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16. Abstract

The usual procedure for predicting or estimating the assimilation capacity of a receiving stream involves application of the Streeter-Phelps Equation. However, such prediction has not provided sufficiently accurate estimates of the assimilation capacity. Previous laboratory research had indicated that if an open jar technique is used to replace the BOD bottle technique for obtaining the O_2 utilization curve, the DO profile in the receiving stream can be more accurately predicted. A section of Black Bear Creek located in Noble and Pawnee Counties, Oklahoma was used to evaluate the open jar technique. Reaeration characteristics were estimated from the physical characteristics of the stream. O_2 uptake data were determined by the open jar technique. A DO profile was predicted for a particular situation. A knownwaste water was introduced into Black Bear Creek (with permission of the Oklahoma Department of Pollution Control) and the resulting DO profile was measured. The open jar technique did predict the DO profile very well.

17a. Descriptors

assimilation, BOD, open jar technique

17b. Identifiers

Streeter-Phelps Equation, Black Bear Creek, Noble county, Pawnee county

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PREDICTION OF ASSIMILATION CAPACITY IN SMALL RECEIVING STREAMS

INTRODUCTION

Increased concern over the quality of the region's surface water comes about largely because of new pollution control laws and regulations and partly because of the need and desirability for regional development without deterioration of environmental quality. In both the planning and developmental stages there is an absolute need to predict or estimate the assimilation capacity of surface waters receiving various point and non-point sources of runoff due to human activity. Many years ago, based on studies of the assimilation capacity of the Ohio River, workers such as Streeter and Phelps developed a technological concept and strategy for estimating the dissolved oxygen profile in a receiving stream which was to receive or was already receiving a flow of waste runoff containing organic pollutants.[1] The mathematical expression of this strategy is known as the dissolved oxygen sag equation. Since 1927 it has been the standard way of estimating assimilation capacity even though various researchers have challenged the concept and many times the estimate of assimilation capacity using the approach has been proven wrong.

The need for making such estimates is obvious and the demand for making them is greater than in the past. Consequently, the knowledge that the old methodology does not suffice dictates an accelerated search for new methodology. A new method for predicting the DO profile, based on laboratory studies, has recently been recommended by Gaudy and coworkers.[2-4] However, this research needed to be carried to the field level in an environment that is amenable to controlled experimentation and measurement. In order to accomplish the needed research, it was essential that a stream be selected in rather close proximity to the bioenvironmental laboratories and one small enough to be monitored and hydraulically characterized without an excessively expensive field investigation. The stream selected was Black Bear Creek.

The primary objective of this research was to test the method of predicting the DO profile which has been recommended by Gaudy and co-workers.[2-4]

Another objective closely allied to the prediction of assimilation capacity is the prediction of river flows from rainfall data. Prediction of flow from rainfall data is extremely important in small watersheds because the rivers (creeks) carrying the runoff are usually not of sufficient size to warrant gauging or flow measurement by USGS. Thus, flow data is not available for such streams, and an indirect method such as prediction from rainfall-runoff relationships is needed.

METHODOLOGY

The capacity of a receiving stream for assimilation of organic matter is directly related to the dissolved oxygen concentration, and the stream standards (effluent standards as well) are determined by the minimum allowable dissolved oxygen in the receiving body. The dissolved oxygen concentration is dependent upon a number of factors, but particularly on the relationship between the flow of waste effluent (i.e., source of organic matter) and the flow in the receiving body. For any given river flow, the dissolved oxygen profile is dependent in the main on two opposing phenomena. Oxygen utilization by the organisms in metabolizing the organic pollutants is a phenomenon causing a decrease in dissolved oxygen whereas oxygen replenishment due to mass transfer of O_2 from the atmosphere to the body of water represents the opposing phenomenon. These two opposing forces are mathematically joined in the well known Streeter-Phelps sag equation. While the equation has not proved very useful, the concept of deoxygenation and reaeration is a useful one and is the basis for the method presented in this report.

Estimating the DO Profile

The method suggested by Gaudy and co-workers for estimating the DO profile in a stream is referred to as the stirred open jar method. The procedure involves the addition of effluent to river water in the laboratory in a 10 liter stirred batch reaction tank. The dissolved oxygen profile developed in the mixture of effluent to river water in this reactor is then determined. Following this, the reaeration kinetics of the stirred system are determined. This information is numerically integrated with the dissolved oxygen profile to determine the oxygen uptake or BOD curve. This BOD curve can then be numerically integrated with the K_2 values in the downstream reaches of the receiving stream, and the DO profile in that stream can be predicted.

A step by step procedure is presented.

Step 1. Determine K_2 values for receiving stream.

The K_2 values for the receiving stream are determined by using the empirical relationship:

$$K_{2(20^{o})} = 3.74 \frac{V}{H^{1.5}}(1.0241)^{T-20}$$

In the above equation the numerical value 3.74 is a constant determined experimentally(5). V is the velocity of the flowing body of water; H is the average depth, and T is the temperature. The average velocity and depth in the river reach are obtained by taking cross sections in the river at various locations during various discharges or stream flows. The velocity is obtained with current meters. Cross sections and velocity readings should be taken at each point where the characteristics of the stream change.

K_2 can then be plotted versus the flow rate (Q) for each location. The type of curves obtained are shown in Figure 1.

Step 2. Determine time of travel in stream.

The time of travel in a stream can be determined by several methods. These include (1) use of average velocity, (2) Manning's equation, (3) time objects floating downstream and (4) fluorescent dye. Timing the movement of fluorescent dye downstream is the most accurate, but also the most expensive.

Step 3. Determine DO profile of stream-effluent mixture.

Add effluent to a volume of the receiving stream water in an open jar reactor in the desired proportion and aerate the system with compressed air for a short time to bring the DO level close to the saturation concentration in order to insure sufficient DO at the start of the test. At this time, a portion of acclimated seed is added to the mixture. Also, the system should have been previously adjusted to the test temperature, usually that expected at the design low flow. Set the mixing device to give a K_2 close to that expected in the field. If this method is routinely conducted, a relationship will be developed between stirring speed and K_2 (see Step 4). Dissolved oxygen is measured electrometrically at various time periods.

A suitable size reactor volume is ten liters, and a simple reactor setup such as shown in Figure 2 is an ample test apparatus. Stirring may be provided by a small propeller and a rheostat-controlled 1/50 hp motor.

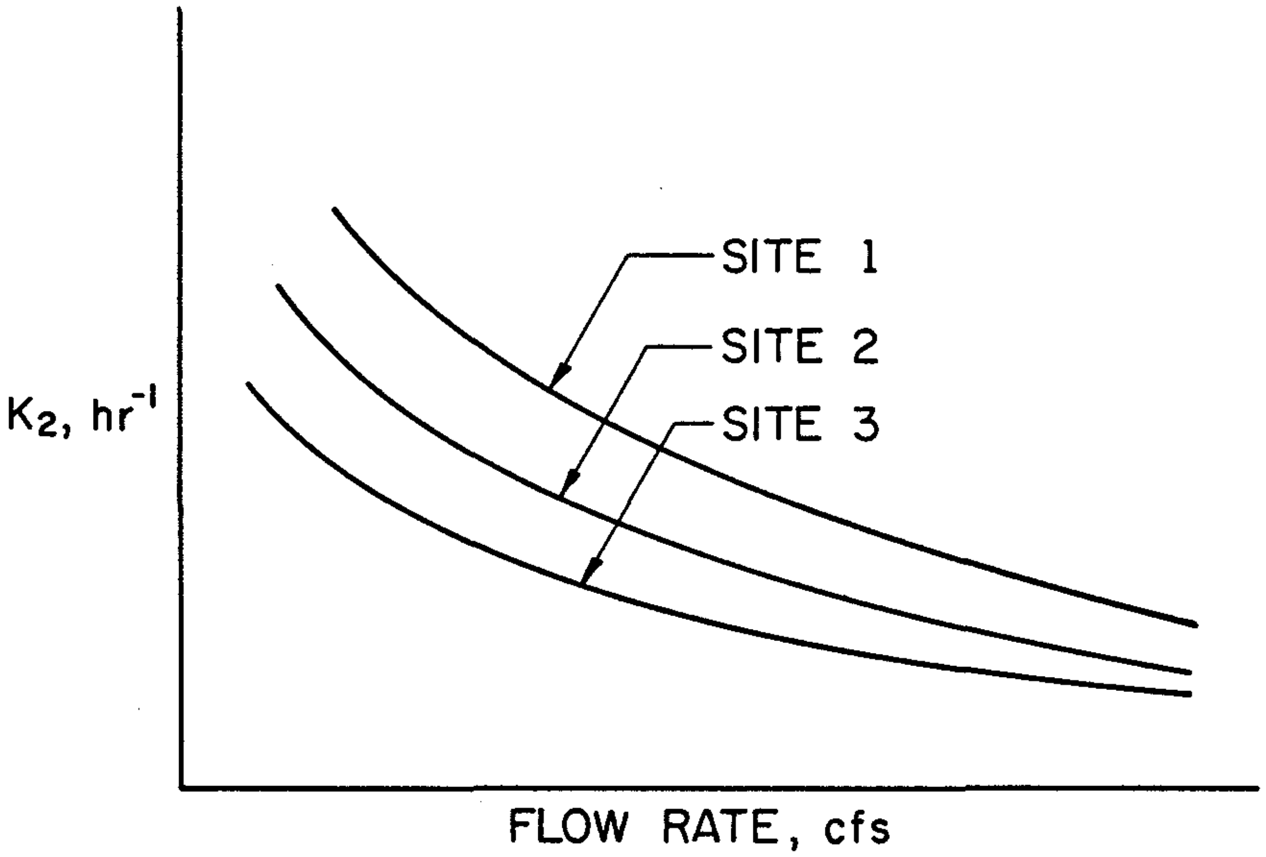

Figure 1. K_2 AS A FUNCTION OF FLOW RATE.

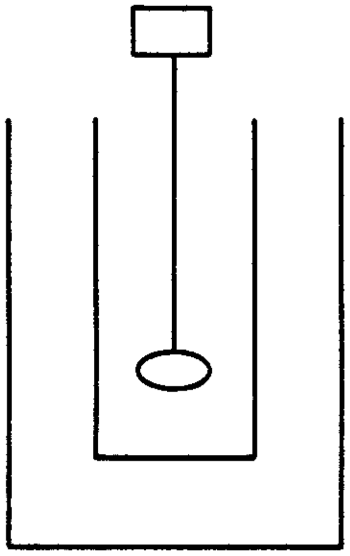

Figure 2. OPEN JAR REACTOR.

An example of the type of data obtained is shown in Figure 3.

Step 4. Determine K_2 in reactor.

After recovery in DO is nearly complete, a bactericidal agent is added to stop further oxygen utilization. After a suitable contact time, the dissolved oxygen is removed by addition of sodium sulfite with catalytic amounts of cobalt chloride. After the dissolved oxygen concentration has been removed, continued monitoring of the system for dissolved oxygen concentration will produce the reaeration curve (see Figure 4). The saturation concentration, C_s, and the reaeration velocity constant, K_2, can be calculated from the reaeration data by a variety of methods available for fitting first order decreasing rate curves.

Step 5. Numerically integrate DO profile and K_2 values to obtain BOD curve.

The calculation procedure is illustrated in Table 1 using data obtained by Peil and Gaudy.[2] In this experiment the dissolved oxygen saturation value and the reaeration constant K_2 were found to be 8.7 mg/l and 0.099 hr^{-1} respectively. The observed dissolved oxygen concentrations at various times throughout the open jar experiment are shown in column 6. The deficit was computed by subtracting the dissolved oxygen concentration from the value of C_s, i.e., 8.7, and these values are recorded in column 2. Each deficit is multiplied by the K_2 value, 0.099 hr^{-1}, and the product is entered in column 3. The time interval is recorded in column 4, and in column 5 the average values during the time interval taken from column 3, e.g., $(0.15 + 0.09) \div 2$, are multiplied by Δt to estimate the amount of oxygen that has been put into the system

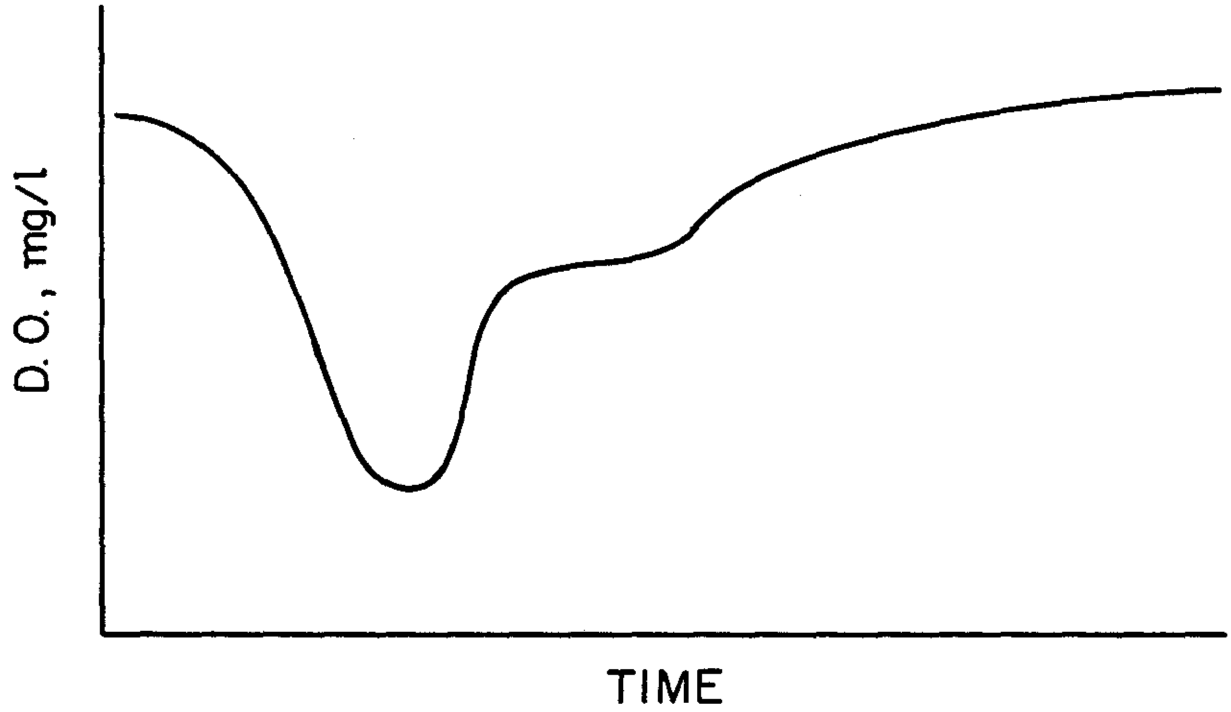

Figure 3. D.O. PROFILE

TABLE 1

Calculation of Oxygen Uptake From Open Jar Reactors

1	2	3	4	5	6	7	8	9
Hour	D mg/l	K_2D mg/l-hr	Δt hr	$K_2D\Delta t$ mg/l	DO mg/l	ΔDO mg/l	5-7 mg/l	O_2 Uptake mg/l
0.00	1.50	0.15	6.25	0.74	7.20	.62	0.12	0
6.25	0.88	0.09	2.75	0.24	7.82	0.00	0.24	0.12
9.00	0.88	0.09	2.50	0.23	7.82	-0.09	0.32	0.36
11.50	0.97	0.10	10.50	2.04	7.73	-1.98	4.02	0.68
22.00	2.95	0.29	2.50	0.85	5.75	-0.95	1.80	4.70
24.50	3.90	0.39	2.00	0.80	4.80	-0.32	1.12	6.50
26.50	4.22	0.42	2.00	0.87	4.48	-0.31	1.18	7.62
28.50	4.53	0.45	1.25	0.57	4.17	-0.21	0.78	8.80
29.75	4.74	0.47	1.75	0.86	3.96	-0.42	1.28	9.58
31.50	5.16	0.51	2.00	1.11	3.54	-0.83	1.94	10.86
33.50	5.99	0.59	2.00	1.25	2.71	-0.63	1.88	12.80
35.50	6.62	0.66	4.75	3.41	2.08	-1.25	4.66	14.68
40.25	7.87	0.78	5.75	4.40	0.83	0.32	4.08	19.34
46.00	7.55	0.75	3.00	2.11	1.15	0.93	1.18	23.42
49.00	6.62	0.66	4.00	2.44	2.08	0.94	1.50	24.60
53.00	5.68	0.56	4.50	2.37	3.02	0.73	1.64	26.10
57.50	4.95	0.49	12.75	6.17	3.75	0.13	6.04	27.74
70.25	4.82	0.48	5.25	2.29	3.88	0.82	1.47	33.78
75.50	4.00	0.40	8.00	2.72	4.70	1.12	1.60	35.25
83.50	2.88	0.29	12.50	3.13	5.82	0.72	2.41	36.85
96.00	2.16	0.21	11.50	2.30	6.54	0.28	2.02	39.26
107.50	1.88	0.19	13.00	2.05	6.82	0.58	1.47	41.28
120.50	1.30	0.13	3.75	0.48	7.40	0.00	0.48	42.75
124.25	1.30	0.13			7.40			43.23
	$C_s = 8.70$ mg/l				$K_2 = 0.099$ hr^{-1}			

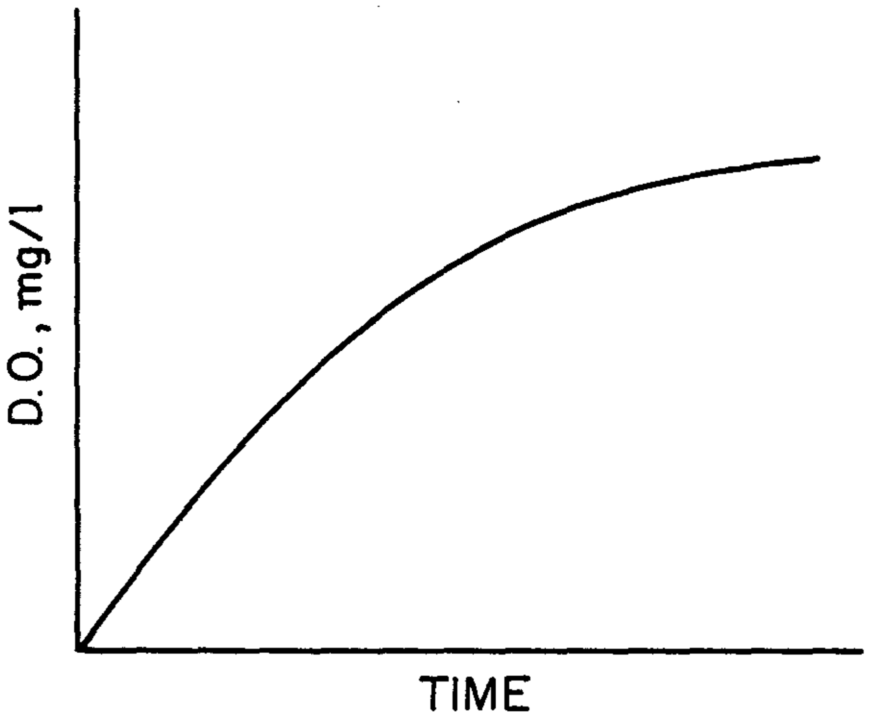

Figure 4. REAERATION IN OPEN JAR REACTOR.

during the time interval (see column 5). In column 7 the change in the dissolved oxygen concentration is recorded. During the first time interval in the example shown, the DO rose 0.62 mg/l. However, during the interval 0.74 mg/l of oxygen entered the system. The difference 0.12 is recorded in column 8 as the oxygen uptake or BOD exerted during this time interval. Similar calculations can now be made for the next time interval, i.e., 6.25 to 9 hrs, and the oxygen uptake during this interval, i.e., 0.24 mg/l, is then added to that in the previous interval, and the accumulated oxygen uptake curve (BOD curve) is given in column 9.

Column 9 can then be plotted to produce a BOD curve similar to that shown in Figure 5.

Step 6. Numerically intergrate BOD curve with stream K_2 values to obtain stream DO value as a function of time.

Table 2 shows an example of a calculation of the dissoved oxygen profile using the oxygen uptake curve developed in Table 1. The oxygen uptake curve from Table 1 was plotted, and the oxygen uptake for BOD values at even hour intervals was read off. These data are shown in columns 1, 2, and 3 of Table 2. Since only a small amount of oxygen was utilized during the first twelve hours, calculations prior to 12 hours have been neglected. For the example given, the DO in the stream at 12 hours was 6.84 mg/l, C_s was 8.8 mg/l and K_2 was 0.120 hrs^{-1}. The oxygen uptake during the four hour interval between 12 and 16 hrs shows the deficits from saturation. The initial deficit, 1.96, was obtained by subtracting the initial DO from the saturation value.

The deficit that existed at the beginning of the four hour interval is assumed to apply over its entire length, and the amount of oxygen added

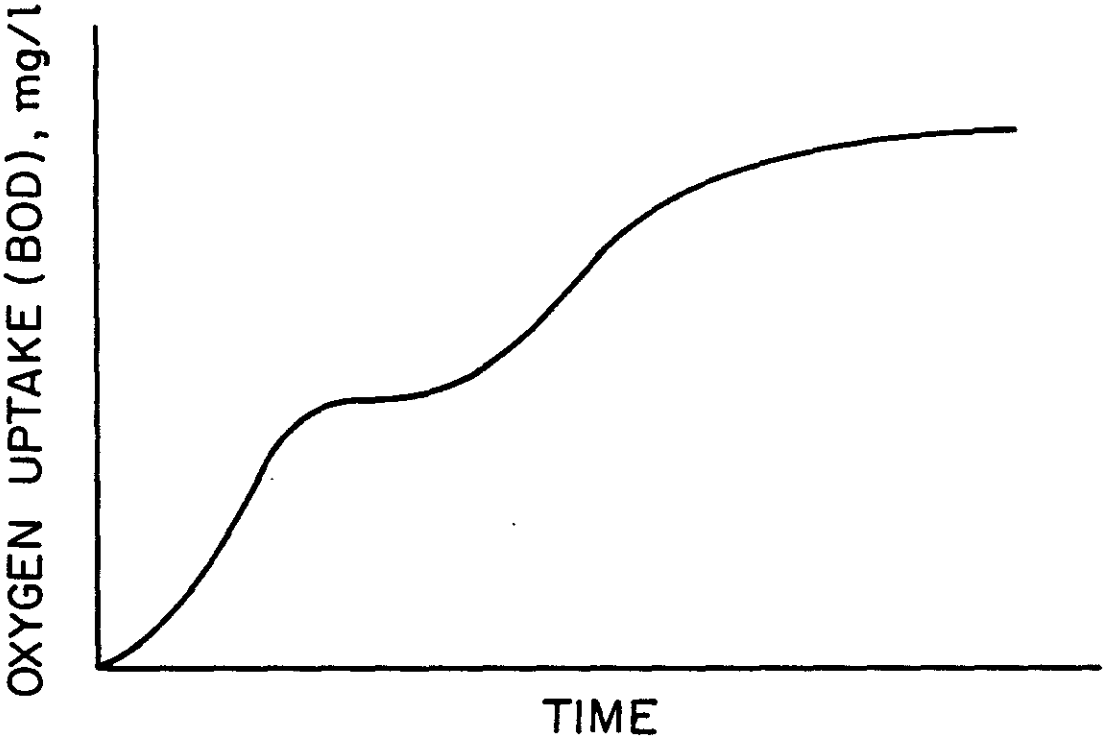

Figure 5. CALCULATED BOD CURVE.

TABLE 2

Calculation of DO Profile From

O_2 Uptake Curves

1	2	3	4	5	6	7	8
Hour	Δt hr	O_2 Uptake mg/l	ΔO_2 mg/l	D mg/l	$K_2D\Delta t$ mg/l	ΔDO mg/l	DO mg/l
12	4	0.80	1.25	1.96	0.94	0.31	6.84
16	2	2.05	0.80	2.27	0.55	0.25	6.53
18	2	2.85	0.90	2.52	0.61	0.29	6.28
20	2	3.75	0.95	2.81	0.67	0.28	5.99
22	2	4.70	1.25	3.09	0.74	0.51	5.71
24	2	5.95	1.25	3.60	0.86	0.39	5.20
26	2	7.20	1.10	3.99	0.96	0.14	4.81
28	2	8.30	1.60	4.13	0.99	0.61	4.67
30	2	9.90	1.30	4.74	1.14	0.16	4.06
32	2	11.20	1.80	4.90	1.18	0.62	3.90
34	2	13.00	2.00	5.52	1.32	0.68	3.28
36	2	15.00	2.00	6.20	1.49	0.51	2.60
38	2	17.00	1.80	6.71	1.61	0.19	2.09
40	2	18.80	1.60	6.90	1.66	-0.06	1.90
42	2	20.40	1.50	6.84	1.64	-0.14	1.96
44	2	21.90	1.50	6.84	1.64	-0.11	2.10
46	2	23.40	0.75	6.59	1.58	-0.83	2.21
48	4	24.15	1.55	4.76	2.77	-1.22	3.04
52	4	25.70	1.50	4.54	2.18	-0.68	4.26
56	4	27.20	1.60	3.86	1.85	-0.25	4.94
60	4	28.80	1.85	3.61	1.73	0.12	5.19
64	4	30.65	2.00	3.73	1.79	0.21	5.07
68	4	32.65	1.65	3.94	1.89	-0.24	4.86
72	4	34.30	1.15	3.70	1.78	-0.63	5.10
76	8	35.45	1.55	3.07	2.95	-1.40	5.73
84	8	37.00	1.45	1.67	1.60	-0.15	7.13

C_s = 8.80 mg/l K_2 = 0.120 hr^{-1}

during the time interval was obtained by multiplying the reaeration constant by the deficit value and Δt. Thus, during the first interval the amount of oxygen put into the system by reaeration was 0.94 mg/l. Column 6 is then subtracted from column 4, and the difference in dissolved oxygen concentration during the time interval is recorded as 0.31 in column 7. Since oxygen uptake in column 4 was greater than oxygen replenished by reaeration, the dissolved oxygen concentration has decreased by the amount 0.31 mg/l. This decrease is reflected in column 8 in which the dissolved oxygen profile values are listed. The calçulations just described are repeated for the next time interval, and the DO profile is thus calculated. In these sample calculations, K_2 remained constant; however, in actual receiving stream situations there may be many K_2 values in the successive downstream reaches. In this case it is necessary to change the multiplier in column 6. A change in K_2 can conceivably cause a change in the oxygen uptake curve. However, such a change after the low point in the predicted profile, i.e., after oxygen uptake has slowed would not appear to cause serious discrepancies in the recovery leg of the profile.

Step 7. Correlate DO profile versus time with time of travel of stream. This step will locate the DO profile with distance.

Predicting low flows

Model Description

The National Weather Service River Forecast System (NWSRFS) conceptual hydrologic model was used to simulate the observed streamflow at the Pawnee gage site. (See Figure 6 for model schematic). The simulation was accomplished by making trial and error runs with the NWSRFS for a period of

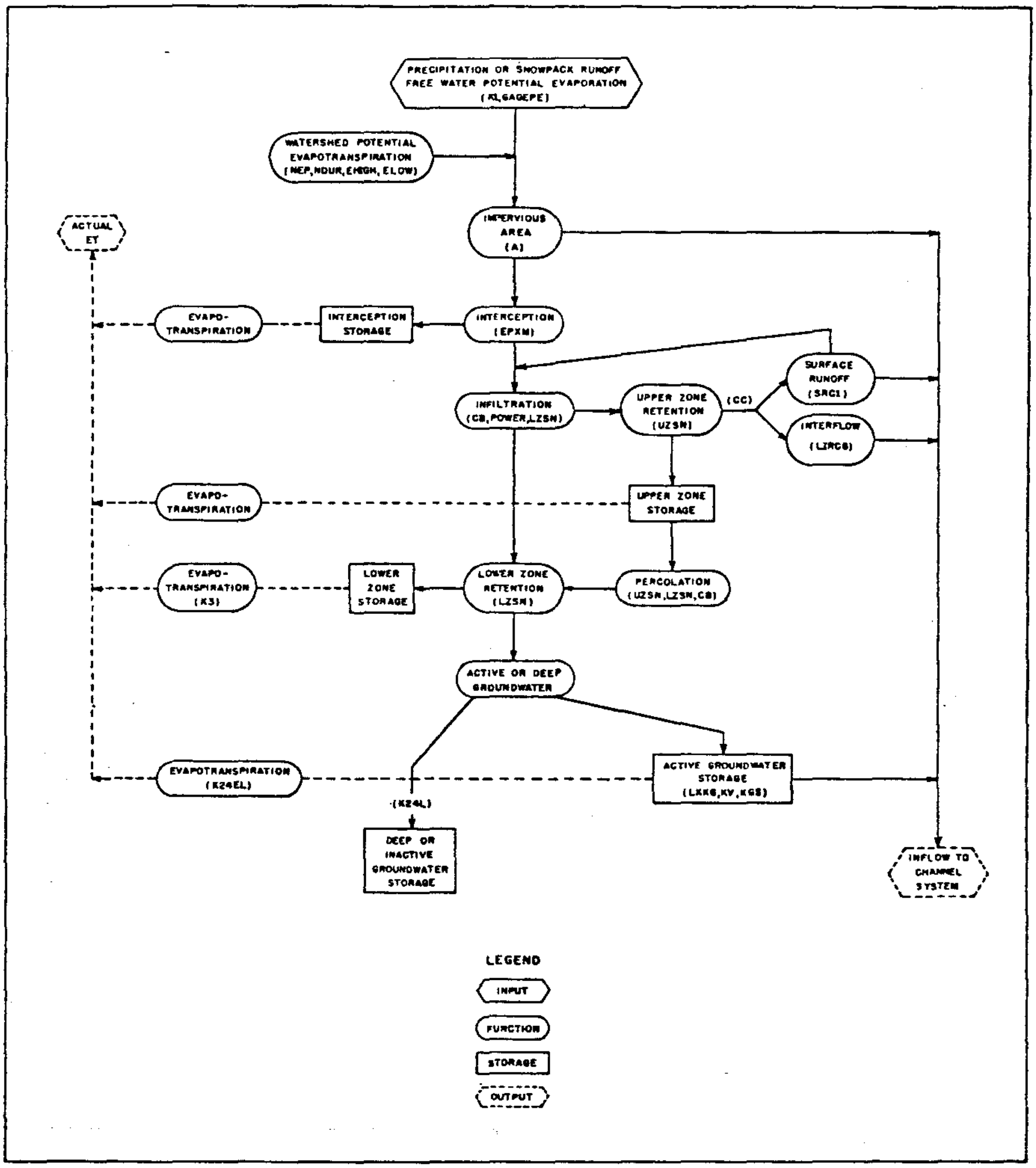

Figure 6. Flowchart of soil moisture accounting portion of the National Weather Service River Forecasting System

record from October 1, 1958 to September 30, 1968. Forty-one trial and error runs were made before the optimum simulation was accomplished.

The optimized model is capable of predicting low flows as well as those of flood magnitude. The only input data needed are the observed or determined rainfall in the basin and a computed evapotranspiration rate.

FIELD STUDIES

The stream selected to field test the open jar reactor method for predicting the assimilation capacity of a stream was Black Bear Creek. The Black Bear watershed is a headwater basin located in Garfield, Noble, and Pawnee counties of Oklahoma. The total drainage area above Pawnee is 576 square miles. The basin exhibits a well-defined drainage pattern, with numerous tributaries contributing runoff to the main stream. A section of the creek between Highway 177 and Pawnee, Oklahoma, was selected as the study area. This area is shown in Figures 7 and 8. Nine sampling stations were established along this reach, with station #9 being located at Highway 177 and station #1 in Pawnee, Oklahoma. The distance between sampling points is shown in Table 3.

Chemical Analysis

A chemical analysis of the stream is not required in using the open jar reactor method for predicting the assimilation capacity of a stream. However, since this study was conducted to field test the method, it was felt that the stream should be characterized in regards to water quality and flow. A water quality profile of the stream would enable one to ascertain whether any inflow between stations was affecting the water quality of the stream.

Samples were collected at the nine stations and analyzed for the following parameters.

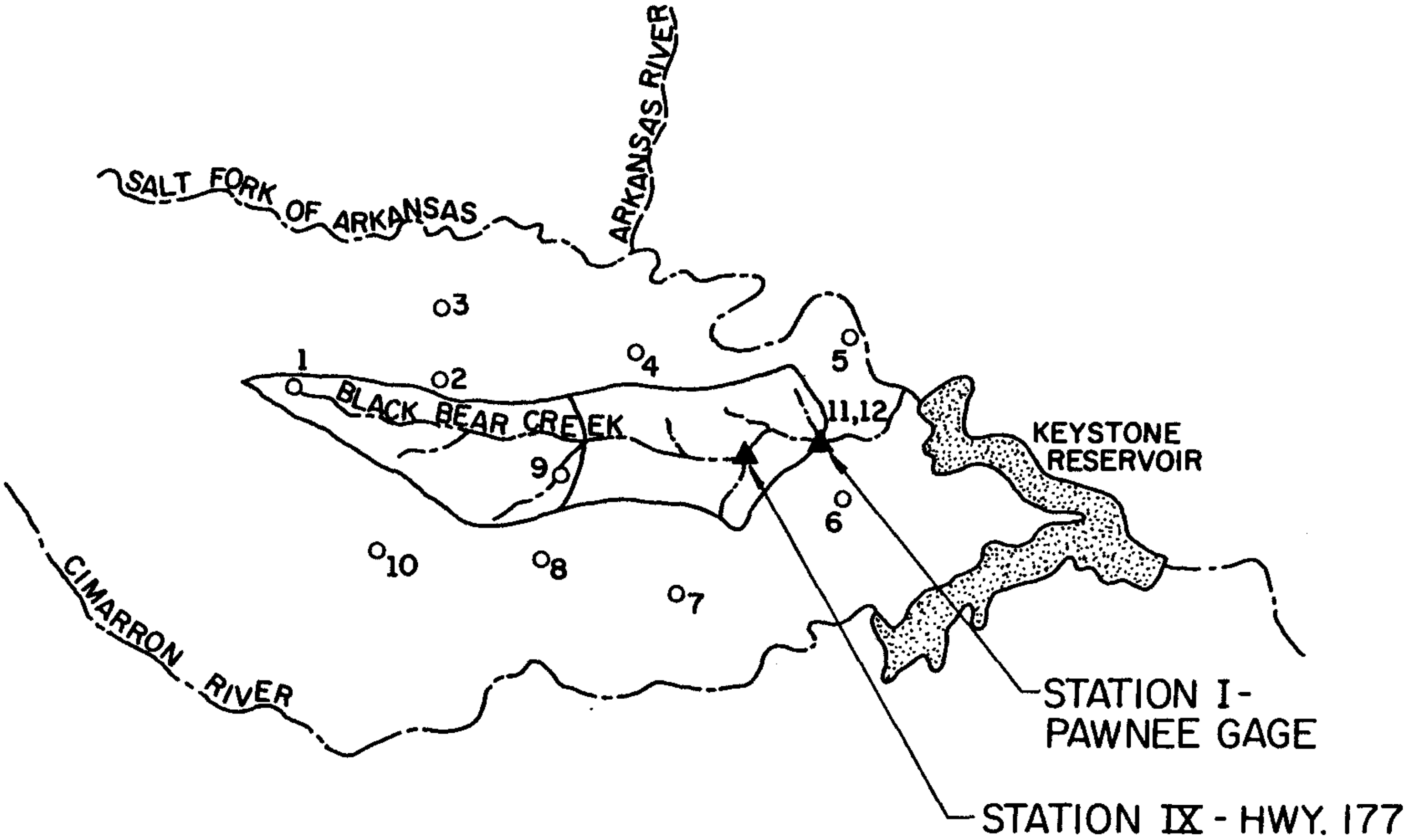

Figure 7. BLACK BEAR CREEK BASIN AND LOCATION OF STATIONS I AND IX.

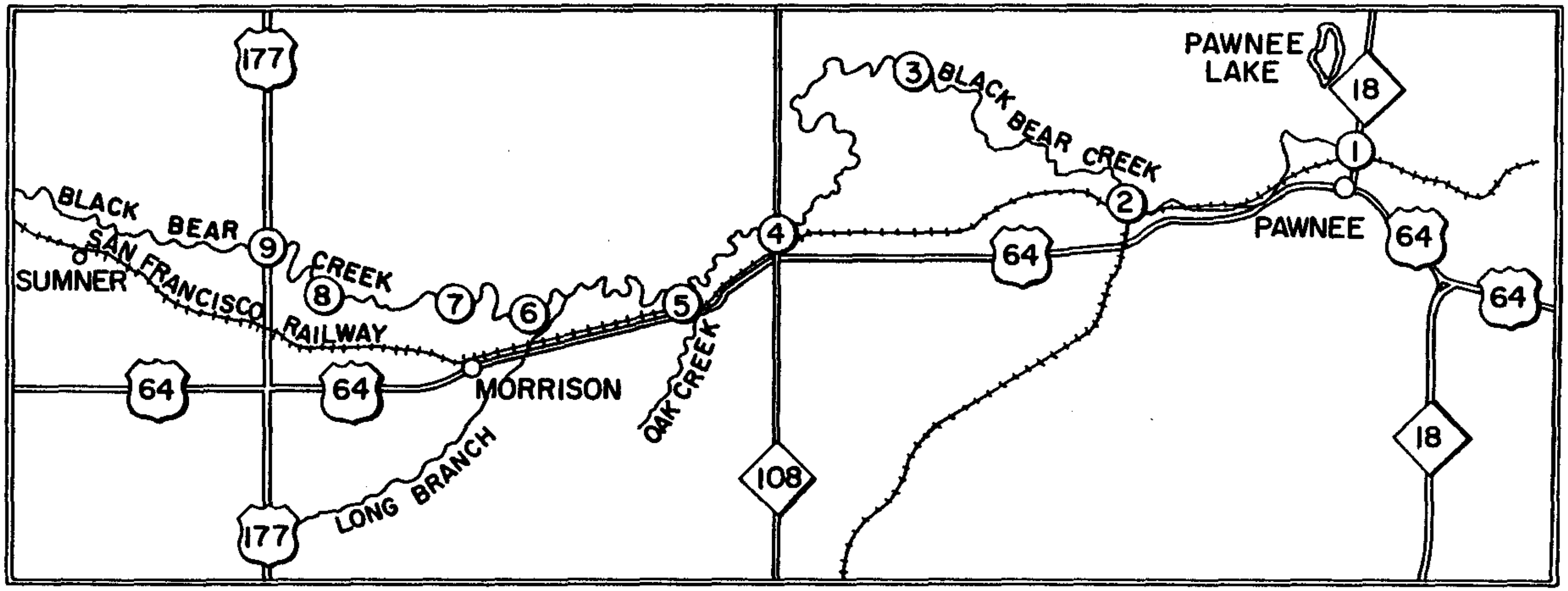

Figure 8. SITE LOCATIONS ON BLACK BEAR CREEK.

TABLE 3
River Miles Between Sampling Points
for Black Bear Creek

Stations		Reach	Miles
From	To		
9	8	A	2.0
8	7	B	2.5
7	6	C	2.0
6	5	D	4.0
5	4	E	3.0
4	3	F	7.5
3	2	G	5.0
2	1	H	3.3

Temperature
Alkalinity
Color
pH
Hardness
Turbidity
Dissolved Oxygen
COD
BOD
Chlorides
Iron
Manganese
Nitrate
Nitrite
Orthophosphate
Total Phosphate
Silica
Sulfate

During the early stages of the study it was found that a major tributary entered Black Bear Creek between sites 5 and 4. Many times the tributary contributed more flow than the mainstream. Therefore, a decision was made to limit the study area to the reach of Black Bear Creek between sites 9 and 5.

Tables 4 to 22 give the chemical analysis for Black Bear Creek from October, 1975 to September, 1976. It can be seen that the Creek maintains a good level of dissolved oxygen. In general the water quality of Black Bear Creek is good.

PREDICTION OF DO PROFILE

Step 1. Determine K_2 values for Black Bear Creek.

Cross sections and velocity measurements were taken at each sampling site. The cross section of the stream for each site is shown in Figures 9 to 11. Then K_2 was calculated by using the relationship:

$$K_{2(20^\circ)} = 3.74 \frac{V}{H}^{1.5}$$

This equation gives K_2 with units of days^{-1}. It is also based upon natural logs. Table 23 gives the calculated values of K_2 in units of hrs^{-1}. K_2 can also be plotted as a function of the flow rate. This relationship is shown in Figure 12.

Step. 2. Determine time of travel in stream.

Table 4

Temperature Analysis

October 1975 to August 1976

Black Bear Creek

Site No.	October	November	December	January	February	March	April	May	June	July	August
1	15	16	10	6.0	10	15	18.5				
2	15	16	10	5.0	10.5	16	18.5				
3		15	10	5.0	10.5	16	19.0				
4		16	10	5.0	11.0	17	19.0				
5	17	16	10	5.0	11.0	17	19.0	17	29	25	31
6		16	10	5.0	11.0	16	19.0	17	30	25.5	31
7		15	10	5.0	10.8	17	19.0	17	30	25	29
8		15	10	4.5	11.0	16	18.0	17	30	26	29
9	18	15	10	5	11.0	17	17.0	17	30	25	29

* Unit is °C.

Table 5
Alkalinity Analysis
October 1975 to August 1976
Black Bear Creek

Site No.	October	November	December	January	February	March	April	May	June	July	August
1	303	275	270	380	315	350	340				
2	317	350	420	375	360	425	340				
3		220	340	395	370	450	370				
4		330	390	380	380	455	400				
5	410	325	390	370	390	475	450	120	80	135	150
6		340	350	370	410	425	400	120	200	185	240
7		335	410	370	410	500	480	110	180	190	250
8		340	400	365	420	475	450	120	200	220	300
9	290	340	380	350	400	475	455	140	170	120	270

* Unit is mg/l.

Table 6
Color Analysis
October 1975 to August 1976
Black Bear Creek

Site No.	October	November	December	January	February	March	April	May	June	July	August
1	165	95	240	20	50	100	120				
2	215	175	240	10	60	130	150				
3		140	140	100	115	250	280				
4		240	140	35	60	230	240				
5	250	290	190	60	60	240	270	4200	290	130	80
6		355	130	40	15	180	200	4200	440	100	100
7		245	160	40	18	180	210	4200	440	105	130
8		160	160	50	5	180	215	4200	330	140	70
9	175	160	240	50	10	180	220	4200	300	120	120

Table 7
pH Analysis
October 1975 to August 1976
Black Bear Creek

Site No.	October	November	December	January	February	March	April	May	June	July	August
1	6.2	8.1	7.4	8.0	8.1	7.9	8.0				
2	7.8	8.1	7.5	7.8	8.1	8.0	8.0				
3		7.6	8.0	8.2	8.15	8.0	7.9				
4		7.95	7.9	8.1	8.2	7.9	8.0				
5	8.6	7.8	7.8	8.3	8.1	8.0	8.0	7.7	7.9	7.6	7.9
6		7.9	8.0	8.2	8.1	8.0	8.1	7.55	7.9	8.0	7.85
7		8.1	7.9	8.3	8.0	8.1	8.15	7.6	7.95	8.0	7.85
8		7.9	7.9	8.3	8.0	8.15	8.1	7.6	8.0	8.1	7.95
9	8.1	7.7	7.7	8.3	7.95	8.1	8.15	7.5	8.0	8.1	8.0

Table 8
Calcium Hardness Analysis
October 1975 to August 1976
Black Bear Creek

Site No.	October	November	December	January	February	March	April	May	June	July	August
1	250	210	130	550	410	255	180				
2	290	270	720	580	360	300	200				
3		240	450	445	350	260	160				
4		750	620	710	450	300	240				
5	420	630	680	795	450	300	280	60	300	320	460
6		510	440	700	450	310	340	80	400	540	500
7		465	710	680	500	320	310	60	300	600	440
8		480	670	715	450	340	340	80	400	440	400
9	413	480	670	720	425	380	380	80	300	460	320

* Unit is mg/l.

Table 9
Total Hardness Analysis
October 1975 to August 1976
Black Bear Creek

Site No.	October	November	December	January	February	March	April	May	June	July	August
1	465	400	210	750	680	420	310				
2	490	520	885	800	710	460	300				
3		420	630	780	700	500	290				
4		860	780	840	740	560	430				
5	710	1400	840	890	800	580	550	120	500	510	83.3
6		920	765	850	760	580	620	120	560	540	867
7		840	930	910	820	620	550	120	400	820	817
8		840	870	890	800	630	650	160	600	800	633
9	710	920	870	940	900	640	660	160	400	720	583

* Unit is mg/l.

Table 10

Turbidity Analysis

October 1975 to August 1976

Black Bear Creek

Site No.	October	November	December	January	February	March	April	May	June	July	August
1	40	30	55	45	20	50	80				
2	70	65	58	55	25	60	100				
3		60	32	140	40	100	140				
4		88	45	30	20	105	155				
5	85	105	55	105	20	115	160	1400	120	35	35
6		135	38	40	5	90	100	1400	185	30	45
7		103	55	50	5	98	110	1400	190	20	65
8		60	78	55	2	85	100	1400	160	25	40
9	45	80	80	80	5	70	110	1400	150	30	58

Table 11

Dissolved Oxygen Analysis
October 1975 to August 1976
Black Bear Creek

Site No.	October	November	December	January	February	March	April	May	June	July	August
1	7.5	9.0	8.0	9.0	9.2	8.5	9.0				
2	9.0	7.0	9.0	9.0	9.0	8.0	8.0				
3		7.0	8.5	10.0	9.0	8.0	9.0				
4		8.0	9.0	9.0	8.8	8.0	9.0				
5	8.5	7.0	9.0	9.0	9.0	8.5	9.0	9.0	7	6	6.5
6		7.5	8.0	10.0	8.8	9.0	9.0	9.0	7	6	6.5
7		8.0	8.5	9.0	9.0	9.0	9.0	9.0	7	6	6.5
8		7.5	9.0	10.0	9.2	8.5	8.0	9.0	7	6	6.5
9	12.0	9.0	9.5	8.0	9.0	8.5	8.0	9.0	7.5	5	6.5

* Unit is mg/l.

Table 12

C.O.D. Analysis

October 1975 to August 1976

Black Bear Creek

Site No.	October	November	December	January	February	March	April	May	June	July	August
1	85.8	56	64	190		77	25				
2	52.0	48	96	130		67	36				
3		128	90	142		80	40				
4		156	44	100		133	35				
5	92.4	140	128	166		96	38	34	82	40	62
6		160	72	188		93	40	21	49	64	36
7		140	66	188		101	41	67	41	66	62
8		140	128	266		85	40	168	39	56	35
9	44.0	220	104	251		75	42	71	41	42	53

* Unit is mg/l.

Table 13

B.O.D.$_5$ Analysis

October 1975 to August 1976

Black Bear Creek

Site No.	October	November	December	January	February	March	April	May	June	July	August
1	36.8		11	32			16				
2	43.5		24	16			30				
3			18	23			30				
4			7	16			23				
5	38.3		18	20			25	22	36	24	48
6			14	21			27	17	27	37	21
7			11	25			28	35	22	39	48
8			21	30			28	42	22	32	21
9	34.5		12	28			30	36	24	25	32

* Unit is mg/l.

Table 14
Chlorides Analysis (Cl)
October 1975 to August 1976
Black Bear Creek

Site No.	October	November	December	January	February	March	April	May	June	July	August
1	340	300	1450	750	680	325	240				
2	400	500	1600	700	760	550	200				
3		1000	1250	710	780	500	160				
4		1500	1250	725	730	625	400				
5	750	2000	1300	925	800	675	480	150	575	800	1350
6		1500	1250	850	860	750	550	200	675	1400	1425
7		1500	1400	900	870	875	600	200	625	1600	1400
8		1400	1500	875	980	900	480	1650	625	1350	850
9	800	2400	1600	825	900	860	615	200	650	1300	900

* Unit is mg/l.

Table 15
Iron Analysis (Fe^{+2})
October 1975 to August 1976
Black Bear Creek

Site No.	October	November	December	January	February	March	April	May	June	July	August
1		0.01	0.40	0.45	0.19	0.1	0.15				
2	0.475	0.24	0.68	0.05	0.24	0.25	0.22				
3		0.04	0.05	0.42	0.36	0.34	0.15				
4		0.2	0.06	0.15	0.25	0.30	0.15				
5	0.325	0.5	0.13	0.35	0.22	0.61	0.16	0.85	0.29	0.45	0.10
6		0.68	0.03	1.25	0.04	0.35	0.15	0.80	0.30	0.50	0.15
7			0.20	0.45	0.05	0.38	0.15	0.55	0.30	0.40	0.41
8		0.23	0.20	0.38	0.08	0.32	0.16	0.30	0.25	0.45	0.17
9	0.450		0.27	0.40	0.04	0.43	0.14	0.28	0.25	0.40	0.22

* Unit is mg/l.

Table 16
Manganese Analysis (Mn^{+2})
October 1975 to August 1976
Black Bear Creek

Site No.	October	November	December	January	February	March	April	May	June	July	August
1	2.5		0.60	0.7	.9	0.40	0.5				
2	1.5		0.80	0.5	1.0	0.80	0.75				
3		1.9		1.0	1.20	0.90	0.6				
4		0.3	0.25	0.4	.85	1.0	0.7				
5	0.5	5.5	0.80	0.8	.90	2.0	1.5	0.1	0.3	0.8	1.20
6		2.7	0.10	0.1	.90	1.25	0.5	0.1	0.2	1.75	1.0
7		0.4	1.0	0.2	1.20	1.45	0.5	0.1	0.4	1.5	2.5
8		0.4	0.90	0.75	1.25	0.95	0.7		0.2	1.2	1.0
9	3.5	6.0	1.0	0.6	.90	1.75	0.9	0.2	0.2	1.1	1.25

* Unit is mg/l.

Table 17

Nitrate Analysis (NO_3^-)
October 1975 to August 1976
Black Bear Creek

Site No.	October	November	December	January	February	March	April	May	June	July	August
1	2.75	0.2	0.2	0.75	0.35	0.25	0.3				
2	0.4	0.41	1.5	0.76	0.50	0.35	0.35				
3		0.13	0.15	1.25	0.70	0.45	0.40				
4		0.13	0.36	2.10	0.40	0.40	0.35				
5	0.45	0.34	0.65	1.60	0.45	0.70	0.55		0.20	0.1	0.25
6		0.41	0.16	0.40	0.30	0.35	0.40		0.25	0.1	0.35
7		0.26	0.67	0.40	0.40	0.35	0.40		0.30		0.75
8		0.64	0.85	0.45	0.35	0.25	0.30		0.30	0.1	0.35
9	0.60	0.69	0.8	0.50	0.30	0.35	0.35		0.30	0.1	0.50

* Unit is mg/l.

Table 18
Nitrite Analysis (NO_2^-)
October 1975 to August 1976
Black Bear Creek

Site No.	October	November	December	January	February	March	April	May	June	July	August
1	0	0	0	0	0	0	0				
2	0	0	0	0	0	0	0				
3		0	0	0	0	0	0				
4		0	0	0	0	0	0				
5	0	0	0	0	0	0	0	0	0	0	0
6		0	0	0	0	0	0	0	0	0	0
7		0	0	0	0	0	0	0	0	0	0
8		0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0

* Unit is mg/l.

Table 19
Orthophosphate Analysis (PO_4^-)
October 1975 to August 1976
Black Bear Creek

Site No.	October	November	December	January	February	March	April	May	June	July	August
1	0.75	<0.01	0.101	0.10	0.08	0.03	1.2				
2	0.28	<0.01	1.20	0.30	0.07	0.01	0.55				
3		0.17	0.10	0.45	0.14	0.05	0.44				
4		<0.01	0.15	0.30	0.52	0.35	0.34				
5	0.23	0.021	0.45	0.55	0.43	0.18	0.42	1.3	0.3	0.2	0.4
6		0.127	0.50	0.70	0.47	0.20	0.57	0.8	0.3	0.13	0.2
7		0.297	0.70	0.55	0.41	0.14	0.39	0.95	0.7	0.15	1.0
8		0.526	0.80	0.95	0.52	0.07	0.55	1.5	1.2	0.18	0.8
9	0.10	1.1	1.0	0.85	0.69	0.16	0.93	1.5	7.0	0.55	0.3

* Unit is mg/l.

Table 20
Total Phosphate Analysis (PO_4^-)
October 1975 to August 1976
Black Bear Creek

Site No.	October	November	December	January	February	March	April	May	June	July	August
1	1.72	1.35	2.40	3.62	1.5	0.98	1.2				
2	1.05	0.38	4.30	4.8	3.5	1.50	1.75				
3		3.50	2.70	3.25	0.78	0.55	0.94				
4		0.49	3.25	4.25	1.20	0.58	2.0				
5	1.00	0.625	2.45	3.75	1.35	0.75	0.9	2.8	1	0.25	1.1
6		0.85	2.40	3.80	1.80	0.70	1.28	2.6	0.7	0.2	0.6
7		1.03	1.70	2.70	1.20	0.95	0.69	2.9	0.5	0.3	1.3
8		1.35	1.80	2.85	4.80	1.00	0.78	2.9	0.7	0.35	1.2
9	0.55	6.0	1.50	2.40	1.50	1.40	0.93	2.8	1	0.85	0.7

* Unit is mg/l.

Table 21
Silica Analysis (Si)
October 1975 to August 1976
Black Bear Creek

Site No.	October	November	December	January	February	March	April	May	June	July	August
1	0.08	4.5	5.4	7.50	4.15	5.20	0.6				
2	4.60	5.0	5.34	4.40	1.9	2.30	1.1				
3		4.55	5.59	5.0	1.7	2.10	1.3				
4		4.0	5.34	3.40	4.85	5.90	1.1				
5	1.20	4.34	5.34	3.90	5.40	6.70	2.2	5.5	5	5.25	5.0
6		4.64	5.25	4.10	6.15	7.30	1.4	6.0	5	5.37	5.0
7		4.29	5.25	3.50	6.75	7.50	1.7	5.5	4.8	4.12	5.6
8		4.86	5.0	4.90	6.40	7.35	1.6	7.0	5.2	4.7	6.0
9	1.40	3.33	5.08	4.20	7.00	8.20	2.4	7.0	5	4.07	6.1

* Unit is mg/l.

Table 22
Sulfates Analysis
October 1975 to August 1976
Black Bear Creek

Site No.	October	November	December	January	February	March	April	May	June	July	August
1	75	66		83	75	85	75				
2	88	81	110	98	90	105	95				
3		52	65	76	90	101	100				
4		35	74	83	94	98	95				
5	65	94	80	96	94	95	93	15	40	45	50
6		100	70	90	90	105	100	15	38	25	37.5
7		90	98	120	100	115	105	35	42	24	41
8		90	92	104	89	104	95	18	35	35	59
9	85	44	95	76	78	106	98	15	300	40	58

* Unit is mg/l.

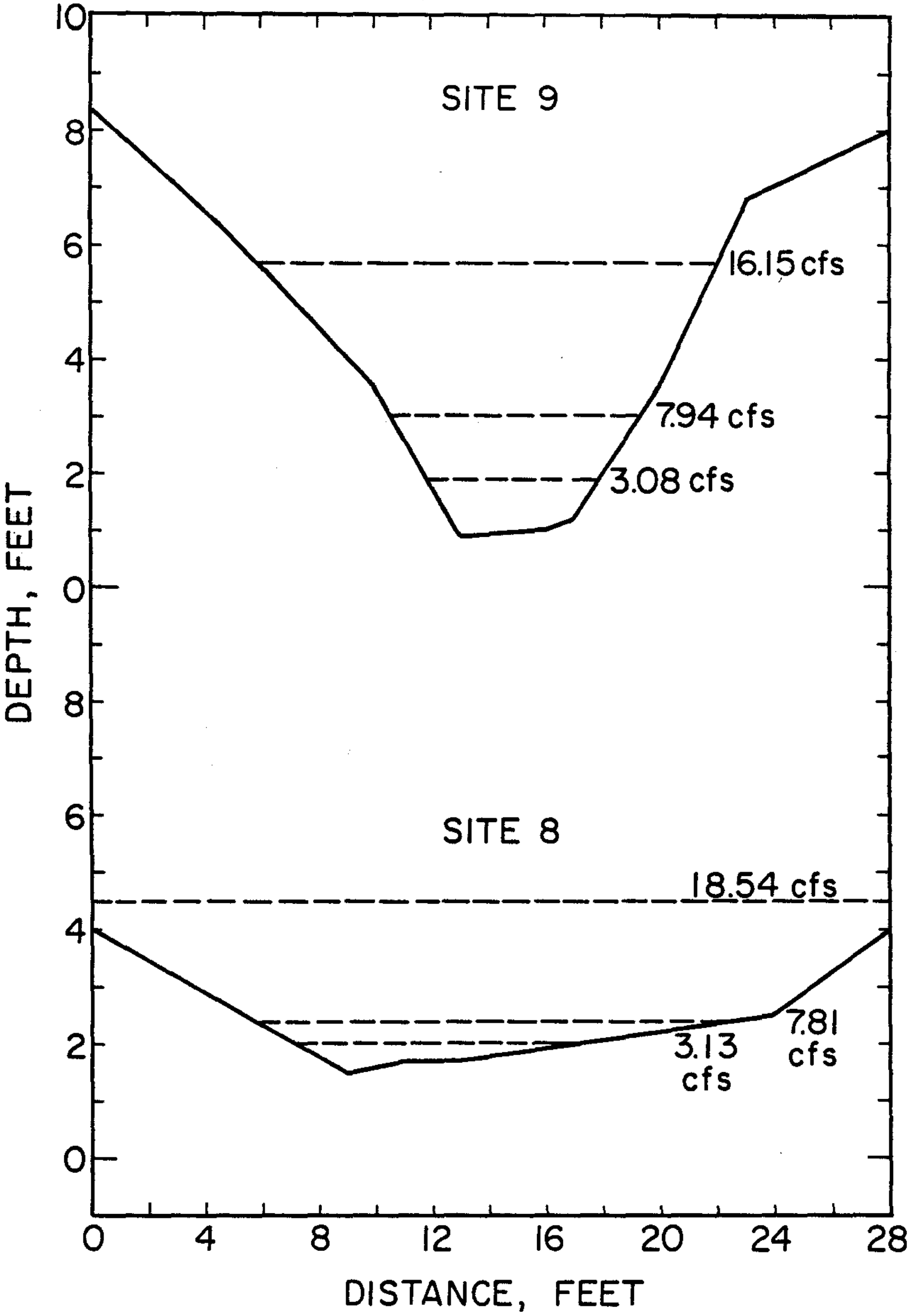

Figure 9. CROSS SECTIONS AT SITES 8 AND 9.

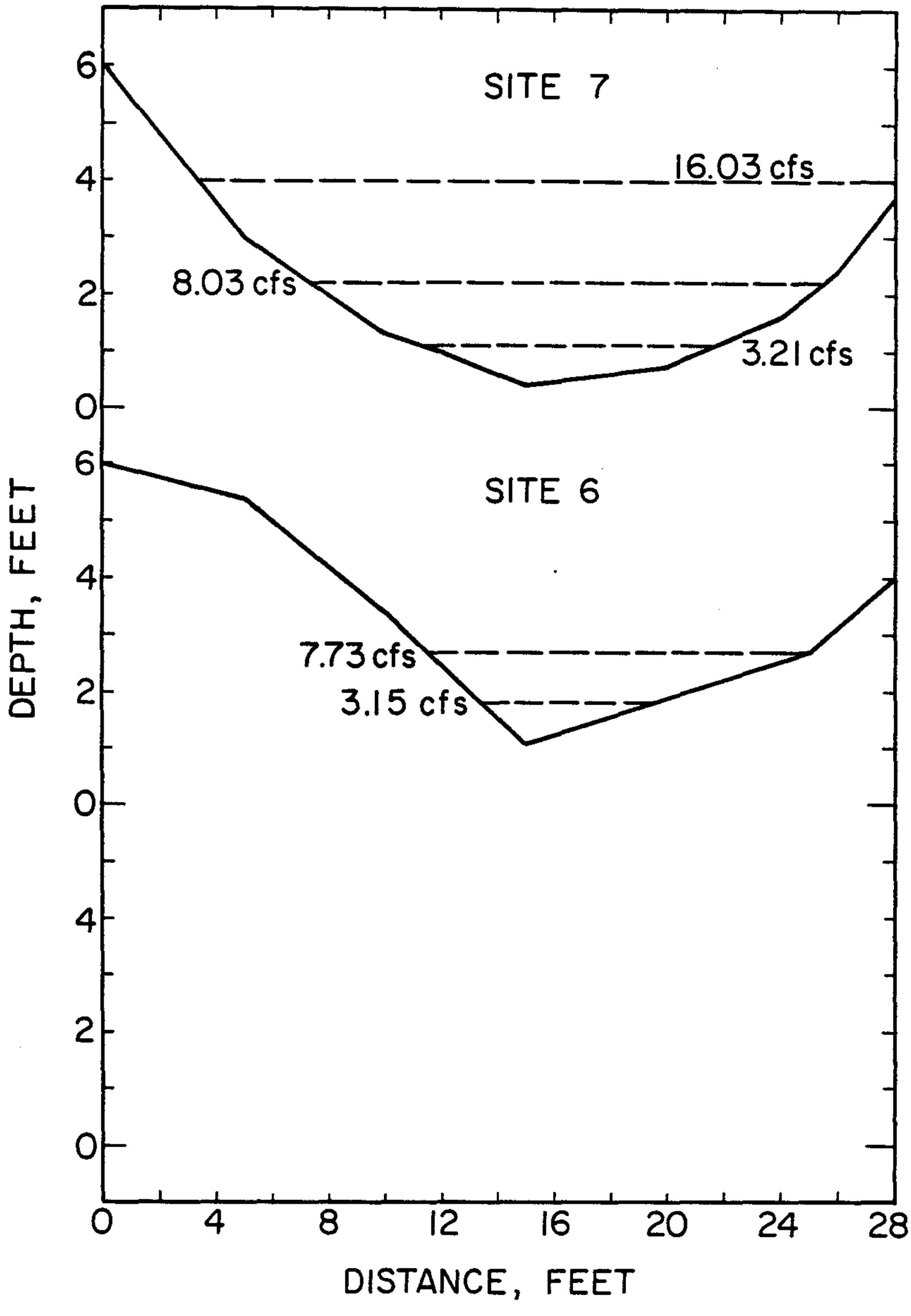

Figure 10. CROSS SECTIONS AT SITES 6 AND 7.

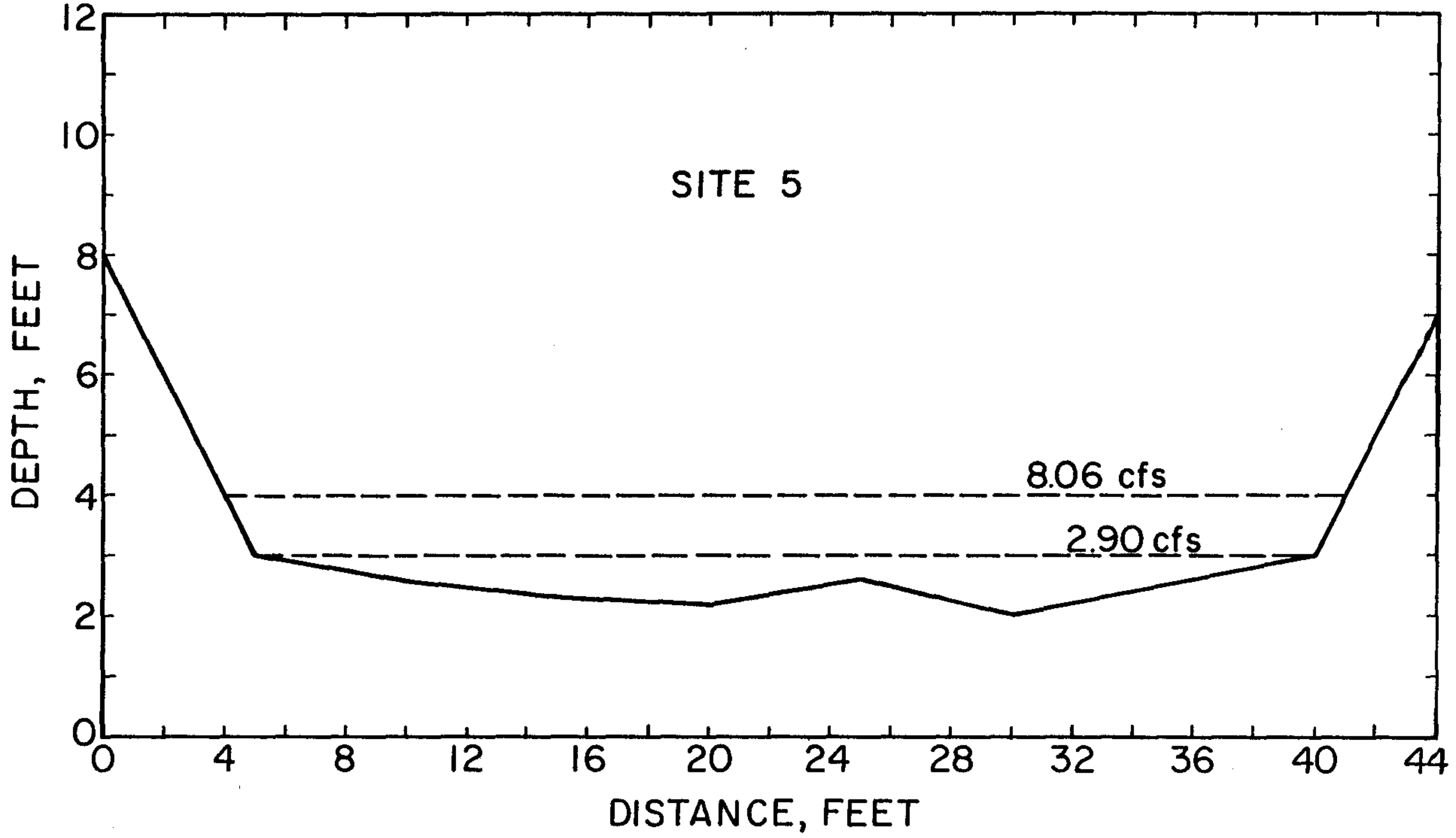

Figure 11. CROSS SECTION AT SITE 5.

TABLE 23

K_2 Values for Black Bear Creek

Site No.	Flow Rate Q ft^3/sec	Depth H ft	Velocity V ft/sec	K_2 hr^{-1}
5	8.06	1.48	0.15	0.013
	3.96	0.93	0.12	0.021
	3.15	0.70	0.144	0.0386
	2.90	0.51	0.16	0.0692
6	18.14	3.07	0.236	0.00685
	7.73	0.83	0.69	0.1415
	4.10	0.45	1.23	0.639
	3.22	0.40	1.12	0.689
	3.15	0.41	1.13	0.693
7	16.03	1.13	0.95	0.123
	8.03	1.17	0.39	0.048
	4.06	0.59	0.51	0.177
	3.30	0.38	0.80	0.538
	3.21	0.46	0.64	0.325
8	18.54	1.10	1.06	0.143
	7.81	0.44	1.08	0.580
	4.01	0.34	0.87	0.678
	2.92	0.30	1.06	1.005
	3.13	0.27	1.14	1.256
9	16.15	1.81	0.81	0.0058
	7.94	1.83	0.50	0.0316
	4.18	0.75	0.95	0.2296
	3.79	0.57	0.92	0.3355
	3.08	0.70	0.79	0.209

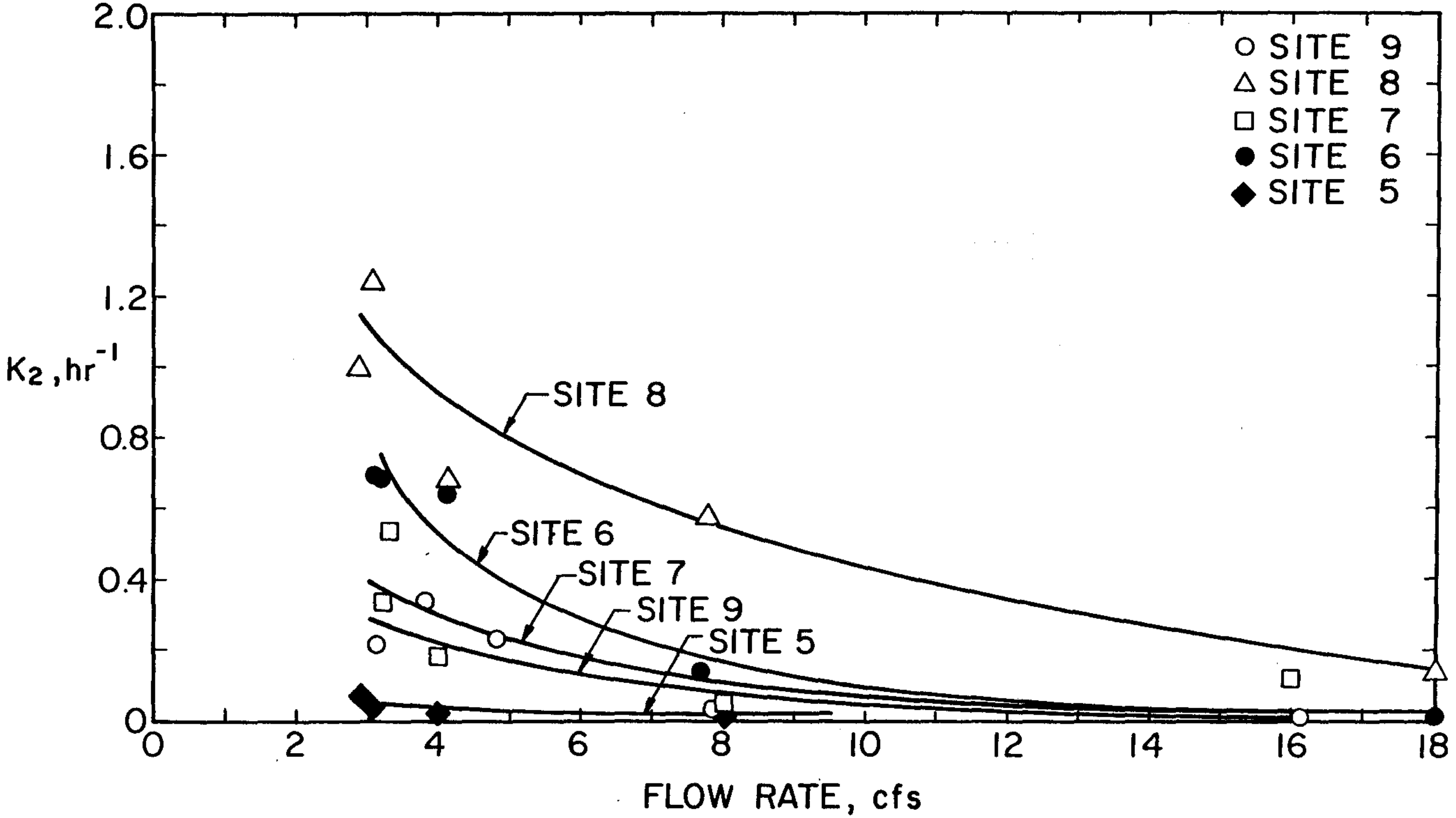

Figure 12. K_2 AS A FUNCTION OF FLOW RATE FOR BLACK BEAR CREEK.

The most desirable method for measuring the time of travel in a stream is the use of flourescent dye. However, an instrument capable of reading the dye concentration was not available for this project. Therefore other methods were used. An attempt was made to let plastic balls float from one site to the next. However, in all cases the balls never reached the next site.

It was decided to use the average velocity to calculate the time of travel and also the Manning Equation was used. Times of travel determined for each reach are shown in Table 24. Figure 13 gives the time of travel as a function of flow rate when the average velocity is used and Figure 14 gives the time of travel as a function of flow rate when Mannings Equation is used.

Step 3. Determine DO profile for stream-effluent mixtures.

Stream water was obtained from Black Bear Creek and placed in two open jar reactors. A synthetic waste water containing sucrose as the carbon source was added to provide a sucrose concentration of 25 mg/l in one reactor and 50 mg/l in the other reactor. The mixing device was set to give a K_2 value of 0.069 hr^{-1}. The dissolved oxygen was recorded at various time periods. The system was maintained at a temperature of 20°C. The results of the open jar reactor tests are shown in Figure 15.

Step 4. Determine K_2 in reactor.

After completing the DO profile in Step 3, 2 mg/l of clorox was added to stop further oxygen utilization. A contact time of 12 hours was allowed. Then 1 g/10 l of sodium sulfite and 0.15g/10 l of cobalt chloride was added to remove the dissolved oxygen. After the dissovled oxygen had been removed the stirring device was set at a selected rpm and the dissolved oxygen in the open jar reactor was monitored. Figure 16 shows the reaeration curve obtained

TABLE 24

Time of Travel in Black Bear Creek

Site	Reach	Flow Rate ft^3/sec	Time of Travel Mannings Equation hr	Time of Travel Average Velocity hr
9-8	A	17.0	3.6	3.0
		8.0	4.5	3.7
		4.0	5.3	3.3
		3.1	7.5	3.0
8-7	B	17.0	5.1	3.7
		8.0	6.4	5.0
		4.0	9.9	11.3
		3.1	10.9	4.0
7-6	C	17.0	2.8	5.0
		8.0	4.5	5.4
		4.0	7.3	7.8
		3.1	8.1	3.1
6-5	D	8.0	8.0	14.0
		4.0	10.9	8.7
		3.1	13.2	9.3

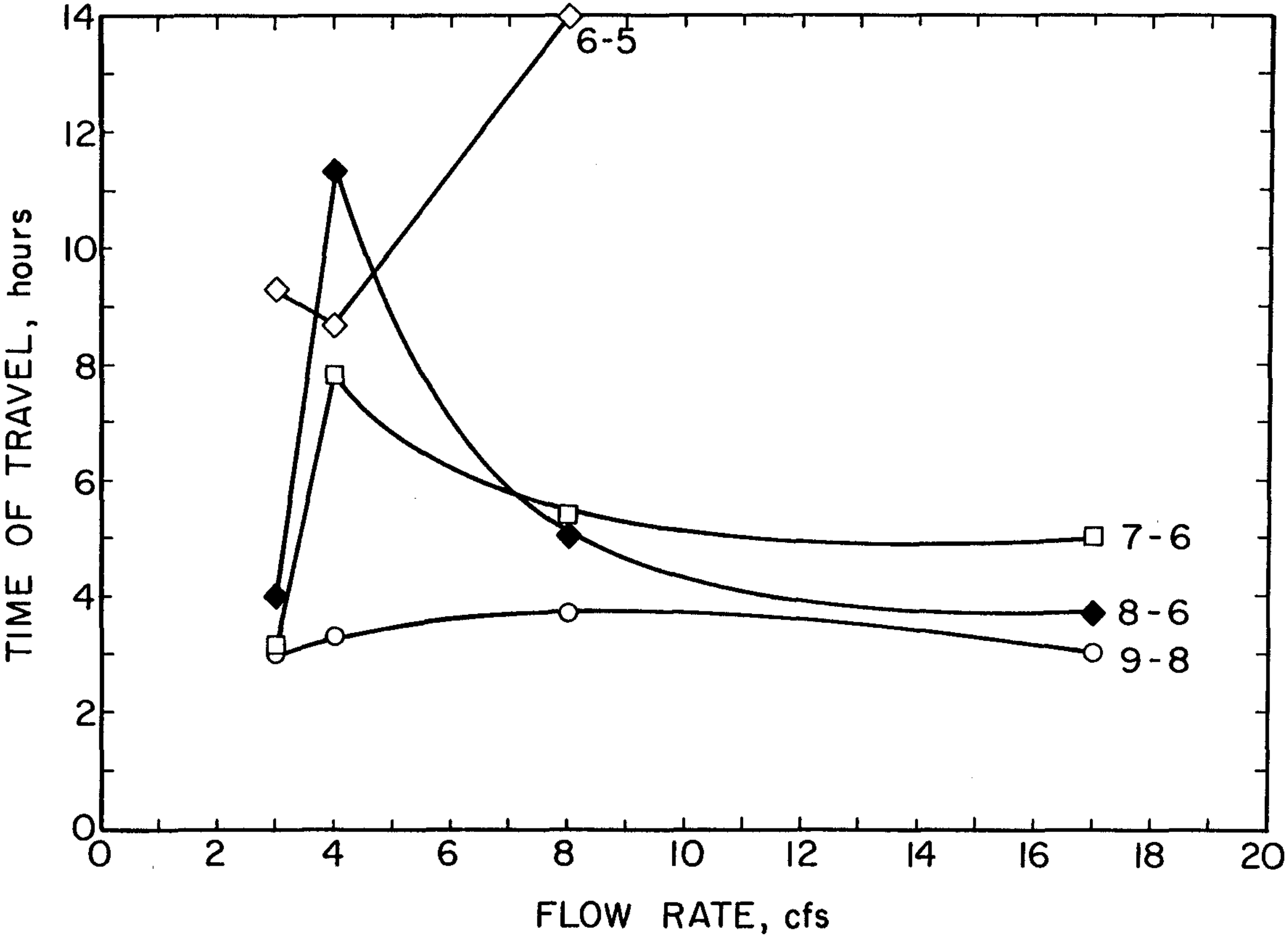

Figure 13. TIME OF TRAVEL AS A FUNCTION OF FLOW RATE. TIME OF TRAVEL BASED UPON AVERAGE VELOCITY.

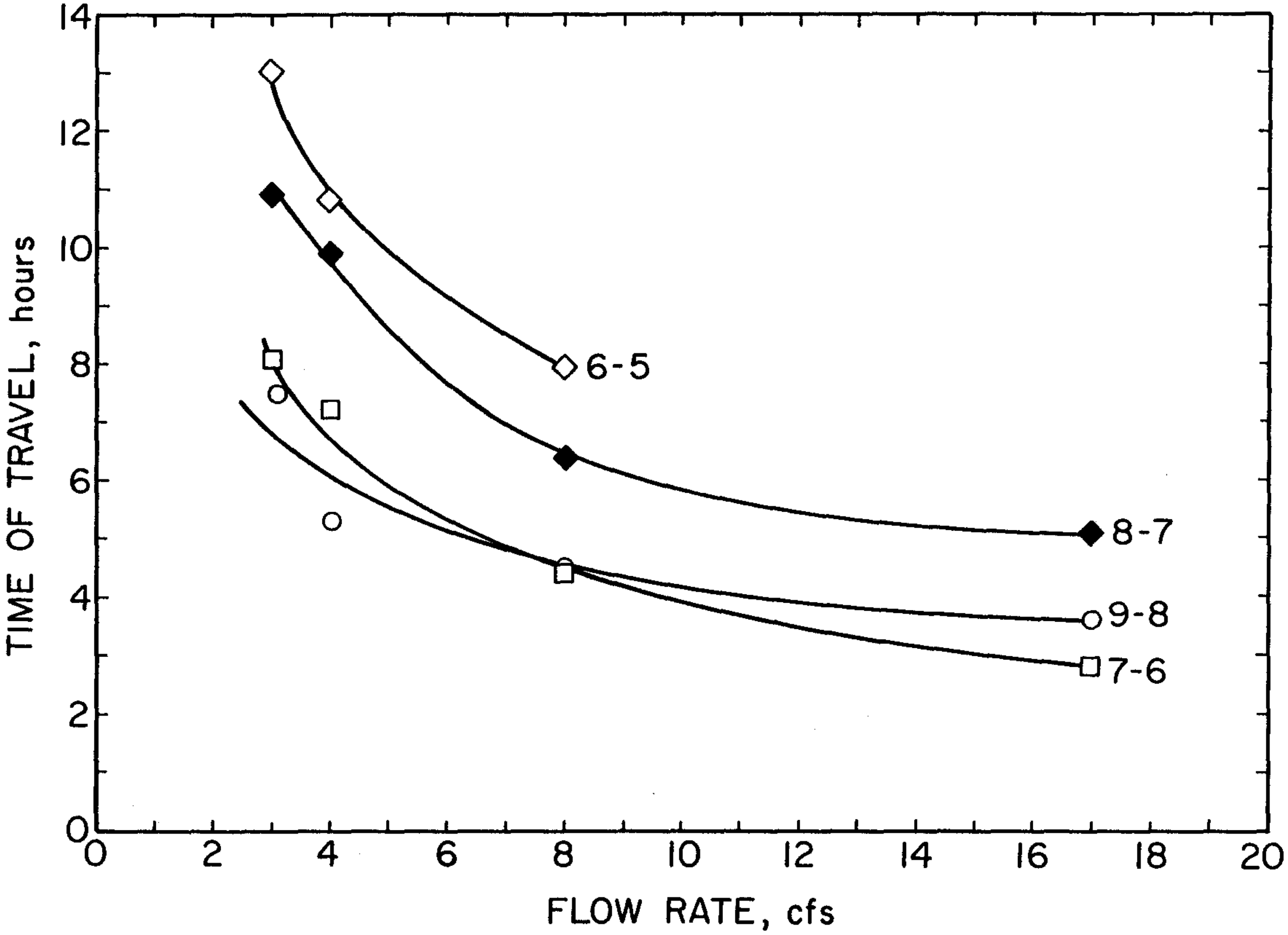

Figure 14. TIME OF TRAVEL AS A FUNCTION OF FLOW RATE. TIME OF TRAVEL BASED UPON MANNINGS EQUATION.

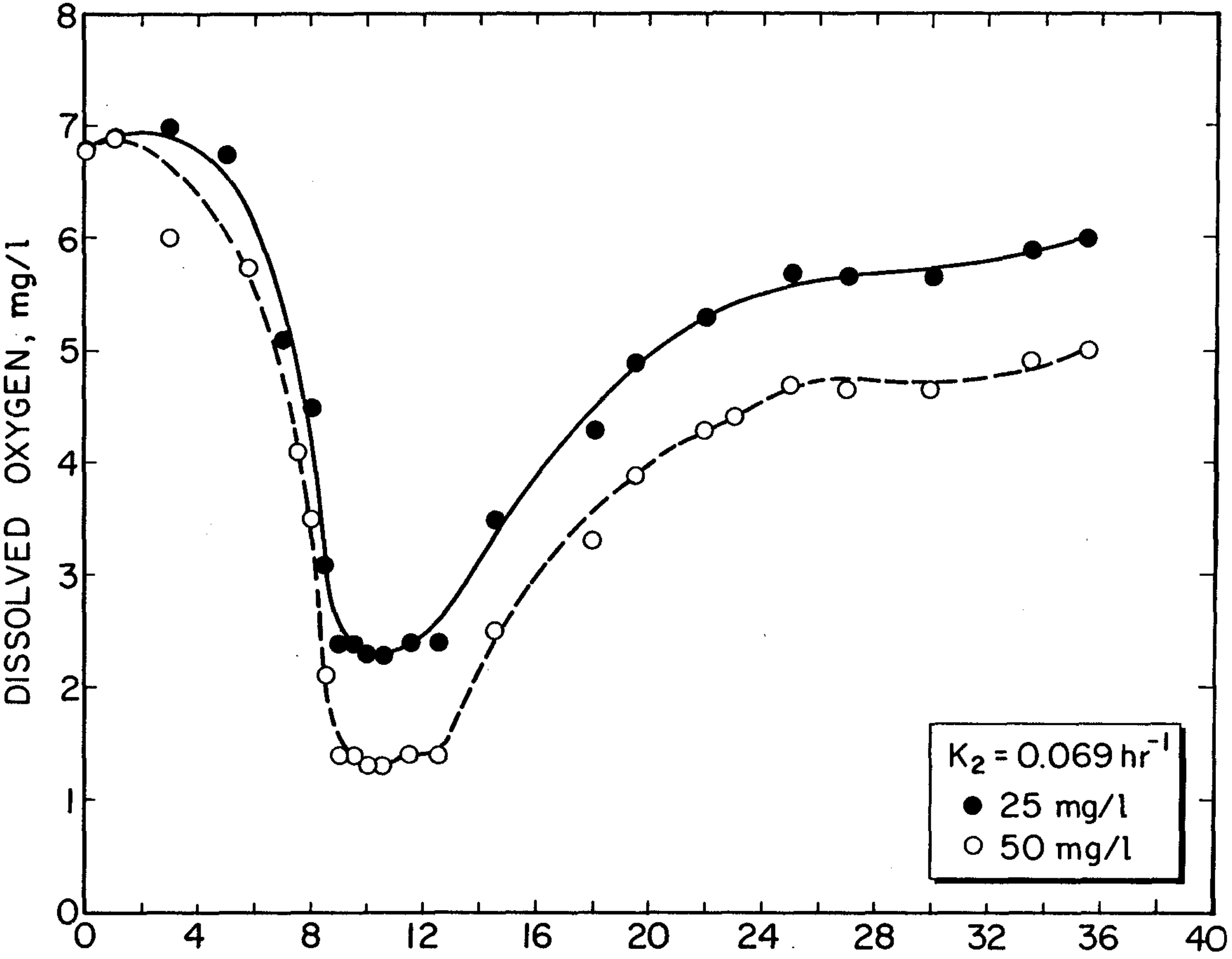

Figure 15. DISSOLVED OXYGEN PROFILES FOR S_i = 25 mg/l AND S_i = 50 mg/l.

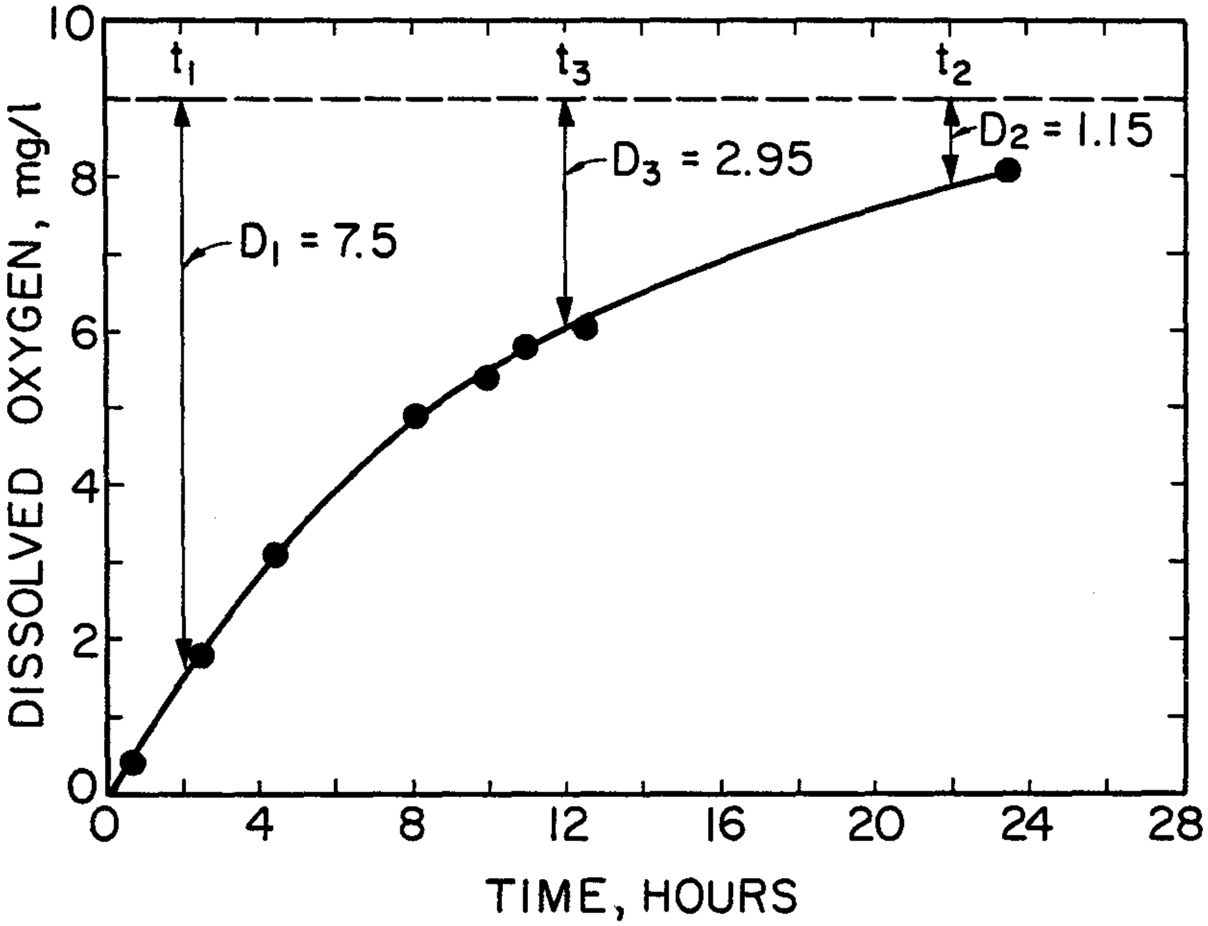

Figure 16. REAERATION CURVE FOR 200 RPM.

for a stirring rpm of 200.

In order to determine K_2 a dissolved oxygen saturation value must be selected. This saturation value may be taken from sources such as Standard Methods[13] or a more accurate value may be calculated.[7] If a saturation value is assumed (C'_s) then

$$C_s = C'_s - \alpha$$

where:

C_s = true dissolved oxygen saturation value

C'_s = assumed dissolved oxygen saturation value

α = correction factor

and

$$\alpha = \frac{D_1 D_2 - D_3^{\,2}}{D_1 + D_2 - 2D_3}$$

where:

D_1 = DO deficit at selected time t_1

D_2 = DO deficit at selected time t_2

D_3 = DO deficit at selected time t_3

$$t_3 = \frac{t_1 + t_2}{2}$$

For determining C_s for the 200 rpm reaeration curve a value of 9.0 mg/l was assumed for C'_s (see Figure 16). Others values selected were

t_1 = 2 hours

t_2 = 22 hours

therefore:

$$t_3 = \frac{2 + 22}{2} = 12 \text{ hours}$$

$$D_1 = 9.0 - 1.5 = 7.5$$

$$D_2 = 9.0 - 7.85 = 1.15$$

$$D_3 = 9.0 - 6.05 = 2.95$$

and

$$\alpha = \frac{D_1D_2 - D_3^2}{D_1 + D_2 - 2D_3} = \frac{7.5 \times 1.15 - (2.95)^2}{7.5 + 1.15 - 2(2.95)}$$

$$\alpha = -0.028$$

therefore:

$$C_s = C'_s - \alpha$$

$$C_s = 9.0 - (-0.028) = 9.028 \text{ mg/l}$$

The next step in determining K_2 is to make a semi-log plot of oxygen deficit as a function of time. The slope of this line is K_2. This plot is shown in Figure 17.

$$K_2 = \frac{\ln \frac{9.03}{1.18}}{22}$$

$$= 0.093 \text{ hour}^{-1}$$

This procedure was then repeated for a number of stirring rpm's. The relationship developed between K_2 and rpm's is shown in Figure 18.

Step 5. Numerically intergrate DO profile and K_2 values to obtain BOD curve.

The numerical intergration for the dissolved oxygen profiles developed in Step 3 are shown in Tables 25 and 26. The oxygen uptake or BOD curves developed by this intergration are shown in Figures 19 and 20.

Step 6. Numerically intergrate BOD curve with stream K_2 values to obtain stream DO value as a function of time.

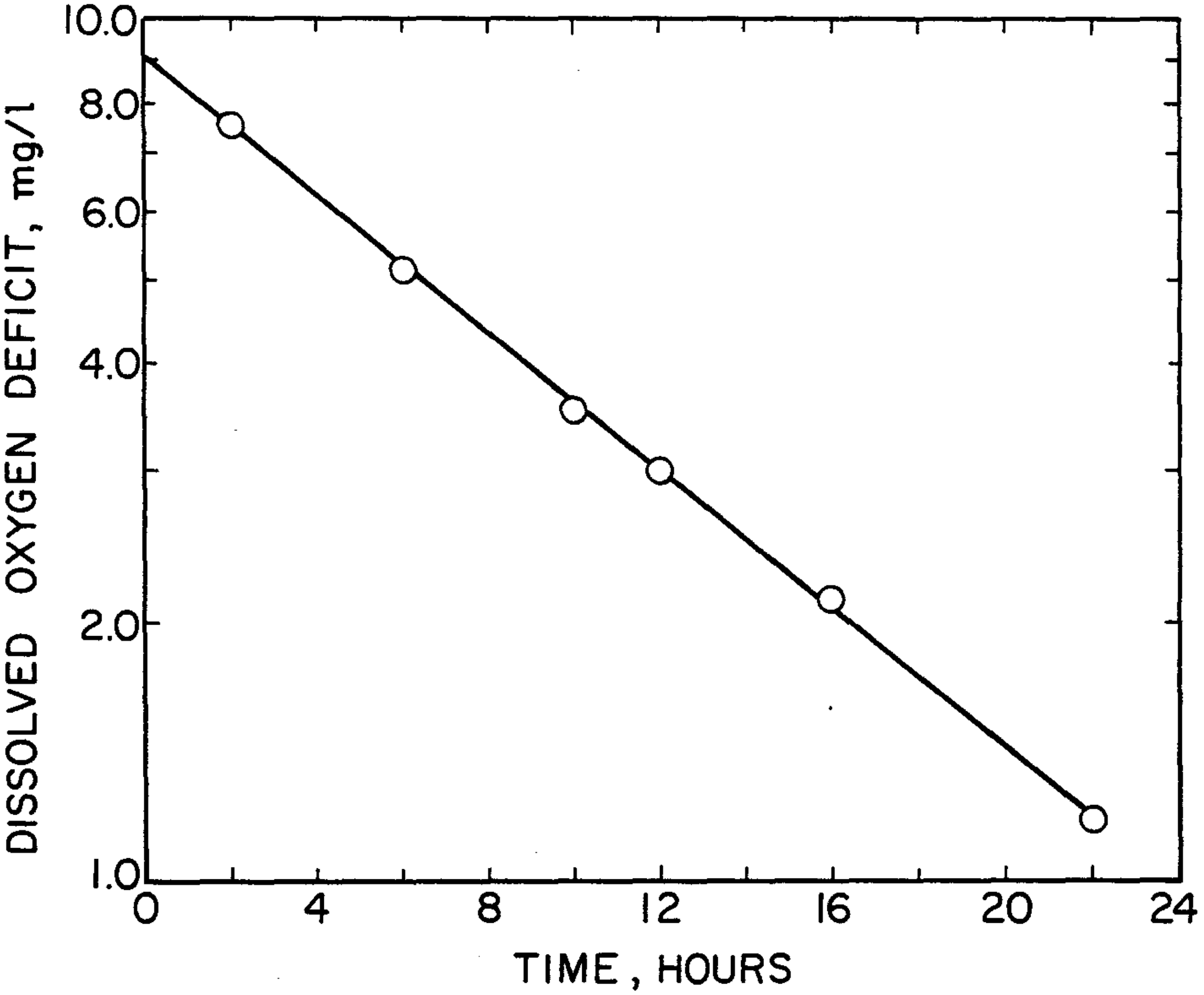

Figure 17. GRAPHICAL DETERMINATION OF K_2.

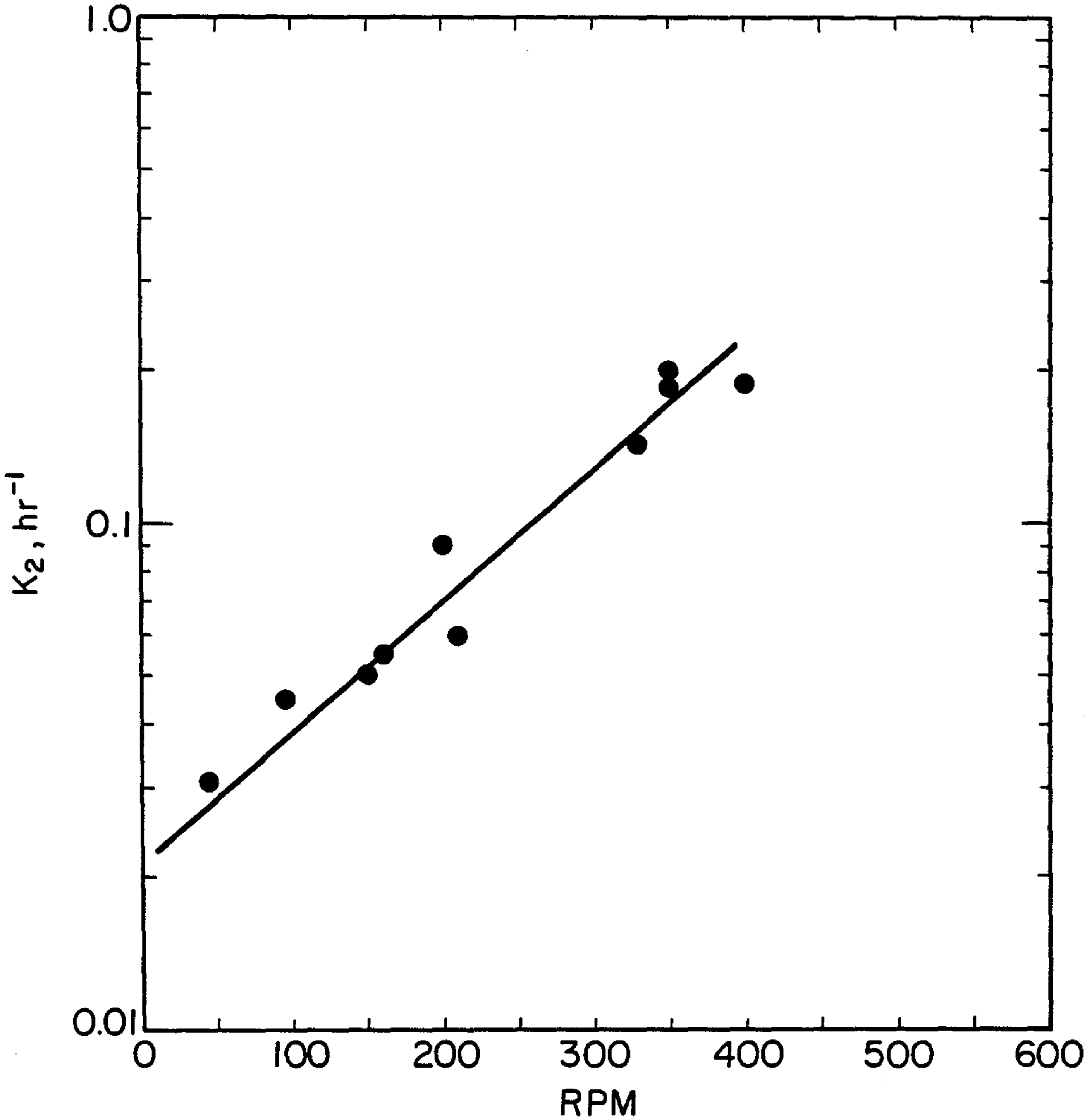

Figure 18. K_2 AS A FUNCTION OF RPM.

TABLE 25
Calculation of Oxygen Uptake From Open Jar Reactor

$K_2 = 0.069\ hr^{-1}$ $C_s = 7.5$ mg/l Sucrose Conc = 25 mg/l

1	2	3	4	5	6	7	8	9
Time hr	DO mg/l	D mg/l	K_2D mg/l/hr	Δt hr	$K_2D\Delta t$ mg/l	ΔDO mg/l	6-7	O_2 Uptake mg/l
0	6.8	0.7	0.048	0	0			0
1.0	6.9	0.6	0.041	1.0	0.041	0.1	0	0
3.0	7.0	0.5	0.035	2.0	0.069	0.1	0	0
5.0	6.75	0.75	0.052	2.0	0.104	-0.25	0.35	0.35
7.5	5.10	2.4	0.166	2.5	0.414	-1.65	2.06	2.4
8.0	4.5	3.0	0.207	0.5	0.104	-0.60	0.70	3.1
8.25	4.1	3.4	0.235	0.25	0.059	-0.40	0.46	3.6
8.5	3.1	4.4	0.304	0.25	0.076	-1.00	1.08	4.7
9.0	2.4	5.1	0.352	0.5	0.176	-0.70	0.88	5.6
9.5	2.4	5.1	0.352	0.5	0.176	0	0.18	5.8
10.0	2.3	5.2	0.359	0.5	0.179	-0.10	0.28	6.1
10.25	2.35	5.15	0.355	0.25	0.089	0.05	0.14	6.2
10.5	2.30	5.20	0.359	0.25	0.090	-0.05	0.14	6.3
11.5	2.40	5.10	0.352	1.0	0.352	0.10	0.25	6.6
12.5	2.40	5.1	0.352	1.0	0.352	0	0.30	6.9
14.5	3.50	4.0	0.276	2.0	0.552	1.10	0	6.9
18.0	4.3	3.2	0.179	3.5	0.628	0.80	0	6.9
19.5	4.9	2.6	0.189	1.5	0.269	0.60	0	6.9
22.0	5.3	2.2	0.152	2.5	0.380	0.40	0	6.9
23.0	5.4	2.1	0.145	1.0	0.145	0.10	0.05	7.0
25.0	5.7	1.8	0.124	2.0	0.248	0.30	0	7.0
27.0	5.65	1.85	0.128	2.0	0.255	-0.05	0.31	7.3
30.0	5.65	1.85	0.128	3.0	0.383	0	0.38	7.7
33.5	5.9	1.6	0.110	3.5	0.386	0.25	0	7.7
35.5	6.0	1.5	0.104	2.0	0.207	0.10	0.10	7.8

TABLE 26

Calculation of Oxygen Uptake From Open Jar Reactor

K_2 = .069 hr^{-1} C_s = 7.5 mg/l Sucrose Conc = 50 mg/l

1	2	3	4	5	6	7	8	9
Time hr	DO mg/l	D mg/l	K_2D mg/l/hr	Δt hr	$K_2D\Delta t$ mg/l	ΔDO mg/l	6-7	O_2 Uptake mg/l
0	6.8	0.7	0.048	0	0	0	0	0
1.0	6.9	0.6	0.414	1.0	0.414	0.1	0	0
3.0	6.0	1.5	0.1035	2.0	0.207	-0.9	1.107	1.1
5.0	5.75	1.95	0.1346	2.0	0.269	-0.25	0.519	1.6
7.5	4.10	3.40	0.2346	2.5	0.586	-1.65	2.337	4.0
8.0	3.5	4.0	0.276	0.5	0.138	-0.60	0.735	4.7
8.25	3.1	4.4	0.304	0.25	0.076	-0.40	0.476	5.2
8.5	2.1	5.4	0.373	0.25	0.093	-1.00	1.10	6.3
9.0	1.4	6.1	0.421	0.5	0.211	-0.70	0.91	7.2
9.5	1.4	6.1	0.421	0.5	0.211	0	0.21	7.4
10.0	1.3	6.2	0.428	0.5	0.214	0.10	0.114	7.5
10.25	1.35	6.15	0.424	0.25	0.110	0.05	0.07	7.6
10.5	1.3	6.2	0.428	0.25	0.107	0.05	0.16	7.7
11.5	1.4	6.1	0.421	1.0	0.421	0.10	0.32	8.0
12.5	1.4	6.1	0.421	1.0	0.421	0	0.42	8.4
14.5	2.5	5.0	0.345	2.0	0.690	1.10	0	8.4
18.0	3.3	4.2	0.290	3.5	1.014	0.80	0.31	8.7
19.5	3.9	3.6	0.248	1.5	0.373	0.60	0	8.7
22.0	4.3	3.2	0.221	2.5	0.552	0.40	0.15	8.9
23.0	4.4	3.1	0.214	1.0	0.214	0.10	0.11	9.0
25.0	4.7	2.8	0.193	2.0	0.386	0.30	0.09	9.1
27.0	4.65	2.85	0.197	2.0	0.393	-0.05	0.44	9.5
30.0	4.65	2.85	0.197	3.0	0.590	0	0.59	10.1
33.5	4.9	2.6	0.180	3.5	0.630	0.3	0.33	10.4
35.5	5.0	2.5	0.173	2.0	0.345	0.1	0.25	10.7

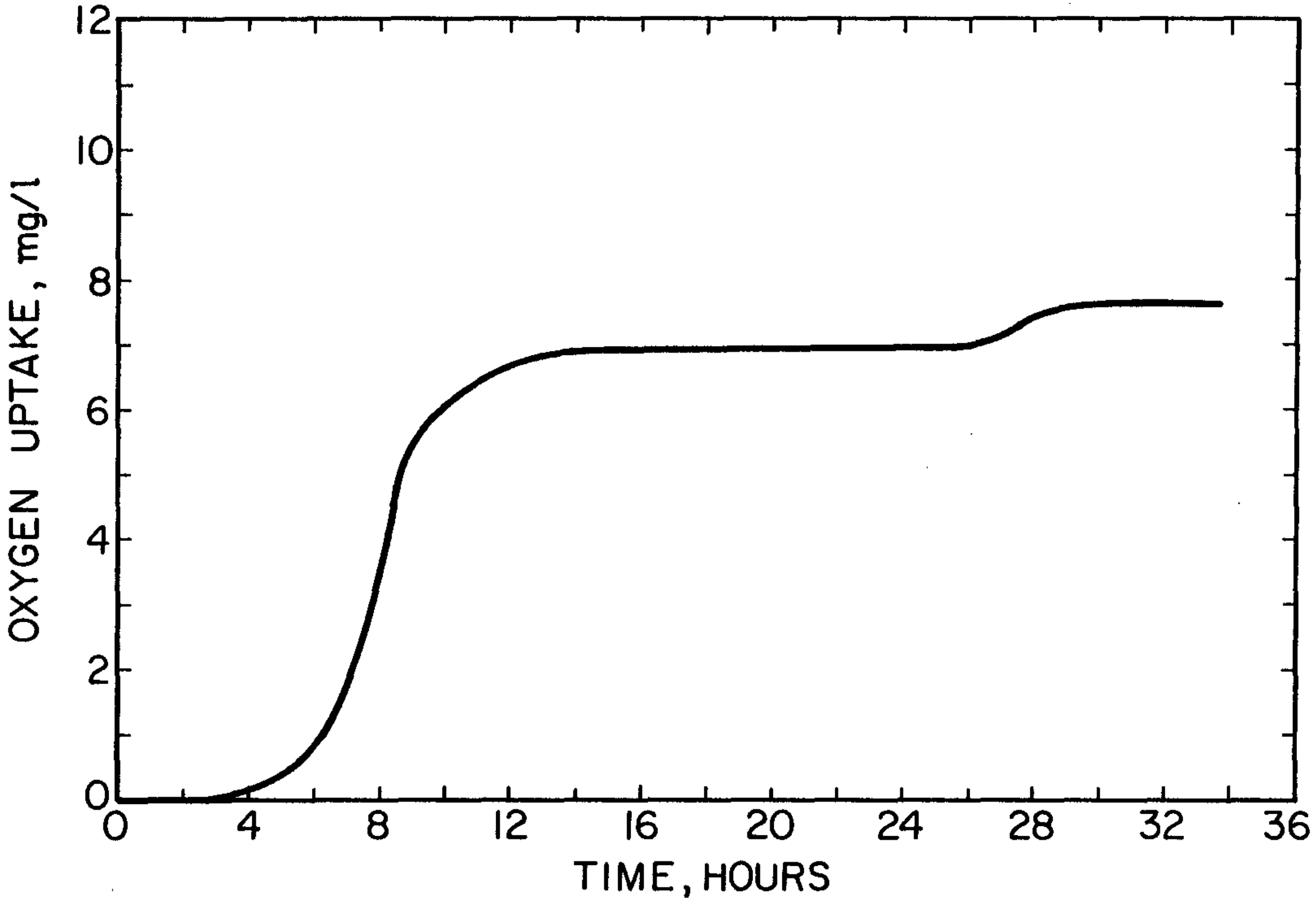

Figure 19. OXYGEN UPTAKE CURVE FOR $K_2 = 0.069\ hr^{-1}$ AND $S_i = 25$ mg/l.

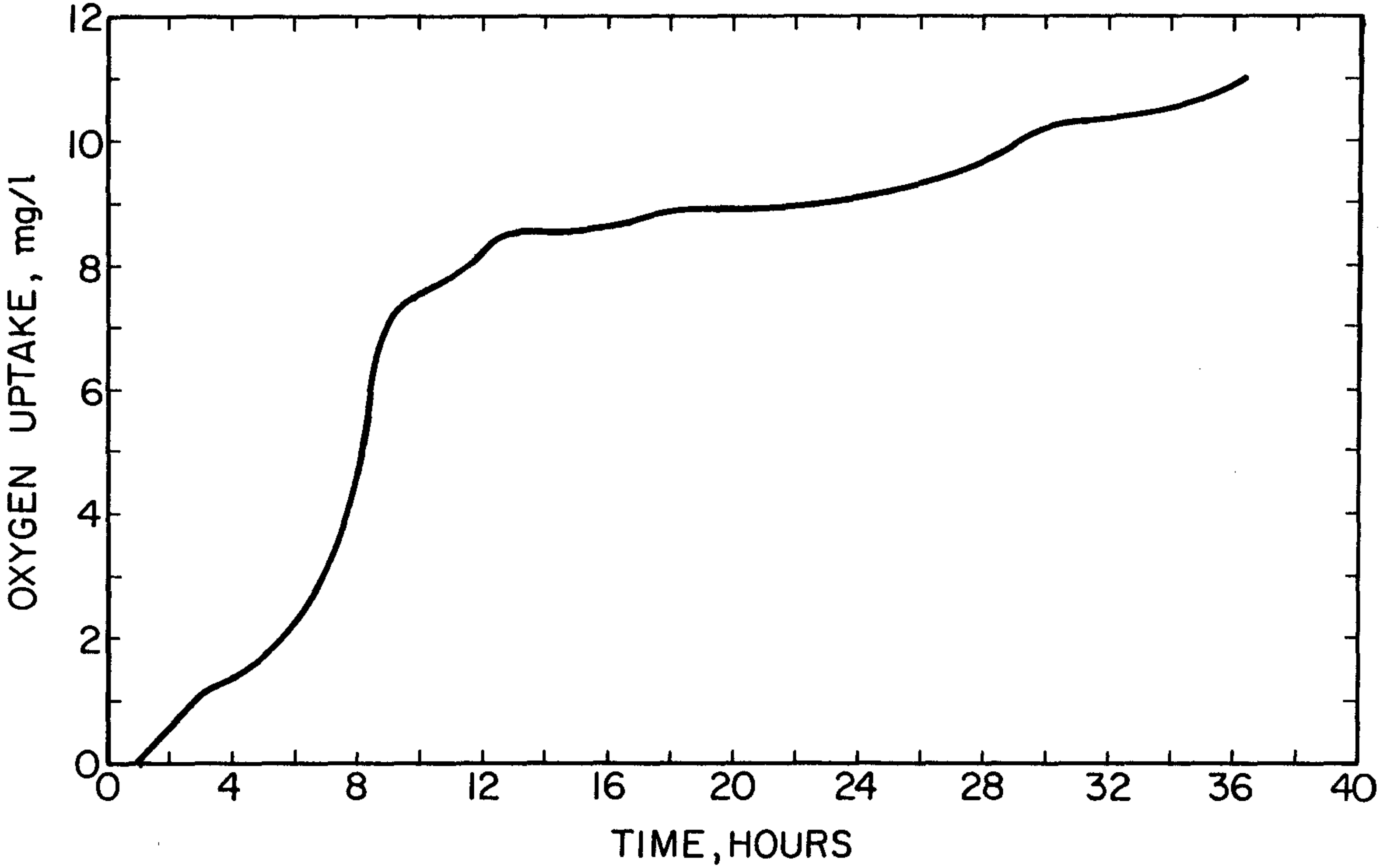

Figure 20. OXYGEN UPTAKE CURVE FOR k_2 = 0.069 hr AND S_i = 50 mg/l.

In order to accomplish this step several factors about the stream must be known or assumed. These include the dissolved oxygen saturation value, the initial DO in the stream, the amount of waste material being discharged to the stream, and the stream flow.

DO saturation (C_s)

In most cases the actual C_s of the stream will not be equal to values given in standard tables. This may be due to dissolved salts, turbidity, and/or other materials being present in the stream water. The stream DO saturation may be determined experimentally. Samples from the stream may be transported to the laboratory where they are aerated until the saturation value is reached. This must be done at the temperature expected in the field. The DO saturation value for Black Bear Creek was determined to be 7.5 mg/l at a temperature of 20°C.

Initial DO in Stream

The initial DO in the stream is also determined from field studies.

Amount of waste material being discharged

In the actual use of this method, the amount of waste material being discharged to the stream will be measured. However, in this study it was necessary that an ample sag be established. Therefore, a waste water was prepared in the laboratory and discharged to Black Bear Creek at a control point with permission of the Oklahoma Pollution Control Department. The waste water consisted of sucrose (table sugar) and a liquid fertilizer. A quantity was added to Black Bear Creek so that there was a sucrose concentration of 50 mg/l in the creek.

Stream flow

The stream flow is important for several reasons. The reaeration rate, K_2, is dependent upon the stream flow. The time of travel between sites is also dependent upon the stream flow. The stream flow in Black Bear Creek was measured a few hours before discharging the waste water to the creek.

Field Study A

The DO profile in Black Bear Creek was predicted for the following conditions:

Q = 6.0 cfs
Temp. = 20°C
Sucrose Concentration = 50 mg/l

K_2 values were selected from Figure 12 for a flow rate of 6.0 cfs. Time of travel for each reach is selected from Figure 13 or Figure 14, and are shown in Table 27. The K_2 values in Figure 12 are for a temperature of 20°C. Therefore, the stream K_2 values will be the same as those given in Figure 12.

The calculations required for predicting the DO profile are shown in Table 28 when the average velocity is used for the time of travel and in Table 29 when Manning's equation is used to determine the time of travel. The DO profiles are shown in Figures 21 and 22, respectively.

In order to check the predicted DO profile, DO measurements were made in the field. It was impractical to add enough waste water to substain an oxygen sag over the entire reach of the stream. The waste water was added to Black Bear Creek over a period of one hour. Therefore, the oxygen sag moved downstream as a plug flow. The DO profile was determined by establishing stations at various points. The DO at each station was determined each ten or fifteen minutes. As the slug of stream that received the waste water passed each point

Table 27

K_2 and Time of Travel Values for Q = 6 cfs

Stream Temp = 20°C

Site	K_2 20°C hr^{-1}	K_2 Stream Temp hr^{-1}	Average K_2 for Reach	Time of Travel, hrs	
				Manning Equation	Average Velocity
9	0.14	0.14			
			0.42	5.1	3.6
8	0.70	0.70			
			0.44	7.7	7.0
7	0.18	0.18			
			0.24	5.3	6.2
6	0.29	0.29			
			0.16	9.1	11.3
5	0.02	0.02			

$$K_{2(T)} = 3.74 \frac{V}{H\ 3/2} (1.0241)^{T-20}$$

$$K_{2_T} = K_{2(20)} \quad 1.0241^{T-20}$$

Table 28
Calculation of DO Profile from
O_2 Uptake Curves

(Time of travel - avg vel)

C_s = 7.5 Temp = 20°C Sucrose Concentration = 50 mg/l Q = 6 cfs

0	1	2	3	4	5	6	7	8
K_2 hr^{-1}	Hours	Δt hr	O_2 Uptake mg/l	ΔO_2 mg/l	D mg/l	$K_2 D \Delta t$ mg/l	ΔDO mg/l	DO mg/l
	0		0					7.0
		2		0.6	0.5	0.4	-0.2	
0.42	2		0.6					6.8
		1.6		0.7	0.7	0.5	-0.2	
	3.6		1.3					6.6
—		0.4		0.1	0.9	0.2	0.1	
	4		1.4					6.7
		2		0.9	0.8	0.7	-0.2	
	6		2.3					6.5
		1		0.8	1.0	0.4	-0.4	
	7		3.1					6.1
		1		1.4	1.4	0.6	-0.8	
0.44	8		4.5					5.3
		1		2.6	2.2	1.0	-1.6	
	9		7.1					3.7
		1		0.4	3.8	1.7	1.3	
	10		7.5					5.0
		0.6		0.2	2.5	0.7	0.5	
	10.6		7.7					5.5
		1.4		0.5	2.0	0.7	0.2	
	12		8.2					5.7
		2		0.3	1.8	0.9	0.6	
	14		8.5					6.3
0.24		2		0.1	1.2	0.6	0.5	
	16		8.6					6.8
		0.8		0.1	0.7	0.1	0	
	16.8		8.7					6.8
—		1.2		0.2	0.7	0.1	-0.1	
	18		8.9					6.7
		2		0	0.8	0.3	0.3	
	20		8.9					7.0
		2		0	0.5	0.2	0.2	
	22		8.9					7.2
		2		0.2	0.3	0.1	-0.1	
0.16	24		9.1					7.1
		2		0.2	0.4	0.1	-0.1	
	26		9.3					7.0
		2		0.4	0.5	0.2	-0.2	
	28		9.7					6.8

Table 29

Calculation of DO Profile from

O_2 Uptake Curves

(Time of travel by Mannings Equation)

C_s = 7.5 mg/l Temp = 20°C Sucrose Concentration = 50 mg/l Q = 6 cfs

0	1	2	3	4	5	6	7	8
K_2 hr^{-1}	Hours	Δt hr	O_2 Uptake mg/l	ΔO_2 mg/l	D mg/l	$K_2 D \Delta t$ mg/l	ΔDO mg/l	DO mg/l
	0		———					7.0
		2		0.6	0.5	0.4	-0.2	
	2		0.6					6.8
0.42		2		0.8	0.7	0.6	-0.2	
	4		1.4					6.6
		1.1		0.2	0.9	0.4	0.2	
	5.1		1.6					6.8
———		0.9		0.8	0.7	0.3	-0.5	
	6		2.4					6.3
		2		2.3	1.2	1.0	-1.3	
	8		4.7					5.0
		2		2.8	2.5	2.2	-0.6	
0.44	10		7.5					4.4
		2		0.7	3.1	2.7	2.0	
	12		8.2					6.4
		0.8		0.3	1.1	0.4	0.1	
———	12.8		8.5					6.5
		1.2		0	2.0	0.6	0.6	
	14		8.5					7.1
		2		0.2	0.4	0.2	0	
0.24	16		8.7					7.1
		2		0.1	0.4	0.2	0.1	
	18		8.8					7.2
		0.1		0	0.3	0	0	
———	18.1		8.8					7.2
		1.9		0	0.3	0.1	0.1	
	20		8.8					7.3
		2		0.1	0.2	0.1	0	
	22		8.9					7.3
		2		0.2	0.2	0.1	-0.1	
0.16	24		9.1					7.2
		2		0.2	0.3	0.1	-0.1	
	26		9.3					7.1
		1.2		0.3	0.4	0.1	-0.2	
	27.2		9.6					6.9
		0.8		0.2	0.6	0.1	-0.1	
	28		9.8					6.8

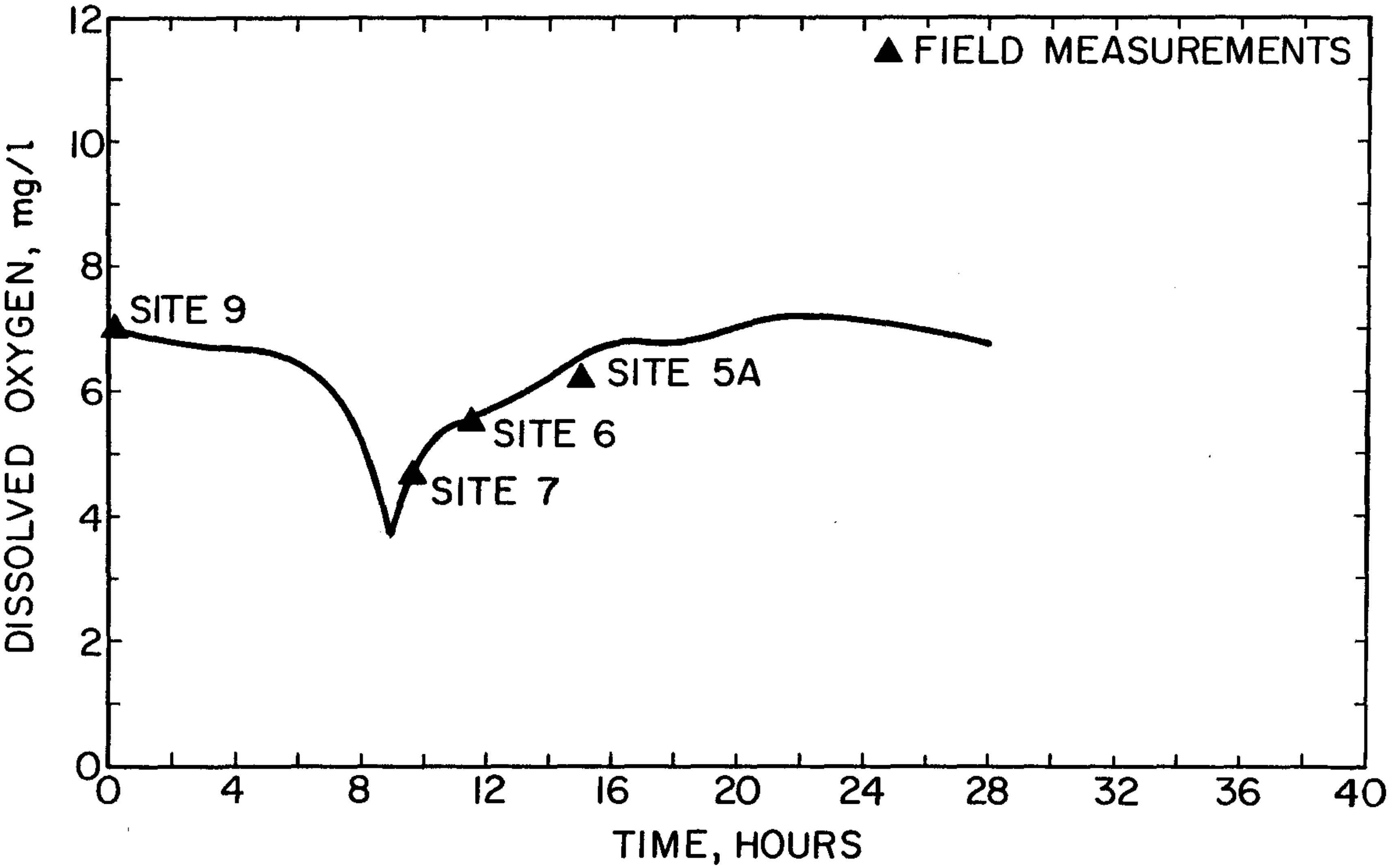

Figure 21. OXYGEN SAG CURVE FOR Q = 6 cfs AND TIME OF TRAVEL BASED UPON AVERAGE VELOCITY.

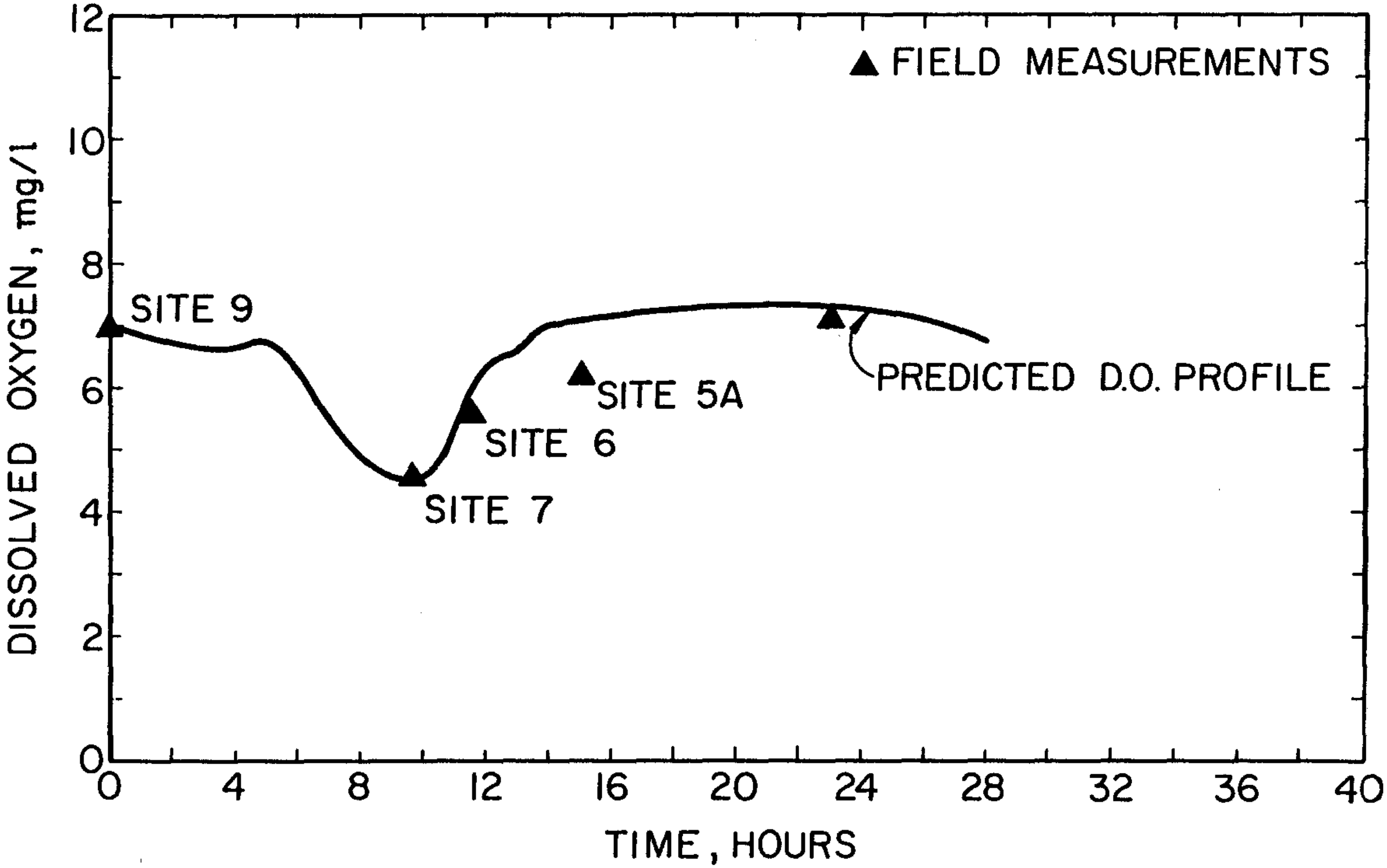

Figure 22. OXYGEN SAG CURVE FOR Q = 6 cfs AND TIME OF TRAVEL BASED UPON MANNINGS EQUATION.

the DO drops to a low point and then recovers to its original DO. The low point is the oxygen sag DO value.

The triangles on Figures 21 and 22 are the DO values obtained by field measurements. The time period is the difference in time between addition of and attainment of the low DO value. It is seen that when the average velocity was used for time of travel a good prediction was made. Mannings Equation did not provide as good of a prediction.

Field Study B

The DO profile in Black Bear Creek was predicted for the following conditions:

Q = 2.6 cfs
Temp. = 20°C
Sucrose Concentration = 50 mg/l

K_2 values were selected from Figure 12 for a flow rate of 2.6 cfs. Since the average velocity predicted the time of travel better than Manning's Equation, only the time of travel by the average velocity is used in this case. Therefore, the time of travel for each reach is selected from Figure 13. The K_2 values and time of travel values are shown in Table 30.

The calculations required for predicting the DO profile are shown in Table 31 and the resulting DO profile is shown in Figure 23. The triangles show the DO values obtained by field measurements. It is seen again that a good prediction of the DO profile as a function of time was made.

Step 7. Correlate DO profile versus time with time of travel of stream.

In Figures 24 and 25 the time scale has been converted to distance and the DO at the four sites are shown. It is seen that the prediction is not

Table 30

K_2 and Time of Travel Values for Q = 2.6 cfs

Stream Temp = 20°C

Site	K_2 20°C	K_2 Stream Temp	Average K_2 for Reach	Time of Travel average velocity
9	0.10	0.10		
			0.65	3.0
8	1.20	1.20		
			0.82	3.0
7	0.44	0.44		
			0.62	4.0
6	0.80	0.80		
			0.43	9.2
5	0.06	0.06		

Table 31

Calculation of DO Profile from O_2 Uptake Curve

(Time of Travel by Average Velocity)

C_s = 7.5 mg/l Temp. = 20°C Sucrose Concentration = 50 mg/l Q = 2.6 cfs

0	1	2	3	4	5	6	7	8
K_2 hr^{-1}	Hour	Δt hr	O_2 Uptake mg/l	Δ O_2 mg/l	D mg/l	$K_2D\Delta t$ mg/l	Δ DO mg/l	DO mg/l
	0		0					7.0
		2		0.6	0.6	0.7	1.0	
0.65	2		0.6					7.1
		1		0.5	0.4	0.3	-0.2	
—	3		1.1					6.9
		1		0.3	0.6	0.5	0.2	
0.82	4		1.4					7.1
		2		1.0	0.4	0.7	-0.3	
—	6		2.4					6.8
		2		2.3	0.7	0.9	-1.4	
	8		4.7					5.4
0.62		0.5		1.6	2.1	0.6	-1.0	
	8.5		6.3					4.4
		0.5		0.9	3.1	1.0	0.1	
	9		7.2					4.5
		0.5		0.2	3.0	0.9	0.7	
	9.5		7.4					5.2
		0.5		0.1	2.3	0.7	0.6	
—	10		7.5					5.8
		2		0.7	1.7	1.5	0.8	
	12		8.2					6.6
0.43		2		0.3	0.9	0.8	0.5	
	14		8.5					7.1
		2		0.2	0.4	0.3	0.1	
	16		8.7					7.2
		2		0.1	0.3	0.3	0.2	
	18		8.8					7.4
		2		0	0.1	0.1	0.1	
	20		8.8					7.5
		2		0.1	0	0	-0.1	
	22		8.9					7.4
		2		0.2	0.1	0.1	-0.1	
	24		9.1					7.3

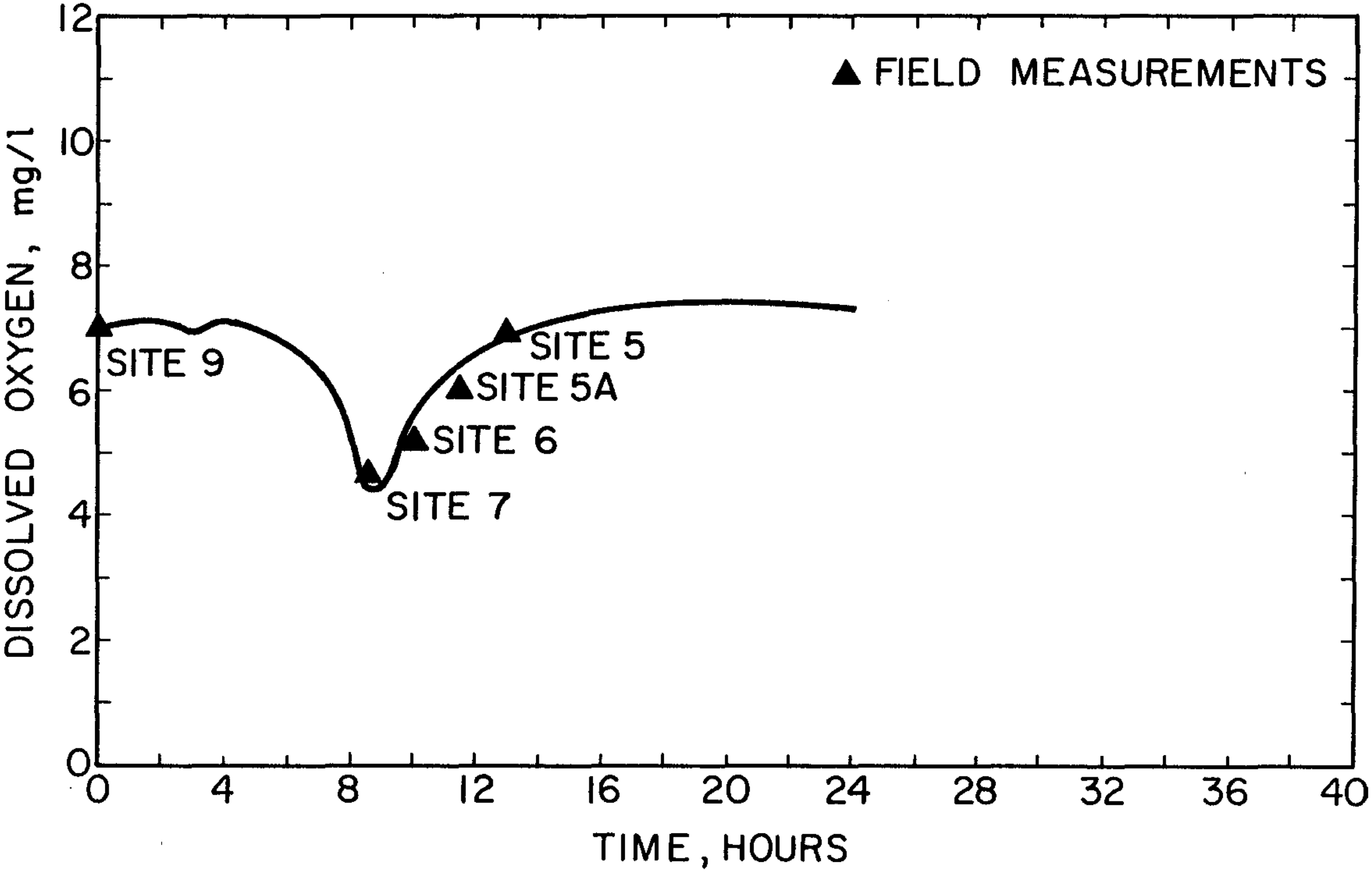

Figure 23. OXYGEN SAG CURVE FOR Q = 2.6 cfs AND TIME OF TRAVEL BASED UPON AVERAGE VELOCITY.

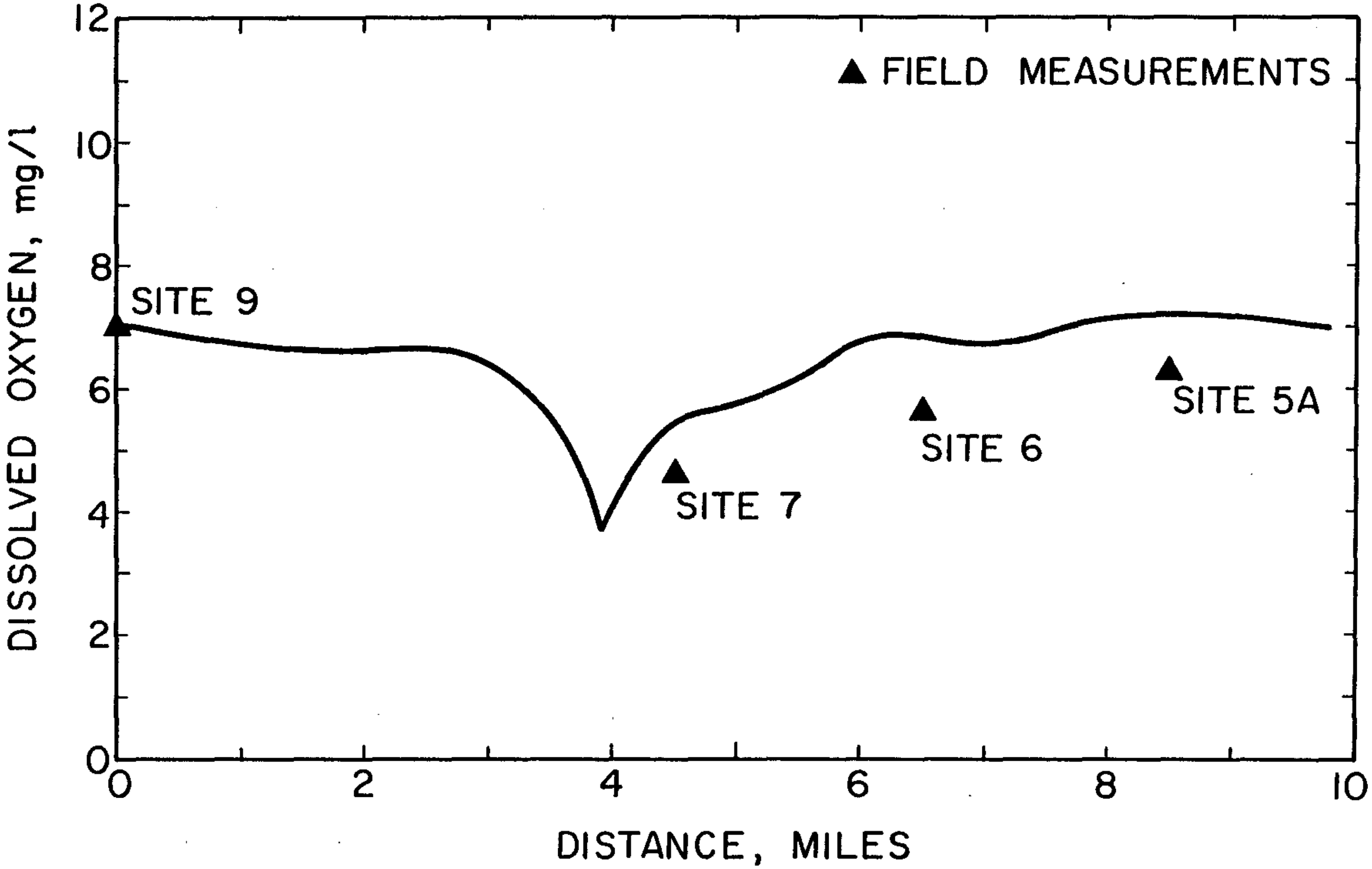

Figure 24. OXYGEN SAG CURVE VS. DISTANCE FOR Q = 6cfs AND TIME OF TRAVEL BASED UPON AVERAGE VELOCITY.

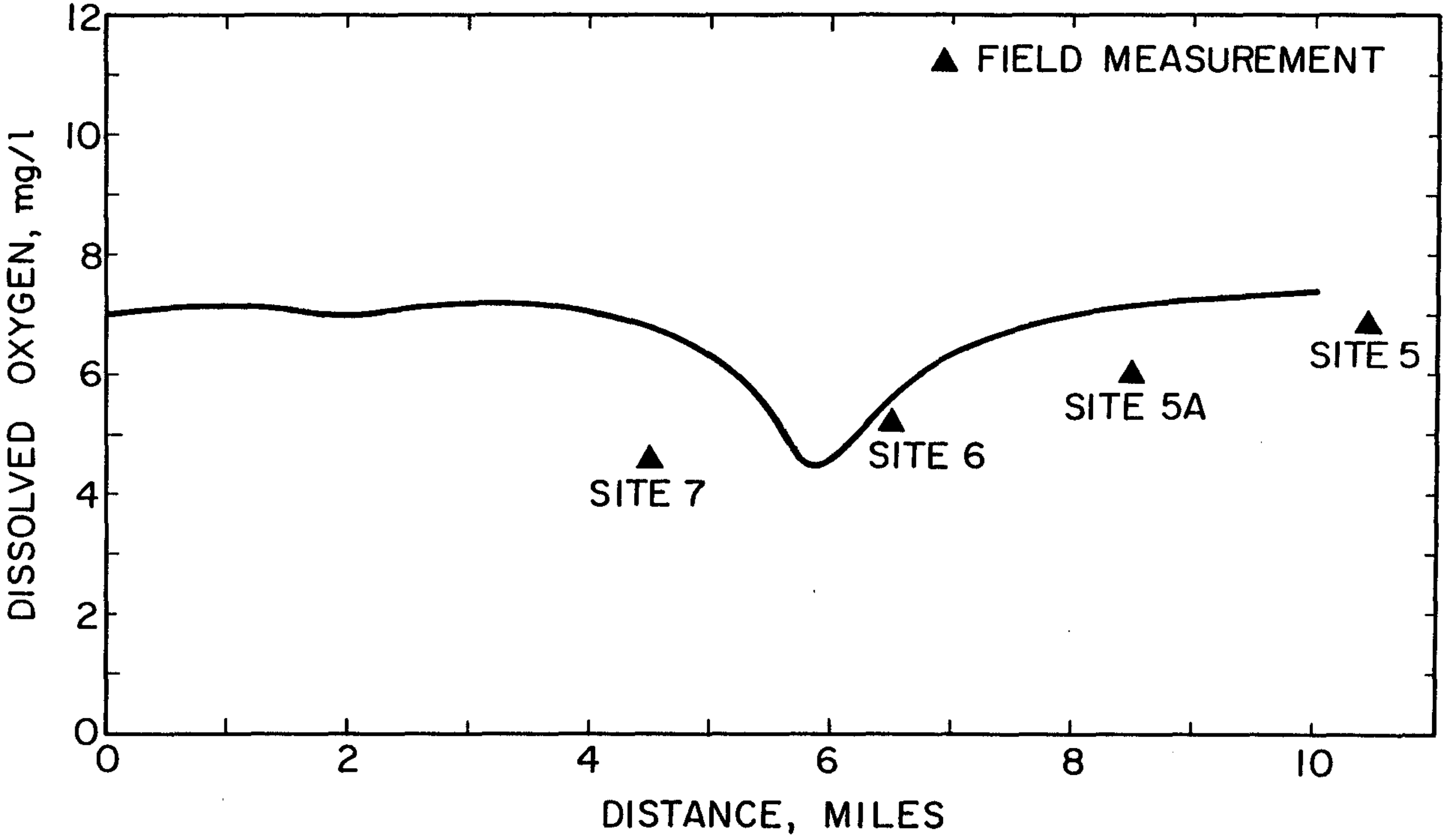

Figure 25. OXYGEN SAG CURVE VS. DISTANCE FOR Q = 2.6 cfs AND TIME OF TRAVEL BASED UPON AVERAGE VELOCITY.

good. Since a good prediction was observed with time and a less than desirable prediction was obtained with distance, it is reasoned that the problem lies with the time of travel data. However, the time of travel of the observed oxygen sag can be used to determine if a better time of travel measurement would produce a better prediction.

The average K_2 values and the time of travel based upon the measured oxygen sag are given in Table 32. The prediction calculations are given in Tables 33 and 34. The resultant DO profiles as a function of time are given in Figures 26 and 28. The resultant DO profiles as a function of distance are given in Figures 27 and 29. It is seen that a very good prediction is made when the time of travel is determined in this manner.

Model Stream Flow Analysis

Flow Calculations

The output from the model gives the average daily flow for the Pawnee gage site. For flow computation at points along the channel other than at the Pawnee gage a drainage area ratio was used. For example, the drainage area above the location in question divided by the drainage area above the Pawnee gage multiplied by the flow at the Pawnee gage gives the flow at the intermediate point.

The model is capable of predicting future flows or recreating past flows.

Low Flow Frequency Analysis

Low flow frequency analyses were made for two locations along the channel - at the Pawnee gage site and for the Highway 177 crossing. The data

Table 32

K_2 and Time of Travel by Oxygen Sag

Site	Q = 6 cfs		Q = 2.6 cfs	
	Average K_2 for reach	Time of travel	Average K_2 for reach	Time of travel
9				
	0.43	9.75	0.74	8.5
7				
	0.24	2.0	0.62	1.5
6				
	0.16	3.25	0.43	1.5
5A				
	0.16		0.43	2.0
5				

TABLE 33

Calculation of DO Profile from O_2 Uptake Curves

(Time of travel by oxygen sag)

C_s = 7.5 mg/l Temp = 20°c Sucrose conc = 50 mg/l Q = 6 cfs

0	1	2	3	4	5	6	7	8
K_2 hr^{-1}	Hours	Δt hr	O_2 uptake mg/l	ΔO_2 mg/l	D mg/l	$K_2 D \Delta t$ mg/l	ΔDO mg/l	DO mg/l
	0		0					7.0
		2		0.6	0.5	0.4	-0.2	
	2		0.6					6.8
		2		0.8	0.7	0.6	-0.2	
	4		1.4					6.6
0.43		2		1.0	0.9	0.8	-0.2	
	6		2.4					6.4
		2		2.3	1.1	0.9	-1.4	
	8		4.7					5.0
		1		2.5	2.5	1.1	-1.4	
	9		7.2					3.6
		1		0.3	3.9	0.9	0.6	
	10		7.5					4.2
0.24		1		0.3	3.3	0.8	0.5	
	11		7.8					4.7
		1		0.4	2.8	0.7	0.3	
	12		8.2					5.0
		1		0.3	2.5	0.4	0.1	
	13		8.5					5.1
		1		0	2.4	0.4	0.4	
	14		8.5					5.5
		1		0	2.0	0.3	0.3	
	15		8.5					5.8
		1		0.2	1.7	0.3	0.1	
	16		8.7					5.9
		2		0.1	1.6	0.5	0.4	
0.16	18		8.8					6.3
		2		0	1.2	0.4	0.4	
	20		8.8					6.7
		2		0.1	0.8	0.3	0.2	
	22		8.9					6.9

TABLE 34

Calculation of DO Profile from

O_2 Uptake Curves

(Time of travel-oxygen sag)

C_s = 7.5 mg/l Temp = 20°C Sucrose Concentration = 50 mg/l Q= 2.6 cfs

0	1	2	3	4	5	6	7	8
K_2 hr^{-1}	Hours	Δt hr	O_2 Uptake mg/l	ΔO_2 mg/l	D mg/l	$K_2D\Delta t$ mg/l	ΔDO mg/l	DO mg/l
0.74	0		0					7.8
		2		0.6	0.5	0.7	0.1	
	2		0.6					7.1
		2		0.8	0.4	0.6	-0.2	
	4		1.4					6.9
		2		1.0	0.6	0.9	-0.1	
	6		2.4					6.8
		2		2.3	0.7	1.0	-1.3	
	8		4.7					5.5
		0.5		1.6	2.0	0.7	-0.9	
	8.5		6.3					4.6
		0.5		0.9	2.9	0.9	0	
0.62	9		7.2					4.6
		0.5		0.2	2.9	0.9	0.7	
	95		7.4					5.3
		0.5		0.1	2.2	0.7	0.6	
	10		7.5					5.9
		1		0.3	1.6	0.7	0.4	
0.43	11		7.8					6.3
		0.5		0.2	1.2	0.3	0.1	
	11.5		8.0					6.4
		0.5		0.2	1.1	0.2	0	
	12		8.2					6.4
		1		0.3	1.1	0.5	0.2	
	13		8.5					6.6
		1		0	0.9	0.4	0.4	
	14		8.5					7.0
		2		0.2	0.5	0.4	0.2	
	16		8.7					7.2
		2		0.1	0.3	0.3	0.2	
	18		8.8					7.4
		2		0	0.1	0.1	0.1	
	20		8.8					7.5
		2		0.1	0	-0	-0.1	
	22		8.9					7.4

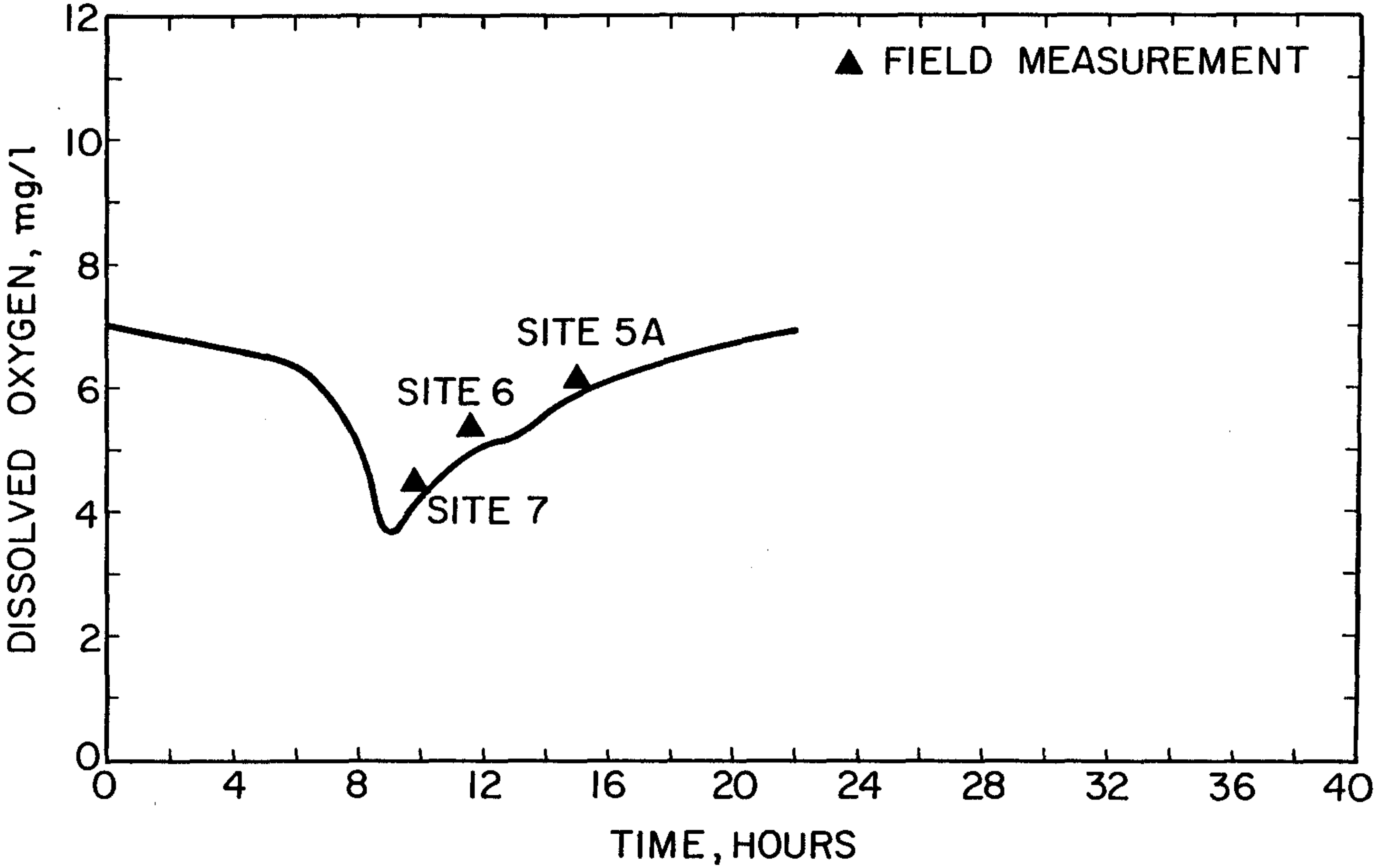

Figure 26. OXYGEN SAG CURVE FOR Q = 6 cfs AND TIME OF TRAVEL BASED UPON OXYGEN SAG.

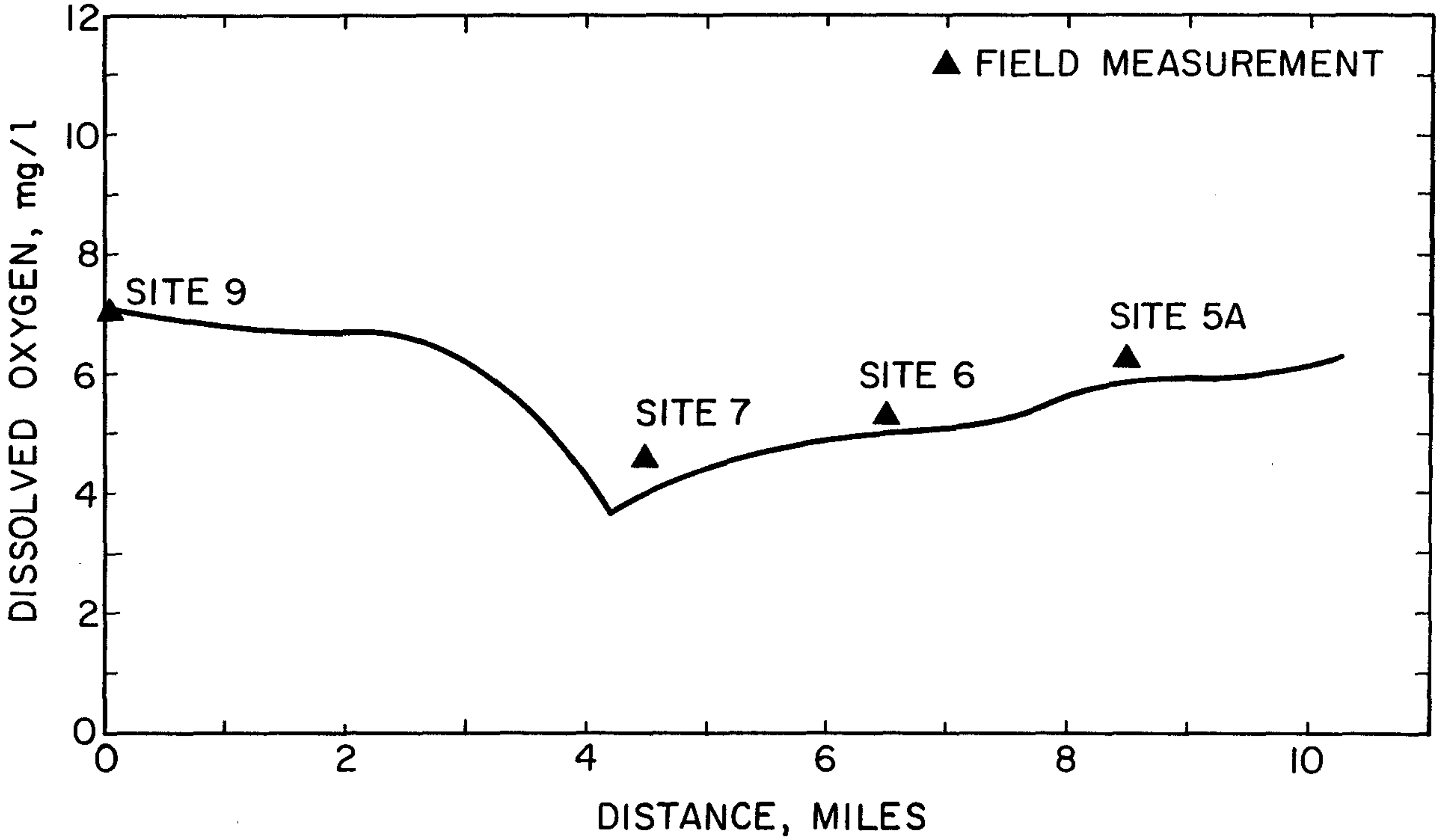

Figure 27. OXYGEN SAG CURVE VS. DISTANCE FOR Q = 6 cfs AND TIME OF TRAVEL BASED UPON OXYGEN SAG.

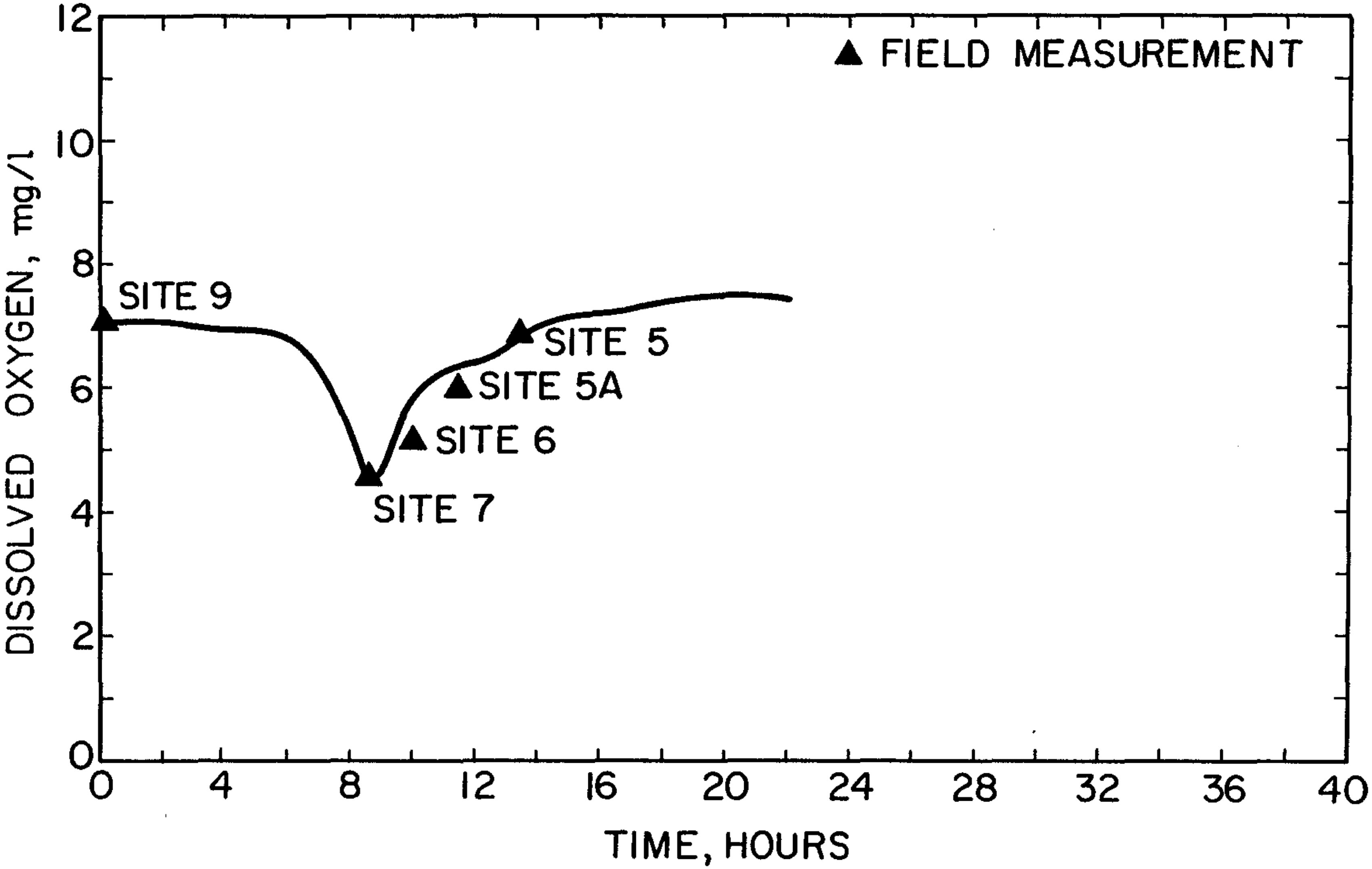

Figure 28. OXYGEN SAG CURVE FOR Q = 2.6 cfs AND TIME OF TRAVEL BASED UPON OXYGEN SAG.

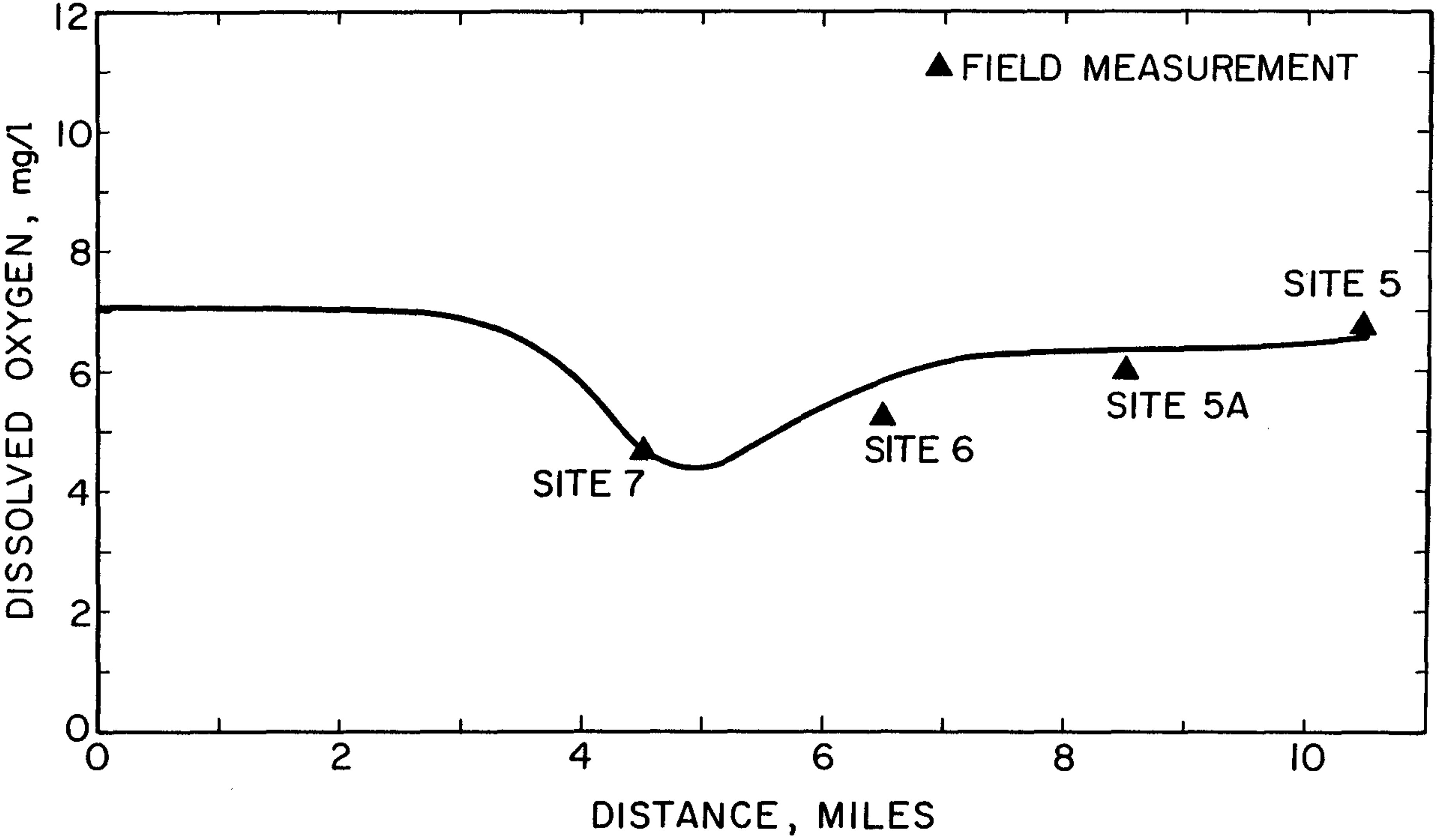

Figure 29. OXYGEN SAG CURVE VS. DISTANCE FOR Q = 2.6 cfs AND TIME OF TRAVEL BASED UPON OXYGEN SAG.

and frequency plots are shown in Tables 35 and 36 and Figures 30 and 31.

Prediction of Stream Flow

Because of the size of the NWSRFS Model it was not activated on the OSU computer system. However, through an agreement with the Tulsa River Forecast Center (RFC) anytime a flow prediction was needed the Tulsa RFC activated the model and provided the flow prediction at the Pawnee gage site. The following is a table of the predicted and actual flows as measured in the field.

	Stream Flow, cfs	
Date	Predicted	Actual
12/12/75		17.2
1/24/76		7.9
2/22/76		4.1
4/17/76		3.1
6/13/76		3.1
4/30/78	2.5	2.6
5/18/78	20.0	6.0

TABLE 35

Plotting Positions for the Low Flow Frequency Curve, Station I

Rank	Recurrence Interval (years)	1 day Mean Discharge cfs	90 day Mean Discharge cfs	183 day Mean Discharge cfs	365 day Mean Discharge cfs
1	30.0	0.0	0.0	0.0	3.4
2	15.0	0.0	0.0	0.3	17.8
3	10.0	0.0	0.0	1.4	27.9
4	7.5	0.0	0.5	1.7	32.8
5	6.0	0.0	0.9	2.5	42.4
6	5.0	0.0	0.9	2.7	49.7
7	4.2	0.0	1.0	4.9	50.3
8	3.7	0.0	1.3	5.8	61.0
9	3.3	0.0	1.4	7.9	61.2
10	3.0	0.0	2.9	11.5	75.0
11	2.7	0.0	3.1	13.7	82.5
12	2.5	0.1	4.0	14.0	86.5
13	2.3	0.2	4.4	14.8	88.2
14	2.1	0.3	4.6	16.2	102.0
15	2.0	0.4	4.7	20.5	104.0
16	1.8	0.7	4.7	20.5	117.0
17	1.7	0.8	5.4	21.3	145.0
18	1.6	1.0	7.5	24.0	154.0
19	1.5	1.2	7.7	38.4	179.0
20	1.5	1.3	8.8	39.8	182.0
21	1.4	1.4	8.9	46.3	191.0
22	1.3	1.4	10.5	49.7	216.0
23	1.3	1.8	12.2	53.1	229.0
24	1.2	1.9	16.3	65.4	230.0
25	1.2	1.9	17.9	96.0	358.0
26	1.1	2.9	31.7	212.0	400.0
27	1.1	3.3	53.2	261.0	437.0
28	1.0	4.4	64.2	311.0	465.0
29	1.0	5.4	82.1	325.0	517.0

TABLE 36

Plotting Positions for Low Flow Frequency Curves, Station II

Rank No.	Recurrence Interval (years)	1 day Mean Discharge cfs	90 day Mean Discharge cfs	183 day Mean Discharge cfs	365 day Mean Discharge cfs
1	30.0	0.0	0.0	0.0	3.2
2	15.0	0.0	0.0	0.3	16.8
3	10.0	0.0	0.0	1.3	26.3
4	7.5	0.0	0.4	1.6	30.9
5	6.0	0.0	0.8	2.4	40.0
6	5.0	0.0	0.9	2.6	46.9
7	4.2	0.0	0.9	4.7	47.5
8	3.7	0.0	1.2	5.5	57.6
9	3.3	0.0	1.3	7.5	57.8
10	3.0	0.0	2.8	10.8	71.0
11	2.7	0.0	2.9	12.9	77.9
12	2.5	1.0	3.8	13.2	81.7
13	2.3	0.1	4.1	13.5	83.3
14	2.1	0.2	4.3	15.3	96.3
15	2.0	0.3	4.5	19.3	98.2
16	1.8	0.6	4.5	19.3	110.5
17	1.7	0.7	5.1	20.1	136.9
18	1.6	0.9	7.1	22.6	146.4
19	1.5	1.1	7.2	36.2	167.0
20	1.5	1.2	8.3	37.8	171.8
21	1.4	1.3	8.4	43.7	180.3
22	1.3	1.3	9.0	46.9	204.0
23	1.3	1.7	11.5	50.1	216.2
24	1.2	1.7	15.3	61.7	217.2
25	1.2	1.7	16.9	90.6	338.0
26	1.1	2.7	29.9	200.2	377.7
27	1.1	3.1	50.2	237.0	412.7
28	1.0	4.1	60.6	293.7	439.1
29	1.0	5.1	77.5	306.9	488.2

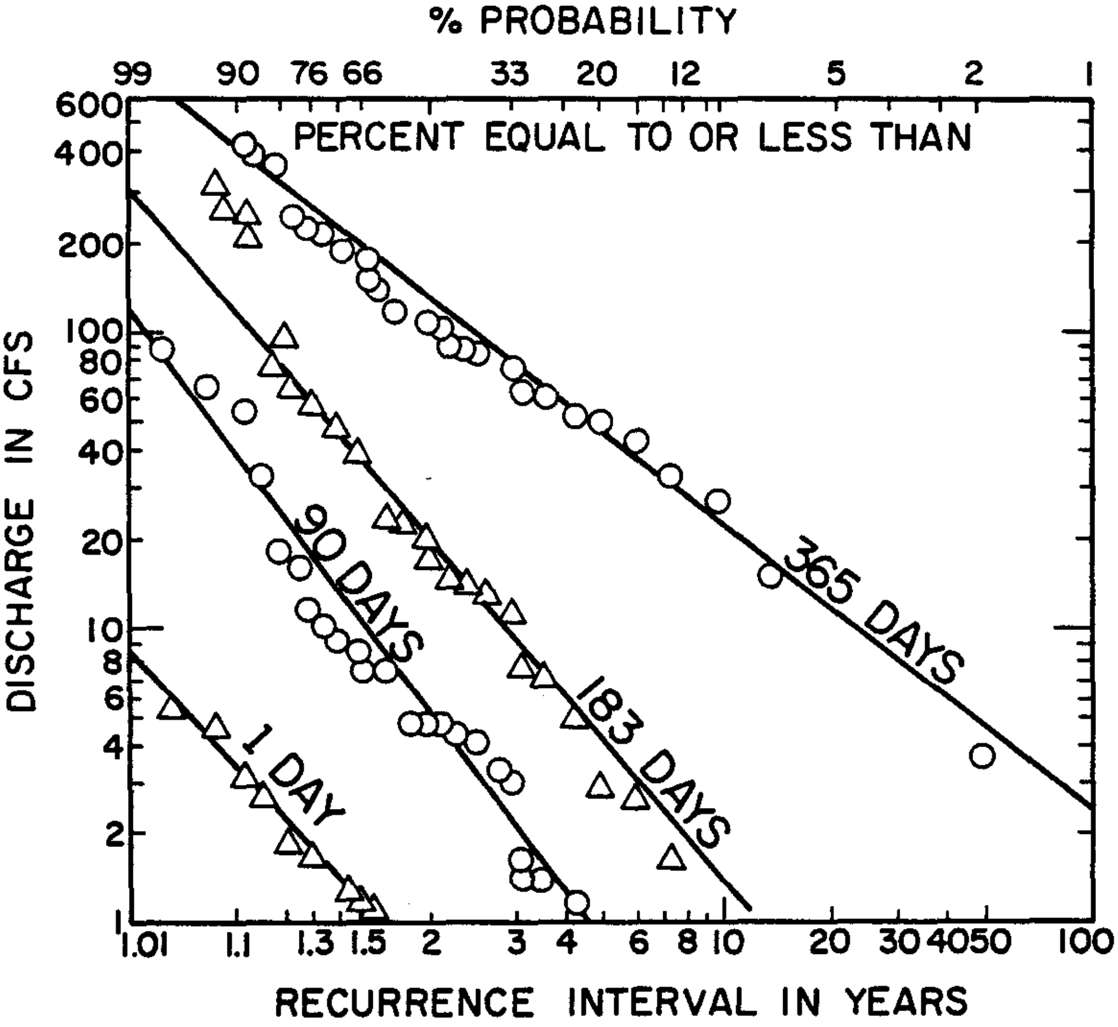

Figure 30. LOW FLOW FREQUENCY CURVE, STATION I.

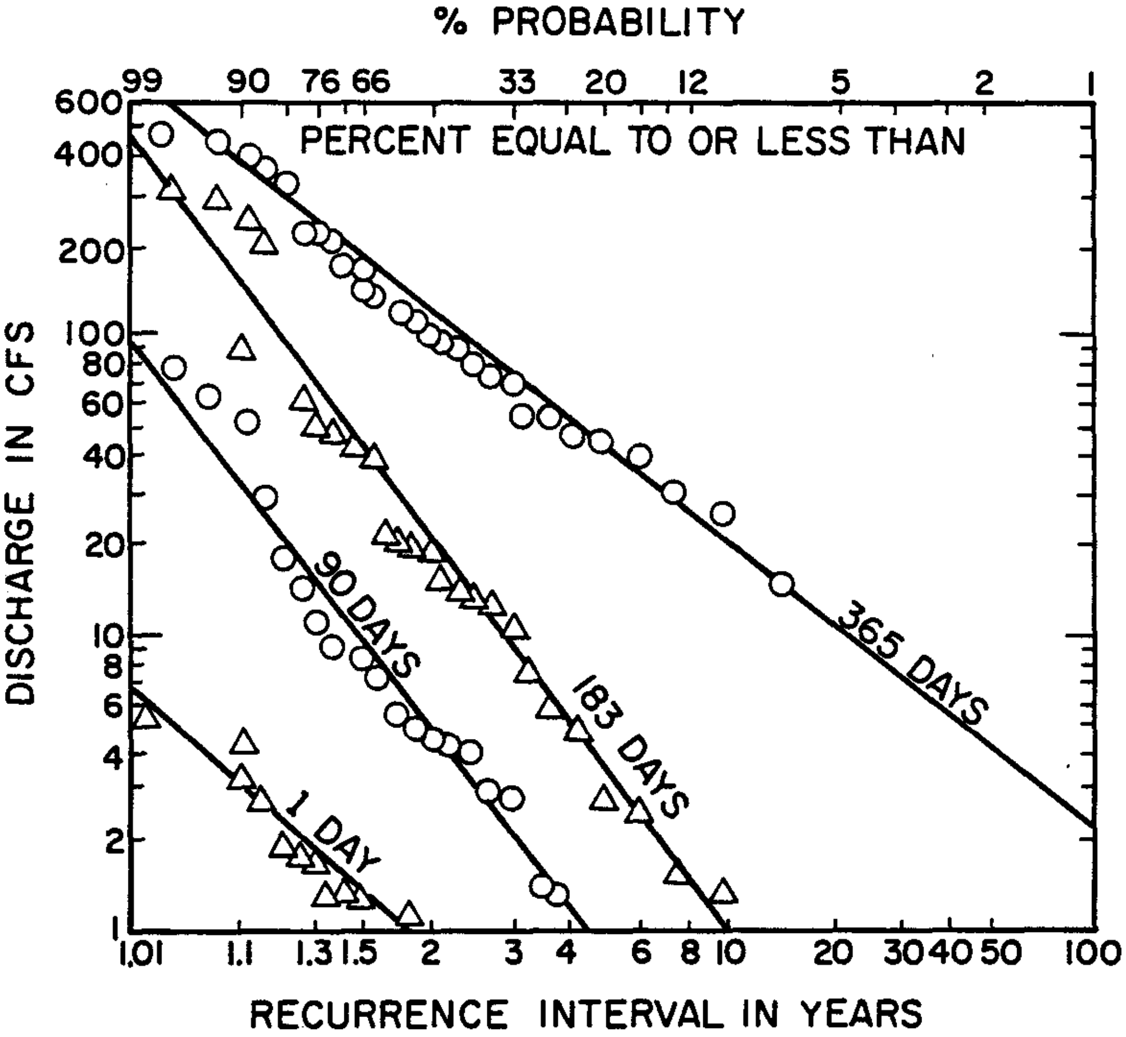

Figure 31. LOW FLOW FREQUENCY CURVE, STATION II.

DISCUSSION

This study has shown that the stirred open jar method is very accurate in estimating the DO Profile in a stream. The only problem encountered in this study was the determination of the time of travel of the stream. In the first attempts at predicting the stream DO Profile the time of travel was determined by using an average velocity and by using the Mannings equation. When the DO Profile was estimated as a function of time, the use of the average velocity for predicting the time of travel gave a good prediction, however the Mannings equation did not. When the DO Profile was predicted as a function of distance along the stream neither the average velocity or the Mannings equation method for predicting the time of travel gave good results. However, when the time of travel was determined by measuring the time of travel of the sag the stirred open jar reactor provided an excellent prediction of the DO Profile both as a function of time and distance. Therefore, it can be said that if an accurate means of determining the time of travel is used, then the stirred open jar reactor method is an excellent means for predicting the DO Profile in a stream.

The use of a fluorescent dye has been used by others to determine the time of travel in a stream. However, this method can be expensive in that the equipment needed to detect the fluorescent dye is quite expensive. It appears that this is an area that needs further work. If an inexpensive means of determining an accurate time of travel of the stream is available, then the stirred open jar reactor method for predicting the assimilation capacity in small receiving streams will provide an inexpensive method.

The NWSRFS Model for predicting streamflow from rainfall data gave mixed results. In one case, the predicted value was very close to that actually measured in the stream, whereas in another case the predicted value was a little bit more than three times the actual flow in the stream. The model was not significantly tested with actual Black Bear flow to make a complete decision. During the time of testing in the field the investigation was hampered due to excessive rainfall and excessive cold weather, therefore it is difficult to make a firm decision in regards to the model.

Since the results of this study provide definite indication of the value of the method used to predict the DO profile it appears that a shorter but more intensive study on the specific subject would be valuable. In such a study better instrumentation for measuring the time of travel should be employed. Such a study would not be concerned with the full extent of the investigation herein reported. For example, it would not be necessary to analyze for the wide range of chemicals or be concerned with predicting runoff. Instead more of the investigational effort would be devoted to testing predicted profiles in the stream.

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