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SIMULATION OF STREAM PROCESSES IN A MODEL RIVER

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ABSTRACT

Various stream processes which contribute to reoxygenation or deoxygenation were studied separately under controlled conditions in aquaria and in a research flume. Stream processes were simulated in one channel of a two channel flume as a model river consisting of benthos and photosynthetic organisms. In the other channel an identical ecosystem was established and stressed with an organic pollutant. The conditions established in these model rivers were those assumed in the development of various sag equations. The stressed ecosystem behaved in accordance with sag equations proving the validity of the classical predictive formulas and validity of simulation of stream processes in the model river.

A formulation for atmospheric reaeration constants for flowing systems as a function of velocity and depth was developed from data obtained in the model river. This formulation agrees fairly well with the formula developed by Churchill (6) through extensive studies on rivers in the Tennessee Valley.

Limitations for the use of the research flume in oxygen balance studies and factors influencing atmospheric reaeration such as wind effects and convection currents were investigated.

CONCLUSIONS

1. Small ecosystems established in aquaria and in the research flume (Model River) are useful tools for simulating stream processes and evaluating the complex factors which interact with various pollutional stresses. A Model River can be used effectively in determining the interrelationships which exist between atmospheric reaeration, photosynthesis, organic load, and benthal demand.

The Model River behaved mathematically in accordance with theoretical oxygen sag formulas.

2. Atmospheric reaeration coefficients in the Model River can be predicted from the following relationship:

$$k_2 \text{ day}^{-1} \text{ at } 20^{\circ}\text{C} = 2.98\ (V/H^{1.5})^{0.703}$$

where V is velocity in feet per second and H is depth in feet. This equation is also applicable to real rivers.

3. Measurement of responses of the model ecosystem to organic pollutional stresses, thermal stresses, and toxic stresses can aid in the development and verification of prediction models.

4. The effects of wind (eliminated from the Model River) will cause significant error in oxygen deficit predictions in shallow slow moving river systems.

5. Prediction of oxygen deficit through use of a sag equation in which net photosynthetic production is included as a constant rate per day will result in a predicted deficit which is lower than actual deficit.

6. Determining reaeration coefficients (k_2), in systems containing photosynthetic producers, by use of the sag equation with net photosynthesis considered as a fixed rate per day, will result in calculated k_2 values lower than actual. For example, experiments are presented in which k_2 values so calculated ranged from 0.06 day^{-1} to -0.88 day^{-1} when the actual k_2 was 0.3 day^{-1}.

7. In many cases, photosynthetic organisms having a positive net daily production of oxygen may not be beneficial to a stream's oxygen state. High production of oxygen during daylight hours may reduce significantly the effectiveness of atmospheric reaeration, and respiration of the organisms during the hours of darkness can result, at the end of a one day cycle, in an oxygen deficit greater than what it would have been if atmospheric reaeration were the only oxygen source.

8. Side wall temperature effects of an out-of-doors small scale ecosystem exposed to the sun must be carefully controlled to

prevent convection currents, particularly if controlled atmospheric reaeration is important to the experiment. The reaeration rate can be underestimated as a result of mixing produced by convection currents.

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LIST OF SYMBOLS

A = unit area of air-water interface;

a = net photosynthetic production of oxygen in milligrams per liter per unit of time;

BOD = Biochemical oxygen demand;

BOD_5 = oxygen required by an organic load during a 5 day period;

C_G = concentration of oxygen in air;

C_L = concentration of oxygen in water at the air-water interface;

C_o = concentration of oxygen in the main body of water;

C_s = saturation concentration of oxygen in water at a given temperature;

D.O. = dissolved oxygen;

D = $(C_s - C_o)$ dissolved oxygen deficit;

$\bar{D}$ = average dissolved oxygen deficit during a time interval;

D_G = coefficient of diffusion of oxygen through the gas film at the air-water interface;

D_L = coefficient of diffusion of oxygen through the liquid film at the air-water interface;

D_o = initial dissolved oxygen deficit;

D_t = dissolved oxygen deficit at any time t;

H = depth of water;

K_1 = rate constant (log base e) at which BOD is being removed from water by biological activity;

K_2 = atmospheric reaeration rate constant (log base e);

K_3 = rate constant (log base e) at which BOD is being removed from water through settling out of suspended solids;

K_4 = initial rate (log base e) of removal of oxygen demand from benthal deposits at the start of a given time period;

K_L = (liquid film coefficient) overall transfer coefficient through liquid film;

k_1 = rate constant (log base 10) at which BOD is being removed from water by biological activity;

k_2 = atmospheric reaeration rate constant (log base 10);

k_3 = rate constant (log base 10) at which BOD is being removed from water through settling out of suspended solids;

k_4 = initial rate (log base 10) of removal of oxygen demand from benthal deposits at the start of a given time period;

$k_{2(20)}$ = atmospheric reaeration rate constant (log base 10) at 20^oC;

k_{2_T} = atmospheric reaeration rate constant (log base 10) at any given temperature;

L = Biochemical oxygen demand;

L_d = Biochemical oxygen demand of benthos per square foot of bottom surface (aerial demand);

L_{d_o} = aerial demand of benthos at the beginning of a time period;

L_o = Biochemical oxygen demand at the beginning of a time period;

L_t = Biochemical oxygen demand at any time t;

P = gross production of oxygen by photosynthesis;

$(P - R)$ = net production of oxygen by photosynthesis;

p_{gas} = partial pressure of oxygen in air;

p_{liquid} = partial pressure of oxygen in water;

Q = rate of flow in liters per minute;

r = rate at which water surface is being renewed;

R = respiration, oxygen consumed by photosynthetic organisms;

s = rate of addition of BOD to the stream by benthos;

T = any given temperature;

t = any given time;

V = mean stream velocity;

v = volume of water undergoing aeration;

y = oxygen consumed per unit of time in degradation of organic load;

y_L = liquid film thickness at air-water interface;

Φ = temperature correction factor used in atmospheric reaeration determinations.

CHAPTER I

Introduction

Rivers are one of our most important natural resources. Rivers provide the water necessary to support the processes of life, and, in addition, provide: water necessary for industry; a means of transportation; a source of food; and numerous benefits, the value of which cannot readily be measured. These countless fringe benefits are in the areas of recreation and mental well being that come from viewing a thing of great aesthetic beauty.

Because of the importance of rivers to life and economic growth, cities sprang up strategically along them. It was natural that the water taken from our streams and rivers be returned to the original source, since this was the most feasible and most economical way to dispose of waste waters. In the early days of our country's development this process offered no particularly destructive results, since our population centers along rivers were relatively small; industry was not extensive; and the waste products of our cities could be assimilated by the streams. This is not the case today. Population and industry have grown at an exponential rate. The waste water products of cities can no longer be discharged into streams without considering the extent to which treatment will be required.

Our nation will continue to grow both in population and affluence. As a result, the industries necessary to support this population increase and continually expanding affluence in turn will grow. There will be more and more consumption of water and an increasing amount of water wastes with which to contend. Complicating this situation, and rightly so, will be an expanding use of our environment for recreational purposes. As more and more of the United States becomes urban, the delights of the rural scene will become more and more valuable.

Streams will continue to be the carrier of waste waters. Those who deal in water management will have to make many critical decisions concerning the treatment necessary before discharge into the streams, or whether the discharge, in fact, can be made. In many cases the decisions will be critical in that the results of the decisions will not be undone easily. The prevention of discharge of a waste that could be assimilated might well result in the stagnation of industry where industrial growth is needed. On the other hand, a decision to allow industrial growth which results in a loading (thermal, inorganic, or organic) which cannot be assimilated by the stream will downgrade the stream or may result in financial disaster to the industry or industries involved, which in good faith selected a site with the approval of the proper authorities only to find that their contribution to the pollutional load taxes the stream beyond its natural ability to maintain previously conceived quality standards, and as a result are forced to curtail operations.

To make these critical decisions is extremely difficult, for the ecosystem is balanced so delicately that the affect on this system by the introduction of some pollutant might be known only after the fact. The stream would have to be stressed with the load and the effects noted. Predetermination of effects by experimentation on a real river in most cases is neither practical nor economically feasible. If, however, a model that simulates stream processes and responds to pollutional stress in much the same manner as the stream is developed, decisions could be made with a degree of confidence not otherwise possible.

Significance of Dissolved Oxygen

A prime consideration in stream assimilative capacity is dissolved oxygen. A positive dissolved oxygen content must be maintained to prevent putrefaction; however, if streams are to support game fish, D.O. must be maintained at not less than 4 to 5 mg/l or higher, depending upon the type of fish. In the process of assimilation, oxygen is consumed by organic load carried in the stream, by the benthal demand, and by the respiration of plants and plankton. Oxygen is provided to the stream by diffusion from the atmosphere and by photosynthesis. These elements of oxygen production and oxygen consumption are interrelated. Delicate balances are maintained. Mathematical relationships have been developed to describe the sources and sinks involved in the oxygen balance. In practice, it is not easy to make predictions based on these equations because of the physical difficulties involved in making observations and determining valid reaction coefficients necessary for solution of the equations.

The predictive formulas used to determine oxygen profiles (oxygen sag equations) along a river stretch have been developed based on certain assumptions. These assumptions are summarized by Dobbins (7):

a. The stream flow is steady and uniform.
b. The process for the stretch as a whole is a steady-state process, the conditions at every cross section being unchanged with time.
c. The removal of BOD by both bacterial oxidation and sedimentation or absorption or both are first

order reactions, the rates of removal at any section being proportional to the amount present.

d. The removal of oxygen by the benthal demand and by plant respiration, the addition of oxygen by photosynthesis and addition of BOD from the benthal layer or the local runoff are all uniform along the stretch.

e. The BOD and oxygen are distributed uniformly over each cross section, thus permitting the equations to be written in the usual one-dimensional form.

However, the validity of sag equations has not been proven experimentally under conditions assumed in their development (13).

Objective

The objective of this research was to simulate stream processes in a model river and to establish in this river the conditions that were assumed in the classical predictive formulation for oxygen deficit and then to determine whether the model will behave under organic stress in accordance with the predictive formula. The predictive formula used was that developed by Streeter and Phelps (3) but modified to include other elements in a stream ecosystem that contribute to or detract from the dissolved oxygen state in addition to biological degradation and atmospheric reaeration.

Scope

This study investigated sources and sinks contributing to oxygen balance and provided controlled experiments in which each source and sink was investigated separately prior to determination of oxygen balance in a stressed ecosystem. Specifically the study included:

a. An investigation into the effect of hydrodynamic conditions in the model river on reoxygenation through surface diffusion. Reaeration coefficients were determined for flow under various conditions of velocity and depth and an empirical formulation for reaeration in the model river was developed. Some peripheral studies such as the effect of wind on reaeration; the effect of convection currents in the model on surface reaeration; comparison of reaeration coefficients as determined in actual practice with true reaeration coefficients; comparison of reaeration coefficients obtained in previous studies on real rivers with reaeration coefficients calculated by using the empirical formula derived for the model river.

b. An investigation of oxygen draw down resulting from bottom sediment. Bottom sediments taken from the Colorado River at Austin and from Lake Austin were used in this study.

c. A study of the role of phytoplankton in the production and consumption of oxygen and its influence in atmospheric reaeration determinations.

d. A combining of the elements in a, b, and c above into a simulated stream ecosystem, and the stressing of that ecosystem with an organic load to determine whether the oxygen profile follows the predictive formulation presently used in stream analysis.

CHAPTER II

Equipment and Procedures

A series of laboratory, aquaria, and model river studies were conducted to determine the separate and combined effects of the following factors on oxygen balance in streams: atmospheric reaeration, biological degradation of organic load, benthal demand and photosynthesis.

The Model River

The model river in which stream processes were simulated (Fig. 2-1 and 2-2) consisted of a metal flume 200 feet in length, 2 feet deep and 2.5 feet wide, with a center removable partition providing two 1.25 feet wide channels. The intake can be provided with either potable water or with water from a control reservoir which is rich in phytoplankton. The phytoplankton population could be controlled by dilution with potable water as system simulation might require. The flow was controllable from 0 to approximately 200 liters per minute per channel through means of a constant head tank and weirs at the inlet. The bottom sediments used in the flume were obtained from nearby Lake Austin.

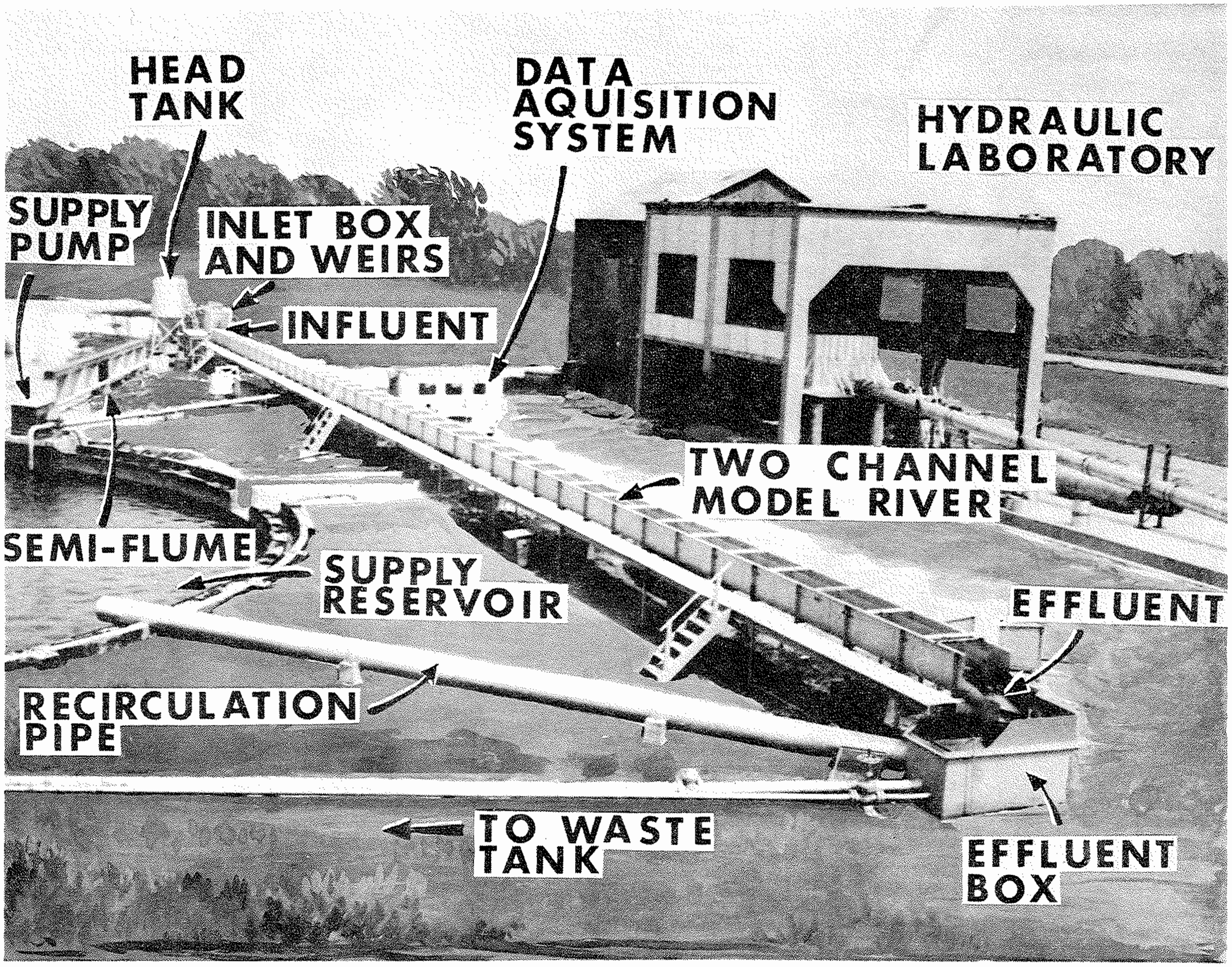


FIGURE 2-1. THE MODEL RIVER

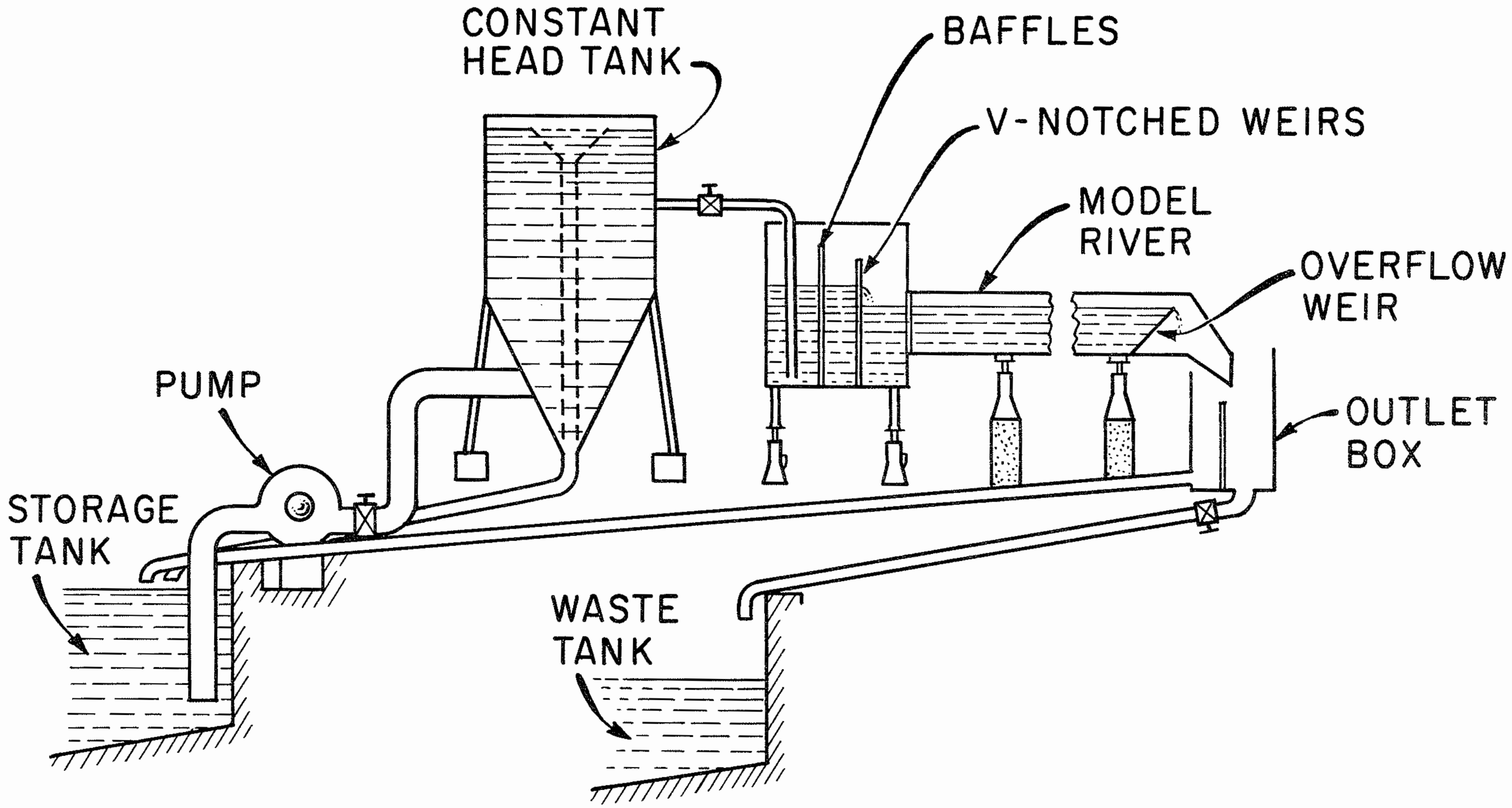


FIG. 2-2 SCHEMATIC OF MODEL RIVER SYSTEM

Instrumentation consisted of dissolved oxygen probes (galvanic), pH meters, a recording pyroheliometer and a recording anemometer.

Determination of Atmospheric Reaeration

In determining coefficients of atmospheric reaeration (k_2) potable water (municipal water) was used in a clean bare channel (devoid of sediment). Since the flume was oriented in a north-south direction and prevailing winds were out of the south, the elimination of wind effect on surface reaeration posed a problem. Baffles were installed extending from the top of the flume to the water surface. These baffles were not entirely successful in eliminating wind effect. As a result it was necessary to cover the flume with a clear, plastic material.

A solution of Na_2SO_3 with cobalt catalyst was mixed with the potable water in a mixing chamber at the inlet end of the flume to draw down the oxygen content. The solution of Na_2SO_3 and cobalt catalyst was dispensed from carboys in which a nitrogen environment was maintained. The nitrogen prevented assimilation of oxygen by the solution thereby providing a consistent dosing mix and relatively constant dissolved oxygen level at the initial station in the flume. Dosage was regulated depending upon the rate of flow to provide low initial dissolved oxygen (1 or 2 mg/l). Care was taken not to go below 1 mg/l to insure that unoxidized Na_2SO_3 would not move down stream and affect results.

Dissolved oxygen and temperature readings were taken along the length of the flume and atmospheric reaeration coefficients (k_2) were determined from the reoxygenation occurring between inlet and exit taking into consideration flow through time.

The dissolved oxygen measurements were taken with galvanic probes to which stirring mechanisms had been fastened to insure a sufficient and constant velocity of flow across the face of the probe. The probe was calibrated (Modified Winkler method) (22) before and after each experiment. During diurnal experiments probes would be calibrated a minimum of four times. This frequency was decided upon to insure against error.

Effect of Convection in k_2 Values

During initial determinations of k_2 values, it seemed that atmospheric reaeration was greater than expected and that the cause was related to the temperature differential between the water flowing in the flume and that of the atmosphere and to radiant heat from the sun. To test this hypothesis an experiment was conducted continuously for 24 hours in August when the atmospheric temperature was hot and the sun bright during the daylight hours. Velocity and depth were held constant and k_2 values were determined on an almost every hour basis. Resulting k_2 values averaged during daylight hours more than twice the night time average.

This discrepency in k_2 values was the result of convection currents established by heat conduction through the metal sides and bottom of the flume during the daylight hours. These convection currents stimulated mixing, increased surface renewal and thereby increased atmospheric reaeration.

In view of the foregoing, and since there was not the means available to the author to insulate side walls and bottom of the flume, valid k_2 values could only be determined by judiciously conducting the experimental determinations when radiant energy would not be a factor and when both water temperature and atmospheric temperature would be approximately the same.

Values of k_2 in Flume Containing Bottom Sediment

Coefficients of reaeration obtained in the clean channel as described above were compared to coefficients obtained in the other channel which contained bottom sediment. Potable water was used and bottom sediment was treated with copper sulfate in order to eliminate benthic effects on the oxygen level. Aeration factors determined for various flows and depths were not measurably different from those obtained in the completely clean flume.

In order to make the comparisons it was important to establish average velocity in the channel. This presented some difficulty since the thickness of the sediment was not constant throughout the length and width of the channel. Velocity was determined in the following manner. The potable water at the inlet was dosed erratically with the Na_2SO_3 solution. Dissolved oxygen was continuously monitored for ten minutes at a point near the inlet end. At approximately the flow through time, dissolved oxygen was monitored near the outlet end. Peaks and valleys were matched and the velocity was determined from the flow through time. Since the velocity and flow quantity determine average depth, a datum level was established and marked on the channel wall so that this would be used to determine average depths and velocities for the subsequent experiments.

Benthal Demand

Bottom sediment was obtained from the Colorado River west of Austin, approximately 1/4 mile downstream of the outfall from the

Austin sewage plant. Experiments were conducted in aquaria and the sediment was analyzed in the laboratory. The analysis consisted of determining BOD, organic fraction and inorganic fraction. Sediment was placed in four aquariums to a depth of 4 inches and covered with 2, 4, 6, and 8 inches of water. Oxygen was reduced to approximately 1.5 mg/l by Na_2SO_3 and D.O. monitoring was initiated. The sediment was devoid of macroinvertebrates, and biological activity was such that the sediment oxygen requirements were adequately satisfied by surface diffusion under the stagnant conditions of the aquaria. Oxygen levels built up in the aquaria until an equilibrium situation was reached. That is, the oxygen requirements of the sediment equalled the oxygen being provided by diffusion.

This experiment was conducted for 457 hours at a constant temperature of 22°C. After 86 hours oxygen requirements for all practical purposes remained constant. The aerial demand of the sediment was related to BOD of the sediment and an initial reaction rate coefficient was determined.

Photosynthesis

In these experiments water from the control reservoir, rich in phytoplankton, was passed through the clean channel. As in the previously discussed surface reaeration experiments, the oxygen was drawn down at the inlet and reoxygenation measured as the water passed through the channel. The amount of reoxygenation as a result of photosynthesis can then be determined since the amount of surface reaeration can be calculated from the factors determined in previous experimentation. The amount of sunlight in $cal/min/cm^2$ was continually recorded by a pyroheliometer. In addition, suspended solids were determined and plankton counts made.

Effect of Na_2SO_3 on Photosynthesis

Prior to beginning the above experiment, there was concern that the Na_2SO_3 used for dosing would affect oxygen production. To test this, a series of aquariums were used. Some of the aquariums had only the phytoplankton rich water. In other of the aquariums Na_2SO_3 in varying amounts were introduced. No discernable differences in oxygen production were detected.

Ecosystem

The elements of deoxygenation and reoxygenation previously considered were combined into two ecosystems. The East channel contained bottom sediment and water rich in phytoplankton. The

West channel, in addition to bottom sediment and to water rich in phytoplankton, was provided with an organic load composed of a solution prepared with powdered milk.

Before beginning the experiment, the aerial oxygen demand of the bottom sediments were determined in the laboratory at a temperature of 20°C by the procedure described above under "Benthal Demand." The average temperature of the water in the flume during the period of the experiment was 16°C. No attempt was made to correct the benthal demand obtained in the laboratory to flume temperature conditions. Examination of the sediments indicated that there was almost a complete absence of macroinvertebrates.

The experiment was initiated by allowing flow in both channels with depth controlled at approximately the one foot level. After several flow through times, it was assumed that the organic load was mixed evenly throughout the water of the West channel, and that the BOD at the beginning of the flume was the same as that at the end. Flow then was stopped in both channels and a stagnant state maintained. For the next six days, readings were taken in both channels at three stations, 25 feet, 100 feet, and 175 feet from the inlet end. These readings included dissolved oxygen, temperature, and pH. In addition, the black and white bottle technique was used as one of the means to determine oxygen production and respiration. Samples of water were taken periodically for determination of the organic and inorganic carbon content of the water, suspended solids and plankton count. Also, sunlight energy during the experiment was continually recorded.

From the East channel, by considering the rate of change in oxygen saturation deficit during the hours of darkness and knowing sediment uptake and surface reaeration, it was possible to obtain an average respiration rate for each night.

The phytoplankton concentration in the East channel remained essentially the same as that in the West channel through the life of the experiment. It was therefore assumed that the respiration rate in the West channel would be the same as that in the East. Based on this assumption, it was possible to determine the average rate of oxygen demand of the organic load during the hours of darkness. A plot of this average rate of demand on semi-log paper, gave a linear relationship. From this plot, a daily average rate and total demand by day was obtained. Using these daily demands and applying the method of Thomas (25) a biological activity rate (k_1) and the initial BOD of the organic load was determined. T.O.C. readings verified the k_1 determination. With these parameters and with previously determined k_2 and benthal demand values, net photosynthesis was obtained from monitored oxygen deficits and the prediction formula for oxygen deficit was tested.

CHAPTER III

Atmospheric Reaeration

Theory and Literature Review

There are two basic laws from which reaeration formulas stem, Dalton's Law of Partial Pressures and Henry's Law. Dalton's Law of Partial Pressure states that the pressure exerted by a mixture of gases is equal to the sum of the separate pressures which each gas would exert if it alone occupied the whole volume. Henry's Law states that the mass of a slightly soluble gas that dissolves in a definite mass of a liquid at a given temperature is very nearly directly proportional to the partial pressure of that gas, provided that the gas does not react chemically with the solvent. To illustrate these two laws, the amount of oxygen dissolved in water, exposed to the atmosphere under standard conditions ($0^{\circ}C$ and 760 mm) is calculated:

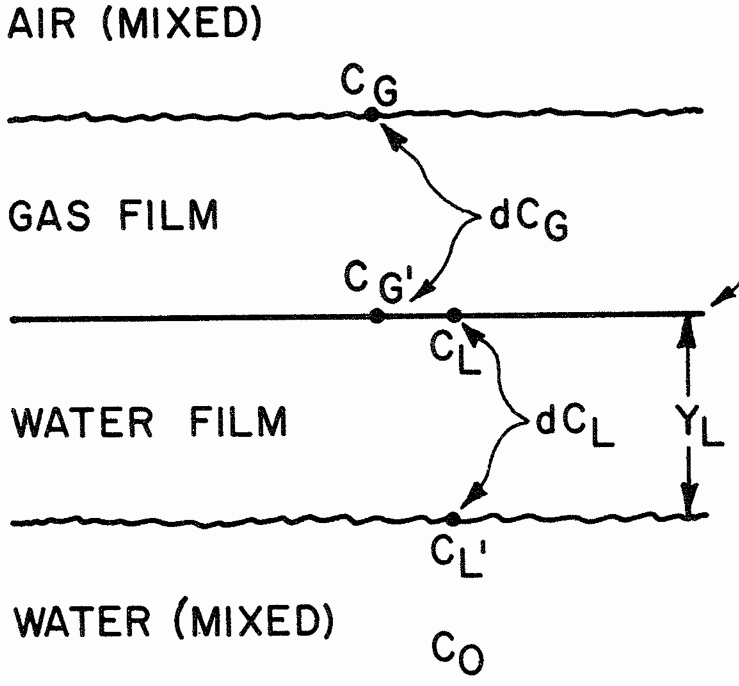
> Solubility of pure oxygen at standard conditions is 70.5 mg/l. The percentage by volume of oxygen in dry atmosphere at standard conditions is 20.9 percent. However, the atmosphere in immediate contact with the water surface will be saturated and the vapor pressure at $0^{\circ}C$ is 4.58 mm. The partial pressure exerted by

the oxygen on the water is 0.209 (760 - 4.58) or 158 mm. The amount of oxygen dissolved under standard conditions is (158/760 x 70.5) mg/l or 14.6 mg/l when equilibrium or saturation is reached.

The rate at which the dissolved oxygen content in water approaches the equilibrium state is directly proportional to the difference between the partial pressure of oxygen in the gas phase and the partial pressure of oxygen in the liquid phase. That is

$$\frac{dc}{dt} = (p_{gas} - p_{liquid}) \qquad (3\text{-}1)$$

The mechanism through which this change in oxygen concentration takes place may be explained by Fick's law and the two film theory as originally postulated by Lewis and Whitman (16). According to this theory, at the water air interface there are two films, a water film and a gas film, Fig. 3-1. These two films offer the major resistance to flow of oxygen from the gas phase into the liquid phase or from the liquid phase into the gas phase depending on whether the partial pressure of oxygen is greater in the gas phase than it is in the liquid phase or whether the alternate is true. The amount of oxygen being transferred from the gas phase through the gas film equals the amount transferred through the liquid film into the liquid



C_G = CONC. OF O_2 IN AIR BODY

C_G' = CONC. O_2 IN AIR AT I.F.

$dC_G = C_G - C_G'$

I.F. = AIR WATER INTERFACE

C_L = CONC. O_2 IN WATER AT I.F.

C_L' = CONC. O_2 AT EDGE WATER FILM

C_O = CONC. O_2 IN WATER BODY = C_L'

Y_L = LIQUID FILM THICKNESS

FIG. 3-1 AIR-WATER INTERFACE

phase. From Fick's law this rate of transfer can be expressed:

$$\frac{dm}{dt} = D_G A \frac{dc_G}{dy_G} = D_L A \frac{dc_L}{dy_L} \qquad (3\text{-}2)$$

where

D_G = coefficient of diffusion through the gas film

$\frac{dc_G}{dy_G}$ = concentration gradient through the gas film

D_L = coefficient of diffusion through the liquid film

$\frac{dc_L}{dy_L}$ = concentration gradient through the liquid film

A = unit area through which the diffusion is taking place

In the case of stream flow, eddy diffusivity through the body of the stream is much greater than diffusivity through the liquid film. It can be assumed in most cases that the concentration gradient in the body of the stream will be so small in comparison to the concentration gradient across the liquid film that it can be considered as being negligible. Therefore, in Fig. 3-1 the concentration C_L' of oxygen at the exit edge of the liquid film can be considered to equal the concentration C_o in the body of the stream. Considering then only the liquid film, since it offers the most resistance to transfer of oxygen and therefore controls the reaction rate, and assuming that the concentration gradient through the liquid film is uniform, the mass transfer rate can be written:

$$\frac{dm}{dt} = D_L A \frac{dc_L}{dy_L} = D_L A \frac{(C_L - C_o)}{y_L} \qquad (3-3)$$

where

y_L = liquid film thickness

C_L = concentration of oxygen in water at the interface

Also it can be assumed that the concentration of oxygen in the water at the gas-water interface is at saturation concentration C_s, therefore, equation (3-3) can be written:

$$\frac{dm}{dt} = D_L A \frac{(C_s - C_o)}{y_L} \qquad (3-4)$$

The term D_L/y_L is referred to as the liquid film coefficient (K_L), and the term $(C_s - C_o)$ represents saturation deficit D. Making substitutions equation (3-4) can be expressed in terms of concentration units:

$$\frac{1}{v}\left(\frac{dm}{dt}\right) = \frac{dc}{dt} = \frac{K_L A}{v} D \qquad (3-5)$$

Since A/v = 1/H where H is stream depth and since a positive change (increase) in concentration with respect to time is a negative change (decrease) in deficit, equation (3-5) can be written:

$$\frac{dD}{dt} = \frac{-K_L}{H} D \tag{3-6}$$

or

$$\frac{dD}{dt} = -K_2 D \tag{3-7}$$

where

K_2 = coefficient of reaeration (base e)

Integrating, solving for K_2 between time limits t_1 and t_2 and deficit D_1 at time t_1 and deficit D_2 at time t_2:

$$K_2 = \frac{\ln D_2 - \ln D_1}{t_2 - t_1}$$

$$k_2 = \frac{K_2}{2.31} = \frac{\log D_2 - \log D_1}{t_2 - t_1} \tag{3-8}$$

where

k_2 = coefficient of reaeration (base 10)

Several factors affect the value of k_2 in a stream. The most important factors are turbulence and temperature. From the foregoing development of a mathematical expression for k_2 it was shown that k_2 was proportional to a film coefficient K_L which in turn was proportional to a coefficient of diffusion D_L of oxygen through the liquid film and inversely proportional to film thickness y_L. In addition, k_2 was directly proportional to the surface area through which the diffusion occurred. Turbulence will stress the surface film, breaking it in places and reducing the effective thickness. It has been conjectured by Bayliss (2) that film thickness increases with exposure time and by Pasveer (20) that the rate of diffusion is maximum at the moment of formation of the water interfacial surface. Turbulence by wave action also increases the area through which diffusion takes place. In any event, whatever may be the explanation, it can be concluded that turbulence increases reaeration. It also can be concluded that in any particular stream, turbulence is a function of stream velocity and stream depth. Most of the equations proposed have indicated a direct relationship to some power of velocity and inversely to some power of depth. Phelps (21) proposed the following formula:

$$k_2 = C \frac{V^n}{H^2} \qquad (3\text{-}9)$$

This formula was developed during research on the Ohio River between Pittsburgh and Louisville. The constants C and n depend upon physical stream conditions which influence turbulence. Irregularity of the stream bottom and the slope of the stream determined C. The range of C was from 0.23 to 131. An empirical relationship was derived for n:

$$n = 1 + \frac{1}{x - 1.17} \qquad (3\text{-}10)$$

where

x = the mean velocity increase per 5 foot increase in river stage.

Other investigators proposed similar formulas in the form:

$$k_2 = C \frac{V^n}{H^m} \qquad (3\text{-}11)$$

Values for C, n, and m recommended by some of the investigators follow:

Investigator			
Churchill, Elmore and Buckingham (5)	5.026	0.969	1.673
O'Connor and Dobbins (18)	5.58	0.5	1.5
Gameson and Truesdale (12)	23.17	0.73	1.5
Langbein and Durham (15)	7.59	1.0	1.33
Owens, Edwards and Gibbs (19)	21.62	0.67	1.85

Temperature also affects k_2. It speeds up the molecular action responsible for diffusion and it reduces the density of the surface film resulting in less resistance to diffusion. In previous studies of k_2 values, 20°C was considered as a standard and corrections were made using the following:

$$k_{2_{(20)}} = \frac{k_{2_{(T)}}}{\Phi^{(T - 20)}} \qquad (3\text{-}12)$$

The value of $\Phi = 1.0241$ used in this work is that proposed by Elmore (10) and recommended by Churchill, et al (5) and Isaacs, et al (14).

In the determination of atmospheric reaeration rates of streams, the effects of wind generally are neglected. In his studies on rivers of the Tennessee Valley over a period of three years, Churchill (6) neglected wind in his prediction formula for stream reaeration. During the first year of study he had set up weather stations on each river being studied; however, after the first year he came to the conclusion that no effects of wind were detectable. As a result, he discontinued recording winds during the balance of his study.

It stands to reason, however, that winds must have an effect on atmospheric reaeration. Winds, by promoting wave action, increase the surface area through which diffusion takes place, and by creating surface turbulence increase the amount of surface renewal, thereby, affecting the film coefficient K_L. O'Connor and Dobbins (18) concluded that for all practical cases:

$$K_L = (D_L r)^{1/2} \qquad (3\text{-}13)$$

where

r = rate of replacement of the surface

The relative effect of wind depends on the physical characteristics of the stream. On a shallow, sluggish stream, wind would play a significant role. Its action in contributing to atmospheric reaeration could be greater than that of the stream's velocity.

Lake experiments (27) indicated that winds will produce a surface velocity 3 percent of the wind velocity for winds up to 5 miles an hour and approximately 1 percent for a 30 mile per hour wind. According to Camp (3) a 5 mile per hour breeze with a surface velocity of 3 percent of wind velocity will result in a surface renewal rate "r" of about 4 per minute with a corresponding value of K_L of 6.2 feet per day. If the stream had a 5 foot depth, k_2 at $20^{\circ}C$ resulting from wind alone would be 0.54 day^{-1}. This would indicate that wind may be a dominant factor in the atmospheric reaeration of sluggish streams.

Laboratory experiments by Downing and Truesdale (8) in which wind speeds from 0 to 9 meters per second were passed over distilled water 24.9 cm deep at 15°C indicated a K_L of 30 feet per day at 9 meters per second (18.2 m.p.h.).

Experimentation

To determine atmospheric reaeration (k_2) in the model river, potable water was passed through the East channel of the flume at various depths and velocities. The East channel was clean (devoid of any bottom sediment). Initial dissolved oxygen conditions were controlled by Na_2SO_3 with cobaltous chloride as a catalyst. The exit dissolved oxygen was determined and k_2 calculated from equation

$$k_2 = \frac{\log D_{t_2} - \log D_{t_1}}{t_2 - t_1} \qquad (3\text{-}8)$$

Included in the difficulties encountered were:

a. erratic inlet dissolved oxygen

b. spurious wind effects

c. thermal and dissolved oxygen stratification and

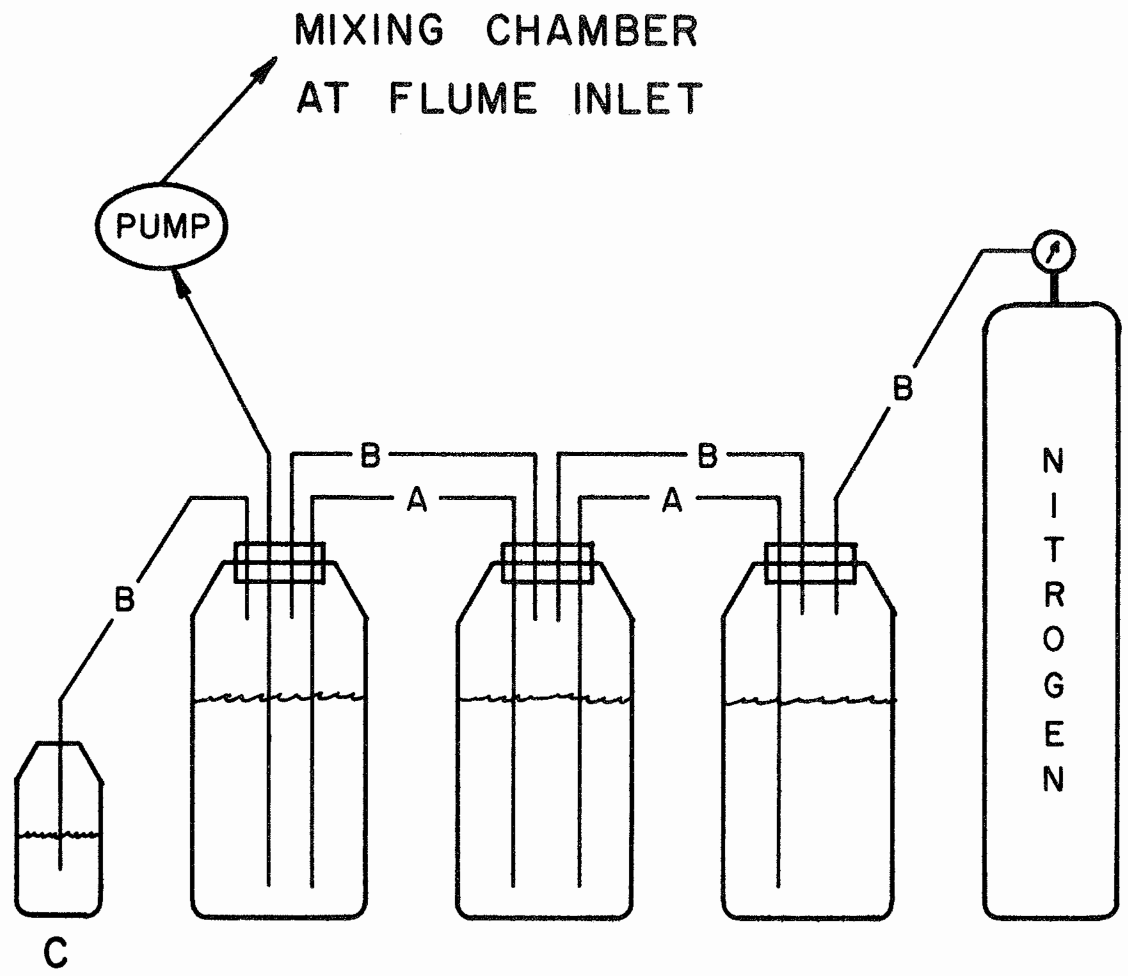
d. mixing effects caused by convection currents.

The experimentation resulted in the development of a mathematical formula for predicting atmospheric reaeration under various flow conditions in a simulated stream. Comparisons between this formula and that developed by Churchill et al (6) indicated a 0.98 correlation.

Controlling Inlet Oxygen

In the first efforts to control inlet dissolved oxygen, a dosing mixture of sodium sulfite (Na_2SO_3) and cobaltous chloride ($CoCl_2 \cdot 6\ H_2O$) to provide the cobalt ion necessary as a catalyst was prepared in 20 liter carboys. Evidently the sulfite was being oxidized in the carboys, with the net result that desired inlet oxygen conditions were not maintained. Next, sulfite and cobaltous chloride solutions were made up in separate carboys and were dosed into the inlet mixing chamber; however, inlet D.O. conditions continued to be erratic. Finally, a dosing mixture of both sulfite and cobaltous chloride over which a nitrogen atmosphere was maintained, Fig. 3-2, succeeded in providing the stable inlet D.O. conditions that were desired for the experiment.

Theoretically, 7.9 mg/l of Na_2SO_3 is required to lower oxygen by 1 mg/l. Actually, it was necessary for the dosing mixture to be prepared on the basis of 10 mg/l of Na_2SO_3 for each mg/l of oxygen draw down desired. Evidently some sulfite was oxidized in the process of preparing the solution and some was being oxidized



A = SIPHONS B = NITROGEN LINES
C = BUBBLING TO INSURE NITROGEN IS FLOWING

FIG. 3-2
METHOD USED TO DOSE FLUMES WITH SOLUTION OF SODIUM SULFITE AND COBALTOUS CHLORIDE

under the turbulence existing in the mixing chamber. The amount of cobaltous chloride premixed into the dosing solution was determined on the basis of providing a minimum of 0.01 mg of cobalt ion per liter of flow.

Elimination of Wind Effects

Since wind would exaggerate surface reaeration in the shallow depths of the flume, it was necessary to eliminate wind effects. Baffles were placed every ten feet. These baffles extended from the top edge of the flume down to the surface of the water flowing in the flume. While this eliminated much of the wind effects, it did not eliminate enough to insure that wind would not affect the validity of determined k_2 factors. It was necessary to cover the entire length of the flume with a polyethylene cover.

Some experiments indicating the magnitude of wind effects on atmospheric reaeration will be described later in this chapter.

Thermal and Dissolved Oxygen Stratification

In the formulation developed earlier in this chapter for the determination of k_2 it is assumed that mixing occurs below the surface film or diffusion is relatively fast below the surface film and that for all practical purposes the concentration of oxygen below the surface film is uniform.

Under certain flow conditions thermal stratification and D.O. stratification developed to a dramatic extent. Table 3-1 and Fig. 3-3 show thermal conditions that occurred on a very hot July day with a flow of 94 liters/min and a depth of 21 inches in the flume. At station E 100 for example, the temperature 1 inch from the surface was $32^{\circ}C$ and at 16.5 inches below the surface was $25.8^{\circ}C$. Table 3-2 and Fig. 3-4 show the dissolved oxygen state under this temperature stratification. The temperature stratification is easily explained. Before the experiment was started the water in the flume was stagnant and had been heated by the sun. Potable water was used for the experiment. When the experiment commenced, the entering relatively cold potable water dropped down underneath the warm water. Since the flow through height is controlled by an end gate, the underflow had to rise in the vicinity of the end gate and flow over the gate. The underflow in effect trapped the warm surface layer to produce a stagnant lens, Fig. 3-5.

Effects of Convection Currents

Judiciously determining k_2 values by selecting velocities

Table 3-1. Temperatures in the East Channel Taken Between 1530 and 1653 hours on July 1, 1969

Flow: 94 liter/min, 21 inch depth

Depth Below Surface	Temperature (°C) At Stations								
	E 0*	E 25	E 50	E 75	E 100	E 125	E 150	E 175*	E 200*
1 "	26.3	29.6	30.2	31.6	32.0	31.5	30.7	29.0	28.0
3 "	25.5	29.5	29.4	31.2	31.0	31.0	30.6	29.0	27.6
5 "	25.3	28.2	28.8	30.0	30.5	30.8	30.4	28.0	27.0
8 "	24.7	27.2	26.5	27.0	28.0	28.0	28.2	27.5	26.7
11 "	24.5	25.5	25.5	26.0	26.4	26.3	26.8	26.3	26.5
14 "	24.7	25.4	25.5	25.7	25.8	26.0	26.2	26.3	26.5
16.5"	24.7	25.4	26.0	26.0	25.8	26.0	26.4	26.5	26.8

Table 3-2. Dissolved Oxygen Deficits in East Channel at the Time of the Temperature Readings Which are Recorded in Table 3-1

Depth Below Surface	D.O. (mg/l) at Stations								
	E 0*	E 25	E 50	E 75	E 100	E 125	E 150	E 175*	E 200*
1 "	5.6	1.8	1.6	1.4	1.7	1.6	1.6	3.6	5.4
3 "	5.9	2.3	2.4	1.9	1.5	1.7	1.7	3.9	5.8
5 "	5.1	4.0	3.5	3.6	2.1	2.3	2.2	4.3	6.1
8 "	6.6	5.2	6.1	5.7	4.9	4.1	4.6	5.5	6.1
11 "	6.9	6.1	6.2	6.2	6.0	6.0	6.0	6.0	6.1
14 "	6.9	6.4	6.2	6.1	6.2	6.1	6.0	6.0	6.1
16.5"	6.9	6.2	6.1	6.1	6.0	6.0	6.0	6.1	6.1

*Illustrates start of underflow at Station E 0 and rise of underflow at E 175 and E 200 to discharge over the end gate.

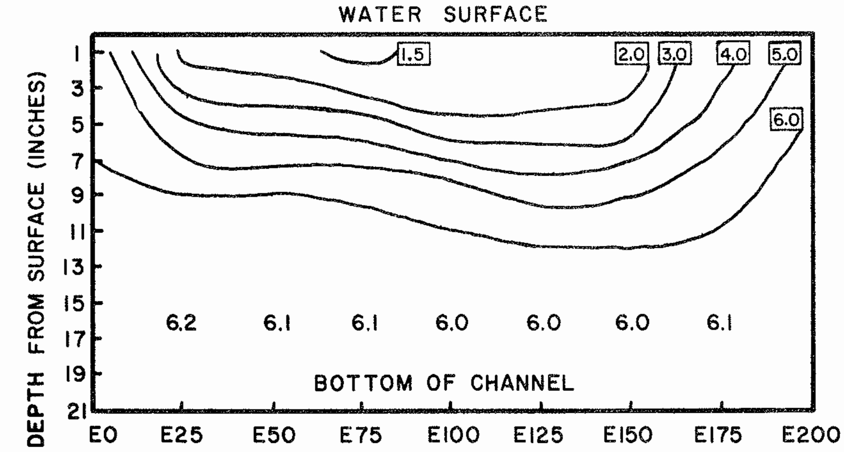


FIG. 3-3 DISSOLVED OXYGEN DEFICIT CONTOURS (MG/L) IN EAST CHANNEL
(FLOW: 94 LITER/MIN., 21 INCH DEPTH)

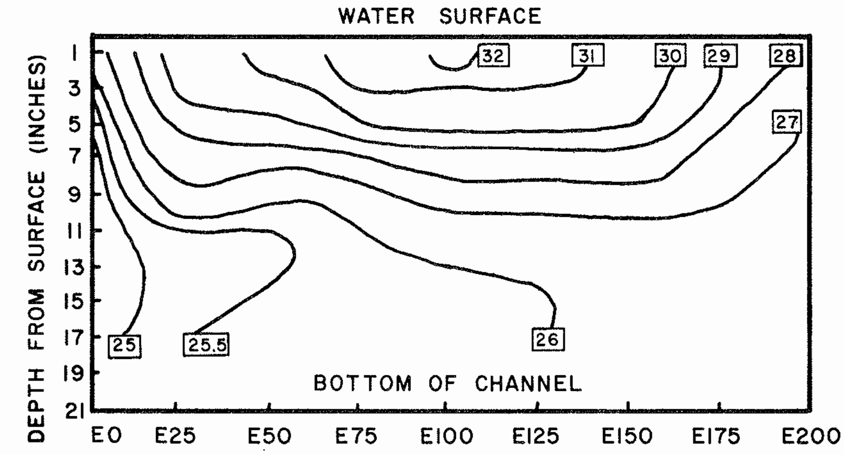


FIG. 3-4 TEMPERATURE CONTOURS (°C) IN EAST CHANNEL
(FLOW: 94 LITER/MIN., 21 INCH DEPTH)

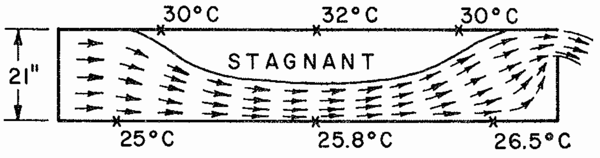


FIG. 3-5 UNDERFLOW IN CHANNEL

and depths to not have thermal stratification resulted in k_2 values that seemed to vary depending upon the time of day that the determinations were made even after temperature corrections were made. In order to try to understand what was happening an experiment was run around the clock. Flow depth was maintained at 4 inches and flow discharge maintained at 52 liters/min. Significant variations in k_2 were noted, Table 3-3. An explanation of the difference in k_2 under the same conditions in velocity and depth is that the difference is caused by convection currents. The experiment was conducted in August, daylight conditions were hot. Temperatures taken in a thermoscreen reached 35°C. The hot sun made the metal side walls of the flume so hot that it was not possible to leave one's hand on the sidewall. Unfortunately, the temperature of the sidewalls was not recorded. The water entering the flume at approximately 26°C was heated by conduction through bottom and sidewalls setting up convection currents. Flow through time was 34 minutes and the temperature rise from entrance to exit, during daylight was as great as 3.5°C; whereas, at night the maximum temperature change from entrance to exit was a decrease of 0.7°C. When applying the flow conditions to the empirical formula which will be derived

Table 3-3. Diurnal Variations in Atmospheric Reaeration Coefficients (August 19-20, 1969)

Flow: 52 liter/min Depth: 4 inch

Daylight		Night	
Time (hr)	k_2* (day^{-1})	Time (hr)	k_2* (day^{-1})
1030	4.44	2110	1.44
1050	4.24	2130	1.44
1130	3.45	2200	1.61
1200	4.62	2220	1.64
1220	3.74	2245	1.72
1240	3.58	0020	2.26
1300	4.30	0040	2.06
1530	4.84	0200	2.26
1730	3.13	0220	1.69
1750	3.16	0430	1.43
1800	4.04	0450	1.41
1820	3.65	0630	1.95
1900	3.51		
1950	3.23		
2020	2.98		
Ave	3.79		1.74

*Corrected to 20°C.

later the calculated k_2 is 1.76 day^{-1}. The average night time value for k_2 was 1.74 day^{-1}. While it should be expected that the night time average k_2 would be consistent with the empirical formula, the fact that it was only 0.02 day^{-1} from the predicted value was a chance happening.

To test the assumption that heating through sides could set up convection currents that would have a significant effect on atmospheric reaeration three aquaria experiments were conducted in which water temperature was lowered with ice, D.O. content dropped with Na_2SO_3 and reaeration monitored. The highest rates of aeration occurred at the lowest temperatures when the water was being heated up primarily by conduction through sides, end walls and bottom at the greatest rate. Paralleling this experiment a similar one was conducted in an insulated container in which heat transfer could come only through the exposed surface. In this experiment reaeration was at the predicted rate whereas in the case of the uninsulated aquaria reaeration rate at the lowest temperatures was several times the predicted rate.

From these experiments it was concluded that mixing caused by convection currents could significantly influence the k_2 values obtained in the model river.

In order to eliminate convection currents it would be necessary to either insulate the flume or to run the experiments at a time when there was no sun and temperature of the water passing through the flume would be very nearly the same as atmospheric temperature.

Reaeration Under Flowing Conditions

To preclude convection effects described above, experiments could have been run at night; however, ideal conditions occurred in October and a battery of experiments to determine reaeration coefficients (k_2) were run at this time. Table 3-4 indicates the flow conditions of these experiments and resulting k_2 values.

Fig. 3-6 is a plot of k_2 (corrected to 20°C) values against $V/H^{1.5}$ for velocities ranging from 0.096 ft/sec to 0.455 ft/sec and depths from 0.113 ft to 0.613 ft. The plotted k_2 represents mean values for a series of test runs at given velocities and depths. Table 3-4 indicates the number of test runs involved in each k_2 determination. Using the method of least squares an expression for k_2 can be derived.

$$k_2 = 2.98 \left[\frac{V}{H^{1.5}}\right]^{0.703} \qquad (3\text{-}14)$$

Table 3-4. Coefficients of Atmospheric Reaeration Under Various Flow Conditions

Flow Conditions				Number of Test Runs	Average k_2 (day^{-1})
Q l/min	Vel. (V) ft/sec	Depth (H) ft	$V/H^{1.5}$		
190	0.455	0.197	5.22	10	10.15
190	0.320	0.280	2.16	13	6.79
190	0.201	0.447	0.67	17	2.47
190	0.146	0.613	0.30	21	1.11
125	0.298	0.197	3.42	19	8.80
125	0.202	0.280	1.36	11	3.67
125	0.131	0.447	0.44	29	1.69
125	0.096	0.613	0.20	21	0.72
90	0.215	0.197	2.47	11	6.17
74	0.124	0.280	0.84	10	2.40
74	0.078	0.447	0.26	22	1.44
45	0.187	0.113	4.94	19	9.16
45	0.108	0.197	1.24	15	2.75
45	0.078	0.274	0.54	21	1.63

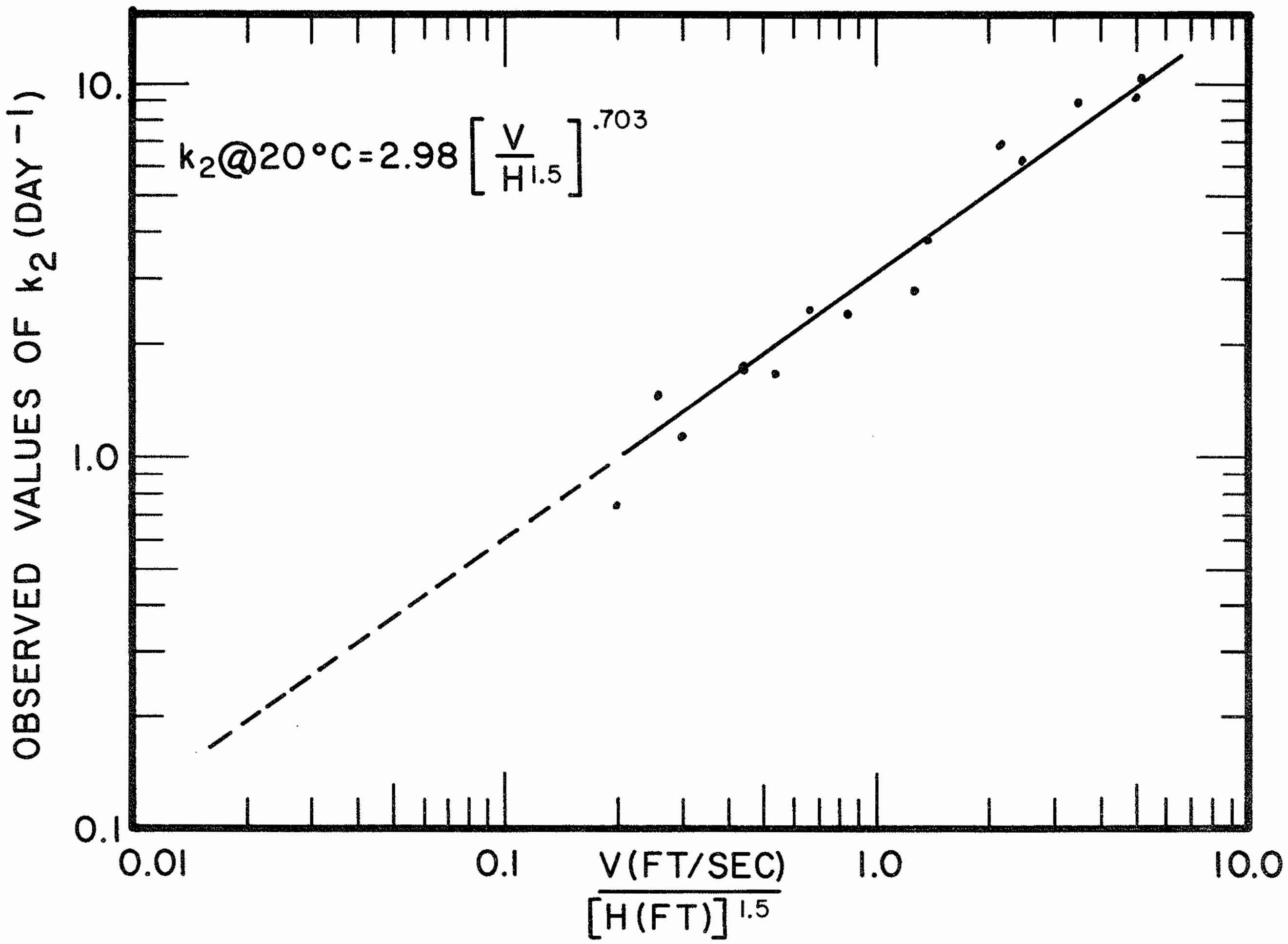


FIG. 3-6 ATMOSPHERIC REAERATION RELATED TO HYDRAULIC CHARACTERISTICS

Since a model river would contain bottom sediment several test runs were made in the channel containing sediment using potable water to determine whether or not the bottom sediment would affect k_2. Sidewalls were wiped down to remove attached algae and the bottom was treated with copper sulfate to inhibit benthal demand. The results indicated the k_2 with inactive bottom sediment followed the developed prediction formula

Reaeration Under Stagnant Conditions

Reaeration coefficients under stagnant conditions were determined by two studies using aquariums in the laboratory. In the first study water was at room temperature when the study was initiated but no attempt was made to control room temperature. Depths of water in the aquariums were 2, 4, 6, 8, 10, and 12 inches. In the second study water and room temperatures were held at 20°C plus or minus 1.5°. Depths of water used were 3, 6, 9, and 12 inches. Reaeration coefficients corrected to 20°C are presented in Table 3-5 and Fig. 3-7.

Magnitude of Wind Effects

In the initial attempts to determine k_2 values, as previously pointed out, baffles were inserted in the flume every ten feet extending

Table 3-5. Coefficients of Atmospheric Reaeration Under Stagnant Conditions

Study No.	Depth (in)	k_2 (day^{-1})
1	2	1.61
	4	0.75
	6	0.58
	8	0.43
	10	0.31
	12	0.29
2	3	0.94
	6	0.62
	9	0.42
	12	0.27

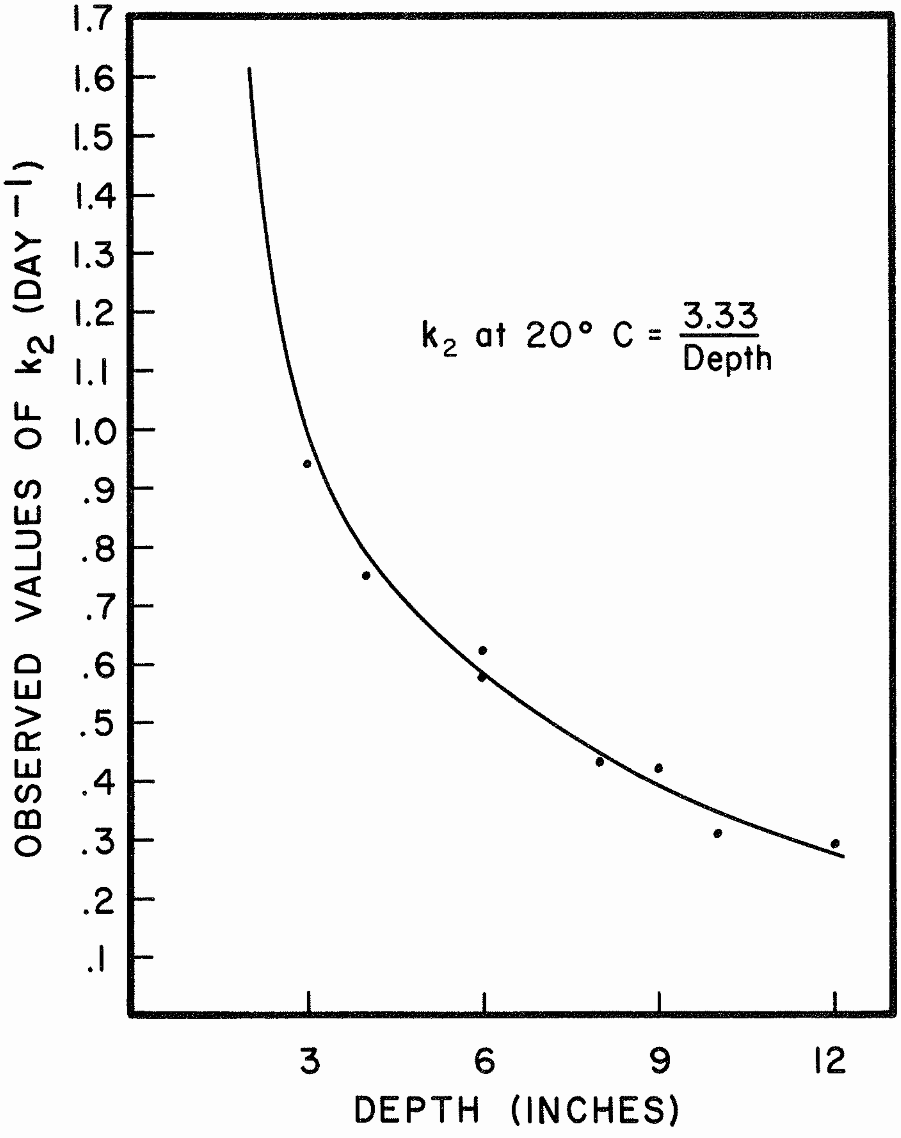


FIG. 3-7 COEFFICIENTS OF ATMOSPHERIC REAERATION UNDER STAGNANT CONDITIONS

from the top of the flume to the surface of the water. While this reduced the effect of wind, it did not eliminate it. Since a whole series of k_2 determinations were made at various conditions of flow and depth, and since wind recordings were made, it is interesting to compare these k_2 values with the valid k_2 values determined after elimination of wind. The rate of atmospheric reaeration was as much as four times as great as it was under "no wind" conditions when the flume was covered. Figure 3-8 illustrates the variation caused by wind. The directions of the wind varied throughout this set of experiments. This would account for the scatter of the plotted points because wind direction did have an effect on the k_2 value. In view of the orientation of the flume, winds from the north or south would have a greater effect than winds from the east or west. Unfortunately, wind direction was not recorded during these experiments.

Three experiments were conducted specifically to determine the effects of wind on a shallow system. A circular tub 7.5 ft in diameter and 22 1/8 inches in depth was used. A recording anemometer was mounted approximately 3 ft above the tank. The direction of the wind was not recorded since the tub was circular and

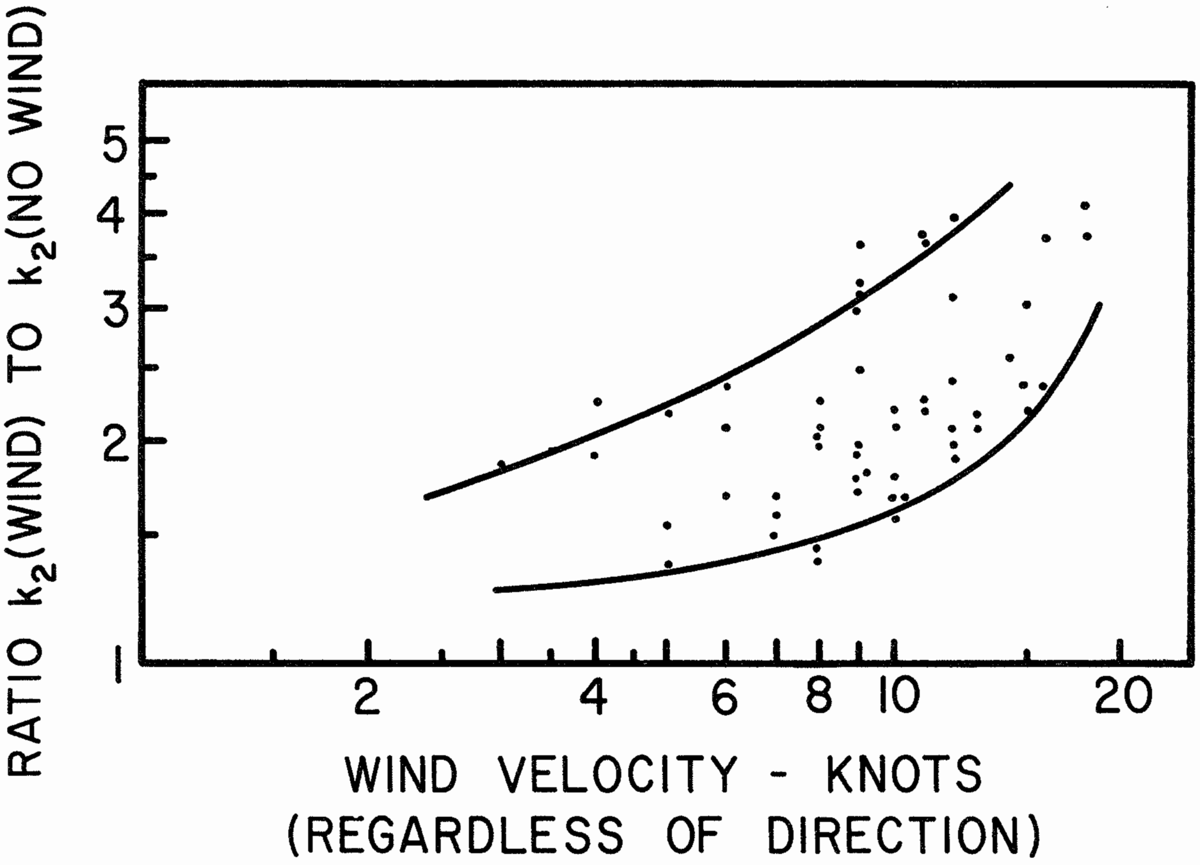
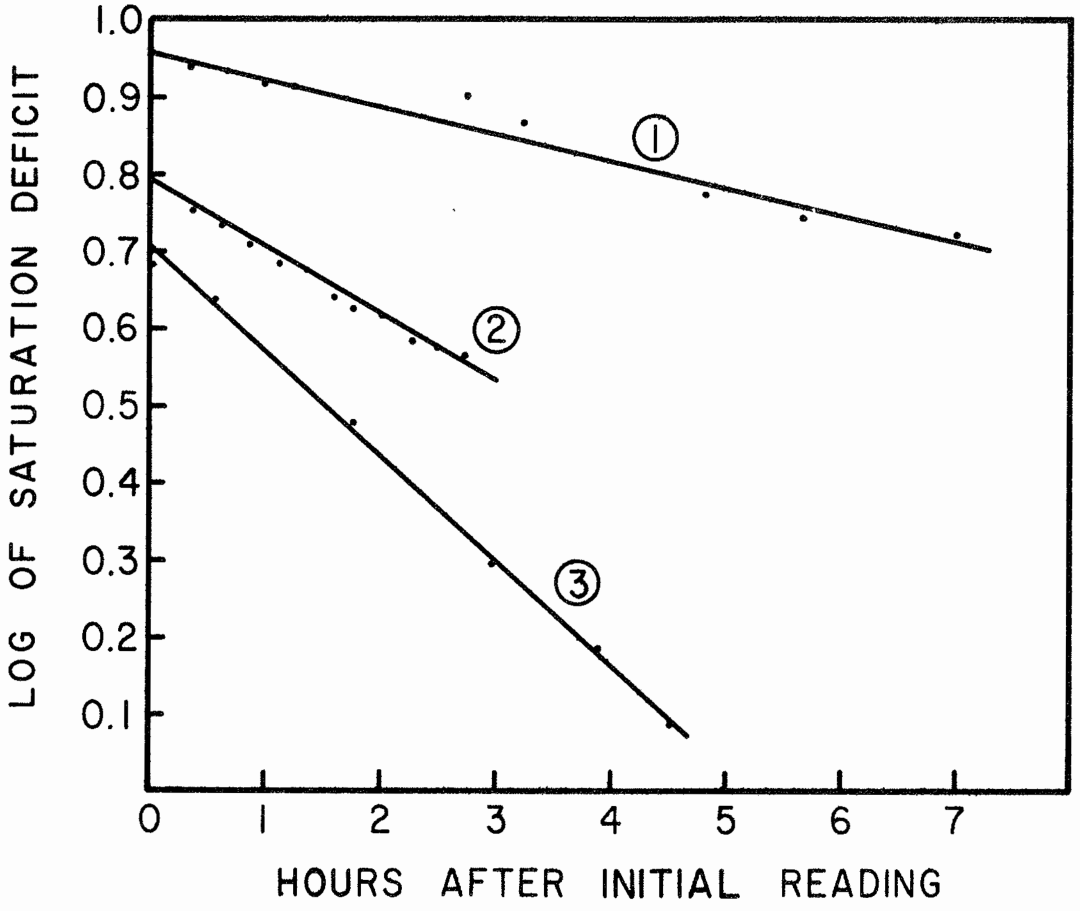


FIG. 3-8 EFFECT OF WIND ON ATMOSPHERIC REAERATION COEFFICIENTS IN FLUME

wind direction was not pertinent. Potable water was used as in previous atmospheric reaeration experiments. Dissolved oxygen level was reduced by Na_2SO_3 and the coefficient of atmospheric reaeration (k_2) was determined. Average wind velocity for the three experiments were 3, 11.5, and 14.0 m.p.h. and the average k_2 values were determined to be 0.81, 2.03, and 3.04 day^{-1}. Since from Fig. 3-7 the reaeration coefficient under stagnant conditions without wind would be 0.15 day^{-1} (3.33/22.125), the ratio of k_2 under wind conditions to k_2 under "no wind" conditions would be 5.4, 13.5, and 20.3 respectively. Figure 3-9 indicates the reaeration rates and wind conditions prevailing during the three experiments.

Model River vs Prediction Formulas for Real River

While the primary purpose of the atmospheric reaeration experiments was to develop a prediction formula for various conditions of flow in a model river, the developed formula was compared to prediction formulas for real streams proposed by the various investigators mentioned in the "Theory Section" of this Chapter. Comparison was made for all combinations of velocity from 1/2 ft per second to 7 ft per second, and depth up to 10 ft from which the calculated reaeration coefficient would be 2.0 or



EXP.	WATER DEPTH (FT.)	AVG. WIND (MPH)	TEMP. (°C)	k_{2T} (day^{-1})	$k_{2(20)}$ (day^{-1})	NO WIND $k'_{2(20)}$ (day^{-1})	$\frac{k_{2(20)}}{k'_{2(20)}}$
①	1.83	3.0	21.5	0.84	0.81	0.15	5.4
②	1.83	11.5	16.2	1.84	2.03	0.15	13.5
③	1.83	14.0	23.0	3.27	3.04	0.15	20.3

FIG. 3-9 EFFECT OF WIND ON k_2 IN PAN

(7.5 FT. IN DIA., DEPTH OF WATER 22 IN.)

less. This range would be applicable to most streams. According to Thomas most American streams have reaeration coefficients ranging from 0.06 to 0.96 day^{-1}. In this range the Flume Formula comes closest to Churchill's Formula. Churchill's Formula is from an analysis of streams in the Tennessee Valley, which according to Thackston and Krenkel (24) is believed to be the most reliable group of field scale reaeration data reported in the literature. Figures 3-10 and 3-11 portray the Flume Formula and Churchill's Formula in the velocity, depth, and k_2 range discussed above. The correlation between the Flume Formula and Churchill's Formula in the range considered is 0.980. Table 3-6 is a comparison of the observed k_2 values in Churchill's study and the predicted values using the Flume Formula.

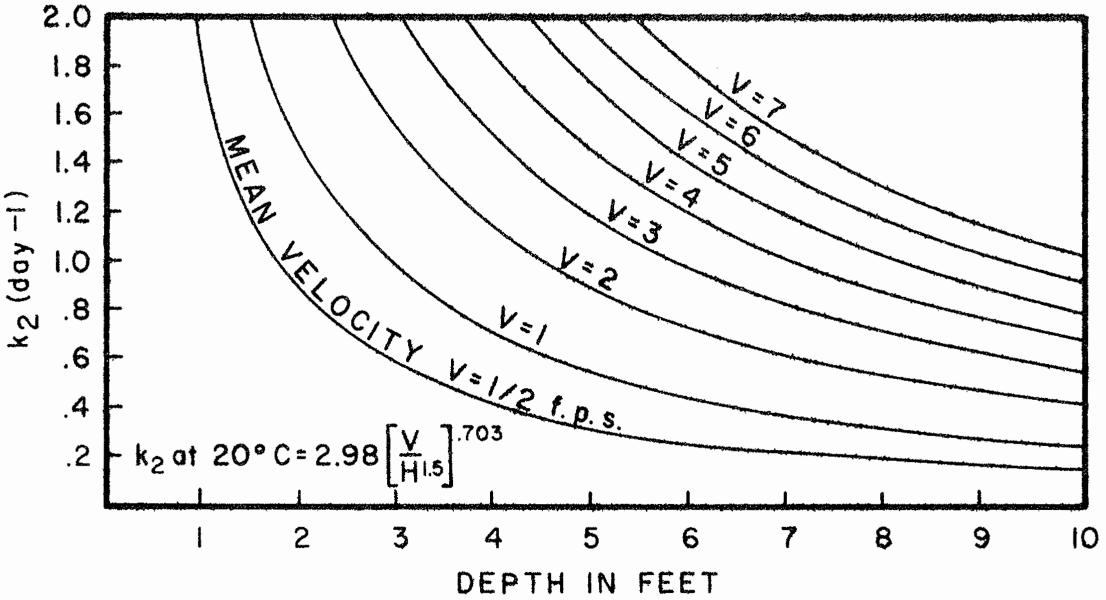


FIG. 3-10 FLUME FORMULA FOR ATMOSPHERIC REAERATION COEFFICIENTS

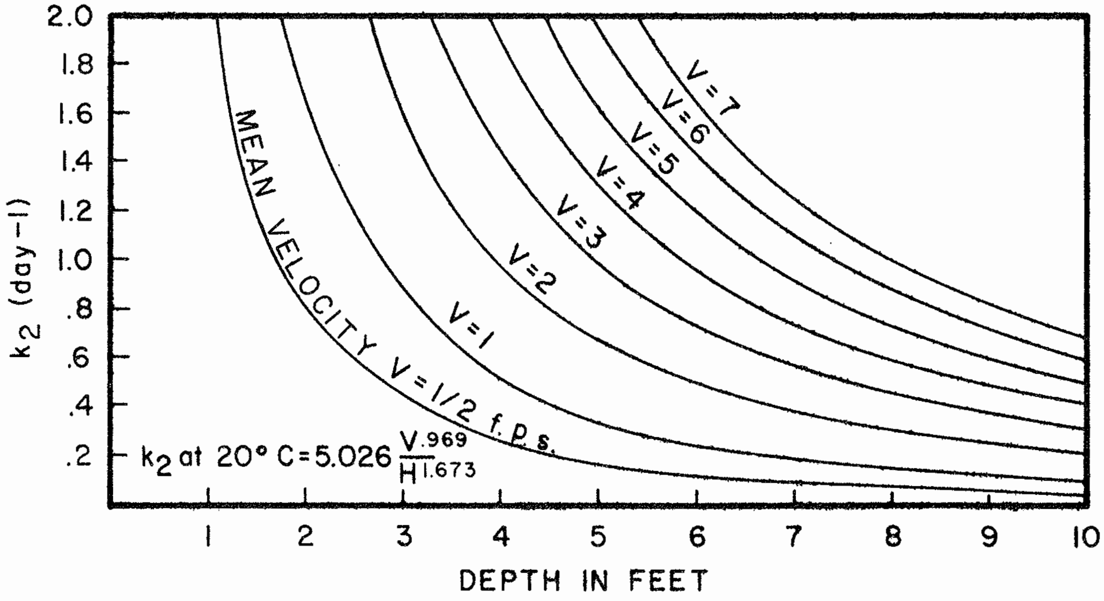


FIG. 3-11 CHURCHILL FORMULA FOR ATMOSPHERIC REAERATION COEFFICIENTS

Table 3-6. Comparison of Predicted k_2 Values by Churchill and Flume Formula with Observed Values from Churchill's Studies (6)

River	River Mile	V. Mean Velocity (ft/sec)	H. Mean Depth (ft)	k_2 Observed (day^{-1})	Calculated k_2*	
					A	B
Clinch	76.9- 76.5	3.07	3.27	2.27	2.05	1.88
Clinch	76.9- 76.5	3.69	5.09	1.44	1.20	1.34
Clinch	72.6- 71.4	2.10	4.42	0.98	0.85	1.05
Clinch	72.6- 71.4	2.68	6.14	0.50	0.63	0.88
Clinch	65.2- 64.7	2.78	5.66	0.74	0.74	0.98
Clinch	63.4- 62.6	2.64	7.17	1.13	0.47	0.74
Holston	44.7- 44.1	4.65	4.54	1.57	1.76	1.78
Holston	30.3- 29.6	2.94	9.50	0.45	0.33	0.59
Holston	23.3- 22.6	2.51	6.29	0.39	0.57	0.80
Holston	23.3- 22.2	3.51	3.72	0.27	0.52	0.81
Holston	22.2- 21.7	3.30	7.07	0.55	0.61	0.88
Holston	21.7- 21.1	3.11	5.44	0.54	0.89	1.09
Holston	21.7- 21.1	4.28	8.06	0.60	0.63	0.91
Holston	21.7- 21.1	2.73	3.88	1.25	1.37	1.44
Fr. Broad	31.3- 30.5	2.41	9.28	0.27	0.28	0.53
Fr. Broad	14.2- 13.8	2.40	3.29	1.88	1.60	1.57
Fr. Broad	14.2- 13.8	3.46	4.74	0.84	1.24	1.39
Fr. Broad	14.2- 13.8	4.02	5.72	0.88	1.04	1.26
Fr. Broad	14.2- 13.8	4.52	6.95	0.92	0.85	1.09
Fr. Broad	13.8- 13.3	1.85	4.29	0.99	0.80	0.99
Fr. Broad	13.8- 13.3	2.75	6.01	0.55	0.67	0.91
Fr. Broad	13.8- 13.3	3.23	7.16	0.88	0.58	0.85
Fr. Broad	13.8- 13.3	3.71	8.49	0.25	0.50	0.79
Hiwassee	115.1-114.8	3.05	3.02	1.71	2.33	2.03

A = Churchill Formula k_2 @ $20^{\circ}C = 5.026\ V^{0.969}/H^{1.673}$

B = Flume Formula k_2 @ $20^{\circ}C = 2.98\ [V/H^{1.5}]^{0.703}$

*Corrected to $20^{\circ}C$

CHAPTER IV

Benthal Decomposition

Theory and Literature Review

Much of pollutional loads that are introduced into a stream are neither soluble, nor colloidal nor sufficiently fine to be held in suspension under the conditions of turbulence that exist in the stream and will settle to the bottom. These bottom deposits may be subject to scour wherein their biochemical oxygen demand is reinstated into the flowing portion of the stream system to be degraded by the biological system in effect in the stream, or are more likely to be deposited in sludge banks in another reach in the stream where they may become a problem, a benthal demand on the stream's dissolved oxygen.

Mechanism of Benthal Decomposition

The mechanism of benthal decomposition is not fully understood. It differs considerably from the biological decomposition that deposits would have experienced had they remained part of the flowing system. By comparison benthal decomposition is a very slow process combining both aerobic and anaerobic activity. While the process is slow, its significance on oxygen balance may be great because of the tendency of large amounts of decomposing material to collect over long periods of time in localized areas. Fair, et al (11) have classified three salient stages through which decomposition progresses. The first is a period of intensive fermentation in which there is a rapid production of the gases by anaerobic decomposition. The second stage is a period of consolidation during which sediments subside, density is increased and gas production greatly retarded. The third stage is that of quiescent stabilization during which anaerobic decomposition is virtually exhausted and benthal oxygen demand is very low.

Benthal Oxygen Demand

The oxygen demand on a stream as a result of benthal deposit comes primarily from:

a. transport of degradable particulates back into the flowing portion of the stream;

b. aerobic stabilization of the top layers of the benthos; and

c. the diffusion of soluble oxidizable products of anaerobic decomposition upward through interstitial water into the stream.

Since the aerobic zone is relatively shallow and the greatest part of decomposition occurs under anaerobic conditions, the actual rate of oxygen demand is probably controlled by the rate of diffusion of the products of anaerobic decomposition into the stream (3, 11, 1). Not all of the products of decomposition result in oxygen drain. Much of the sediments original BOD may escape the river system as gaseous products of anaerobic decomposition formed during the stage of intensive fermentation. In Fair's experiments (11) as much as 40 percent of the initial demand was lost in this manner.

Decomposition Reaction Rate

The rate at which decomposition proceeds cannot be expressed as a monomolecular reaction. The reaction is a retardent one. That is, the reduction in biodegradable material proceeds at a reduced rate which can be explained by the fact that the organisms involved will degrade most easily degradable materials first and also by the fact that the consolidation taking place with time increases the difficulty with which diffusion of oxidizable soluble products of decomposition through the interstitial water to the aerobic zone can occur. Experiments by Fair (11) indicated that the reduction in benthic load per unit area can be expressed by the retardent formula

$$\frac{-dL_d}{dt} = \frac{K_4}{1 + bt} L_d \qquad (4-1)$$

where

K_4 = initial reaction rate (base e)

L_d = aerial demand (the biochemical oxygen demand expressed in gms per unit of sediment surface area)

b = rate of retardation

The Effect of Stream D.O. on Benthal Demand

Investigators (3, 11, 1) have indicated that the benthal uptake is independent of the amount of dissolved oxygen in the stream. On the other hand, other investigators (17, 9) have concluded that oxygen uptake of the benthos is dependent upon the oxygen concentration in the overlying stream. The latter investigators came to their conclusion from experiments with muds containing heavy population of macroinvertebrates and is therefore understandable. The invertebrates have decreased respiration rates under low D.O. Also their burrowing in the surface layers would tend to increase diffusion into the surface layers increasing the aerobic zone and the greater the D.O. the greater would be the aerobic activity. However, a significant macroinvertebrate community would be typical of old sediment, sediment in the quiescent stage and not typical of high benthal demand.

Effect of Depth of Benthos on Demand

Considering benthos having the same percentage of volatile materials, the general consensus is that the greater the thickness of benthos the greater is the oxygen demand. However, McDonnel and Hall (17) and Edwards and Rolley (9) came to the conclusion that the oxygen uptake rates of benthal systems are essentially independent of sample depth. As in the case of D.O. effect, these investigators' studies were on muds having a high macroinvertebrate population whose respiration demand was greater than microbial demand and whose activity is confined to the aerobic zone.

Experimentation

The purpose of the experiment was to determine by aquaria studies the oxygen demand of bottom sediments taken from the Colorado River, approximately 1/4 mile downstream of the outfall from the Austin sewage treatment plant. The sediment was composed primarily of sand having approximately 3 percent volatile fraction. The sediment was collected on September 11, 1969 and placed in four aquaria to a depth of four inches and potable water was used to provide water depths above the sediment of 2, 4, 6 and 8 inches. Experimentation was started on September 24. The delay between setting up the aquariums and beginning the experiment was considered necessary so that results would not be influenced by increased activity caused by the disturbance involved in setting up the experiment, and so that resuspended fines would have time to settle out. This was observed by measuring BOD_5 of composite samples of aquaria water. BOD_5 dropped from an average of 18.4 mg/l on September 11 to 2.2 mg/l on September 24.

Aerial Demand

On September 24 the dissolved oxygen in the four aquaria was reduced by Na_2SO_3 and cobalt catalyst and dissolved oxygen was monitored with a galvanic probe. Room temperature was maintained relatively constant averaging 22^oC. The temperature in the aquariums ranged from 21.3^oC to 22.8^oC. The amount of oxygen provided by diffusion through the surface exceeded the amount required by benthic decomposition and as a result the dissolved oxygen level in the aquariums gradually built up until equilibrium was reached in each aquarium. That is, a dissolved oxygen concentration was reached so that the oxygen produced by atmospheric reaeration was just equal to that demanded by the benthal decomposition. Figure 4-1 illustrates the D.O. buildup to the equilibrium point in Aquarium No. 1. Equilibrium was established after 86 hours. Dissolved oxygen was monitored for 457 hours after commencement of the experiment. Water was lost during this period as a result of evaporation. This was taken into consideration in determining the benthal demand. Table 4-1 illustrates the experimental results obtained with the aquarium in which the initial water depth was 8 inches and indicates the method of calculating benthal demand per square foot of surface per day. Similar calculations were made from the experimental values obtained in the other aquariums. Table 4-2 provides a summary of the benthal demand in each aquarium. The results are reasonably close; especially in view of the fact that it was impractical to make the sediment homogenous before placing it in the aquariums. In obtaining the sediment from the Colorado River bottom, it was attempted to obtain sediment from the top two inches, which was then placed in a 40 gallon container and then transferred from the container into the aquaria without mixing. As a result the benthal demand in each container should differ.

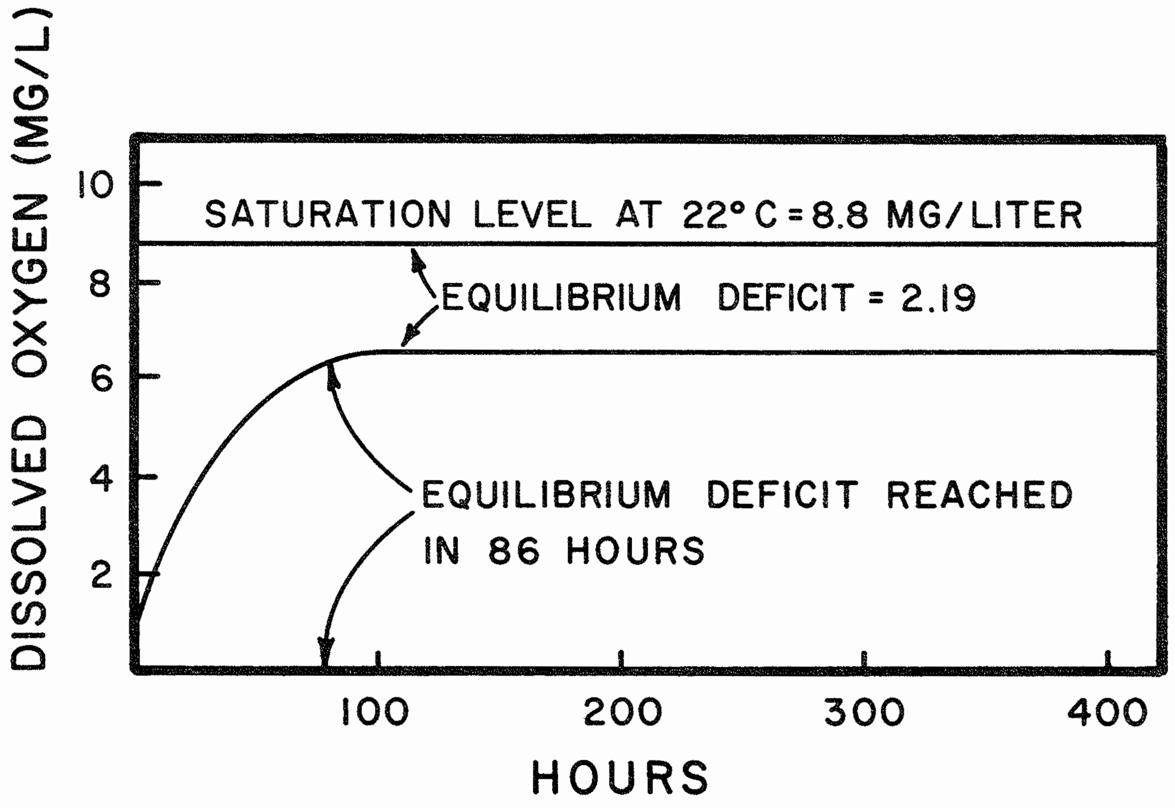


FIG. 4-1 EQUILIBRIUM CONDITION IN AQUARIUM #1

Table 4-1. Determining Benthal Demand in Aquarium #1

Initial Depth = 8 in (0.667 ft)

Depth at 86 hr 45 min = 0.642 ft

Depth at 457 hr = 0.541 ft

Evaporation per hour = 0.000275 ft

$k_{2_{(20)}} = 0.277 \div \text{depth}$

Time From Start (hr)	Depth (ft)	Evap. (ft)	$k_{2_{(20)}}$ (day^{-1})	Temp. (^{o}C)	Temp. Corr. Fact	$k_{2_{(T)}}$ (day^{-1})	Deficit (mg/l)	$k_{2_{(T)}} \times D$
0	0.66667							
87	0.64274	0.023925	0.431	22.0	1.049	0.452	2.26	1.0215
94	0.64082	0.025850	0.432	22.0	1.049	0.453	2.26	1.0238
109	0.63669	0.029975	0.435	21.8	1.044	0.456	2.07	0.9439
118	0.63422	0.023450	0.437	22.0	1.049	0.458	2.07	0.9431
126	0.63202	0.034650	0.438	22.0	1.049	0.459	1.98	0.9088
164	0.62157	0.045100	0.446	21.3	1.031	0.468	2.08	0.9734
169	0.62019	0.046475	0.447	21.5	1.037	0.469	2.20	1.0318
171	0.61965	0.047020	0.447	21.3	1.031	0.469	2.40	1.1256
174	0.61882	0.047850	0.448	21.3	1.031	0.470	2.14	1.0058
190	0.61442	0.052250	0.451	21.8	1.044	0.473	2.48	1.1730
214	0.60782	0.588500	0.456	21.8	1.044	0.478	2.20	1.0516
457	0.54100	0.125670	0.512	21.5	1.037	0.537	2.19	1.1760
Ave.	0.61900		0.448	21.7	1.041	0.470	2.19	1.0320

Benthal Demand:

$= 2.3\, k_{2_{(T)}} \times D = 2.38 \text{ mg/l/day}$

$= 2.38 \times 0.619 \times 28.32 = 41.7 \text{ mg/ft}^2\text{day}$

Table 4-2. Benthal Demand in Aquariums

Aquarium	Nominal Depth (in)	Equilibrium Period				
		Ave. Depth (ft)	Equilibrium Deficit (mg/l)	$k_2(T)$	Benthal Demand	
					(mg/l/day)	(mg/ft^2 day)
1	8	0.619	2.19	0.47	2.380	41.7
2	6	0.449	1.99	0.65	2.974	37.8
3	4	0.288	2.80	1.01	6.529	53.2
4	2	0.135	2.45	2.17	12.209	46.6
					Average	44.8

Initial Reaction Rate Coefficient (k_4)

In order to determine an initial rate for benthic decomposition, the organic content of the sediment was determined at the start of the experiment of September 24th by a five day BOD test with a determination of the biological reaction rate K_1 and the ultimate oxygen demand Ld_o.

Two cores throughout the entire sediment depth were taken from each of the four aquariums and were weighed wet. One core from each of the aquariums was mixed and 12 samples weighing from 3 to 5 grams, wet weight, were taken from each mixed core and prepared for BOD test. The second core from each aquarium was mixed into a composite sample. Approximately half of this composite sample was weighed and placed in a 103°C drying oven. From the balance of the composite sample another 12 BOD bottles were prepared. Incubation was at 20°C and BOD determinations were made after six hours, 1, 2, 3, 4, and 5 days. A biological reaction rate K_1 and an ultimate BOD were calculated for each aquarium using the graphical method of Thomas (25). The average value of K_1 obtained was 0.54 day^{-1}.

After completion of the drying and weighing of a portion of the composite sample, the dry to wet weight ratio was calculated. Ultimate BOD determinations in mg/gm dry weight of sediment is presented in Table 4-3.

The average weight of the cores was 50 grams and the cross sectional area of each core was 0.5 inches^2. Since the cores were taken through the entire depth of the sediment, the weight of the sediment in the aquariums per square foot of sediment surface was:

$$\frac{50 \text{ gms}}{0.5 \text{ in}^2} \times \frac{144 \text{ in}^2}{\text{ft}^2} = 14{,}400 \text{ gms/ft}^2$$

Since the average ultimate BOD was 0.542 mg/gm of sediment, Table 4-3, the average aerial BOD was:

$$\frac{14.4 \text{ kg}}{\text{ft}^2} \times \frac{0.542 \text{ gm}}{\text{kg}} = 7.807 \text{ gm/ft}^2$$

As indicated previously the decomposition of benthos is a retardent reaction, Equation (4-1). However, the rate of retardation is normally small and for a short period of time (1 day) the initial reaction rate K_4 can be determined with sufficient accuracy by neglecting retardation. Since the average benthic oxygen demand, Table 4-2, was 44.8 mg/ft^2 per day an initial reaction

Table 4-3. Aerial BOD and Initial Reaction Rate Coefficients (k_4)

Aquarium	BOD (mg/gm)	Ave. Sediment Weight (gm/ft^2)	Aerial Demand L_d (mg/ft^2)	Initial Demand ($mg/ft^2/day$)	K_4 (day^{-1})	K_4 (day^{-1})
1	0.481	14,400	6,926	41.7	0.0060	0.0025
2	0.465	14,400	6,696	37.8	0.0056	0.0024
3	0.706	14,400	10,166	53.2	0.0052	0.0022
4	0.530	14,400	7,632	46.6	0.0061	0.0026
Composite	0.529	14,400	7,617			
Ave.	0.542	14,400	7,807	44.8	0.0058	0.0025

rate can be calculated:

$$k_4 = \frac{0.0448\ \text{gm}}{\text{ft}^2} \times \frac{\text{ft}^2}{7.805} = 0.0058\ \text{day}^{-1}$$

$$k_4 = \frac{0.0058}{2.31} = 0.0025\ \text{day}^{-1}$$

Table 4-3 indicates the initial demands and reaction rate coefficients obtained in each aquarium.

CHAPTER V

Photosynthesis

Theory and Literature Review

The oxygen state of a stream may be greatly influenced by the photosynthetic oxygen production of plants, green algae and blue green algae. Chlorophyl in these plants enable them to synthesize matter using energy from the sun, CO_2 and bicarbonates from the stream and as a byproduct generate oxygen. This may, in many cases, be a more significant factor on stream oxygenation than atmospheric reaeration.

In determining the allowable pollutional load on a stream, reoxygenation by photosynthetic production is usually neglected since it is felt that this source may not be completely dependable. The amount of photosynthetic organisms may vary and the oxygen production rate is affected by such things as the availability and intensity of sunlight, temperature, and the availability of a carbon source and other nutrients.

While this production of oxygen may be neglected in deciding on the allowable maximum pollutional load, it cannot be neglected in a stream analysis if it is significant. Camp (3) has modified the classical Streeter-Phelps formula to account for sinks and sources other than biological demand and atmospheric reaeration. In the Camp modifications, photosynthetic oxygen production is considered as a constant rate per day which is determined by the black and white bottle technique.

In the black and white bottle technique stream samples are collected at various depths in the stream. Part of the samples are placed in transparent bottles and part in opaque bottles and resuspended in the streams at the depths from which they were obtained. The resuspended samples are left in position for a day or several days. The differences in dissolved oxygen between the white and black bottles, divided by the number of days they are in the stream, serve as a measure of the net production of oxygen per day by the phytoplankton in the stream. Whether or not this is a good method is debatable. The glass bottle may filter out some of the effective energy and also the behavior of photosynthetic organisms in a stagnant environment may be considerably different from what it is in the turbulent environment of the stream (13).

If a simple system could be established in which there are only two elements contributing to the oxygen state, namely atmospheric reaeration and net photosynthetic production, and if it is assumed as Camp (4) does that for practical purposes photosynthetic production can be considered as a fixed rate, then the system can be described in terms of saturation deficit as follows:

$$\frac{dD}{dt} = -K_2 D - a \qquad (5\text{-}1)$$

where

a = rate of net photosynthetic production

Integrating equation (5-1) and converting natural logs to base 10, photosynthetic production can be expressed:

$$a = \frac{2.3k_2 \left[D_o\, 10^{-k_2 t} - D_t\right]}{1 - 10^{-k_2 t}} \qquad (5\text{-}2)$$

and saturation deficit can be predicted from:

$$D_t = D_o\, 10^{-k_2 t} - \frac{a}{2.3k_2}\left(1 - 10^{-k_2 t}\right) \qquad (5\text{-}3)$$

where

D_o = initial state of deficit and

D_t = deficit after some time t

Experimentation

The purpose of these experiments involving phytoplankton was to determine by direct calculations (1) the amount of photosynthetic production that can be expected and (2) the applicability of considering photosynthetic activity at a constant rate per day in predicting deficit.

Effect of Na_2SO_3 on Oxygen Production

Since Na_2SO_3 would be used in these experiments on photosynthesis, it was necessary to determine whether Na_2SO_3 would have any effect on photosynthetic properties of phytoplankton.

The phytoplankton rich reservoir and five aquariums each containing 50 liters of water from the reservoir were used. Oxygen was purged from one of the aquariums by bubbling nitrogen through it. The remaining four aquariums were dosed respectively with 60 mg/l, 50 mg/l, 40 mg/l and 30 mg/l of Na_2SO_3 + cobalt catalyst. A series of samples of water from reservoir and aquariums were collected and reinserted in the reservoir or aquariums from which they were taken. After 1, 2, 3, and 4 hours three white and three black bottles each were drawn from reservoir and aquariums. Dissolved oxygen in each bottle was determined by the Winkler method and photosynthetic oxygen production determined as the difference between white and black bottles. The results are summarized in Table 5-1.

Since the experiments in which photosynthetic production in the flume have a maximum flow through time of slightly more than 1.5 hours, it can be concluded that Na_2SO_3 will not have any noticeable effect on production.

Photosynthetic Production of Oxygen in the Flume

To determine the amount of oxygen production in the flume, two experiments were conducted using water from the reservoir in a clean flume devoid of sediment. In this very simple system only atmospheric reaeration and net photosynthesis contributed to the oxygen state.

In the first experiment the flow was 85 l/min, channel depth 6 inches and flow velocity 7.2 ft/min and flow through time of 27.8 minutes. The incoming water from the reservoir was dosed with Na_2SO_3 at the mixing box in the flume inlet. Dissolved oxygen readings were taken at the zero station and at the 200 ft point, synchronized so that the readings at the terminal point could be matched with D.O. readings taken 27 to 28 minutes previously

Table 5-1. Photosynthetic Oxygen Production in Reservoir and Aquaria (untreated) Compared with O_2 Production in Aquaria Treated with Na_2SO_3

Time	Reservoir*	Aquaria				
		Nitrogen Purged	60 mg/l Na_2SO_3	50 mg/l Na_2SO_3	40 mg/l Na_2SO_3	30 mg/l Na_2SO_3
1 hr	0.9	0.8	0.9	0.8	0.8	0.9
2 hr	1.2	1.3	1.4	1.0	1.1	1.2
3 hr	1.6	1.6	1.8	1.5	1.6	1.6
4 hr	1.9	2.2	2.1	1.9	1.9	1.8

*D.O. production is measured in mg/l.

at the inlet. The change in oxygen content then is the result of atmospheric reaeration and the photosynthetic and respiration activity of the phytoplankton in the water. An hourly rate of net production can be determined as follows (see Table 5-2):

$$a = \frac{60}{27.8} [\Delta D - 2.31 k_2 \frac{27.8}{1440} \bar{D}] \qquad (5-4)$$

where

$\bar{D}$ = average deficit during flow through period

ΔD = change in deficit in 27.8 minute flow through

Figure 5-1 portrays the rate per hour of oxygen production and the cumulative production in a 24 hour period. Production began at approximately 0730 and ended at approximately 1940. Oxygen generated during the production phase was 18.0 mg/l while oxygen consumed during the respiration phase was 10.5 mg/l with a net contribution of 7.5 mg/l. The maximum rate of net production occurred at approximately 1130 at which time it reached 2.6 mg/l/hr.

For the second experiment, a velocity was established to provide a $k_{2(20)}$ more in line with what would be expected in most streams. Most American streams according to Thomas (26) fall in a k_2 range from 0.06 to 0.96 day^{-1}. The flow rate was 27.2 liters per minute providing a velocity of 1.54 ft per minute at depth of six

Table 5-2. Determining Photosynthetic Production for First Experiment July 10-11, 1969. (Velocity = 7.2 ft/min Flow Through Time = 27.8 min Depth = 6 in)

Ave. temp. = 29.3^{o}

$a = \frac{60}{27.8} [-\Delta D - 231 k_{2_{(T)}} \frac{27.8}{1440} \bar{D}]$

$k_{2_{(20)}} = 1.6$

$k_{2_{(T)}} = 1.6 (1.242) = 1.987$

$a = 2.158 [-\Delta D - 0.0886 \bar{D}]$ mg/l/hr

Time	D_o	D	ΔD	$\bar{D}$	$0.0886 \bar{D}$	$2.158 [-\Delta D - 0.0886 \bar{D}]$
0730-0757	4.57	4.04	-0.53	4.305	0.3815	0.32
0742-0809	4.04	3.40	-0.64	3.720	0.3296	0.67
0930-0957	5.92	4.52	-1.40	5.220	0.4626	2.02
0945-1012	5.58	4.09	-1.49	4.835	0.4284	2.29
0957-1024	4.54	3.25	-1.29	3.895	0.3451	2.04
1108-1135	4.14	2.71	-1.43	3.425	0.3036	2.43
1130-1157	4.36	2.59	-1.57	3.575	0.3167	2.70
1447-1514	4.86	3.89	-0.97	4.370	0.3873	1.26
1525-1552	4.95	3.89	-1.06	4.420	0.3916	1.44
1534-1601	4.84	3.82	-1.02	4.330	0.3837	1.37
1858-1925	3.66	3.08	-0.58	3.370	0.2986	0.61
1922-1949	3.50	3.02	-0.48	3.260	0.2889	0.41
1935-2002	3.41	3.09	-0.32	3.250	0.2879	0.07
2045-2112	4.03	4.17	0.14	4.100	0.3634	-1.08
2150-2217	4.03	4.03	0.00	4.030	0.3571	-0.77
2300-2327	3.98	3.90	0.00	3.980	0.3527	-0.76
2402-2429	4.04	3.91	-0.13	3.975	0.3523	-0.48
0100-0127	3.98	3.89	-0.09	3.935	0.3487	-0.56
0130-0157	3.90	3.90	0.00	3.900	0.3445	-0.74
0320-0347	3.98	3.98	0.00	3.980	0.3527	-0.76
0350-0417	3.92	3.89	-0.03	3.905	0.3461	-0.68
0410-0437	3.76	3.98	0.22	3.870	0.3430	-1.21
0430-0457	3.70	3.98	0.28	3.840	0.3404	-1.34
0550-0617	5.76	6.12	0.36	5.940	0.5264	-1.91
0629-0656	5.62	5.63	0.01	5.625	0.4985	-1.10
0640-0707	4.96	5.19	0.23	5.075	0.4497	-1.47

inches and surface reaeration factor ($20^{\circ}C$) was calculated to be 0.68 day^{-1}. Initial readings were taken at station 25 instead of at station 0 to preclude the possibility of any unoxidized Na_2SO_3 moving into the system and resulting in erroneous reoxygenation determinations, and matching readings were taken at station 175. As in the previous experiment the rate of photosynthesis and the cumulative oxygen provided over a period of 24 hours was determined, see Figure 5-2. Photosynthetic production exceeded respiration commencing at 0730 and predominated until 1730 after which time respiration took over. The maximum rate of production occurred at approximately 1300 hours and was equal to 1.2 mg/l per hour. Total net production during the daylight hours equalled 7.4 mg/l and respiration during the hours of darkness equalled 7.2 mg/l. Net production resulting from photosynthesis was 0.20 mg/l.

Applicability of Assumption "a" = Constant Rate per Day

From Figures 5-1 and 5-2 it is obvious that photosynthetic production could only be considered to have a constant rate for short periods of time and the application of equation (5-3) for time equal to one day and "a" equal to production per day is questionable.

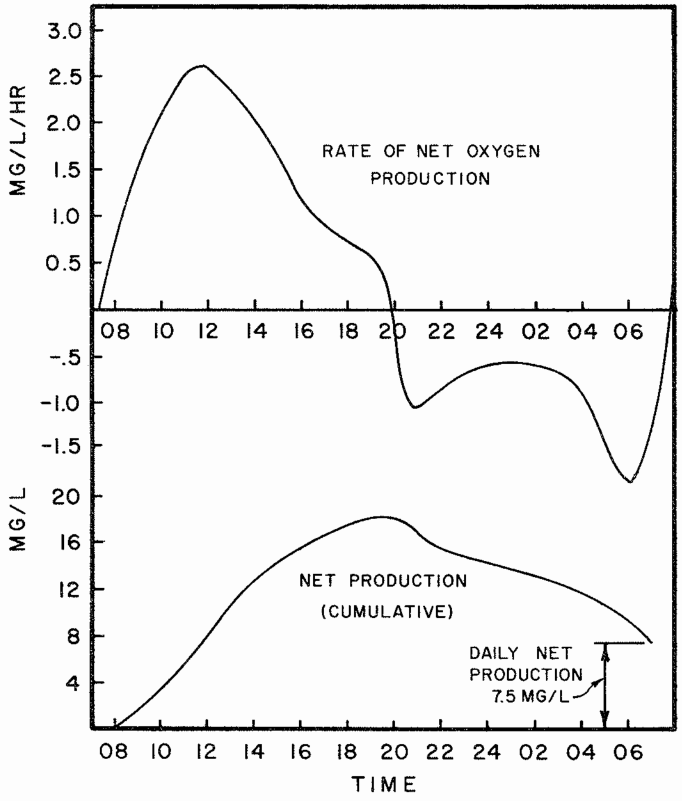


FIG. 5-1 NET PHOTOSYNTHETIC OXYGEN PRODUCTION (EXPERIMENT JULY 10-11, 1969)

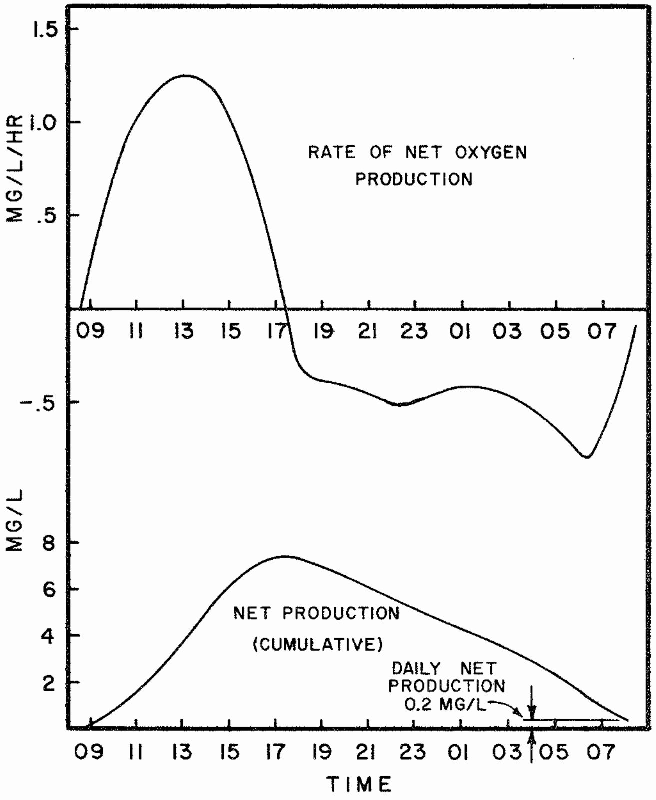


FIG. 5-2 NET PHOTOSYNTHETIC OXYGEN PRODUCTION (EXPERIMENT NOV. 13-14, 1969)

In the first experiment assuming an initial dissolved oxygen (D_o) of 6.0 mg/l at 0730 and by an iterative process, using the applicable hourly rates determined from Figure 5-1 for "a" and an hourly rate for $k_2 = 0.0828$ hr^{-1} (corrected to average temperature) and using a two hour period to calculate the parameters in equation (5-3) the deficit at the end of 24 hours (12 iterations) is predicted to be 3.92 mg/l, Table 5-3. On the other hand using equation (5-3) but with "a" = 7.5 mg/l/day and $k_2 = 1.987$ day^{-1} and making one predictive calculation results in a deficit of -1.6 mg/l or supersaturation.

Following the same iterative procedure for the second experiment, commencing with an initial deficit (D_o) of 6.0 mg/l, and an hourly rate for $k_2 = 0.026$ hr^{-1}, the final dissolved oxygen deficit (D) after 24 hours would 3.89 mg/l, Table 5-4. On the other hand, the predicted final dissolved oxygen deficit if t = 1 day and a = 0.20 mg/l/day would 1.3 mg/l.

It would seem from the two preceding experiments that serious error may result from considering photosynthesis as being a constant rate over a period of one day, especially if there is considerable photosynthetic activity. Also, the greater the surface reaeration rate (k_2) the greater will be the error in prediction.

Table 5-3. Predicted Oxygen Deficit (Experiment July 10-11, 1969)

Ave. temp. = 29.3 °C

$k_{2(20)} = 1.6$ day^{-1}

$k_{2(T)} = 1.987$

$$D = D_o\, 10^{-k_2 t} - \frac{a}{2.3k_2}(1 - 10^{-k_2 t})$$

$t = 2$ hr, $k_2 = 0.0828$ hr^{-1}

$\therefore D = 0.68 - 1.66\,a$

Time	D_o	$0.68D_o$	a	1.66 a	D
0730-0930	6.00	4.08	1.15	1.91	2.17
0930-1130	2.17	1.48	2.25	3.73	-2.25
1130-1330	-2.25	-1.53	2.45	4.07	-5.60
1330-1530	-5.60	-3.81	1.80	2.99	-6.80
1530-1730	-6.80	-4.62	1.00	1.66	-6.28
1730-1930	-6.28	-4.27	0.60	1.00	-5.27
1930-2130	-5.27	-3.58	-0.90	-1.49	-2.09
2130-2330	-2.09	-1.42	-0.75	-1.25	-0.17
2330-0130	-0.17	-0.11	-0.55	-0.91	0.80
0130-0330	0.80	0.54	-0.60	-1.00	1.54
0330-0530	1.54	1.05	-1.15	-1.91	2.96
0530-0730	2.96	2.01	-1.15	-1.91	3.92

Table 5-4. Predicted Oxygen Deficit
(Experiment Nov. 13-14, 1969)

Ave. temp. = 17.1°

$k_{2(20)} = 0.68\ \text{day}^{-1}$

$k_{2(T)} = 0.63$

$$D = D_o\ 10^{-k_2 t} - \frac{a}{2.3k_2}(1 - 10^{-k_2 t})$$

$t = 2$ hr, $k_2 = 0.026\ \text{hr}^{-1}$

$$\therefore D = 0.89\ D_o - 1.90\ a$$

Time	D_o	$0.89\ D_o$	a	1.90 a	D (mg/l)
0830-1030	6.00	5.34	0.45	0.85	4.49
1030-1230	4.49	4.00	1.07	2.03	1.97
1230-1430	1.97	1.75	1.20	2.28	-0.53
1430-1630	-0.53	-0.47	0.78	1.40	-1.87
1630-1830	-1.87	-1.66	0.02	0.04	-1.70
1830-2030	-1.70	-1.51	-0.38	-0.72	-0.79
2030-2230	-0.79	-0.70	-0.45	-0.86	0.16
2230-0030	0.16	0.14	-0.45	-0.86	1.00
0030-0230	1.00	0.89	-0.40	-0.76	1.65
0230-0430	1.65	1.47	-0.49	-0.93	2.39
0430-0630	2.39	2.13	-0.67	-1.27	3.40
0630-0830	3.40	3.03	-0.45	-0.86	3.89

Equation (5-3) taking t = 1 day does not make allowance for the increase in dissolved oxygen in the system during the productive phase which reduces the driving force for atmospheric reaeration.

Deoxygenation of System as a Net Result of Photosynthetic Organisms

In the preceding section it was hypothetically assumed that there was an initial deficit of 6 mg/l and that the flume was sufficiently long to contain one day's flow.

Deficit after one day's time was predicted to be 3.92 mg/l in the case of the first experiment and 3.89 mg/l in the case of the second experiment. The calculations are shown in Table 5-3 and 5-4. Considering the first experiment, if instead of photosynthetic production there was no production at all the deficit after one day would have been $D_o\ 10^{-k_2 t}$ or $6 \times 10^{-1.987} = 0.06$ mg/l. Since photosynthetic production resulted in a one day deficit of 3.92 mg/l, the net daily effect of algae in this case was deoxygenation rather than reoxygenation. The same oxygen state would have been produced if instead of photosynthetic producers an organic load of approximately 50 mg/l of BOD (assuming $k_1 = 0.2$) had been introduced into the system instead of photosynthetic organisms. Similarly, the one day deficit in the case of the second experiment would have been 1.4 mg/l instead of 3.89 mg/l if the organisms had not been in the system.

Determination of k_2 from Sag Formula

Often a formula for predicting oxygen deficit is used in the determination of k_2. The initial deficit and ending deficit one day or more in time downstream are measured quantities and the other factors are determined by experimentation, and k_2 is then calculated, usually by the trial and error method. The k_2 value then is that factor which equates the predictive equation to the measured deficit. If this were done in the case of the two experiments using ending deficits of 3.92 and 3.89 mg/l the determined k_2 values would be -0.47 and 0.19 instead of the actual 1.987 day^{-1} and 0.63 day^{-1}.

CHAPTER VI

Ecosystem

Theory and Literature Review

The simplest system that normally is considered is one in which there is a biodegradable pollutant suspended or dissolved in the flowing stream exerting an oxygen demand and atmospheric reaeration as the only oxygen source. If the biodegradable material has an oxygen demand L_t at time t, since the degrading action normally is considered to be monomolecular, it can be expressed in the form:

$$\frac{dL}{dt} = -K_1 L_t \qquad (6-1)$$

Since this oxygen demand is being supplied from the stream's oxygen resources, the saturation deficit of the stream is increasing at the same rate as the oxygen demand is decreasing. The change in deficit attributable to BOD can be expressed:

$$\frac{dD_1}{dt} = \frac{-dL}{dt} = K_1 L_t \qquad (6-2)$$

Simultaneously, oxygen is being supplied to the system at a rate directly proportional to the deficit D_t at any given time:

$$\frac{dD_2}{dt} = -K_2\ D_t \qquad (6\text{-}3)$$

The overall rate of oxygen removal or supply can be expressed:

$$\frac{dD}{dt} = \frac{dD_1}{dt} + \frac{dD_2}{dt}$$

$$= K_1\ L_t - K_2\ D_t \qquad (6\text{-}4)$$

Integrating and solving for D and converting from natural log to common log yields the following equation:

$$D_t = \frac{k_1\ L_o}{k_2 - k_1}\ (10^{-k_1 t} - 10^{-k_2 t}) + D_o\ 10^{-k_2 t} \qquad (6\text{-}5)$$

where

L_o = initial demand ($t = 0$)

This is the Streeter and Phelps (23) oxygen sag formula.

If this system contains a degradable load some of which is settling to the bottom, the rate of BOD lost by settling is directly proportional to the BOD remaining at any time t. Equation (6-1) therefore would be modified:

$$\frac{dL}{dt} = (K_1 + K_3)\ L_t = 2.3\ (k_1 + k_3)\ L_t \qquad (6\text{-}6)$$

where

K_3 = rate constant for BOD removal by sedimentation (base e)

Assuming that the condition exists wherein the settling BOD becomes part of the bottom sediment but the amount of bottom sediment is small and the reaction rate so slow that there is no measurable oxygen draw down from the bottom sediment, the equation (6-5) would have to be modified to predict deficit:

$$D_t = \frac{k_1 L_o}{k_2 - k_1 - k_3} \left(10^{-(k_1 + k_3)t} - 10^{-k_2 t}\right) + D_o\, 10^{-k_2 t} \qquad (6\text{-}7)$$

If photosynthetic producers of oxygen are added to the system then:

$$\begin{aligned} D_t = {} & \frac{k_1 L_o}{k_2 - k_1 - k_3} \left(10^{-(k_1 + k_3)t} - 10^{-k_2 t}\right) - \\ & \frac{a}{2.3k_2} \left(1 - 10^{-k_2 t}\right) + D_o\, 10^{-k_2 t} \end{aligned} \qquad (6\text{-}8)$$

If benthic demand has a measurable effect on the stream's oxygen deficit then the equation (6-8) becomes:

$$\begin{aligned} D_t = {} & \frac{k_1}{k_2 - k_1 - k_3} \left[L_o - \frac{s}{2.3\,(k_1 + k_3)}\right] \times \\ & \left[10^{-(k_1 + k_3)\, t} - 10^{-k_2 t}\right] + \\ & \frac{k_1}{k_2} \left[\frac{s}{2.3\,(k_1 - k_3)} - \frac{a}{2.3k_1}\right] \left(1 - 10^{-k_2 t}\right) + \\ & D_o\, 10^{-k_2 t} \end{aligned}$$

where

s = rate of addition of BOD to the stream from the benthos.

This is the general form of the oxygen sag equation. Camp (3) makes an excellent development and presentation of these equations.

Experimentation

Two ecosystems were established, one in the east side of the flume, the other in the west side. The system in the East Flume consisted of benthal demand and respiration of phytoplankton as oxygen consumers and the atmosphere and photosynthetic production as oxygen contributors. In the West Flume an identical system was established and then stressed with a soluble organic load. The purpose of the experiment was to establish conditions in a flume that approached the assumptions that were made in the development of the oxygen sag equations and to test the validity of the equations. The experiments also test the use of sag equations to determine atmospheric reaeration coefficients k_2.

Since the organic load with which the West Flume was stressed was soluble, sedimentation as a factor was eliminated. Accordingly, the general equation can be modified:

$$D_t = \frac{k_1}{k_2 - k_1} [L_o - \frac{s}{2.3\,k_1}] (10^{-k_1 t} - 10^{-k_2 t}) +$$

$$\frac{1}{2.3k_2} (s - a) (1 - 10^{-k_2 t}) + D_o\, 10^{-k_2 t} \qquad (6\text{-}10)$$

This is the equation applicable to the ecosystem that was established in the west side of the flume.

In order to test the validity of the equation for prediction of deficit, it was necessary that there be a sufficiently long detention time in the flume. Since the flume is only 200 ft in length this would be impossible with any flow velocity other than one approaching zero. It was decided therefore to run the experiment under stagnant conditions for several days, monitoring dissolved oxygen.

Benthal Demand

Before beginning the experiment the benthal demand of the bottom sediment was determined in the manner similar to the experiment previously described in Chapter IV. Bottom sediment from the east side and west side were placed in aquariums to the same depth as employed in the flume. Oxygen demand was determined by calculating reaeration by atmospheric diffusion at the equilibrium deficit. Aerial load L_d was determined from core samples. The aerial load of the west side sediment was higher than that in the east side. This was a reasonable finding because the west side bottom material had been treated in a previous experiment (not described in this work) with biologically active material taken from the aeration tank of the Austin sewage treatment plant. The reaction rate coefficient (k_4) for both bottoms was 0.001. Cores were taken at stations in both sides of the flume 25 ft, 100 ft, and 175 ft from the inlet end. BOD determinations were made. The average BOD at each station is given in Table 6-1.

Table 6-1. Average BOD of Bottom Sediment of Model River

Station	East Flume (mg/gm)	West Flume (mg/gm)
25	0.787	1.090
100	0.713	0.847
175	0.894	1.050
Average	0.798	0.996

The average weight per core was 50 grams and each core represented 0.5 inches^2 of bottom surface. Aerial load from Table 6-1 was then:

East Flume

$$144/0.5 \times 50 \text{ gms} \times 0.798 \text{ mg/gm} = 11.46 \text{ gms/ft}^2$$

West Flume

$$144/0.5 \times 50 \text{ gms} \times 0.996 \text{ mg/gm} = 14.34 \text{ gms/ft}^2$$

and aerial demand ($2.3k_4\ L_d$) was 26.5 mg of oxygen per square foot per day for the East Flume, and 30.3 mg/ft^2/day for the West Flume. Water depth was 11 1/4 inches and therefore benthal demand on the system was 0.9 mg O_2/liter/day for the East Flume and 1.1 mg O_2/liter/day for the West Flume.

Initial Conditions

To set up an initial condition for the experiment 70 liter/min flow of water from the phytoplankton rich reservoir was established simultaneously in both channels. This gave a flow through time of approximately 100 min. Physical and chemical analysis of samples of the reservoir water taken during five months prior to experiment are presented in Table 6-2. The East Flume was dosed with Na_2SO_3 to lower initial oxygen and the West Flume was dosed with a milk solution composed of 500 gms of powdered milk in 20 liters of water. Dosing rate was 70 ml/min or 1 ml of dose per liter of flow. Also, 1 ml of seed obtained from the Austin sewage treatment plant's aeration tank was introduced into the inlet mixing box per liter of flow. After 2.5 hours of flow, it was assumed that

Table 6-2. Analysis of Water Samples from Reservoir

Item	Samples During Period July - Dec. 1969*									Average
	1	2	3	4	5	6	7	8	9	
BOD_5 (filtered)	4.5	3.2	11.5	13.2	12.9	7.5	5.6	10.9	10.9	8.9
pH	8.7	8.8	8.9	8.9	8.9	8.9	8.5	8.9	8.9	8.8
Total Solids	377	352	342	366	383	318	390	396	380	367
Fixed	267	248	194	242	229	141	244	245	219	225
Volatile	110	104	148	124	154	177	146	151	161	142
Suspended Solids	18	16	48	25	32	38	17	11	22	25
Hardness	215	217	231	202	192	224	263	269	252	229
Alkalinity	147	132	139	133	129	127	175	161	145	143

*Except for pH all values are in mg/l.

a uniform condition of BOD and phytoplankton existed throughout the flumes. Flow and dosing was stopped and a stagnant condition was maintained throughout the experiment. Monitoring stations were established in the East Flume at the 25 ft point (E 25), the 100 ft point (E 100), and at the 175 ft point (E 175). Similarly monitoring points were established in the West Flume at W 25, W 100, and W 175. The initial conditions were established at 1600 on December 16; however it was decided not to begin monitoring until 0830 on December 17. This was to allow some time for organisms to adjust to the new environment. The initial D.O. readings taken at 0830 on December 17 were:

Station	East Flume	West Flume
25	7.1	3.5
100	7.5	2.7
175	7.3	2.6

This would tend to indicate that a uniform condition existed throughout each flume. Monitoring continued until 0900 on December 23. Figures 6-1 through 6-6 portray data obtained during this period.

As previously indicated, equation (6-10) supposedly describes the oxygen saturation deficit in the system established in the West Flume. Benthic demand is known and so is the reaeration

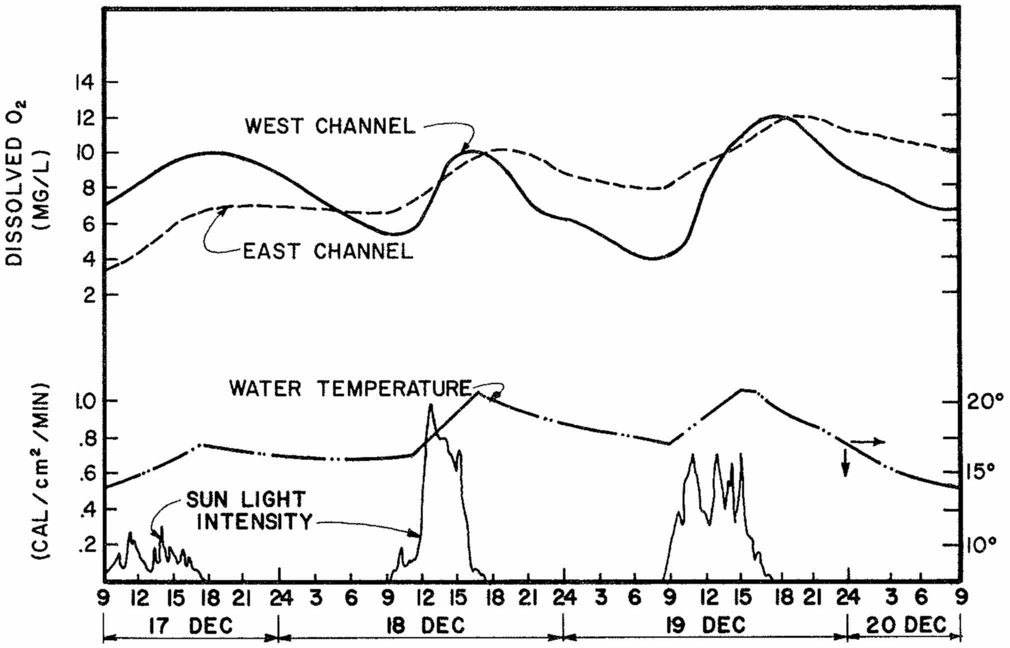


FIG. 6-1 STATION 25 EXPERIMENTAL RESULTS DEC 17-20, 1969

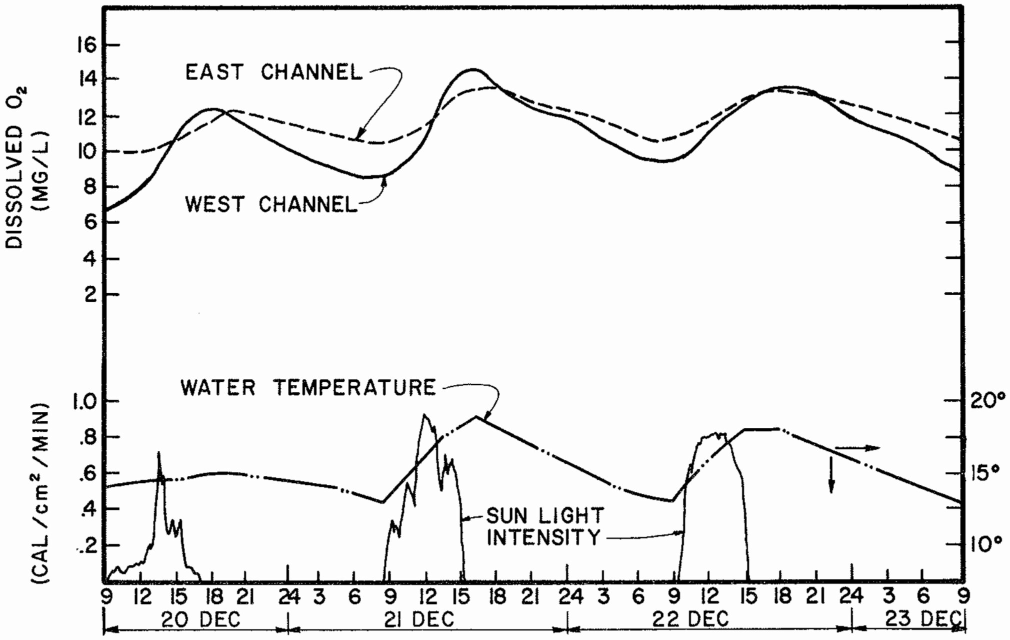


FIG. 6-2 STATION 25 EXPERIMENTAL RESULTS DEC 20-23, 1969

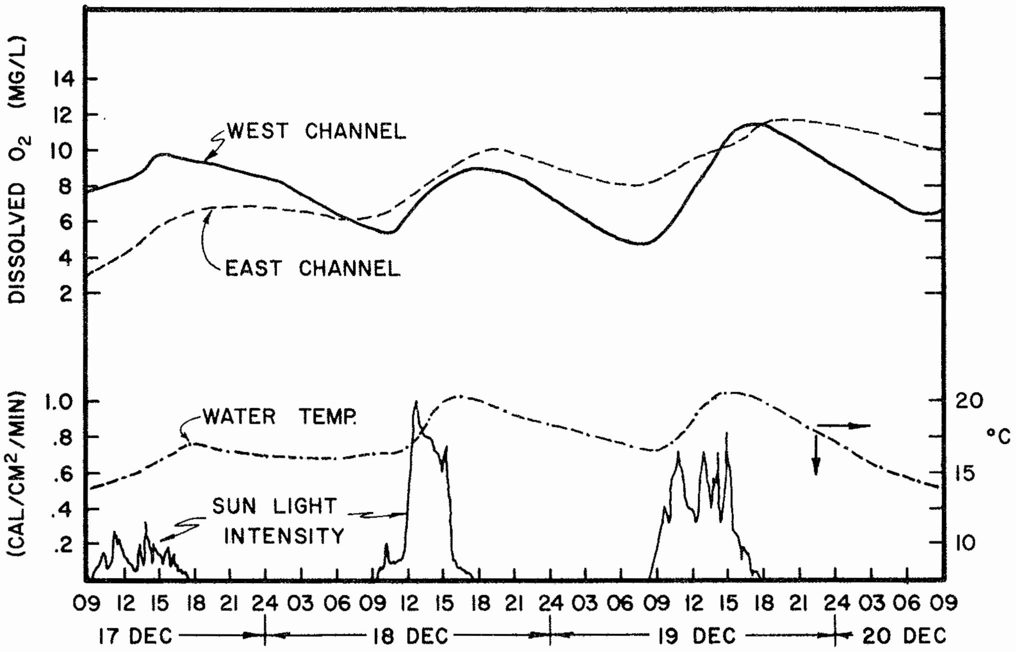


FIG. 6-3 STATION 100 EXPERIMENTAL RESULTS DEC 17-20, 1969

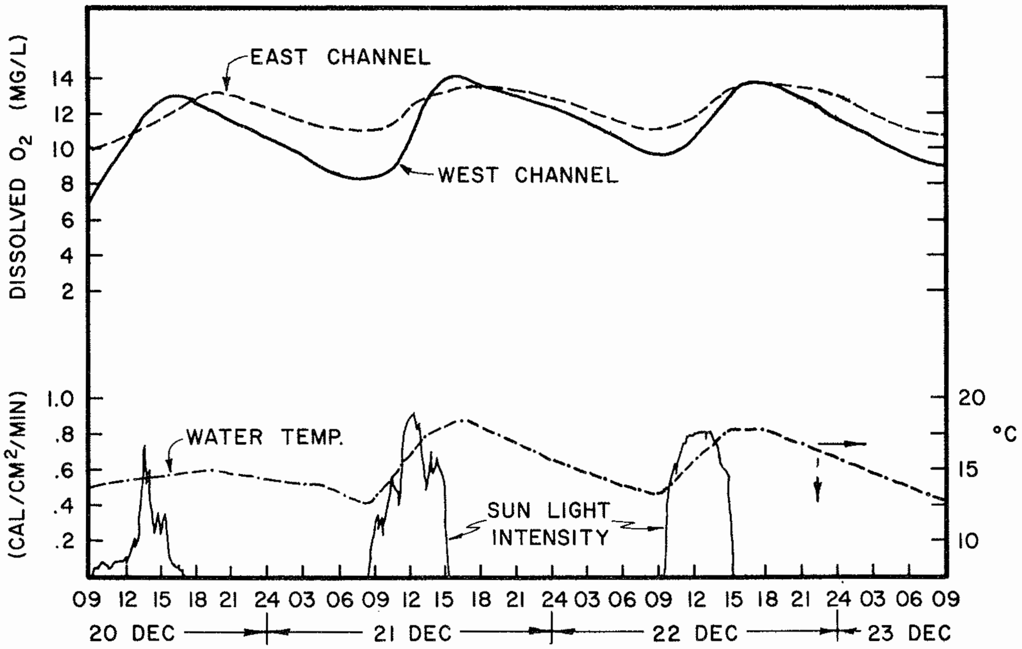


FIG. 6-4 STATION 100 EXPERIMENTAL RESULTS DEC 20-23, 1969

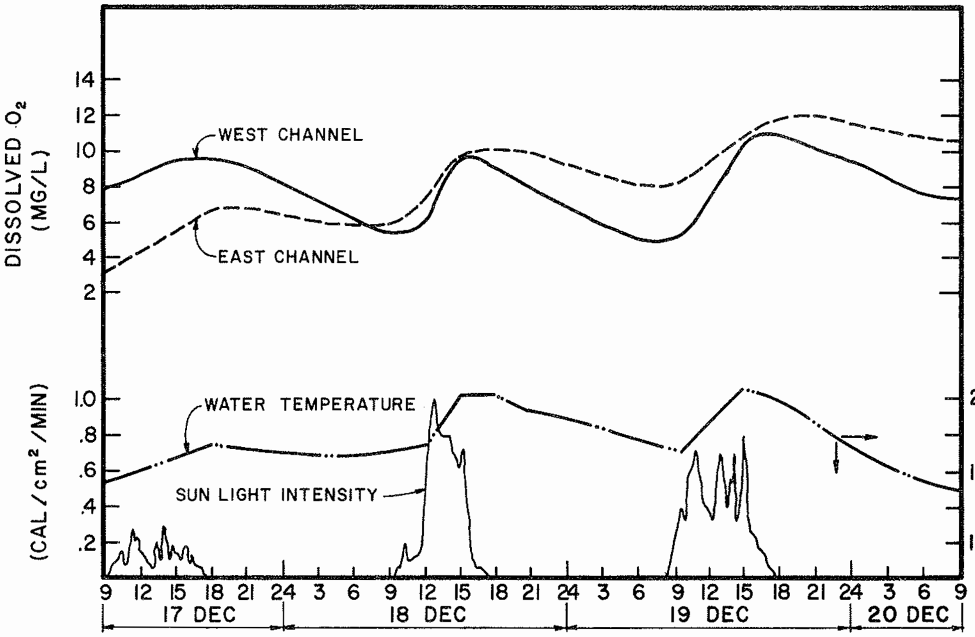


FIG. 6-5 STATION 175 EXPERIMENTAL RESULTS FOR DEC 17-20, 1969

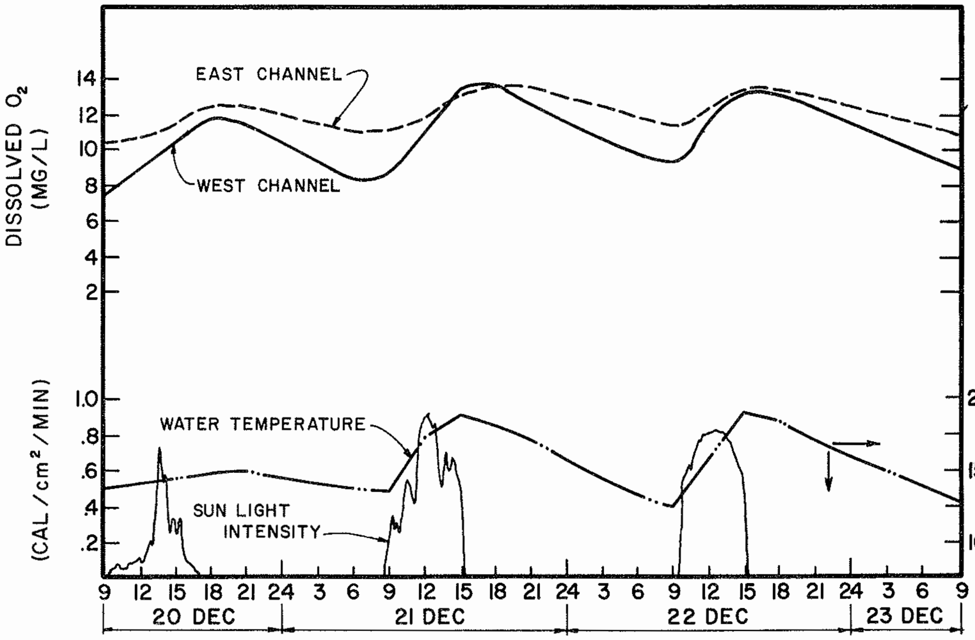


FIG. 6-6 STATION 175 EXPERIMENTAL RESULTS FOR DEC 20-23, 1969

coefficient (k_2) for stagnant water 11 1/4 inches in depth (k_2 = 0.3 day^{-1}). Before the equation can be solved and tested against measured deficits, the biological reaction rate (k_1), the initial organic load (L_o), and the rate of photosynthetic oxygen production must be determined.

Determination of k_1 and L_o

The normal method of obtaining k_1 and L_o would be to use the Standard Methods BOD incubation technique, determining the BOD on each of five or more consecutive days and from this using a method such as presented by Thomas (25). However, the author decided that another method was available to him after a count of phytoplankton in samples taken at 0300 hours on December 21, 4.5 days after the start of the experiment. The samples were taken at Stations E 100 and W 100 and indicated that the number of organisms were essentially the same in both East and West Flume, Table 6-3. Since the initial phytoplankton in both East and West Flume came from the same source and since the number of organisms were approximately the same in East and West Flume 4.5 days after start of the experiment, it was reasoned that the density of phytoplankton in the East Flume was approximately equal to the density in the West

Flume throughout the life of the experiment. It was then assumed that the rate of respiration during the hours of darkness would be the same in both East and West Flume. Based on this assumption a method was available for determining k_1 and L_o from dissolved oxygen readings.

Table 6-3. Organism Count in Sample Taken at 0300 Hours on December 21, 1969

Organisms	Number per ml Station 100 E	 Station 100 W
Aggmenellum	9	37
Phormidium		1
Staurastrum	448	302
Closterium	4	
Chloroccum	23	49
Ankistrodesmus		17
Total	484	406

Considering the East Flume, the following relationship exists:

$$\frac{dD}{dt} = -K_2 D + s - (P - R) \qquad (6\text{-}11)$$

where

P = photosynthetic production of oxygen

R = oxygen consumed by respiration

$(P - R)$ = a = net photosynthetic production

If dissolved oxygen readings are taken at short time intervals, $t_2 - t_1$, and if K_2 and benthic demand (s) are known, then for that time interval:

$$(P - R) = s - K_2 \frac{(D_2 - D_1)}{2} - (D_2 - D_1) \qquad (6\text{-}12)$$

where

D_2 = oxygen deficit at time t_2

D_1 = oxygen deficit at time t_1

If several time intervals are selected during the hours of darkness $(P = 0)$, then an average respiration rate R can be determined.

An equation similar to (6-1) can be written for the West Flume applicable for a short time interval:

$$(P - y - R) = -K_2 \frac{(D_2 - D_1)}{2} - (D_2 - D_1) \qquad (6\text{-}13)$$

where

y = oxygen consumed in degradation of organic load including BOD contributed to the water by the benthos

Using identical time intervals for equations (6-12) and (6-13) and substituting the respiration values (R) into equation (6-13), the average amount of oxygen consumed due to organic load can be determined for the time intervals used.

In this experiment two hour time intervals from midnight to 0600 were used to determine R and y. The average "y" was considered to be the hourly biological demand exerted at 0300. A semi-log plot of average values of y against time showed a linear relationship, Figure 6-7. The geometrical average between consecutive values of y was selected from the plot. These values multiplied by 24 established a daily demand. Knowing the daily demand, K_1 and L_o were determined by the method previously mentioned (25). The K_1 value obtained was 0.27 or $k_1 = 0.117$ and L_o at 0300 on December 18 was calculated as 33.7 mg/liter.

The biological reaction rate k_1 was also determined by the use of a Beckman Total Organic Carbon Analyzer. Total carbon (T.C.), inorganic carbon (I.C.), and total organic carbon (T.O.C.) determinations were made periodically on samples taken from East and West Flume. The differences in T.O.C. between East and West were assumed to be the result of the organic load imposed upon the West Flume. The oxygen demand of this organic load at the time

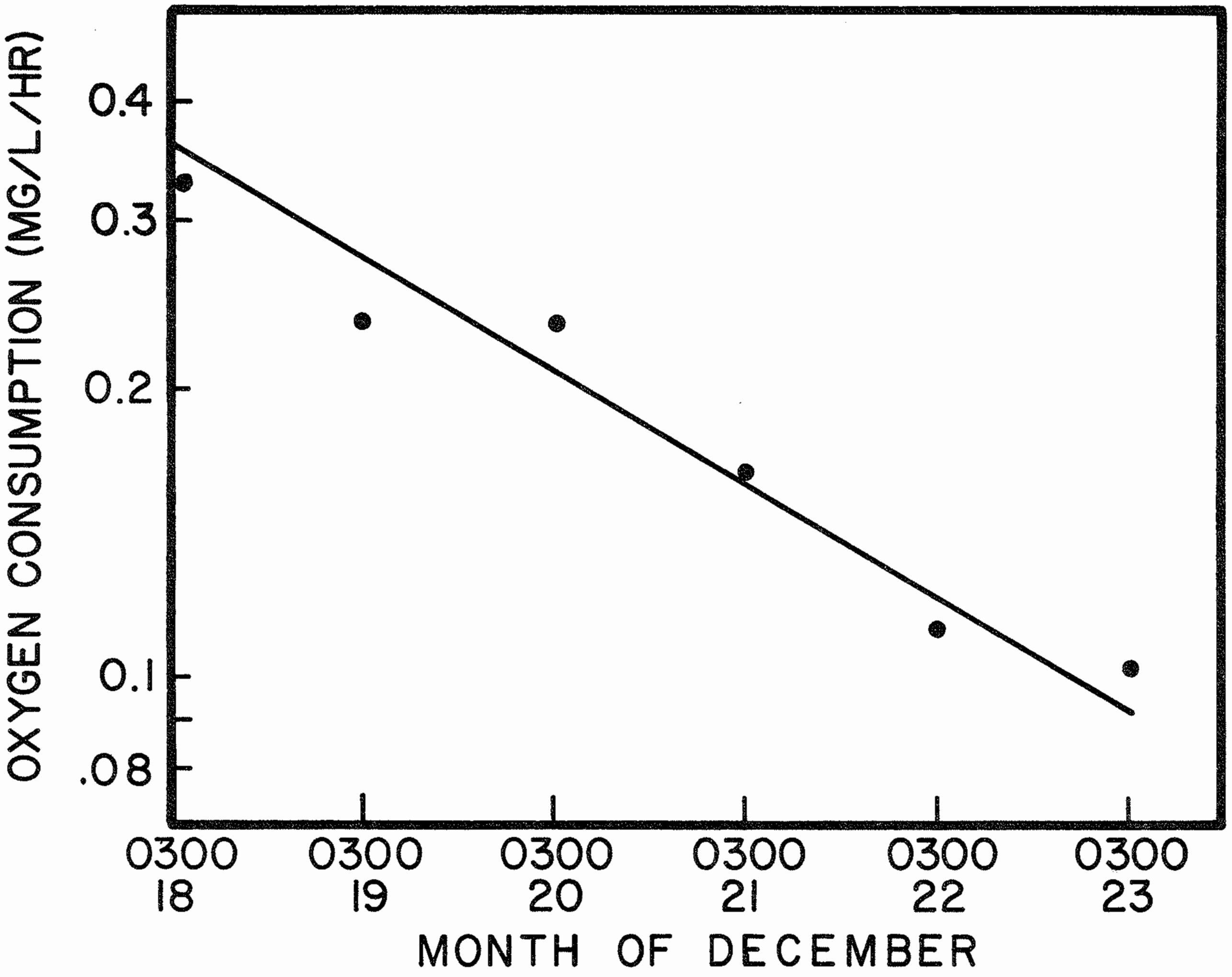


FIG. 6-7 AVERAGE HOURLY RATE OF OXYGEN CONSUMPTION IN WEST FLUME AS A RESULT OF ORGANIC LOADING

the sample was taken is the difference in T.O.C. multiplied by 2.67, the ratio of the molecular weight of oxygen to carbon. Table 6-4 presents the T.C., I.C., T.O.C., and oxygen demand determinations. Figure 6-8, a plot of oxygen demand, indicates a biological reaction rate k_1 of 0.121 day^{-1} which is a close agreement with the k_1 of 0.117 day^{-1} obtained by the method previously described.

Determination of Net Photosynthesis

Using equation (6-12) and measured deficits in the East Flume every two hours, converting s and K_2 to rates per two hours, net photosynthesis (P - R) in the East Flume was determined for each two hour period.

Similarly by using equation (6-13) the quantity (P - y - R) was determined for the West Flume for each two hour period. Table 6-5 demonstrates the calculations for a day starting at 0900 on December 18 and ending at 0900 on December 19 using the data obtained at station W 100. The next step was to determine the oxygen consumed (y) by the organic load in each two hour period so that it can be removed from (P - y - R) yielding (P - R) which is net oxygen produced by photosynthesis, the "a" term in

Table 6-4. Carbon Determinations Using Beckman Total Organic Carbon Analyzer

Date and Time		Station*			Ave.	Station*			Ave.	Ave.* T.O.C. Difference	O_2** Demand
		25 E	100 E	175 E		25 W	100 W	175W			
Dec. 16	T.C.	63.2	65.0	62.5	63.5	78	72	74	74.7		
@	I.C.	31.2	31.0	31.5	31.2	30	31.5	30.2	30.6		
1500	T.O.C.	32.0	34.0	31.0	32.3	48	40.5	43.8	44.1	11.8	31.5
Dec. 17	T.C.	61.0	57.5	60.0	59.5	70	72.5	69.5	70.4		
@	I.C.	30.6	30.1	31.0	30.6	30.7	30.8	30.5	30.7		
1500	T.O.C.	30.4	27.4	29.0	28.9	39.3	41.7	39.0	39.7	10.8	28.8
Dec. 18	T.C.	59.5	57.5	59.7	58.9	70.5	69.5	71.0	70.3		
@	I.C.	30.7	31.2	30.9	30.9	30.9	33.7	33.7	32.7		
1130	T.O.C.	28.8	26.3	28.8	28.0	36.8	35.8	37.3	36.6	8.6	23.0
Dec. 19	T.C.	58.1	58.1	58.2	58.1	67.8	68.4	67.3	67.8		
@	I.C.	29.4	29.9	29.8	29.7	33.4	33.0	33.3	33.2		
1500	T.O.C.	28.7	28.2	28.4	28.4	34.4	35.4	34.0	34.6	6.2	16.6
Dec. 20	T.C.	54.0	53.7	54.0	53.9	61.5	59.7	61.0	60.7		
@	I.C.	28.4	27.3	27.7	27.8	31.4	31.3	31.1	31.2		
2340	T.O.C.	25.6	26.4	26.3	26.1	30.1	28.4	29.9	29.5	3.4	9.1
Dec. 21	T.C.	54.5	55.0	54.3	54.6	60.0	62.8	63.7	62.2		
@	I.C.	27.0	26.5	26.7	26.7	29.2	29.1	29.3	29.2		
1800	T.O.C.	27.5	28.5	27.6	27.9	30.8	33.7	34.4	33.0	5.1	13.6
Dec. 22	T.C.	53.0	53.0		53.0	58.5	58.5		58.5		
@	I.C.	29.2	29.3		29.2	31.4	32.5		31.9		
1500	T.O.C.	23.8	23.7		23.8	27.1	26.0		26.6	2.8	7.46

*Readings in mg/l

T.C. = Total Carbon

I.C. = Inorganic Carbon

T.O.C. = Total Organic Carbon

**Oxygen demand of the organic load imposed on the West Flume

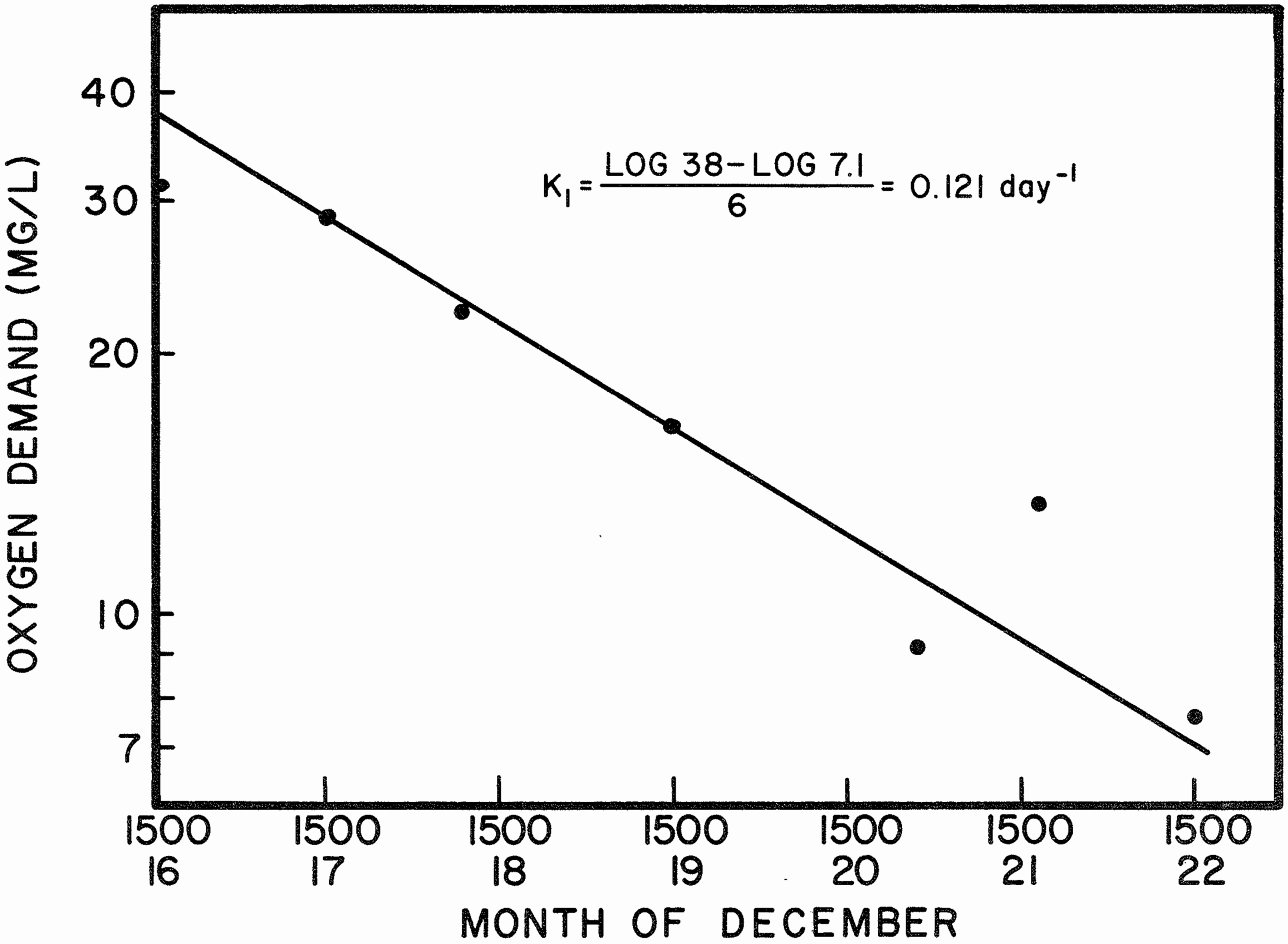


FIG. 6-8 OXYGEN DEMAND IN WEST FLUME CALCULATED FROM T.O.C. DETERMINATIONS

Table 6-5. Calculating (P - y - R) at Station W 100
0900 Dec. 18 - 0900 Dec. 19

$K_2 = 0.72\ \text{day}^{-1}$ $= 0.06/2\ \text{hr}$			$(P - y - R) = -K_2\bar{D} - \Delta D$				
Time	D	D_o	ΔD	K_2	$\bar{D}$	$K_2\bar{D}$	(P - y - R)
0900-1100	4.35	4.41	-0.06	0.06	4.38	0.2628	-0.2028
1100-1300	2.54	4.35	-1.82	0.06	3.45	0.2070	1.6130
1300-1500	1.08	2.54	-1.46	0.06	1.81	0.1086	1.3514
1500-1700	0.08	1.08	-1.00	0.06	0.58	0.0348	0.9652
1700-1900	0.12	0.08	0.04	0.06	0.10	0.0060	-0.0460
1900-2100	0.88	0.12	0.76	0.06	0.50	0.300	-0.7900
2100-2300	1.72	0.88	0.84	0.06	1.30	0.0780	-0.9180
2300-0100	2.56	1.72	0.84	0.06	2.14	0.1284	-0.9684
0100-0300	3.52	2.56	0.96	0.06	3.04	0.1824	-1.1424
0300-0500	4.25	3.51	0.74	0.06	3.88	0.2334	-0.9734
0500-0700	5.10	4.24	0.86	0.06	4.67	0.2808	-1.1408
0700-0900	5.00	5.10	-0.10	0.06	5.05	0.3030	-0.2030

equation (6-10). Also it is necessary to determine L_o, the organic oxygen demand at the beginning of each period. Since it was determined that k_1 was 0.117 and the initial BOD of the organic load at 0300 on December 18 was 33.7 mg/l, L_o at the start of the day 0900 on December 18 was arrived at by multiplying 33.7 x $10^{-k_1 t}$ = 31.6 mg/liter. If k_1 per day is converted to k_1 per two hour period then an L_o for the beginning of each two hour period is readily determined by multiplying the previous L_o by $10^{-k_1 t}$. The difference between L_o at the beginning of one period and the beginning of a subsequent period represents the oxygen consumed (y) by the organic load during the period. Table 6-6 shows the calculations for (y) and (P - R) for two hour periods between 0900 on December 18 and 0900 on December 19.

Predicting Oxygen Deficit in the West Flume

In Chapter V the validity of using an equation which does not take into account the diurnal characteristics of photosynthetic production for predicting oxygen deficits for one or more days in time was questioned. The use of equation (6-10) must therefore be predicated upon an iterative procedure wherein predictions are made over short periods of time so that net photosynthesis could

Table 6-6. Calculating Net Photosynthetic Production (P - R) at Station W 100 (Dec. 18-19)

Time	L_o (mg/l)	k_1 (hr^{-1})	t (hr)	k_1t	10^{-k_1t}	L (mg/l)	y (mg/l)	(P - y - R)	(P - R)
0900-1100	31.6	0.00488	2	0.00976	0.9775	30.89	0.71	-0.2028	0.5072
1100-1300		0.00488	4	0.01952	0.9560	30.21	0.68	1.6130	2.2930
1300-1500		0.00488	6	0.02928	0.9346	29.53	0.68	1.3517	2.0317
1500-1700		0.00488	8	0.03904	0.9141	28.88	0.65	0.9652	1.6152
1700-1900		0.00488	10	0.04880	0.8936	28.24	0.64	-0.0460	0.5940
1900-2100		0.00488	12	0.05856	0.8741	27.62	0.62	-0.7900	-0.1700
2100-2300		0.00488	14	0.06832	0.8547	27.01	0.61	-0.9180	-0.3080
2300-0100		0.00488	16	0.07808	0.8354	26.40	0.61	-0.9684	-0.3584
0100-0300		0.00488	18	0.08784	0.8170	25.82	0.58	-1.1424	-0.5624
0300-0500		0.00488	20	0.09760	0.7987	25.24	0.58	-0.9734	-0.3934
0500-0700		0.00488	22	0.10736	0.7812	24.68	0.56	-1.1408	-0.5808
0700-0900		0.00488	24	0.11720	0.7634	24.12	0.56	-0.2030	0.3570

be assumed as a constant rate term without introducing a large error.

If the initial deficit is used to start the iterative process (4.4 mg/l at 0900 on December 18), after 12 iterations using equation (6-10), the predicted deficit at Station W 100 at 0900 on December 19 was 5.0 mg/l. The actual measured deficit was 5.0 mg/l. Table 6-7 is a presentation of the calculations involved in the iterative procedure. The iterative procedure using equation (6-10) gave excellent results, Figure 6-9 through 6-13. In practice however, the time interval used in the predictive equations is a day and the use of daily net photosynthesis as a constant rate term results in error. Whether the error is significant or not depends not only on the amount of photosynthetic activity but also on the reaeration coefficient. The larger the k_2 value the larger will be the error in prediction. The error resulting from prediction using a one day span is always on the unsafe side, predicting a smaller dissolved oxygen deficit than is actually the case. Table 6-8 illustrates the difference in results obtained by using a one day time span as opposed to the iterative procedure. From this it can be seen that equation (6-10) must be used with care.

Table 6-7. Calculation of Oxygen Deficit Prediction at Station W 100 (0900 Dec. 18 - 0900 Dec. 19)

$k_1 = 0.00488 \text{ hr}^{-1}$

$k_2 = 0.01291 \text{ hr}^{-1}$

$t = 2$ hr

$s = 0.046$ mg/l/hr

$$D_t = \frac{k_1}{k_2 - k_1} [L_o - \frac{s}{2.3k_1}] (10^{-k_1 t} - 10^{-k_2 t}) + \frac{1}{2.3k_2} [s - a] (1 - 10^{-k_2 t}) + D_o \, 10^{-k_2 t}$$

$$D_t = 0.0214 [L_o - 4.07] + 0.9619 [s - a] + 0.9423 D_o$$

Time	L_o (mg/l)	$L_o - 4.07$ (mg/l)	$0.0214 \times [L_o - 4.07]$* (mg/l)	s (mg/l/2 hr)	a (mg/l/2 hr)	s - a (mg/l/2 hr)	0.9619 [s - a]* (mg/l)	D_o (mg/l)	$0.9423 D_o$* (mg/l)	D_t** (mg/l)
9-11	31.6	27.53	0.5891	0.092	0.5072	-0.4152	-0.3993	4.4100	4.1555	4.3453
11-13	30.9	26.83	0.5742	0.092	2.2930	-2.2010	-2.1171	4.3453	4.0945	2.5516
13-15	30.2	26.13	0.5592	0.092	2.0317	-1.9397	-1.8657	2.5516	2.4043	1.0978
15-17	29.5	25.43	0.5442	0.092	1.6252	-1.5332	-1.4747	1.0978	1.0344	0.1039
17-19	28.9	24.83	0.5314	0.092	0.5940	-0.5020	-0.4828	0.1039	0.0979	0.1465
19-21	28.2	24.13	0.5164	0.092	-0.1700	0.2620	0.2520	0.1465	0.1380	0.9064
21-23	27.6	23.53	0.5035	0.092	-0.3080	0.4000	0.3847	0.9064	0.8541	1.7423
23-01	27.0	22.93	0.4907	0.092	-0.3584	0.4504	0.4332	1.7423	1.6417	2.5656
01-03	26.4	22.33	0.4779	0.092	-0.5624	0.6544	0.6294	2.5656	2.4175	3.5248
03-05	25.8	21.73	0.4650	0.092	-0.3934	0.4854	0.4669	3.5248	3.3214	4.2533
05-07	25.2	21.13	0.4522	0.092	-0.5808	0.6728	0.6471	4.2533	4.0078	5.1071
07-09	24.7	20.63	0.4415	0.092	0.3570	-0.2650	-0.2549	5.1071	4.8124	4.9990

*Sum of columns marked with asterisk = D_t

**D_t = sum of columns marked with asterisk.

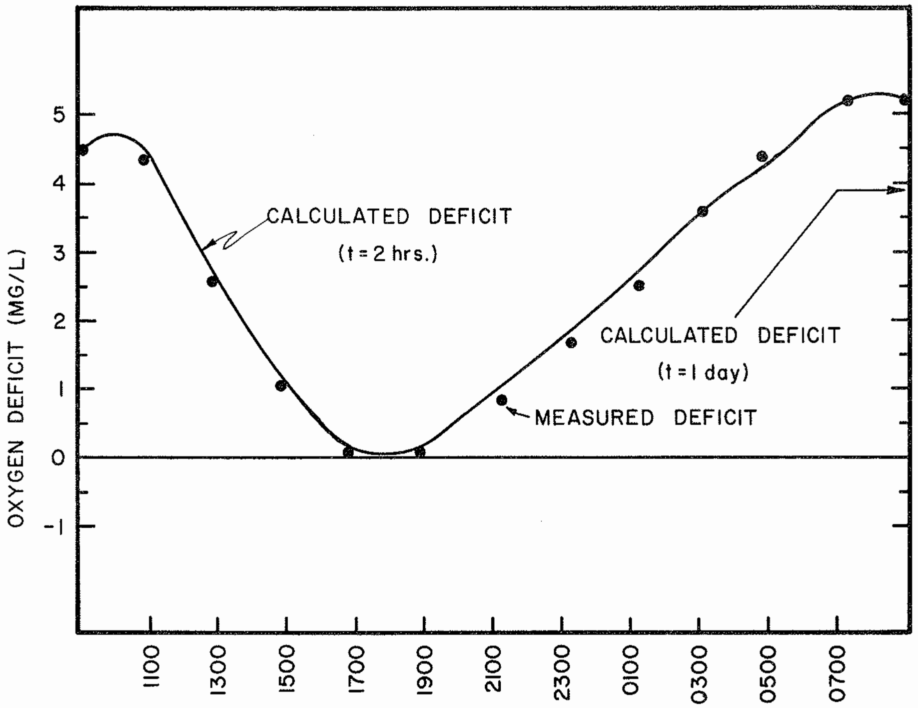


FIG. 6-9 CALCULATED AND MEASURED OXYGEN DEFICITS AT STATION W100 (0900 DEC 18 - 0900 DEC 19)

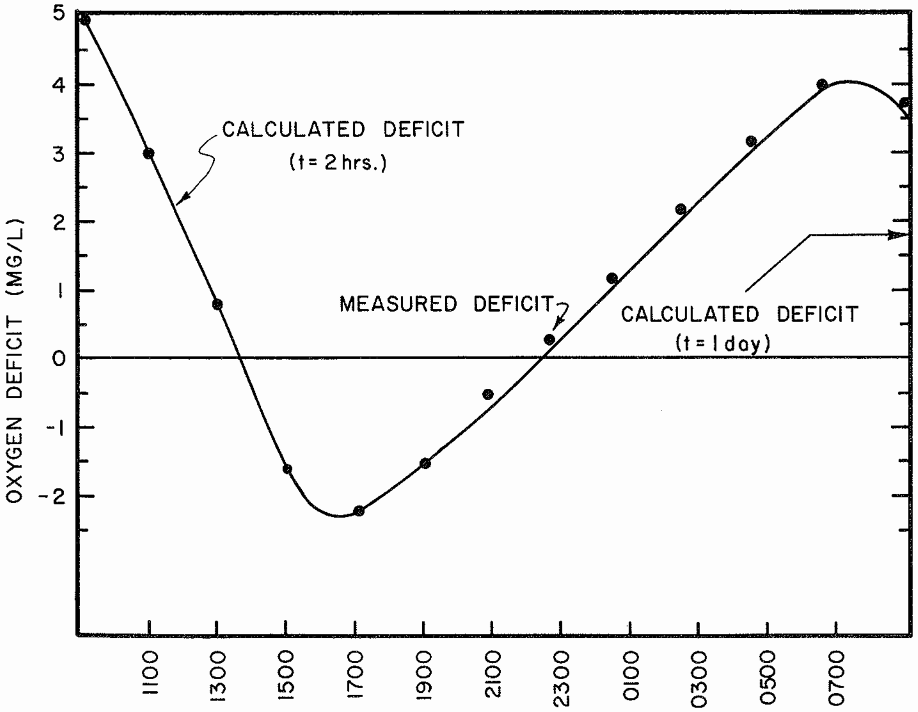


FIG. 6-10 CALCULATED AND MEASURED OXYGEN DEFICITS AT STATION W100 (0900 DEC 19 - 0900 DEC 20)

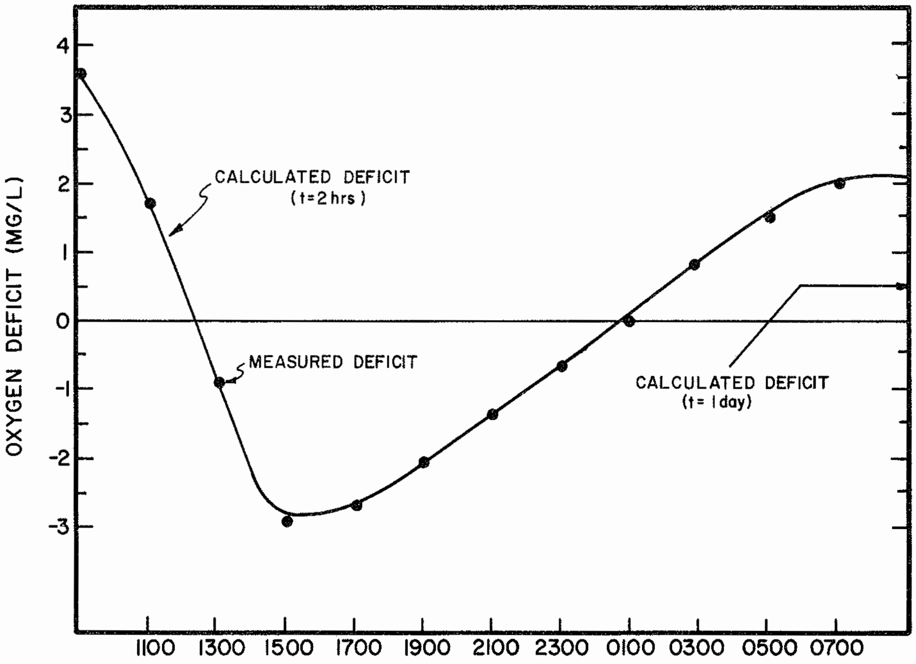


FIG. 6-11 CALCULATED AND MEASURED OXYGEN DEFICITS AT STATION W100 (0900 DEC 20-0900 DEC 21)

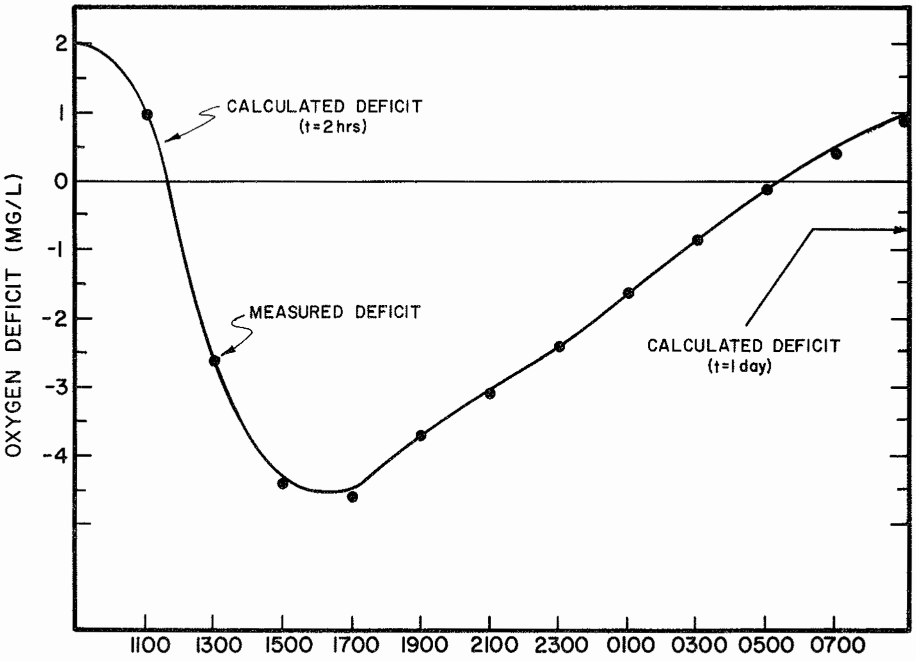


FIG. 6-12 CALCULATED AND MEASURED OXYGEN DEFICITS AT STATION W100 (0900 DEC. 21-0900 DEC 22)

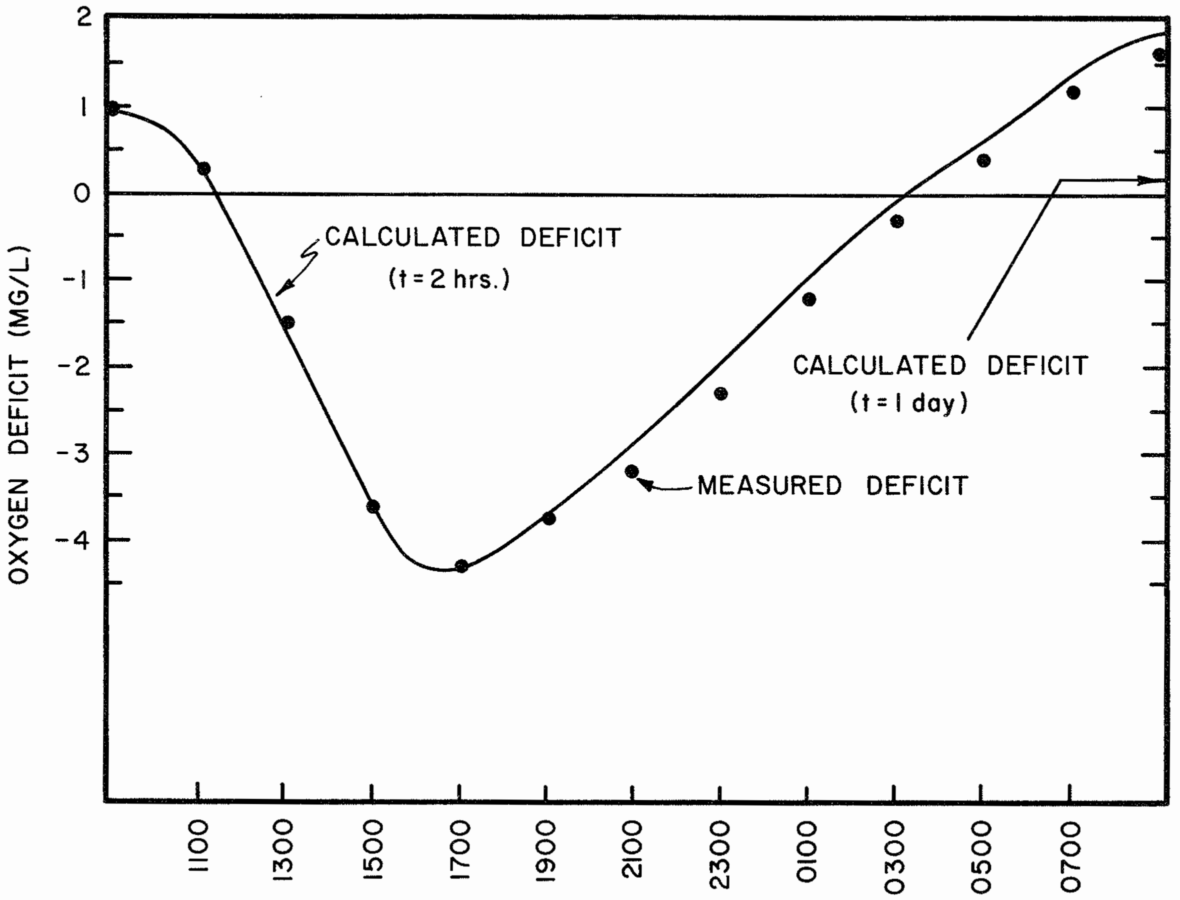


FIG. 6-13 CALCULATED AND MEASURED OXYGEN DEFICITS AT STATION W100 (0900 DEC 22 - 0900 DEC 23)

Table 6-8. Measured Oxygen Deficits vs. Predicted in West Channel

Dec.(1)	Station W 25(2)			Station W 100(2)			Station W 175(2)		
	Meas.	Pred.(3)	Pred.(4)	Meas.	Pred.(3)	Pred.(4)	Meas.	Pred.(3)	Pred.(4)
18	4.4			4.4			4.6		
19	5.5	5.3	3.9	5.0	5.0	3.9	5.0	4.8	3.6
20	3.6	4.0	2.2	3.6	3.5	1.8	3.0	3.3	1.8
21	1.9	1.8	0.7	2.0	2.1	0.5	1.9	1.7	0.6
22	1.3	1.4	-0.1	0.9	1.0	-0.7	1.5	1.6	0.0
23	1.4	1.5	0.0	1.6	1.8	0.2	1.8	1.8	0.3

(1) Time of measured and predicted values is 0900 hours

(2) Values are given in mg/l

(3) Prediction using iteration procedure with t = 2 hr

(4) Prediction using t = 1 day

All terms in equation (6-10) were independently determined with the exception of net photosynthetic production "a". Originally it was the intent of the author to determine net photosynthesis in the East Flume and use the values obtained in predicting deficit in the West Flume. This approach did not give satisfactory results. The photosynthetic organisms in the East Flume, while essentially equivalent in number to those in the West Flume, did not behave in the same manner as those in the West Flume. Net photosynthesis in the West Flume greatly exceeded that in the East Flume. Evidentally the imposed organic load in the West Flume stimulated net production. Table 6-9 illustrates the net daily production in East and West Flumes and Figures 6-14 through 6-16 indicate the hourly rate of net production in the Flumes. The West Flume had a much greater rate of oxygen production than did the East Flume during daylight hours; however during the hours of darkness respiration in both Flumes was essentially the same. Figures 6-14 through 6-16 therefore substantiate the assumption made earlier in determining k_1 and L_o from dissolved oxygen readings.

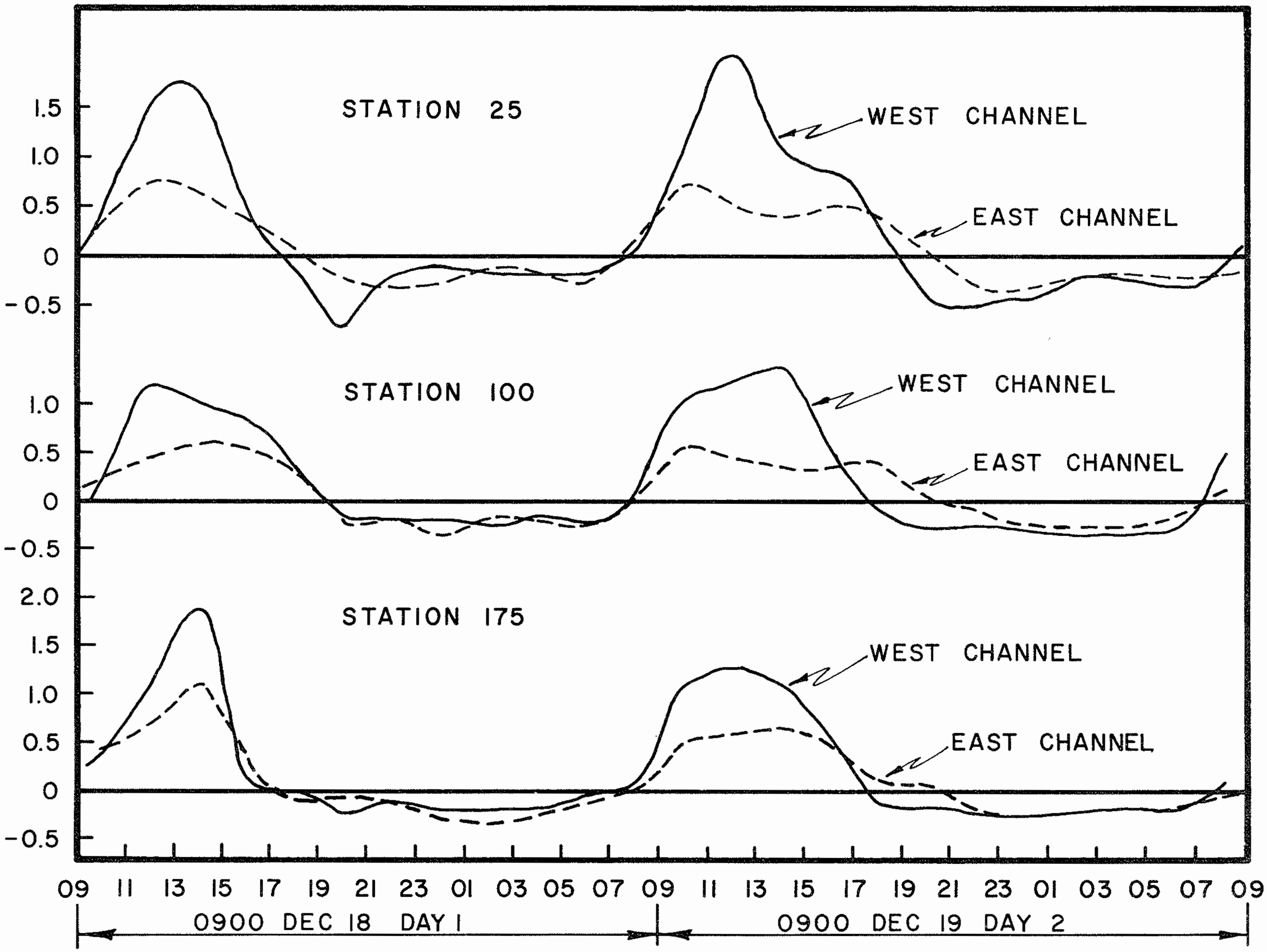


FIG. 6-14 HOURLY RATE OF NET PHOTOSYNTHETIC OXYGEN PROD.

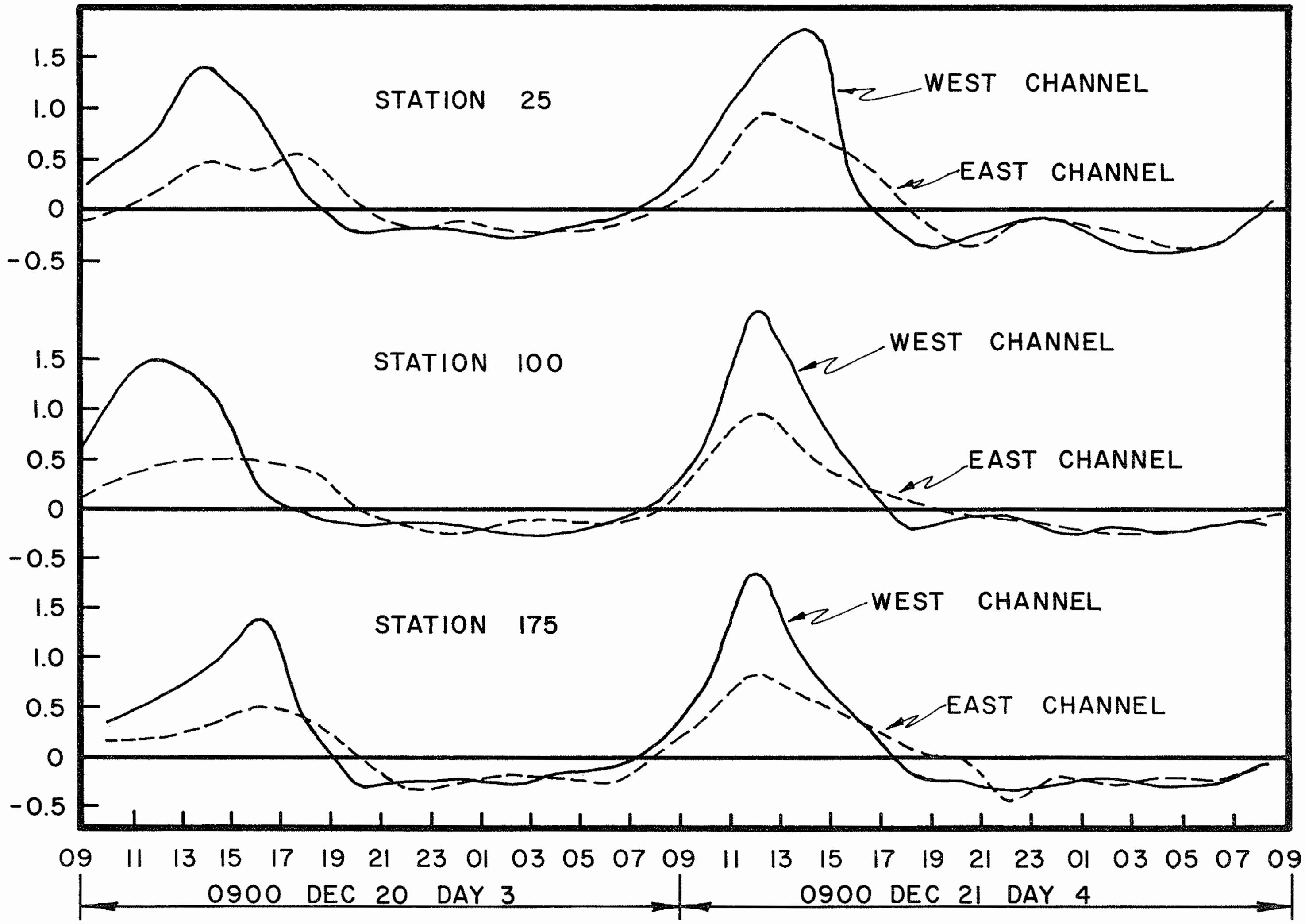


FIG. 6-15 HOURLY RATE OF NET PHOTOSYNTHETIC OXYGEN PROD.

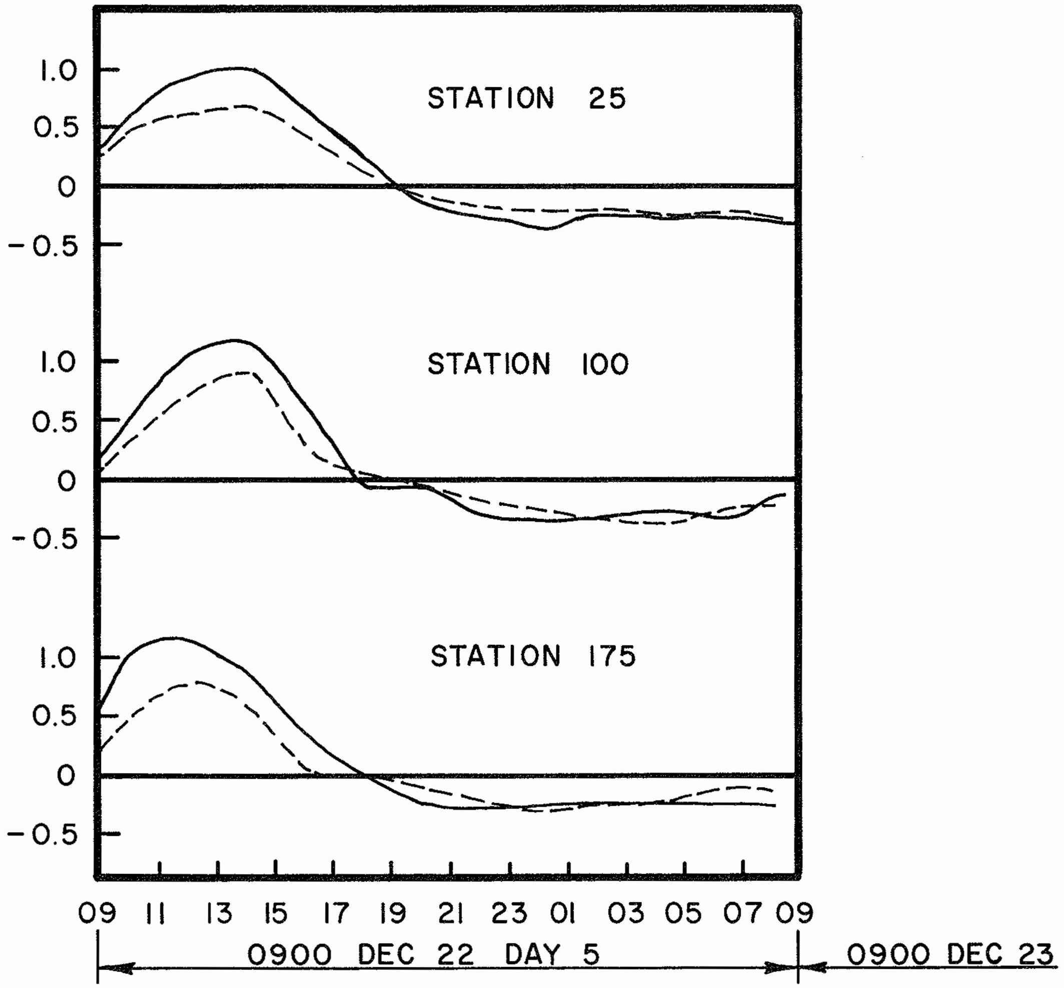


FIG. 6-16 HOURLY RATE OF NET PHOTOSYNTHETIC OXYGEN PRODUCTION

Table 6-9. Comparison of Daily Net Photosynthetic Oxygen Production in East and West Channels

Dec.	Station 25 East (mg/l)	Station 25 West (mg/l)	Station 100 East (mg/l)	Station 100 West (mg/l)	Station 175 East (mg/l)	Station 175 West (mg/l)
18-19*	1.26	4.80	1.30	4.79	1.74	5.38
19-20	1.87	6.31	2.85	6.50	2.59	6.45
20-21	1.81	5.81	1.94	6.01	1.32	5.37
21-22	1.47	4.79	1.83	5.60	1.73	4.57
22-23	1.40	3.50	1.18	2.94	0.65	3.17

*From 0900 hrs to 0900 hrs

Use of Sag Equations to Determine k_2

As previously indicated in Chapter V sag equations have been used to determine the atmospheric reaeration coefficients applicable to a stream or stretch of stream. By knowing a beginning deficit and measuring this deficit at some point in time downstream, k_2 can be determined if all other parameters of an equation are known. If photosynthesis is a contributing factor to reoxygenation and formulas such as (6-8), (6-9), or (6-10) are used with t = one or more days the calculated k_2 will be erroneous. It will be lower than the actual case. Camp (25) stated that his field studies determined that atmospheric reaeration was considerably lower than what should have been expected from literature. The studies however were conducted on the Merrimack River in Massachusetts. Photosynthetic activity was high and Camp determined k_2 values by backing into them, knowing the beginning and ending deficits and all parameters affecting oxygen. He used a trial and error method to solve for his k_2 values. It would seem that the conditions existant in the Merrimack system and this technique resulted in erroneous k_2 values.

Table 6-10 compares the k_2 values that would be obtained if sag equation (6-10) was used not as a means of predicting deficit but as a means of determining the atmospheric reaeration coefficient applicable to the system.

Table 6-10. Atmospheric Reaeration Coefficients Determined From Sag Equation Compared to Actual k_2

Date (Dec.)	k_2 (day^{-1})		
	W 25	W 100	W 175
18-19	0.05	0.00	0.06
19-20	0.02	0.04	0.02
20-21	0.04	-0.16	0.05
21-22	-0.83	-0.54	-0.45
22-23	-0.61	-0.88	-0.50

Actual k_2 = 0.3 day^{-1}

Determining "a" by Bottle Technique

As previously indicated, the photosynthetic production was determined by incremental observations of dissolved oxygen using a galvanic probe. However, BOD bottles were used in the first three days of the experiment in the East Flume. The reason for lowering the oxygen content in the East Flume at the start of the experiment was to facilitate the use of the bottles. After the third day oxygen build up was so high that the bottle technique was no longer applicable. Table 6-11 provides a comparison between oxygen production as obtained by incremental determination and production determined by use of the bottle technique. On the average bottles indicate only 53 percent of the production by photosynthesis. The exact reason for this is not known. The glass in the bottles may filter out some of the energy. Perhaps there were some photosynthetic organisms in the bottom sediment; however, some precautions had been taken to eliminate attached photosynthetic organisms. Before starting the experiment the sidewalls of the flume were scrubbed down to remove any algae growing on the walls. Also water at high velocity and low depth was run for a time through the flumes for the purpose of washing away any algae

Table 6-11. Net Photosynthetic Oxygen Production Determined by Bottle Technique Compared to Direct Measurement

Time and Date	Oxygen Production (mg/l)	Bottle Test (mg/l)	% Indicated Bottle
Station E 25:			
0900 Dec. 17 to 1730 Dec. 17	4.0	1.9	48
0900 Dec. 17 to 0900 Dec. 18	1.9	1.2	63
0900 Dec. 17 to 1800 Dec. 18	6.2	3.6	57
0900 Dec. 17 to 0740 Dec. 19	3.5	2.4	68
0900 Dec. 17 to 1800 Dec. 19	8.5	4.9	57
Station E 100:			
0900 Dec. 17 to 1730 Dec. 17	4.2	2.0	48
0900 Dec. 17 to 0900 Dec. 18	1.9	1.1	58
0900 Dec. 17 to 1800 Dec. 18	6.1	3.1	51
0900 Dec. 17 to 0740 Dec. 19	4.1	2.0	49
0900 Dec. 17 to 1800 Dec. 19	8.1	4.0	49
Station E 175:			
0900 Dec. 17 to 1730 Dec. 17	4.8	2.2	46
0900 Dec. 17 to 0900 Dec. 18	0.9	1.2	
0900 Dec. 17 to 1800 Dec. 18	5.7	2.9	51
0900 Dec. 17 to 0740 Dec. 19	3.5	1.6	46
0900 Dec. 17 to 1800 Dec. 19	8.3	4.3	52
		Average	53

growing on the surface. When the experiment started there was no algae on the walls of the flume and there were no obvious growths on the bottom.

From this experiment it would seem that even under stagnant conditions the bottle technique as a method of estimating oxygen production can result in serious errors.

CHAPTER VII

Discussion

One of the most important considerations in the ecological health of a stream is the amount of dissolved oxygen present. The bacterial growth stimulated by waste discharged into a stream results in the consumption of oxygen. When oxygen reaches the level of 5 mg/l or less fish life begins to be affected. Many species of fish cannot survive in less than 4 to 5 mg/l of dissolved oxygen, depending on the water temperature. If the pollutional load is great all of the dissolved oxygen is consumed and the stream goes anaerobic. Oxygen therefore is a controlling factor. For a stream to maintain fish life pollutional loads are allowable only in amounts that can be assimilated by the stream. The assimilative load is that load, the degradation of which, when superimposed on other elements contributing oxygen will not result in oxygen less than the predetermined quality standard of 4 to 5 mg/l.

In order to determine the magnitude of the assimilative load it is necessary first of all to quantify the rate of oxygenation by the only dependable source of oxygen available to the stream, the atmosphere. This in itself is a difficult task. Many investigators have attacked this problem. All are agreed that diffusion of atmospheric oxygen into a stream is dependent upon the turbulence existing in the stream. Some investigators equate it to surface renewal, the rate at which the surface film is replaced. Others rationally equate it to velocity and depth since turbulence is directly related to velocity and inversely related to depth. It would seem that there are as many formulas for prediction of the reaeration constant as there are investigators. These formulas give widely divergent results. They were developed as a result of "observations" of reaeration in specific streams and therefore may be applicable only to the streams studied.

"Observation" as used in the literature is a loose term. It means a calculated value derived from observed conditions in the stream. "Observed" connotates a degree of accuracy which may not be the case. If as in the case of Churchill's (6) studies of rivers in the Tennessee Valley, an investigator if fortunate enough to select reaches of streams which:

a. have uniform cross section and slope

b. are sufficiently long to have a measureable dissolved oxygen increase within the reach

c. have low dissolved oxygen at the point of entrance into the reach

d. have low BOD so that there will be no measureable demand during the time in the reach

e. have an absence of photosynthetic producers

f. have no benthal demand

then there is good reason to believe that the "observed" coefficient of reaeration (k_2) is valid. Churchill studied rivers downstream of impoundment dams, water from which was released to the rivers, after prolonged storage, with low D.O. and with a five day BOD usually less than 1 mg/l and with a low concentration of phytoplankton (insignificant in so far as oxygen production was concerned). In addition the bottoms of the streams were practically free of organic pollution. Churchill therefore was able to make an extensive study under conditions that normally could be achieved only in a laboratory. His was in effect a full scale model study.

If, however, a study of reaeration is made in a stream which contains BOD, photosynthetic producers and benthal demand then the "observed" k_2 is a calculated value derived by use of the Streeter-Phelps sag formula or modification of it. If determined values of k_2 are to be valid then the other parameters in the applicable equation must be valid. Herein lies a problem. The bottle techniques for determining the biological reaction rate constant k_1 and photosynthetic production in all likelihood will not give sufficiently precise results on which to make a k_2 determination. Therefore, the multiple correlation of k_2 values thusly obtained for the development of a predictive formula will result in a questionable formula. Another factor that may cause error in "observed" k_2 values is that the assumptions under which the formulas were developed are not obtained readily in a real stream. The degree of applicability of a sag formula and its use in calculating k_2 depends then on how closely real conditions approach the ideal assumptions.

In determining reaeration in the flume it was not the intent of the author to determine a predictive formula for atmospheric reaeration in streams. The purpose was to determine a calibration formula for the model river so that a predetermined k_2 for a given experiment could be achieved by an adjustment of velocity and depth or could be determined from velocity and depth. Since the cross section of flow along the flume is uniform, the bottom slope constant, the entrance D.O. low, and since potable water was used (no BOD and no photosynthetic producers) and since the bottom had no benthal demand, conditions were ideal for determining k_2 values and a predictive formula applicable to the flume.

As indicated previously the laboratory conditions achieved in the flume were very nearly achieved on the Tennessee Valley streams which Churchill studied. It is interesting to note that the flume predictive formula derived from velocities from 0.078 ft/sec to 0.455 ft/sec and from depths from 0.113 ft to 0.613 ft will yield k_2 values comparable to those calculated from Churchhill's formula for all combinations of velocities up to 7 ft/sec and depths up to 10 ft wherein k_2 values are 2 day^{-1} or less. This range should cover a large part of the streams in the U.S. In view of the above it would seem that the formula developed for predicting k_2 values in the flume is valid also for streams.

In the predictive formulas thus far developed the effects of wind are neglected. Since the rate at which diffusion of atmospheric oxygen is controlled by the resistance of the surface film and that increased reaeration results from disturbance of surface film (surface renewal), it would seem logical that the wind would play an important role in atmospheric reaeration, especially in a shallow sluggish system. It was found that a brisk wind increased aeration of water in a 7.5 ft diameter pan, 22 inches deep at a rate of 20 times that which would have been expected under no wind conditions. The effect of winds on stream reaeration is an area in which research should be conducted. In the flume studies wind was eliminated by covering the flume.

As indicated above, the determination of stream reoxygenation in which there are photosynthetic producers leads to error in k_2 determination because the black and white bottle technique does not give precise values for production. However, the error in calculating k_2 resulting from use of net daily production, as if photosynthesis was a constant rate per day, is even greater. In the flume studies, direct calculation of photosynthetic production and respiration were made without resorting to black and white bottles and errors were minimized by considering photosynthetic production to be a constant rate only over short periods of time (i.e. 2 hours).

Usually, in predicting oxygen deficits photosynthesis is omitted since production by this means is not a dependable source of oxygen in a stream, but nevertheless it is assumed that the presence of photosynthetic producers is beneficial to the oxygen state of the stream. This may not be a safe assumption. Two experiments were presented in which the net effect of phytoplankton activity was deoxygenation rather than reoxygenation. Photosynthesis during the hours of daylight produced supersaturation and a loss of oxygen to the atmosphere which when added to respiration during the hours of darkness resulted in a dissolved oxygen state lower than if there had been no photosynthetic producers in the first place. In fact the net effect of photosynthesis was equivalent in one of the experiments to a load of 50 mg/l BOD assuming a k_1 of 0.2 day^{-1}.

In the above, the difficulties involved in the determination of k_2 values have been discussed at length. The whole purpose of determining k_2 is to use this rate constant in an applicable sag formula of oxygen deficit. Also it was previously mentioned that the sag formula was developed based on certain assumptions (assumptions are listed in the introduction). According to Isaacs and Gaudy (14) the applicability of sag equations have not been experimentally proven for the conditions assumed in their development. In the flume the conditions assumed in the development of the sag equations existed. By controlled experiments each of the contributing factors to reoxygenation and deoxygenation were studied and then combined into an ecosystem. The ecosystem functioned in accordance with a sag formula. It is the belief of the author that the applicability of the sag equation has been experimentally proven for the conditions assumed in its development.

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