THE EUTROPHIC POTENTIAL OF WAHIAWA RESERVOIR SEDIMENTS

by

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ABSTRACT

In recent times the increased influx of nutrients and organic matter as a result of man's activities into some waterways has resulted in the accelerated eutrophication of these waters. This has been found to be the case in Wahiawa Reservoir. Secondarily-treated sewage effluent discharges into the reservoir have been implicated as the primary cause of the eutrophic conditions present in the reservoir.

Studies have been undertaken and management alternatives are being considered to improve the trophic status of the reservoir. The nutrient mass balance has been determined and the source of the major portion of the nutrient influx to be from the Wahiawa Sewage Treatment Plant (STP). Corrective measures will probably be directed toward further treatment or diversion of this source.

The relative importance of in situ nutrient sources, such as N fixation and the sediment, have not, however, been determined. The eutrophication potential of the sediment and its relative importance and impact on the selection of a management alternative was the objective of this study. To ascertain this effect, sediment-water contact studies were carried out.

Sediment was incubated with four different types of water simulating aerobic and anaerobic conditions in the hypolimnion of the Wahiawa Reservoir. Samples were withdrawn periodically and analyzed for nutrients, chemical oxygen demand (COD), and other constituents. After parameters reached a steadystate, the algal growth potential (AGP) of the waters was determined.

Under aerobic conditions, the sediment tended to have an oligotrophic effect on the water. Phosphorus was adsorbed by the sediment, N release from the sediment was inhibited by the development of a surface-oxidized layer, and the COD of the water was decreased. This effect was verified by the poor AGP of the water, which was P deficient.

The sediment was found to be capable of deoxygenating dissolved 0₂saturated water. Substances causing a COD were released from the sediment under anaerobic conditions and the measured COD increase was about 10 mg/l, exceeding the increase resulting from the STP effluent and other sources. The COD levels maintained verified the capability of sediments to deoxygenate saturated waters.

Under anaerobic conditions, considerable N release from the sediment occurred. The increase alone far exceeded critical levels and was attributed to the release of NH₃ (5.7 to 8.2 mg/l NH₃-N) from sediments. The level of $PO_{\overline{\overline{\overline{u}}}}$ in most systems far exceeded critical limits but particulate $PO_{\overline{\overline{\overline{u}}}}$ was generally unavailable for algal growth according to test results. Results of dissolved $PO_{\overline{\overline{\overline{u}}}}$ from the sediment occurred only in low-turbidity waters under reducing conditions. The concentration of dissolved $PO_{\overline{\overline{\overline{u}}}}$ exceeded by 3 to 4 times the critical levels established in the reservoir. The high AGP in some reactor waters was verification of the eutrophication potential of the sediment. However, considering the dilution capacity of the reservoir, the concentration of P, but no N, maintained by release from the sediment would be rendered insignificant during periods of high influx and mixing.

The loading rates for sediment N and P under anaerobic conditions were of significance when compared to established guidelines. However, the sediment was of minor importance relative to the nutrient loading from other

sources to the reservoir. Even with the removal of a majority of the nutrient inputs by diversion or further treatment of the Wahiawa SIP effluent, sediment still accounted for only 18% of the N and less than 1% of the P loading to the reservoir.

Sediments were found to be able to cause or maintain eutrophic conditions in the test reactors under anaerobic conditions. However, the nutrient contribution was of minor importance relative to other sources. Corrective measures with respect to nutrients released from the sediment are not required, but stabilization of the O_2 demand from substances released from the sediment may be required to improve dissolved O_2 levels in the deeper portions of the reservoir.

A nutrient model of the reservoir shows that diversion of the Wahiawa STP effluent will result in a 65% reduction of N and a 46% reduction of P in the epilimnion of the reservoir. New steady-state conditions were expected to be attained within 30 days, while new steady-state conditions for the hypolimnion and sediments may require about two years.

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INTRODUCTION

The Wahiawa Reservoir, which is also known as Lake Wilson, is located in the Schofield plateau in central Oahu, Hawaii and encircles the town of Wahiawa (Fig. 1). The reservoir was constructed in 1906 by the Waialua Sugar Company by damming the confluence of the North and South Forks of the Kaukonahua Stream. The resulting 121.41-ha (300-acre), 9.4265 x 10^{6} -cm³ (2.5bil gal) capacity reservoir has since been increased to 11.355 x 10^{6} -cm³ (3bil gal) capacity by the installation of a temporary rubber dam over the spillway. The maximum depth of the reservoir at the confluence is about 27 m (98.5 ft) and the average depth is about 8 m (26.2 ft).

The impoundment was originally used to provide irrigation waters for the cane fields of the Waialua Sugar Company. Two major uses have since been added. Treated effluent from the Wahiawa Sewage Treatment Plant (STP) has been discharged since 1928 into the reservoir. Currently, secondarily treated effluents from the Wahiawa and Whitmore Village STPs are being discharged respectively into the South and North Forks. The third major use was added with the stocking of game fish in the reservoir as a site for a sport fishery (Schmitt 1973) in the 1950s.

Investigations have indicated that the reservoir is in a euthrophic condition. Measurements of standing crop, chlorophyll a, areal nutrient loadings, and nutrient concentrations support this conclusion (Schmitt 1973). In addition, sediment quality reflects a definite eutrophic condition downstream of the Wahiawa STP discharge. Algal growth potential (AGP) studies support this result with N limiting in surface waters and P in deeper waters (Young et al. 1975). Fish kills occurred in 1962, 1968, and 1971, and the total kill was a reported 4.5 metric tons (5 tons) for 1975.¹

As a result of the kills, the three major uses of the reservoir can no longer be considered compatible. The Waialua Sugar Company cannot withdraw the design quantity of water without creating conditions that lead to fish kills. The discharge of STP effluents is a prime cause of the eutrophic conditions. Nutrient inputs from the Wahiawa and Whitmore Village STPs contribute about 77% of the total P and 74% of the total N to the reservoir. This represents 391.23 kg/ha/yr (349 1b/acre/yr) of the total N and 137.88 kg/ha/ yr (123 1b/acre/yr) of the total P. The Wahiawa STP contributes 40 times as much N and 8 times as much P as the Whitmore Village STP (Young et al. 1975).

Because of the high level of nutrient loadings from the Wahiawa STP, further treatment or diversion must be carried out to improve the trophic status of the reservoir. Six alternatives were presented and discussed in a previous study (Young et al. 1975). The six alternatives were:

- 1. Secondary treatment with continued freshwater disposal
- 2. Secondary treatment with reuse of the effluent
- 3. Secondary treatment with disposal by subsurface injection
- 4. Diversion of present flow to the proposed Waialua ocean outfall
- 5. Tertiary treatment with continued disposal into the reservoir
- 6. Mechanical aeration of the reservoir.

Alternative 1 refers to the status quo and is most economical but does not solve the problem. Alternative 3 may not be allowed due to the possible contamination of groundwater supplies. Alternative 4, diversion to the pro-

¹William S. Devick 1975: personal communication.



FIGURE 1. WAHIAWA RESERVOIR

N

posed Waialua ocean outfall, is prohibitively costly. Alternative 6, mechanical aeration of the reservoir, affords only a temporary solution and is currently being practiced during low-water conditions. At present the feasible, permanent solution to the problem would be reuse of the effluent or tertiary treatment of the STP effluent.

Before any management alternatives can be fully evaluated, the effect of other possible nutrient sources to the reservoir must be assessed. The alternatives tend to direct corrective measures toward removal of sewage treatment plant effluents. Treatment of stream inflow loadings does not appear to be practical due to the large water volumes (Dunst et al. 1974). Another source of nutrients and organic loading to the reservoir is bottom sediment. The purpose of this study is to assess the eutrophic effect of sediments to determine whether control is necessary and whether the six alternatives suggested for improving the status of the reservoir are sufficient.

Answers were sought in this study for the following:

- 1. The level of nutrients and oxygen-demanding constituents that may be released or removed by sediments
- 2. The extent to which the equilibrated water in sediment-water systems can support algal growth
- 3. The extent of deoxygenation in overlying water
- 4. The possibility of sediments requiring rehabilitation in order to improve the trophic status of the reservoir
- 5. The evaluation of management alternatives concerning the effects of the sediment.

MATERIALS AND METHODS

Summary of the Method

The experimental method was designed to assess the probable effects of sediment on the overlying water in Wahiawa Reservoir. Lake sediment was incubated with four types of water and monitored periodically for various parameters. Subsequently, AGP tests were performed to assess the effects of sediments on water.

There were eight systems of reactors, with four different waters incubated under two different conditions. The conditions were designed to simulate those observed in situ at the deeper portions of the reservoir, therefore all reactors were incubated in the dark at lake bottom temperatures with undisturbed sediment. One series of reactors was aerated to assess the effects of sediment on oxygenated water and one series was incubated under anaerobic conditions.

Water samples were withdrawn periodically and volume in the reactors was restored with water from the original source. Both replacement water and samples were analyzed for NH_3-N , organic N, $NO_2^2 + NO_3^2$, $PO_{\overline{4}}^{\overline{4}}$ and total P or dissolved $PO_{\overline{4}}^{\overline{4}}$ and total dissolved P, pH, alkalinity, turbidity, temperature, chemical oxygen demand (COD), and dissolved oxygen (DO).

Sediments were analyzed at the beginning and after the completion of the test period. Sediment parameters monitored included NH_3-N , organic N, NO_2^2 +

 NO_3 , organic C, total P, and solids content.

After water quality analyses indicated that equilibrium conditions were attained, the reactor tests were terminated and the AGP of the water was determined.

Selection and Location of In Situ Sediment Sampling Site

Sediment utilized in the study was obtained simultaneously from Station 2 in the Wahiawa Reservoir with the water sampling station in the basin (Fig. 1). Selection was based on the reservoir and sediment characteristics as follows:

1. Wahiawa Reservoir has its greatest depth at Station 2. Hence, reaeration of the hypolimnion is probably poorest due to stratification and O_2 demand. Hypolimnetic O_2 deficience is have been observed and anoxic conditions have been considered as responsible for several fish kills. Seasonal aeration during low-water periods has been employed to avoid the development of critical conditions.

2. The characteristics of sediment in the reservoir were determined in a separate study (Young et al. 1975). Data indicates that nutrients tend to accumulate at Station 2.

Selection and Location of In Situ Water Sampling Site

The four types of water used in the study were Ku Tree Reservoir surface water (Sta. 11), Wahiawa Reservoir surface water (Sta. 2s), Wahiawa Reservoir bottom waters (1 m above the reservoir bottom [Sta. 2d]), and distilled or reverse osmosis-deionized water (see Fig. 1 for locations).

Ku Tree Reservoir water was utilized to ascertain the effect of sediment on waters flowing into the reservoir which have not been subjected to runoff and sewage treatment plant discharges. Nutrients are typically low at Ku Tree and the maximum effects of sediment on water quality can be assessed. Water from the surface of Wahiawa Reservoir was utilized to assess the effects of sediment on waters affected by runoff and STP effluents. Bottom water from Wahiawa Reservoir Station 2 was used as a field control, to assess the effects of sediment on waters already high in nutrients, to determine the effect of settling detritus and organic matter on sedimentwater nutrient relationships and to ascertain the possible effect of the Station 2 (high-nutrient content) sediments serving as a nutrient source to surface waters during periods of turnover. Distilled or reverse osmosisdeionized water was used as a laboratory control and to ascertain the effects of sediment on water low in nutrients, dissolved solids, pH, alkalinity, and bacteria. This latter condition represents the maximum diffusional gradient between sediment and water.

In Situ Sampling Procedure and Preservation of Sediment and Water

There was no definite procedure for mud sampling in the 13th edition of *Standard methods* (APHA 1971) but precautions were taken to obtain representative samples. A "mud-snapper" dredge was used to obtain sediment samples. The device was dropped with the jaws in an open position to the bottom of

the reservoir. Either the device snapped shut on impact or it sealed itself in the mud bottom and was snapped shut when the retrieving line, which was also attached to the trigger device, was pulled. The retrieved mud sample was then transferred to either $18.9-\ell$ (5-gal) or $2-\ell$ ($\frac{1}{2}$ -gal) polyethylene bottles. The containers were filled flush to the top with mud to remove as much air as possible. Sediments were stored at 4°C until incubation in the sediment-water reactors. Chemical preservatives were not used due to possible interferences with the physical, chemical, or biological factors governin sediment-water exchanges. The elapsed time between field sampling and incubation in the reactors ranged from 4 to 60 days.

Surface waters were collected at the sediment sampling site at the Wahiawa Reservoir and Ku Tree Reservoir by dipping polyethylene containers just beneath the surface of the water. Bottom samples from Wahiawa Reservoir were collected 1 m above the reservoir bottom by using a Van Dorn bottle, while surface waters were measured directly. As with sediments, preservation of the water sample consisted of storage at 4°C. Replacement water was utilized within two weeks of collection.

The appearance of each individual sediment grab sample suggested that surface sediments were being collected. The samples consisted of a brown surface layer and a lower layer of brown mixed with streaks of black-colored sediment presumably due to FeS; the texture was fine-grained and no benthic fauna was observed. Preliminary analysis indicated a high clay content with more than 80% less than the 5- μ size. A slight sulfide odor was detected.

Wahiawa Reservoir bottom waters were typically turbid, reddish brown in color, and had a noticeable odor. The surface waters were relatively clear and odorless except during low water or rainy periods. Ku Tree Reservoir water was normally clear. During the study period, the range and median turbidity for Wahiawa Reservoir Station 2s (surface) and 2d (bottom) was 3.6 to 38 and 5.3 JTU and 21 to 210 and 55 JTU, respectively, and for Ku Tree Reservoir, these same values were 5.4 to 22 and 13 JTU.

Description of Reactor Setup

The reactors were set up in an attempt to study the sediment-water relationships under conditions similar to that at the sediment-water interface in Wahiawa Reservoir. Reactors were incubated in the dark under quiescent aerobic and anaerobic conditions at lake bottom temperatures. Anaerobic conditions represented those observed in the hypolimnion while the aerobic conditions were used in the assessment of the impact of sediments on oxygenated waters and evaluates the alternative of aeration of the reservoir.

Sediment and water samples were placed into approximately 16-*l*, wide mouth, "seed" display, glass bottles imported from the Orient by Jade Food Products Incorporated in Honolulu, Hawaii. A relatively large reactor was selected to minimize the effects of flushing and short circuiting during routine sampling of the reactors.

Approximately 2.5 L of sediment were placed in the reactors to obtain a sediment depth of 5 to 6 cm. This depth was chosen after a review of various studies (Grissinger and McDowell 1970; Hayes, Reid, and Cameron 1958; Keeney 1974; Mortimer 1941; Pamatmat and Jones 1973).

Sediments were mixed manually prior to placement in the reactors. Water

was added to the reactors by siphoning through a tygon tube with the discharge end of the tube extending into a 50-ml beaker set upright in the sediment with the top of the beaker set flush with the surface of the mud. This arrangement was selected to minimize initial mixing of the sediment and the water.

There were four series of tests using a combined total of 22 reactors denoted as Aerobic Series 1 and 2 and Anaerobic Series 1 and 2 (subsets A and B). The first letter A or R represents respectively, aerobic or anaerobic. The numbers 1, 2, 3, and 4 represent the type of water incubated; 1 represents distilled-deionized or reverse osmosis-deionized water; 2, the Ku Tree Reservoir; 3, the Wahiawa Reservoir surface; and 4, the Wahiawa Reservoir bottom water. The reactors are described in Table 1.

AEROBIC SERIES 1 AND 2 REACTORS. In the aerobic reactors, air was bubbled in slowly at mid-depth through a glass tubing, from a silent Giant aquarium pump, so that the water was kept saturated but the sediment undisturbed. All reactors were incubated in the dark at 16 to 22.5°C for Series 1 and 19.5 to 20.0°C for Series 2 reactors (Fig. 2).

ANAEROBIC SERIES 1 REACTORS. The purpose of this phase was to study the effect of sediment on overlying water under anaerobic conditions. As replacement water was not deoxygenated throughout the series, the O_2 demand of sediments was ascertained.

The mixed sediments were placed into the reactors. A Plexiglas lid was then sealed on the reactor vessel with silicon glue. Through an opening in the cover, 12.5 & of H₂O were added as described. An air space of about 1 to 1.5 & remained. The opening was then stoppered and sealed with silicon glue. A glass tube extended to the mid-depth of the H₂O for reactor sampling. A replacement H₂O tube also served as a gas pressure release device. Glass tubing was fitted with tygon tubing and sealed by clamping with pinchcocks. The reactors are illustrated in Figure 3. The bottles were incubated in the dark at temperatures from 16 to 22.5°C.

ANAEROBIC SERIES 2 REACTORS. There were several differences in the arrangement of Series 2 reactors from Series 1. Replacement H_2O was deoxygenated as much as practicable with He and no air space was left in the reactors. The purpose of this phase of the study was to determine the sediment-water nutrient relationship under completely anaerobic conditions.

There were a total of eight reactors, duplicates for each of the four types of water. The sampling arrangement is illustrated in Figure 4. Sediment from the same batch was placed into each pair of duplicate reactors. The Plexiglas cover was then sealed on with silicon glue. The replacement H_2O was then deoxygenated to less than 0.5 mg/ ℓ by bubbling with He. Helium was selected instead of N gas that had been utilized in other studies (Fillos and Molof 1972) due to possible fixation of N by anaerobic bacteria (Howard et al. 1970; Keirn and Brezonik 1971). The 0.5-mg/ ℓ dissolved O₂ level corresponds to a redox potential at which considerable solutes are released (Mortimer 1941). Water was then siphoned through an opening in the reactor and allowed to overflow. The opening was then stoppered shut. Replacement H_2O and sample H_2O glass tubing ports were fitted with rubber stoppers. The reactors were incubated in the dark at 19.5 to 20.0°C.

Reactor and Condition	Water Type (Station)	Sediment Collection (1975)	Initial Incubation (1975)	Length of Run (days)	Sediment Volume (%)	Sediment Height (cm)	Water Volume (ℓ)
Aerobic Ser. 1 Al' - aerobic Al - aerobic A2 - aerobic A3 - aerobic A4 - aerobic	distilled-deionized distilled-deionized Ku Tree Res. (11) Wahiawa Res. surf. (2s) Wahiawa Res. bott. (2d)	03/22 05/24 06/05 06/05 06/05	03/31 05/31 06/13 06/17 06/09	175 68 86 89 106	2.0 2.5 2.5 2.5 2.5	 	12.5 12.5 12.5 12.5
Aerobic Ser. 2 AlA - aerobic A2A - aerobic A3A - aerobic A4A - aerobic	DD [*] and ROD [†] Ku Tree Res. (11) Wahiawa Res. surf. (2s) Wahiawa Res. bott. (2d)	10/02 10/02 11/19 11/19	12/03 12/03 11/26 11/26	70 70 70 70	2.9 2.9 3.0 3.0		12.5 12.5 12.5 12.5
Anaerobic Ser. 1 R1 - anaerobic R2 - anaerobic R3 - anaerobic R4 - anaerobic	distilled-deionized distilled-deionized Wahiawa Res. surf. (2s) Wahiawa Res. bott. (2d)	05/24 05/24 05/24 05/24	05/31 06/03 06/03 06/03	147 149 155 162	2.5 2.5 2.5 2.5		12.5 12.5 12.5 12.5
Anaerobic Ser. 2 R1A,B -anaerobic R2A,B -anaerobic R3A,B -anaerobic R4A,B -anaerobic	DD* and ROD [†] Ku Tree Res. (11) Wahiawa Res. surf. (2s) Wahiawa Res. bott. (2d)	08/24, 10/09 08/24 08/24 10/09	10/13 10/02 10/06 10/13	94 112, 202 89 89	2.8, 2.7 2.7, 2.7 2.5, 2.5 2.8, 2.8	5.8, 5.8 5.8, 5.8 6.1, 6.4	13.6, 13.7 13.7, 13.7 13.9, 13.5 13.0, 13.6

TABLE 1. DESCRIPTION OF REACTORS

*Distilled-deionized. †Reverse osmosis-deionized.



FIGURE 2. DIAGRAM OF AEROBIC REACTORS







FIGURE 4. DIAGRAM OF ANAEROBIC SERIES 2 REACTORS

Sampling Technique and Analysis of Reactor Water

Samples were withdrawn from the reactors at a rate such that the detention time was less than the theoretical detention time in Wahiawa Reservoir, calculated to be approximately 57 days. Actual detention times of hypolimnetic water in the reservoir may be longer due to stratification. Reactor volume was restored with replacement water obtained from the original location. Replacement water was usually utilized within two weeks of collection. Selection of sample volumes was based on requirements for the various analyses.

In the aerobic reactors, routine samples were drawn at mid-depth through a tygon tube attached to a glass tube which extended into the reactor water. Replacement water was subsequently poured into the reactor. Dissolved oxygen samples were obtained by direct siphoning into 60-ml DO bottles.

In the Anaerobic Series 1 reactors, replacement water was placed in a $1-\ell$ Erlenmeyer flask. A tygon tubing connection was made between the flask and the reactor replacement water port. The same attachment was made between the sample port and the sampling flask. A vacuum was applied to the sampling flask and water was withdrawn from the mid-depth of the reactor. Clamps to the replacement water port were simultaneously released and the vacuum created by the water withdrawn from the reactor siphoned in replacement water. A flaw observed in this system was that atmospheric O_2 was allowed to enter the reactor due to that contained in the air in the replacement water tygon tube.

In the Anaerobic Series 2 reactors, replacement water was put into a 4-L flask and deoxygenated by bubbling with He (Fig. 4). Enough water was placed in the flask to restore volume in the replicate reactors and to obtain a portion for analysis. The replacement water tube was filled with water, clamped, and connected to the reactor replacement water tube such that there was no air space. An effluent line was connected to the sampling flask and effluent port of the reactor. The replacement water flask was placed in an elevated position. The clamp was released and the pressure head differential caused flow into and out of the reactor. After a measured portion was withdrawn, the replacement water line was clamped and the effluent line was removed simultaneously. Before both lines were emptied, DO samples were taken by extending the lines into the bottom of 60-mL DO bottles. This proved to be an effective method of DO sampling.

Sediment Sampling Technique and Analysis in the Laboratory

In the Aerobic Series 1 and the Anaerobic Series 1 reactors, sediments were manually mixed and a portion was taken for analysis from this batch as the initial sediment sample. In the Series 2 reactors, sediment samples were taken directly from the reactor in an attempt to obtain more representative samples. Samples were collected with a spatula and transferred to 100-ml beakers.

Stratification of the sediments was observed. Three layers were observed in the aerobic reactors: an oxidized surface layer of about 1-cm thick, beneath it a brown-black layer of about 0.75-cm thick, followed by sediment of initial color. In the Aerobic Series 1 reactors, attempts were made to obtain a sample from each layer. A spatula was used to sample and remove each overlying layer. In the Aerobic Series 2 reactors, the layers were manually stirred into a homogeneous mixture and a portion was taken for analysis. This was to more accurately assess the net amount of N in each reactor to determine the N balance.

Two layers were observed in most of the anaerobic reactors. In the Series 1 reactors, surface and bottom samples were obtained. In the Series 2, the sediment was manually stirred and a portion was taken for analysis. The stirring was effected again to obtain a more representative sample for determination of the N balance.

All sediment samples were analyzed for moisture content, organic C, Total P, NH₃-N, organic N, and NO $_2^2$ + NO $_3^2$. In the Aerobic and Anaerobic Series 2 reactors, approximate specific-gravity measurements were made. Measurements of pH were made at the end of each run on surface and subsurface sediments of all Series 2 reactors. Approximate measurements of the gross amount of sediment contained within the reactors were made for Series 2 systems.

Analytical Methods

ANALYTICAL METHODS FOR WATER. Alkalinity, NH₃-N, organic N, COD, DO, and digestion of total and total dissolved P were analyzed according to procedures in the 13th edition of *Standard methods* (APHA 1971). Prepared total and total dissolved P samples, $PO_{\overline{4}}^{\overline{2}}$ and dissolved $PO_{\overline{4}}^{\overline{2}}$ were determined on a Technicon Autoanalyzer II according to Industrial Systems (1971) Method No. 155-71W. Dissolved P is defined as P present after filtration through a 0.45- μ membrane. NO₂ + NO₃ was also analyzed on a Technicon Industrial Systems (1971) Autoanalyzer II according to Industrial Method No. 100-70W. Where DO measurements were made by a meter, a YSI Model 57 meter was used. Temperature was measured with a mercury thermometer. Turbidity was determined on a Hach Model 2100A turbidimeter. An Orion Research Ionanalyzer Specific Ion Meter Model 401 or a Photovolt Model 126A pH meter was used to measure pH.

In all Series 1 reactors, NH_3-N and organic N were determined by nesslerization of the distilled samples due to the low levels of NH_3 in the aerobic reactors and the low organic N in all reactors. Ammonia nitrogen in the anaerobic reactors was also determined by nesslerization to maintain analytical consistency. In the Series 2 reactors, the indicating H_3BO_3 method was used to determine N due to the large errors observed for low N values inherent in the nesslerization method. Differences in the nesslerization and the indicating H_3BO_3 method were measured as both methods were used for assaying final NH_3 values in the anaerobic reactors of Series 1. Comparative values are presented in Table 2.

TADEL Z. COMPANYSON	OF MITS IN VALUES DI	RESSEENTZATION	AND TITINATION
Reactor Sample	Nesslerization (mg N/L)	Titration (mg N/L)	% Decrease
Rl - day 147 R2 - day 149	7.90 4.90	6.54	17
R3 - day 155 R4 - day 162	7.57	6.60 12.89	13 3

TABLE 2. COMPARISON OF NH3-N VALUES BY NESSLERIZATION AND TITRATION

ANALYTICAL METHODS FOR SEDIMENT. Organic and NH₃-N determinations were performed on sediment samples prior to drying according to *Standard methods* (APHA 1971). Subsequent moisture content determinations were made by drying the sediment overnight at 103°C. The sediment was then ground to a fine powder. The following analyses were performed on the ground sediment. Total P extracted by HC104 and HNO3 digestion in microkjeldahl flasks according to a procedure used in soils characterization (University of Hawaii 1974). Nitrate + nitrite nitrogen was extracted according to Moskva (1965). The P and N extracts were analyzed on a Technicon Industrial Systems Autoanalyzer in the same manner as the H₂O samples. Organic C was determined according to the Walkley-Black procedure (Chapman and Pratt 1961).

At the termination of the reactor tests, subsequent to removal of the H_2O , the pH of the sediments was measured with the same instruments used for pH measurements of H_2O samples.

Approximate measurements were made to determine the gross amount of sediment in the reactors. For the Series 2 reactors, a market scale with 0.028-kg ($\frac{1}{16}$ -1b) graduations was used to weigh the container and the sediment. Moisture content values were used to determine the amount of dry sediment. In the Series 1 reactors, no direct measures of sediment weight in the reactors were made since the approximate volumes were known. Approximate wet specific gravity measurements were made on Series 2 sediments using volumetrically measured porcelain cups. Applying these data and known moisture contents, the approximate dry weight of sediment in the Series 1 reactors was calculated.

Algal Growth Potential

After equilibrium conditions were reached in the sediment-water systems, samples were taken to determine the algal growth potential (AGP) of the water. This would determine whether the sediments could supply nutrients for growth, remove nutrients, or have no effect on algal growth. Data obtained here were compared with AGP results already performed on Wahiawa Reservoir waters (Young et al. 1975).

Analysis and preparation of these static tests were carried out according to the U.S. Environmental Protection Agency (1971) Algal assay procedure bottle test. Sample flasks were incubated in a light box. Light intensity ranged from 3,229.2 to 4,305.6 lx (300 to 400 ft-c.). Due to laboratory limitations, temperatures ranged from 22 to 29°C, whereas the recommended temperature is 24 \pm 2°C. The test algal species utilized was Selenastrum capricornutum. Growth was monitored by measuring relative fluorescence of the incubated cultures. After growth reached a plateau, cell counts were made to assess the maximum standing crop.

For the Series 1 reactors, samples were drawn prior to the termination fo the reactors. Elapsed reactor incubation time for the samples ranged from 93 to 96 days for the anaerobic reactors and 40 to 115 days for the aerobic reactors. Samples were autoclaved and inoculated in triplicate.

For the Series 2 reactors, samples were taken at the termination of each reactor test. The elapsed time ranged from 89 to 112 days for the anaerobic reactors and 70 days for the aerobic reactors. In the anaerobic reactors, a total of 6 flasks for each sample were run. This included triplicates of $0.45-\mu$ membrane-filtered water. Samples were neutralized from a pH of 4.0 and 4.3 to a pH of 6.8 and 7.0, respectively, with 0.02N Na₂CO₃ to more accurately simulate in situ pH conditions.

RESULTS AND DISCUSSION

In Situ Conditions during the Period of Study

Monitoring was done at the Ku Tree Reservoir and at the Wahiawa Reservoir Station 2 surface and bottom waters and the results are presented graphically in Figures 5 to 13.

Nutrient levels at the Ku Tree Reservoir were in the range usually considered as oligotrophic. Orthophosphate is typically less than 0.005 mg P/ ℓ and inorganic N is less than 0.16 mg N/ ℓ , well below the limits of 0.01 mg inorganic P/ ℓ and 0.30 mg inorganic N/ ℓ recommended by Sawyer (1947) for control of algal blooms in temperate Wisconsin lakes.

Factors affecting the limnology of Wahiawa Reservoir include climate, season, water level changes, and artificial aeration.

Water levels decreased to a minimum in autumn (Fig. 5). Thermal stratification is more significant in summer and less significant in winter (Fig. 6). The decrease in the degree of stratification may be attributed to surface cooling in response to air temperatures, drawdown enhancing heat transfer and mixing, and artificial aeration. Surface cooling occurs in winter at Station 2s with decreasing air temperatures. The abrupt changes in turbidity, alkalinity, N, and P at Station 2d (Figs. 8, 10, 11, 13) which occurred on 9 October 1975 are evidence that turnover occurred at that time. The turnover was partly the result of artificial aeration which began at about that time.

Dissolved oxygen levels at Station 2s were in a cycle of supersaturation in summer and subsaturation in winter (Fig. 7). The alkaline pH in summer at Station 2s corresponded to the supersaturated DO levels, illustrating the effect of the longer day on algal growth and DO production at the time (Fig. 9). Dissolved oxygen levels increased subsequently with increases in water levels in the winter. In the hypolimnion, O_2 is typically at less than 10% saturation, confirming eutrophic conditions (Beeton 1965). Dissolved oxygen was less than 1 mg/ ℓ , below the level of 1 to 2 mg/ ℓ recommended for control of the release of dissolved substances (Fillos and Molof 1972; Fillos and Swanson 1975; Mortimer 1971).

The sequence of events of N and P increase in the hypolimnion of Wahiawa Reservoir was similar to that observed for Esthwaite water by Mortimer (1941). Nitrogen and P in the hypolimnion increased during stagnation and decreased during overturn on 9 October 1975. Increases in P in the hypolimnion may have been due to release from the sediment (Mortimer 1941) or sedimentation of particulate P (Golterman 1973) as the concentrations of both $PO\overline{4}$ and particulate P (total and $PO\overline{4}$) increased. The increase in N was attributed to release of NH₃ from the sediment (Mortimer 1941), although mineralization of settling organics is also a possible source (Brezonik 1973).

In the surface water of the reservoir, N and P levels far exceeded that recommended for control of algal blooms in temperate lakes (Sawyer 1947). Changes in concentration occurred concurrently with seasonal and H_2O level changes. The concentration of total N appeared to have been governed by H_2O















FIGURE 11. IN SITU NITROGEN





FIGURE 13. PHOSPHORUS AT STATION 2d

levels as there was a steady increase during drawdown and a decrease as the H_2O level rose. Inorganic N was low and the level of organic N was at a maximum during the summer while $PO_{\frac{1}{4}}^{\frac{1}{2}}$ was still present in large quantities, suggesting that N is the limiting nutrient because of the low concentration during the growing season (Porcella and Bishop 1975).

Total P and $PO_{4}^{=}$ decreased in the hypolimnion and epilimnion at the overturn. The decrease in the hypolimnion could have been attributed to the introduction of DO and the subsequent oxidation of Fe⁺⁺, resulting in precipitation of P as ferric compounds (Mortimer 1941; Serruya et al. 1974), as well as the dilution effects of mixing. The decrease in the epilimnion may have been due to the dilution and introduction of Fe⁺⁺ as a result of mixing and subsequent oxidation and precipitation of P by ferric compounds. Another possible cause of the decrease was sorption of PO_{4}^{-} on suspended particles and subsequent sedimentation (Grissinger and McDowell 1970). An increase in turbidity occurred concurrently with the decrease in P. In addition, the large discrepancy between filtrable and unfiltrable P forms in hypolimnetic waters could have been attributed to sorption on suspended sediment or precipitation of P comounds. This may explain the results of previous investigations that P is limiting in the bottom waters of the reservoir (Young et al. 1975).

Influence of Laboratory Methods in the Application of Results

Several considerations should be taken into account in evaluating the applicability of the results of this experiment. The tests were an attempt to simulate in situ conditions in the hypolimnion of Wahiawa Reservoir. Hence, incubation of these reactors was in the dark at lake-bottom temperatures. The results for aerobic conditions could be applied to the situation where aeration is practiced in the reservoir or as a simulation of the lake during unstratified, aerobic conditions, and the effects of artificial aeration on the trophic status improvement of the lake. The results for the Anaerobic Series 1 reactors can be a simulation of the effects of sediment on aerobic waters. This could be the case when destratification in the reservoir results in the contact of aerobic waters with sediment. The results for the Anaerobic Series 2 reactors could represent conditions of stagnation and O_2 deficiency and could be used to assess the impact of sediment on anoxic waters.

Sediment was kept undisturbed to simulate presumed conditions at the reservoir bottom. Release of N (Austin and Lee 1973) and P (Zicker, Berger, and Hasler 1956) has been found to be much greater with sediment kept in motion. The initial set-up of the reactors is illustrative of this hypothesis. Mixing of sediment introduced large amounts of suspended nutrients to the water column (Table 3), but subsequent sedimentation resulted in removal of significant amounts of total P and organic N as can be noted in Figures 14 to 16 for reactors A1 and A2A.

The results for reactors Al' and Al in Appendix Tables A.1 and A.2 are evidence that the minimal changes resulted from varying the sediment depth by 20%. The change in N concentrations is verification that the entire depth of sediment is involved. Qualitative changes occurred in the top 2 cm of the sediment. Konrad et al. (1970) recommended that sediment cores should be taken to determine the actual in situ depth involved in exchange.

Varying the sampling frequency for the anaerobic reactor R2B yielded a

		Turbidity		i yana she	Total N		Total P				
Reactor	Before	After	Net Change	Before	After	Net Change	Before	After	Net Change		
		(JTU)	1	2 ¹ 1 1 1	(mg N/L)			(mg P/l)			
A1 '		-,-			0.49	0.49		0.141	0.141		
A1		88	88		0.28	0.28		0.340	0.340		
A2	15	20	5	0.23	0.43	0.20	0.007	0.202	0.013		
A3	4	6	2	1.02	1.13	0.11	0.219	0.223	0.004		
A4	35	52	17	4.89	5.25	0.36	0.312	0.338	0.026		
AIA		11	11		0.25	0.25		0.003*	0.003*		
A2A	22	150	128	0.37	2.63	2.26	0.007*	0.021*	0.014*		
A3A	9	17	8	3.50	3.50	nd	0.106*	0.068*	-0.038*		
A4A	88	96	8	2.51	2.56	0.05	0.012*	0.012*	nd		
Rl		11	11		0.06	0.06		0.098	0.098		
R2	18	25	7	0.20	0.75	0.55	0.006	0.027	0.021		
R3	- 4	8	4	0.77	0.91	0.14	0.211	0.198	-0.013		
R4	40	42	2	4.30	5.42	1.12	0.310	0.306	-0.004		
RIA		4	4		0.08	0.08		0.009*	0.009*		
R1B		2	2		0.06	0.06		0.006*	0.006*		
R2A	18	71	53	0.31	0.63	0.32	0.014*	0.007*	-0.007*		
R2B	18	25	7	0.31	0.41	0.10	0.014*	0.008*	-0.006*		
R3A	5	23	18	2.94	3.33	0.39	0.049*	0.049*	nd		
R3B	5	8	3	2.94	3.33	0.39	0.049*	0.049*	-0.016*		
R4A	165	160	-5	2.98	2.04	-0.94	0.080*	0.080*	-0.029*		
R4B	165	170	5	2.98	1.98	-1.00	0.080*	0.080*	-0.026*		

TABLE 3. EFFICIENCY OF REACTOR SETUP

* = Dissolved.

nd = Nondetectable.







FIGURE 15. TOTAL DISSOLVED PHOSPHORUS IN AEROBIC SERIES 2 REACTORS



FIGURE 16. ORGANIC NITROGEN IN AEROBIC SERIES 2 REACTORS
flushing effect when samples were drawn daily. At weekly or longer sampling intervals, steady-state conditions were maintained.

The validity of the experimental reactors systems is supported by comparing the results for reactors Al' and Al and the Anaerobic Series 2 reactors Al and Al'. Total N and NH₃-N did not differ by more than 8% or 0.5 mg N/ ℓ for the Anaerobic Series 2 reactor replicates. In addition, total dissolved P concentrations were essentially equivalent. The replicability of microcosmic studies has been documented elsewhere (Abbott 1966).

Sediment Characteristics

Sediment chemical characteristics are presented in Tables 4 and 5. Characterization of sediments according to organic C and organic N levels yielded the observation that the sediment was similar in properties to partially stabilized domestic waste water sludge and had a significant N contribution potential (Ballinger and McKee 1971). Comparison of NH_3 -N data with those presented by Brezonik (1973) for Florida lakes confirms that the reservoir is eutrophic. He reported median values of NH_4 -N for eutrophic lakes of about 0.31 mg NH_4 -N/g dry weight of sediment and less than 0.20 mg/g for oligotrophic lakes. Typical values at Wahiawa Reservoir Station 2 were greater than 0.40 mg N/g.

On a weight to volume basis, total N was in the order of 1,000 mg N/ ℓ , NH₃-N about 150 mg N/ ℓ , total P about 500 mg P/ ℓ , and organic C about 8,000 mg/ ℓ . Concentrations in the sediments were several orders of magnitude greater than concentrations in the water column. Thus, a high concentration gradient existed between sediment and water and is evidence of the potential for nutrient contribution by diffusional fluxes. It should be noted however that this is only applicable to the concentration in the pore water and not the N, P, and C concentration in the solid phase.

Changes in ammonia concentration in the sediments reflected changes in trophic status. For the aerobic reactors, the NH_3 content in the oxidized surface layer and highly reduced brown-black layer decreased to low levels characteristic of oligotrophic lakes. The level of NH_3 -N in bottom layers progressed toward mesotrophic conditions. In the anaerobic reactors, NH_3 decreased but still remained at a level comparable to eutrophic lakes. Longer incubation periods resulted in greater decreases in NH_3 , evidence that given sufficient time, the trophic status of the sediments may improve.

Organic C and organic N levels tended to be greater in surface sediments of the aerobic reactors at the end of testing, verifying that immobilization or net mineralization is less under aerobic conditions (Keeney 1973). Levels of both constituents did not change significantly and the trophic status remained the same with respect to organic C and organic N.

Analytical methods for total P and organic C were not sensitive enough to be used to detect changes during incubation. Levels of P were comparable to those reported for Wisconsin lakes (Williams et al. 1971) and Lake Kinneret (Serruya 1971).

The sediment pH at the termination of reactor tests was in a range from 6.7 to 7.0 except for the pH in the surface oxidized layer of the aerobic reactors which was about 4.4. The low pH may be attributed to the oxidation of sulfides (FeS, H_2S , or FeS₂) to sulfuric acid (Hutchinson 1957), the diffusion of low pH water into the sediment, or the reduction in buffering

Sample	NH3-N	Org. N	NO ₂ + NO ₃ -N	Total N	Total P	Org. C	p	H
			(mg	/g)				
A1'-0 A1'-175s A1'-175m A1'-175d	0.47 nd 0.05 0.13	3.00 3.21 2.92 2.76	0.0044 0.0070 0.0045 0.0029	3.47 3.22 2.97 2.89	1.43 1.46 1.42 1.47	24.4 26.7 26.5 26.2		
A1-0 A1-68s A1-68m A1-68d	0.47 nd 0.10 0.43	2.61 2.96 2.82 2.79	0.0033 0.0094 0.0053 0.0057	3.08 2.97 2.93 3.03	1.46 1.47 1.43 1.47	28.4 24.8 24.0 23.5		
A2-0 A2-89s A2-89m A2-89d	0.48 0.01 0.09 0.22	2.92 3.14 3.98 2.86	0.0077 0.0090 0.0072 0.0037	3.41 3.16 3.08 3.08	1.55 1.58 1.62 1.62	25.5 26.5 25.7 25.9		-
A3-0 A3-86s A3-86m A3-86d	0.48 0.01 0.09 0.24	2.92 3.22 2.94 2.88	0.0032 0.0127 0.0052 0.0033	3.40 3.25 3.04 3.12	1.52 1.46 1.45 1.55	26.1 25.9 25.5 25.6		
A4-0 A4-106s A4-106m A4-106d	0.51 0.03 0.09 0.19	3.15 3.34 3.32 3.60	0.0031 0.0116 0.0048 0.0041	3.66 3.38 3.41 3.79	1.60 1.74 1.77 1.64	28.7 28.4 27.4 26.2		· ·
A1A-0 A1A-70 A2A-0	0.53 0.27 0.52	2.78 2.67 2.74	0.0042 0.0044 0.0040	3.31 2.94 3.26	1.59 1.64 1.62	27.1 25.6 26.5	4.4s	6.7d
A2A-70	0.23	2.62	0.0037	2.85	1.62	25.5	4.4s	6.7d
A3A-0 A3A-70 A4A-0	0.54 0.22 0.55	2.90 2.86 2.93	0.0037 0.0033 0.0040	3.44 3.08 3.48	1.68 1.63 1.56	27.7 27.2 26.7	4.4s	6.7d
A4A-70	0.24	2.84	0.0039	3.08	1.52	27.5	4.4s	6.7d

TABLE 4. SEDIMENT CHEMICAL DATA: AEROBIC REACTORS

NOTE: s = surface

m = middle

d = deep.

R1-0 0.42 2.80 0.0036 3.22 1.48 27.0	
RI = 14/s 0.32 2.70 0.0045 3.02 1.38 21.1	
$R_{1-14/d}$ 0.30 2.65 0.0044 2.95 1.47 21.4 R2, R3, R4-0 0.48 2,89 0.0032 3.37 1.42 26.3	
R2-149s 0.21 2.75 0.0038 2.96 1.48 25.9	
R2-149d 0.25 2.66 0.0043 2.91 1.44 26.4 R3-155s 0.26 2.71 0.0039 2.87 1.45 24.4	
R3-155d 0.28 2.60 0.0037 2.88 1.41 23.2	
R4-162s 0.33 2.78 0.0032 3.11 1.53 24.6 R4-162d 0.33 2.64 0.0025 3.07 1.57 24.8	
1020 0.55 2.04 0.0055 5.07 1.57 24.0	
R1A-0 0.45 2.73 0.0076 3.19 1.54 27.1	
RIA-94 0.41 2.68 0.0056 3.10 1.52 24.9	6.9
R1B-94 0.40 2.68 0.0043 3.08 1.53 25.6	6.8
R2A-0 0.45 2.71 0.0070 3.17 1.50 25.2	
R2B-0 0.45 2.68 0.0095 3.14 1.50 22.2	
$R_{2A} = 1125$ 0.29 2.53 0.0044 2.82 1.55 23.5 R2A = 112d 0.32 2.56 0.0049 2.88 1.49 23.2	5.7 6.8
R3A-0 0.46 2.60 0.0063 3.07 1.59 24.9 R3B-0 0.44 2.61 0.0054 3.06 1.53 23.6	
R3A-89 0.35 2.72 0.0042 3.07 1.60 23.7	7.0
R3B-89 0.36 2.74 0.0046 3.10 1.59 24.4	7.0
R4A-0 0.48 2.90 0.0052 3.38 1.96 22.6	
R4B-0 0.47 2.85 0.0032 3.32 1.97 24.8 R4A-89 0.40 2.90 0.0058 3.32 1.97 24.8	6 0
R4B-89 0.40 2.93 0.0045 3.33 1.95 27.5	5.9

TABLE 5. SEDIMENT CHEMICAL DATA: ANAEROBIC REACTORS

0 = initial levels; numbers indicate termination time. s = surface.

d = deep.

capacity of the waters due to bicarbonate uptake in nitrification. The observation of an oxidized surface layer in situ during sampling verified that the low level of DO was sufficient to develop this layer. Beneath this surface layer, a highly-reduced, brown-black FeS layer was observed.

Appearance of the Sediment

AEROBIC REACTORS. Three stratified layers observed in the sediments of the aerobic reactors are a qualitative indication of redox potential (Eh) changes (Mortimer 1941). The surface light-brown oxidized layer corresponds to oxidative conditions with an Eh of greater than +250 mV. The intermediate brown-black layer represents the most highly reduced zone of sediment and the K_{Eh} in this layer is probably negative (Fillos and Molof 1972; Hutchinson 1957). The bottom layer probably has an Eh between that of the top two layers as depicted in Figure 17. Mortimer (1941) measured a progressive decrease of Eh with sediment depth.

The orange surface floc observed in the aerobic reactors with Station 2d water is attributed to oxidation of Fe⁺⁺ present in replacement H₂O and subsequent oxidation and precipitation as ferric complexes (Fe₂O₃ NH₂O) (Gorham 1958; Mortimer 1942). The presence of Fe⁺⁺ in the Station 2d water was highly probable as Fe⁺⁺ is dissolved out of mud under anoxic conditions (Mortimer 1941) in the reservoir hypolimnion. The probable absence of Fe⁺⁺ in the Station 11, 2s, and distilled-deionized H₂O accounts for the absence of this floc in other aerobic reactors. This was suggestive that Fe⁺⁺ is not released from the sediments under aerobic conditions. Hayes, Reid, and Cameron (1958) suggested that this surface floc represents the real oxidized layer, but results here demonstrate that this was not the case.

ANAEROBIC REACTORS. The brown-black FeS layer occurred at the surface of the sediment in these reactors except in reactors with distilled-deionized This was suggestive that under anoxic conditions sediments are more re-H₂0. ducing at the surface (Hutchinson 1957). The absence of this layer in the reactors with distilled-deionized H_2O is evidence that either the distilled H_2O is inhibitory to reducing bacteria or that reducing bacteria, absent or in low concentration in the H₂O, are responsible for the highly-reduced condition. The former situation is more likely since there was no $SO_{\overline{4}}$ source for the reducing bacteria. A thin surface oxidized layer was observed in reactors R1, R2, and R3, verifying that conditions in these systems are oxidizing. The presence of an orange-red floc in reactors R1 and R2 was confirmation that conditions in the sediment were reducing enough at a point in the test period to cause release of Fe^{++} , but the reappearance of dissolved O_2 in the H₂O, indicative of oxidizing conditions, resulted in oxidation and precipitation of ferric complexes.

Reactor Water Quality Results

The water quality changes with time are presented in tabular form in Appendix Tables A.1 to A.21. Appendix Tables A.1 to A.5 are for the Aerobic Series 1 reactors, Tables A.6 to A.9 for the Aerobic Series 2, Tables A.10 to A.13 for the Anaerobic Series 1, and Tables A.14 to A.2. for the Anaerobic Series 2 reactors. The average replacement water quality is given in Table 6.





	17-5- <u>6-1</u> -6-6-6-6-1-1			You di Laining	Nitrogen									
Reactor	DO	Turb.	pН	Alk.	NH 3	Org.	NO2+ NO3	Total	P0	Total	Diss. POT	Total Diss.	COD	Volume Replcd.
	(mg/l)	(JTU)	•	(mg/l)		(mg	N/L)			(mg	P/l)		(mg/l)	(m&)
A1'			5.5				· · ·							500
A1			5.5											500
A2		10	6.0	3	0.01	0.17	0.01	0.19	0.002	0.007	· · · ·			500
A3		55	8.2	10	0.11	1.27	0.02	1.40	0.141	0.287				500
A4		33	6.1	40	6.31	0.59	nd	6.90	0.380	0.440				500
AIA			5.5											900
A2A		23	6.3	4	0.01	0.18	0.06	0.25	0.003	0.008	0.007	0.008	8	900
A3A	'	20	6.5	8	0.24	0.79	1.52	2.55	0.157	0.215	0.095	0.123	15	900
A4A		140	6.3	12	0.68	0.68	0.32	1.68	0.053	0.100	0.018	0.022	19	900
RÌ	8.7		5.5			· · ·			8 a 	÷				500
R2	8.9	9	6.2	4	0.11	0.24	nd	0.35	0.014	0.026		ы с — _		500
R3	9.4	5	7.8	11	0.26	1.23	0.32	1.81	0.140	0.254				500
R4	2.2	57	6.3	46	6.37	0.80	0.05	7.22	0.500	0.608				500
RIA-RIB	0.6		5.5					, - `		a <mark>a</mark> 5				900
R2A	0.6	15	6.6	4	0.02	0.16	0.04	0.22	0.003	0.011	0.004	0.006	8	900
R2B	0.4	15	6.5	4	0.02	0.15	0.05	0.22	0.004	0.010	0.004	0.006	8	900
R3A-R3B	0.5	21	7.2	13	0.71	0.92	1.67	3.30	0.142	0.201	0.039	0.055	15	900
R4A-R4B	0.7-0.6	156	6.9	9	0.83	0.84	0.22	1.89	0. 078	0.096	0.020	0.030	21	900

TABLE 6. MEAN REPLACEMENT WATER CONCENTRATIONS

Turbidity

An example of turbidity changes under aerobic conditions is given in Figure 18 and under anaerobic conditions in Figure 19. The net change in turbidity is presented in Table 7.

Turbidity in the aerobic reactors decreased to low levels. The intermediate increase may have been due to bacteriological activity.

In the Anaerobic Series 1 reactors, two periods of increase and decrease in turbidity occurred. This could have been attributed to the response of different species of bacteria under changing conditions. Turbidity in Anaerobic Series 2 reactors followed the pattern observed in the aerobic reactors. Turbidity increased during incubation in the Anaerobic Series 1, but not in the Anaerobic Series 2 reactors and there the differences in testing methods and bacteriological activity is shown (Table 7.).

pH and Alkalinity

Steady state and changes in pH and alkalinity are presented in Table 7.

In the aerobic reactors, pH decreased to acidic levels and alkalinity decreased to zero (Fig. 20). Hutchinson (1957) suggested that the production of organic acids and release from deeper layers may decrease pH, but the pH decrease occurred rather rapidly for this to be the situation. The oxidation of pyrites (FeS₂) and FeS to H_2SO_4 may result in pH reduction. Chen, Keeney, and Konrad (1972) found that pH decrease may also result from the oxidation of H_2S to H_2SO_4 . The pH decrease occurred concurrently with an increase in NO_3 and a decrease in NH₃ in the H_2O column. The formation of HNO₃ may result from NH₃ oxidation (Sawyer and McCarty 1967):

 $pH < 7 NH_4^+ + 1\frac{1}{2}O_2 \rightarrow NO_2^- + 2H_4^+ + H_2O_2^-$

 $pH > 7 2NH_3 + 30_2 - 2NO_2^2 + 2H^+ + 2H_2O$

In Figure 21 the pH, alkalinity, NO_3^- , and NH_3 relationship is illustrated. The pH decrease has been observed in other aerobic-release studies (Austin and Lee 1973).

In the anaerobic reactors, pH stabilized between 6.4 and 6.7 (Fig. 22). This was similar to those of the H_2O in the hypolimnion of the reservoir verifying that the testing method closely represents in situ conditions. The initial increase in pH in the anaerobic reactors is probably due to $-SO_4$ and NO_3 reduction and the release of bases. The subsequent decrease in pH may be due to the production and release of organic acids and CO_2 from sediment. The increase to steady-state may be evidence that a balance between organic acid production and alkalinity release has been attained.

The initial increase of alkalinity in the aerobic (Fig. 23) and the anaerobic (Fig. 24) reactors may be due to the release of $(NH_4)_2CO_3$ (Hutchinson 1957). In the Anaerobic Series 1 reactors, changes in alkalinity occurred concurrently with changes in NH₃. A typical example is illustrated in Figure 25. Further increases in alkalinity in the Anaerobic Series 2 reactors were measured after NH₃ levels were found to be at steady-state (Fig. 26), and may have been due to continued release of $(NH_4)_2CO_3$ and the release of Fe(HCO₃)₂ and Mn(HCO₃)₂ under reducing conditions. Conditions in the Anaerobic Series 2 reactors may have been more reducing than in the Anaerobic



FIGURE 18. TURBIDITY IN AEROBIC SERIES 2 REACTORS





		pН			Alkalini	ty		Turbid		COD			
Reactor	1	Ĕ	Ċ	1	E (mg/l)	C		E (JTU)) C	1	Ĕ (mg/Ջ)	C	
A1 '	5.5	4.2	-1.3	0	0	0	0	<]	< +1				
Al	5.5	4.0	-1.5	0	0	0	0	<1	< +1				
A2	6.0	3.8	-2.2	3	0	3	10	<1	-10				
A3	8.2	4.0	-4.2	10	0	10	5	<1	-5				
A4	6.1	4.0	-2.1	40	0	40	33	<]	-33				
AIA	5.5	4.0	-1.5	0	0	0	1.	1	-1	0	3	+3	
A2A	6.3	4.1	-2.2	4	0	-4	23	3	-23	8	5	-3	
A3A	6.5	4.2	-2.3	8	0	-8	20	2	-20	15	8	-7	
A4A	6.3	4.3	-2.0	12	0	-12	140	15	-125	18	5	-13	
RI	5.5	6.3	+0.8	0	42	+42	0	60	+60				
R2	6.2	6.3	+0.1	4	52, 32	+48, +2	89	50	+41				
R3	7.8	6.5	-1.3	11	60	+49	5	100	+95				
R4	6.3	6.5	+0.2	46	95	+49	57	200	+143				
RIA	5.5	6.4	+0.9	0	40	+40	0	3	+3	· 0	. 8	+8	
RIB	5.5	6.4	+0.9	0	39	+39	0	3	+3	0	10	+10	
R2A	6.6	6.4	-0.2	4	60	+56	15	7	-8	8	20	+12	
R2B	6.5	6.4	-0.1	4	56	+52	15	5	-10	8	17	+9	
R3A	7.2	6.5	-0.7	13	74	+61	21	4	-17	15	27	+12	
R3B	7.2	6.5	-0.7	13	70	+57	21	4	-17	15	23	+8	
R4A	6.9	6.6	-0.3	9	68	+59	156	69	-87	21	22	+1	
R4B	6.9	6.6	-0.3	9	70	+61	156	69	-87	21	22	+1	

TABLE 7. CHANGES IN pH, ALKALINITY, TURBIDITY, AND COD IN REACTOR WATER DURING INCUBATION

I = mean influent, E = maximum or equilibrium concentration, C = concentration change.



FIGURE 20. pH IN AEROBIC SERIES 2 REACTORS























FIGURE 25. RELATIONSHIP OF ALKALINITY AND AMMONIA IN ANAEROBIC SERIES 1 REACTORS



FIGURE 26. RELATIONSHIP OF ALKALINITY AND AMMONIA IN ANAEROBIC SERIES 2 REACTORS

Series 1 reactors. Alkalinity decreases in the aerobic reactors may result from organic acid production, presence of DO, oxidation of NH_3 to NO_2 , and the resorption of bases due to HCO_3 use by *Nitrosomonas* and *Nitrobacter*.

The net change in alkalinity concentration for the anaerobic reactors for each series appears to be nearly equivalent except for the reactors with distilled-deionized H_2O , again stressing the importance of bacteriological activity. The initial rapid increase and subsequent slower linear increase in the anaerobic reactors is proof that processes of diffusion control the release of alkalinity. The initial lag in alkalinity increase in reactors RIA and B may be due to bacterial inhibition in the distilled deionized water.

Decreases in pH and alkalinity in aerobic conditions and the increase in anaerobic conditions were also reported by Mortimer (1941).

Dissolved Oxygen

Water was kept aerated and dissolved O_2 saturation levels were maintained in the aerobic reactors. In the Anaerobic Series 2 reactors, H_2O was deoxygenated to low levels. Completely anoxic conditions in reactors with Station 11 and 2d H_2O were attained at a faster rate than in reactors with Station 2s and distilled-deionized H_2O . The higher COD in Station 2d H_2O could account for this and the more reducing conditions observed qualitatively by the darker black sediment surface in the reactors with Station 11 H_2O , possibly as a result of differing sediment or bacteriological characteristics of the H_2O , may account for this difference.

In the Anaerobic Series 1 reactors, replacement water was not deoxygenated, hence the deoxygenation capacity of the sediments could assessed. Completely anoxic conditions were attained at some time in the test period of reactors R2, R3, and R4. This is attributed to the depletion by BOD and COD of the water and the O_2 demand of the sediment. Dissolved O_2 was partly depleted in the reactors with distilled-deionized H_2O . The absence of O_2 demanding substances and the low amount of bacteriological activity in the water may account for this. However, dissolved O_2 in this reactor was still depleted to less than 30% saturation. The occurrence of dissolved O_2 in reactors R2 and R3 is evidence that sediments will be stabilized with respect to O_2 demand, given adequate time.

Chemical Oxygen Demand

Chemical oxygen demand (COD) was determined for the Series 2 reactors under aerobic (Fig. 27) and anaerobic (Fig. 28) conditions. Steady state levels and net changes are presented in Table 7.

Steady levels in the aerobic reactors A2A, A3A, and A4A were all less than the mean COD concentration in the replacement water, which is confirmation that O_2 -demanding constituents are oxidized or adsorbed by sediments under aerobic conditions. Release from reactor A1A was measured, verification that sediments act as COD buffers under oxygenated conditions. The initial COD increase in reactor A1A and slow decrease in reactor A3A may have been due to COD release from sediment prior to full development of the oxidized layer or due possibly to growth of nitrifying bacteria using HCO⁻ as C source.







FIGURE 28. CHEMICAL OXYGEN DEMAND IN ANAEROBIC SERIES 2 REACTORS, SUBSET A

Ogunrombi and Dobbins (1970) concluded that the development of an oxidized layer decreased COD release. A continued decrease was measured in reactors A2A and A4A due to the high initial levels and sedimentation of particulate COD which would mask any slight initial release. The net change in concentration does not appear to be related to replacement water concentrations.

In the anaerobic reactors, higher release and increases in COD levels were measured. Fillos and Molof (1972) found that COD release increased sharply when dissolved O_2 was less than 1.5 mg/ ℓ . Steady state levels in all reactors except reactors R4A and B increased by about 10 mg/ ℓ , verifying that the quantity released is independent of concentration in the overlying water. The minimal increase may be due to the high turbidity resulting in sorption and sedimentation of some sorbed and particulate COD. There was an initial COD decrease followed by an increase for most reactors. This was due to the response to changing Eh conditions.

Chemical oxygen demand results confirm that sediment under anaerobic conditions can release and sustain high levels of COD sufficient to deoxygenate saturated waters. Hence, sediments must be stabilized with respect to O_2 demand.

Phosphorus

Steady state P levels and net concentration changes are given in Table 8.

EFFECTS OF AERATION. Under oxygenated conditions, the sediments appear to be able to efficiently remove P from water (Figs. 29, 30). A rapid initial decrease occurred in reactors initially high in P in the water column and this may be attributed to sedimentation of particulate P and sorption of dissolved P. A slight increase occurred in reactors initially low in P and this may be attributed to release prior to full development of the oxidized layer. The residual dissolved in reactor A3A and the absence of P in other reactors may be attributed to the high replacement H_2O concentration.

Results showed that suspended sediments were capable of sorbing P and thus removing it from solution by subsequent sedimentation (Grissinger and McDowell 1970). The high percentage of clays in suspended sediments (Johnson and Moldenhauer 1970) and the high sorptive capacity of clays (Holt, Dowdy, and Timmons 1970) support this concept. The total dissolved P increase and decrease in the Aerobic Series 2 reactors coincided with a change in turbidity (Fig. 31). The initial decrease in turbidity but increase in P in reactor A4A may be attributed to P release prior to development of a fully oxidized sediment layer (Figs. 32, 33). A rapid decrease of total P in the Series 1 reactors also coincided with a rapid decrease in turbidity. The pattern of P decrease in reactor A3A (Fig. 34) was evidence that sorption occurred because of the high levels of replacement H₂O and initial dissolved P and the low equilibrium levels attained despite the low turbidity in this reactor. Other possible mechanisms for P removal included bacterial uptake of sorbed P (Holden 1959) and precipitation reactions (Norvell 1974).

In most of the reactors, P was essentially nondetectable at termination. In no case did $PO\overline{\frac{1}{4}}$ exceed 0.006 mg P/ ℓ and total P, 0.010 mg P/ ℓ .

EFFECTS OF DEOXYGENATION. Results for P in the Anaerobic Series 1 and Series 2 reactors were quite different and these results will be discussed separately. Differences were attributed to differences in test conditions, the major difference being the presence of DO in replacement waters for the

Deseter		P	0륜		Total P	2. 2. 10. 10. 10. 2016. 10. 17.	Di	ssolved P	P0≣	Total Dissolved P			
Reactor	1	Е	° C	1	E	С	1	E	° c ∣	1	E	С	
						(mg	P/l)						
A1'	-	nd	-	-	nd		-	x 💾	-	_	-	-	
A1	-	nd	-	-	nd		-	-	, – ¹	-	-	-	
A2	0.003	nd	0.003	0.008	nd	-0.008	-	-	-	-	-	-	
A3	0.146	nd	0.146	0.287	0.010	-0.267	· · -	-	-	-	-	-	
A4	0.380	nd	0.380	0.440	nd	-0.440	-	-		-	-	-	
A 1 A	_	ام م	_	-	0 001	+0 001	а. 1	e e		_	nd	_	
A1A 424	0 002	0 002	0 001	0 008	0.007	-0.001		0 001	-0 006	0 008	nd	-0 008	
AZA	0.003	0.002	0.001	0.008	0.005	-0.005	0.007	0.001	-0.000	0.000		-0.000	
AJA	0.157	0.004	0.153	0.215	0.010	-0.205	0.095	0.006	-0.009	0.123	0.005	-0.110	
A4A	0.053	0.006	0.04/	0.100	0.006	-0.094	0.018	na	-0.016	0.022	na	-0.022	
R1	-	nd	-	-	nd		· _	nd	-	-	0.002		
R2	0.014	0.006	-0.008	0.026	0.010	-0.016	-	nd	-	-	0.001	-	
R3	0.140	0.010	-0.130	0.254	0.020	-0.234	-	0.001	-	-	0.001	-	
R4	0.500	0.042*	-0.458	0.608	0.110*	-0.498	-	0.002	-	-	0.002	-	
		0 0 0 I											
RIA	-	0.004	+0.004	-	0.005	+0.005	-	nd	-	-	nd	-	
RIB	-	0.005	+0.005	-	0.007	+0.007		nd	-	-	nd	-	
R2A	0.003	0.032	+0.029	0.011	0.040	+0.029	0.004	0.020'	+0.016	0.006	0.027'	+0.021	
R2B	0.004	0.036	+0.032'	0.010	0.038	+0.028	0.004	0.028'	+0.024	0.006	0.028'	+0.022	
R3A	0.142	0.070	-0.072	0.201	0.060	-0.141	0.039	0.038'	-0.001	0.055	0.033'	-0.022	
R3B	0.142	0.070	-0.072	0.201	0.070	-0.131	0.039	0.029'	-0.010	0.055	0.033'	-0.022	
R4A	0.078	0.065	-0.013	0.096	0.080	-0.016	0.020	0.006	-0.014	0.030	0.006	-0.024	
R4B	0.078	0.075	-0.003	0.096	0.090	-0.006	0.020	0.004	-0.016	0.030	0.006	-0.024	

TABLE 8. PHOSPHOROUS CONCENTRATION CHANGES IN REACTOR WATER DURING INCUBATION

*decreasing concentration. 'increasing concentration.

I = mean influent concentration.

E = equilibrium reactor water concentration.C = concentration change (E - I).











FIGURE 31. RELATIONSHIP OF TURBIDITY TO DISSOLVED PHOSPHORUS IN AEROBIC SERIES 2 REACTORS



FIGURE 32. PATTERN OF OXIDIZED-SEDIMENT LAYER DEVELOPMENT









Series 1 reactors and the resulting slightly oxic conditions. Application of the results from Anaerobic Series 1 reactors to in situ conditions seemed more appropriate because waters in the reservoir were oxygenated prior to mixing into the hypolimnion and contact with sediments.

Anaerobic Series 1 Reactors. The pattern of changes in total P and PO_{4}^{-} similarly verified that the removal of one corresponds with the removal of the other (Figs. 34, 35). Phosphorus decreased to low levels in all reactors except for reactor R4. The presence of O_{2} in the replacement water and the presence of a thin oxidized sediment layer may account for this removal. The orange-red floc observed in reactors R1 and R2 was verification that precipitation processes were active and conditions were oxidizing enough to prevent P release and to oxidize released Fe⁺⁺. The absence of a brown-black reduced layer in the reactor with distilled-deionized water was illustrative of the role of bacteriological activity in reducing the Eh of sediments and probably of the water. The removal of P in reactor R3 was evidence that sorption processes were active as the precipitated orange-red floc was not observed (although soluble FePO₄•2H₂O may also have been formed) and P removal did not coincide with a change in turbidity.

Conditions were probably reducing in reactor R4 because it did not have the thin, oxidized sediment layer observed in the other reactors. Highest equilibrium P levels occurred in this reactor. Although the presence of Fe⁺⁺ was likely, the absence of an orange-red floc was confirmation of reducing conditions. The initial decrease in P may have been attributed to sorption onto sediment because of the initial oxic condition present in the reactor. The subsequent increase was associated with an increase in turbidity, evidence of the influence of bacteriological activity (Porcella, Kumagai, and Middlebrooks 1970). The increase in turbidity may have been the result of gas production and ebullition resuspending the sediments (Sanville at al. 1974). The increase was also observed to occur simultaneously with a decrease in DO to low levels verifying that P was released as a result of an Eh drop and solubilization of precipitated P compounds.

Levels of dissolved P in samples at the end of testing were less than or equal to 0.002 mg P/ ℓ . The high PO $\frac{\pi}{4}$ values was evidence that most of the PO $\frac{\pi}{4}$ was adsorbed on, or reacted with, filtrable matter. The important question was whether this PO $\frac{\pi}{4}$ thus removed was available to the biota. Hence, the role of suspended sediment may be significant. Algal growth potential results were confirmation that sorbed PO $\frac{\pi}{4}$ is not available as growth was not observed in the low dissolved P-high PO $\frac{\pi}{4}$ samples, but consideration should be given to other limiting factors such as micronutrients, trace metals, and vitamins.

In typical anaerobic conditions, P is expected to be released from the sediment to the H₂O column (Fillos and Molof 1972; Fillos and Swanson 1975; Mortimer 1941). However, the clay-like nature of the sediment may have caused the removal of P despite the anoxic conditions. The independence of P sorption on clays to Eh status has been documented (Serruya 1971). However, the slightly oxic conditions in the reactors may be sufficient to allow sorption of P. The slightly oxic conditions in situ in the reservoir hypolimnion may also account for the low dissolved PO_{4}^{Ξ} in that layer relative to the epilimnion.

Results from this work were evidence that sediment P was not a problem due to the sorptive capacity of bottom and suspended sediments even under anoxic conditions. Evidence from this research suggests that the sediment





acts as a P sink and has a corrective impact on the H₂O column.

Anaerobic Series 2 Reactors. The pattern for total dissolved P and dissolved PO_{4}^{-} in the H₂O column was similar (Fig. 36). Since conditions may initially favor sorption, the initial decrease of dissolved P (Fig. 37) may be attributed to sorption because development of the reduced sediment layer, which is indicative of reducing conditions, were not observed or fully developed. This was evidence that sediments can sorb P despite the absence of DO in the H₂O column, and release or nonsorption of P may require reducing conditions in the sediment. Evidence of this was the subsequent P increase after the decrease in all reactors, except for the reactors with distilleddeionized H₂O, which did not develop the highly-reduced, brown-black sediment layer. Following this increase, steady-state conditions existed in reactors R4A and B, but a continued release occurred for the reactors containing Station 2s and 11 water.

In reactors R4A and B, the steady state attained by dissolved P in the H₂O column may be attributed to the formation of a thin oxidized layer. The reactors were also highly turbid and dissolved P could have been sorbed and removed by sedimenting suspended sediments (Fig. 38). The high $PO\overline{\frac{1}{4}}$ values, relative to dissolved $PO\overline{\frac{1}{4}}$, support the concept that suspended sediment can sorb PO.

No P release was detectable in the distilled-deionized H_2O reactors. This may have been due to the lesser amount of bacteria and COD in the H_2O column that must be present to render conditions reducing enough for P release or perhaps the H_2O has an inhibitory effect on reducing-bacteria in the sediment. Results for these and the other anaerobic reactors with distilled-deionized H_2O were evidence of the importance of bacteriological activity on P release.

From the limited $PO_{\overline{4}}^{\overline{\pm}}$ and total P data, the sediments appeared to act as total P and $PO_{\overline{4}}^{\overline{\pm}}$ buffers, releasing the substance to solutions low in P and removing it from solutions high in P. Minimal release occurred in reactors with distilled-deionized H₂O due to insufficient reducing conditions or insufficient bacteriological activity.

The relationship of total P, PO_{4}^{Ξ} , dissolved total P, and dissolved PO_{4}^{Ξ} is illustrated in Figure 36 for reactor R2B. The level of total dissolved P and dissolved PO_{4}^{Ξ} was very similar. The parallel increase in dissolved P and PO_{Ξ}^{Ξ} verified that release can be attributed to the dissolved P fraction.

Nitrogen

Steady state, maximum N concentrations and net changes are presented in Table 9.

NITROGEN CONCENTRATION CHANGES UNDER OXIC CONDITIONS. The typical pattern of N changes in the aerobic reactors is illustrated in Figure 39. The initial rapid increase was attributed to the liberation of NH_3 from sediment prior to sufficient development of the oxidized sediment layer. The maximum in total N occurred after the maximum in NH_3 ; therefore, liberation of NH_3 was continuing but the decrease in NH_3 was attributed to nitrification. The maximum N concentration was associated with the maximum NO_3 level and occurred after 17 days of incubation. The subsequent decrease in N was due to the development of the surface oxidized layer or a decrease in leachable sediment







FIGURE 37. TOTAL DISSOLVED PHOSPHORUS IN ANAEROBIC SERIES 2 REACTORS, SUBSET A



FIGURE 38. RELATIONSHIP OF TURBIDITY TO DISSOLVED PHOSPHORUS IN ANAEROBIC SERIES 2 REACTORS

or	5 Total N					rganic	N		NH 3	-N		N	$0_2 + N$	103-N		Organic N		
ct	1	EM	E 70	CM	I.	EM	См	I.	EM	EE	См	1	EM	E 70	См	1	EE	CE
Rea									-(mg N	/l)								
A1' A1	- -	4.4 4.4		4.4 4.4	-	4.0	4.0 4.2	-	2.9	0.1	2.9	-	3.2 3.2	1.7	3.2 3.2	-	0.1	0.1
A2 A3 A4	1.4 6.9	4.7 5.1 7.9		4.5 3.7 1.0	0.1 6.3	4.7	4.6	0.1 6.3	3.5 4.0 6.9	0.1 0.1	3.9 0.6	0.1	3.9 5.4	2.2 2.5 3.4	3.9 5.4	1.3	0.3	-1.0
A1A A2A A3A A4A	- 0.3 2.6 1.7	7.0 7.5 7.5 7.5	2.7 2.7 3.3 3.1	7.0 7.2 5.0 5.8	- 0.1 1.7 1.0	6.7 7.0 7.2 7.2	6.7 7.0 5.5 6.2	- 0.1 0.2 0.7	3.5 3.5 3.9 5.0	0.1 0.1 0.1 0.1	3.5 3.5 3.7 4.3	- 0.1 1.5 0.3	5.2 5.6 5.6 5.2	2.6 2.5 3.1 2.9	5.2 5.6 4.1 4.9	- 0.2 0.8 0.7	0.1 0.1 0.2 0.2	- -0.1 -0.5 -0.3
		EE		С _Е		ε _E	С _Е				С _Е		EE		С _Е			
R1 R2 R3 R4	- 0.4 1.8 7.2	8.2 7.7 8.1 13.5		6.7* 6.2* 5.0* 5.9*	- 0.2 0.6 6.4	8.1 6.9 7.6 2.9	6.8* 5.6* 6.1* 6.3*	- 0.1 0.3 6.4	8.1 6.9 7.6 12.9		6.6* 5.7* 5.9* 6.1*	0.1 0.3 0.1	0.1 0.5 0.1 0.1	1. * *	0.5 -0.3 -	0.2 1.2 0.8	0.3 0.2 0.2 0.6	0.3 -1.0 -0.2
R1A R1B R2A R2B R3A R3B R4A R4B	- 0.2 3.3 3.3 1.9 1.9	5.4 5.6 6.2 8.0 8.0 8.7 9.0		5.9' 6.1' 7.0' 6.6' 7.1'' 6.9'' 7.1' 7.7'	- 0.1 2.4 2.4 1.0 1.0	5.3 5.5 6.4 5.9 7.3 7.2 8.2 8.3	5.8' 6.0' 6.7' 5.6' 5.3' 7.4' 7.8'	- 0.1 0.7 0.7 0.8 0.8	5.3 5.5 6.4 5.9 7.3 7.2 8.2 8.3	, , , , , , , , , , , , , , , , , , ,	5.8' 6.9' 6.4' 7.3' 7.0' 7.7' 8.2'	- 0.1 0.1 1.7 1.7 2 2	0.1 0.1 0.1 0.1 0.1 0.1 0.1		-1.7 -1.6 -0.2 -0.2	- 0.2 0.9 0.9 0.8 0.8	0.1 0.2 0.3 0.5 0.5 0.4 0.4	0.1 0.2 0.1 -0.4 -0.4 -0.4 -0.4

TABLE 9. NITROGEN CONCENTRATION CHANGES IN REACTOR WATER DURING INCUBATION

I = mean influent concentration.

E_M = maximum observed concentration.
E_E = observed equilibrium concentration.
E₇₀ = concentration after 70 days of incubation.

C_M, E = equilibrium, maximum concentration change. *adjusted for reactor water volume and method of analysis

"adjusted for volume and NO_2 and NO_3 loss. 'adjusted for reactor water volumes.



FIGURE 39. TYPICAL PATTERN OF NITROGEN CHANGES IN THE AEROBIC REACTORS
NH₃. The presence of NO₃ + NO₂ in the H₂O was attributed to nitrification of NH₃ and not to release from sediments. Chen, Keeney, and Konrad (1972 α) concluded that NO₃ and NO₂ are not formed in acid sediments or under undisturbed conditions, similar to conditions in this study. The appearance of NO₃ + NO₂, i.e., nitrification, causes a pH decrease.

After the maximum N concentration, there was a short period of rapid N decrease between the 17th and 24th day of incubation. This may possibly be attributed to the high initial $NO_2^2 + NO_3^2$ content in the H₂O and the low content in the sediments, resulting in a rapid initial diffusional flux into the sediment. The period of slower and linear decrease that followed continued until the end of the incubation period. The rate of decrease during this period was the net result of difference in replacement H₂O-sample withdrawal N, denitrification in sediments, continued N release and sorption or biological uptake by sediments. Evidence of denitrification, sorption or bacteriological uptake, occurred in reactor Al'. Sampling losses did not account for all of the N decrease. The loss to the sediment occurred at a rate of 8.5 μ g N/ ℓ /day. Possible evidence of continued NH₃ release was shown by results for reactor Al'. The longer test period resulted in less sediment NH₃ in deeper layers than in other reactors, but this may also be attributed to bacteriological uptake.

The concentrations of inorganic N attained in the reactor H_2O as a result of sediment release far exceeded the critical level of 0.26 mg soluble inorganic N/ ℓ reported earlier for Wahiawa Reservoir (Young et al. 1975) and the 0.30 mg inorganic N/ ℓ recommended for control of algal growths by others (Sawyer 1947; Vollenweider 1968). The subsequent development of an oxidized layer was found to inhibit N release and this layer may have even served as a N sink. Hence, denitrification and flushing effects could decrease N to low levels. The results for reactor Al' were evidence that nitrification of released NH₃ followed by denitrification could remove N as has been reported elsewhere (Keeney, Schmidt, and Wilkinson 1975).

Results verified that sediments do not nitrify when the oxidized layer is not present and the H_2O is oxygenated. More NH_3 was released to waters which had the least amount of N.

The high initial N level in reactor A2A was attributed to mixing with sediments. This action can introduce high levels of N to H_2O . Austin and Lee (1973) found that stirring of sediments resulted in 50 times more N release than for undisturbed conditions. However, the observation of firmly-packed, fine grain-sized sediments during field sampling was evidence that disturbance of sediment may not be representative of the in situ conditions in the reservoir.

The development of an oxidized layer controls NH_3 release, and the DO supply in H_2O had only an indirect role because release occurred in oxygenated waters but was inhibited when the oxidized layer developed fully.

NITROGEN CONCENTRATION CHANGES UNDER ANOXIC CONDITIONS. Increases in N were attributed to release of NH_3 from the sediment (Fig. 40). The rapid initial increase followed by a slower rate of increase and steady state conditions was evidence that diffusional processes control release (Fig. 41).

Maximum and steady state inorganic N levels in all reactors far exceed that found to be critical for Wahiawa Reservoir (Young et al. 1975). The maintenance of this level despite losses due to sample withdrawal is evidence that NH_3 was continually released by sediment or that diffusional







FIGURE 41. TOTAL NITROGEN IN ANAEROBIC SERIES 2 REACTORS, SUBSET A

processes will maintain this particular level of NH₃. The net change was between 5.8 to 8.2 mg N/ ℓ , and appeared to be independent of the concentration in the overlying H₂O, due to the lack of buffering capacity of the sediments under anaerobic conditions. The validity of these data was supported by in situ data for N. The maximum NH₃ level in the hypolimnion of Wahiawa Reservoir was 6.5 mg N/ ℓ greater than the average surface H₂O concentration.

The net increase of NH_3 for the Anaerobic Series 2 reactors was slightly greater for reactors R4A and B, than for reactors R3A and B, R2A and B, and R1A and B. This may be attributed to the higher (qualitatively expected due to turbidity levels) solids and, possibly, the higher bacteriological content in reactors R4A and B than in the other reactors. Competition for exchange sites on the clays in sediment by other cations may increase the NH_3 concentration (Keeney 1974). The reverse was true, however, for the Anaerobic Series 1 reactors. This may be attributed to the slightly oxic conditions present in these reactors so that the sediments served as NH_3 buffers as occurred with the aerobic reactors.

The amount of $NO_2^- + NO_3^-$ was not a significant factor in most reactors and remained at a low level in reactor R2. Nitrification was not attained in reactor R1 although DO was relatively high. This was due to the inability of nitrifying bacteria to thrive in the anaerobic sediments; however, nitrification occurred in the aerobic distilled-deionized water reactors.

The increase in organic N in reactors R2, R3, and R4 may be due to bacterial uptake or release in sediments associated with turbidity increase. The increase in reactors R1, R1A, and B may be attributed to diffusion of soluble organic N to organic N deficient H_2O . Austin and Lee (1973) measured an increase in soluble Kjeldahl N in their anaerobic studies. Highest steady state concentrations were associated with highest replacement H_2O concentrations. A buffering tendency was evident as there was an increase in H_2O low in organic N and a decrease in H_2O high in organic N.

NITROGEN BALANCE. Nitrogen balance results are presented in Table 10.

Aerobic Reactors. There was a net loss of unaccounted for N in the aerobic reactors. Several explanations for this include losses due to denitrification in sediments as a result of NO3 diffusion into anoxic lower sediments and subsequent denitrification (Chen et al. 1972b; Keeney, Schmidt, and Wilkinson 1975), experimental error, chemical losses of NO2 due to reaction with amino groups under acid conditions, and conversion of NH3 to molecular N in the lower anaerobic sediments (Brezonik 1973, citing Malina and Crane). Fixation of molecular N may decrease the actual loss measured. Loss rates in Aerobic Series 2 reactors were from 8 to 10%, verification that sediment can act as a N sink under aerobic conditions.

The inorganic N balance confirms that denitrification or immobilization was occurring. However, sediment organic N decreased in Aerobic Series 2 reactors but increased in surface sediments of Aerobic Series 1 reactors, evidence that immobilization does occur but that the net reaction was mineralization and denitrification.

Anaerobic Reactors. A net loss of N occurred in the Anaerobic Series 1 reactors. Possible explanations for this loss are similar to those of the aerobic reactors. Because sediment quantity was estimated, whether or not this was a true loss cannot be accurately assessed. Hence, sediments may act as a N sink under anaerobic conditions.

For most Anaerobic Series 2 reactors, there was a net unaccounted for

	on ys)		Total N			Inorgani	c N		NH3-N	
leactor	icubati me (da	Net Loss or Gain	Net Loss or Gain	Rate	Net Loss or Gain	Net Loss or Gain	Rate	Net Loss or Gain	Net Loss or Gain	Rate
<u>~</u>	<u> </u>	(mg N)	(%)	(mg/m²/day)	(mg N)	(%)	(mg/m ⁻ /day)	(mg N)	(%)	(mg/m ⁻ /day)
Al' Al A2 A3 A4 Aver	175 68 86 89 106 age	-292.28 - 33.95 -121.66 -117.28 - 64.05	-13.1 - 1.4 - 4.6 - 4.3 <u>- 2.1</u> - 5.1	-29.1 - 8.7 -24.7 -23.0 <u>-10.5</u> -19.2	-220.43 -202.32 -218.30 -214.91 -337.61	-71.8 -53.1 -52.8 -54.9 -63.2 -59.2	-21.9 -51.9 -42.8 -43.6 -55.6 -43.2			
A1A A2A A3A A4A Aver	70 70 70 70 age	-232.34 -259.72 -268.20 -278.15	-8.2 -9.5 -8.9 -9.5 -9.0	-57.9 -64.8 -66.8 <u>-71.8</u> -65.3	-141.32 -161.81 -221.63 -201.02	-31.0 -36.8 -41.7 -39.6 -37.3	-35.7 -40.3 -55.2 <u>-50.1</u> -45.3			
R1 R2 R3 R4 Aver	147 149 155 162 age	- 39.52 -258.70 -261.40 -146.77	-1.5 -9.4 -9.4 -5.1 -6.4	- 4.7 -30.3 -29.4 -15.8 -20.1	+69.79 -85.89 -32.25 +16.89	+20.1 -26.6 - 8.1 + 3.4 - 2.8	+ 8.3 -10.0 - 3.6 + 1.8 - 0.8	+ 68.95 - 94.22 - 32.88 +129.73	+20.1 -23.9 - 8.3 +26.2 + 3.5	+ 8.2 -11.0 - 3.7 +14.0 + 1.9
R1A R1B R2A R3A R3B R4A R4B Aver	94 95 112 89 89 89 89 age	+ 35.99 +120.18 - 65.62 +114.90 +142.94 + 75.05 +162.93	+1.2 +4.4 2.7 +4.5 +5.3 +2.5 +5.4 +3.0	+ 6.6 +22.3 -10.2 +22.5 +28.0 +14.7 +10.6 +13.5	+78.38 +80.26 +51.75 +29.18 +43.03 +88.51 +96.88	+18.3 +19.9 +14.5 + 6.8 +10.0 +19.7 +21.7 +15.8	+14.5 +14.9 + 8.1 + 5.7 + 8.5 +17.4 +19.0 +12.6	+ 80.26 + 82.77 + 54.12 + 67.74 + 80.51 + 94.14 +111.21	+19.0 +20.9 +15.5 +17.6 +20.7 +21.5 +25.5 +20.1	+14.9 +15.4 + 8.4 +13.3 +15.8 +18.5 +21.8 +15.4

TABLE 10. NITROGEN BALANCE RESULTS

increase in N according to the N balance. Thus, sediments under completely anoxic conditions may serve as a N source. The increase of N may be attributed to bacterial N fixation in anoxic waters (Brezonik 1973) or in sediments (Howard et al. 1970; Keirn and Brezonik 1971).

A net mineralization occurred in most reactors as there was a net gain in NH_3 and inorganic N. The loss of inorganic N and NH_3 in reactors R2 and R3 may be due to nitrification of NH_3 and subsequent denitrification. For the Anaerobic Series 1 reactors, there was a net decrease in sediment organic N, confirmation that mineralization was occurring. For the Anaerobic Series 2 reactors, sediment organic N concentrations were about the same, representative of a balance between uptake and mineralization reactions.

The net N loss calculated for Series 1 reactors may be due to the addition of O_2 in these reactors inducing nitrification-denitrification. The net gain in total and NH₃-N may be due to the following reaction:

 N_2 + bacteria \rightarrow organic N + bacteria \rightarrow NH₄

CHANGES IN SEDIMENT NITROGEN

Effects of Oxic Conditions. The three distinct layers of sediment observed in the aerobic reactors were also distinguished by the variation in N from the analysis of Aerobic Series sediments. Higher NH₃ levels occurred in deeper sediments. This may be attributed to higher rates of NH₃ assimilation under the aerobic conditions present in the oxidized surface layer (Keeney 1973), NH₃ release was only from the top few centimeters or nitrification of NH₃ occurred in the oxic layer of the sediments (Holt, Dowdy, and Timmons 1970), but conditions were conducive to nitrification (Chen, Keeney, and Konrad 1972 α). Longer incubation time resulted in further NH₃ decreases confirming that continued release, uptake, or nitrification was occurring. The decrease of available nitrogen (NH₄) was significant under aerobic conditions (49 to 81%) and is evidence that, with time, inorganic N will be depleted.

Total N in the Aerobic Series 1 sediments were higher in the sediment surface, evidence that diffusional fluxes were causing a migration of N from subsurface to surface sediments (Feng 1971).

Organic N at the oxidized sediment surface of Series 1 reactors was greater than initial values while concentrations were less in the reduced, deeper sediments. This is consistent with the findings of Keeney (1973) that more assimilation occurs in oxic sediments.

Nitrate and nitrite concentrations were greater at the sediment surface which illustrates that diffusion to sediment from water was occurring and losses of N due to denitrification was likely or that nitrification of NH_3 was occurring in surface sediments. Nitrite and nitrate levels in underlying, reduced sediments were less than initial levels while concentrations at the surface were greater. Thus, denitrification occurred in anoxic sediments while nitrification or NO_3 adsorption occurred in surface sediments.

In all reactors, NH_3 and total N decreased due to release to H_2O . The entire depth of sediment undergoes a change.

Effects of Anoxic Conditions. In the Anaerobic Series 1 reactors, all forms of N, except $NO_2 + NO_3$ -N, decreased, evidence of a net release or loss from sediments. Nitrite and nitrate nitrogen increased, probably due to the presence of O_2 and nitrification occurring in the thin oxidized layer.

Results from the Anaerobic Series 2 reactors were erratic. Total and

organic N increased in some reactors but decreased in others. Sorption or uptake of N from H_2O or uptake of molecular N may have been occurring. Nitrite and nitrate nitrogen and NH_3 decreased in all sediments so that there was a net release due to denitrification or immobilization reaction.

The entire depth of sediment changed uniformly with respect to NH_3 . Increased sediment depth may result in more changes in the overlying water. Comparison between Series 1 and 2 reactors showed that more NH_3 would have been released or converted in sediments with increased incubation time. Rates of NH_3 loss were about 33% greater on the average in Series 1 than in Series 2 reactors (1.16 μ g/g/day), possibly due to the slightly more oxic condition of Series 1 reactors which enhanced nitrification at the sediment surface and possibly increased the rate of assimilation (Keeney 1973).

COMPARISON OF NITROGEN RELATIONSHIPS UNDER OXIC AND ANOXIC CONDITIONS. There were numerous differences in N relationships between aerobic and anaerobic conditions. The major difference was that N was released under anaerobic conditions but was not released under fully-oxidized conditions.

The total N balance for all Series 2 reactors (where more precise measurements were made) was evidence that the sediment acted as a N sink under aerobic conditions but may act as a N source under anaerobic conditions.

Under aerobic conditions, N release is minimal and flushing may remove N, while under anaerobic conditions continued release occurs. However, the presence of an oxidized layer appears to be more important in controlling NH₃ release. There was an initial release in the aerobic reactors and in the Anaerobic Series 1 reactors although dissolved O_2 levels were high in the H₂O column. This proves that NH₃ release was independent of the Eh of the H₂O (Fillos and Swanson 1975). Development of a thick oxidized layer in the aerobic reactors inhibited release after 2 weeks. In reactor R1, DO levels were high (greater than 3 mg/ ℓ) but continued NH₃ release was measured. Only a thin oxidized layer was observed in this reactor. Ammonia release was thus controlled at DO levels greater than 3 to 4 mg/ ℓ or a level required for development of a thick oxidized layer (approximately 50 mm before NH₃ release was inhibited). This was contrary to the findings of Fillos and Molof (1972) and Mortimer (1971) that solute release is controlled below a DO level of 1 to 2 mg/ ℓ .

Algal Growth Potential

Algal growth potential (AGP) results are presented in Table 11.

According to AGP data (Table 12) reported by Sturm and Payne (1973), a maximum standing crop of less than 5,000 cells/ml is characteristic for oligotrophic conditions, 5,000 to 100,000 cells/ml for mesotrophic and more than 100,000 cells/ml for eutrophic conditions.

Mesotrophic levels of growth occurred with the buffered, autoclaved H_2O of reactors A2A and A4A. There was no growth for other aerobic reactor H_2O samples. The lack of substantial growth may be attributed to the low P level or other nutrients and was evidence that the sediment had a rehabilitating effect under aeration. It was reported in previous studies that a high level of growth was obtained with Wahiawa Reservoir surface waters (Young et al. 1975). The absence of the potential for high algal growth in H_2O from reactor A3A was evidence of the rehabilitative effect of sediments under aerobic

7	2
1	2
-	_

Reactor Samples	Maximum Standing Crop (cells/m&)	P0≣ (mg	Diss. P0∓ P/l)	lnorganic N (mg N/೩)	N:P Ratio
A1'-114a		nd		1.17	inf.
Al - 53a		nd		2.62	inf.
A2 - 40a		nd		3.02	inf.
A3 - 71a		nd		2.58	inf.
A4 - 79a		nd		3.15	inf.
A1A- 70d			nd	2.64	inf.
- 70a		0.001		2.64	2,600
- 70b		0.001		2.64	2,600
A2A- 70d			0.001	2.60	2,600
- 70a		0.002		2.60	1,300
- 70b	55,100	0.002		2.60	1,300
A3A- 70d	1		0.006	3.18	530
- 70a		0.006		3.18	530
- 70b'		0.006		3.18	530
A4A- 70d			nd	3.00	inf.
- 70a		0.005		3.00	600
- 70b'	75,800	0.005		3.00	600
R1 - 96a		0.003	nd	8.00	2,700
R2 - 93a		0.003	nd	6.04	2,000
R3 - 93a		0.004	0.001	7.66	1,900
R4 - 93a	2,300	0.009	0.002	12.05	120
R1A- 94a		0.004		5.12	1,300
- 94d			nd	5.12	inf.
R1B- 94a	"	0.005		5.80	1,200
- 94d			0.002	5.80	2.900
R2A-112a		0.032		5.94	190
-112d			0.019	5.94	310
R3A- 89a	282,000	0.070		7.51	110
- 89d	105,000		0.036	7.51	210
R3B- 89a	310,000	0.070		7.28	100
- 89d	117,000		0.029	7.28	250
R4A- 89a		0.063		8.22	130
- 89d			0.006	8.22	1,400
R4B- 89a		0.078		8.49	110
- 89d	4. 		0.004	8.49	2,100

TABLE 11. ALGAL GROWTH POTENTIAL RESULTS

NOTE: Numbers following reactor type represent days samples were drawn.

a = autoclaved samples.

b = autoclaved samples, buffered to pH 6.8. b' = autoclaved samples, buffered to pH 6.9. d = $0.45-\mu$ membrane filtered samples.

- nd = nondetectable.

inf. = infinite.

Test Water	Trophic Level	Sampling Date	10 ⁶ cells/&
Burntside	0	02/70	0.005
Burntside		05/70	0.005
Burntside R.	0	08/69	0.005
Burntside R.		12/69	0.005
Burntside R.		02/70	0.005
Burntside R.		05/70	0.005
Waldo Lake	0	07/70	0.005
Waldo Lake		08/70	0.005
Waldo Lake		09/70	0.005
Lawrence Lake	0	10/70	0.005
Lake James	0-M	08/70	0.005
Lake James		08/70	0.06
Lake James		09/70	0.08
Lake Michie	м	07/70	0.005
Lake Michie		08/70	0.005
Triangle Lake Triangle Lake	м	08/70 09/70	0.005
Castle Lake	м	09/70	0.005
Shagawa Lake	E	12/69	0.80
Shagawa Lake		02/70	0.90
Shagawa Lake		05/70	0.50
University Lake	E	07/70	20
University Lake		08/70	0.35
University Lake		09/70	0.005
University Lake		10/70	0.005
Clines Pond	E	07/70	18
Clines Pond		08/70	0.100
Clines Pond		09/70	0.700
Clear Lake	E	09/70	4.0
SOURCE: Sturm and 0 = oligotrophic. M = mesotrophic.	Payne (1973)	•	

TABLE 12. SUMMARY OF ALGAL ASSAYS UTILIZING Selenastrum capricornutum

E = eutrophic.

conditions.

A eutrophic level of growth occurred with waters from reactors R3A and B of the Anaerobic Series 2 reactors. The mass of growth was similar to that for in situ samples from the surface of Wahiawa Reservoir. The amount appeared to be related to P availability. The initial adsorption of P in these reactors followed by a subsequent release was evidence that the sediments may have had a eutrophic effect on overlying H_2O . The high growth rates for the autoclaved samples was evidence that particulate $PO_{\frac{1}{4}}$ may be utilized by the test organism, *Selenastrum capricornutum*, or that autoclaving solubilized the nutrients.

The absence of growth for waters from reactors R1A and B and the filtered waters from reactors R4A and B may be attributed to low levels of dissolved $PO_{\frac{1}{4}}^{-}$. The absence of growth for autoclaved waters from reactors R4A and B was confirmation that particulate $PO_{\frac{1}{4}}^{-}$ is not utilizable. (This may be due to pH, absence of other nutrients $[CO_2, HCO_3]$ or presence of unknown toxicants.) A low amount of growth, less than 5,000 cells/m, occurred with H₂O from reactor R4, consistent with the results of previous tests on hypolimnetic waters from the reservoir, evidence of the representativeness of the Anaerobic Series 1 reactors systems.

The nonavailability of $PO\bar{\bar{a}}$ was probably due to adsorption onto suspended clays. Phosphorus appeared to be at a sufficient level to stimulate algal growth but there was no growth measured in reactors R2A and B samples. This may have been due to possible inhibitory or toxic substances in the Ku Tree Reservoir waters, or the fact that N or P was not limiting. Nitrogen and P were not limiting in these waters in earlier studies (Young et al. 1975). The low quantity of growth or zero growth in waters from the Anaerobic Series 1 reactors was attributed to the low level of dissolved $PO\bar{\bar{a}}$. It was concluded in earlier studies that P limits in deeper water and the ratio of N to P in the reactor waters from this research is supportive of this conclusion. An explanation for this is the effectiveness of bottom and suspended sediments in adsorbing dissolved $PO\bar{\bar{a}}$. The minimum N to P ratio was 110, far greater than the 7 to 1 ratio considered typical of algae (Porcella and Bishop 1975).

Sediments appeared to have a noneutrophic effect in most of the reactors under anaerobic conditions. Under oxygenated conditions, the absence of growth in samples from reactors with waters from Station 2s and in most of the other reactor samples was evidence of the rehabiliting effect of sediments under aerobic conditions. Evidence that sediments can maintain or cause eutrophic conditions was ascertained in samples from reactors R3A and B. The absence of algal growth in the Ku Tree Reservoir reactor water samples was evidence that removal of external inputs may result in oligotrophy. Apparently, certain growth factors required by algae are contributed by STP effluents or runoff. To fully assess this theory, indigenous algae should be used for algal growth potential tests.

Discussion of the Eutrophic Effects of Sediments

DISSOLVED OXYGEN AND CHEMICAL OXYGEN DEMAND. The changes in the sediment-water systems simulating the hypolimnion of the reservoir were verification that the O_2 demand of sediments and H_2O could deoxygenate and keep DO levels below 1 to 2 mg/&, the level recommended for control of solute release (Fillos and Molof 1972; Mortimer 1971). The release of substances exerting a COD was further evidence of the importance of sediment O_2 demand.

The changes in Reactor R1 were verification that sediments alone could cause deoxygenation of waters to less than 3 mg/ L and cause NH₃-N release.

Comparison of COD levels in Wahiawa Reservoir surface waters and Ku Tree Reservoir waters yielded evidence that the organic loading to the Wahiawa Reservoir may result in a net COD increase of 7 mg/ ℓ . Similar comparison of epilimnetic and hypolimnetic waters at Wahiawa Reservoir showed that sediment can increase the COD by an equivalent amount. In the test systems, substances from the sediment were found to increase the COD by 10 mg/L. Thus, sediment appears to be able to increase the COD by an equivalent, or greater amount, than any external loading source. Although larger H₂O volumes are probably affected by any external loading and the net loading from external inputs may be greater than from the sediment, the effect of sediment on the COD in immediately overlying H_2O is of greater importance relative to the above considerations. The increase (>10 mg/l) and maintenance (>20 mg/l) of the high level of COD relative to the DO saturation (about 9 mg/ ℓ) is proof that the sediment exerts such a significant and continuing O_2 demand that the DO in the hypolimnion is depleted. This is of critical importance as fish life may be destroyed and significant amounts of solutes, including nutrients, may be released with the onset of anaerobic conditions.

SIGNIFICANCE OF NITROGEN AND PHOSPHORUS IN REACTORS. The significance of the N and P in the reactor waters can be assessed by comparison with results from other studies. In temperate Wisconsin lakes, Sawyer (1947) found that algal growths were controlled at inorganic P levels of less than 0.01 mg P/ℓ and inorganic N of less than 0.30 mg N/ ℓ . Similar observations were reported elsewhere (Bartsch 1972; Mackenthum, Kewp, and Stewart 1968; Sylvestor 1961; Vollenweider 1968). Critical levels in Wahiawa Reservoir determined in a previous study were 0.01 mg/ ℓ soluble inorganic P and 0.26 mg/ ℓ soluble inorganic N (Young et al. 1975).

Under oxygenated conditions, the concentration of P decreased below these limits and P was not detected in most reactors. Nitrogen release from the sediment was inhibited and the high concentration in the waters was due to release prior to the development of the surface oxidized sediment layer. Flushing and losses to sediment were expected to decrease the N concentration to low, insignificant levels.

Under anaerobic conditions the net change and the actual concentration of inorganic N exceeded the critical levels reported for the reservoir by at least 18 times. The concentration of $PO\overline{\overline{4}}$, in general, exceeded the limit except in reactors with distilled-deionized H₂O and reactors R2 and R3. However, the availability of the sorbed or reacted $PO\overline{\overline{4}}$ fraction is questionable. Soluble inorganic P levels exceeded the critical levels only in the Anaerobic Series 2 reactors with the Ku Tree Reservoir and the Wahiawa Reservoir surface waters by about 3 to 5 times. The results showed that the concentration of dissolved P in H₂O is reduced by sorption onto suspended sediments and release from the sediment does not occur if conditions are not reducing enough. Hence, the sediment P contribution is only significant for low-turbid waters under highly reduced conditions.

The concentration of N and P, measured in reactors where P release occurred, were significant. However, the volume of overlying H_2O in situ in which such sediment-released nutrient can have any effect is an important consideration. If the sediments affect only the immediate overlying H O, then subsequent mixing and dilution during overturn may render the contribution insignificant. In the absence of external nutrient sources, dilutions of 3 to 1 and 25 to 1 may respectively render insignificant the effect of inorganic P and inorganic N. In situ evidence of this situation is given in Figures 11 to 13 for N and P. The high N and P in the hypolimnion and P in the epilimnion decreased sharply at the overturn, and no N and P increases in the epilimnion, as a result of mixing with hypolimnetic waters high in nutrients, was noticeable. From comparison of inorganic N values immediately before and after the overturn, the dilution was from 6 or 7 to 1, enough to render insignificant the P contribution from the sediment. To fully assess the impact of the sediment on nutrients in H_2O , the net loading from the sediment should be ascertained.

NITROGEN AND PHOSPHOROUS LOADING RATES. Vollenweider (1968) developed nutrient loading guidelines as a function of the mean depth of the H_2O body (Table 13). The appropriate depth should be considered in applying Vollenweider's guidelines to the results of this research. Sediment was collected from the deepest portion of the reservoir. Preliminary analysis of the sediment showed that the N and P levels were related to H_2O column depth in the reservoir (Young et al. 1975). Relative release rates for shallower portions of the reservoir were presumed to be the same (in proportionate relation to depth) as that measured in this study, and actual release rates were scaled down accordingly. Therefore, the calculation of permissible loading rates for the entire reservoir should take into account the depth at Station 2. The limiting rates applicable to the reservoir are summarized in Table 14.

Mean	Permis Loading,	sible up to:	Dangerous in Exce	Loading ss of:	
to	Total	Total	Total	Total	
10.	N	P	N	Р	
(m)		(g/m	/yr)		
5	1.0	0.07	2.0	0.13	
10	1.5	0.10	3.0	0.20	
50	4.0	0.25	8.0	0.50	
100	6.0	0.40	12.0	0.80	
150	7.5	0.50	15.0	1.00	
200	9.0	0.60	18.0	1.20	

SOURCE: Vollenweider (1968).

There was P release from the sediment only in the Anaerobic Series 2 reactors with the Ku Tree Reservoir and Wahiawa Reservoir surface waters, and the rates were well within Vollenweider's dangerous loading limits under all conditions (Table 15).

Nitrogen release rates are presented in Table 16. Maximum release rates for N exceeded Vollenweider's guidelines by 2 to 33 times depending on the H₂O level considered (Table 17). Under fully oxidized conditions in the sediment, there was no N release. In the anaerobic reactors, equilibrium release rates of N were about 50% for Series 1 and 120% for Series 2 compared to Vollenweider's dangerous loading limits. The significance of sediment N release rates thus was less in the Anaerobic Series 1 than in the Series 2 reactors, possibly because of the slightly more oxic conditions in the former, which resulted in a thin, oxidized surface barrier decreasing the amount of N release. Release rates at steady-state should be of primary concern as

	1			N		Р
Location	Condition	Depth (m)	P _A (mg N/	P _D m²/day)	₽ _A (mg P/r	P _D n²/day)
Station 2	low water	13.4	4.67	9.41	0.31	0.62
Station 2	high water	25.0	6.67	13.35	0.43	0.86
Station 2	mean depth	21.3	6.05	12.10	0.39	0.78
Entire Wahiawa Reservoir	mean depth	8	3.56	7.12	0.25	0.49
P _A = allowat	ole loading rat	es.			-	

TABLE 14. VOLLENWEIDER'S GUIDELINES AS APPLIED TO WAHIAWA RESERVOIR

 P_D = dangerous loading rates.

	WITH	VOLLENWEI	DER'S (1968)	GUIDELIN	ES	
		Low	/ Water	Hig	h Water	Mea	n Depth
Reactor	Release Rate (mg P/m²day)	PA	PD	PA	P _D (%)	PA	P _D
	Maximum Rate						
R2A	0.299	97	48	70	35	77	38
R2B	0.091	29	15	21	10	23	12
R3A	0.349	113	56	81	40	89	45
R3B	0.169	55	27	39	20	43	22
	Average Rate						
R2B	0.045	15	18	10	5	12	6
R3A	0.140	45	22	33	16	36	18

TABLE 15. PHOSPHOROUS RELEASE RATES IN COMPARISON WITH VOLLENWEIDER'S (1968) GUIDELINES

 P_A = allowable loading rates.

 P_D = dangerous loading rates.

TABLE	16. NITROGEN	RELEASE RATES	FROM SEDIMENT
Reactor	Incubation Time	Maximum Rate	Equilibrium Rate
	(days)	(mg	N/m²/day)
		lot	al Nitrogen
A1'	175	69.5	
Al	68	69.5	
A2	86	98.9	
A3	89	87.5	,
A4	106	55.0	
Average		76.1	
AIA	70	131.3	
A2A	70	106.8	
A3A	70	155.3	
A4A	70	127.2	
Average		130.2	
		Ammo	nia Nitrogen
R1	147	42.1	7.9
R2	149	27.1	8.0
R3	155	23.1	6.1*
R4	162	23.0	5.0
Average		28.8	6.8
RIA	94	25.5	11.9
RIB	94	28.9	12.3
R2A	112	46.3	14.1
R2B	202	45.9	13.0
R3A	89	41.7	14.8

14.6

16.6

16.8

14.3

39.1

59.6

62.3

43.7

*Nitrification accounted for.

89

89

89

R3B

R4A

R4B

Average

Peactor	Maximum Rates							Equilibrium Rates	,					
Reactor	(mg N/m²/day)	PAL	PAH	PAM	PDL	PDH	PDM	(mg N/m²/day)	PAL	PAH	PAM	PDL	PDH	PDM
A1 '	69.5	14.8	10.4	11.5	7.4	5.2	5.7					- attender & ange und		
A1	69.5	14.8	10.4	11.5	7.4	5.2	5.7							
A2	98.9	21.1	14.8	16.3	10.6	7.4	8.2							
A3	87.5	18.7	13.1	14.5	9.3	6.6	7.2							
Α4	55.0	11.7	8.3	9.1	5.9	4.1	4.6							
AIA	131.3	28.0	19.7	21.7	14.0	9.9	10.9							
A2A	106.8	22.8	16.0	17.7	11.4	8.0	8.8							
A3A	155.3	33.1	23.3	25.7	16.6	11.6	12.8							
A4A	127.2	27.1	19.1	21.0	13.6	9.5	10.5							
	(mg NH ₄ -N/m ² /day	·)						(mg NH ₄ -N/m²/day)						
R1	42.1	9.0	6.3	7.0	4.5	3.2	3.5	7.9	1.7	1.2	1.3	0.8	0.6	0.6
R2	27.1	5.8	4.1	4.5	2.9	2.0	2.2	8.0	1.7	1.2	1.3	0.8	0.6	0.6
R3	23.1	4.9	3.5	3.8	2.5	1.7	1.9	6.1*	1.3	0.9	1.0	0.7	0.5	0.5
R4	23.0	4.9	3.4	3.8	2.4	1.7	1.9	5.0	1.1	0.8	0.8	0.5	0.4	0.4
RIA	25.5	5.4	3.8	4.2	2.7	1.9	2.1	11.9	2.5	1.8	2.0	1.3	0.9	1.0
RIB	28.9	6.2	4.3	4.8	3.1	2.2	2.4	12.3	2.6	1.8	2.0	1.3	0.9	1.0
R2A	46.3	9.9	6.9	7.7	4.9	3.5	3.8	14.1	3.0	2.1	2.3	1.5	1.0	1.2
R2B	45.9	9.8	6.9	7.6	4.9	3.4	3.8	13.0	2.8	2.0	2.2	1.4	1.0	1.1
R3A	41.7	8.9	6.3	6.9	4.4	3.1	3.4	14.8	3.2	2.2	2.4	1.6	1.1	1.2
R3B	39.1	8.3	5.9	6.5	4.2	2.9	3.2	14.6	3.1	2.2	2.4	1.6	1.1	1.2
R4A	59.6	12.7	8.9	9.9	6.4	4.5	4.9	16.6	3.5	2.5	2.7	1.8	1.3	1.4
R4B	62.3	13.3	9.3	10.5	6.6	4.7	5.1	16.8	3.6	2.5	2.8	1.8	1.3	1.4

TABLE 17. NITROGEN RELEASE RATES RATIO TO VOLLENWEIDER'S GUIDELINES

*Nitrification accounted.

 P_{AL} = allowable loading at low water. P_{AH} = allowable loading at high water.

PAM = allowable loading at mean water.

PDL = dangerous loading at low water.

PDH = dangerous loading at high water.

PDM = dangerous loading at mean water.

this would be a simulation of stagnation conditions in the reservoir hypolimnion. Maximum release may occur during the initial onset of anoxic conditions or during periods of flushing or overturn when a high NH_3 gradient exists in the H_2O column or when the surface oxidized sediment layer is not yet developed or is destroyed. Incubation time may have had an effect on N release rates since steady-state levels for the Anaerobic Series 2 reactors were greater than for the series 1 reactors. Maximum release rates were not time dependent and were calculated to be greater for the Aerobic and Anaerobic Series 2 reactors than for the Series 1 reactors.

The sediment contribution of N and P accounted for a significant fraction of or exceeded the dangerous loading limits recommended by Vollenweider. However, the relative importance of these release rates can only be appropriately ascertained by comparison with other nutrient sources and loading rates as in Table 18 (Young et al. 1975). The N loading rate from the sediment was found to exceed dangerous loading limits.

TABLE TO: NOTA	ILNI DALANCE AN	LUADIN	d MAILS		IAWA NESERVO	ALK S
	Loading	Rates	R		Ratic	to
Sources	N	Р	% of	Total	Vollenwe	eider's ³
	(mg/m ² ,	/day)	N	Р	N	Р
Streams	13.8	9.0	9	18	1.9	18
Wahiawa STP	104.7	33.7	69	69	14.7	68
Whitmore Village STP	2.6	4.1	2	8	0.4	8
Urban Runoff	23.2	2.2	15	4	3.3	4
Sediment Release ¹	8.5	0.1	5	<1	1.2	1
Total	152.8	49.1		2 6	21.5	99
Sinks		-	1			
Outlet and Spillway Aerated Sediment ²	30.3 (38.3)	20.9				
Net Balance	122.8 (74.5)	21.2	3		17.2 (11.9)	57
			1			

TABLE 18. NUTRIENT BALANCE AND LOADING RATES IN WAHIAWA RESERVOIR

¹Steady-state release rate under anaerobic conditions for Series 2 reactors adjusted for in situ mean depth.
²Nitrogen balance in Aerobic Series 2 reactors.
³Dangerous limits (Vollenweider 1971).

Under anaerobic conditions typical of the hypolimnion in Wahiawa Reservoir, the sediment contribution was found to be only 5% of the total N and less than 1% of the total P loading. Hence, sediments appear to be a relatively minor source of nutrient in relation to other inputs. The only possible external nutrient input that can be practically eliminated at present is the STP discharge. The relative significance of the nutrient release from the sediment after removal of the input from the Wahiawa STP discharge can be determined from Table 19. The sediment will then contribute only 18% of the total N and less than 1% of the total P.

The results in Table 19 are also indicative that under aerobic conditions sediment and outflows can account for all of the N input after the Wahiawa STP effluent is diverted. However, this would require aeration of all the sediments in the entire reservoir which is not feasible or practical.

It appears that the sediment is a relatively minor source of nutrient relative to other inputs to the reservoir. Even with the removal of the Wahiawa STP effluent, the importance of other noncontrollable inputs far ex-

	Loading	Rates	% of	Total
Sources	N (mg/m ²	P /day)	Ň	P
Streams Whitmore Village STP Urban Runoff Sediment Release	13.8 2.6 23.2 8.5	9.0 4.1 2.2 <0.1	29 5 48 18	59 27 14 <1
Total	48.1	15.3		
Sinks				
Outlet and Spillway Aerated Sediment	9.4 (38.3)	6.5		
Net Balance	38.7 (-0.6)	8.8	· ·	-

TABLE 19. NUTRIENT LOADING AFTER REMOVAL OF WAHIAWA STP INPUT

ceeds that of sediment. Therefore, rehabilitation of the sediment does not seem to be required for nutrients. A factor not considered, however, is the form of the nutrient contributed. The N and P released by sediments were in chemical forms readily available for biological assimilation whereas urban runoff, stream inflows, and STP discharges may have significant amounts of nutrients tied up in an organic form which may be deposited prior to mineralization.

SUMMARY OF THE TROPHIC EFFECTS OF SEDIMENTS AND APPLICATION OF RESULTS TO IN SITU CONDITIONS. Dissolved oxygen and nutrient levels are prime indicators of trophic status (Table 20). The effect of sediment on DO was found to be significant. In turn, O_2 supply was found to play a critical role in nutrient exchange in the reactors. Under aerated conditions a rehabilitory effect occurred, while under anaerobic conditions a eutrophying effect occurred on influent and surface waters of Wahiawa Reservoir Station 2s. The sediment had a rehabilitory effect on hypolimnetic waters. It can be concluded that the sediment can cause eutrophication of waters at the surface of the Wahiawa and the Ku Tree reservoirs, therefore removal of external inputs may not be sufficient to change the lake to oligotrophic conditions.

The O_2 demand of the sediment was found to be significant. In Anaerobic Series 1 reactors, the sediments caused deoxygenation of waters below the level of 1 to 2 mg/& DO recommended for control of sediments (Fillos and Molof 1972; Mortimer 1971). In situ DO levels verified the experimental results. Release of COD from sediment and maintenance of high COD levels (relative to saturation DO conditions) were measured under anaerobic conditions. Under aerobic conditions, COD levels were decreased. Results indicate that the sediment must be stabilized for O_2 -demanding constituents. With time, the O_2 demand of the sediment decreased. Decreasing the O_2 -demanding inputs and a period of aeration could result in stabilization of the sediment. But since a high level of organic matter remained in the sediment after incubation in the reactors, this may require a long period of time. Immediate improvement of the reservoir may require removal of sediment, which will require the analysis of core samples, coupled with diversion of STP effluents. Aeration is a possible method of control for O_2 -demanding substances and does

			Fina	Reactor	• Water Trop	hic Stat	us		
Reactor	Initial Reactor Water			Diss.	Inorganic		Sediment	Final	Status
	Trophic Status	DO	P0 [‡]	P0=	Ň	AGP	NH 3	Status	Change
			•		-	•	•	•	
AL	0		0		E >	0	0	0	+
AI	0		0		E	0	0	0	+
A2	0		0		E	0	0	0	+
A3	E		0	-	E	0	0	0	+
A4	Е		0		E	0	0	0	+
AIA	0		0	0	E	0	0	0	+
A2A	0		0	0	E	0-M	0	0	+ *
A3A	F F		м	M	E	0	0	м	+
A4A	Ē		м	0	Ē	0-M	0	0	+
DI	0	F	0	0	F	0	E .	м	_
	0	5	м	0		0	с с	M	_
RZ D2	0	. E	E1 M	0	E E	0	с с	n M	
K3	E	с г		0	E F	0	Ē	M N	+
К4	E	E	E	U	E,	U .	E	M	+
RIA	0		0	0	Ē	0	E E	0	-
RIB	0		0	0	E	0	E	0	-
R2A	0		E	E	E	0	E E	E	-
R2B	0		E	Е	E	0	E	E	-
R3A	F		E	E	E	E	E	E	_ "
R3B	Ē		E	Ē	E	Ē	Ē	Ē	-
RLA	E		F	M	Ē	ō	F	Ā	* + .
RLR			F	0	E F	0	F	M	+
עדא	E	-		0	- -	v			2011 B 24

TABLE 20. SEDIMENT EFFECTS ON REACTOR WATER TROPHIC STATUS

0 = oligotrophic. M = mesotrophic. E = eutrophic.

+ = improvement.
- = deterioration.

not require the removal of STP inputs.

The sediment was efficient in removing P. Even with continued P input, contact between H_2O and sediment under oxic conditions resulted in P sorption. However, the depth of the reservoir and stratification causes isolation of the epilimnion from contact with sediment. Hence, high inputs of P must be diverted or treated for P removal to improve the P status of the reservoir even if aeration is practiced. The low concentration of Cu^{++} , Fe⁺⁺, and Fe⁺⁺⁺ in the epilimnion would also rule out precipitation as a significant or effective method of P removal during aeration of the reservoir.

The effect of anaerobic sediment on the amount of P in H_20 varied with removal occurring in some reactors and release in others. In addition, $PO_{\overline{4}}^{\overline{2}}$ may have been released while the level of dissolved P decreased. For Anaerobic Series 1 reactors, the slightly oxic conditions may have been sufficient to minimize P release. A rehabilitative effect occurred in all Anaerobic Series 2 reactors except in the Ku Tree Reservoir and the Wahiawa Reservoir surface H_20 reactors. In these latter reactors, a eutrophic effect on P occurred with the release of P to high eutrophic levels of P. Therefore, sediment could serve as a significant source of P to influent and surface waters of the reservoir. However, calculated P release rates fell within Vollenweider's (1968) permissible loading limits. This is evidence that removal of external inputs may result in trophic improvement of the epilimnion even if the hypolimnion is allowed to remain anaerobic.

Several factors can be used to illustrate the critical role of suspended sediment on P. Under aerated conditions, a turbidity decrease was found to coincide with a P decrease in the H₂O column. There was a large difference between $PO_{\overline{4}}^{\pm}$ and dissolved $PO_{\overline{4}}^{\pm}$ levels which may be due to sorption of $PO_{\overline{4}}^{\pm}$ on particulate matter. The low levels of dissolved $PO_{\overline{4}}^{\pm}$ in the hypolimnion and higher levels in surface waters, which is atypical of eutrophic lakes (Hutchinson 1957), compared to the high turbidity and high $PO_{\overline{4}}^{\pm}$ in the hypolimnion and low turbidity and similar level of $PO_{\overline{4}}^{\pm}$ as dissolved $PO_{\overline{4}}^{\pm}$ in the epilimnion, is illustrative of the critical role of suspended sediments. This observation is supported by the high levels of turbidity and $PO_{\overline{4}}^{\pm}$ and near nondetectable dissolved $PO_{\overline{4}}^{\pm}$ levels in the Anaerobic Series 1 reactors. In addition, the high level of dissolved $PO_{\overline{4}}^{\pm}$ levels. This difference is attributed to sorption on filtrable matter.

According to the AGP results for reactor R3A and B samples, some of the sorbed dissolved PO₄ (PO₄-dissolved PO₄) may be available to algae. However, no growth occurred with the high $PO\overline{z}$ -low dissolved $PO\overline{z}$ water from reactors R4A and B and the Anaerobic Series 1 reactors. The difference in sorbed P utilization may be attributed to the nature of the suspended matter. Visible suspended matter was observed in the reactors in which no algal growth was achieved, while with the reactor R3A and B samples the H2O was colored but appeared nonturbid. The presence of high amounts of in situ sediment in the hypolimnion of the Wahiawa Reservoir may serve to control the release of dissolved $PO_{\overline{4}}$ by sorption despite anoxic conditions, and is illustrative of the concept that sorption of P onto clays is Eh-independent (Serruya 1971). The observation that P is limiting in hypolimnetic waters but not in epilimnetic waters is confirmation of the rehabilatory effect of bottom and suspended sediment with respect to P. This is evidence that sediment P is not as significant a factor as suspended sediment and that lake stratification will prevent sediments from contributing available P to epilimnetic waters. Therefore, removal of external P may be sufficient to improve the trophic status of the reservoir.

Fully oxidized conditions were observed to control N release from sediments. If external N inputs are removed, oxygenation and subsequent flushing (90%/yr) could decrease the N levels in the reservoir. In addition, under aerobic conditions, sediments may serve as a N sink as a result of NO⁻ diffusion into subsurface sediments and denitrification.

Removal of external N inputs may not be sufficient to improve the trophic status of the reservoir if anaerobic conditions are allowed to continue in the hypolimnion. Substantial N contribution from sediment occurred under experimental and in situ anoxic conditions. The level of organic N in sediment is support to the conclusion that there is substantial potential N contribution (Ballinger and McKee 1971).

The importance of controlling sediment N relative to P was supported by the evidence that N is limiting to growth in the epilimnion of the reservoir (Young et al. 1975). The absence of inorganic N and the presence of inorganic P during the growing season in the reservoir also is support to this conclusion. Nitrogen release and subsequent mixing of the reservoir H_2O may increase available N and enhance eutrophic conditions. According to the relative release rates of N and P (Table 21), the sediment N is of greater importance and, since it is the limiting nutrient in surface waters, this further stresses the importance of sediment on the trophic status of the reservoir.

	Ratio Considering	Ratio Considering								
Reactor	Maximum P	Average P								
	Release Rates	Release Rates								
R2A	47	·								
R2B	143	289								
R3A	42	106								
R3B	60									

TABLE 21. N:P RELEASE RATES

The concentration of N and P in situ far exceeds that of recommended levels for eutrophication control. Therefore, P may be decreased to a level where it is limiting. Phosphorous release by sediment appears to be minimal under anaerobic conditions. Suspended sediment may render dissolved $PO_{\overline{4}}$ unavailable. Thus, P removal from external inputs will improve the trophic status of the reservoir and control of sediment is not required. The technological ease of P removal also seems to favor P control.

Evaluation of Management Alternatives for Wahiawa Reservoir

Several alternatives should be considered in the evaluation of management alternatives to improve the status of the reservoir. Nuisance eutrophic conditions in the reservoir have not been qualitatively observed during field sampling over the past 2 years (1974 to 1976). Fish kills have occurred and this is apparently the major problem associated with the eutrophic conditions in the reservoir. Trophic improvement would benefit sport fishery, but would not be necessary for the two other major uses of the reservoir. Should steps be considered to improve the trophic status of the reservoir, the degree of nutrient removal should be tempered with that required for fish production. Consideration should be given to the N and P levels from stream inflows and runoff as these exceeded recommended loading limits. The combined nutrient load from sediments, STP effluents, urban runoff, and stream inflows has not resulted in severe deterioration of the H_2O body or other detrimental effects except for the isolated instances of fish kills.

Results of this research show that the N contribution from sediment is substantial while that from P is of lesser importance. The O_2 demand of the sediments is sufficient to deoxygenate hypolimnetic waters to near anaerobic conditions. However, the impact of STP effluents is far greater than that of urban runoff and stream inflows which are, in turn, much greater than the sediments.

Control of either N or P external inputs will improve the trophic status of the reservoir. Continued secondary treatment with waste water disposal into the reservoir would not improve the trophic conditions in the reservoir and would render the three major uses incompatible. Diversion of STP effluents by effluent reuse and disposal by subsurface injection or diversion to the proposed Waialua outfall would result in a definite improvement of the trophic status of the reservoir.

A nutrient model was developed to predict the changes that would occur in Wahiawa Reservoir following removal of the nutrient inputs from the Wahiawa STP. Results show that diversion of this nutrient source will decrease nutrient inputs to the reservoir by four times and nutrient levels in the reservoir epilimnion at Station 2 by 65% for N and 46% for P. Mean epilimnion nutrient concentrations would be decreased to 0.45 mg total N/ ℓ and 0.109 mg total P/ ℓ . Results are applicable to the basin of Wahiawa Reservoir (Sta. 2). As N is the limiting nutrient in the surface waters of the reservoir, reduction of this constituent in the reservoir epilimnion will result in improvement of the trophic status of the H₂O body. Contributions of N and P from urban runoff and streams ill, however, still result in excessive loading rates.

The existing conditions are presented in Figure 42. Changes in the percent nutrient storage and sediment release rates are hypothesized and shown respectively in Figures 43 and 44. The time required for the sediment to reach a new steady state with respect to NH_3-N is about 600 days (Fig. 45). The new steady-state conditions are shown in Figure 46. The new steady-state conditions would be attained in the epilimnion within a month and in the hypolimnion within about 2 years (Fig. 47). The development of this model was based on in situ nutrient data, nutrient input data to the reservoir as taken from Young et al. (1975), and the following assumptions:

- 1. Nutrient concentrations at Station 2s represent the average for the entire reservoir epilimnion.
- 2. Average nutrient concentrations prior to the overturn in the hypolimnion equal the concentration at Stations 2s + 2d/4. The factor 4 is used because comparison of nutrient content in the reservoir water before and after the overturn on 2 and 9 October 1975 shows that this is the approximate dilution factor.
- 3. Hypolimnion nutrient concentrations after the overturn equal the concentration at Stations 2s + 2d/2.
- 4. Epilimnion is confined to the top 3 m of the reservoir.





FIGURE 43. RELATIONSHIP OF NUTRIENT STORAGE TO LOADING RATE







FIGURE 45. CHANGE IN SEDIMENT NH3-N IN ANAEROBIC REACTORS WITH STATION 2d WATER



WAHIAWA STP INPUTS



Epilimnion volume = % capacity • 3.2 km² • 3 m Hypolimnion volume = total volume - epilimnion volume Total volume = 3 bil gal

- 5. There are ideal flushing times for nutrients.
- 6. The net storage rate pattern follows Figure 42.
- 7. The new residence times increased according to the percent increase in the net nutrient storage.
- 8. Sediment nutrient release is a function of the deposition rate of nutrients (Fig. 44).
- 9. The model is based on stratified conditions.

Tertiary treatment for only P may be sufficient and preferred although N is presently limiting as there is substantial N contribution but not P from sediments. Up to 99% of the P can be removed by physical unit procession such as sorption, reverse osmosis, and distillation and 95 to 98% by chemical precipitation (Metcalf and Eddy 1972). Applying these efficiencies, tertiary treatment would result in a reduction of P loading to less than 1.7 mg $P/m^2/$ day from the Wahiawa STP and the N to P ratio or nutrient inputs to the reservoir would increase to 9 to 1 resulting in P sensitivity in the reservoir as the typical N to P ratio for algae is 7 to 1 (Porcella and Bishop 1975). This alternative may render sediments unimportant as P release from sediments is of insignificance or is controlled by suspended sediments. The relative technological ease of P removal supports this alternative. In addition, tertiary treatment could reduce significant amounts of N and COD depending on the treatment selected. Unit processes, such as reverse osmosis and ion exchange, can also decrease N levels by 99% and 90%, respectively, and COD by 90% and 40%, respectively. Tertiary treatment of the effluent may be nearly as efficient as diversion as a means of reducing the nutrient load to the reservoir. Use of tertiary treatment followed by disposal into the reservoir would also provide a significant amount of H_2O to the reservoir during low H₂O periods.

Mechanical or artificial aeration may be sufficient to maintain high DO levels in the hypolimnion of the reservoir and in the epilimnion during the night, and to control the sediment nutrient contribution during critical low H_2O conditions, but this will afford only a temporary means of control. Continued influx of STP effluent will sustain a high level of P and N in the trophic zone of the reservoir and exert an O₂-demanding load. Because aeration is currently done only at the basin of the reservoir, the rest of the reservoir would still be subject to the eutrophying effects of the effluents. In addition, aeration of the sediment surface is required to stabilize the O₂ demand of sediments and control solute release but this may result in disturbance of the sediments resulting in the release of more nutrients.

Control of sediments may not be necessary for both N and P if STP effluents are diverted or treated for P removal only. There is a significant amount of N contribution relative to P from sediments, but if P is sensitive in the epilimnion as a result of reduction in STP nutrients, the amount of N contributed may be rendered unimportant. The organic load, however, must be accounted for because according to in situ observations and laboratory results, deoxygenation by sediment and O_2 -demanding substances as well as COD release is of significance in creating anoxic conditions. However, reduction of nutrient inputs may decrease algal growth and the resulting amount of algae settling into the hypolimnion which may exert an O_2 demand as a result of decomposition. Thus, reduction of nutrient inputs will decrease to O_2 demand, which in turn will raise DO levels and control nutrient release.

CONCLUSIONS

Evaluation of the research results has led to the following conclusions:

1. Sediments have an oligotrophic effect under anaerobic conditions and on Whiawa Reservoir hypolimnetic waters under anaerobic conditions, but a eutrophic effect under anaerobic conditions on Ku Tree Reservoir and Wahiawa Reservoir surface and distilled-deionized waters.

2. The N, P, and COD levels sustained and increased as a result of contact with sediments under anaerobic conditions exceed critical nutrient and saturated DO levels, evidence of the eutrophic potential of the sediments. However, subsequent dilution during overturn may render P and COD contributions insignificant.

3. Phosphorous release rates under anaerobic conditions are within Vollenweider's permissible loading limits. Nitrogen release rates exceeded Vollenweider's dangerous loading limits.

4. The combined sediment and water O_2 demand was capable of deoxygenating DO-saturated waters. The sediments alone decreased DO to less than 3 mg/ ℓ .

5. Sediment is a minor source of nutrients relative to other sources in Wahiawa Reservoir, contributing less than 1% of the total P and about 5% of the total N. With removal of nutrient inputs from the Wahiawa STP, sediment will account for less than 1% of the total P and about 18% of the total N. Nutrient diversion of the Wahiawa STP will result in a 65% reduction of N and 46% reduction of P in the epilimnion of the reservoir. The time required to reach new steady-state conditions is about one month for the epilimnion and two years for the hypolimnion and sediments.

6. Nutrients from sediments supported eutrophic levels of algal growth in the AGP tests. According to the N to P ratio of the H_2O , N to P release-rate ratios and growth levels, P would become limiting.

7. Phosphorous release is significant only to low-turbidity waters under sufficiently reducing conditions. However, suspended matter may serve to control the release of dissolved $PO_{\overline{4}}^{\overline{\Xi}}$ by adsorption, precipitation, or biological uptake, rendering it unavailable for algal utilization.

8. The O_2 demand and N contribution from sediments are evidence that sediments require corrective measures with respect to these parameters. Phosphorus does not appear to be a significant factor in sediment.

9. Corrective measures for sediment control will not have a significant impact on nutrient levels. However, the O_2 status of the reservoir may be significantly improved.

10. The development of an oxidized surface sediment layer inhibited alkalinity, color, N, P, and COD release. In addition, P will be adsorbed or precipitated and COD decreased if the H_2O is oxygenated.

11. Under anaerobic conditions alkalinity, color, N, and COD are released. Whether P is released is dependent on whether conditions are sufficiently reducing. Nitrogen may also be released even though the H_2O is oxygenated if the oxidized layer is not fully developed.

12. The sediment acts as a net total N and inorganic N sink under aerobic conditions but as a net source or sink of total N and source of inorganic N under anaerobic conditions. The percent total N loss was related to the incubation time in the reactor.

13. The oxidized layer is formed by O_2 diffusion into the mud. The thickness required to inhibit the release of solutes is approximately 50 mm. The DO level required for the development of this surface layer is greater than 3 to 4 mg/ ℓ .

14. Concentrations of N, P, and organic C in sediment far exceeded that in the H_2O column and are evidence of the eutrophic potential of the sediment.

15. Aeration may improve the status of the reservoir. If STP effluents are diverted, subsequent dilution and flushing could significantly decrease the level of nutrients in the reservoir because sediment nutrient release will be controlled. However, release from sediments in nonaerated areas and inflows may contribute significant levels of nutrients.

16. Aeration alone is not fully sufficient as a corrective measure. It is a solution to the problem only in one area of the reservoir. Continued STP inputs and release from sediment elsewhere in the reservoir and stream inflows will sustain the high levels of N and P in the epilimnion of the reservoir required for algal growth. In addition, aeration of the sediment surface is required to control nutrient release; however, this process may resuspend and mix the sediments releasing more nutrients.

17. In relation to sediment, management alternatives should favor P removal as suspended sediment may serve to adsorb and control released sediment P while N is released in significant quantities.

18. Bacteriological activity affected several processes including enhancing the mixing and resuspension of sediments, rendering conditions sufficiently reducing to enhance the release of nutrients, affecting N transformations, and deoxygenating the reactor waters and changing the buffering capacity of the H_2O .

19. Mixing of sediments with the H_2O column could release significant amounts of nutrients to the H_2O column.

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Elapsed Time	DO	Temp	Turb	pН	Alk	NH 3	Org.	NO2 +	Total	P0 [≣]	Total	Vol. Drawn														
(days)	(mg/l)	(°C)	(JTU)		(mg/l)		m	ng N/l		mg	P/l	(mL)														
0		17		5.4	1	0.35	0.14	<0.01	0.49	0.018	0.141	750														
1		16.5		5.7	3	1.38	0.19	<0.01	1.57	0.018	0.061	500														
3		19		5.4	4	1.97	0.17	<0.01	2.14	0.018	0.937	500														
7		19		5.2	5	2.75	0.21	0.15	3.11	0.010	0.052	500														
10		16		5.4	3	2.16	0.27	1.26	3.69	0.012	0.048	500														
14		17.5		3.9	0	0.86	0.30	3.15	4.31	0.009	0.037	500														
17		20		3.7	0	0.42	0.18	3.13	3.73	0.008	0.041	500														
21		21	22	3.7	0	0.23	0.13	3.05	3.41	0.010	0.010	500														
25		19	14	3.7	0	0.20	0.17	2.99	3.36	0.013	0.016	500														
28		19	10	3.8	0	0.17	0.17	2.76	3.10	0.015	0.015	500														
49		19	5.5	4.0	0	0.23	0.12	2.18	2.53	0.014	0.014	500														
56		19.5	5	3.8	0	0.09	0.09	1.91	2.09	0.014	0.018	500														
70	9.8	18	2.7	3.7	0	0.04	nd	1.67	1.71	nd	nd	500														
85	9.8	18.5	1.5	4.0	0	nd	0.14	1.62	1.76	0.003	0.003	500														
100	9.3	18.5	0.5	4.5	0	nd	nd	1.45	1.45	nd	0.003	500														
114		20	0.3	4.2	0	0.02	0.17	1.15	1.34	nd	nd	500														
175	9.0	20	5.5	4.2	0	0.03	0.14	0.60	0.77	nd	nd															

.

APPENDIX TABLE A.1. REACTOR A1' WATER QUALITY

NOTE: Incubation Water Source - Distilled Deionized Water.

Incubation Date - 3/31/75 to 9/22/75.

							Ni	trogen		Phos	ohorus	
Elapsed Time	DO	Temp	Turb	рН	Alk	NH 3	Org.	NO2_+ NO3	Total	P04	Total	Vol. Drawn
(days)	(mg/%)	(°C)	(JTU)		(mg/%)		m	g N/&		mg	P/&	(mL)
0		19.5	88	5.8	4	0.22	0.06	nd	0.28	0.025	0.340	750
1			58	5.9	5	0.88	0.05	nd	0.93	0.030	0.132	600
3			45	5.5	5	1.80	0.11	0.02	1.93	0.030	0.070	600
7	9.8	19	45	5.6	7	3.03	0.08	0.11	3.22	0.022	0.069	500
10	9.6	19	44	6.4	6	2.76	0.08	1.03	3.87	0.022	0.050	500
13			38	4.4	0	1.17	0.27	3.03	4.47	0.014	0.040	500
17	9.6	18.5	27	4.1	0	0.62	0.28	3.07	3.97	0.009	0.032	500
20	9.7	18.5	20	4.4	0	0.31	0.18	3.05	3.54	0.006	0.025	500
24	9.6	18.5	14	3.6	0	0.16	0.14	3.00	3.30	0.004	0.016	500
27	9.3	18.5	10	3.7	0	0.11	0.22	2.90	3.23	0.004	0.004	500
35	9.0	18.5	4.8	4.5	0	0.16	0.08	2.71	2.95	0.002	0.004	500
41	9.1	20	2.6	4.6	1	0.20	0.11	2.60	2.91	nd	0.009	500
48	8.8	21	0.7	3.7	0	0.16	0.06	2.50	2.72	nd	nd	500
53		20	0.4	3.9	0	0.47	nd	2.25	2.72	nd	nd	500
62	8.4	22.5	0.1	3.8	0	0.06	nd	2.23	2.29	nd	0.002	500
68	8.4	22	0.2	4.0	0	0.01	0.03	2.05	2.09	nd	0.003	

APPENDIX TABLE A.2. REACTOR AI WATER QUALITY

NOTE: Incubation Water Source - Distilled Deionized Water.

Incubation Date - 5/31/75 to 8/7/75.

							Ni	trogen		Phos	ohorus	and the second secon
Elapsed Time	DO	Temp	Turb	pН	Alk	NH 3	Org.	NO ₂ _+ NO ₃	Total	P0 [≣]	Total	Vol. Drawn
(days)	(mg/l)	(°C)	(JTU)		(mg/l)		m	g N/ℓ		mg	P/l	(mL)
0	9.8	11	20	6.1	3	0.21	0.21	0.01	0.43	0.005	0.020	500
1	9.6	18.5	23	6.5	8	1.76	0.28	<0.01	2.04	0.005	0.014	500
3	9.7	19	21	6.2	12	2.72	0.24	0.01	2.97	0.005	0.018	500
7	9.7	18.5	21	6.0	12	3.47	0.20	0.11	3.68	0.007	0.017	500
- 11	9.4	18.5	23	6.2	4	2.72	0.49	1.58	4.79	0.008	0.036	500
14	9.3	19	20	3.9	0	1.44	0.23	2.83	4.50	0.010	0.023	500
18	9.2	18.5	17	3.8	0	0.90	0.22	3.05	4.17	0.007	0.017	500
22	9.0	18.5	14	4.3	0	0.50	0.28	3.25	4.03	0.004	0.038	500
25	9.2	18.5	12	4.1	0	0.43	0.28	3.25	3.96	0.003	0.014	500
28	9.1	20	10	4.4	0	0.40	0.21	3.08	3.69	0.003	0.018	500
35	8.7	21	6.7	3.7	0	0.33	0.16	3.15	3.64	0.001	0.004	500
40		20	5.6	3.6	0	0.32	0.34	2.70	3.36	nd	0.001	500
49	8.4	22.5	3.4	3.6	0	0.16	nd	2.56	2.72	nd	0.006	500
56	8.5	21	2.2	4.2	0	0.28	0.12	2.43	2.83	nd	0.004	500
67	8.4	22	1.2	3.7	0	nd	nd	2.25	2.25	nd	nd	500
75	8.3	22	1.0	3.7	0	nd	0.21	1.95	2.16	nd	0.010	500
82		22.2	0.6	3.9	0	nd	0.11	1.90	2.01	nd	nd	500
89	8.8	19.5	0.5	3.9	0	0.04	0.09	1.82	1.95	nd	nd	

APPENDIX TABLE A.3. REACTOR A2 WATER QUALITY

NOTE: Incubation Water Source - Ku Tree Reservoir (Station 11).

Incubation Date - 6/13/75 to 9/10/75.

							Nit	rogen		Phosp	horus	
Elapsed Time	DO	Temp	Turb	рH	A1k	NH 3	Org.	NO2_+ NO3	Total	PO4	Total	Vol. Drawn
(days)	(mg/l)	(°C)	(JTU)	24	(mg/l)		mg	N/2		mg	P/l	(mL)
0 1	10.7	10 18.5	6.3 10	6.3 6.4	10 13	0.24	0.84	0.04	1.13	0.093	0.223	500 500
7	9.6	18.5	18	6.9	14	4.04	0.73	0.14	4.91	0.055	0.127	500
10 14 18 21	9.3 9.1 9.1 9.2	18.5 18.5 18.5 18.5	21 19 16 12	6.4 4.0 4.0 4.3	8 0 0 0	3.47 1.25 0.69 0.50	0.42 0.31 0.49 0.40	1.16 3.45 3.80 3.85	5.05 5.01 4.98 4.75	0.047 0.034 0.017 0.015	0.093 0.072 0.057 0.050	500 500 500 500
24 28 34 41	9.1 9.3 9.4 9.4	20 16 17 16.5	10 7.9 4.7 2.7	4.2 3.8 3.8 3.7	0 0 0 0	0.40 0.31 0.43 0.30	0.37 0.39 0.52 0.22	3.70 3.75 3.35 3.09	4.47 4.45 4.30 3.61	0.024 0.011 0.007 0.004	0.054 0.034 0.022 0.017	500 500 500 500
52 63 71 78 86	8.5 8.4 8.3 8.3	21 22 22 22 19.5	0.9 0.5 0.4 0.4 0.5	4.1 4.0 4.2 4.0 3.9	0 0 0 0	0.13 0.08 0.12 nd 0.06	0.11 0.21 0.24 0.27 0.28	2.98 2.80 2.46 2.37 2.15	3.22 3.09 2.82 2.64 2.49	0.003 0.003 nd 0.004 nd	0.012 0.013 0.010 0.012 0.006	500 500 500 500

APPENDIX TABLE A.4. REACTOR A3 WATER QUALITY

NOTE: Incubation Water Source - Lake Wilson Surface (Station 2s). Incubation Date - 6/17/75.

							Nitr	ogen_	1.8.8.8.9.7.9.2.2.0. 9 .	Phosp	horus	
Elapsed Time	DO	Temp	Turb	pН	Alk	NH 3	Org.	NO ₂ _+ NO ₃	Total	P0 [‡]	Total	Vol. Drawn
(days)	(mg/l)	(°C)	(JTU)		(mg/l)		mg	N/2		mg	P/l	(mL)
0	1.5	10	52	6.4	57	5.11	0.14	nd	5.25	2.76	0.338	500
1	9.8	18.5	39	7.2	35	5.92	0.04	0.01	5.96	0.271	0.271	500
3	10.1	18.5	37	7.2	30	6.31	0.39	0.01	6.71	0.260	0.269	500
7	9.7	19	31	7.1	33	7.11	0.44	0.23	7.78	0.229	0.237	500
10	9.7	19	33	6.4	25	5.74	0.52	1.77	8.03	0.227	0.246	500
14	9.9	18.5	32	4.1	0	1.63	0.59	5.35	7.57	0.192	0.210	500
18	9.4	18.5	29	4.0	0	1.39	0.32	5.10	6.81	0.158	0.180	500
22	9.1	18.5	10	3.7	0	0.94	0.17	5.10	6.21	0.063	0.063	500
26	9.1	18.5	5.4	4.1	0	0.61	0.23	5.05	5.89	0.028	0.039	500
29	9.2	18.5	3.9	3.9	0	0.68	0.09	4.90	5.67	0.025	0.034	500
36	6.7	16	2.6	3.8	0	0.63	0.24	4.20	5.07	0.013	0.013	500
42	9.3	17	1.1	3.8	0	0.59	0.21	4.10	4.90	0.006	0.011	500
49	9.4	16.5	0.8	3.7	0	0.46	0.13	3.97	4.56	0.008	0.008	500
60	8.5	21	0.4	4.0	0	0.22	nd	3.75	3.97	nd	0.005	500
71	8.3	22	0.3	4.0	0	0.18	0.13	3.36	3.67	0.002	0.006	500
79	8.2	22	0.2	3.6	0	0.15	0.07	3.00	3.22	nd	0.002	1000
86			0.2	4.0	0	0.02	0.12	3.36	3.50	nd	0.003	500
98	9.0	19.7	0.2	4.0	0	nd	0.14	3.16	3.30	nd	nd	500
106	9.0	20.0	0.3	4.0	0	0.06	0.15	2.64	2.85	nd	nd	

APPENDIX TABLE A.5. REACTOR A4 WATER QUALITY

NOTE: Incubation Water Source - Lake Wilson Bottom, 1 m from Bottom (Station 2d). Incubation Date - 6/9/75 to 9/23/75.

		12 2					Nitr	ogen		Phosp	horus		
Elapsed Time	DO	Temp	Turb	рΗ	Alk	NH ₃	Org.	NO2_+ NO3	Total	P0 [≣]	Total	COD	Vol. Drawn
(days)	(mg/l)	(°C)	(JTU)		(mg/l)		mg	N/&		mg	P/l	(mg/l)	(mL)
0	10.7	20.0	11	5.5	3	0.17	0.08	<0.01	0.25	0.003'	0.003'	3	900
1	10.9	20.0	16	6.3	5	1.34	0.03	0.03	1.40	0.006'	0.006'	2	900
3	11.2	20.0	18	6.7	8	2.46	0.11	0.02	2.59	0.006	0.043	4	900
7	10.9	20.0	25	6.5	10	3.47	0.25	0.55	4.27	0.008'	0.101'	5	900
10	11.0	20.0	28	6.3	3	2.77	0.25	2.58	5.60	0.009'	0.0111	2	900
14	11.2	20.0	23	4.2	0	1.37	0.34	5.30	7.01	0.004'	0.004'	2	900
17	11.4	20.0	19	4.1	0	1.01	0.14	4.68	5.83	0.009'	0.009'	2	900
21	11.6	20.0	14	4.0	0	0.67	0.20	3.63	4.50	0.007	0.017	5	900
24	9.8	20.0	10	4.0	0	0.34	0.11	3.48	3.93	0.006	0.050		900
28	9.9	19.8	7.1	3.9	0	0.28	0.08	3.52	3.88	0.005	0.008	3	900
35	10.3	20.0	3.4	3.8	0	0.17	0.08	3.40	3.65	0.002	0.002	1	900
42	9.9	20.0	1.7	4.0	0	0.14	0.11	3.24	3.49	nd	0.002	3	900
49	9.8	19.9	0.9	4.0	0	0.14	0.06	2.99	3.19	nd	nd	2	900
56	9.8	20.0	0.5	4.0	0	0.08	0.03	2.96	3.07	nd	nd	4	900
63	9.8	20.0	0.3	4.1	0	0.03	0.06	2.76	2.85	nd	nd	3	900
70	9.9	19.9	0.3	4.0	0	nd	0.08	2.64	2.72	0.001	0.002'	1	
70'			350			nd!	0.06'	2.68'	2.74	nd '	nd '	-	

APPENDIX TABLE A.6. REACTOR AIA WATER QUALITY

NOTE: Incubation Water - Distilled or Reverse Osmosis Deionized Water. Incubation Date - 12/3/75 to 2/11/76.

nd = nondetectable.

' = analysis on 0.45- μ filtrated samples (dissolved).

							Nitr	ogen		Phos	ohorus		
Elapsed Time	DO	Temp	Turb	рH	Alk	NH3	Org.	NO ₂ + NO ₃	Total	P0 [‡]	Total	COD	Vol. Drawn
(days)	(mg/l)	(°C)	(JTU)		(mg/l)		mg	N/2		mg	P/l	(mg/l)	(ml)
0	6.6	22.2	150	5.6	3	0.62	1.93	0.08	2.63	0.024'	0.024	78	900
1	10.7	20.0	135	6.6	7	1.68	0.50	0.09	3.27	0.019'	0,020'	22	900
3	10.9	20.0	105	6.5	9	2.97	0.42	0.08	3.47	0.009'	0.032'	10	900
7	10.9	20.0	69	6.3	10	3.89	0.42	0.60	4.91	0.008'	0.009'	10	900
10	10.5	20.0	59	6.1	3	2.83	0.48	2.64	5.95	0.013'	0.020'	11	900
14	11.1	20.0	48	4.2	0	1.37	0.53	5.60	7.50	0.008'	0.009'	9	900
17	11.2	20.0	40	4.1	0	1.06	0.36	5.31	6.73	0.003'	0.003	8	900
21	11.2	20.0	33	4.0	0	0.70	0.34	4.21	5.25	0.017	0.043	8	900
24	9.6	20.0	27	4.1	0	0.36	0.28	3.60	4.24	0.014	0.053	-	900
28	9.8	19.8	21	4.1	0	0.28	0.22	3.52	4.02	0.010	0.019	9	900
35	9.6	20.0	15	3.9	0	0.22	0.25	3.31	3.78	0.005	0.012	8	900
42	9.8	20.0	10	4.1	0	0.25	0.20	3.18	3.63	0.003	0.006	4	900
49	9.5	20.0	7.8	4.1	0	0.11	0.08	2.89	3.08	0.002	0.003	6	900
56	9.5	20.0	5.2	4.1	0	0.14	0.08	2.89	3.11	nd	0.003	6	900
63	9.7	20.0	3.8	4.1	0	0.08	0.14	2.70	2.92	nd	0.001	8	900
70	9.5	19.9	3.4	4.1	0	0.03	0.11	2.57	2.71	0.002	0.005	4	
70'						0.03'	0.11'	2.63'	2.77'	0.001	0.001		

APPENDIX TABLE A.7. REACTOR A2A WATER QUALITY

NOTE: Incubation Water Source - Ku Tree Reservoir (Station 11).

Incubation Date - 12/3/75 to 2/11/76.

nd = nondetectable.

' = results of $0.45-\mu$ filtrated (dissolved) samples.

				*		5	Nit	rogen		Phos	phorus		
Elapsed Time	DO	Temp	Turb	рН	Alk	NH 3	Org.	NO2_+ NO3	Total	P0 [‡]	Total	COD	Vol. Drawn
(days)	(mg/l)	(°C)	(JTU)		(mg/l)		mg	N/2		mg	P/l	(mg/l)	(ml)
0	9.9	17.5	17	6.5	12	0.50	0.76	2.24	3.50	0.056'	0.068'	15	900
1	10.6	19.6	11	6.7	14	2.49	0.70	2.24	5.43	0.024'	0.038'	15	900
3	10.6	20.0	5.8	6.8	12	3.52	0.53	2.52	6.57	0.020'	0.035'		900
7	10.3	20.0	5.1	4.7	0	2.41	0.50	4.44	7.35	0.013'	0.017'	14	900
10	10.7	20.0	6.1	4.5	0	2.10	0.36	4.86	7.32	0.006'	0.046'	(?) 7	900
14	10.7	20.0	7.7	4.3	0	1.68	0.33	5.49	7.50	0.003'	0.014	9	900
17	10.8	20.0	7.7	4.2	0	1.51	0.48	5.58	7.57	0.009'	0.019'	10	900
21	11.0	20.0	7.2	4.2	0	0.98	0.36	4.90	6.24	0.006'	0.008'	9	900
24	11.2	19.8	6.7	4.1	0	0.62	0.28	4.68	5.58	0.009'	0.015'	8	900
28	11.4	19.8	5.8	4.1	0	0.42	0.14	4.93	5.49	0.008	0.023	6	900
35		19.8	4.1	4.3	0	0.28	0.22	4.56	5.06	0.005	0.011	12	900
42	9.6	20.0	3.9	4.1	0	0.20	0.28	4.21	4.69	0.002	0.007	7	900
49	9.5	20.0	2.9	4.2	0	0.25	0.25	3.78	4,28	0.004	0.008	10	900
56	9.6	19.9	2.6	4.2	0	0.17	0.17	3.46	3.80	0.003	0.010	8	900
63	9.6	19.8	1.9	4.2	0	0.08	0.14	3.39	3.61	0.004	0.011	7	900
70	9.5	19.8	1.4	3.9	0	0.06	0.20	3.12	3.38	0.006	0.011	8	
70'		2 				0.06'	0.08'		N .	0.006'	0.006'		

APPENDIX TABLE A.8. REACTOR A3A WATER QUALITY

NOTE: Incubation Water Source - Lake Wilson Surface Water (Station 2s). Incubation Date - 11/26/75 to 2/4/76. ' = results of 0.45-µ filtrated (dissolved) samples.

							Nitr	ogen		Phosp	horus		
Elapsed Time	DO	Temp	Turb	pН	Alk	NH 3	Org.	NO ₂ _+ NO ₃	Total	P04	Total	COD	Vol. Drawn
(days)	(mg/l)	(°C)	(JTU)		(mg/l)		mg	N/2		mg	P/l	(mg/l)	(ml)
0	7.7	17.5	96	6.3	21	1.85	0.62	0.09	2.56	0.009'	0.012'	16	900
1	11.0	19.6	87	7.1	22	3.42	0.56	0.17	4.15	0.006'	0.009'	14	900
3	11.0	20.0	81	7.2	22	4.52	0.56	0.21	5.19	0.006'	0.010'		900
7	10.4	20.0	72	6.2	4	3.39	0.59	3.76	7.74	0.015'	0.024'	10	900
10	11.2	20.0	94	4.7	0	1.82	0.45	4.32	6.59	0.016'	0.056'	11	900
14	11.1	20.0	105	4.4	0	1.43	0.50	5.31	7.24	0.011'	0.037'	19	900
17	11.2	20.0	125	4.3	.0	1.23	0.56	4.95	6.74	0.009'	0.019'	8	900
21	11.2	20.0	115	4.2	0	0.73	0.48	4.30	5.51	0.008'	0.012'		900
24	11.2	20.0	82	4.1	0	0.50	0.34	4.32	5.16	0.006'	0.009'	7	900
28	11.4	19.9	53	4.2	0	0.34	0.25	4.64	5.23	0.015	0.040	5	900
35		19.8	30	4.3	0	0.25	0.22	4.16	4.63	0.010	0.016	6	900
42	9.7	20.0	24	4.2	0	0.25	0.25	3.93	4.43	0.008	0.016	7	900
49	9.7	20.0	24	4.3	0	0.36	0.25	3.42	4.03	0.006	0.012	6	900
56	9.6	20.0	23	4.3	0	0.20	0.14	3.18	3.52	0.008	0.010	4	900
63	9.7	19.8	19	4.2	Ō	0.16	0.11	3.21	3.46	0.006	0.009		900
70	9.8	19.8	17	4.2	Õ	0.06	0.14	2.94	3.14	0.005	0.006	4	900
70'	2.2		.,		·	nd'	0.11	,.	J	nd'	nd '		

APPENDIX TABLE A.9. REACTOR A4A WATER QUALITY

NOTE: Incubation Water Source - Lake Wilson Bottom (One Meter Off Bottom) Waters. Incubation Date - 11/26/75 to 2/4/76.

nd = nondetectable.

' = results of $0.45-\mu$ filtrated (dissolved) samples.

								Nit	rogen		Phospho	orus	
Elapsed Time	Effl. DO	Infl. DO	Temp	Turb	pН	Alk	NH 3	Org.	NO2_+ NO3	Total	P04	Total	Vol. Drawn
(days)	mg	/&	(°C)	(JTU)		(mg/l)		mg	N/l		mg P,	le	(mL)
0	6.4p		18.5	11			0.05	0.01	nd	0.06	0.010	0.098	800
1			'	17	5.2	2	0.51	0.05	nd	0.56	0.013	0.044	650
3	6.4		18.5	16	5.4	5	1.57	nd	<0.01	1.58	0.010	0.019	650
7	6.7	8.4p		15	5.6	9	2.82	nd	nd	2.82	nd	0.013	525
10	6.8	8.7	19	18	6.0	17	3.45	nd	<0.01	3.45	nd	0.006	400
13	6.8	9.1	18.5	22	5.9	18	3.61	0.28	0.01	3.90	0.004	0.023	500
17	4.6		18.5	30	5.7	21	4.33	0.17	<0.01	4.50	0.002	0.016	525
20	5.0	9.0	18.5	31	6.0	24	4.22	0.25	<0.01	4.47	0.003	0.009	510
24	4.4	8.4	18.5	51	6.1	27	4.53	0.14	<0.01	4.67	0.003	0.010	510
27	3.9	9.0	18.5	63	6.0	28	4.92	0.14	0.01	5.07	0.003	0.003	500
35	5.1	8.4	18.5	58	6.0	35	5.14	0.25	<0.01	5.39	0.005	0.005	525
41	3.8	8.0	20.0	84	6.6	58	6.77	nd	<0.01	6.77	0.008	0.021	500
48	4.2w	9.5w		78	6.2	34	7.04	nd	0.01	7.05	0.006	0.011	500
58	3.5	7	17.5	49	6.4	36	6.71	0.19	0.02	6.92	0.003	0.010	500
69	3.7	8.4	21.5	16	6.0	40	7.33	nd	0.03	7.36	nd	0.003	500
75	3.4	8.5	22	21	5.9	39	7.75	0.25	<0.01	8.00	0.001	0.003	500
83	4.7	8.7	22.5	26	5.8	44	8.08	0.67	0.01	8.76	0.003	0.003	500
90	3.2	8.5	22	37	5.8	44	8.01	nd	<0.01	8.01	0.003-nd'	0.003	500
96	2.7	8.6	22.3	45	5.9	40	8.00	0.25	<0.01	8.25	0.003-0.003'	0.006	700
107	2.3	8.5	19.6	48	6.2	44	8.15	0.32	0.01	8.48	0.003	0.006	500
116	2.8	8.4	20	59	6.1	42	8.42	0.22	<0.01	8.66	0.031 (?)	nd	520
125	2.9	9.1	20	43	6.3	46	7.93	0.05	<0.01	7.98	0.003	0.003	500
139	2.7	9.4	20	36	6.3	41	6.53	0.22	0.02	6.77	0.001	0.006	500
147	2.6		20	32	6.3	40	7.90	0.27	0.01	8.18	nd	0.009	
147'							6.54	0.14'	0.03'	6.71	nd '	0.002'	

APPENDIX TABLE A.10. REACTOR R1 WATER QUALITY

NOTE: Incubation Water Source - Distilled Deionized Water.

Incubation Date - 5/31/75 to 10/25/75.

' = dissolved (0.45- μ filtrated).

nd = nondetectable.

p = meter analysis.

w = Winkler method.

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								Nitr	ogen		Phosp	horus	
Elapsed Time	Effl. DO	Infl. DO	Temp	Turb	pН	Alk	NH 3	Org.	NO2_+ NO3	Total	P0 [≣]	Total	Vol. Drawn
(days)	mg	g/l	(°C)	(JTU)		(mg/l)		mg	N/&		mg	P/l	(m&)
0 38 45	8.4p 2.2 0.2w		16 20 21	25 19 50	5.4 6.1 6.3	3 29 48	0.60 4.56 6.52	0.15 0.19 0.56	<0.01 0.94 0.16	0.75 5.69 7.24	0.013 0.003 0.008	0.027 0.018 0.041	650 500 500
52	0.1	10 21	18	33	6.2	54 //8	6.37	0.56	0.08	7.01 6.65	0.008	0.037	500 500
59 66 72 80	<0.1 <0.1 <0.1 0.2	9.2 9.3 9.8	21.5 22 22.5	45 41 56	6.2 6.1 5.9	40 55 56 48	6.55 6.71 7.05	0.23	0.02 0.03 0.06 0.06	6.81 7.45 7.48	0.009 0.006 0.003	0.030 0.031 0.018 0.017	550 500 500
87 93 105 113	0.3 0.6 0.6 0.5	9.5 10.6 5.0 9.6	22.5 22.5 20 20	40 33 26 18	5.9 6.1 6.2	44 40 34 33	6.48 5.89 6.05 4.92	0.28 0.32 0.32 0.20	0.10 0.15 0.30 0.81	6.86 6.36 6.67 5.93	0.003 0.003 0.006 0.003	0.015 0.015 0.019 0.007	500 750 500 500
122 136 149 149'	0.6 0.6 0.4	5.5 9.9 	20 20 20	38 24 16	6.3 6.2 6.3	31 32 32	4.86 5.02 4.90 4.10t	0.32 0.25 0.15 0.42t	0.78 0.56 0.44 0.43'	5.96 5.83 5.49 4.95	0.003 0.005 0.006 nd'	0.009 0.008 0.013 0.001'	500 500

APPENDIX TABLE A.11. REACTOR R2 WATER QUALITY

NOTE: Incubation Water Source - Ku Tree Reservoir (Station 11).

Incubation Date - 6/3/75 to 10/30/75.

' = 0.45- μ filtrated samples.

t = values obtained by titration.

p = meter analysis.

w = Winkler method.

								Nit	rogen		Phosp	horus	
Elapsed Time	Effl. DO	Infl. DO	Temp	Turb	рН	Alk	NH 3	Org.	NO ₂ _+ NO ₃	Total	P04 [≡]	Total	Vol. Drawn
(days)	mg	12	(°C)	(JTU)		(mg/l)		m	g N/L		mg	P/&	(m&)
0	10.2p	11.8p	16	7.8	5.8	3	0.57	0.34	0.01	0.91	0.095	0.198	600
30 1. r	1.3	9.5	19.5	32	6.0	22	3.92	0.11	2.60	6.63	0.019	0.051	500
45	1.1W	9.0	21	94	5.9	32	5./1	0.29	0.23	6.23	0.017	0.0/1	500
52	0.1	0.4	10	/5	0.1	43	5.01	0.23	0.05	6.09	0.013	0.059	500
59	<0.1	9.4	23	52	6.3	47	6.48	nd	<0.01	6.48	0.015	0.050	500
66	<0.1	10.0w	21.5	59	6.4	64	6.75	0.33	0.01	7.09	0.014	0.042	500
72	<0.1	9.5	22	47	6.2	63	7.29	0.80	0.01	8.10	0.012	0.042	500
80	<0.1		22.5	49	6.1	63	7.89	0.75	0.01	8.65	0.006	0.025	500
87	<0.1	10.2	22.5	50	6.1	65	8.04	0.88	<0.01	8.92	0,004	0.023	500
93	nd	10.6	22.5	68	6.2	58	7.66	0.57	<0.01	8.23	0.004	0.035	500
104	1.8	4.8	20.1	49	6.4	62	7.70	0.68	0.01	8.39	0.003	0.038	500
113	nd	6.7	20	62	6.6	62	7.60	0.27	nd	7.87	0.006	0.020	500
122	<01	10 1	20	76	65	62	7 52	0 52	0 01	8 06	0.008	0 012	500
136	0.4	11 1	20	95	6.5	50	7 22	0.27	0.01	7 61	0.000	0.012	500
155	0.1		20	110	6 5	56	7.57	0.27	0.10	8 02	0.007	0.024	500
155	~••		20		U . U	7	6.60t	0.47t	0.13'	0.02	0.001'	0.001	200

APPENDIX TABLE A.12. REACTOR R3 WATER QUALITY

NOTE: Incubation Water Source - Lake Wilson Surface (Station 2s).

Incubation Date - 6/3/75 to 11/5/75.

' = 0.45- μ filtrated samples.

t = values obtained by titration.

p = meter analysis.

w = Winkler method.

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Phosphorus Nitrogen Vol. Elapsed Effl. Infl. N02_+ P04 Temp Turb pH Alk NH₃ Total Total Org. Time DO Drawn NO₃ DO ----mg/l----(°C) (ml) (days) (JTU) (mq/l)-----mg N/2------mg P/l----0 16 600 6.0p 2.6p 42 6.2 0.42 <0.01 05.42 0.307 30 5.00 0.307 14 1.3 0.171 19 6.1 55 6.09 0.51 06.60 0.101 520 ---22 nd 2.8 21 1.1 19 26 6.2 6.08 0.49 06.57 0.070 0.115 510 50 nd 28 0.087 500 1.0 3.5 19 27 6.3 72 8.44 0.35 0.01 08.80 0.057 36 1.1 2.6 19 6.2 86 0.40 0.057 0.078 500 50 9.91 <0.01 10.31 42 1.2 1.9 17 110 6.5 70 10.50 1.06 0.02 11.58 0.033 0.081 500 48 <0.2w 18 1.1w 125 6.2 71 10.62 0.78 0.01 11.41 0.066 0.160 500 55 <0.2 3.2 18 160 6.4 67 0.165 500 10.28 0.84 0.01 11.13 0.090 66 0.6 1.7 21.5 185 6.3 77 11.16 0.02 11.18 0.069 0.157 500 nd 72 0.150 500 0.3 1.0 22 180 6.3 78 11.18 1.02 0.01 12.91 0.069 80 0.5 0.102 0.148 500 0.7 22.5 6.2 82 12.58 0.94 0.02 13.54 170 0.8 0.132 500 87 0.9 22 180 6.1 89 12.58 1.74 0.02 14.34 0.080 0.4 6.3 78 12.04 0.900 0.145 700 93 0.9 22 220 0.74 0.01 12.79 0.141 104 0.2 12.42 12.84 0.091 500 0.7 200 6.3 90 0.38 0.04 20 113 87 13.58 0.069 0.116 500 <0.1 1.1 20 190 6.5 12.74 0.79 0.05 0.078 122 <0.1 6.5 12.78 0.58 0.078 500 0.3 175 94 0.03 13.39 20 136 0.070 0.109 500 < 0.1 10.4 20 165 6.5 94 12.90 0.56 0.08 13.54 0.044 0.044 162 < 0.1----20 255 6.5 98 13.30 0.75 0.02 14.07 ---0.002' 162 12.89t 1.36t 0.03' 14.28' 0.002'

APPENDIX TABLE A.13. REACTOR R4 WATER QUALITY

NOTE: Incubation Water Source - Lake Wilson Bottom Waters (Station 2d - 1 m from Bottom). Incubation Date - 6/3/75 to 11/12/75.

' = 0.45- μ filtrated samples.

t = values obtained by titration.

p = meter measurement

w = Winkler method.

	2 1 100 100						Nitrogen			Phosphorus			5
Elapsed Time	DO	Temp	Turb	рН	Alk	NH 3	Org.	NO ₂ + NO ₃	Total	P0 [≣]	Total	COD	Vol. Drawn
(days)	(mg/l)	(°C)	(JTU)		(mg/%)		mg	N/2		mg	P/l	(mg/l)	(ml)
0	0.9	20.3	4.5	4.8	0	0.08	nd	nd	0.08	0.007*	0.009*	10	900
7	0.6	20.0	1.7	5.5	0	0.97	0.09	0.01	1.07	nd*	nd*	1	725
14	0.4	20.0	1.5	5.9	4	1.55	0.11	0.01	1.67	nd*	nd*	2	900
21	0.3	20.0	2.4	6.5	12	2.61	0.17	nd	2.78	nd*	nd*	5	900
28	0.2	19.8	4.6	6.6	17	3.30	0.22	0.01	3.53	0.001*	0.005*	2	875
35	<0.1	19.9	6.2	6.5	21	3.61	0.11	0.01	3.73	nd*	nd*	2	860
42	<0.1	20.0	6.9	6.2	23	4.08	0.17	0.01	4.26	nd*	nd*	3	900
49	<0.1	20.0	4.1	6.3	28	4.45	0.17	0.02	4.64	nd*	nd*	5	880
56	0.1	20.0	3.7	6.3	31	4.70	0.11	0.02	4.83	0.001*	0.001*	7	890
63	<0.05	20.0	4.9	6.2	34	5.26	0.11	0.02	5.39	0.002*	0.002*	5	900
70	<0.1	20.0	3.3	6.3	37	5.32	0.11	<0.01'	5.43	0.004'	0.004	5	900
77	<0.1	20.0	3.4	6.5	40	5.52	0.11	<0.01'	5.63	0.004'	0.005'		900
84	0.1	20.0	6.2	6.6	23	5.38	0.06	<0.01'	5.44	0.006'	0.009'	9	900
91	0.1	20.0	3.9	6.4	36	5.25	0.11	<0.01'	5.36	0.003'	0.003'	8	900
94	<0.1	20.0	2.5	6.4	33	5.12 5.04*	0.22 0.22*	<0.01' 0.02*	5.34 5.28*	0.004' nd*	0.005' nd*	6	

APPENDIX TABLE A.14. REACTOR RIA WATER QUALITY

NOTE: Incubation Water Source - Distilled or Reverse Osmosis Deionized Water. Incubation Date - 10/13/75 to 1/15/76.

nd = nondetectable.

' = unfiltrated samples.

 $* = 0.45 - \mu$ filtrated (dissolved) samples.

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						Nitrogen			Phos	Phosphorus			
Elapsed Time	DO	Temp	Turb	рH	Alk	NH ₃	Org.	NO2_+ NO3	Total	P0 [≣]	Total	COD	Vol. Drawn
(days)	(mg/%)	(°C)	(JTU)		(mg/l)		mg	N/2		mg	P/&	(mg/l)	(ml)
0	0.9	20.7	1.5	4.3	0	0.06	nd	<0.01	0.06	0.004*	0.006*	4	900
7	0.4	20	0.6	5.2	1	1.11	0.09	nd	1.20	nd*	0.003*	4	750
14	0.7	20.0	0.6	5.9	5	1.66	0.11	<0.01	1.78	nd*	nd*	9	900
21	0.4	20.0	1.5	6.4	13	2.36	0.22	nd	2.58	nd*	nd*	5	900
28	0.1	19.9	3.1	6.5	16	3.27	0.22	0.01	3.50	0.001*	0.003*	6	900
35	<0.1	19.9	5.2	6.3	19	3.50	0.17	<0.01	3.67	nd*	nd*	3	860
42	<0.1	20.0	7.3	6.2	26	4.17	0.11	0.01	4.29	nd*	nd*	4	890
49	<0.1	20.0	4.2	6.3	30	4.79	0.17	0.02	4.98	nd*	nd*	10	880
56	0.1	20.0	4.5	6.4	31	4.76	0.17	0.01	4.94	nd*	nd*	5	890
63	<0.1	20.0	4.9	6.3	33	5.26	0.17	0.02	5.45	nd*	nd*	8	900
70	<0.05	20.0	2.5	6.3	36	5.38	0.17	<0.01'	5.55	0.003'	0.003	6	900
77	<0.1	20.0	3.2	6.5	36	5.40	0.11	<0.01'	5.51	0.0061	0.006'	7	900
84	<0.1	20.0	5.4	6.6	28	5.24	0.11	<0.01'	5.35	0.004'	0.010'	9	900
91	0.1	20.0	3.6	6.4	39	5.54	0.14	<0.01'	5.68	0.005'	0.009'	12	900
94	<0.1	20.0	1.1	6.4	40	5.80 5.80*	0.22 0.22'	<0.01' 0.02	6.02 6.04*	0.005' 0.002*	0.006' 0.002*	10	

APPENDIX TABLE A.15. REACTOR RIB WATER QUALITY

NOTE: Incubation Water Source - Distilled or Reverse Osmosis Deionized Water. Incubation Date - 10/13/75 to 1/15/76.

nd = nondetectable.

' = unfiltrated samples.

* = 0.45- μ filtrated (dissolved) samples.

							Nitrogen			Phosp			
Elapsed Time (days)	DO (mg/l)	Temp (°C)	Turb (JTU)	рH	Alk (mg/l)	NH 3	Org.	NO ₂ + NO ₃ N/2	Total	P04 mg I	Total P/l	COD (mg/l)	Vol. Drawn (ml)
0 8 18 25	1.2 0.1 nd nd	20 20 20 19.5	71 16 22 20	6.3 6.4 6.5 6.6	4 21 28 38	0.19 2.86 3.65 4.52	0.42 0.17 0.18 0.33	0.02 0.02 0.04 0.03	0.63 3.05 3.87 4.88	0.004* 0.007* nd*	0.007* 0.007* nd*	172 11 13 16	925 900 700 900
32 39 46 53	nd nd nd nd	19.4 20 20 20	42 31 27 18	6.7 6.4 6.4 6.4	36 36 40 38	5.24 5.69 5.91 5.68	0.28 0.28 0.28 0.17	0.02 0.03 0.02 0.02	5.54 6.00 6.21 5.87	nd* 0.003* 0.001* 0.001*	0.003* 0.005* 0.003* 0.001*	16 17 14 14	900 900 875 880
60 67 74 81	nd nd nd nd	20.0 20.0 20.0 20.0	9.4 8.9 9.7 6.8	6.3 6.5 6.4 6.4	48 50 49 58	6.19 5.91 6.38 6.58	0.22 0.28 0.22 0.39	0.02 0.02 0.03 <0.01	6.43 6.21 6.63 6.97	nd* 0.003* 0.004* 0.018'	nd* 0.003* 0.005* 0.031 '	20 13 16 17	880 900 900 900
88 95 102	nd nd nd	19.8 19.9 19.8	7.6 13 6.9	6.5 6.8 6.6	58 41 61	6.66 6.56 6.64	0.28 0.22 0.28	<0.01' <0.01' <0.01'	6.95 6.78 6.92	0.027' 0.026' 0.030'- 0.021*	0.039' 0.038' 0.030'- 0.021*	19 20 20	900 900 1500
109	nd nd	19.9	5.6 8.2	6.5 6.5	50 61	6.30 5.94 5.94*	0.31 0.36 0.22*	<0.01' <0.01' 0.02	6.30 6.18*	0.044' 0.032' 0.019*	0.046' 0.050' 0.027*	20	

APPENDIX TABLE A.16. REACTOR R2A WATER QUALITY

NOTE: Incubation Water Source - Ku Tree Reservoir. Incubation Date - 10/2/75 to 1/22/76.

nd = nondetectable.

' = unfiltrated samples.

 $* = 0.45 - \mu$ filtrated (dissolved) samples.

APPENDIX TABLE A.17. REACTOR R2B WATER QUALITY

							Nit	rogen		Phos	phorus		
Elapsed	DO	Temp	Turb	ъН	Alk	NH .	Ora.	NO2_+	Total	D	Iss.	COD	Vol.
Time	/ ///	(0-)	(pin	/ //			NO 3	local	P04	Total		Drawn
(days)	(mg/l)	(°C)	(JTU)		(mg/l)		mç	3 N/2		mg	P/2	(mg/l)	(m£)
0	0.8	20	25	6.5	5	0.11	0.28	0.02	0.41	0.004	0.008		900
8	<0.1	20	12	6.6	19	2.69	0.14	0.05	2.88	0.017	0.018	17	900
18	nd	20	22	6.5	27	4.11	0.14	0.03	4.28	nd	0.012	18	700
25	nd	19.7	17	6.6	37	4.72	0.28	0.02	5.04	nd	0.001	18	900
32	nd	19.4	42	6.7	36	5.62	0.28	0.03	5.93	0.001	nd	21	900
39	nd	20.0	28	6.5	34	5.68	0.33	0.03	6.04	0.001	0.003	20	900
46	nd	19.8	23	6.4	38	5.85	0.28	0.03	6.16	0.001	0.004	19	875
53	nd	20.0	18	6.3	40	5.72	0.11	0.03	5.86	0.001	0.010	20	880
60	nd	20.0	8.3	6.4	42	6.04	0.22	0.03	6.29	0.004	0.001	24	880
67	nd	20.0	7.6	6.4	40	5.91	0.22	0.03	6.14	0.002	0.004		900
74	nd	20.0	8.6	6.4	45	6.00	0.22	0.03	6.25	0.005	0.005		900
81	nd	20.0	6.3	6.4	49	5.94	0.34	<0.01	6.28	0.008*	0.017*	18	900
88	nd	19.8	7.0	6.6	50	5.8	0.22	0.02	6.06	0.010*	0.017*	19	900
95	nd	19.9	10	6.7	39	5.71	0.17	<0.01	5.88	0.009*	0.021		900
102	nd	19.8	7.7	6.6	48	5.99	0.25	<0.01	6.24	0.009*	0.007*	16	900
109	nd	19.9	5.9	6.7	53	5.88	0.25	<0.01	6.13	0.017*	0.017*	14	940
116	nd	19.8	5.4	6.5	58	5.57	0.22	<0.01	5.79	0.009	0.009	20	1050
										0.013*	0.015*	~	
130	nd	19.8	4.5	6.7	57	5.77	0.17	<0.01	5.94	0.011	0.011	18	1050
										0.011*	0.019*	120000	142 21 21 22 22 22 22
144	nd	19.7	5.5	6.6	59	5.82	0.17	<0.01*	6.00	0.012	0.012	17	1050
						22 22				0.019*	0.019*		
158	nd	19.5	4.8	6.7	58	5.99	0.11	0.01*	6.11	0.022	0.022	25	1050
150					-0				<i>.</i>	0.024*	0.024*		
159	nd	19.7	4.9	6./	58	5.94	0.22	<0.01*	6.14	0.019	0.019	17	1050
160		10.7			-1					0.023*	0.023*		
160	na	19.7	0.2	0.0	54	5.49	0.22	<0.01*	5./1	0.020	0.020	18	1050
141		10.5		1 -	1.0	1 00		0 01+	e 16	0.023*	0.023*		1050
101	na	19.5	0.0	0./	40	4.98	0.17	0.01*	5.10	0.017	0.017	17	1050
175	- 1	10.7	- /		F 1.	c			F 14	0.023*	0.024*		1050
1/5	na	19.7	5.0	0.0	54	5.21	0.25	<0.01*	5.40	0.019	0.019	15	1050
202		10.0	r 1.	1 -	-1	5 01		(0 014	6 50	0.023*	0.035*		1010
202	na	19.0	2.4	0./	20	5.94	0.50	<0.01×	0.50	0.026	0.020	24	1040
2021	0.1	10.8	17	6 9	F9	7 79	0.53	0 02+	8 33	0.030*	0.030*	10	1000
202	0.1	19.0	17	0.0	20	1.10	0.53	0.02*	0.33	1.13	2 00+	19	1000
216	-	20	6 1	6 0	61	10 52	0.16	0 01±	10 69	3.00*	3.00*	24	1000
210	na .	20	0.4	0.9	04	10.55	0.14	0.01*	10,00	1.09+	5.50	24	1000
								3		4.30*	5.00*		

NOTE: Incubation Water Source - Ku Tree Reservoir (Station 11). Incubation Date - 10/2/75 to 5/5/76. nd = nondetectable. ' = N and P spikes. * = unfiltrated sample results.

							Nitrogen			Phosph			
Elapsed Time	DO	Temp	Turb	pН	Alk	NH ₃	Org.	NO ₂ _+ NO ₃	Total	P04	Total	COD	Vol. Drawn
(days)	(mg/l)	(°C)	(JTU)		(mg/l)		mg	N/2		mg F	·/&	(mg/l)	(ml)
0	0.9	17	23	6.9	18	0.83	1.00	1.50	3.33	0.033*	0.049*		950
4	0.4	20	9.4	6.7	28	2.44	0.70	0.93	4.07	0.008*	0.015*		900
14	0.5	20	11	6.7	36	4.20	0.46	0.10	4.76	nd	0.008*		700
21	0.1	19.4	9.4	6.9	46	4.99	0.55	0.04	5.58	0.006*	0.006*		900
28	<0.1	19.4	13	7.5	46	5.74	0.50	0.03	6.27	0.011*	0.011*		880
35	<0.1	19.9	11	6.8	46	5.99	0.55	0.09	6.63	0.0118*	0.0118*	21	880
42	nd	19.9	12	6.6	53	6.69	0.67	0.04	7.40	0.024*	0.024*		880
49	nd	20.0	12	6.5	53	7.02	0.73	0.13	7.88	0.026*	0.029*	21	900
56	<0.05	20.0	4.8	6.5	57	7.22	0.62	0.10	7.94	0.030*	0.040*	22	900
63	<0.1	20.0	8.1	6.5	62	7.22	0.56	0.09	7.87	0.014*	0.014*		900
70	<0.1	20.0	8.8	6.5	59	7.40	0.62	0.09	8.11	0.023*	0.023*	23	900
77	<0.1	20.0	7.1	6.5	43	7.34	0.67	0.07'	8.88	0.036'	0.051'	18	900
84	nd	19.8	6.0	6.6	66	7.28	0.50	0.06'	7.84	0.049'	0.049'	25	900
89	nd	19.9	4.2	6.7	77	7.50 7.45*	0.56 0.53*	0.01' 0.02	8.07 8.00*	0.070' 0.036*	0.076' 0.036*	30	

APPENDIX TABLE A.18. REACTOR R3A WATER QUALITY

NOTE: Incubation Water Source - Lake Wilson Surface.

Incubation Date - 10/6/75 to 1/3/76.

nd = nondetectable.

' = unfiltrated samples.

 $* = 0.45 - \mu$ filtrated (dissolved) samples.

			<i>.</i>			Nitrogen				Phosp			
Elapsed Time	DO	Temp	Turb	рH	Alk	NH 3	Org.	NO2_+	Total	P0 [‡]	Total	COD	Vol. Drawn
(days)	(mg/l)	(°C)	(JTU)		(mg/l)		mg	N/2		mg	P/l	(mg/l)	(ml)
0	1.2	15.6	8	7.1	18	0.86	0.97	1.50	3.33	0.017*	0.033*		950
14	0.4	20 19.5	5.1 8.4	6.8 7.1	29 34	2.30 3.74	0.73	0.92	3.95	0.004* nd*	0.016*		900 700
21	0.1	19.4	7.4	7.0	45	4.50	0.55	0.05	5.10	0.011*	0.016*		900
35	<0.1	19.2	11	6.7	47 48	6.04	0.50	0.04	6.76	0.018*	0.018*	23	880
42 49	nd	19.9	13	6.6	52 54	6.58	0.56	0.06	7.20	0.020*	0.020*	' 20	880
56	<0.05	20.0	4.3	6.5	56	6.97	0.56	0.13	7.66	0.028*	0.035*	23	900
63 70 77 84	<0.1 <0.1 <0.05 nd	20.0 20.0 20.0 19.8	7.6 8.7 6.9 7.1	6.8 6.5 6.5 6.6	64 58 64 61	7.17 7.34 7.22 7.22	0.50 0.50 0.56 0.45	0.10 0.11 0.09' 0.10'	7.77 7.95 7.87 7.77	0.018* 0.025* 0.043' 0.059'	0.031* 0.031* 0.067' 0.061'	21 20 23	900 900 900 900
89	nd	19.6	5.0	6.7	76	7.28 7.31*	0.56 0.50*	<0.01' 0.02	7.85 7.83*	0.070' 0.029*	0.079' 0.033	24	

APPENDIX TABLE A.19. REACTOR R3B WATER QUALITY

NOTE: Incubation Water Source - Lake Wilson Surface.

Incubation Date - 10/6/75 to 1/3/76.

nd = nondetectable.

' = unfiltrated samples.

* = 0.45- μ filtrated (dissolved) samples.

						Nitrogen				Phosphorus			
Elapsed Time	DO	Temp	Turb	pН	Alk	NH 3	Org.	NO2_+ NO3	Total	P0	Total	COD	Vol. Drawn
(days)	(mg/l)	(°C)	(JTU)		(mg/l)		mg	N/2		mg	P/l	(mg/l)	(mL)
0 7	0.9	18 19.6	160 120	6.5	4	0.78	0.95	0.31	2.04	0.038* 0.003*	0.051*	29 24	900 700
14	<0.1	19.5	120	6.8	27	4.26	0.50	0.05	4.81	0.017*	0.019*	28	900
21 28 35	<0.1 0.1 nd	19.2 19.8 20.0	130 135 130	6.7 6.6 6.5	34 37 42	5.66 6.13 7.14	0.39 0.50 0.45	0.07 0.05 0.03	6.12 6.68 7.62	0.006* 0.002* 0.003*	0.006* 0.006* 0.019*	16 45 25	900 880 875
42 49 56	nd <0.1 <0.1	20.0 20.0 20.0	120 75 78	6.2 6.4 6.4	47 49 57	7.14 7.84 8.10	0.39 0.34 0.39	0.10 0.03 0.05	7.63 8.21 8.54	0.007* 0.011* 0.007*	0.016* 0.011* 0.007*	38 27 23	890 890 900
63 70 77 84	0.1 <0.1 nd 0.1	19.8 19.9 19.8 19.9	100 89 79 82	6.5 6.5 6.6 6.6	54 60 59 50	8.23 8.37 8.04 8.12	0.39 0.50 0.39 0.34	0.07 0.04 0.03 0.03	8.69 8.91 8.46 8.49	0.012* 0.073' 0.068' 0.058'	0.025* 0.087' 0.073' 0.062'	25 23 26 21	900 900 900 900
89	nd	19.8	69	6.6	68	8.20 8.29*	0.48 0.56*	0.02' 0.02	8.70 8.87*	0.063' 0.006*	0.104' 0.006*	22	'

APPENDIX TABLE A.20. REACTOR R4A WATER QUALITY

NOTE: Incubation Water - Lake Wilson Bottom.

Incubation Date - 10/13/75 to 1/10/76.

nd = nondetectable.

' = unfiltrated samples.

 \star = 0.45- μ filtrated (dissolved) samples.

						Nitrogen			Phosp	horus			
Elapsed Time	DO	Temp	Turb	рH	Alk	NH ₃	Org.	NO2_+ NO3	Total	P04	Total	COD	Vol. Drawn
(days)	(mg/l)	(°C)	(JTU)		(mg/l)		mg	N/2		mg	P/&	(mg/l)	(ml)
07	1.4	17.7	170	6.5	4	0.72	0.95	0.31	1.98	0.038*	0.054*	29	900
14	0.1	19.5	125	6.8	26	4.24	0.48	0.05	4.84	0.008*	0.01/*	14	900
21 28	<0.1 <0.1	19.2 19.8	135 140	6.7 6.7	31 36	5.74 6.21	0.50 0.50	0.06 0.05	6.30 6.76	0.005* 0.001*	0.005* 0.001*	27 23	900 900
35	nd	19.8	130	6.5	42	7.16	0.50	0.04	7.70	0.003*	0.016*	24	875
42 49 56	nd <0.1 nd	20.0 20.0 20.0	120 75 83	6.5 6.4 6.5	45 49 58	7.25 7.92 8.14	0.45 0.45 0.50	0.04 0.04 0.05	7.74 8.41 8.69	0.005* 0.010* 0.006*	0.006* 0.010* 0.006*	20 23	890 890 900
63 70 77 84	<0.1 0.1 nd nd	19.8 19.9 19.8 19.9	110 93 81 88	6.5 6.5 6.7 6.7	54 62 57 51	8.46 8.51 8.10 8.27	0.50 0.50 0.39 0.34	0.06 0.05' 0.03' 0.03'	9.02 9.06 8.52 8.64	0.010* 0.099' 0.073' 0.070'	0.010* 0.134' 0.073' 0.063'	23 20 22 26	900 900 900 900
89	nd	19.8	68	6.6	70	8.48 8.34*	0.39 0.45*	0.01' 0.02	8.88 8.81	0.078' 0.004*	0.104' 0.005*	21	

APPENDIX TABLE A.21. REACTOR R4B WATER QUALITY

NOTE: Incubation Water - Lake Wilson Bottom.

Incubation Date - 10/13/75 to 1/10/76.

nd = nondetectable.

' = unfiltrated samples.

* = 0.45- μ filtrated (dissolved) samples.