen flux, and nitrifier populations. In streams with long travel times, nitrifier populations are known to become established on particulate matter suspended in the water column (Lees, 1955). However, according to Tuffey and others (1974) and Finstein and others (1978), nitrification in shallow, surface-active streams is due to bacteria populations attached to bottom material. Other factors that provide a favorable environment for nitrification are sufficient dissolved oxygen and ammonia, water temperatures greater than 20°C, and near neutral or slightly alkaline pH.

Both Little Lick and Big Lick Creeks are shallow and have average depths of about 2 ft. If present, bacterial populations would likely be attached to bottom material. However, these streams cannot be considered surface active because both have slopes of less than 5 ft/mi and velocities of less than 0.2 ft/s.

In this study, first-order kinetics was generally used to calculate nitrification rates. Nitrate-load increase is often a more reliable index to nitrification rates than ammonia-load decrease, especially for stream reaches where ground-water accrual is minimal (Lopez-Bernal, and others, 1978). Thus, the deoxygenation rate for NBOD, K_n, was calculated by the equation:

$$K_n = \frac{1}{t} \ln \left[\frac{C_{NH_3,U}}{C_{NH_3,U} + C_{NO_3,D} - C_{NO_3,U}}\right] \tag{14}$$

where

C_{NH_3} and C_{NO_3} are the loads of ammonia and nitrate nitrogen, respectively, in pounds per day,

U and D the subscripts indicating upstream and downstream locations, respectively,

ln the natural logarithm, base e,

and

t the traveltime between the sites, in days.

Equation (12) was used to calculate values for K_n for all modeled reaches of Little Lick and Big Lick Creeks. Values at 20°C ranged from zero to 0.35 day^{-1} and averaged 0.12 day^{-1}. This average is the minimum "normal" value for K_n reported by Thomann (1972, p. 97). These low rates of nitrification are probably due to the low dissolved-oxygen concentrations of both streams during the three surveys (table 19). These low oxygen concentrations are less than the threshold concentrations that inhibit the nitrification process (Knowles, Downing, and Barrett, 1965). Thus, a minimum K_n value of 0.10 day^{-1} at 20°C, reported by Thomann (1972), was used in most reaches of both streams for all three model calibrations.

Table 19.--Averages of the mean daily in-stream dissolved-oxygen concentrations for Little Lick and Big Lick Creeks, Blackford and Delaware Counties, Ind.

[DO measured by Indiana State Board of Health]

Stream	August 3, 1977		October 20, 1977		September 21, 1978	
	Number of stations	Average DO (mg/L)	Number of stations	Average DO (mg/L)	Number of stations	Average DO (mg/L)
Little Lick Creek	4	2.27	4	<1.00	6	1.18
Big Lick Creek	8	3.11	8	3.20	13	2.32

Water-quality data collected in August 1977 indicated that zero-order kinetics describe nitrification for two stream reaches on Little Lick Creek better than first-order kinetics. (See "Model Calibration Results.") For these two reaches, the nitrogenous deoxygenation rate, $K_{n,zero}$, was calculated by the equation:

$$K_{n,\ zero} = \frac{C_u - C_d}{t} \qquad (15)$$

where

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

and

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

Values for $K_{n,zero}$ of 182.0 and 529.0 (lb/d)/d (at 20°C) were calculated for the two reaches immediately downstream from RM 1.37.

All nitrogenous decay rates were adjusted for temperature by the following equation:

$$(K)_T \text{ nitrogenous} = K_{20°C}(1.09^{T-20°C}) \tag{16}$$

where

T is the stream temperature, in degrees Celsius,

$(K)_T$ the base-e first-order decay rate or zero-order decay rate at T,

$K_{20°C}$ the base-e reaction constant at 20° Celsius,

and

1.09 a constant applicable over a typical field-temperature range (Shindala, 1972).

Benthic-Oxygen Demand

In many large rivers, benthic-oxygen demand can be omitted as a significant oxygen demand. However, in shallow rivers and streams, benthic-oxygen demand can be one of the most important factors affecting the dissolved-oxygen dynamics. For example, a benthic-oxygen demand of 4 $(g/m^2)/d$ (grams per square meter per day), in a river 10 ft deep uses 1.3 (mg/L)/d dissolved oxygen. The same benthic-oxygen demand in a shallow stream 1 ft deep uses 13.1 (mg/L)/d dissolved oxygen.

Benthic-oxygen demand is dependent on the rate of deposition and the oxygen demand of the deposits. The accumulation of CBOD on the stream bottom is related to the period of stable hydrologic conditions, which aids settling. A velocity of 0.6 ft/s is generally assumed to be the critical settling velocity for organic solids (Velz, 1970, p. 162). The oxygen demand of the deposit is a function of the amount of accumulation and the rate of consumption. For short periods of time after scouring, sufficient to remove previous deposits, the level of accumulation is low.

If the rate of settling is greater than the rate of consumption, CBOD will accumulate on the stream bottom. Probably only the upper 1 to 2 in. 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), and, thus, can be removed from the water without exerting an oxygen demand until it is resuspended during a scour.

There are several indications that benthic-oxygen demand was an important factor in both Little Lick and Big Lick Creeks during the three water-quality surveys. First, stream velocities were well below the critical settling velocity of 0.6 ft/s suggested by Velz (1970, p. 162). Gage records indicated a minimum of 5 days of benthic accumulation before each of the three surveys. For the August 1977 survey, the period of accumulation was estimated to be more than 30 days. Second, rates of in-stream CBOD decay, K_r, were generally greater than rates of CBOD oxidation, K_d (tables 10-15). Thus, significant amounts of CBOD were being removed by processes other than microbial oxidation. Most of this nonoxidation removal was probably due to settling. Third, visual inspections of the stream bottom during the three water-quality surveys and during the two time-of-travel studies revealed benthic deposits in nearly all reaches of both Little Lick and Big Lick Creeks. In several pooled areas, the depth of these deposits exceeded 1 ft.

Benthic-oxygen demand was not measured during the water-quality surveys, but it was calculated by a method suggested by Phelps (1944, p. 125). The method estimates the amount of CBOD accumulation on the stream bottom as follows:

$$L_d = \frac{R}{K^1}(1 - e^{-K^1 t}) \tag{17}$$

where

L_d is the accumulated deposit of CBOD, in pounds,

R the daily deposit of CBOD, 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.

R, the rate of deposition for a reach is calculated by the equation:

$$R = L_i(e^{-K^1 t} - e^{-K_r t}) \tag{18}$$

where

L_i is the initial CBOD load, in pounds per day.

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

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

where

D is the benthic-oxygen demand, in pounds per day.

D is customarily reported in grams per square meter per day $[(g/m^2)/d]$. To convert D to this unit the following conversion is used:

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

where

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

and

A the bottom-surface area, in square meters.

The reaction-rate coefficient for benthic-oxygen demand, K^1, is approximately equivalent to the deoxygenation rate for CBOD, K_d, for fresh benthic deposits; for example, those created from untreated wastewater. For aged deposits, the reaction-rate coefficient is somewhat less. Values of K^1 reported by Velz (1970, p. 167) and converted to base e ranged from 0.02 to 0.12 day^{-1} at 25°C.

Phelps' method of calculating benthic-oxygen demand for Little Lick and Big Lick Creeks produced unrealistic results. Oxygen demand, which ranged from 0 to 715 $(g/m^2)/d$, was generally too high for use in the calibration models.

The over estimation is due to two principal sources of error. First, the method assumes that the entire thickness of the bottom sediment is equally available for oxidation. However, laboratory data indicate that the benthic-oxygen demand is independent of the thickness of the deposit (Edwards and Rolley, 1965; McDonnell and Hall, 1969). Second, the method assumes that all the nonoxidized CBOD settles to the bottom. Other potentially important means of removing CBOD are volatilization, biological extraction, and adsorption (Gannon, 1966; Streeter, 1930; Thomas, 1948).

The accuracy of the Phelps calculation is also limited because nonmicrobial sources of benthic-oxygen demand are ignored. These sources include the end products of aerobic and anaerobic decomposition, resuspension, and macro-invertebrate respiration (Baity, 1938; Fair and others, 1941; Edwards and Rolley, 1965; and McDonnell and Hall, 1969). 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 dependent on dissolved-oxygen concentration of the overlying water when the concentration is above 1.5 mg/L (Baity, 1938; Hanes and Irvine, 1968).

Estimates of benthic oxygen uptake by various sediment materials are given in table 20. The wide variation in these values represent the influence of differing environmental conditions; for example, the nature and magnitude of invertebrate populations, dissolved-oxygen concentration, and sediment depths.

Oxygen deficit unattributable to other oxygen sinks (CBOD and NBOD) was assumed to be caused by benthic-oxygen demand. This residual oxygen demand ranged from 0.0 to 10.0 $(g/m^2)/d$ at 20°C (tables 10-15), which is within the reported ranges for benthic-oxygen demand (table 20).

Table 20.--Benthic-oxygen uptake by various sediment materials

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 the physical absorption of oxygen from the atmosphere. It is generally the single most important parameter used in describing a stream's ability to assimilate biodegradable material.

The literature is replete with equations using a variety of independent variables to predict atmospheric reaeration. A description and evaluation for many of these equations can be found in Bennett and Rathbun (1972) and Rathbun (1977).

During the summer of 1978, the Indiana State Board of Health made direct measurements of atmospheric reaeration rates, K_a, at two reaches on Big Lick Creek and one reach on Little Lick Creek. K_a was measured with a modified tracer technique that uses ethylene and propane gases suggested by Rathbun and others (1975). The data and pertinent hydrologic characteristics of the stream reaches are presented in table 21.

Table 21.--Reach characteristics and measured reaeration rates for Little Lick and Big Lick Creeks, Blackford and Delaware Counties, Ind.

[h, hour; data collected by Indiana State Board of Health]

Reach	Distance (mi)	Average slope[1] (ft/mi)	Average depth[1] (ft)	Travel-time (h)	Average discharge[1] (ft^3/s)	Measured K_a (day^{-1}, at 20°C)	
						Ethylene	Propane
Little Lick Creek RM 0.77 to RM 0.25	0.29	2.41	0.70	2.13	3.36	3.48	4.56
Big Lick Creek RM 14.10 to RM 13.85	.25	3.80	.50	3.75	1.45	2.83	1.39
Big Lick Creek RM 3.56 to RM 2.77	.79	3.70	1.07	5.92	7.20	3.80	3.45

[1]Average calculated from upstream and downstream measurements.

Values of K_a were calculated with seven diversified reaeration equations for the stream conditions during the measurement surveys (table 22). The calculated values were compared to the average observed values by the standard error of estimate. This statistic is defined by the equation (Rathbun, 1977):

$$\text{Standard error} = \left[\frac{\sum_{i=1}^{N} (K_c - K_o)^2}{N}\right]^{\frac{1}{2}} \tag{21}$$

where

N is the number of sample values,

K_c the calculated value of K_a,

and

K_o the observed value of K_a.

The equation of Parkhurst and Pomeroy (1972) produced a standard error of only 1.12, the lowest value among the seven equations that were tested (table 22). This equation was the only one to predict reaeration rate in terms of water-surface slope, stream velocity, and stream depth. It was used to estimate reaeration throughout this study.

Reaeration coefficients were adjusted for temperature by the following equation:

$$(K)_T \text{ reaeration} = (K)_{20°C}(1.021^{T-20°C}), \tag{22}$$

where

T is the stream temperature, in degrees Celsius,

$(K)_T$ the base-e reaction constant at temperature T, in day^{-1},

$(K)_{20°C}$ the base-e reaction constant at 20° Celsius, in day^{-1},

and

1.021 a constant applicable over a typical field-temperature range (Shindala, 1972).

Table 22.--Average observed and calculated values of reaeration rates and standard error of estimate for Little Lick and Big Lick Creeks, Blackford and Delaware Counties, Ind.

Reach	1	2	3	4	5	6	7	8
Little Lick Creek RM 0.77 to RM 0.25	4.02	16.80	11.80	6.70	16.4	13.4	3.09	2.36
Big Lick Creek RM 14.10 to RM 13.85	2.11	15.10	4.00	1.90	11.6	8.00	2.70	.86
Big Lick Creek RM 3.56 to RM 2.78	3.20	6.80	2.20	1.40	5.20	3.10	1.60	1.31
Standard error	---	10.72	4.66	1.87	9.08	6.39	1.12	3.56

1. Average of observed K_a values for ethylene and propane.
2. $K_a = 117.36 U^{-412} (S/5280)^{0.273}$ (Bennett and Rathbun, 1972)
3. $K_a = 11.61\, U^{0.969}/D^{1.673}$ (Churchill and others, 1962)
4. $K_a = 7.62\, U/D^{1.33}$ (Langbein and Durum, 1967)
5. $K_a = 86{,}400\, (D_m, U)^{0.5}/CD^{1.5}$ (O'Connor and Dobbins, 1958)
6. $K_a = 21.71\, U^{0.67}/D^{1.85}$ (Owens and others, 1964)
7. $K_a = 54.48\, [1 + 0.17(U/(gD)^{0.5})^{2}]$ (Parkhurst and Pomeroy, 1972)
8. $K_a = 0.11\, SU$ (Tsivoglou and Neal, 1976)

where

K_a is the reaeration rate, at 20°C, in reciprocal days,
U the stream velocity, in feet per second,
D the depth, in feet,
S the slope, in feet per mile,
g the acceleration due to gravity, in feet per second-squared,

and

D_m the molecular diffusion coefficient, in feet-squared per second.

Photosynthesis

Net photosynthesis played a small role in the dissolved-oxygen budgets of Little Lick and Big Lick Creeks. For the August and October 1977 surveys, dissolved-oxygen concentration was measured at all stream sites every 3 to 4 hours. Dissolved-oxygen concentration during the two surveys fluctuated an average of only 1.3 and 2.3 mg/L for Little Lick and Big Lick Creeks, respectively.

Primary productivity was calculated from diel-oxygen fluctuations as suggested by Odum (1956). Calculations were made with a computer program developed by Stephens and Jennings (1976). The low diel DO fluctuations and reaeration rates for both creeks produced net photosynthesis values of less than 0.3 $(g/m^2)/d$. These values were considered negligible compared to other factors and were not included in the model.

Linear Runoff

The computer model has the capability of adjusting flows linearly along a stream reach. Presumably, such changes in flow are due to seepage, either into or out of the surface flow resulting from interaction with ground water. The method of calculating linear runoff flows is described in the section entitled "Data Collection".

The water quality of seepage into the streams was estimated from instream data collected upstream from discharge outfalls. Water-quality data collected from Little Lick Creek at RM 1.82 during the October 1977 survey were used in the October 1977 model calibrations. The data included ultimate CBOD, 0.9 mg/L; NBOD, 1.3 mg/L; and dissolved oxygen, 2.5 mg/L. These same data were also used in the August 1977 model calibration because suitable background data were not collected during the August 1977 survey. Water-quality data collected from Little Lick Creek at RM 3.22 during the September 1978 survey were used in the September 1978 model calibration. The data included ultimate CBOD, 3.7 mg/L; NBOD, 2.2 mg/L; and dissolved oxygen, 2.5 mg/L.

Model-Calibration Results

Results of the calibration of the three sets of water-quality data are presented in figures 15-38. These figures include the calculated and observed concentrations of CBOD, NBOD, and dissolved oxygen, and observed flows.

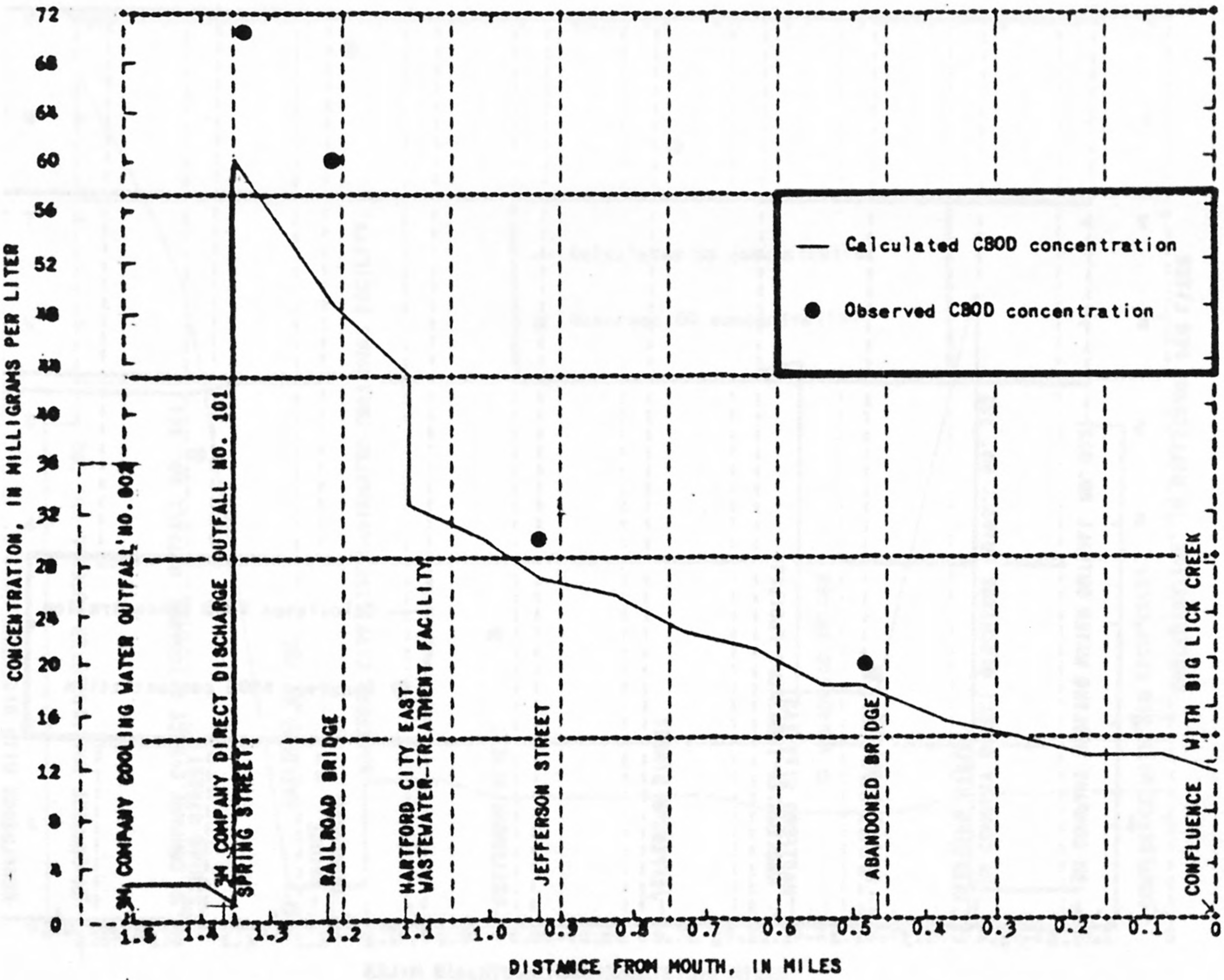

Figure 15.-- Calculated and observed carbonaceous biochemical-oxygen-demand concentrations in Little Lick Creek, August 3, 1977.

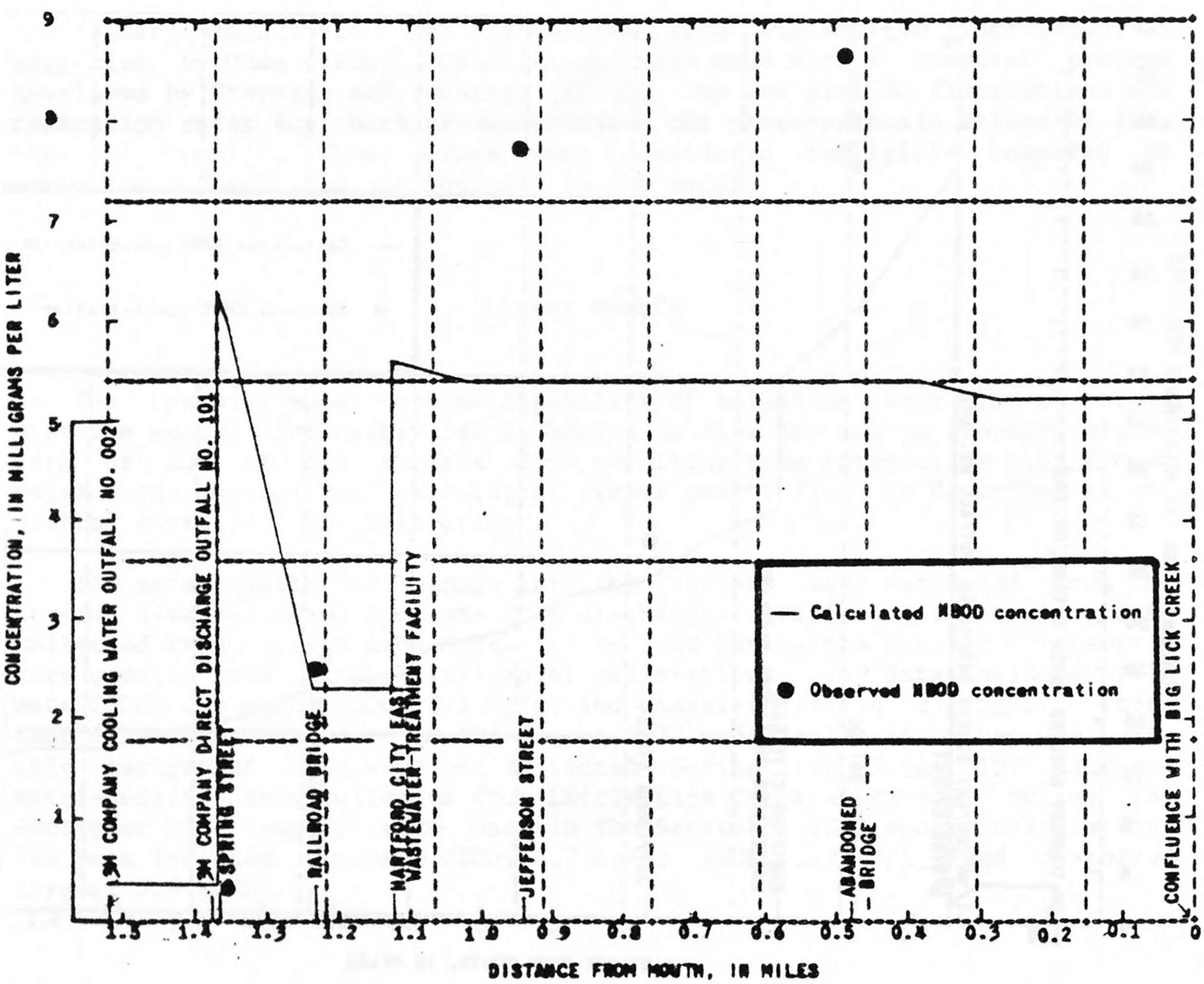

Figure 18.-- Calculated and observed nitrogenous biochemical-oxygen-demand concentrations in Little Lick Creek, August 3, 1977.

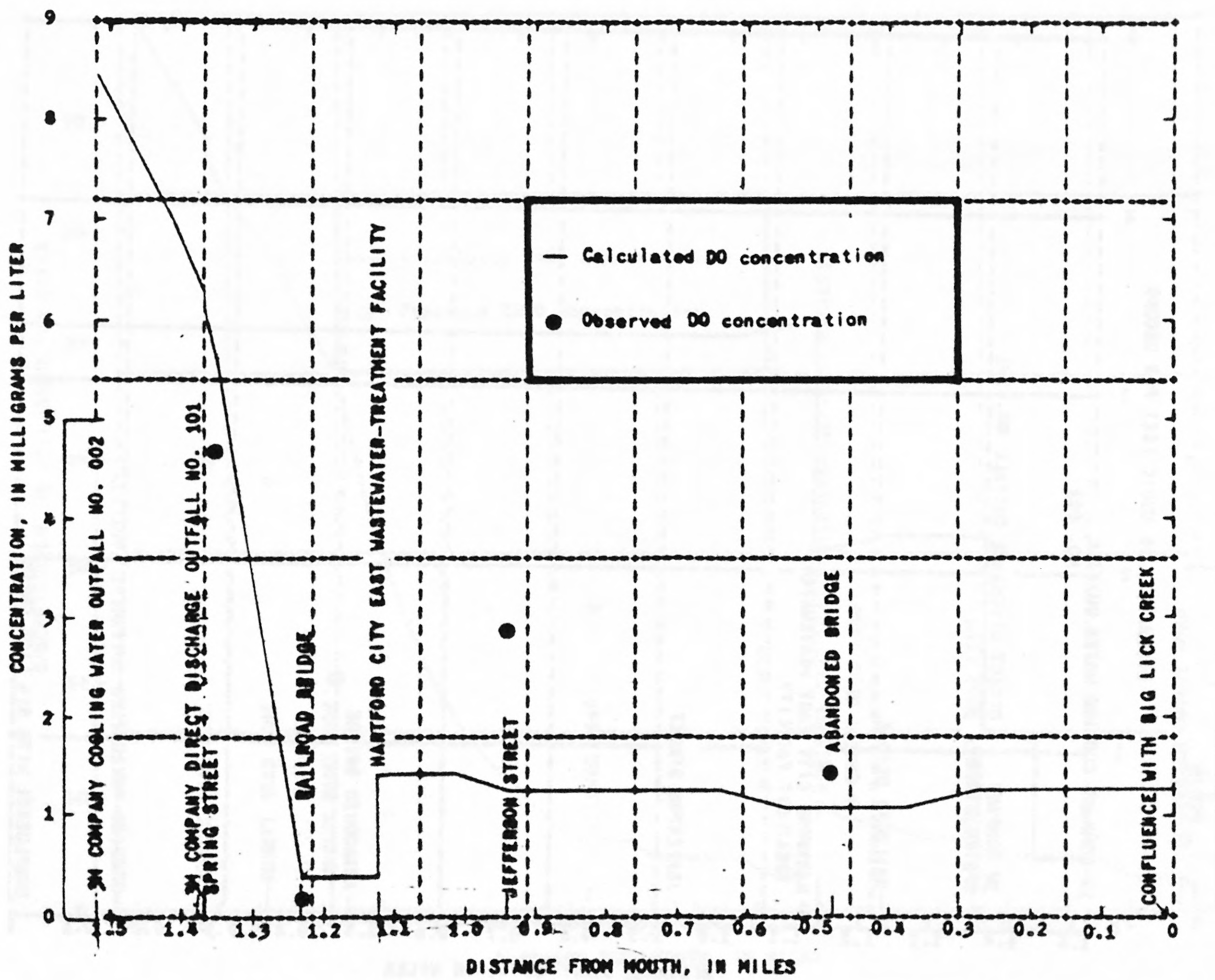

Figure 17.— Calculated and observed dissolved-oxygen-concentrations in Little Lick Creek, August 3, 1977.

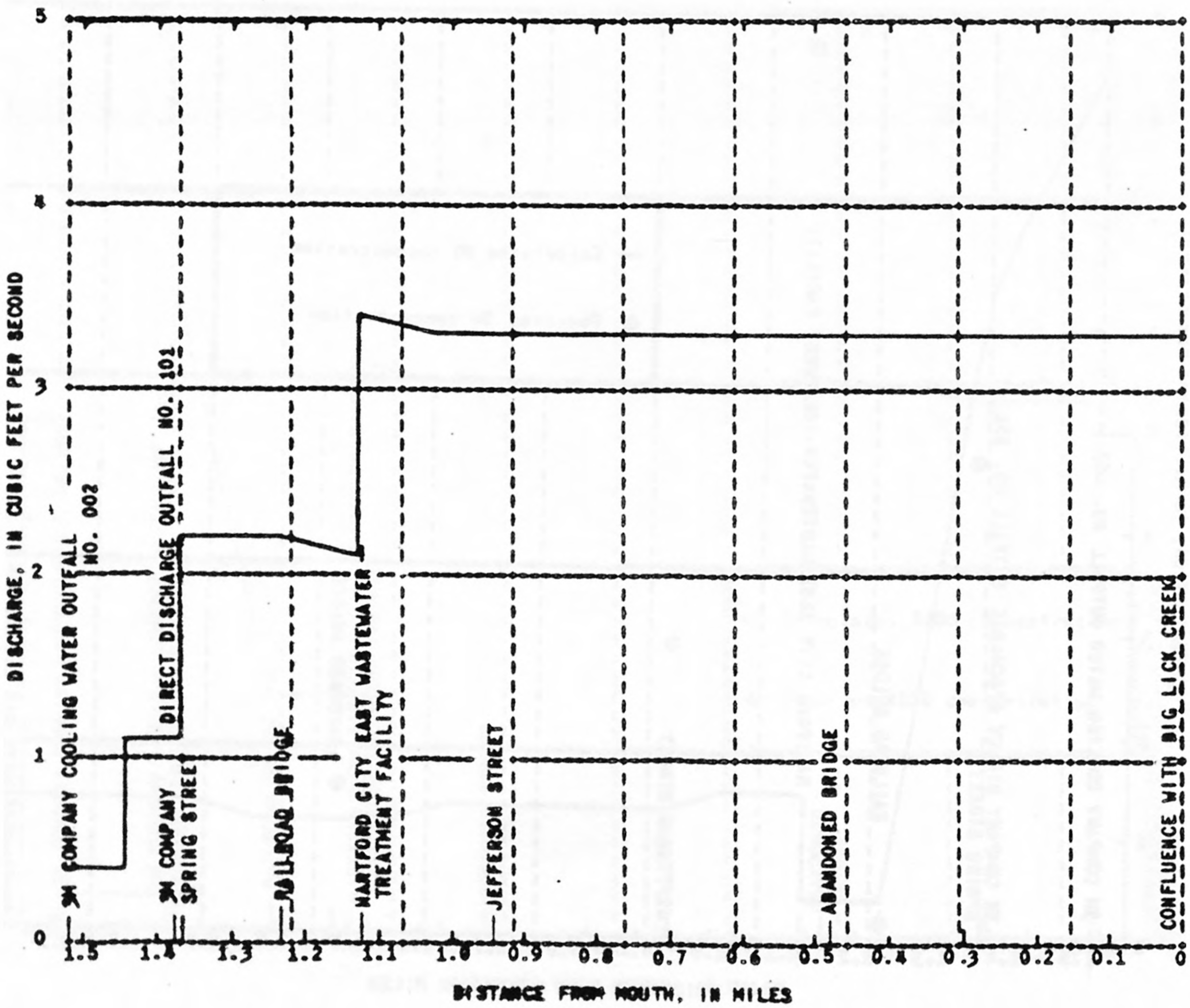

Figure 18.— Discharge in Little Lick Creek, August 3, 1977.

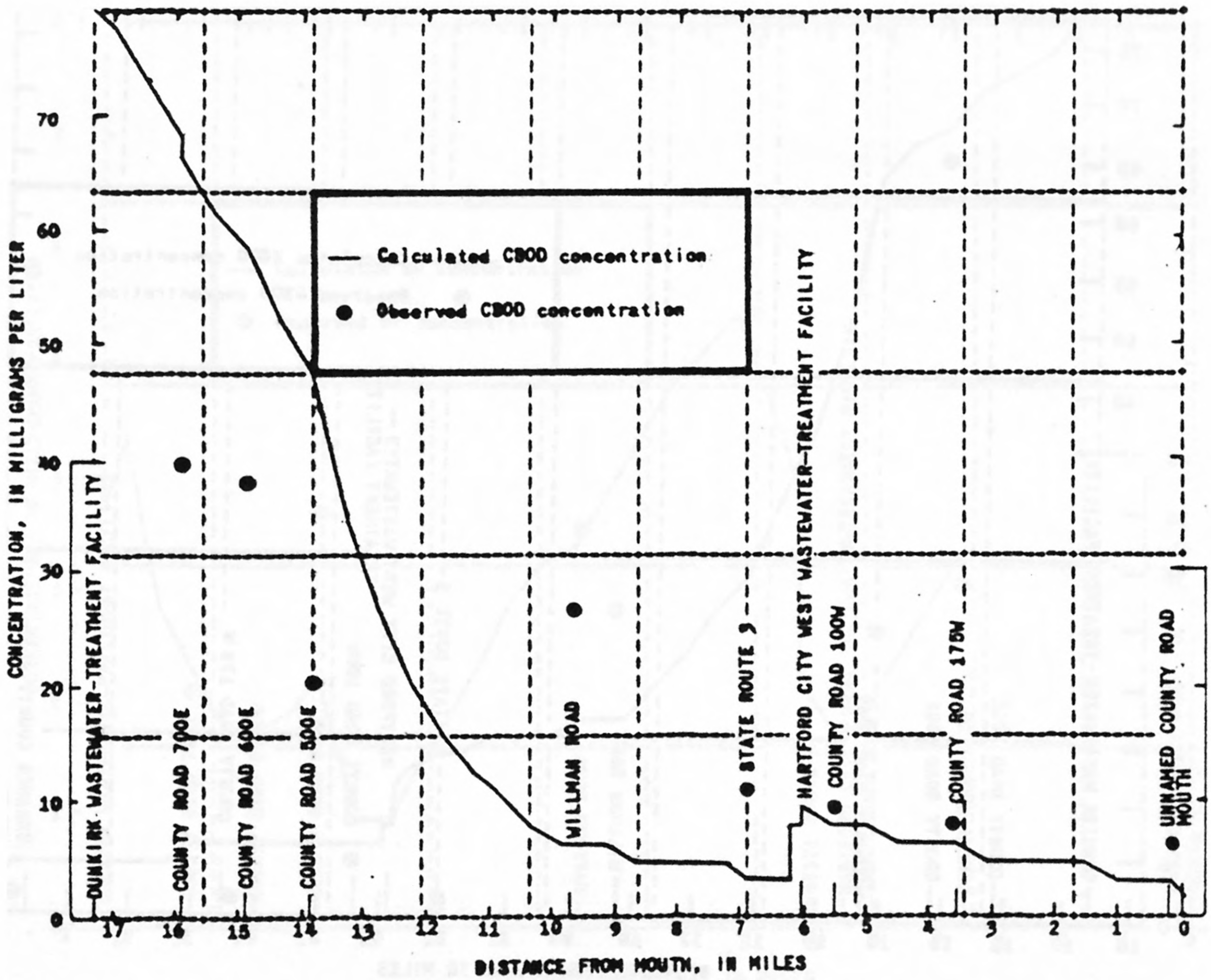

Figure 19.— Calculated and observed carbonaceous biochemical-oxygen-demand concentrations in Big Lick Creek, August 3, 1977.

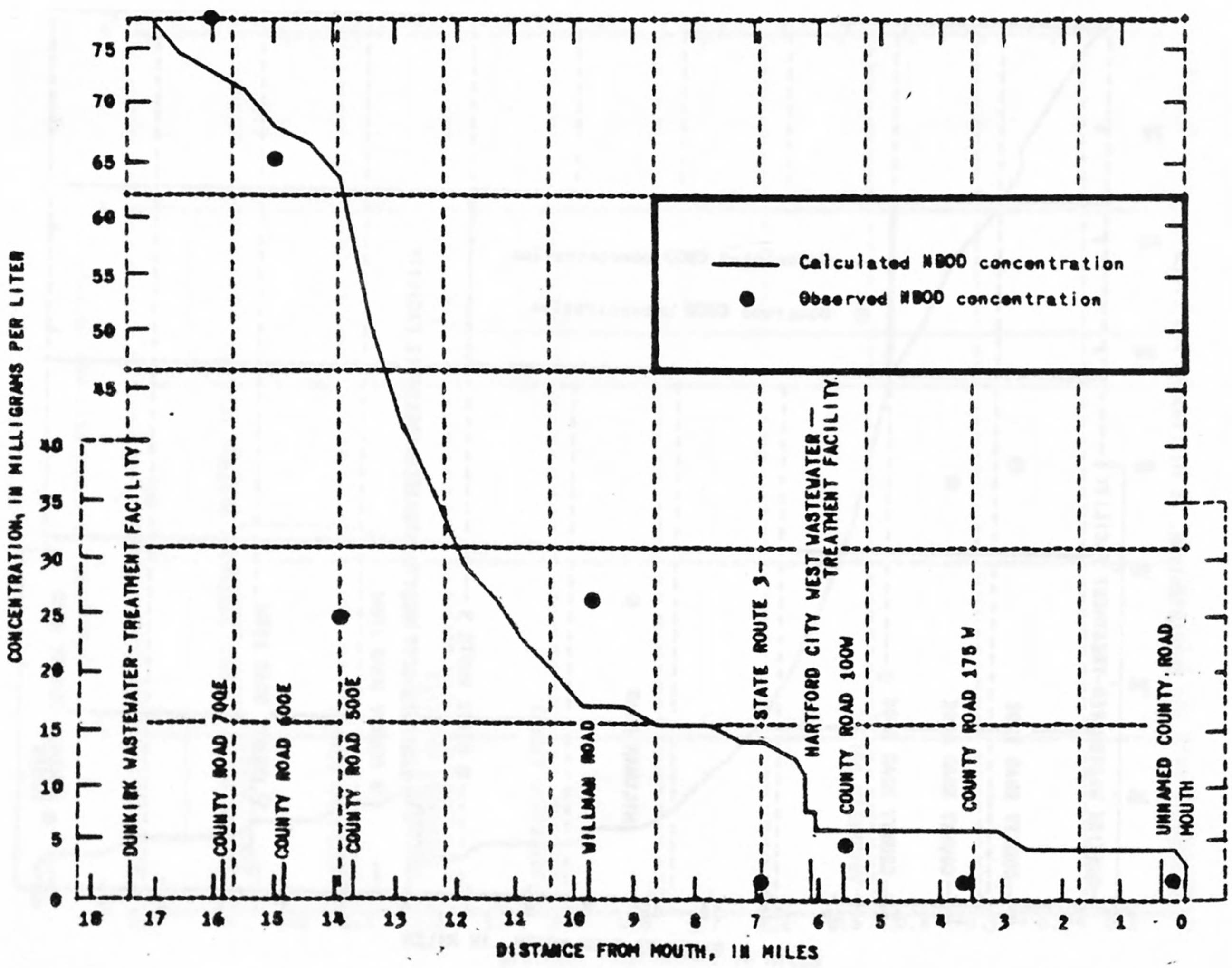

Figure 20.— Calculated and observed nitrogenous biochemical-oxygen-demand concentrations in Big Lick Creek, August 3, 1977.

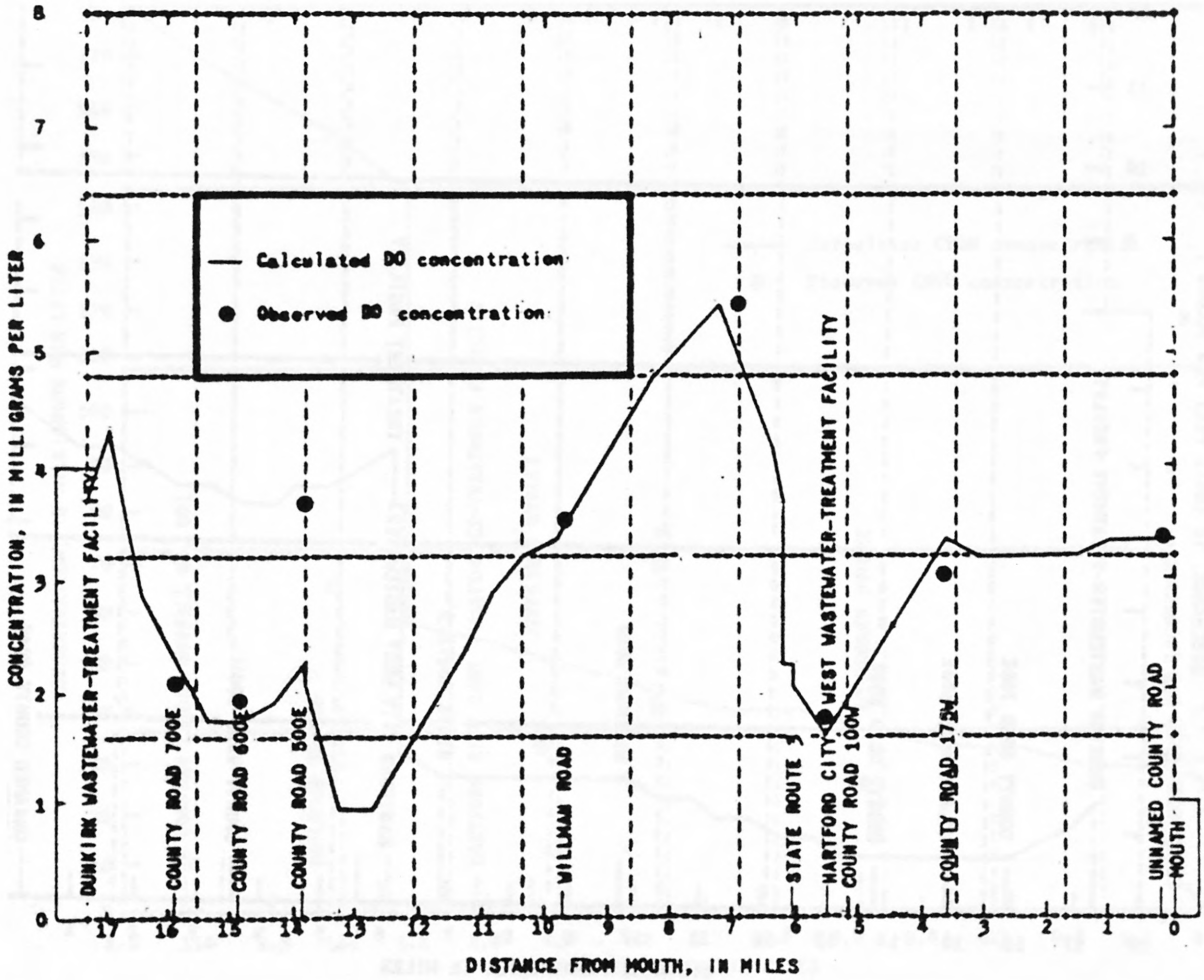

Figure 21.— Calculated and observed dissolved-oxgyen concentrations in Big Lick Creek, August 3, 1977.

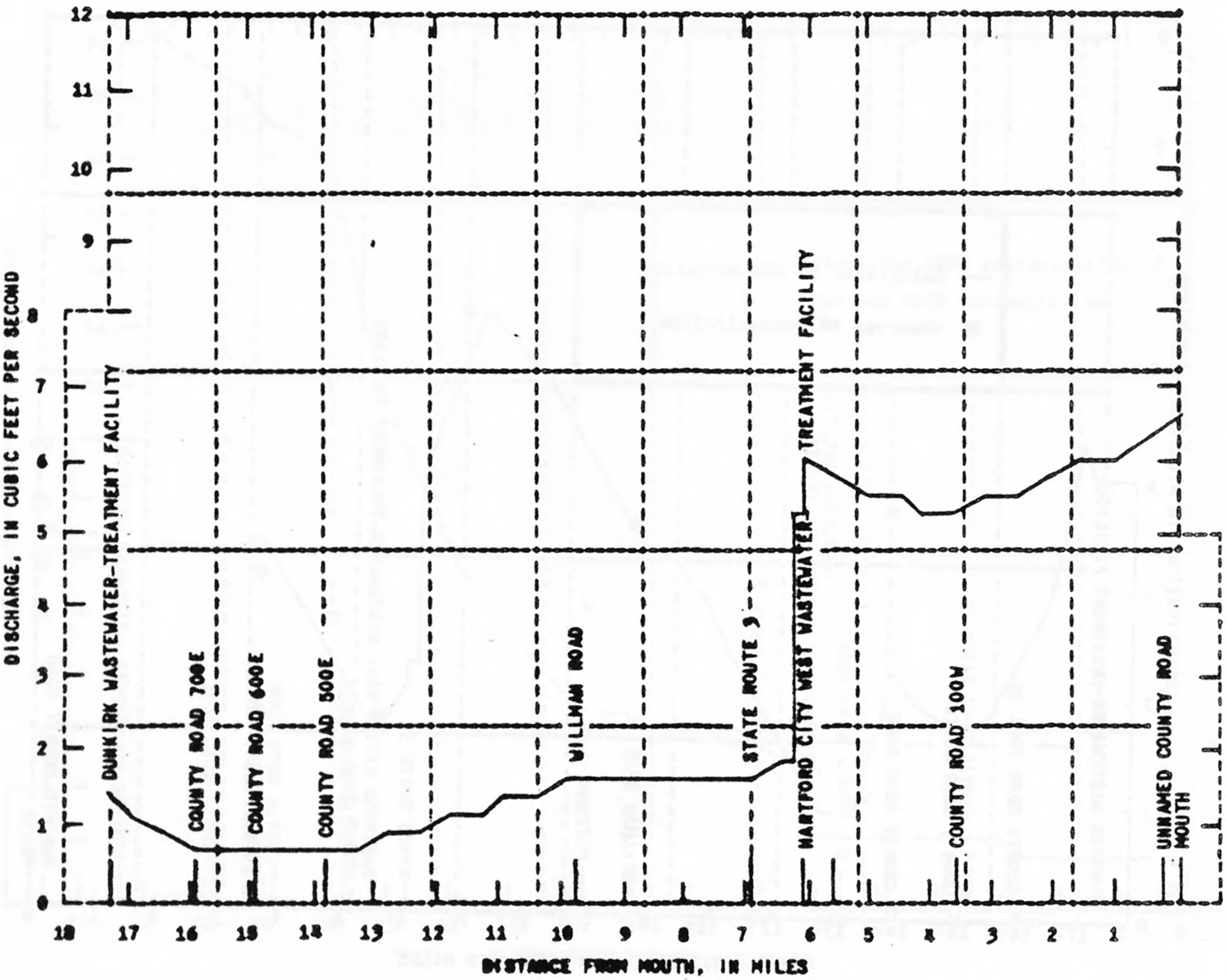

Figure 22.— Discharge in Big Lick Creek, August 3, 1977.

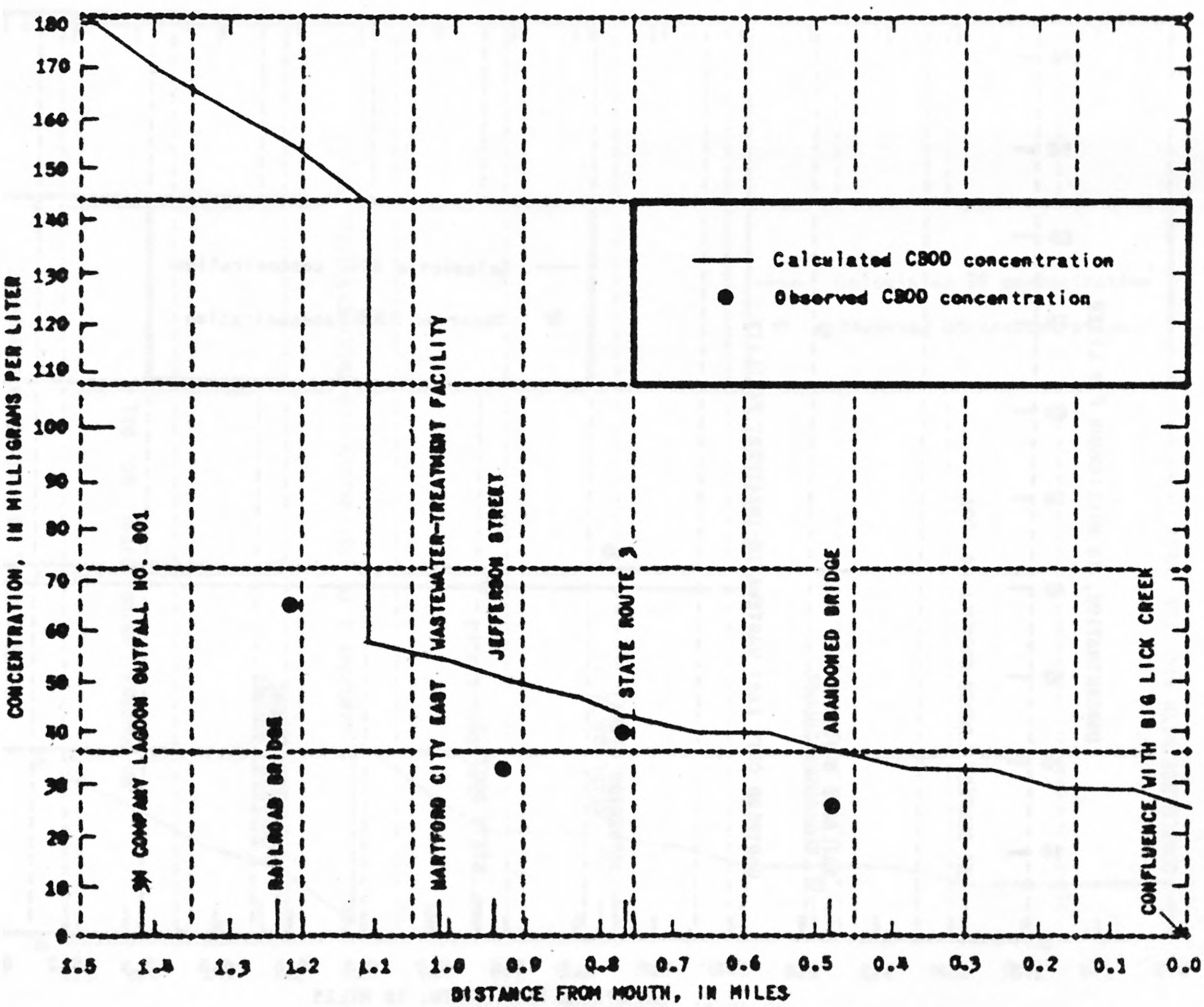

Figure 23.-- Calculated and observed carbonaceous biochemical-oxygen-demand concentrations in Little Lick Creek, October 20, 1977.

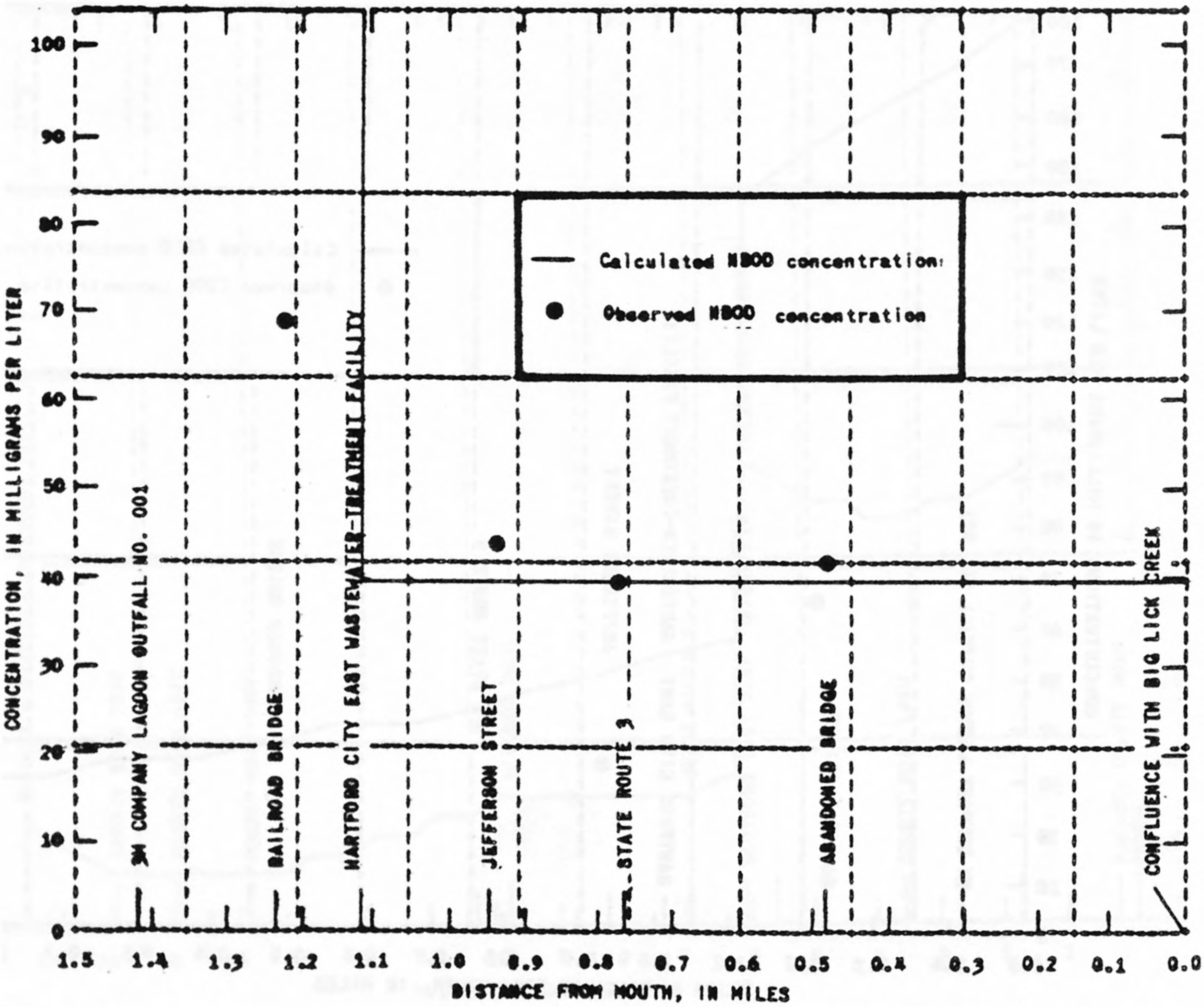

Figure 24.— Calculated and observed nitrogenous biochemical-oxygen-demand concentrations in Little Lick Creek, October 20, 1977.

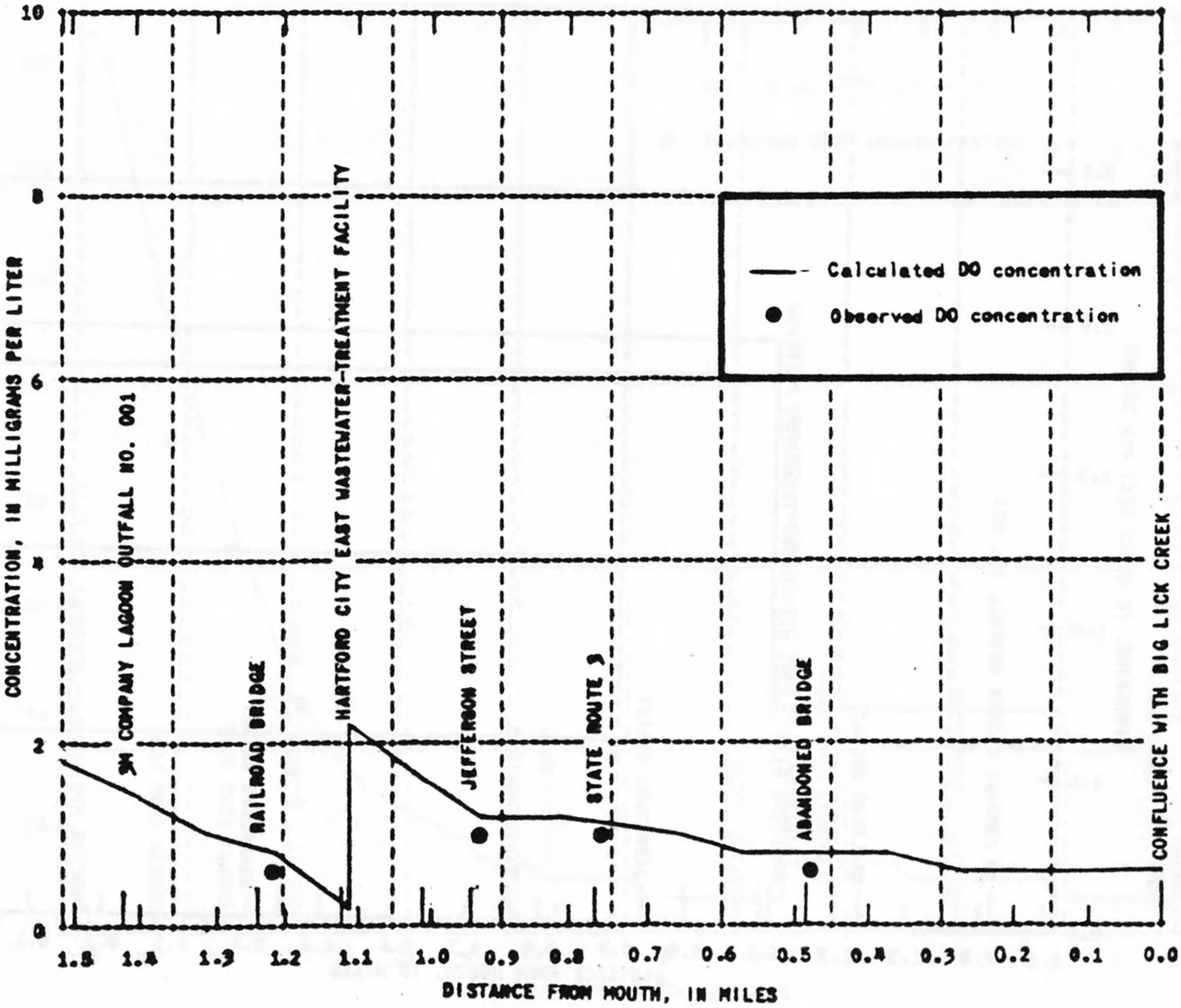

Figure 25.— Calculated and observed dissolved-oxygen concentrations in Little Lick Creek, October 20, 1977.

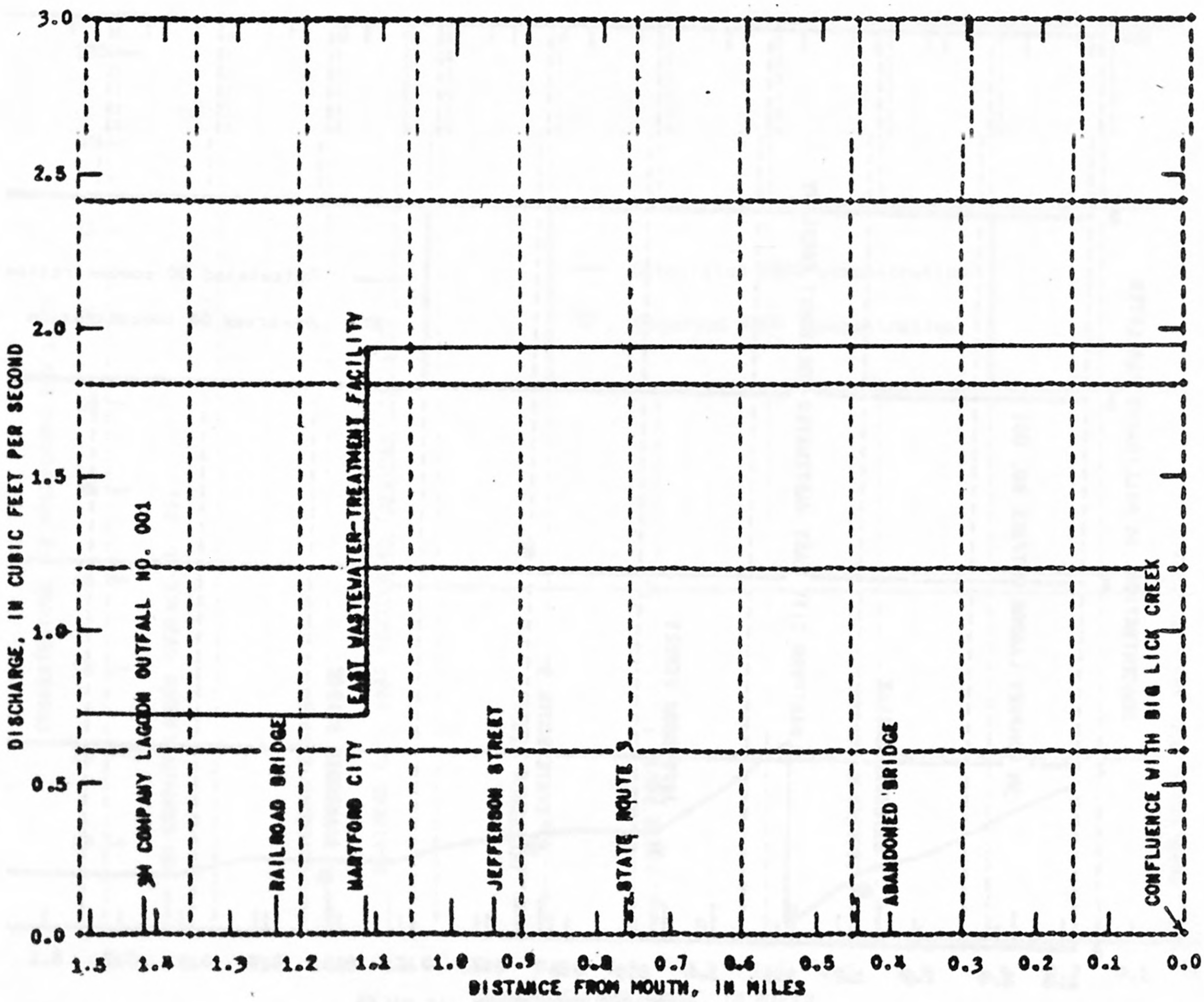

Figure 28.— Discharge in Little Lick Creek, October 20, 1977.

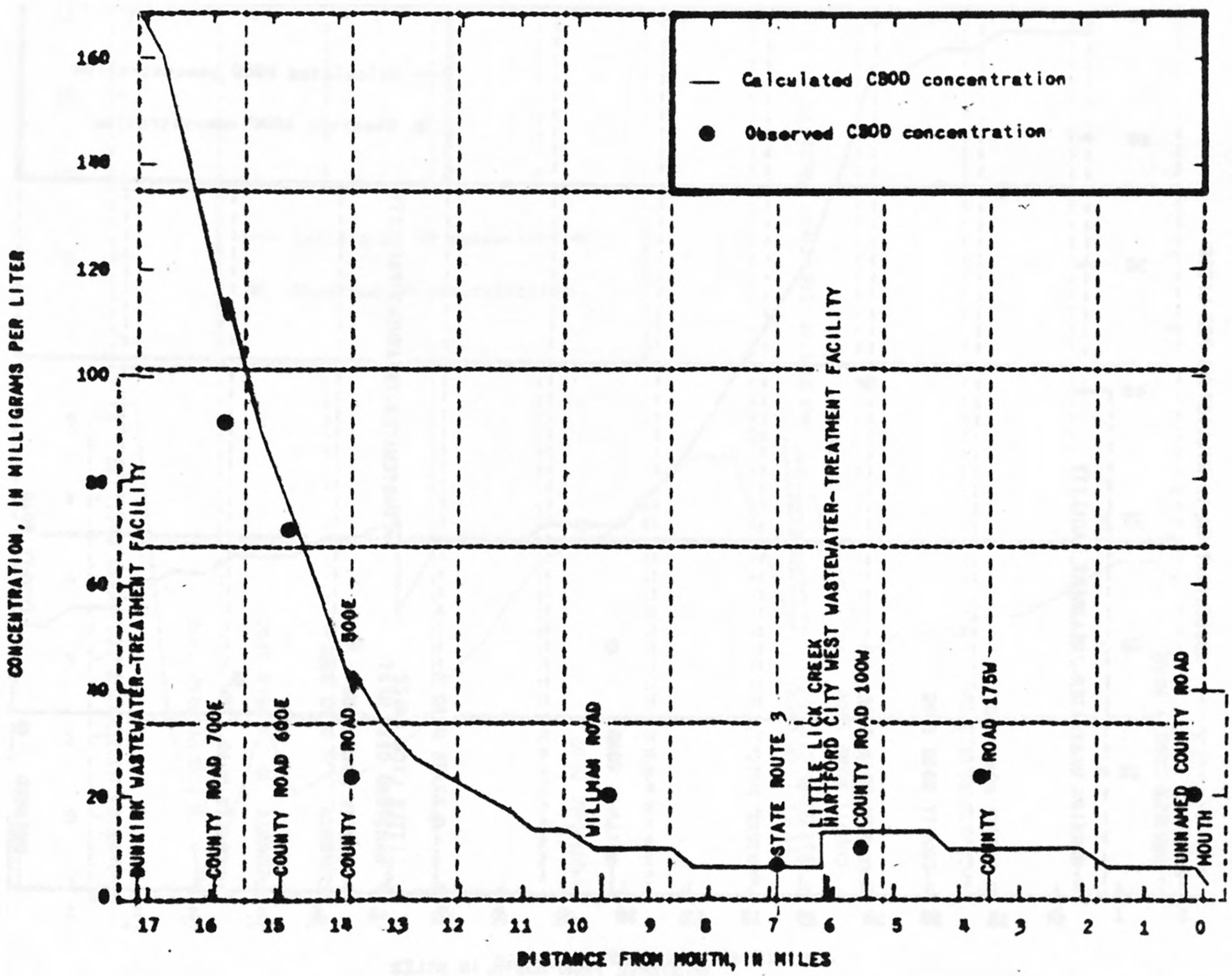

Figure 27.— Calculated and observed carbonaceous biochemical-oxygen-demand concentrations in Big Lick Creek, October 20, 1977.

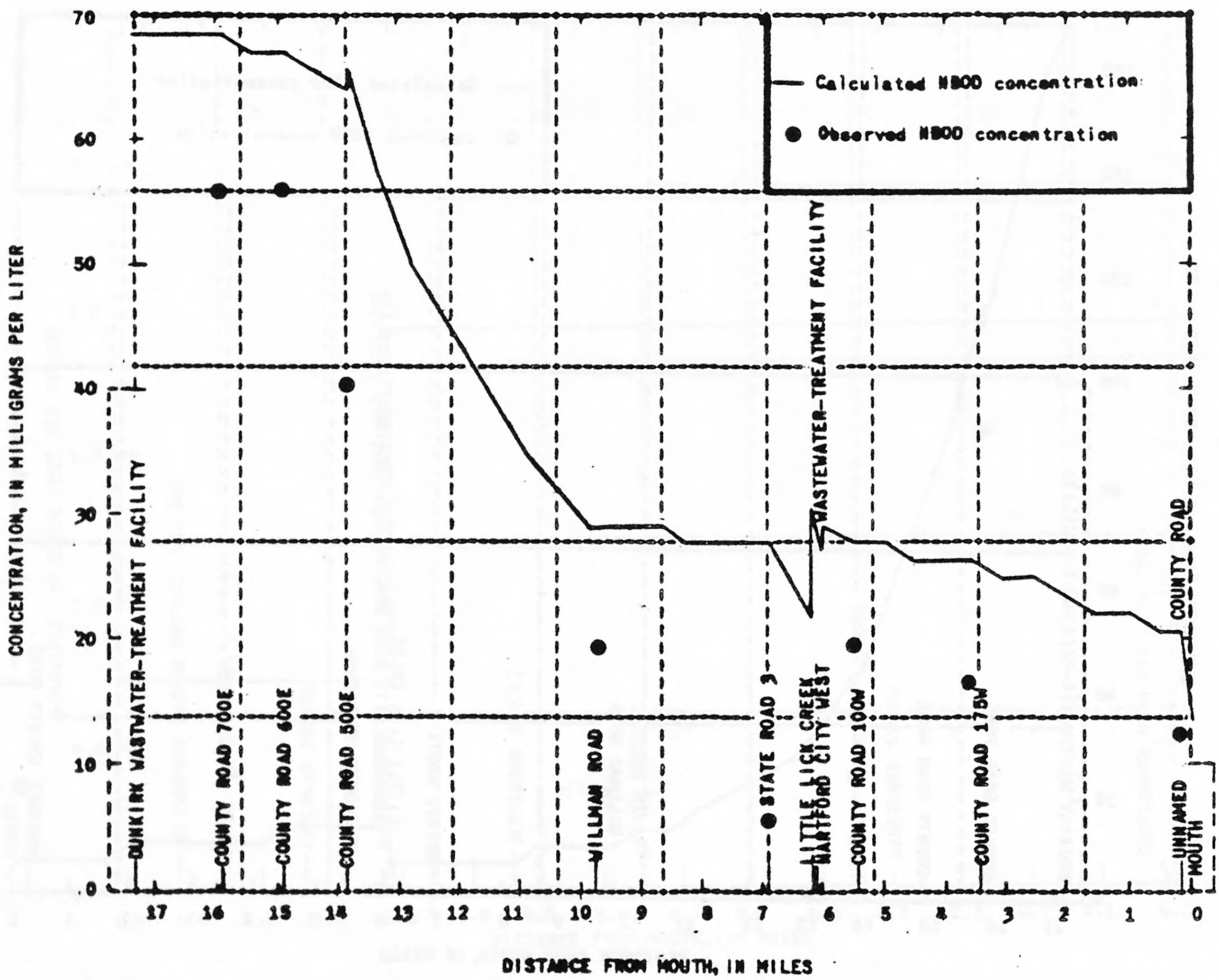

Figure 28.— Calculated and observed nitrogenous biochemical-oxygen-demand concentrations in Big Lick Creek, October 20, 1977

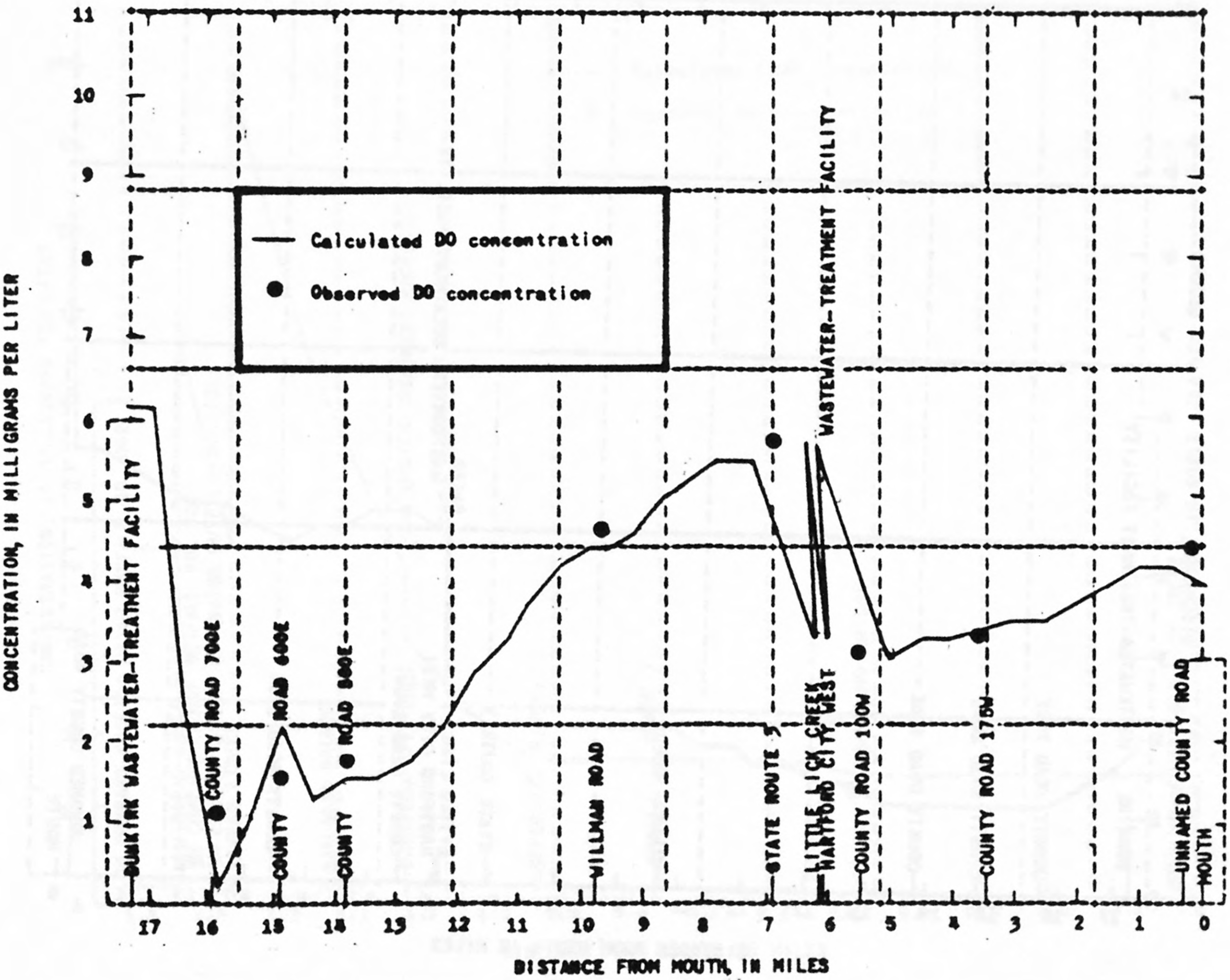

Figure 29.-- Calculated and observed dissolved-oxygen concentrations in Big Lick Creek, October 20, 1977.

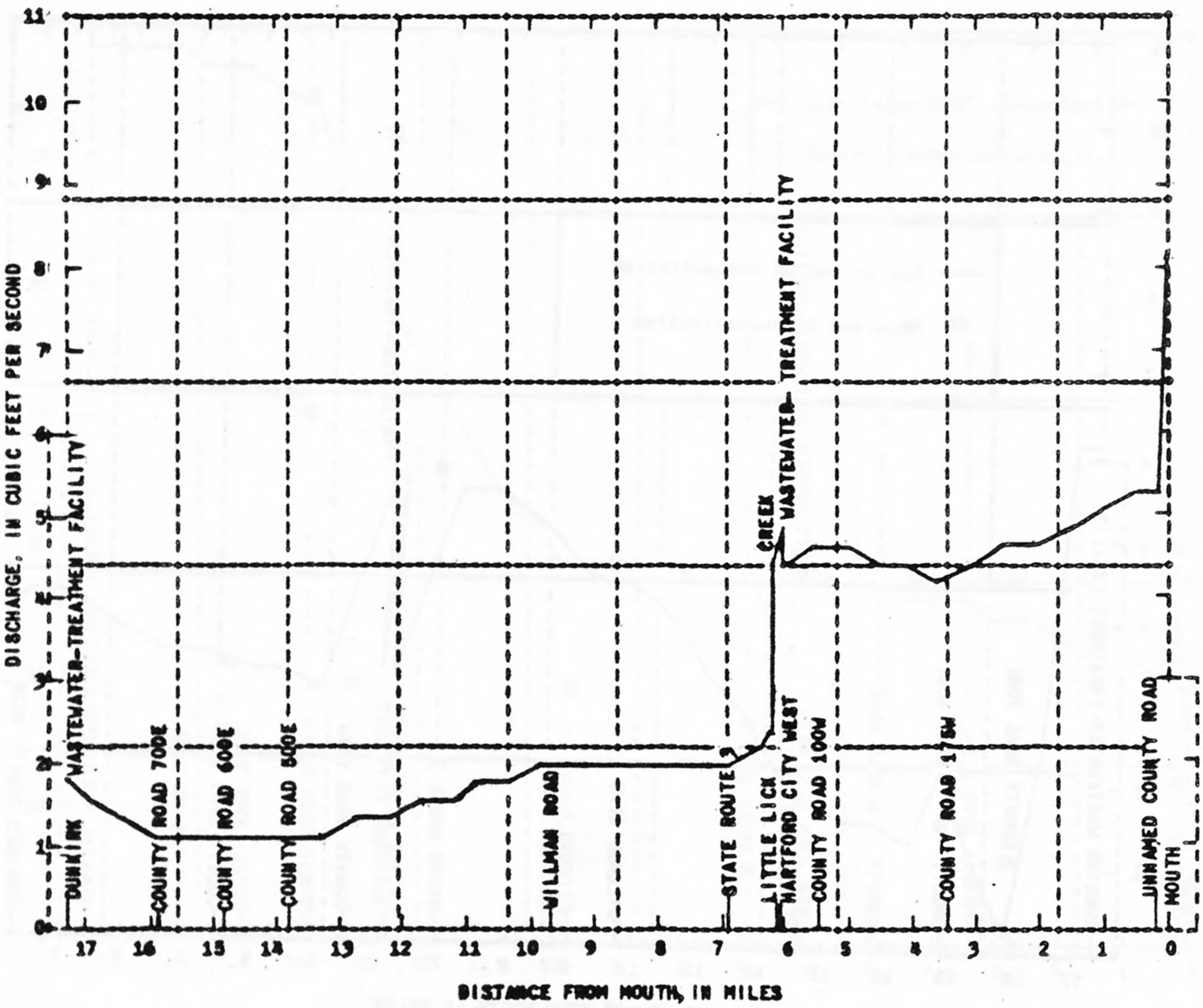

Figure 38.— Discharge in Big Lick Creek, October 20, 1977.

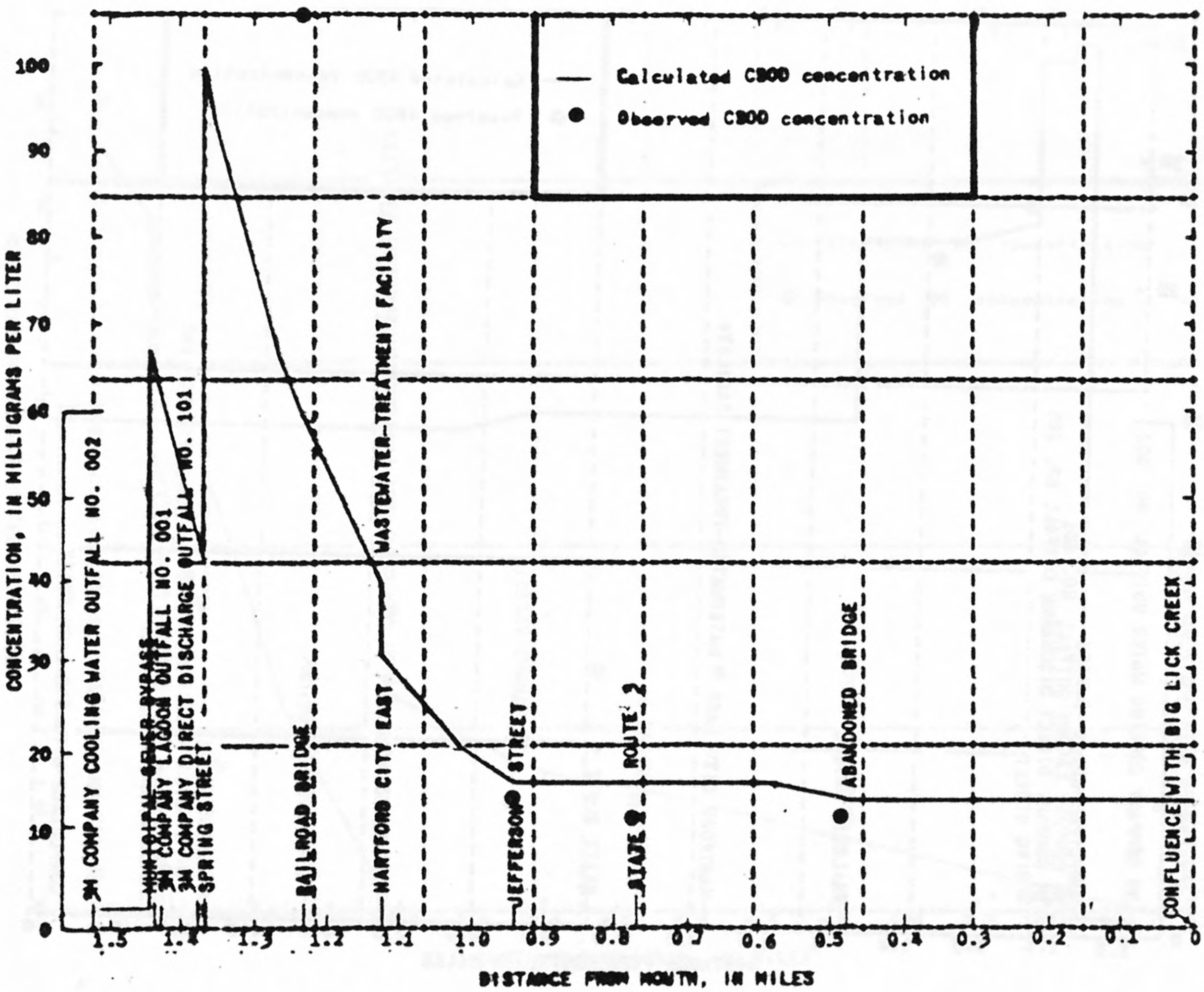

Figure 31.-- Calculated and observed carbonaceous biochemical-oxygen-demand concentrations in Little Lick Creek, September 21, 1978.

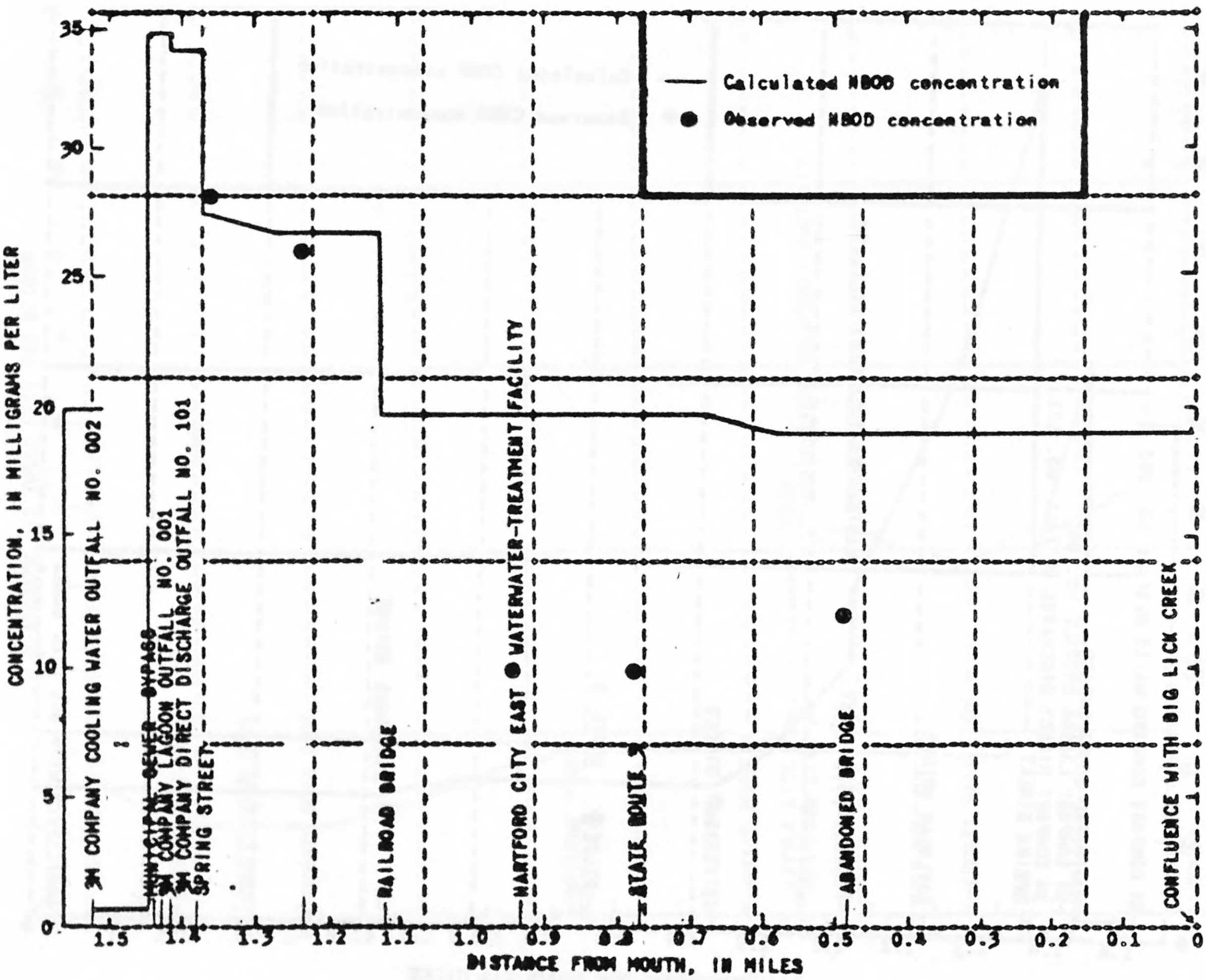

Figure 32.—Calculated and observed nitrogenous biochemical-oxygen-demand concentrations in Little Lick Creek, September 21, 1978.

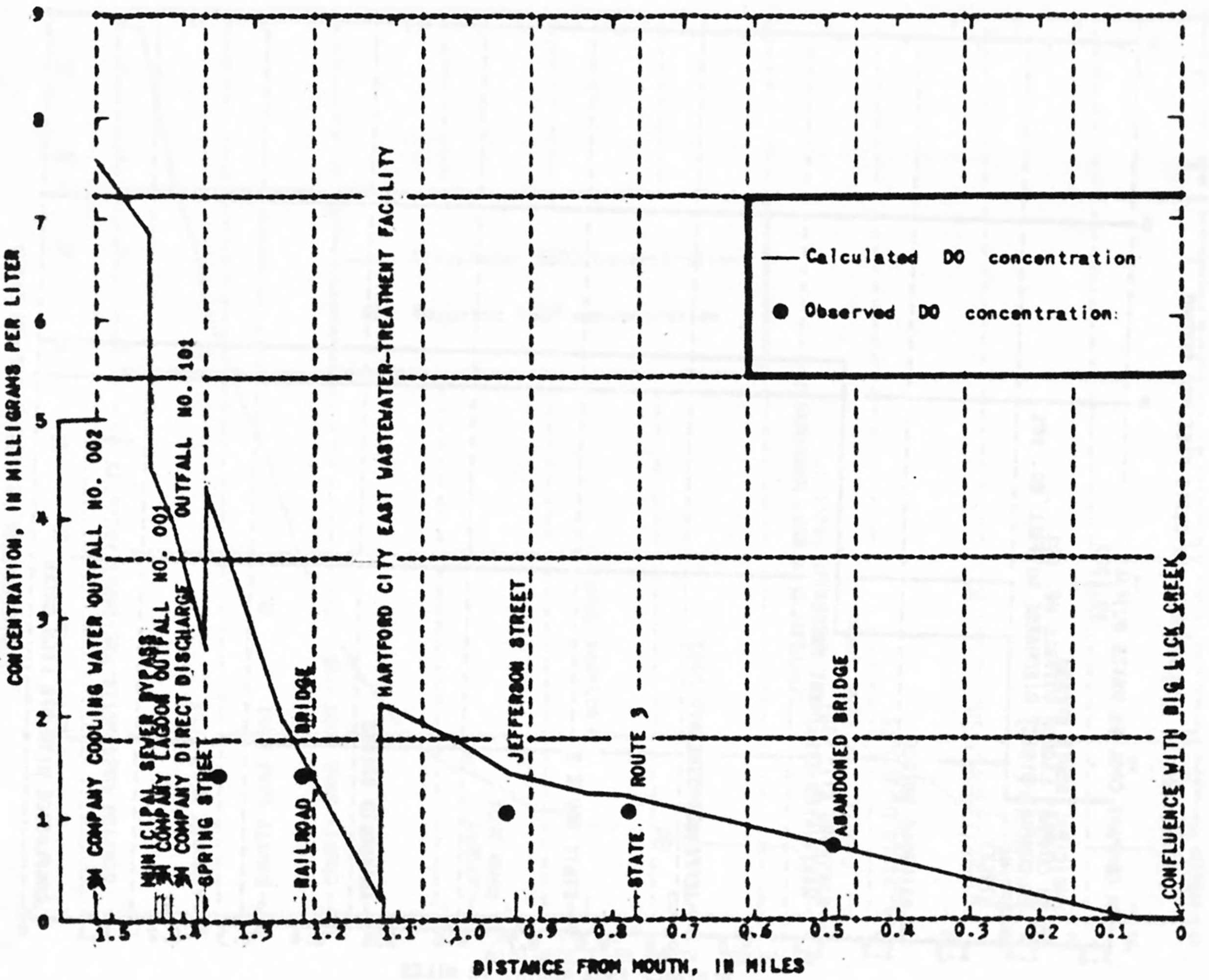

Figure 33.-- Calculated and observed dissolved-oxygen concentrations in Little Lick Creek, September 21, 1978.

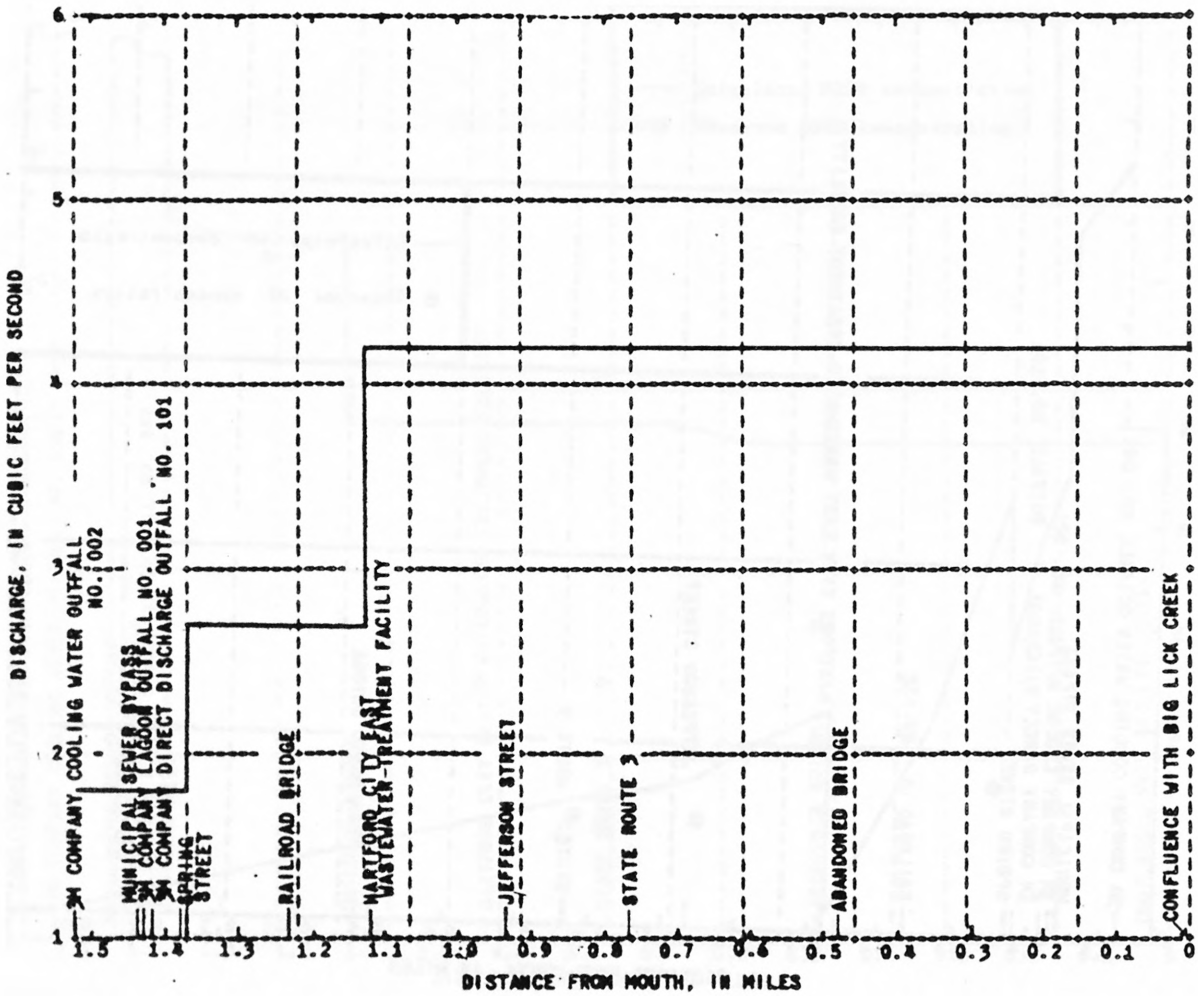

Figure 34.— Discharge in Little Lick Creek, September 21, 1978.

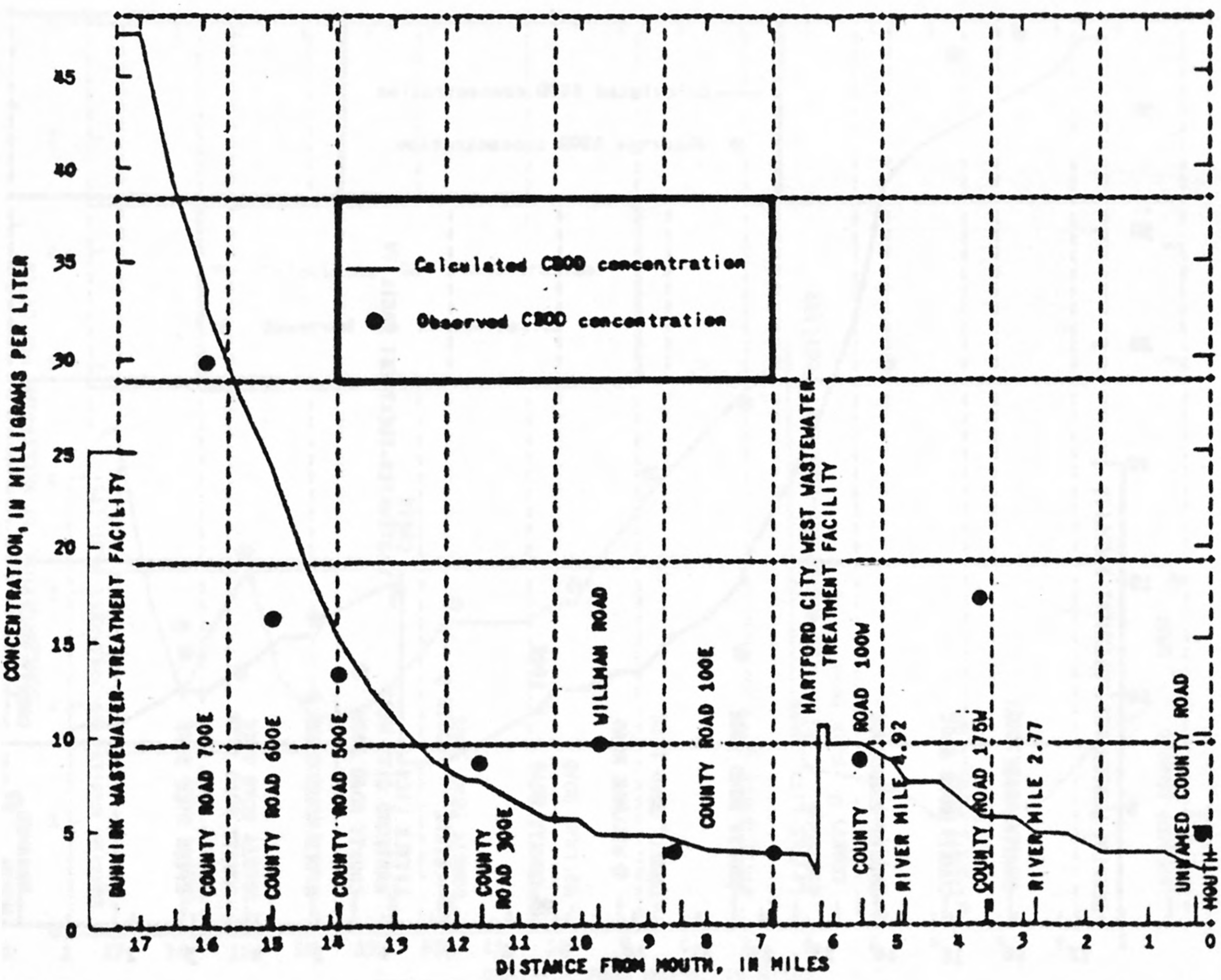

Figure 35.— Calculated and observed carbonaceous biochemical-oxygen-demand concentrations in Big Lick Creek, September 21, 1978.

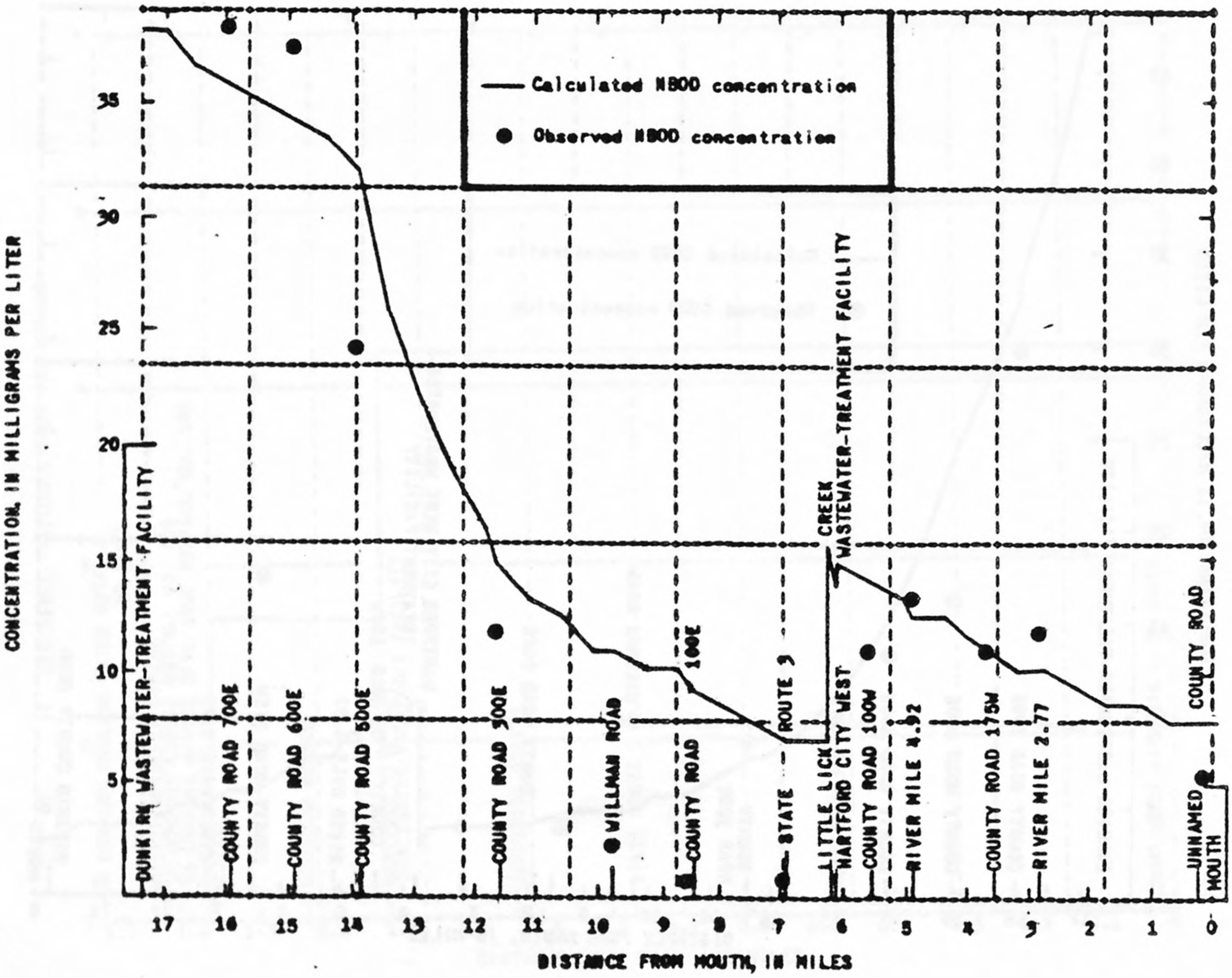

Figure 38.— Calculated and observed nitrogenous biochemical-oxygen-demand concentrations in Big Lick Creek, September 21, 1978.

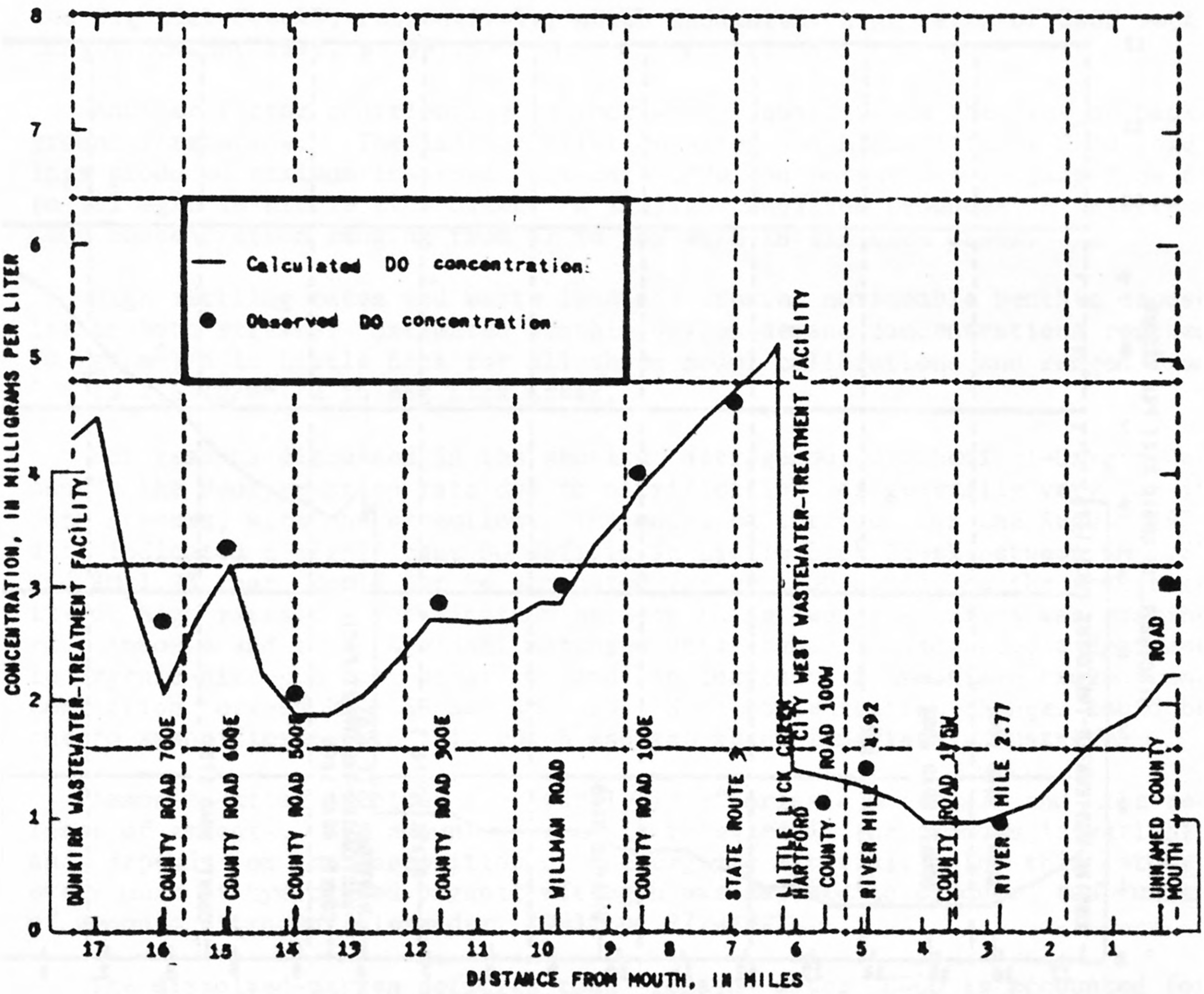

Figure. 37.— Calculated and observed dissolved-oxygen concentrations in Big Lick Creek, September 21, 1978.

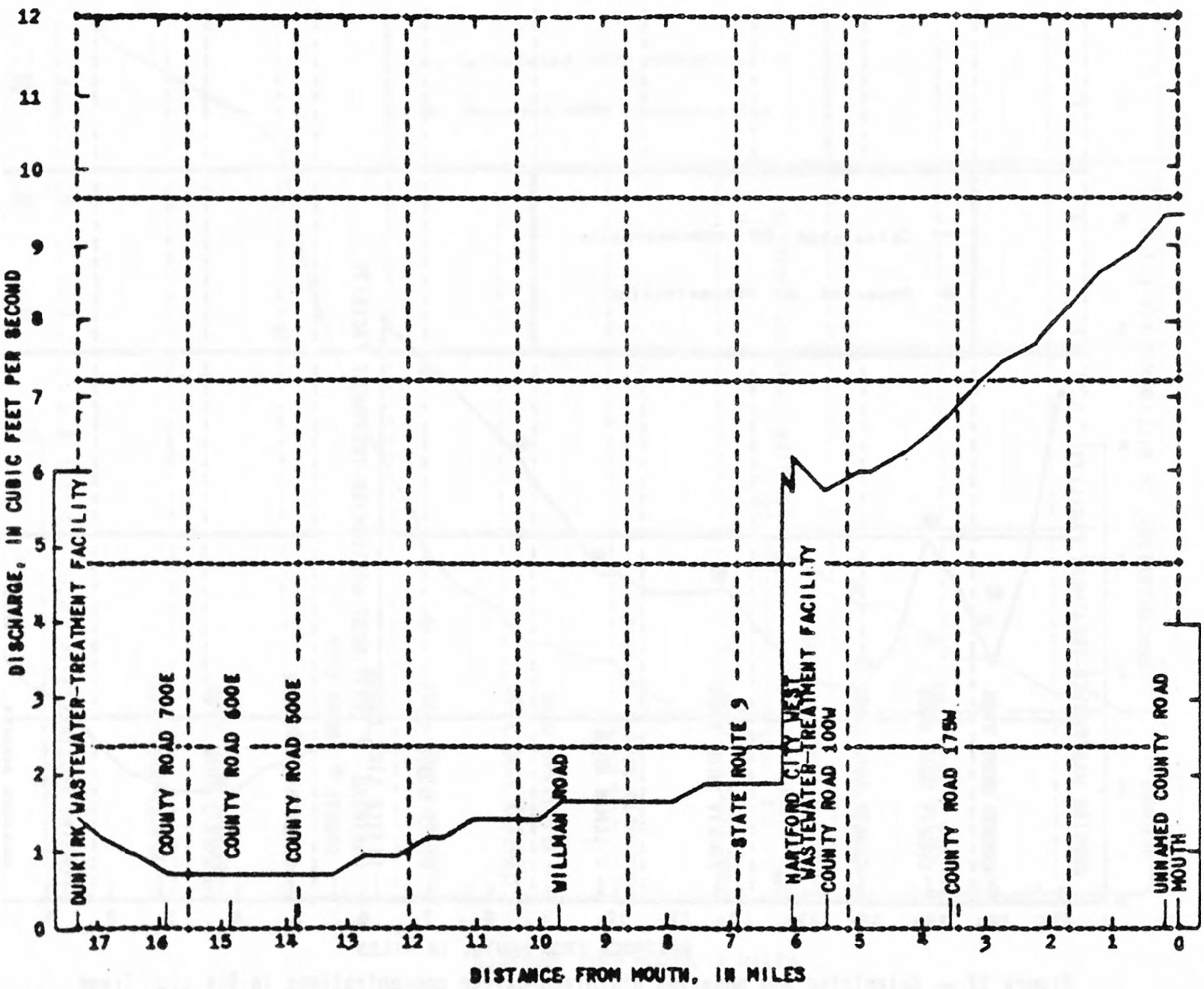

Figure 38.— Discharge in Big Lick Creek, September 21, 1978.

The data indicate that the flat topography of southwestern Blackford County affected the water quality during the three water-quality surveys. The channel-controlled streams were slow moving with little mechanical mixing. Reaeration rates were low and averaged 0.71 day^{-1} for Little Lick Creek and 1.9 day^{-1} for Big Lick Creek. Rates of in-stream CBOD removal were high in both streams. During the September 1978 survey, the Hartford City municipal sewer was bypassing into Little Lick Creek at RM 1.44. Values of K_r, downstream from this outfall, were 10.0 day^{-1} at 20°C. On other surveys, maximum K_r values were 2.97 and 1.59 day^{-1} at 20°C for Little Lick and Big Lick Creeks, respectively, which indicated high rates of CBOD settling (Thomann, 1972, p. 97).

Another factor contributing to poor water quality was the lack of background streamflow. The lack of dilution water and high ultimate CBOD loadings produced maximum in-stream ultimate CBOD concentrations ranging from 61 to 181 mg/L in Little Lick Creek. A similar condition produced an in-stream CBOD concentration ranging from 47 to 169 mg/L in Big Lick Creek.

High settling rates and waste loadings created noticeable benthic deposits in both streams. Estimated benthic-oxygen-demand concentrations reached 10 $(gm/m^2)/d$ in Little Lick for all three model calibrations and ranged from 0.5 to 2.5 $(g/m^2)/d$ in Big Lick Creek.

For reasons discussed in the section "Nitrogenous Biochemical-Oxygen Demand", the deoxygenation rate due to nitrification was generally very low in both streams, with one exception. The model calibration for the August 1977 data indicated a significant DO deficit in Little Lick Creek between RM 1.37 and RM 1.23 that could not be accounted for by CBOD alone, so the possibility of high rates of nitrification between these two river miles was examined. Ammonia and total Kjeldahl nitrogen data (table 3) indicated a decrease in organic-nitrogen concentration and an increase in ammonia-nitrogen concentration between RM 1.36 and RM 1.23. Such concentration changes could be due to ammonification in this reach and the reach immediately upstream.

Ammonification involves the hydrolysis of organic material and the release of ammonia. The amount of ammonia released in the process is variable and depends on the composition of the organic material. In this study, every unit of hydrolyzed organic nitrogen was assumed to produce two units of ammonia nitrogen (Alexander, 1961, p. 272-292).

The dissolved-oxygen deficits that remain after CBOD is accounted for are 28.44 and 41.4 $(g/m^2)/d$ for the reaches from RM 1.37 to 1.36 and RM 1.36 to 1.23, respectively. The deficits due to nitrification (for assumed ammonification) and benthic-oxygen demand were also calculated. The calculations indicated that either process could have explained the remaining deficits.

In the two reaches mentioned in the preceding paragraph, benthic-oxygen demand was limited to a maximum of 10 $(g/m^2)/d$, the maximum value estimated in other reaches during the surveys. Rates of nitrification that accounted for the remaining deficit were calculated with both first-order and zero-order kinetics. The high rates of nitrification in the stream indicated an attached population of bacterial nitrifiers. Calculated values of $K_{n,zero}$ were 181.6 and 529.5 (lb/d)/d at 20°C for the upstream and downstream reaches, respectively. These values compare reasonably with other zero-order rates calculated by the authors for small streams in Indiana (Wilber and others, 1979a, p. 29; 1979b, p. 43).

Ammonification was assumed to be the source of ammonia used for nitrification. However, the model does not provide an option for including ammonification. Thus, for modeling, the calculated amount of ammonia nitrogen required to provide the needed deficit was input at RM 1.37. The amount of ammonia nitrogen required to produce the desired DO deficit was 7.3 lb/d, which provided an "artificial" NBOD concentration at 3M Company direct discharge outfall number 101 of 11.1 mg/L (table 10).

Though the method of calculating the unexplained DO deficit is considered reasonable by the authors, it is also highly speculative. The stream conditions during the August 1977 survey were very different from those during the other two surveys. Maximum calculated values of either nitrification or benthic demand could have accounted for the unexplained deficit. Additional data indicating the extent and magnitude of these two processes are needed to define their impact on Little Lick and Big Lick Creeks.

The DO concentrations in Little Lick Creek consistently decreased from the headwaters to the mouth, where concentrations from the three surveys averaged 0.95 mg/L. Little Lick Creek contributed to the DO deficit in Big Lick Creek below their confluence because the average calculated DO concentration in Big Lick upstream from the confluence was 5.4 mg/L.

A depression of the DO concentration curve was noted in Big Lick Creek below the Dunkirk wastewater-treatment facility (figs. 17, 21, and 25). Minimum DO concentrations calculated at RM 15.97 averaged 0.55 mg/L for the three sets of data. Immediately upstream from the confluence with Little Lick at RM 6.18, the calculated DO concentration had recovered to its initial upstream value.

In-stream DO concentrations were reduced at RM 6.06, downstream from the confluence with Little Lick Creek and the Hartford City West wastewater-treatment facility outfall. Though DO concentrations increased downstream, reaeration was not sufficient to raise concentrations to upstream levels. Thus, calculated DO concentrations for the three surveys averaged 3.4 mg/L at the mouth of Big Lick Creek.

The degree to which the calculated CBOD, NBOD, and DO concentrations approximated the corresponding in-stream observations was evaluated with the normalized error given by the equation:

$$\text{Normalized error} = \left[\sum_{i=1}^{N} \frac{A_c - A_o}{A_o\,N}\right] 100 \text{ percent} \tag{23}$$

where

N is the number of observations,

and

A_c and A_o the calculated and observed values, respectively (Rathbun, 1977).

This statistic is commonly used to assign an absolute percentage error to a set of observed and calculated values.

Normalized errors for DO concentration indicated good agreement between observed and calculated values. The highest error, 7.44 percent, was generated by data from the September 1978 survey (table 23). Normalized errors for calculated CBOD values were low for the August 1977 and September 1978 surveys data, but the normalized error for the October 1977 data was nearly 16 percent. The very large errors calculated for NBOD resulted because ammonia-nitrogen concentrations were used to estimate "observed" NBOD concentrations. However, in-stream DO concentrations indicated that other factors, such as ammonification and settling, also influenced ammonia-nitrogen concentrations. Thus, rates of nitrification calculated only from ammonia-nitrogen data were misleading. Rates of nitrification were estimated from both ammonia- and nitrate-nitrogen data as described in "Nitrogenous Biochemical-Oxygen Demand." Thus, no attempt was made to approximate the "observed" in-stream NBOD concentrations with calculated values.

Table 23.--Normalized-error values for constituents used in the calibration model, Little Lick and Big Lick Blackford and Delaware Counties, Ind.

Date of survey	Constituent	Normalized error (percent)
August 3, 1977	DO	0.79
	CBOD	-2.25
	NBOD	239.94
October 20, 1977	DO	4.78
	CBOD	15.80
	NBOD	64.91
September 21, 1978	DO	7.44
	CBOD	-3.13
	NBOD	226.91

In general, the variation between observed and calculated concentrations of DO and CBOD is greatest in the upper reaches of Little Lick Creek. Several factors are responsible for these deviations. Because of the short length of the stream segment, stream sampling stations on Little Lick Creek were located very close to discharge outfalls. Single samples collected in mid-channel may not have been representative of the average stream condition for the mixing zone downstream from the outfalls. This was especially true for stream station 030-2 just 0.01 mile downstream from the 3M Company outfall No. 101. A better method for sampling these sites would have been to collect samples in equal-width increments across the stream transect and to composite the samples so that the volume from each increment was proportional to the discharge. Other potential sources of error include failure to dechlorinate stream samples collected downstream from dischargers during the first two surveys before CBOD analysis and determining ultimate CBOD by a method that uses several dilution ratios (Grant, 1976, p. 6; Colston, 1975, p. 195).

MODEL VERIFICATION

After the model has been calibrated, the calibration coefficients should be verified. This verification can be done by one of two ways: (1) If all data can be collected at conditions similar to those used for the simulation study, model verification requires that only one additional set of stream data be collected to evaluate the calibration coefficients (Hines and others, 1977); (2) if the data cannot be collected under conditions similar to those used for simulation, the relation between the changing stream conditions and the model coefficients must be quantitatively defined. This method of verification requires much more data than the other method, and the model can be considered verified only if it can successfully predict the change in water quality after a significant change in the input to the system (O'Connor, 1976, p. 19).

The water-quality data collected on Little Lick and Big Lick Creeks could not produce a verified model with either verification method. The first verification method could not be used because of the varied effluent-discharge conditions under which the three sets of data were collected, and the second method could not be used because three sampling surveys were not sufficient to develop quantitative relationships between the varied effluent discharges and the rate coefficients used in the model. (See tables 10-15).

For small streams in which effluent discharges provide a significant part of the total streamflow, changes in effluent waste load can be expected to modify processes that influence the in-stream dissolved-oxygen regime. For example, changing waste-load conditions on Little Lick Creek during the three surveys altered the calculated values of K_r, benthic-oxygen demand, and, possibly, nitrification. Calculations characterizing the relation between stream conditions and model coefficients for small streams such as Little Lick and Big Lick Creeks may require more data than those for large rivers.

Though the current model cannot be considered verified, it can still be useful for waste-assimilation studies. The model can be used to indicate the stream processes that are significantly affecting DO concentration and to identify problem areas where more data are required. Additionally, the model can be used to select general levels of waste treatment that are compatible with the assimilative capacity of the stream. Though the accuracy of an unverified model cannot be determined, the model can provide valuable qualitative information necessary for basin planning.

WASTE-LOAD ASSIMILATION

Data collected during the three water-quality surveys indicate that Little Lick and Big Lick Creeks have no assimilative capacity. Both streams have average DO concentrations consistently below the State standard of 5.0 mg/L. However, improvements in effluent discharged to the streams are scheduled to begin in 1980 with the closing of the Hartford City East wastewater-treatment facility and upgrading of the Hartford City West facility. By 1983, the 3M Company is required either to meet stringent effluent standards or to cease discharging effluent to the stream. These changes could significantly improve the water quality in the Big Lick Creek basin.

Unfortunately, the effect of improved wastewater-treatment on parameters such as K_d, K_n, and benthic-oxygen demand cannot be quantified because data for model calibration were collected at discharges that differed greatly from projected effluent discharge conditions. For this reason, the waste-assimilation model incorporated rate coefficients derived from models of other small streams in Indiana as well as from results of other studies. (See "Procedures.")

Though the authors attempted to use realistic coefficient values in the model, the resulting study is hypothetical and represents examples of possible changes in stream water quality that might result from projected improvements in effluent discharge. Construction of a model that can truly simulate future stream conditions requires calibrating and verifying the model with data collected after the anticipated changes in effluent discharge have been made.

Procedures

Waste-load assimilation was studied during both the critical 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 for the years 1978, 1980, 1983, 1985, 1990, 1995, and 2000 (Indiana State Board of Health, 1978). The critical condition rationale is useful for water-quality planning and management because it narrows the scope of the modeling effort and examines the stream during periods of minimum assimilative capacity (Hines and others, 1975, p. B5-B6).

In the NPDES permits (Indiana State Board of Health, 1978), daily maximum and daily average discharge loadings are given for industries and weekly average and monthly averages are given for the municipalities (table 1).

Procedures and standards for establishing the waste-load assimilation capacity of streams were furnished by the Indiana State Board of Health 1977). To determine this assimilation capacity, 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). These initial loading criteria applied to both CBOD and ammonia. Where no permit had been issued for CBOD, the combined data from the Monthly Report of Operations and data from the ISBH Surveillance Section were used to determine appropriate initial effluent concentrations.

Restrictions for ammonia-nitrogen concentration in the three municipal wastewater-treatment facility effluents were not given in NPDES permits. Initial concentrations for the waste-assimilation studies were based on data from the ISBH Surveillance Section. In no case, however, was the initial ammonia-nitrogen concentration assumed to be less than 15 mg/L, which is equivalent to an NBOD concentration of 65 mg/L (Aolad Hossain, Indiana State Board of Health, oral commun., 1978).

The observed dissolved-oxygen concentrations of effluents at the three wastewater-treatment facilities averaged 46 percent of saturation during the two water-quality surveys. If the dissolved-oxygen concentrations of the effluents had been assumed to be 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. Because the aeration of wastewater effluents before discharge would be relatively inexpensive compared to additional waste treatment, the initial dissolved-oxygen concentration of the wastewater effluents throughout the study was assumed to be 80 percent of saturation (Aolad Hossain, Indiana State Board of Health, oral commun., 1978). Calculated DO concentrations for the 3M Company outfalls were based on average percentages of saturation for the three water-quality surveys, and for lagoon outfall No. 001[1] and cooling-water outfall No. 002 these values were 80 and 98 percent, respectively.

Where the initial loads of CBOD and NBOD from the discharge effluents violated in-stream water-quality standards, the loads were adjusted until appropriate standards were met. The maximum loads of CBOD and NBOD that just met Indiana water-quality standards defined the assimilative capacity of the streams.

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[1]The NPDES permit for 3M Company provides for discharge from outfall No. 001 or No. 101, but not both. For the waste-assimilation study, outfall No. 001 was used. However, because the two outfalls are close to each other, modeling results should apply equally well to outfall No. 101 as well.

Unpublished construction-grant information, available through the Indiana State Board of Health, indicates that the Hartford City East wastewater-treatment facility is scheduled to cease operating during normal flow conditions by 1980. Flow to this plant will be diverted to the West facility, which is being upgraded to advanced wastewater treatment (sand filters). Thus, the waste-assimilation models for years 1980-2000 assumed that all municipal waste for Hartford City will be treated at the West facility.

The future status of the 3M Company discharge from outfall No. 001 was in doubt as of this writing. On the basis of the best available information from the ISBH (Aolad Hossain, Indiana State Board of Health, oral commun., 1978), the authors assumed that effluent from this outfall would be diverted to the Hartford City West wastewater-treatment facility for treatment by 1983. Thus, for all waste-assimilation calculations for years 1983-2000, the authors assumed zero discharge from this outfall.

Guidelines for defining the critical streamflow and temperature conditions for use in the waste-assimilation studies were provided by the Indiana State Board of Health (1977). Waste effluents were assumed to be the only source of flow in both Little Lick and Big Lick Creeks. The log-Pearson method (Riggs, 1972) was used to calculate the $Q_{7,10}$ flows at the U.S. Geological Survey gage near Hartford City from 6 years of discharge data (U.S. Geological Survey, 1978, p. 80). Summer $Q_{7,10}$ flow at the gage used in the summer waste-assimilation study was estimated to be 0.67 ft^3/s, and the annual $Q_{7,10}$ flow at the same gage used in the winter waste-assimilation study was estimated to be 0.45 ft^3/s. The only source of flow in Big Lick Creek upstream from the gage was assumed to be the Dunkirk wastewater-treatment facility. Projected flows from this facility were greater than both the estimated summer and annual $Q_{7,10}$ flows at the gage. The difference was assumed to be flow lost to the stream sediments and was subtracted as linear runoff in proportion to distance downstream from Dunkirk. Linear runoff in other reaches of Little Lick and Big Lick Creeks was assumed to be zero.

A temperature of 24.0°C was used in the summer waste-load assimilation model. This temperature was based on the mean daily water temperature, which is exceeded 10-20 percent of the time for the months June through August. A temperature of 8.2°C was used in the winter waste-load assimilation model. This temperature was the average of the daily mean water temperature for November, the month with the lowest flow.

Temperatures for Little Lick and Big Lick Creeks were estimated by the following equation:

$$T = M + A\,[\sin\,(0.0172\,\underline{d} + C)] \quad \text{(Shampine, 1977, p. 13)} \qquad (24)$$

where

T is the stream temperature at a given site on a specific day,

M is 12.30, the mean annual stream temperature, in degrees Celsius,

A is 11.27, the stream temperature amplitude, in degrees Celsius,

$\underline{d}$ is the Julian date,

and

C is 4.32, the angle-phase coefficient, in radians.

The calibrated model indicated that, under present basin discharge conditions, Little Lick and Big Lick Creeks cannot meet in-stream DO or ammonia standards, and, therefore, that significant decreases in basin waste inputs will be needed. For the calibration models, the large difference between K_r and K_d downstream from effluent outfalls indicated that benthic deposits were caused by settleable material from the effluents. Nonpoint sources of benthic deposits could not be measured but were assumed to be negligible during low flows. Thus, decreased waste loads would probably reduce benthic-oxygen demand, which averaged 2.3 $(g/m^2)/d$ for the three calibration models. A value of 0.2 $(g/m^2)/d$, which is characteristic of clean streams with sandy bottoms (Thomann, 1972), was used for both summer and winter waste-load assimilation studies. Decreased waste loads would probably also lower the deoxygenation rate for CBOD. The experience of the authors indicates that a K_d of 0.15 day^{-1} generally describes CBOD deoxygenation for clean streams in Indiana. This rate was used for both summer and winter waste-assimilation studies.

Reduced waste loads and low benthic-oxygen demand imply decreased, settleable organic material. Thus K_r was assumed to equal K_d.

The improved DO regime should result in higher rates of nitrification (Knowles, Downing, and Barrett, 1965). Thus, the summer waste-assimilation study was based on K_n values of 0.1, 0.3, and 0.6 day^{-1}, which correspond to minimum, average, and maximum first-order rates for rivers (Thomann, 1972). The value 0.1 day^{-1} was used in the calibration models; thus, 0.3 and 0.6 day^{-1} represent progressively higher rates of nitrification, which would be probable under improved water-quality conditions. However, since these higher rates are not based on observation, additional data would be needed before an appropriate K_n value for Little Lick and Big Lick Creeks could be selected.

During winter, nitrification was assumed to be negligible, owing to the inhibition of nitrifying organisms at low stream temperatures (Thomann and others, 1971). Consequently, for the winter waste-load assimilation study, ammonia nitrogen was treated as a nonbiodegradable constituent, and K_n was set equal to zero.

Reaeration rate coefficients were computed by the Parkhurst-Pomeroy equation, as discussed in the section "Reaeration."

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

Algal effects, as in the model calibration, were not included in the waste-load assimilation study.

Results and Discussion

According to the Indiana State Board of Health (1978), 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 at 5-year intervals to the end of the planning period (year 2000) and may be used as input into the calibrated waste-load allocation model.

For this study, the second modeling technique was used. Accordingly, the ISBH projected waste loads and flows for the existing effluent discharges to the year 2000 (table 24). These projections were used in the calibrated model, and the necessary concentrations were determined for the effluent discharges to meet current water-quality standards. The goals were a minimum in-stream dissolved-oxygen concentration of 5.0 mg/L and maximum ammonia-nitrogen concentrations of 2.5 mg/L and 4.0 mg/L for the summer and winter low flows, respectively.

In summer the 3M Company lagoon outfall No. 001 on Little Lick Creek is limited by in-stream ammonia toxicity to 4.9 mg/L ammonia nitrogen (21.2 mg/L NBOD), owing to dilution from the 3M Company cooling water outfall No. 002 upstream. In-stream ammonia toxicity limits the effluent ammonia-nitrogen concentration for K_n equal to 0.1 or 0.3 day^{-1}. In-stream DO concentration limits the effluent ammonia-nitrogen concentration for K_n equal to 0.6 day^{-1} (fig. 39).

Because of a lack of upstream dilution, ammonia-nitrogen concentration from the Dunkirk wastewater-treatment facility is restricted to a maximum of 2.5 mg/L (10.8 mg/L NBOD) by the in-stream ammonia-toxicity standard. This standard limits ammonia-nitrogen discharge for K_n equal to 0.1 and 0.3 day^{-1}. The small increases in projected discharge do not significantly alter reaeration in the upper reaches of Big Lick Creek. Thus, the allowable discharge concentrations of CBOD and NBOD remain virtually unchanged from 1980 through 2000 (fig. 40).

The waste loadings from the upstream dischargers (3M Company outfall No. 001 and the Dunkirk wastewater-treatment facility) had to be considered in determining the summer assimilative capacity of Big Lick Creek downstream from the Hartford City West wastewater-treatment facility. As mentioned previously, when K_n was assumed to be 0.1 or 0.3 day^{-1}, in-stream ammonia-toxicity standards limited ammonia-nitrogen concentrations in both these upstream discharge effluents. Because ammonia is generally more difficult to remove from effluent than CBOD is, maximum allowable ammonia-nitrogen concentrations and corresponding CBOD concentrations from figures 39 and 40 were used in determining the summer waste-assimilation capacity of Big Lick Creek downstream from the Hartford City West wastewater-treatment facility.

Table 24.--Population and flow projections through the year 2000 for municipalities in the Big Lick Creek basin, Blackford and Delaware Counties, Ind.

[Vince Sommers, Indiana State Board of Health, written commun., 1978]

Input	Year						
	1978	1980	1983	1985	1990	1995	2000
Hartford City East wastewater-treatment facility							
Population	4,688	------	------	------	------	------	------
Flow (Mgal/d)	1.10	------	------	------	------	------	------
Hartford City West wastewater-treatment facility							
Population	3,410	8,235	8,439	8,576	8,917	9,259	9,600
Flow (Mgal/d)	0.80	1.93	1.97	2.00	2.06	2.13	2.20
Dunkirk wastewater-treatment facility							
Population	3,314	3,557	3,596	3,635	3,704	3,797	3,840
Flow (Mgal/d)	0.89	0.90	0.92	0.93	0.95	0.98	1.00

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

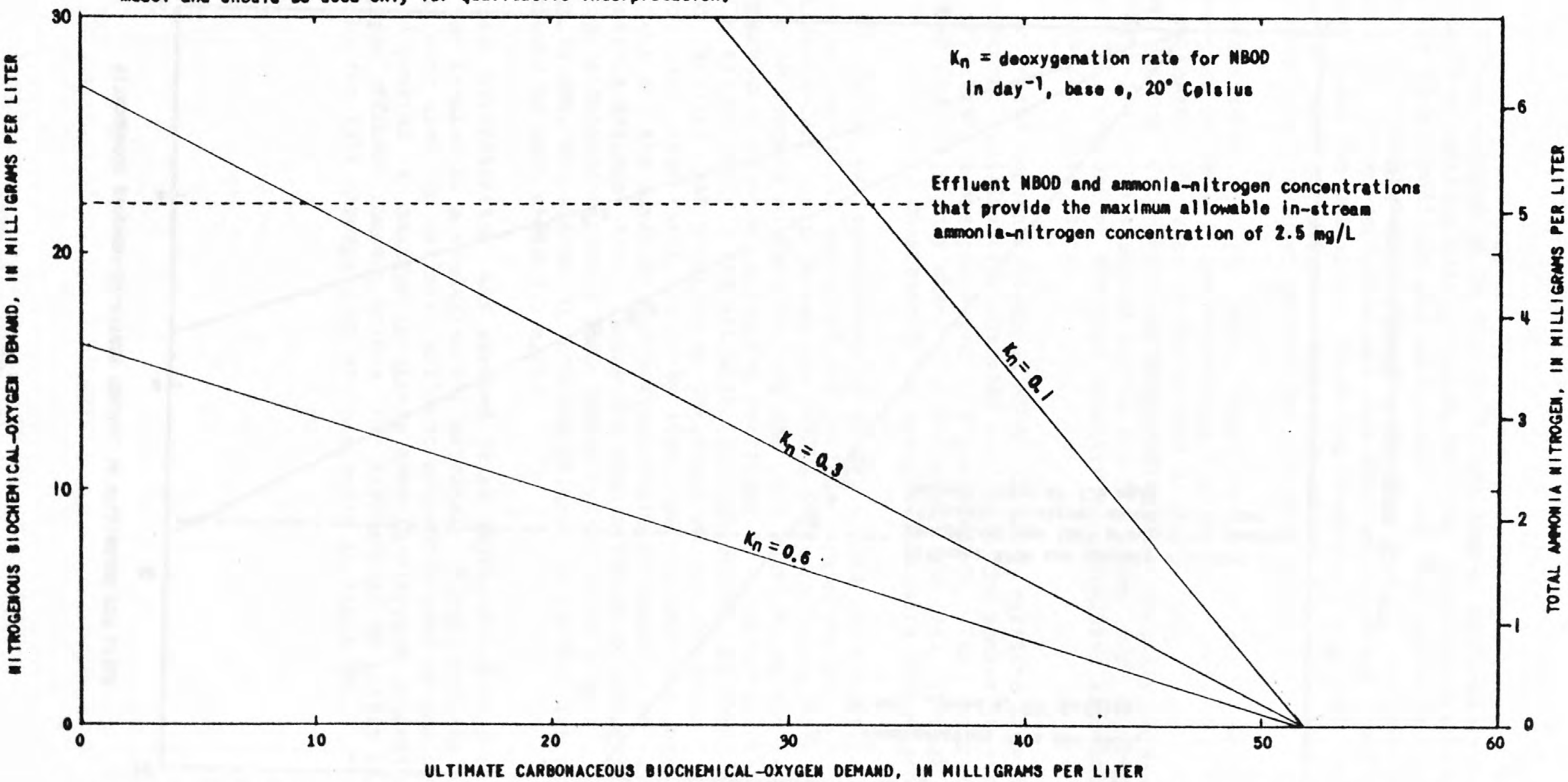

Figure 39.-- Projected alternative ultimate carbonaceous and nitrogenous waste loadings for the 3M Company outfall No. 001 on Little Lick Creek for 1980 that meet the minimum 24-hour average dissolved-oxygen concentration (5.0 mg/L) currently required for Indiana streams during summer low flows.

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

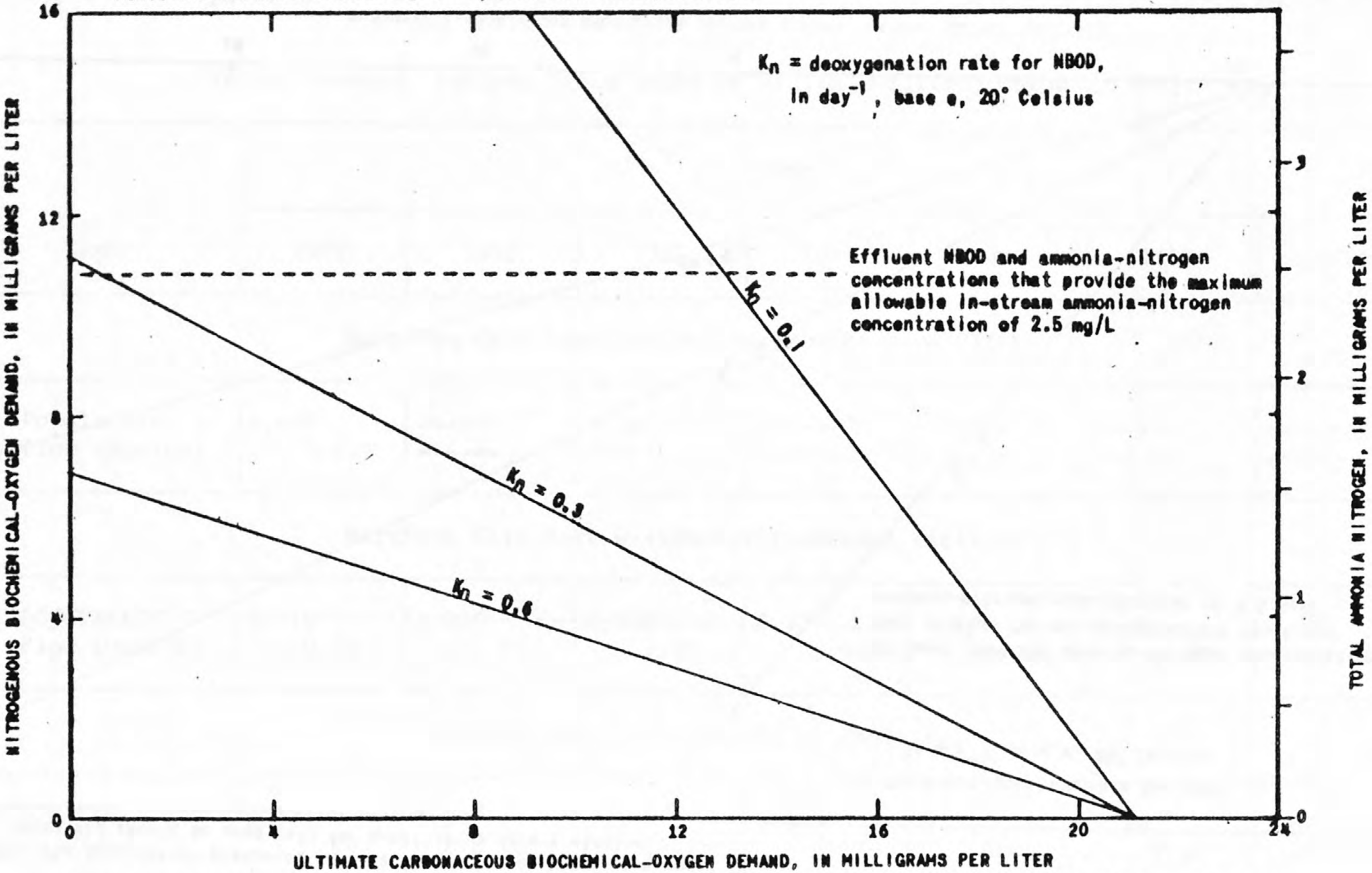

Figure 40.-- Projected alternateve ultimate carbonaceous and nitrogenous waste loadings for the Dunkirk wastewater-treatment facility on Big Lick Creek for the years 1980 through 2000 that meet the minimum 24-hour average dissolved-oxygen concentration (5.0 mg/L) currently required for Indiana streams during summer low flows.

When K_n was assumed to be 0.6 day^{-1}, the summer waste-assimilation study downstream from Hartford City provided for two upstream-discharger conditions. The first condition was zero CBOD and maximum NBOD concentrations from both 3M Company outfall No. 001 and the Dunkirk wastewater-treatment facility. The second condition was zero NBOD and maximum CBOD concentrations from these two outfalls. These two conditions represent the possible extremes of upstream effluent loads that affect the allowable load inputs from the Hartford City West wastewater-treatment facility.

For years 1983 through 2000, flow from the 3M Company outfall No. 001 was assumed to be zero. (See "Discharge Loadings.") This assumption provided a noticeable increase in calculated allowable waste-load concentration from the Hartford City West wastewater-treatment facility between 1980 and 1983 (figs. 41-44). Waste-load curves are not drawn for the years between 1983 and 2000 because of the near equality of calculated allowable CBOD and NBOD values for these years.

The projected concentrations of NBOD in the Hartford City West wastewater-treatment facility effluent that will meet the summer in-stream ammonia-toxicity standard are presented in figures 41-44. The toxicity standard limits NBOD discharge only where K_n = 0.1 day^{-1} for 1983 through 2000. Under other conditions, in-stream DO concentration limits NBOD discharge.

For the winter waste-assimilation study, K_n was assumed to be zero, and the only oxygen sinks were CBOD and benthic-oxygen demand. Maximum calculated ultimate-CBOD loads (based on NPDES 5-day CBOD concentration limitations) for 3M Company outfall No. 001 and the Dunkirk wastewater-treatment facility produced minimum calculated in-stream DO concentrations of 8.8 and 10.3 mg/L, respectively. The ultimate CBOD concentrations from the Hartford City West facility that provided an in-stream DO concentration of 5.0 mg/L were then calculated (table 25). By 1980, the new NPDES effluent-discharge restrictions for the advanced wastewater-treatment facility at Hartford City will require a maximum daily 5-day BOD concentration of 10 mg/L. The corresponding calculated ultimate CBOD concentration is 24.7 mg/L. If this requirement is met, the winter DO concentrations in Little Lick and Big Lick Creeks should be well above 5.0 mg/L.

Because nitrification was assumed to be negligible during the winter, ammonia was treated as a nondegradable material. Simple mass-balancing calculations were used to estimate effluent concentrations of ammonia nitrogen that would provide a maximum in-stream ammonia-nitrogen concentration of 4 mg/L. These effluent concentrations for dischargers on Little Lick and Big Lick Creeks for 1978 through 2000 are presented in table 26.

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

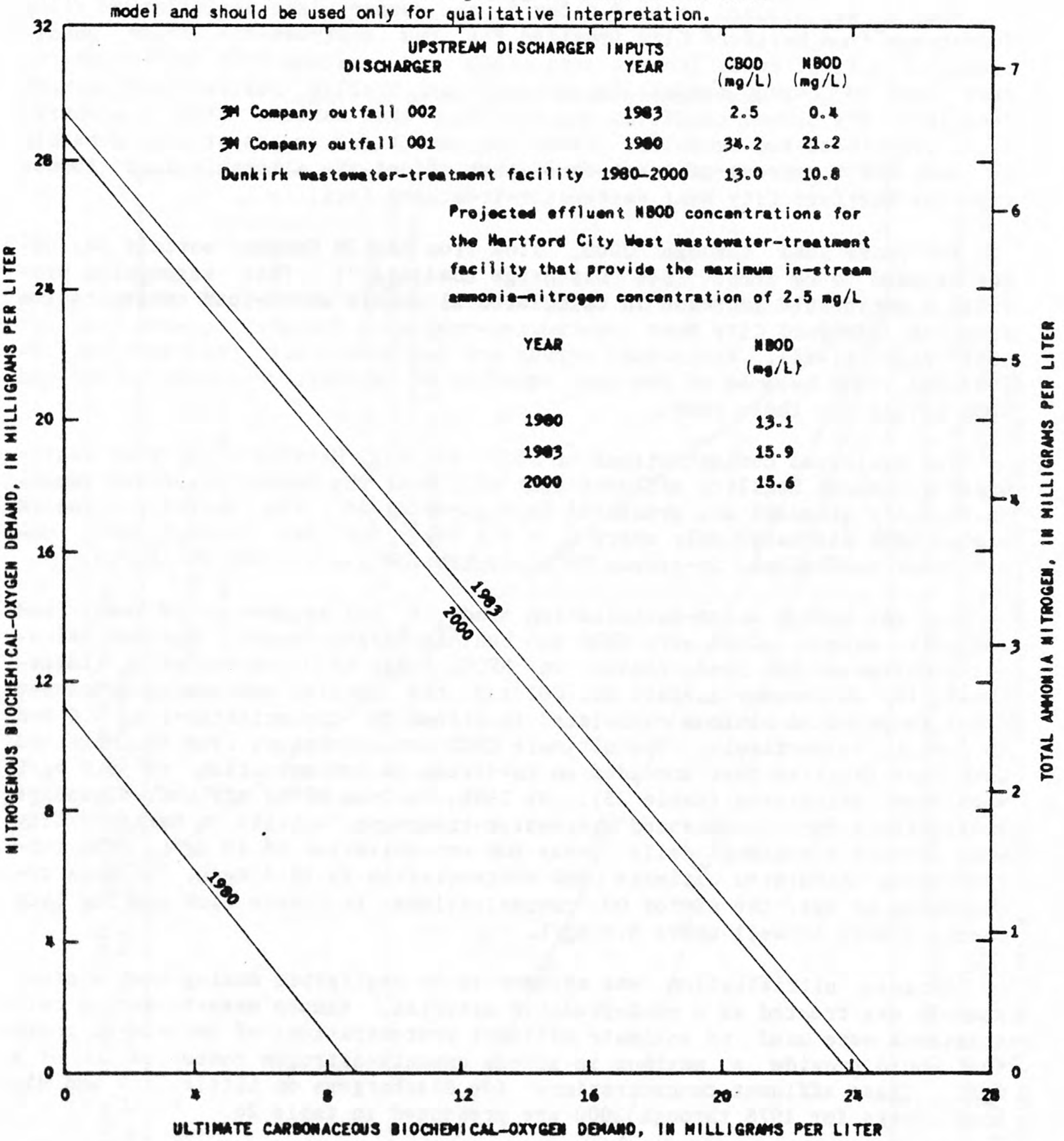

Figure 41.-- Projected alternative ultimate carbonaceous and nitrogenous waste loadings for the Hartford City West wastewater-treatment facility on Big Lick Creek that meet the minimum 24-hour average dissolved-oxygen concentration (5.0 mg/L) currently required for Indiana streams during summer low flows, where Kn (deoxygenation rate for NBOD) is 0.1 day -1.

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

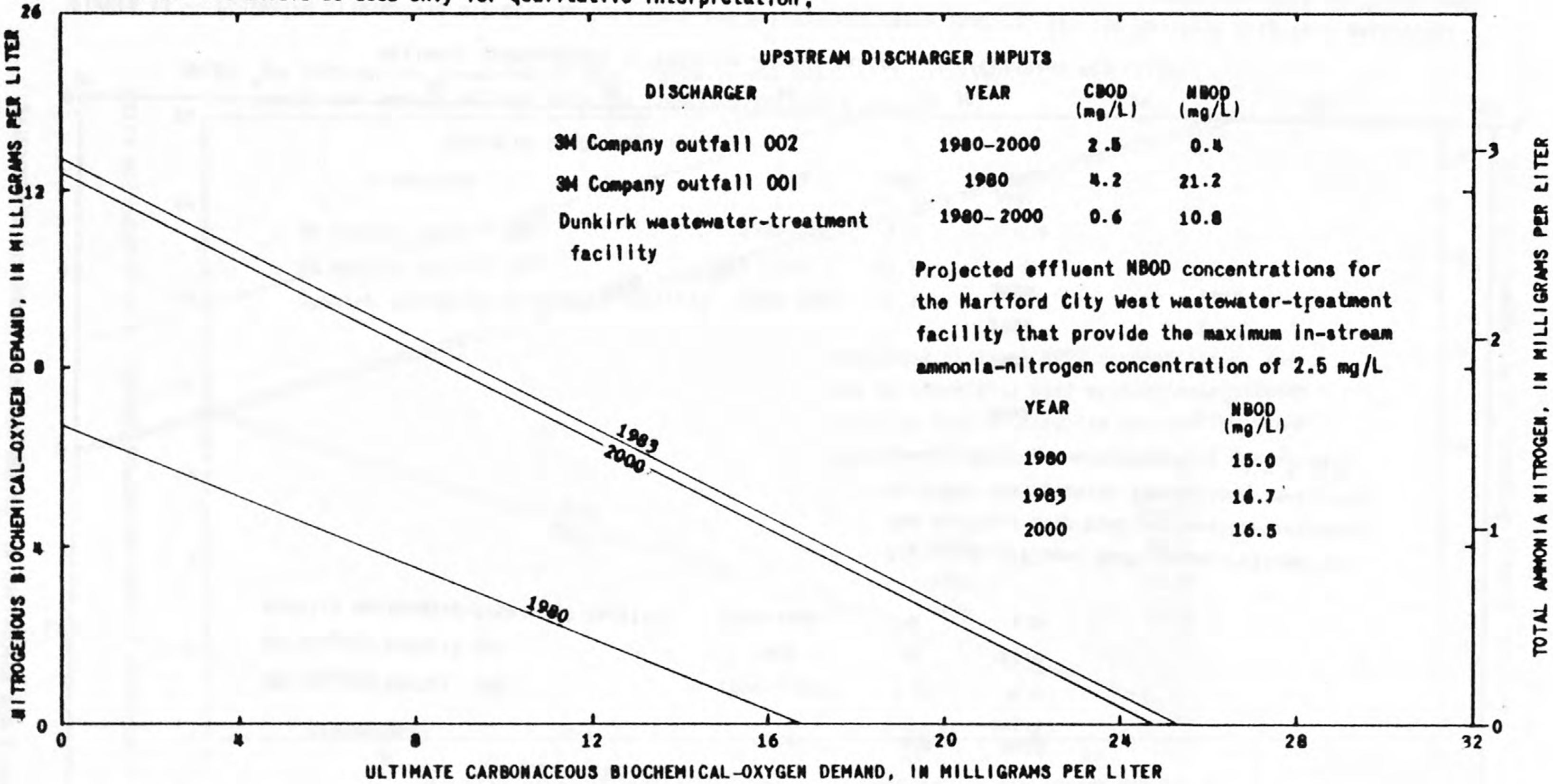

Figure 42.-- Projected alternative ultimate carbonaceous and nitrogenous waste loadings for the Hartford City West wastewater-treatment facility on Big Lick Creek that meet the minimum 24-hour average dissolved-oxygen concentration (5.0 mg/L) currently required for Indiana streams during summer low flows, where K_n (deoxygenation rate for NBOD) is 0.3 day^{-1}.

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

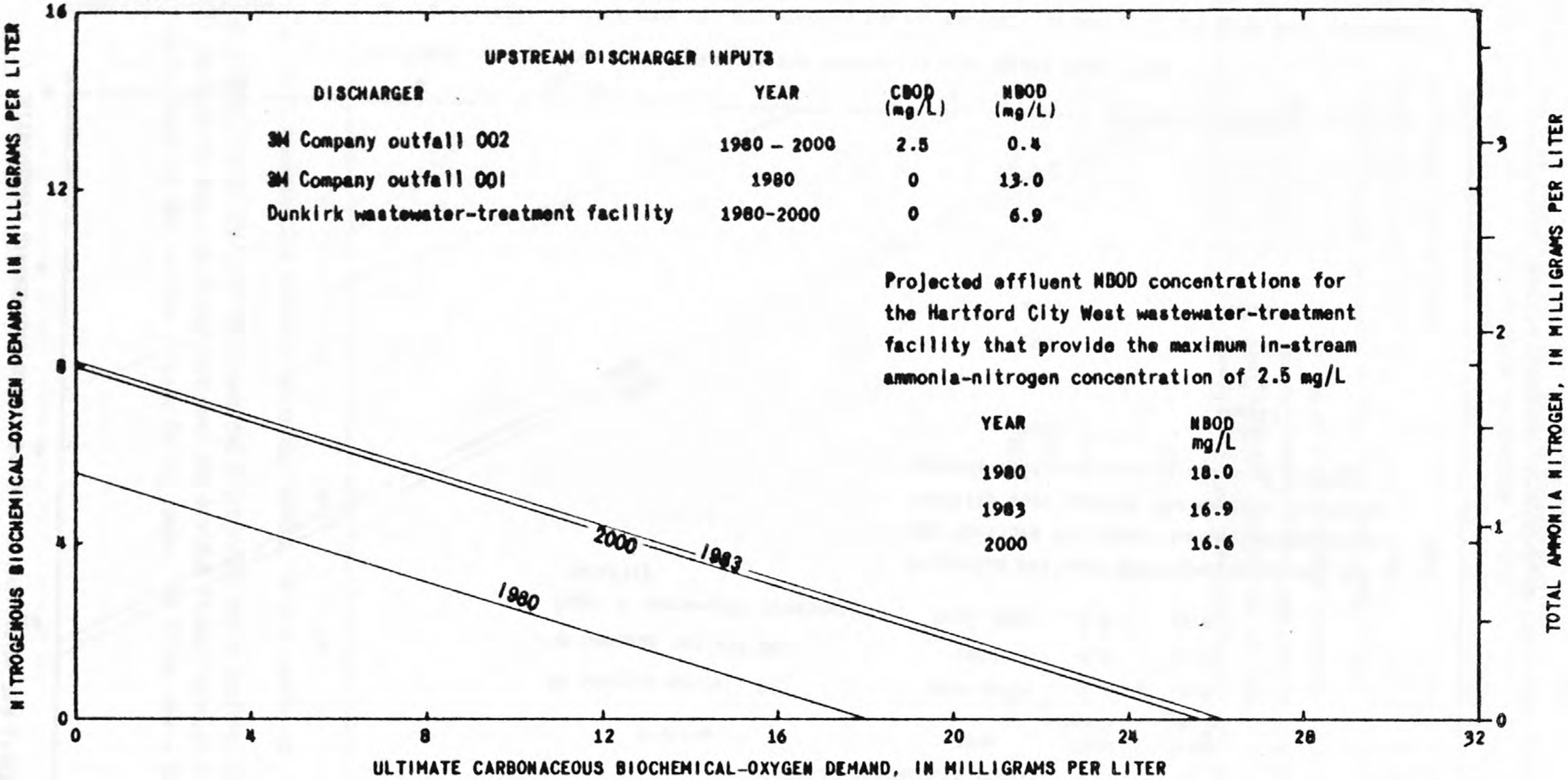

Figure 43.-- Projected alternative ultimate carbonaceous and nitrogenous waste loadings for the Hartford City West wastewater-treatment facility on Big Lick Creek that meet the minimum 24-hour average dissolved-oxygen concentration (5.0 mg/L) currently required for Indiana streams during summer low flows, where K_n (deoxygenation rate for NBOD) is 0.6 day^{-1} and the 3M Company outfall No. 001 and Dunkirk wastewater-treatment facility are discharging maximum projected concentrations of NBOD.

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

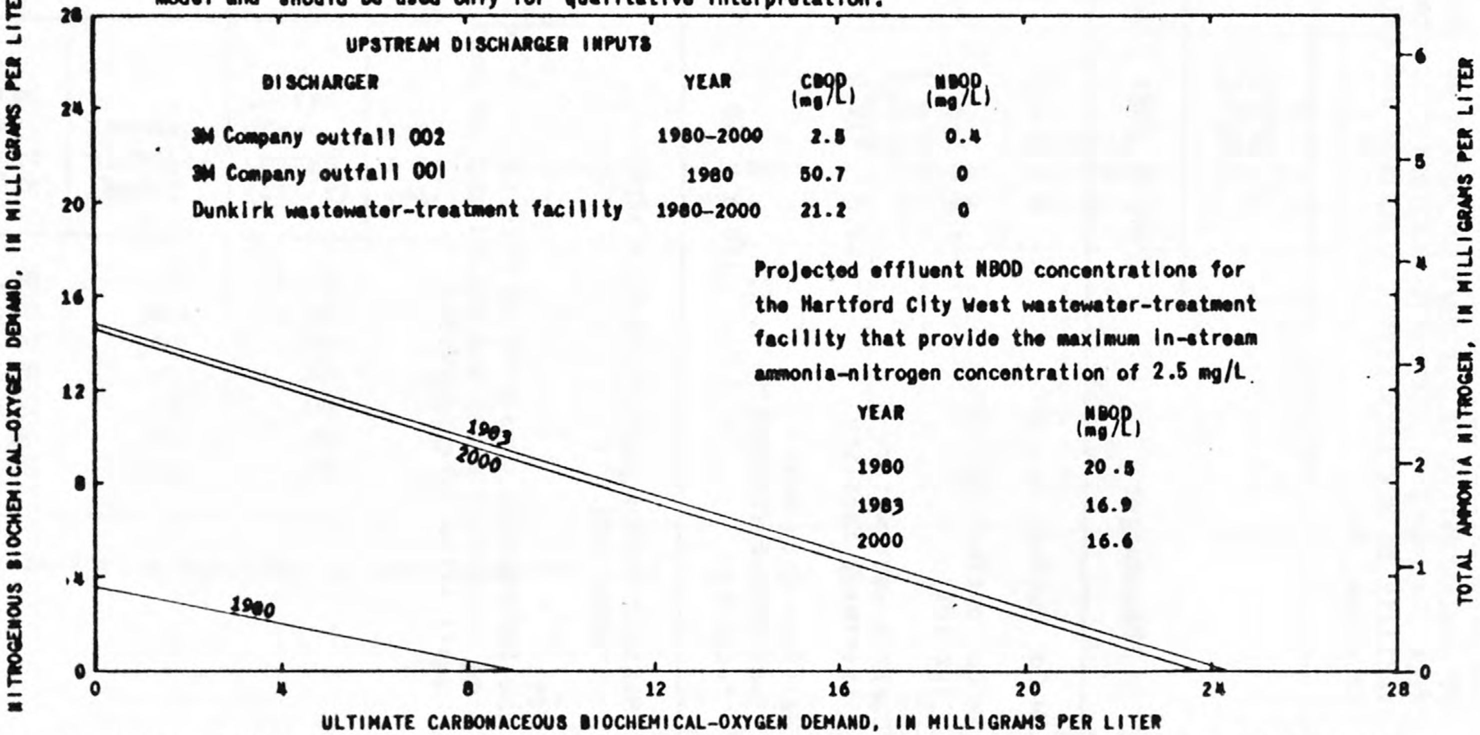

Figure 44.-- Projected alternative ultimate carbonaceous and nitrogenous waste loadings for the Hartford City West wastewater-treatment facility on Big Lick Creek that meet the minimum 24-hour average dissolved-oxygen concentration (5.0 mg/L) currently required for Indiana streams during summer low flows, where K_n (deoxygenation rate for NBOD) is 0.6 day^{-1} and the 3M Company outfall No. 001 and Dunkirk wastewater-treatment facility are discharging maximum projected concentrations of CBOD.

Table 25.--Calculated ultimate CBOD concentrations for dischargers that provide a minimum in-stream DO concentration of 5.0 mg/L in winter downstream from the Hartford City West wastewater-treatment facility on Big Lick Creek, Blackford and Delaware Counties, Ind.

Discharger	CBOD (mg/L)		
	1980	1983	2000
3M Co. outfall No. 002	2.5	2.5	2.5
3M Co. outfall No. 001 (or 101)	[1]77.0	[1]77.0	[1]77.0
Dunkrik wastewater-treatment facility	[1]19.0	[1]19.0	[1]19.0
Hartford City West wastewater-treatment facility	118.0	120.5	118.5

[1]Maximum values calculated from NPDES information.

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

Table 26.--Total ammonia-nitrogen concentrations from dischargers that will provide an in-stream total ammonia-nitrogen concentration of 4.0 mg/L in Little Lick and Big Lick Creeks during winter low flows

	3M Co. outfall No. 002		3M Co. outfall No. 001		Hartford City East wastewater-treatment facility		Dunkirk wastewater-treatment facility		Hartford City West wastewater-treatment facility	
Year	Projected discharge (ft^3/s)	Ammonia nitrogen (mg/L)	Projected discharge (ft^3/s)	Ammonia nitrogen (mg/L)	Projected discharge (ft^3/s)	Ammonia nitrogen (mg/L)	Projected discharge (ft^3/s)	Ammonia nitrogen (mg/L)	Projected discharge (ft^3/s)	Ammonia nitrogen (mg/L)
1978	1.00	0.40	1.00	5.33	1.71	5.33	1.38	4.00	1.24	4.00
1980	1.00	.40	1.00	7.60	.00	----	1.40	4.00	2.99	4.00
1983	1.00	.40	.00	----	.00	----	1.43	4.00	3.05	5.18
1985	1.00	.40	.00	----	.00	----	1.44	4.00	3.10	5.16
1990	1.00	.40	.00	----	.00	----	1.47	4.00	3.19	5.13
1995	1.00	.40	.00	----	.00	----	1.52	4.00	3.30	5.09
2000	1.00	.40	.00	----	.00	----	1.55	4.00	3.41	5.06

Note: The following equation is used to convert concentration to load.

$$L = 5.39\ CQ$$

where

L is load, in pounds per day,

C the concentration, in milligrams per liter,

and

Q the discharge, in cubic feet per second.

SUMMARY AND CONCLUSIONS

A one-dimensional, steady-state, dissolved-oxygen model was calibrated with three sets of water-quality data. A simulation model was developed to evaluate various waste-load options for the industrial and municipal dischargers on Little Lick and Big Lick Creeks. The model is limited to qualitative evaluation because it was not based on a calibrated or verified model.

The generally low DO concentrations of both Little Lick and Big Lick Creeks during the three water-quality surveys are probably due to low rates of reaeration, large waste loads, and benthic-oxygen demand.

The model calculations indicate that under present (1977-1978) basin conditions, the streams afford virtually no assimilative capacity and that reductions in effluent waste loads are needed for both municipal and industrial dischargers. The hypothetical waste-assimilation study was based on the assumption that decreased waste loads would reduce benthic-oxygen demand and, thus, provide assimilative capacity. The resulting higher in-stream DO concentrations could be expected to change the rate of nitrification. Thus, the summer assimilative capacity was calculated for three rates of nitrification.

The hypothetical summer and winter waste-assimilation studies assumed that nonpoint-source contributions to benthic deposits were negligible and that a reduction in effluent waste loads would decrease benthic-oxygen demand. The summer study also provided for an increase in the rates of nitrification. Calculations indicated that ammonia toxicity would limit NBOD concentrations from major dischargers in summer at low rates of nitrification.

Under NPDES discharge restrictions, projected in-stream DO concentrations did not fall below 5.0 mg/L during winter low flow. Owing to a lack of dilution, current NBOD concentrations in discharge effluents would have to be reduced to meet the maximum in-stream ammonia-nitrogen standard, 4.0 mg/L.

Because of the low assimilative capacity of Little Lick and Big Lick Creeks, the effluent-load concentrations from additional dischargers to the streams might be limited to in-stream background concentrations.

During low flow, virtually all flow in both Little Lick and Big Lick Creeks is from effluent dischargers. Present plans indicate that within a few years the number of dischargers will decrease, and the quality of effluent will improve. The assumptions made in the hypothetical waste-assimilation study were designed to accommodate these changes and were based on the best information available. However, the validity of these assumptions is largely unknown. Especially critical are changes in rates of nitrification and benthic-oxygen demand. A re-evaluation of the stream system after the anticipated improvement in effluent-discharge loadings would permit quantitative interpretation of the waste-assimilation study.

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