THE EFFECT OF WASTE WATER LAGOON EFFLUENT
UPON A RECEIVING STREAM

by

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THE EFFECT OF WASTE WATER LAGOON EFFLUENT UPON A RECEIVING STREAM

INTRODUCTION

Rapidly increasing population and industrialization has created a demand for more water of better quality and simultaneously produced larger volumes of wastes which pose an increasing threat to the purity of our water resources. Streams provide water for municipal water supplies, industrial use, agricultural use, fisheries, and recreation. Pollution of our streams must be prevented to protect the health and welfare of our population and to preserve this vital resource for all beneficial purposes. During the 19th and early 20th centuries, disposal of wastes to the nearest watercourse was common practice because of a lack of legal control and adequate knowledge of the consequences of pollution. Fortunately, there has been a great effort in recent years to reverse this policy by either prevention of the disposal of wastes into streams, or by requiring adequate treatment prior to discharge.

The construction, operation, and maintenance of a waste treatment plant is costly. Small communities and industries often find it difficult to finance conventional waste treatment processes. Oxidation lagoons are now being used for waste stabilization. They provide satisfactory biological treatment with a minimum of operating expense. The initial costs depend upon the value
of desirable land and the suitability of the soil.

The lagoon is normally 3 to 5 feet deep and may assume any geometrical shape. It is preferrably located so that it is exposed to the action of the prevailing winds and to the maximum available sunlight. Such a lagoon provides an excellent environment for the growth of algae. The treatment process in a lagoon can proceed without odor or nuisance under aerobic conditions. The required dissolved oxygen is supplied both by surface reaeration and by the photosynthetic process of the algae.

Lagoons were originally used in arid climates where evaporation was equal to or greater than the waste inflow, therefore an effluent did not result. Because of increasing popularity and the necessity of waste treatment by smaller communities and industries, lagoons are now being used in maritime regions where evaporation is insufficient to eliminate an effluent. The resulting effluent is normally discharged into a nearby stream or watercourse.

Object of this Thesis

The conditions resulting from the discharge of lagoon effluents into a receiving stream must be carefully considered. The creation of an environment favorable to algal growth can make a stream undesirable for recreational use and water supplies because of the resulting taste and odors. Water uses may require disinfection of lagoon
effluents prior to discharge. The death of algae cells resulting from disinfection will increase the amount of decomposable organic matter in the stream.

The object of this thesis is to investigate the conditions arising from the disposal of normal and disinfected lagoon effluents into a receiving stream.

DISCUSSION OF PROBLEM

The nature of the stream and the lagoon is of great importance. An examination of these systems and the factors affecting them is required.

A stream is a complex system with a state of dynamic balance existing within the biological community. A stable equilibrium cannot be expected because there are so many continually varying factors which affect the density of the existing populations (7, p. 200). The balance therefore is dynamic in that there are infinite combinations of circumstances for which the system will attain a temporary equilibrium. For example, when pollution is introduced into a stream, many changes take place. With the addition of organic material, bacterial populations and respiration rates will increase causing depletion of the oxygen in the stream. Anaerobic decomposition would result, with odors being produced. As oxygen is resupplied to the system, and nutrient concentrations decrease, aerobic conditions would develop. In each case,
a temporary balance between the biological population and the environment exists.

The principle of biological balance in a stream also applies to an oxidation lagoon and its effluent. The relative concentrations of organic material, biologically active components, and mixing currents are the primary differences that exist between the two systems.

Factors Affecting System Balance

The factors which affect a waterborne biological system are physical, chemical, and biological in nature. Temperature is one of the major physical factors. Microorganisms can grow and carry on their life activities at the optimum rate only within a rather limited temperature range (6, p. 58). Biochemical reactions in general follow the Van't Hoff rule of a doubling of reaction rate for a 10° C. increase in temperature over a restricted range (11, p. 153). The amount of oxygen that may be dissolved in water is primarily dependent upon temperature with saturation values decreasing as temperature increases. Biological activity of the organisms on the other hand increases with an increase in temperature. Therefore, within the range of the organisms, as temperature increases, oxygen demand is greater, but the available supply is less. This effect can be critical to the system balance.
Sunlight is a source of energy which has an important influence on the water biological scheme. Algae utilize light energy and carbon dioxide in the synthesis of their organic food requirements. The oxygen given off in this process is often a major source for other organisms. Mixing action in a lagoon can be provided by the thermal currents produced by light energy.

Chemical factors may be divided into three groups. They are nutrition, hydrogen ion concentration (pH), and toxic effects (10, p. 132). Organisms must have some source of energy to utilize nutrients. This energy is obtained by the oxidation of organic compounds which are either taken from the system or synthesized by the organism. Some of the oxidizing agents employed in this process are oxygen, nitrates, nitrites, sulfates, and carbonates. The organic compounds are oxidized to carbon dioxide and water, and the oxidizing agents are reduced if the system is aerobic. Complex nitrogen compounds will be oxidized to ammonia.

Macronutrients and micronutrients are the terms given to mineral nutrients and refer to the amount required by living cells. For both animals and plants, the major macronutrients are sodium, chlorine, potassium, calcium, phosphorus, and magnesium. The principal micronutrients are iron, copper, manganese, and zinc (8, p. 8). Vitamins, often called growth factors, are necessary
nutritional elements. They are required in very small amounts and cannot be manufactured by cells that require them (8, p. 8).

The Hydrogen Ion Concentration (pH) is an important factor influencing the biological population. Every organism has a definite pH tolerance range (10, p. 132). This range varies for different organisms.

The primary sources of toxic materials in a water biological system are industrial waste and agricultural pesticides. Studies of the toxic effects of some wastes on biological treatment processes have been made. More information on this subject is needed.

Every organism in a biological system has a specific function. Some of these functions are well defined and easily visible whereas others are not. One of the principles of microbiology is that for every naturally occurring organic compound there is some microorganism that will metabolize it (10, p. 132). Higher biological forms feed upon bacteria and other lower forms. The available food supply controls the population.

Living organisms are divided into two groups based upon their food requirements. These are heterotrophs and autotrophs. Heterotrophs are incapable of manufacturing their own food (7, p. 197). They obtain their energy from organic compounds and require oxygen in their metabolism. In this respect, they are considered to be animal
like. The classification is subdivided into primary and secondary groups. The primary heterotrophs feed on bacteria and small plants such as algae. Secondary heterotrophs feed on primary heterotrophs (10, p. 133).

Autotrophs are able to grow in a purely inorganic medium. They utilize carbon dioxide and ammonia or nitrate to synthesize their own food (8, p. 11). The photosynthetic autotrophs of primary interest are algae. They convert light energy into chemical energy in the process of photosynthesis. One of the by-products of their metabolism is oxygen.

Bacteria may be either heterotrophic or autotrophic. Figure 1 is a simplified expression of the basic concept of the life cycles in a water biological system such as an oxidation lagoon.

The effects of the disposal of a lagoon effluent upon the chemical and biological characteristics of a stream are important. The condition resulting from a disinfected effluent would be different from that of the regular effluent. For this reason, it is necessary to consider disinfection.

**Disinfection**

The microorganisms in human wastes can survive the oxidation lagoon treatment process. If a lagoon effluent is discharged upstream from a public water supply or recreational area, disinfection will be required. The
Figure 1. Basic food cycle of a lagoon.
purpose of disinfection is to destroy any bacteria that may be pathogenic or capable of transmitting disease. Some of the disinfectants which may be used are ammonia, sulfur dioxide, ozone, silver compounds, ultraviolet light, bromine, and chlorine. Chlorine can be easily applied, is economical, and is the principal disinfectant used. Discussion will be limited to the use of chlorine.

Chlorine is one of the most active elements. It will readily combine with or oxidize many organic and inorganic compounds. Residual chlorine is measured in a water system as free available chlorine and combined available chlorine. Free available chlorine exists in water as Cl₂, HOCI, and as the OCl⁻ ion. The chemical reactions are as follows (II, p. 249):

\[ \text{Cl}_2 + \text{H}_2\text{O} \rightleftharpoons \text{HOCI} + \text{H}^+ + \text{Cl}^- \]
\[ \text{HOCI} \rightleftharpoons \text{H}^+ + \text{OCl}^- \]

Below a pH of 5, chlorine will be present in the molecular form of Cl₂. Between 5 and 6, it exists almost entirely as HOCI. Above a pH of 6, OCl⁻ ions are present, becoming predominant above pH 7.5 (2, p. 205).

Combined available chlorine exists as ammonia compounds. Ammonia reacts with hypochlorous acid to form monochloramines, dichloramines, and trichloramines as follows (II, p. 249):

\[ \text{NH}_3 + \text{HOCI} \rightarrow \text{NH}_4\text{Cl} + \text{H}_2\text{O} \quad \text{monochloramine} \]
\[ \text{NH}_3 + 2\text{HOCI} \rightarrow \text{NH}_2\text{Cl}_2 + 2\text{H}_2\text{O} \quad \text{dichloramine} \]
Above a pH of 8.5 only monochloramine will exist. Between 8.5 and 4.5 both monochloramine and dichloramine will be present. At pH 4.5, dichloramine will predominate, and below 4.4, trichloramine will be produced (2, p. 215).

The cause of death as a result of chlorination is not known. It is assumed that chlorine will combine with protein substance in the cell wall of microorganisms, interfering with reproduction and growth, and eventually resulting in death of the organism. Another explanation is that chlorine inhibits a key enzymatic process of the cell and thus stops its metabolism (2, p. 209). Death of microorganisms subjected to chlorination is not instantaneous at normal chlorine levels.

Organisms are known to have varying resistances to the effects of chlorine. It has been well established that pathogenic organisms are less resistant than non pathogens (5, p.8). In one experiment, it was determined that a 100% kill of 21 strains of E. Typhi was effected by a 0.1 mg/l chlorine dose for 15 to 30 seconds. For E. Coli organisms, under the same test conditions, 9 strains required a 0.15 mg/l dose, 10 strains required 0.2 mg/l, and 9 strains required 0.25 mg/l (5, p.14). It is on the basis of such tests that the coliform bacteria is used as an indicator of pollution.

The effectiveness and speed of the bacterial kill is
dependent upon suspended solids concentration, pH, temperature, form of chlorine present, strength of dosage, and contact time. When suspended solids are present, complete kill requires time for chlorine to penetrate the solids. An increase in temperature and a decrease in pH will accelerate the chemical reactions. Free available chlorine will give faster results than combined available chlorine. Greater dosages will produce more rapid results. A longer contact time will insure a more effective kill. Under the most favorable conditions of no turbidity, a pH of 7.0, and a temperature of 20°C, 100% destruction of bacteria, with equal contact times, requires 25 times as much combined available chlorine as free available chlorine. Combined available chlorine will require a contact period 100 times that of free available chlorine to give the same kill with equal dosages (2, p. 219).

Chlorine is also used as an algicide. An indicated range of lethal dosages is 0.25 to 1.5 mg/l depending on the algae type (2, p. 112). A large number of the algae in a lagoon effluent would be killed under normal chlorination practices. Upon discharge into a stream, the dead cells would create an increased organic load subject to decomposition.

The normal practice in the chlorination of a waste is to add chlorine in quantities such that after a given
period of time a specified residual will remain. The normal requirement by state health agencies is a 0.5 mg/l residual after 30 minutes of contact. Under these circumstances, available chlorine will be discharged into the stream receiving the waste. The chlorine may have adverse effects upon the stream life as demonstrated by a reduction in the natural stream bacterial population. Chlorine in quantities of 0.05 to 0.2 mg/l is reported to be toxic to fish (7, p. 33).

METHOD OF STUDY

The effects of stream pollution will depend on the distance below the disposal point. Organic bottom deposits will be maximum near the outfall unless stream velocity is sufficient to carry solids away. Oxygen depletion by bacteria may be critical at points downstream as a result of bacterial growth characteristics. Algae growth, promoted by the abundance of the proper nutrients, will be most noticeable in slow moving waters below the outfall. The conditions downstream are quite varied both with respect to cause and effect.

The general objective of any study of stream pollution would be to arrive at methods of evaluating stream variables and conditions for the purpose of formulating behavior prediction equations. Solar energy, temperature, properties of the channel, composition of the waste,
bottom deposits, added dilution, and pollution—all of these are variables. Many can be measured for today, or evaluated for yesterday, but can not be easily predicted for tomorrow.

This thesis is limited to the evaluation of parameters normally used to describe pollution, as they apply to stream disposal of a lagoon effluent, with and without chlorination.

It would be desirable to follow an 'element' of water as it flows downstream and observe the changes that occur. This was done through the use of a circulating device which would provide conditions similar to those in a stream. The 'element' of water was isolated from the stream and analyzed for changes as time progressed.

Facilities

To obtain the necessary control for this study, a device as shown in Figure 2 was constructed. It consists of 4 water-tight channels with circulation of water provided by a constant speed paddle assembly. The velocity, mixing action, and surface disturbances induced by the paddles are assumed to be consistent. The model was located in a room where temperature was constant \( (14.5^{\circ} \pm 1^{\circ} \text{C.}) \) and ventilation adequate. Artificial lighting was provided by five, four tube fluorescent light fixtures suspended 15 inches above the average water surface in the
Channel Length = 7 feet
Channel Width = 5\frac{1}{2} inches
Channel Depth = 11\frac{1}{2} inches
Paddle Speed = 16 \text{ rpm}
Material used = Wood
Coating = Fibre Glass Resin
Color = Medium Grey

Figure 2. Mixing device
channels. The intensity of light at the water surface was approximately 550 foot candles. The lights were on for a continuous period of 12 hours each day. No attempt was made to reproduce natural stream bottom effects. The model was constructed of wood and coated with a fibre glass resin. A medium grey color was selected for the coating so as to nearly approximate the absorptive and reflective characteristics of natural stream banks.

Experimental Procedure

Two series of tests, designated Test Run No. 1 and Test Run No. 2, were completed. The river water for both was taken from the Willamette River at Corvallis, Oregon, on March 1 and March 20, 1962. The lagoon effluent used was obtained from the Experimental Waste Water Oxidation Lagoon which is operated by the Oregon State University Engineering Experiment Station in conjunction with the City of Corvallis, Oregon.

For Test Run No. 1, the ratio of lagoon effluent to river water was 1/5 for both the chlorinated and unchlorinated channels. A 1/10 dilution was used for Test Run No. 2. An equal water surface level was maintained in all channels throughout the tests. No water was added to the system during any tests. The samples withdrawn constituted less than 10% of the total volume within the channel. Water lost to evaporation was not measured.
The chlorinated effluent was dosed at 3 mg/l as total available chlorine, with a hypochlorite solution. A 15 minute contact period was allowed prior to mixing with the river water. The 15 minute residual for Test Run No. 1 was 1.5 mg/l; 0.5 mg/l as free available chlorine and 1.0 mg/l as combined available chlorine. For Test Run No. 2, the 15 minute residual was 0.5 mg/l as combined available chlorine.

A 15 minute mixing time was allowed following the addition of the lagoon effluents before the first sample was taken. This sample was designated as the zero time sample. Three channels, one containing river water only, one with river water plus unchlorinated effluent, and one with river water plus chlorinated effluent were sampled periodically for 7 days. The fourth channel was filled with river water and used as needed for other tests.

Tests Performed

The Biochemical Oxygen Demand (BOD) test is a controlled laboratory measure of the oxygen required for stabilization of a waste product under aerobic conditions. Oxygen is utilized by bacteria and other organisms for their respiration requirements in the initial phases of the test. Since the results are dependent upon bacterial action, the procedures and conditions of the test are critical and must be interpreted in the analysis of data.
To obtain uniformity such that information from various sources can be compared and utilized to its fullest value, the American Public Health Association and other interested groups have suggested standard procedures for the performance of the BOD test. These are given in detail in the book *Standard Methods for the Examination of Water and Wastewater*, hereafter referred to as *Standard Methods* (I, p. 318).

Analysis of the reactions that take place during the BOD test indicate two distinct demands for oxygen. Dead organic matter is transformed into initial products of decomposition by bacterial action. Oxygen is used for bacterial respiration in this process. Initial products are then oxidized to intermediate and final products with oxygen being used in the formation of end products. These reactions can be characterized by the following word equations:

(a) Organic Matter $\overset{\text{Bact}}{\text{O}_2} \rightarrow$ Initial products

(b) Initial Products $\overset{\text{O}_2}{\text{Bact}} \rightarrow$ Intermediate products

(c) Intermediate Products $\overset{\text{O}_2}{\text{Bact}} \rightarrow$ Final products

Specific equations for (b) and (c) above are as follows:

(d) $2\text{NH}_3 + 3\text{O}_2 \overset{\text{Bact}}{\rightarrow} 2\text{NO}_2^- + 2\text{H}^+ + 2\text{H}_2\text{O}$

(e) $2\text{NO}_2^- + 2\text{H}^+ + \text{O}_2 \overset{\text{Bact}}{\rightarrow} 2\text{NO}_3^- + 2\text{H}^+$ (II, p. 274).

The oxygen used for bacterial respiration in the BOD
reaction is termed First Stage BOD. This stage is mathematically characterized by the equation

\[ y = L_a (1 - e^{-Kt}) \]  

\[ (1) \]

in which \( L_a \) is the ultimate first stage BOD, \( y \) is the BOD measured at time \( t \), \( e \) is the natural log base, \( K \) is a rate constant (4, p. 521). In the second or nitrification stage, oxygen is being utilized for bacterial respiration and for the formation of nitrites and nitrates. Mathematical formulation of the nitrification stage is more difficult and is generally not done.

BOD information is normally reported as either a 5 day BOD or an ultimate first stage BOD. The 5 day value does not differentiate between first and second stage reactions. Its use stems from the general observation that the 5 day BOD of ordinary domestic sewage is approximately 2/3 of the estimated ultimate first stage BOD. The ultimate first stage BOD is calculated using equation 1.

There are several methods proposed for the calculation of the rate constant "K". Thomas (12, p. 123) has proposed a method which is a simple graphical approximation for the evaluation of the constants of the BOD curve. Moore, Thomas, and Snow (9, p. 1343) have suggested a method involving a few calculations and the use of a standard curve. This method is perhaps the most convenient to use.
The BOD tests for this study were performed according to the procedures in Standard Methods (I, p. 318) at an incubation temperature 20° C. One, three, five and seven day BOD values were determined for each sample. Available incubator space prevented duplication of samples, therefore values are based on single bottle determinations. The data obtained for each sample were plotted and appear in the appendix. One, two, and three day values were read from the curves and used to calculate \( K \) and \( L_a \) by the method suggested by Moore, Thomas, and Snow (9, p. 1343). Values of \( K \) and \( L_a \) are plotted as functions of sample time in figures 3 and 4.

Compounds of nitrogen are important for plant and animal growth. They will exist in the organic state as proteins or in the inorganic state as ammonia, nitrites, and nitrates. Nitrogen, as it exists in wastes, will normally be in transition from the organic to inorganic states. The changes which take place can be characterized by the following relationships (II, p. 291):

\[
\text{Protein (Organic N) + Bact.} \rightarrow \text{NH}_3 \\
\text{NH}_3 + 3\text{O}_2 \xrightarrow{\text{Bact.}} \text{NO}_2^- + \text{H} + \text{H}_2\text{O} \\
2\text{NO}_2^- + \text{O}_2 \xrightarrow{\text{Bact.}} 2\text{NO}_3^-
\]

Nitrogen is returned to the organic state by plants as follows (II, p. 290):
Figure 3. $L_a$ and $K$ versus sample time for test run no. 1.
Figure 4. $L_a$ and $K$ versus sample time for test run no. 2.
NO$_3^-$ + CO$_2$ + Green Plants + Sunlight $\rightarrow$ Protein.

The relationships between nitrogen compounds present can be an indicator of pollution. High nitrate concentrations generally indicate a stable condition. High nitrite and ammonia concentrations are often accepted as an indicator of recent pollution and a highly unstable condition.

The nitrogen tests performed on the samples taken for analysis in this project were ammonia, nitrogen, nitrite nitrogen, and nitrate nitrogen. Colorimetric determination procedures were used with the aid of a spectrophotometer. Samples were filtered to remove turbidity. The first 50 milliliters of filtrate were discarded. A reagent blank was used in all determinations, with correction for sample color. Nitrogen determination methods were as follows: Ammonia by the Direct Nesslerization Method (I, p. 295), nitrite by the Diazotization Method (I, p. 303), and nitrate by the Tenative Brucine Method (I, p. 178). Results of the ammonia and nitrite nitrogen tests are shown in figures 5 and 6. Nitrate concentrations were zero in all tests.

Phosphorus determinations are essential in assessing the biological productivity potential of surface waters (II, p. 330). Algal blooms are attributed to an abundance of nitrogen and phosphorus. Phosphates and polyphosphates are the only inorganic phosphorus forms of importance.
Figure 5. NH$_3$-N and NO$_2$-N versus sample time for test run no. 1.
Figure 6. NH$_3$-N and NO$_2$-N versus sample time for test run no. 2.
Organically bound phosphates are generally of minor consideration (II, p. 325). Domestic wastes are normally rich in phosphates, especially since the advent of synthetic detergents which are compounds of phosphorous.

Colorimetric methods of analysis were used for the determination of phosphates in this study. Samples were filtered prior to determinations. The first 50 milliliters of filtrate were discarded. A reagent blank was used, and data were corrected for sample color. The Stannous Chloride Method for determination of orthophosphate (I, p. 202) and total phosphate (I, p. 204) was used. Orthophosphate concentrations are plotted as a function of sample time in figures 7 and 8. Polyphosphate concentrations equal to the total phosphate minus the orthophosphate, are shown in table 2 in the appendix.

Algae concentrations were determined by microscopic cell counts at 100 diameters magnification using a counting cell 1 mm. in depth. Counts were recorded as cells per cubic millimeter. The only cells counted were those typical of the lagoon effluent. The dominant species were Chlorella and Scenedesmus. Concentrations are shown in figures 7 and 8. The concentration in the river water was essentially zero.

Tests for the coliform organism were made using the membrane filter technique as given in Standard Methods (I, p. 508). A 47 mm type HA filter, grid marked, with
Figure 7. PO₄ and algae concentration versus sample time for test run no. 1.
Figure 8. $PO_4$ and algae concentration versus sample time for test run no. 2.
0.45 micron pore openings was utilized together with M-Endo Broth M. F. 0749-01 as produced by Difco Laboratories. Metallic sheen colonies were counted and recorded as colonies per milliliter, with values rounded to the nearest significant digit. Counts less than 1/ml were recorded as zero, whereas a count of 11/ml would be recorded as 10/ml. Results are shown in table 2 in the appendix.

Chlorine residuals were determined within 10 minutes after samples were taken using an amperometric titrator as specified in Standard Methods (1, p. 94). Results appear in table 2.

Temperature was measured in the mixing device when samples were taken. The temperature remained between 13.5 and 15.5°C at all times.

The hydrogen ion concentration (pH) was measured within 20 minutes after samples were taken using a glass electrode pH meter. The pH in all channels remained between 7.5 and 7.8 for both test runs.

The Dissolved Oxygen, as measured by the Winkler Method (Azide Modification) (1, p. 309), was near saturation in all samples taken during the test. No significant deficit or surplus of oxygen existed. The oxygen present at any time is equal to the quantity supplied by algae and surface reaeration minus that utilized for biological respiration. Excess oxygen may be lost through
the surface to the atmosphere. No attempt was made to measure this quantity since the required equipment was not available.

Stream reaeration studies indicate that when the oxygen demand is small, the oxygen transfer may be described by the equation;

\[ \frac{\Delta D}{\Delta t} = -K_2 D \]

where \( D \) is the saturation deficit at time \( T \) and \( K_2 \) is a reaeration rate constant. Since \( \Delta D = -\Delta DO \), the equation becomes

\[ \frac{\Delta DO}{\Delta t} = K_2 D \]

where \( DO \) is the dissolved oxygen as measured. The following method was used to determine the possible rate of oxygen transfer from the atmosphere to the water in the circulating device.

The test was carried out during a dark cycle such that algal production of oxygen was zero. The oxygen concentration in the extra channel containing river water was depressed by the addition of Sodium Sulfite. The change in dissolved oxygen and the oxygen usage were then measured as a function of time. The oxygen supplied to the system during the time increment was equal to the measured increase in dissolved oxygen plus the oxygen utilized. The values obtained are as follows:

At \( T = 0 \), \( DO = 0.7 \text{ mg/l} \)
At \( T = 5.23 \) hrs., \( DO = 1.9 \) mg/l and \( BOD = 0.1 \) mg/l

\( DO \) at Saturation (14.5° C.) = 10.3 mg/l

\( O_2 \) supplied = 1.9 - 0.7 + 0.1 = 1.3 mg/l

Average \( D = 10.3 - (1.9 + 0.7)/2 = 9.0 \) mg/l

\( K_2 = 1.3/(5.25)(9.0) = 0.0276/\text{hr.} = 0.066/\text{day} \)

The value of the rate constant as determined by this method is 0.66/day.

**DISCUSSION OF RESULTS**

Unstable conditions were encountered during the initial period of both test series, as indicated by the scatter of data points in figures 3 and 4. This may be attributed to environmental changes as reflected by the removal of the river water and lagoon effluent from their natural habitats, increasing their temperatures, and changing from natural to artificial light. Coliform bacteria were present in the lagoon effluent and river water in both test series (see Table 2). Chlorination produced a complete kill of these organisms in both the lagoon effluent and the river water. Coliform present in the unchlorinated channels disappeared gradually.

The chlorine residual in the lagoon effluent prior to mixing with the river water was higher than desired in Test Run No. 1. The effect of this residual can be observed in the relationships of figure 5. Ammonia and nitrite nitrogen concentrations were less in the
chlorinated channel. A greater concentration would be expected as a result of reduced algal demand for these nutrients. The excess chlorine apparently retarded the nitrifying bacteria. The ammonia and nitrite concentrations in Test Run No. 2 were as expected. The chlorine dose was less, and nitrogen compounds were least in the unchlorinated channel where algal use was greater.

Algal concentrations were very low in the river water as a result of limited nitrogen and phosphate concentrations. Addition of lagoon effluent provided sufficient nutrients to support algal growth. This was indicated by significant concentration increases in the unchlorinated channel.

Several factors essential for the interpretation of BOD results, including the effects of nitrification, could not be measured. The BOD versus incubation time curves appearing in the appendix were plotted on the assumption that nitrification existed. All calculations dependent upon BOD data were made using the values from the first three days of the incubation period.

Studies by others (3, p. 177) (13, p. 157) indicate that the presence of algae has a definite effect upon the measured biochemical oxygen demand. An increase in the concentration of either live or dead algal cells will cause an apparent increase in BOD (3, p. 179). Test results show that on an ultimate demand basis, with equal
algae concentrations, the oxygen consumed in algal respiration under dark incubation is no greater than that required for the aerobic oxidation of dead algal cells (3, p. 178). Further tests indicate that although the apparent ultimate BOD of live and dead cells is nearly the same, the reaction velocity constant "K" was observed to vary, with no consistent pattern developed. This was attributed to the possible changes in the organic material induced by the method employed to kill the algae (13, p. 162).

To aid in the evaluation of the biochemical oxygen demand data, the general equation

\[ KL = \frac{dL}{dT} \]

was evaluated for the condition \( L = L_a \) where \( L_a \) is equal to the ultimate BOD of the sample, \( L \) is the BOD remaining at time \( T \), and \( K \) is the reaction velocity constant. When \( K \) and \( L_a \) values are given, the equation reduces to the expression

\[ KL_a = \Delta L / \Delta T \]

where \( \Delta L / \Delta T \) is the slope of the BOD versus incubation time curve at the point where \( L = L_a \). By definition, this condition occurs when the incubation time \( T = 0 \). Since the BOD satisfied in time \( T \) is directly proportional to the oxygen used in the same period of time, the value of \( \Delta L / \Delta T \) can be called an oxygen use rate and designated "B"
<table>
<thead>
<tr>
<th>Test Run No. 1</th>
<th>River</th>
<th>River + Eff.</th>
<th>River + Cl₂ Eff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>K L B</td>
<td>K L B</td>
<td>K L B</td>
</tr>
<tr>
<td>0</td>
<td>0.22 6.2 1.36</td>
<td>0.14</td>
<td>9.0 1.26</td>
</tr>
<tr>
<td>1</td>
<td>0.20 5.2 1.04</td>
<td>0.19</td>
<td>6.2 1.18</td>
</tr>
<tr>
<td>2</td>
<td>0.17 4.3 0.73</td>
<td>0.24</td>
<td>4.7 1.13</td>
</tr>
<tr>
<td>3</td>
<td>0.16 4.3 0.69</td>
<td>0.29</td>
<td>5.5 1.6</td>
</tr>
<tr>
<td>4</td>
<td>0.17 4.5 0.76</td>
<td>0.25</td>
<td>7.5 1.88</td>
</tr>
<tr>
<td>5</td>
<td>0.18 4.7 0.85</td>
<td>0.18</td>
<td>10.0 1.80</td>
</tr>
<tr>
<td>6</td>
<td>0.20 5.0 1.0</td>
<td>0.10</td>
<td>13.0 1.30</td>
</tr>
<tr>
<td>7</td>
<td>0.23 5.3 1.22</td>
<td>0.05</td>
<td>16.0 0.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test Run No. 2</th>
<th>River</th>
<th>River + Eff.</th>
<th>River + Cl₂ Eff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>K L B</td>
<td>K L B</td>
<td>K L B</td>
</tr>
<tr>
<td>0</td>
<td>0.25 1.2 0.3</td>
<td>0.47</td>
<td>3.0 1.41</td>
</tr>
<tr>
<td>1</td>
<td>0.19 2.0 0.38</td>
<td>0.39</td>
<td>4.2 1.64</td>
</tr>
<tr>
<td>2</td>
<td>0.15 2.5 0.375</td>
<td>0.28</td>
<td>6.0 1.68</td>
</tr>
<tr>
<td>3</td>
<td>0.15 2.5 0.35</td>
<td>0.12</td>
<td>7.0 0.84</td>
</tr>
<tr>
<td>4</td>
<td>0.13 2.7 0.35</td>
<td>0.07</td>
<td>7.6 0.53</td>
</tr>
<tr>
<td>5</td>
<td>0.12 2.7 0.33</td>
<td>0.07</td>
<td>7.7 0.54</td>
</tr>
<tr>
<td>6</td>
<td>0.09 2.6 0.23</td>
<td>0.11</td>
<td>7.5 0.83</td>
</tr>
<tr>
<td>7</td>
<td>0.03 2.5 0.08</td>
<td>0.14</td>
<td>6.2 0.87</td>
</tr>
</tbody>
</table>
for convenience. The dimensions of \( B \) are mg/l/day when \( K \) is on a per day basis. The values of \( K \) and \( L_a \) used in calculating \( B \) were obtained from the trend curves in figures 3 and 4. Values of \( B \) appear in Table I.

The basic relationship between the parameters \( K \), \( L_a \), and \( B \) as they apply to the specific test data are important. The values of \( K \) and \( L_a \) will uniquely define the BOD versus incubation time curve. The value of \( B \) indicates the rate of oxygen use in the sample at the time it was taken, as determined by the BOD test. It does not directly indicate an actual stream condition, but can be used to interpret oxygen relationships in the stream providing values are available for successive days.

Algae present in a BOD sample subjected to a dark incubation test will produce a respirational oxygen demand. If it is assumed that for the duration of the test, the respiration rate of the cells present remains constant, the indicated BOD due to algae alone could be shown as a BOD curve with a constant slope. If this curve were superimposed upon a standard BOD curve, the observed effect would be a decrease in \( K \) and an increase in BOD such that no ultimate value would be reached. However, the methods used to calculate the ultimate BOD would establish a value for \( L_a \). Therefore, it could be said that the relative effect of the presence of algae in a sample would be to increase the apparent value of \( L_a \).
and decrease K. The corresponding value of B would increase. These considerations were used in the evaluation of the BOD data.

An equilibrium condition in the river water used in both tests is indicated by the consistency in the BOD measured in successive samples. The lack of BOD depletion, and the relatively constant values for K and B indicates a balance between growth and death in the system.

The changes which took place in the channels containing unchlorinated effluent differed in magnitude in the two test runs, but followed similar trends. The results of Test Run No. 1 show a decrease in $L_a$ and an increase in K during the first 2 days. The BOD is apparently being satisfied at an increasing rate. Algal respiration effects on the measured values are probably low but significant. After the second day, $L_a$ increases and K decreases. This indicates that the percentage of the oxygen demand exerted by algal respiration is rapidly increasing.

Significant algal respiration demands would normally not be exerted in a stream or in the test model. Instead, an excess of oxygen would be produced. Therefore, the BOD test is an indication of the conditions existing in a stream during total darkness and cannot be applied to daylight conditions.

In Test Run No. 2, the unchlorinated samples displayed
an initial increase in $L_a$ and a decrease in $K$ for the first 4 days. This may be attributed to increased algal respiration resulting from measured algal growth. Following the 4th day, $K$ increases, and $L_a$ decreases. Although the cell count indicates an increase in the algae population, limited nutrients, as indicated by the near zero concentrations of phosphate and nitrite, would result in a decreased respirational rate and eventual death. This decreased respirational rate by the algae would produce the results indicated.

The trends experienced in the chlorinated channels were similar. The BOD results for the first few days in Test Run No. 1 were inhibited by the high chlorine dose. After the second day, the residual chlorine in the channel was dissipated, and biological activity was increasing. The high dosage of chlorine may have removed some of the potential BOD by direct oxidation and at the same time added decomposable organic matter as dead algae cells. After the second day, $L_a$ decreased and the $K$ increased. This would indicate that as time progressed, the biological breakdown of organic material becomes easier and a BOD reduction resulted.

The chlorinated results in Test Run No. 2 indicate an increase in $L_a$ and a decrease in $K$ during the first 3 days. The BOD increase can be related to the increase in organic matter being made available for aerobic
decomposition through the death of algae. Although the chlorine dosage was sufficient to affect the initial \( K \) value, the inhibiting effect upon the subsequent reactions was not as great as in Test Run No. 1. After the third day, \( L_a \) decreased and \( K \) increased, indicating that the added organic matter is more readily degradable as time progresses and the remaining BOD is being satisfied more rapidly.

The oxygen use rates for the chlorinated and unchlorinated samples within a test run are nearly the same (see Table I). This indicates that under dark conditions, similar to the BOD test, oxygen consumption will be nearly equal for chlorinated and unchlorinated samples. The value of \( B \) does not account for oxygen production by algae, therefore is not indicative of daylight conditions.
CONCLUSIONS

1. Coliform bacteria survive the lagoon treatment process, therefore disinfection prior to discharge into a stream may be required.

2. The nutrients and "seed" provided by a 1/10 dilution of unchlorinated effluent were sufficient to cause algal growth in the river water used.

3. Algal growth will result in an increase in the apparent BOD as measured by the standard dark incubation method, therefore this test will not indicate the true conditions in a stream high in green algae concentrations.

4. Chlorination increased the decomposable organic matter in the model, as measured by the BOD test, with a maximum value occurring after a 2 to 3 day lag.

5. Chlorination of the lagoon effluent resulted in a decrease in algae concentration.

6. The nutrients added to a stream with a chlorinated effluent are available for subsequent algal growth.

7. The differences in the oxygen use rates (B) of the chlorinated and unchlorinated samples are small, as measured by the dark incubation BOD test.


APPENDIX
<table>
<thead>
<tr>
<th>Test</th>
<th>TIME</th>
<th>RIVER plus</th>
<th>RIVER plus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>days</td>
<td>EFF.</td>
<td>Cl(_2) EFF.</td>
</tr>
<tr>
<td>Test Run 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COLIFORM TEST Colonies/ml</td>
<td></td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Lagoon Effluent Count = 500/ml</td>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Test Run 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COLIFORM TEST Colonies/ml</td>
<td></td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>Lagoon Effluent Count = 700/ml</td>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Test Run 1</td>
<td></td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Cl(_2) RESIDUAL Effluent Residual</td>
<td>1</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>1.5 mg/l at 15 min.</td>
<td>2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total Available Cl(_2)</td>
<td>7</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Test Run 2</td>
<td></td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>Cl(_2) RESIDUAL Effluent Residual</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0.5 mg/l at 15 min.</td>
<td>7</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Test Run 1</td>
<td></td>
<td>0.04</td>
<td>3.21</td>
</tr>
<tr>
<td>POLYPHOSPHATE CONCENTRATION, mg/l</td>
<td>5.2</td>
<td>0</td>
<td>2.46</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0</td>
<td>2.13</td>
</tr>
<tr>
<td>Test Run 2</td>
<td></td>
<td>0.04</td>
<td>4.01</td>
</tr>
<tr>
<td>POLYPHOSPHATE CONCENTRATION, mg/l</td>
<td>4.01</td>
<td>3.2</td>
<td>3.04</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.01</td>
<td>3.14</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.02</td>
<td>0.4</td>
</tr>
</tbody>
</table>
BOD vs INCUBATION TIME
Test Run No. 1
8:00 A.M. March 1, 1962
O Lagoon Effluent Only

Figure 9.
<table>
<thead>
<tr>
<th>Test Run No.</th>
<th>0.00 Day</th>
<th>8:00 A.M., March 1, 1962</th>
</tr>
</thead>
<tbody>
<tr>
<td>River Water Only</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>River Water + Effluent</td>
<td>Δ</td>
<td></td>
</tr>
<tr>
<td>River Water + Cl₂ Effluent</td>
<td>□</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 10.**

BOD vs INCUBATION TIME

<table>
<thead>
<tr>
<th>Time, days</th>
<th>BOD, mg/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

Figure 10.
BOD vs INCUBATION TIME
Test Run No. 1  1,00 Day
8:00 A.M.  March 2, 1962
- River Water Only
- River Water + Effluent
- River Water + Cl₂ Effluent

Figure 11.
BOD vs INCUBATION TIME
Test Run No. 1 2.00 Day
8:00 A.M. March 3, 1962
○ River Water Only
△ River Water + Effluent
□ River Water + Cl₂ Effluent

Figure 12.
BOD vs INCUBATION TIME

Test Run No. 1  3.25 Day
2:00 P.M.  March 4, 1962

○ River Water Only
△ River Water + Effluent
□ River Water + Cl₂ Effluent

Figure 13.
BOD vs INCUBATION TIME

Test Run No. 1 5.21 Day
1:00 P.M.  March 6, 1962

- River Water Only
- River Water + Effluent
- River Water + Cl₂ Effluent

Figure 14.
BOD vs INCUBATION TIME

Test Run No. 1
7.00 Day
8:00 A.M., March 8, 1962

- River Water Only
- River Water + Effluent
- River Water + Cl₂ Effluent

Figure 15.
BOD vs INCUBATION TIME
Test Run No. 2
2:00 P.M., March 20, 1962
○ Lagoon Effluent Only

Figure 16.
BOD vs INCUBATION TIME

Test Run No. 2 0.00 Day
2:00 P.M. March 20, 1962
- River Water Only
- River Water + Effluent
- River Water + Cl₂ Effluent

Figure 17.
BOD vs INCUBATION TIME

Test Run No. 2 1.00 Day
2:00 P.M. March 21, 1962

○ River Water Only
△ River Water + Effluent
□ River Water + Cl₂ Effluent

Figure 18.
BOD vs INCUBATION TIME
Test Run No. 2  2.0 Day
2:00 P.M.  March 22, 1962
○ River Water Only
△ River Water + Effluent
□ River Water + Cl₂ Effluent

Figure 19.
BOD vs INCUBATION TIME
Test Run No. 2 3.0 Day
2:00 P.M. March 23, 1962
○ River Water Only
△ River Water + Effluent
□ River Water + Cl₂ Effluent

Figure 20.