# ARTIFICIAL CIRCULATION OF HAWAIIAN PRAWN PONDS



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SEA GRANT COOPERATIVE REPORT
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ABSTRACT

*A low-energy water circulator was field tested in a Hawaiian prawn pond over a four-month period. In calm conditions without artificial circulation, the prawn pond developed thermal stratification with bottom oxygen concentrations reaching a minimum of less than 5 mg/l during late afternoon. With artificial circulation, bottom oxygen concentrations often exceeded 12 mg/l during late afternoon. Artificial circulation caused an average increase in daily maximum bottom temperatures of 2.8°C, compared with uncirculated conditions. Minimum daily bottom oxygen concentrations averaged 1.0 mg/l higher; and average maximum daily bottom oxygen concentrations averaged 4.0 mg/l higher during artificial circulation. Alkalinity and conductivity doubled during the study period apparently due to manure applications. Plant nutrients, phosphorus, and nitrogen were present as organic fractions, not inorganic. Chlorophyll a concentrations increased greatly as a result of manure application, and Secchi disc transparencies decreased from about 40 cm to 10-12 cm during manure treatment. Benthic fauna populations (oligochaete worms and chironomid midge larvae) increased greatly during manure treatment. Artificial circulation reduced stratification and resulted in a more even distribution of prawns within the pond.*

*Prawns harvested from the circulated half of the pond were larger than those on the uncirculated side. On the circulated side 49.0% were market sized, compared with only 33.5% on the uncirculated side. Although insufficient prawn production data is available from the short length of this study period, the preliminary results indicate greater production potentials due to artificial circulation.*

## PREFACE

This study was funded primarily by a Small Business Innovation Research Grant through the National Science Foundation. The purpose of this NSF grant program is to help small businesses conduct research and development on innovative, high technology concepts which the business might not otherwise be able to do. The overall objective is to help create a healthy market position for the business and thus lead to increased employment opportunities for U.S. citizens, and a stronger position in the world market for U.S. products and skills.

In addition to the NSF grant, the Hawaii State Aquaculture Development Program and the University of Hawaii Sea Grant Program have funded a parallel evaluation of pond circulators during 1982/83. This project is now slated to increase greatly in scope during 1983/84 to include further evaluation of pond circulation techniques; mathematical modeling of oxygen fluxes with the goal of predicting oxygen depletion problems through the use of simple pond measurements and personal computers; and development of artificial aeration equipment and techniques.

SEACO, Incorporated has supported this project by helping develop the first prototype pond circulator (PC-I) with corporation funds before outside support was provided. During this NSF Phase I project, SEACO provided the circulators and emergency aerator, plus personnel and logistic support, at no cost to this contract.

The Hawaii Institute of Marine Biology has supported this program by providing substantial salary, equipment and logistic support.

The owners of Kohala Prawn Farm exceeded the demands of this contract in time, energy and effort in order to help ensure its success. In addition to providing access to their pond and allowing its use in an experimental situation, they closely monitored all activities, collected samples and data, provided a laboratory and electricity to operate the circulator.

Lastly, Aquatic Farms, LTD. has supported this program by providing free access to their commercial production prawn ponds, a pond-side laboratory, electricity to operate the pond circulators as well as encouragement and advice.

All of the above are contributing to a successful development and evaluation of pond circulators. The evaluation provided here is only a portion of the work thus far completed in this overall program, and of the work planned during the next two years. The present report is therefore an interim view. Additional reports and evaluations will follow.

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## INTRODUCTION

The economic viability of pond aquaculture in Hawaii is very sensitive to the rate of production per acre for the cultured species (Shang, 1981). With prawn (*Macrobrachium rosenbergii*) farming, for example, all farms are unprofitable or marginally profitable at production rates of 1,500 lbs/acre or less (Table 1). At production rates of 3,000 lbs/acre, all farms show a profit ranging from 14.3% return on initial investment for a 1-acre farm to 74.6% for a 100-acre farm. Prawn production in Hawaii now averages about 2,000 lbs/acre, which means that farms of less than 20 acres generally will operate at a loss or at best show only a modest return on investment.

Early prawn production test in Hawaii in small tanks and ponds indicated that production rates in excess of 3,000 lbs/acre/yr should be easily attainable. Based on these test and projections, the Hawaiian prawn industry was created. Indeed, some ponds in some years have produced 3,000 lbs/acre or more. Some ponds consistently produce these quantities. Unfortunately, most ponds produce much less. The statewide average is probably 2,000 lbs/acre/yr or less, and some large farms have even averaged about 1,200 lbs/acre/yr.

Some of the disappointing production from prawn ponds is due to poor management practices in terms of stocking, harvesting, water quality monitoring, oxygen control and possibly other things, but not all of the differences can be attributed to these factors. Based on our preliminary observations and discussions with prawn farmers during early 1982, we became convinced that thermal and oxygen stratification within ponds was also a major factor causing low prawn production, especially in large ponds. A literature search revealed almost no useful information on the nature and extent of stratification within Hawaiian prawn ponds, even though it was "common knowledge" among prawn farmers. Even the manual labor force was aware that these ponds often developed strong thermal stratification. Anyone wading in a pond during a calm, hot summer day instantly knew that his feet were much cooler than his knees. Even though this condition was common knowledge, its importance to the prawns was not fully appreciated and little was done to compensate for it. Further, many people felt that it was a phenomenon common primarily to calm sites, and of not much general concern to the Hawaiian prawn industry as a whole.

About that same time we became familiar with work done at Auburn University, Alabama, by Dr. Charles D. Busch and others with low-energy water circulation devices in catfish ponds. Catfish ponds in the southern U.S. often develop strong thermal stratification during the summer months which can persist for days, weeks or even months. Such stratification can result in anaerobic conditions in the bottom waters and sediments. These anaerobic conditions effectively reduce the habitat available to the catfish, reduce the growth of catfish, and can even result in massive

Table 1. Rate of Return on Initial Investment by Production Level, Farm Price, and Farm Size (data from Shang, 1981)

| Production Level (lb/acre) | Price/lb ($) | Rate of Return by Farm Size (%) | | | | |
|---|---|---|---|---|---|---|
| | | 1 Acre | 10 Acres | 20 Acres | 50 Acres | 100 Acres |
| 1,500 | 4.00 | NE | NE | NE | NE | NE |
| 2,000 | 4.00 | NE | NE | 2.1 | 11.9 | 19.2 |
| 2,500 | 4.00 | 2.7 | 7.2 | 26.4 | 37.6 | 46.9 |
| 3,000 | 4.00 | 14.3 | 28.9 | 50.8 | 63.2 | 74.6 |

Note: NE = negative rate of return

fish kills during sudden destratification. Busch's circulators were designed to reduce thermal stratification while at the same time cause a redistribution of oxygen from near the pond's surface to oxygen-depleted regions near the bottom.

Although the Busch circulators and their design concepts are intriguing, they appear to have certain limitations in terms of water withdrawal depths, water volumes circulated, and ease of construction. Another type of circulation device developed by Dr. James Garton of Oklahoma State University for lake and reservoir destratification seemed to overcome some of these difficulties, but it does not seem particularly suited for Hawaiian prawn ponds which are typically three feet or less in depth. Consequently, a new circulation device was developed and is described in this report. The new device draws heavily on the principles and research of Busch and Garton. It is designed to move large volumes of water in shallow ponds. It redistributes oxygen, but neither adds nor removes oxygen from the water.

The overall intent of our research program is to increase prawn production through the reduction or elimination of limnological factors hindering prawn growth and survival in grow-out ponds. To achieve this objective we must first detect and document those limnological factors which are impediments to prawn production. Once identified, we can then hypothesize and test corrective measures.

Within this context we were convinced that thermal stratification and its associated conditions are major factors hindering prawn production. An obvious solution to this perceived problem is the use of artificial circulation devices. A series of such devices, incorporating a number of innovative concepts, were constructed. This NSF-funded effort covers the testing of these devices and documents what we did, what we found, and our conclusions based on the results of these efforts.

## DESCRIPTION OF CIRCULATORS

### PC-I and PC-II

Prior to and during the NSF project funding period, two prototype pond circulation devices were constructed and tested. The first prototype (PC-I) was built during June 1982 and placed in operation at Aquatic Farms Pond No. 5. A copy of the PC-I was built soon thereafter and began operation in Aquatic Farms Pond No. 6 during July. The second PC-I was later shipped to Kohala Prawn Farm where it began operation on December 16, 1982.

The PC-I includes a 16¼-inch diameter rolled steel (16 gauge) shroud which is beveled at a 45° angle at its intake (upper) end, and is formed into a 45° angle at its discharge (lower) end (Fig. 1). When properly positioned and in operation, the shroud is at a 45° angle with the bottom. The intake is parallel to the pond's surface, and the lower elbow rests on the sediment surface. This orientation allows water to be drawn in from the surface of the pond and discharged at the bottom of the pond.

A set of floatation tires, mounted on an axle, keeps the intake end of the PC-I elevated and keeps the circulator motor above water. The tires also rotate on their axle, and thus facilitate entry and removal of the PC-I from the pond since they will roll on the pond bank (Fig. 2).

The PC-I motor is mounted on an angle iron frame which is welded to the shroud (Figs. 1 and 3). The motor is a ¼-h.p., 115-volt, totally enclosed, fan-cooled (TEFC) electric motor with speed reduction gears which produce 60 RPM on the drive shaft. The motor drew 3.7 amps during full load with two fan blades on the drive shaft. The drive shaft was ½-inch stainless steel with a thrust bearing on its lower end, and one alignment bearing at its upper end. A second alignment bearing was later added to the upper end to improve alignment of the shaft with the flexible coupling on the motor. Two 16-inch aluminum, five-bladed fans with clockwise rotation and 29° pitch were attached to the drive shaft. The lower blade was positioned near the weld on the 45° elbow (Fig. 3).

During the initial operation weeds wrapped around the drive shaft and caused the shaft to dislodge from the flexible coupling. This problem was solved by placing an expanded metal grating over the intake (Fig. 4). This in turn created another problem since the strong surface currents created by the PC-I drew floating weeds and other debris onto the grate, and thus greatly reduced the flow volume. This was overcome by placing a floating frame and netting around the PC-I (Figs. 5A and 5B). The netting hung down below the surface about 8 inches and prevented most floating materials from lodging on the intake grating. Some floating or suspended debris still occasionally lodged on the grating and had to be manually removed.

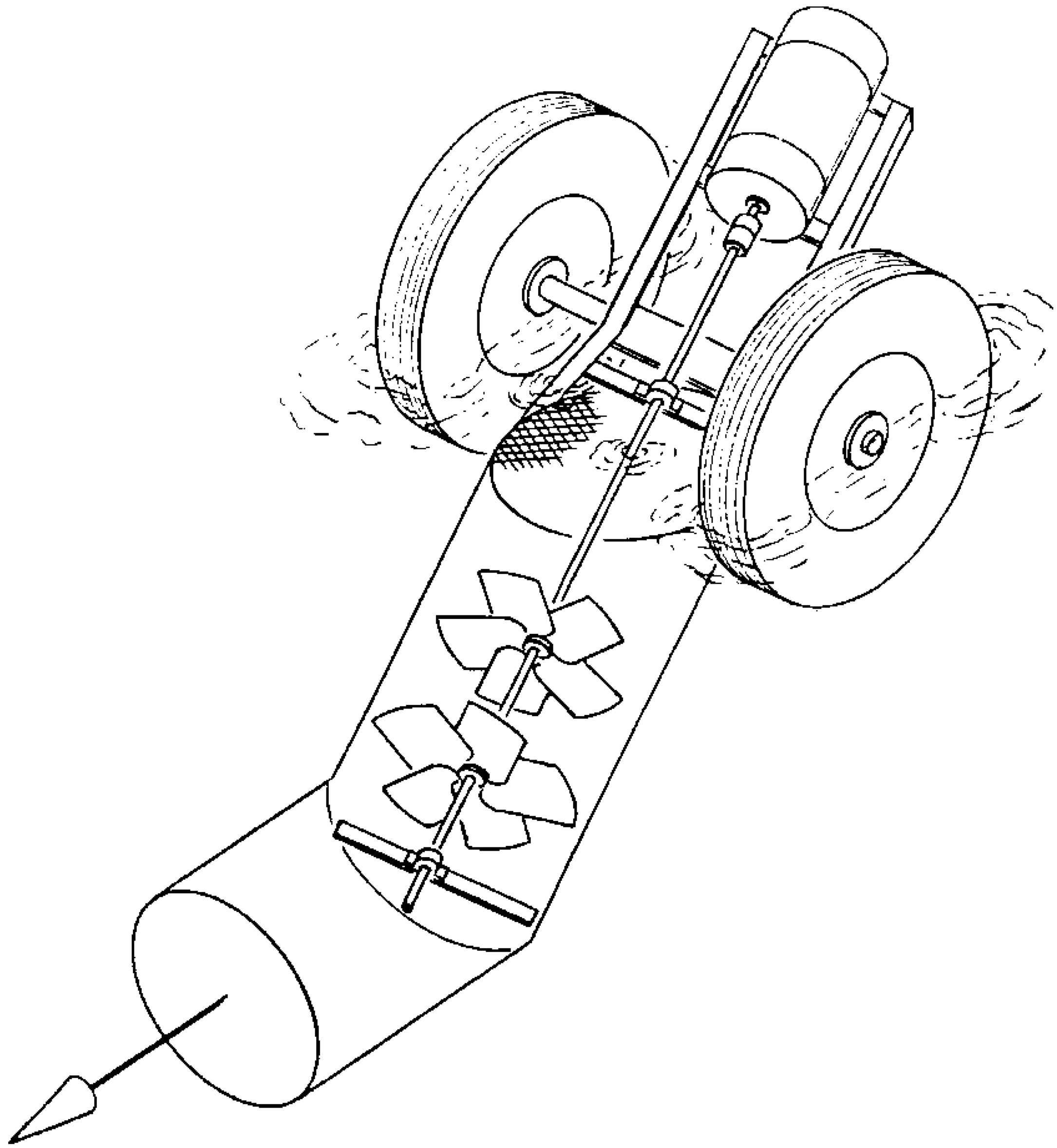

Figure 1. The first pond circulator (PC-I) developed before the NSF grant period. This version has two 16-inch fan blades and a heavy steel shroud which helps draw warm water from the surface and discharge the water near the pond's bottom. This version is operational over a narrow water depth range.


Figure 2. The Pond Circulator (PC-I) being removed from the prawn pond. The foam-filled tires roll on the bank, and thus facilitate removal of the circulator during harvest.

Figure 3. Pond Circulator (PC-I) viewed from discharge end. One of the two 16-inch fan blades is visible within the shroud.

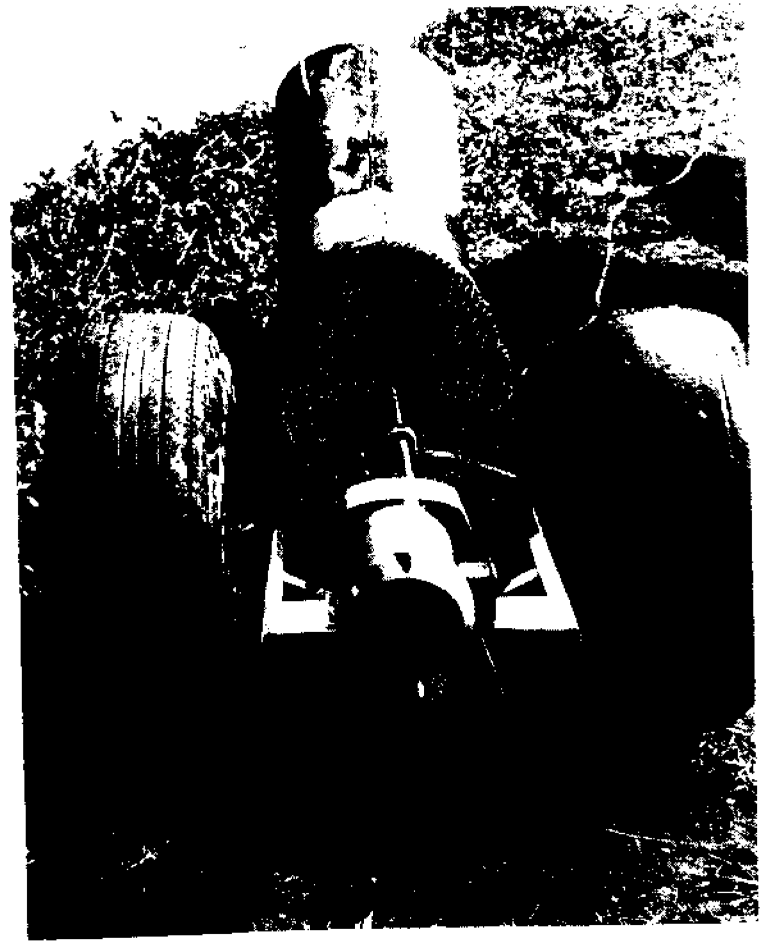

Figure 4. Pond Circulator (PC-I) viewed from the intake end. An expanded metal screen was placed over the intake to prevent weeds from wrapping around the fan blade.

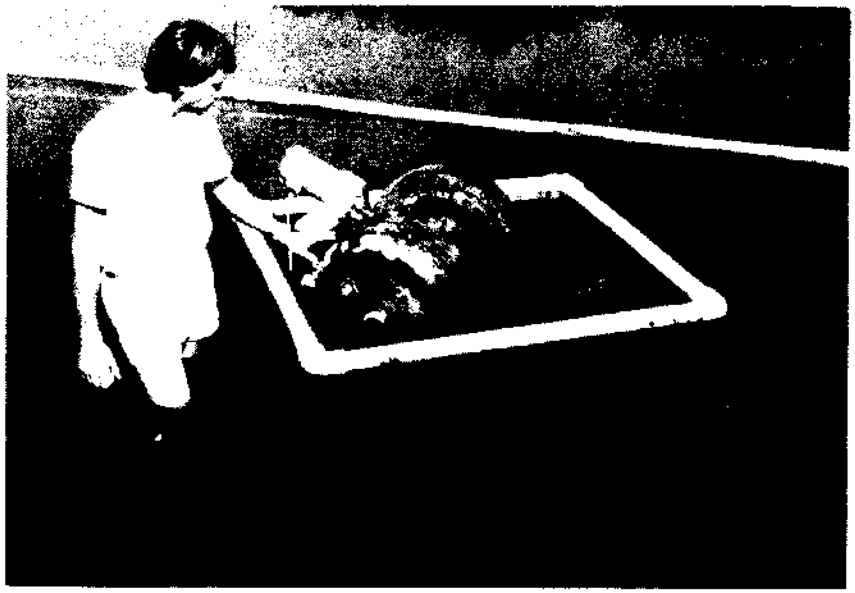

Figure 5A. Pond Circulator (PC-I) in operation at Kohala Prawn Farm. The square frame supports plastic netting which prevents weeds and other debris from clogging the intake screen.

Figure 5B. The frame and netting being removed. The frame consists of 2-inch PVC plastic pipes.

During the last month of this grant a second prototype pond circulator (PC-II) was built and tested. The PC-II was similar to the PC-I, except that the heavy steel shroud was reduced to only 6 inches in length, and a single 24-inch aluminum fan blade, aluminum with clockwise rotation and 27° pitch, replaced the two 16-inch fan blades (Fig. 6). The PC-II also had an extendible, 1½-inch PVC pipe attachment on its lower end. This extension could be adjusted for different water depths such that the fan blade would be positioned at 45° or other desired angle. The same motor used in the PC-I was mounted on a wooden frame, which was in turn bolted to the angle iron frame which supported the floatation tire axle and the drive shaft bearings for the fan blade. A pipe bracket on the upper end of the motor mount forms a handle for easy removal of the PC-II from the pond. This bracket also allows two pipes to be extended through the bracket into the pond bottom (pipes not shown in Fig. 6). These pipes prevent movement of the PC-II, which is prone to move about during operation because of its lighter weight and greater thrust. The electrical current draw under load was 3.9 amps.

Flow Rates

The PC-I produced a flow volume, measured with a flow meter, of about 1,500 gpm. During 12 hours of circulation, this flow will result in the pumping of 1,080,000 gallons of water. A one-acre pond with an average depth of 2½ feet contains about 815,000 gallons of water. Thus, during 12 hours of circulation, the equivalent of 1.3 pond volumes passes through the circulator. Most of the pumped water is drawn from the upper 6 inchs of the pond, which contains 163,000 gallons of water. During 12 hours of circulation, the equivalent of this surface layer is pumped through the circulator 6.6 times.

The flow rates on the PC-II were not measured, but should well exceed 2,000 gpm based on calculated flows from a similar design by Dr. James Garton of Oklahoma State (personal communication, 1982).

The largest pond in which we tested the pond circulators was only 0.5 acres. Based on these observations, however, we believe that a ¼-h.p. pond circulator with a single 24-inch blade (i.e., the PC-II design) should be able to adequately circulate a one-acre pond under most conditions.

Cost to Operate

The PC-I drew 3.7 amps, while the PC-II drew 3.9 amps. The cost to operate the PC-II is then:

(a) Kilowatts = (Volts x Amps)/1,000.
= (115 x 3.9)/1,000
= 0.4485

(b) Costs per month of continuous operation @ $.13/kw-hr.
Costs = (kw draw) x (hrs/mo)x(kw-hr cost)
= (0.4485) x (730 hrs/mo) x ($0.13/hr)
= $42.56/mo

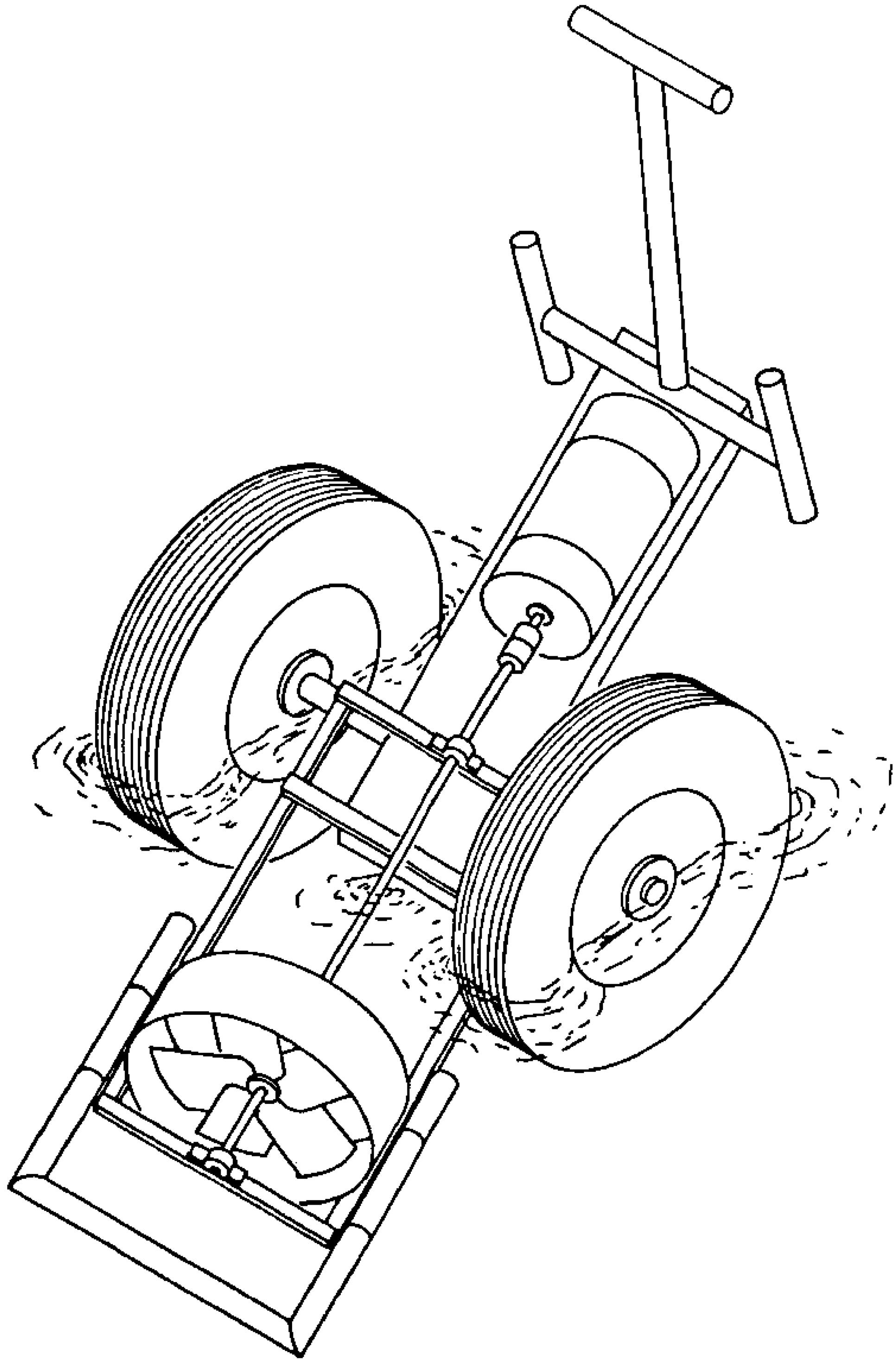

Figure 6. The second pond circulator (PC-II) developed during the NSF grant period. This version has a single 24-inch fan blade, a small shroud around the blade, and an extendible plastic pipe to accommodate a wide range of water depths.

Although continuous operation will cost $42.56/month, it is unnecessary to run the circulator full time. It is unnecessary to run the circulator at times when the bottom oxygen levels are high and the pond is not thermally stratified; the circulator needs to run only during daylight hours, and then only on those days when wind and solar irradiance conditions are likely to cause substantial stratification. We do not have sufficient information at this time to estimate what percent of the time a circulator need operate at a given site, but on the average we believe that it need not operate more than 15% to 20% of the time. This will vary between sites (wind or calm) and seasonally. If the circulator need run only 20% of the time, the monthly cost to run it is thus reduced from $42.56/month to $8.54/month or $102.43/year. At $4.00/lb for prawns, this amounts to a yearly production of only 26 lbs. If the annual production of the pond is 2,000 lbs of prawns, a trivial increase in prawn production of only 3% or so would pay for all the expense (depreciation and operating costs) of a circulator.

Optimization of circulator operation should have high priority for future research. We envision this research involving the following: (a) A period of information gathering on weather parameters such as wind velocity, wind direction, solar irradiance, and air temperature, and pond stratification parameters such as surface and bottom temperatures; (b) Mathematical model development whereby the relationships between pond stratification and meteorological conditions are defined; (c) The adaptation of the model to a personal computer located on site. The computer can receive input from an on-site weather station and thus the computer can control the on/off operation of all pond circulators at the site; and (d) The above control system is tested on site.

An invention disclosure has been filed with the U.S. patent office on the pond circulator concepts and designs described herein. A patent should be applied for in the near future.

## DESCRIPTION OF STUDY SITES

### Kohala Prawn Farm

The commercial prawn pond at Kohala Prawn Farm used in this study is located on the Island of Hawaii in the Kohala District (Lat. 20° 14.8'N, Long. 155° 51.0'W, Fig. 7). The Kohala area is considered a cold and windy site for prawn farming. Wind velocities during average tradewind conditions range from 18 to 20 knots (U. S. Weather Service, 1978). These strong winds cause substantial evaporative losses from ponds, and can easily reduce water temperatures by several degrees C (Klemetson and Rogers, in press).

The Kohala Prawn Pond used in this experiment measured 455 feet long by 32 feet wide and had a surface of 0.34 acres (0.12 ha). The average water depth was about 2 feet (0.6 m), but the depth varied from less than 2 feet at the influent end, to more than 3 feet (0.9 m) at the effluent end (Fig. 8). Total water volume was thus about 0.7 acre/foot (840 $m^3$). The pond bottom consisted of a layer of soft sediment from 3 to 6 inches thick, overlying a hard-packed layer which formed the original pond bottom. The pond was built during 1980.

On October 31, 1982, the pond was divided in half longitudinally by a clear, 12-mil plastic barrier (Fig. 9). The barrier's bottom edge had steel reinforcing rods rolled into it, and the bottom edge was then pushed into the soft pond bottom. The upper edge of the barrier was held above the water's surface by nylon twine attached, through grommets in the plastic, to vertical reinforcing rods driven into the pond bottom. The plastic barrier thus extended above the water's surface and into the pond bottom such that water in the two halves of the pond was effectively isolated.

Fresh irrigation water was continuously flushed into each half of the pond at 4 gpm, or 8 gpm (30 L/min) for the whole pond (Fig. 8). Water was discharged from the pond through 4-inch PVC plastic pipes which drew water from each half of the pond and into the drain. The water level remained constant, except when the pond was harvested. The flow rate through the pond was equivalent to 5% of the pond's volume per day.

The pond has a unique, proprietary design which facilitates the harvest and measurement of the prawns (Yunker and Barclay, 1981). To harvest, the prawns are crowded into a special trough at one end of the pond, and the water level is lowered until the edges of the trough are just below the surface. A valve is then opened on a pipe leading from the end of the trough and the prawns are drained into a catchment where they can be sorted, weighed and measured.

A single, Prototype I (PC-I) pond circulator was placed in the west side of the pond (Fig. 8) and operated continuously from December 16, 1982,

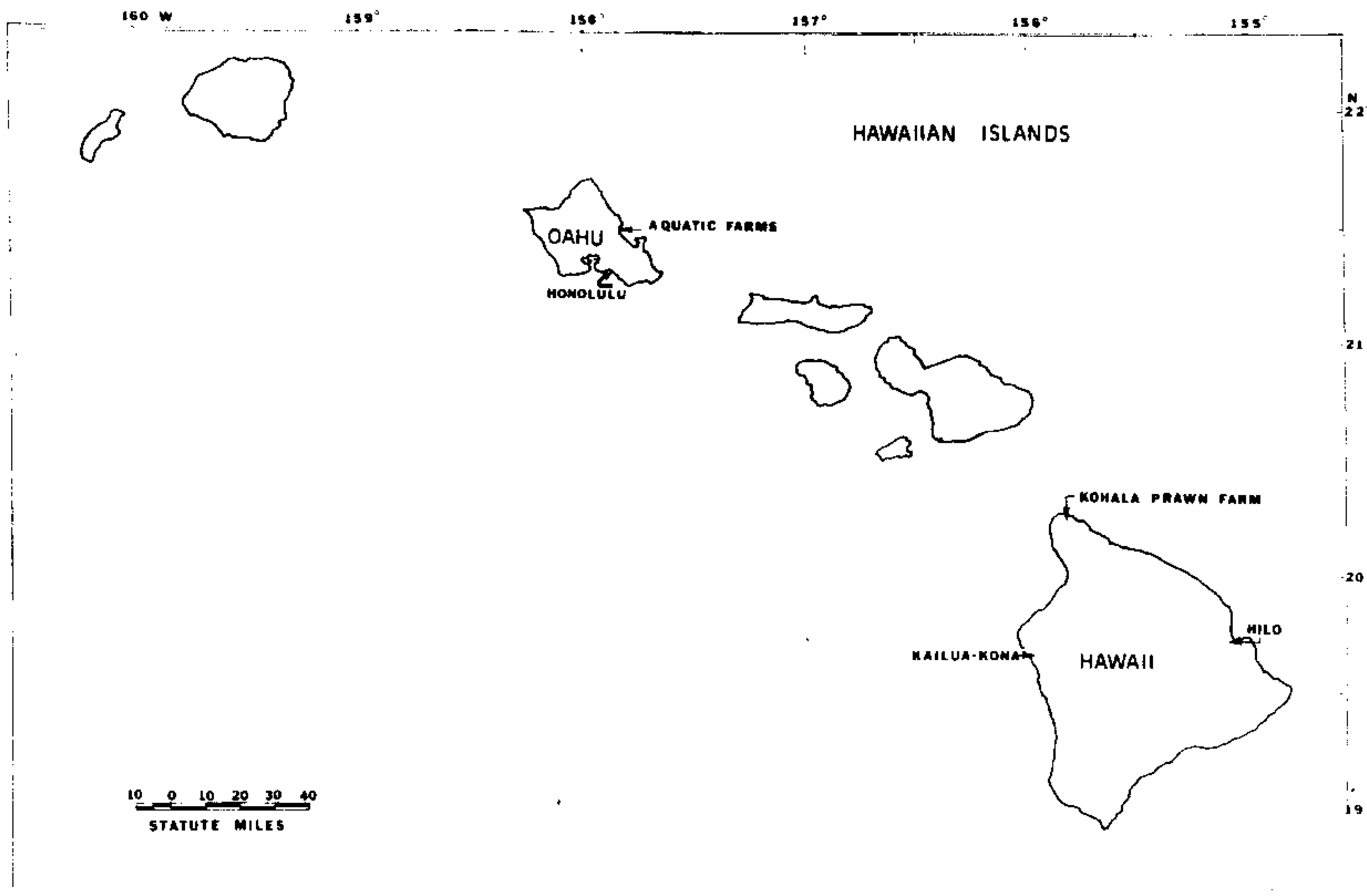


Figure 7. Map of the Hawaiian Islands indicating Kohala Prawn Farm on the island of Hawaii and Aquatic Farms on Oahu

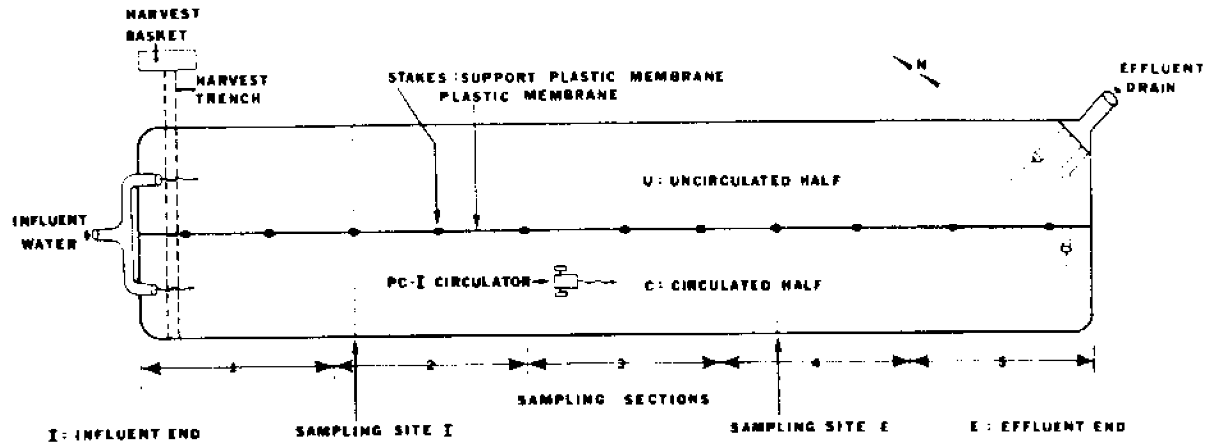


Figure 8. Schematic of Kohala Prawn Farm's pond where PC-I pond circulator was evaluated between December 1982 and March 1983. The pond was divided in half by a plastic membrane, and only the lower half was circulated by the PC-I. Continuous oxygen and temperature measurements were made at sampling site E. Water was continuously added at 4 gpm to both halves of the pond at the influent end (I end), and discharged through separate drain lines at the effluent end (E end).

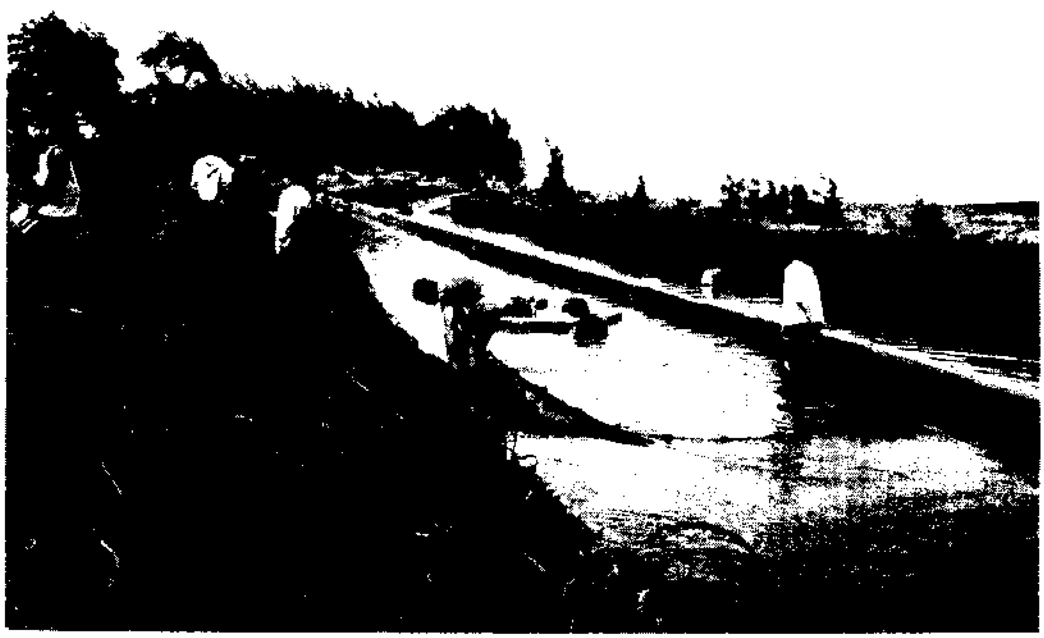

Figure 9. Each half of the pond was harvested separately. The plastic partition is easily seen in the center of the pond since the water level was lowered during the harvest operation.

through March 16, 1983. The circulator was located 200 feet from the influent end of the pond, and its discharge was directed toward the opposite end.

PVC plastic pipe markers were driven into the pond bank every 91 feet (28 m) along the longitudinal axis, thus "dividing" the pond into five equal sections (Fig. 8). Section 1 was at the influent end, while section 5 was the effluent end. This facilitated sample collection and monitoring.

Aquatic Farms

Aquatic Farms is a commercial prawn farm located near Kaneohe on the Island of Oahu (Lat. 21° 31.2'N, Long. 157° 50.9'W, Fig. 7). Although the farm is located on the windward side of the island, it is nestled close to high volcanic cliffs which shelter the site and produce calm wind conditions most of the time. Wind velocities were not recorded at the site during the experiment, but they generally are less than 6 to 8 knots during normal tradewind conditions. These calm conditions typically result in warmer water temperatures, more frequent thermal stratification, and much stronger stratification than at windy sites.

Artificial circulation evaluations began at Aquatic Farms during June 1982. These evaluations were largely supported by funds from the University of Hawaii Sea Grant Program, the Hawaii State Aquaculture Development Program, Aquatic Farms and the Hawaii Institute of Marine Biology. SEACO, Incorporated, supported this work by providing water circulation devices and technical assistance. The bulk of the results from the Aquatic Farms research will be described in later reports; we will present only a small portion here for comparison with the results from Kohala Prawn Farm, and to complement the findings at Kohala.

Three ponds used in our study at Aquatic Farms were nearly equal in size, and contiguous. Pond 4 was not circulated, and measured 145 feet by 155 feet with a surface area of 0.52 acres (0.21 ha). Pond 5 was circulated nearly continuously, and measured 128 feet by 150 feet with a surface area of 0.44 acres (0.18 ha). Pond 6 was occasionally circulated, and measured 135 by 150 feet with a surface area of 0.46 acres (0.19 ha). All three ponds had nearly level bottoms with maximum depth of 0.90 to 1.00 meters. Soft bottom sediments were thickest near the outlets of each pond, and measured more than 0.35 m in places. These ponds were all built during 1977.

Water exchange in the Aquatic Farms ponds normally was not continuous. Instead, the ponds were usually drawn down by 1/3 their volume during harvest (every three weeks), and then refilled. In addition, if water quality parameters indicated a deterioration of water quality, the pond was again lowered by 1/3 its volume and refilled. This discontinuous method of flushing results in an average daily exchange rate of about 2%.

# METHODS AND MATERIALS

## Kohala Prawn Pond

Dissolved Oxygen and Temperature: Dissolved oxygen and temperature with depth profiles were measured about once weekly with a YSI dissolved oxygen (D.O.) meter and self-stirring probe. Measurements were made at four locations in the pond, two each on each half. Sampling sites were 100 feet from each end of the pond, and were designated site I (influent end) and site E (effluent end) (Fig. 8). Measurements were made at 10 cm depth intervals between the pond's surface and bottom.

In addition to oxygen depth profiles, dissolved oxygen near the pond bottom was measured continuously at site E on each half of the pond from December 31, 1982, through March 15, 1983. This continuous monitoring station was set up 100 feet from the effluent end of the pond at site E (Figs. 8 and 10). The D.O. meters, probe cable reels and Rustrak strip recorders were housed in two weather-resistant cases on the pond's bank. The D.O. cables led from the meters to the probes which were attached to cement blocks, one on the circulated half of the pond and one on the uncirculated half. The probe tips were about 10 cm off the bottom, and each had a self-stirrer. Continuous D.O. values were recorded on the Rustrak strip recorders.

Surface and bottom temperatures were also measured continuously at the same location as continuous bottom D.O.'s (site E). Ryan thermographs were attached to the cement blocks which held the D.O. probes, and thus measured bottom temperatures on each half of the pond. In addition, Ryan thermographs were also attached to the underside of urethane floats and thus measured near surface temperatures. The thermographs' temperature sensors were at the 5 cm depth, and were shaded from direct sunlight by the foam float. We used battery-driven thermographs (Model No. J-180 WP) on the circulated half of the pond, and spring-driven thermographs (Model No. F-15) on the uncirculated half.

Transparencies: Secchi disc (20 cm) transparencies were measured almost daily at sites I and E on each half of the pond. The Secchi disc was lowered into the pond from the end of a 2-meter long PVC plastic pipe, and transparency measurements were estimated to the nearest cm.

Alkalinity and Conductivity: Alkalinity and conductivity samples were collected monthly at Sites I and E (10 cm depth) using a specially constructed collection device. The collection device consisted of a 10-foot long lightweight titanium tube (7/8-inch diameter) to which the sample bottle (1-l polyethylene) was attached. A ¼-inch diameter stainless steel tube was attached to the sample bottle's screw cap, and led to the other end of the titanium tube by guides. Hand holds at the operator's end of the device provided leverage such that the operator could extend the sample collection bottle out into the pond and lower it to any

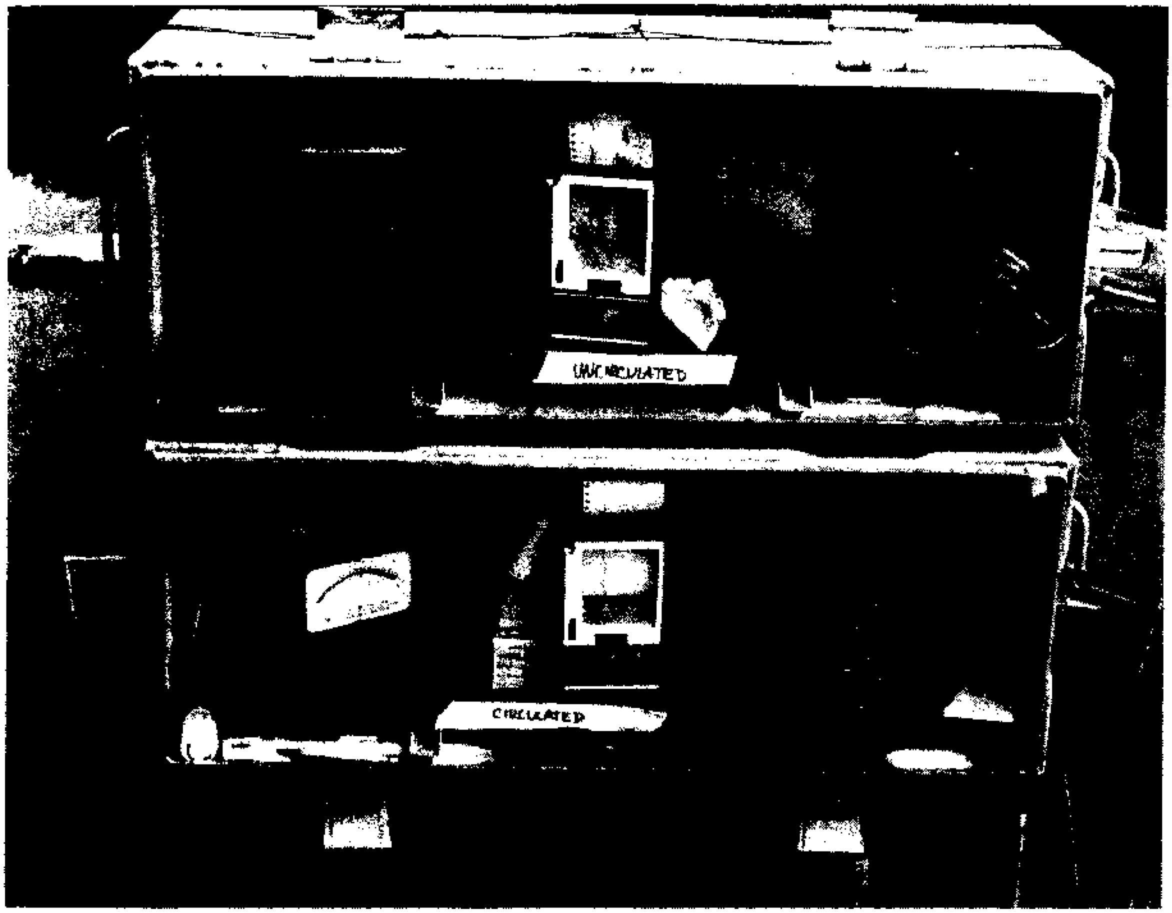


Figure 10. Instrument cases at Kohala Prawn Farm sampling site E used to house continuous oxygen-monitoring equipment. The covers to the cases were removed, revealing the YSI dissolved oxygen meters, Rustrak recorders, and D.O. probe reels. The bottom dissolved oxygen concentrations on the circulated and uncirculated halves of the pond were continuously monitored at this site.

desired depth. Once at the desired depth, the operator could remove the sample bottle cap by means of the stainless steel tube to collect the water sample. The cap was re-attached, and the sample retrieved. This device allowed the operator to collect undisturbed water samples while standing on the pond bank, without stirring the pond bottom, and without getting wet.

After collection, alkalinity and conductivity samples were stored in a refrigerator until analyzed. Conductivity was measured with a Lab-Line Lectro MHO-Meter, while alkalinity was measured by titrating with 0.02N HCL to a 4.5 pH endpoint. Welch (1948) describes these techniques in more detail.

Nutrient Samples: Water samples were collected monthly from the 10 cm depth at sites I and E, on both sides of the pond with the water sampling device described above. Water was filtered under pressure through a 47-mm diameter, 1.2μ glass filter into a 30 ml, 10% HCL and distilled water-rinsed polyethylene sample bottle. These sample bottles were frozen until analyzed. Analyses included soluble phosphorus, total phosphorus, ammonia, nitrate plus nitrite, total nitrogen, and silica. Total phosphorus and nitrogen were measured after the samples were irradiated by ultraviolet light to decompose the dissolved organic factions. Analytical techniques are described in more detail by The American Public Health Association (1980).

The first set of nutrient samples was collected from the surface and bottom at sites I and E, but not on each half of the pond since the plastic divider was not yet installed. Thereafter, samples were collected at the 10 cm depths as described.

Chlorophylls: Water samples were collected weekly at the 10 cm depth on both halves of the pond at sites I and E using another special water collection device. This device consisted of a 4-inch diameter plexiglass tube with a series of inlet ports and a ball valve which allowed water to be selectively withdrawn from any 10 cm depth interval ranging from the pond's surface to bottom (Fig. 11). The device also had a delivery tube on the bottom such that the water sample could be withdrawn without introducing air into the sample bottle. Water was collected with this device either by wading into the pond, or by use of a movable pier. The clear plexiglass allowed visual inspection to avoid sediment contamination (re-suspended sediment from pond bottom).

The chlorophyll water samples were filtered at the shore-side laboratory. From 200 to 500 ml of sample was filtered (depending on filtration rate) through 47-mm diameter, 1.2μ glass filter. Magnesium carbonate was added to the filter, and the filters were placed individually in perforated millipore petri dishes. The dishes were then placed in quart Mason jars with dessicant, and the jars were sealed and frozen until analyzed. During analysis, the samples were ground with 90% acetone in a tissue grinder, placed in test tubes and extracted for

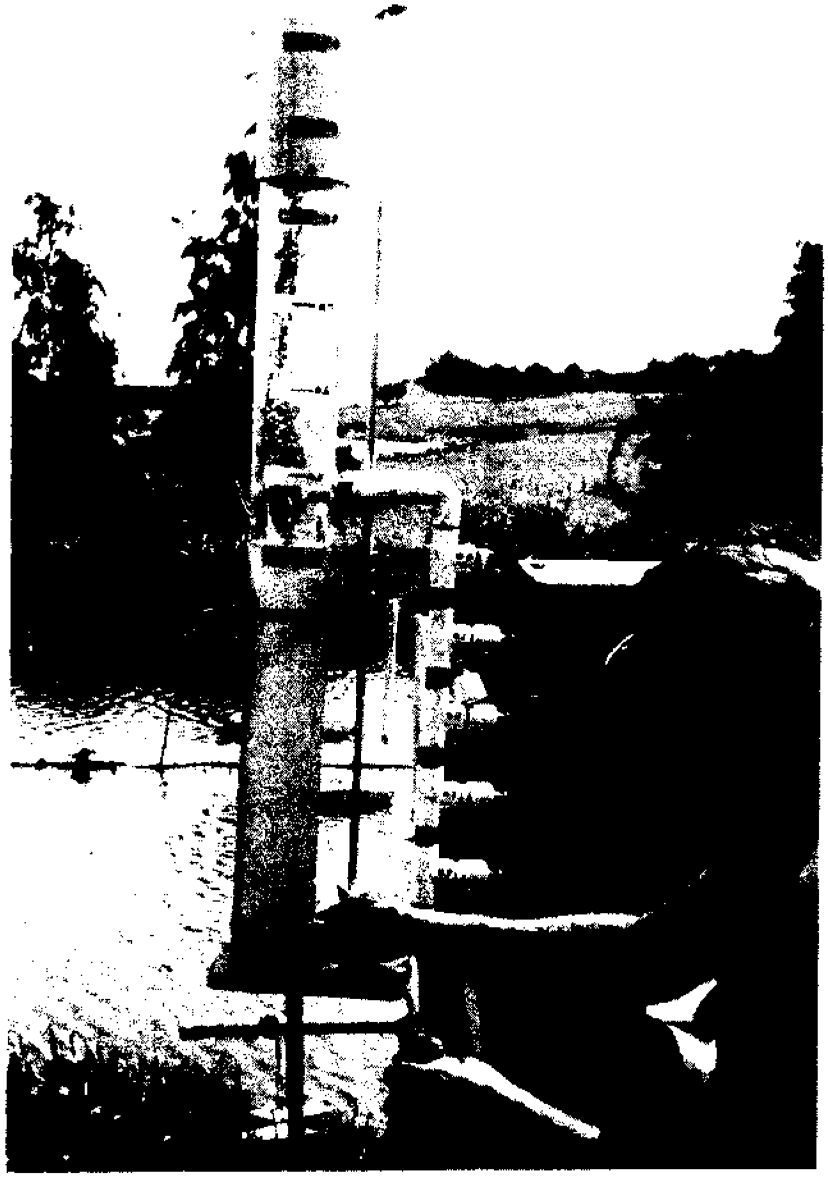

Figure 11. Water is withdrawn from special plexiglass collection device used to collect water samples for chlorophyll, suspended solids, and water respiration rates. Water is withdrawn from the device through a delivery tube near the bottom.

three days in the dark at -15°C. The samples were then centrifuged and analyzed in a Beckman DBG spectrophotometer. The formula used to calculate chlorophylls a (active + pheophytin), b, and c plus carotene are given by Jeffrey and Humphrey (1975). Fast (1968) describes the chlorophyll procedures used in more detail.

Suspended Solids: The same water samples used for chlorophyll measurements were also used for suspended solids. From 200 to 450 ml of water was filtered through a 47-mm diameter, 1.2μ glass filter. The filters were pre-rinsed in distilled water, dried at 60°C, and weighed. After weighing, the filter was placed in a plastic petri dish until filtration. After filtration the filter was put back in the petri dish. After drying at 60°C, it was again weighed and the dry weight of the suspended solids was determined by the difference in weights.

Water Oxygen Demand: The same water samples used for chlorophyll and suspended solids measurements were also used for water oxygen demands. After collection, the water was drained into 300 ml darkened B.O.D. bottles, plus 300 ml clear B.O.D. bottles. The dark bottles had been darkened by painting and taping the outside of the bottle, including the glass stopper, to exclude all light. The water in the clear bottles was fixed with Winkler reagents soon after collection to provide an estimate of initial D.O. concentrations. The dark bottles, after their stoppers were replaced, had two layers of aluminum foil placed over the stoppers to further exclude light. They were suspended in the pond at about the 10 cm depth. The dark bottles were incubated in the pond from three to four hours, at which time they were retrieved and their oxygen concentrations determined. All oxygen measurements were determined using a modified Winkler technique described by Fast and Hulguist (1982). The hourly rate of oxygen depletion was determined by the decrease in oxygen during the incubation period and by incubation time. The incubations normally occurred between 1000 and 1400 hours.

Sediment Oxygen Demand: Sediment oxygen demands were determined using a 1-meter diameter, hemispherical, plexiglass dome. The dome was darkened with tape and paint on its outer surface to exclude all light. The dome had a small stirrer blade which rotated within the dome at 20 RPM. This rate was sufficient to maintain well mixed water within the dome, but not great enough to suspend sediment.

To set the dome, a portable "pier" was wheeled to the sample site and placed in the water (Fig. 12). The dome was then carried out on the pier and carefully lowered to the bottom. This technique was used to prevent disturbance of the pond bottom since such disturbance can cause a substantial drop in initial D.O. We never observed any such drop using our technique. To facililate lowering of the dome, a 1½-inch valve on the top of the dome was opened to allow air to escape. The valve was closed after the dome was set.

After the dome was set, water was siphoned from the inside of the dome using a plexiglass cylinder and a base fitting on the dome. This

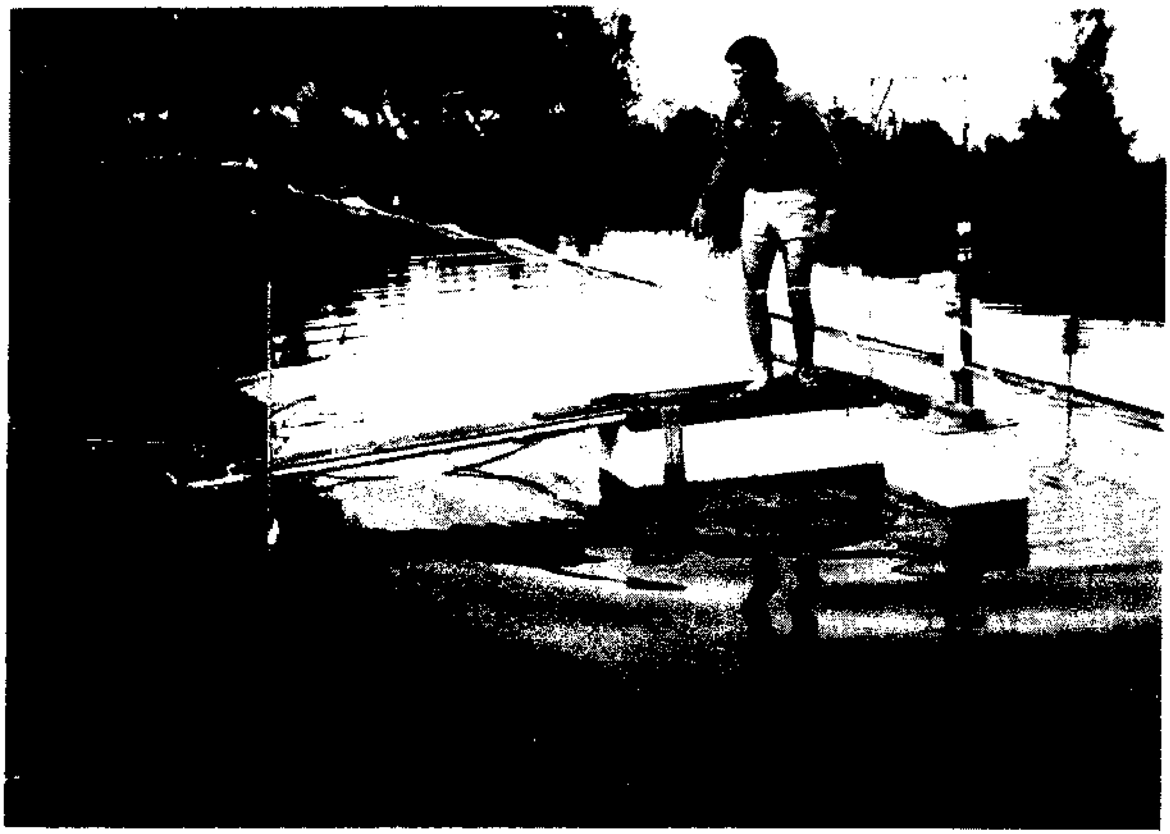

Figure 12. The portable pier used to make dome sets (benthic respiration) and to collect water samples without disturbing the bottom. The pier has wheels (submerged in the picture), which allow it to be easily installed in or removed from the pond. The dome has just been set in the pond, and only its pipe extensions are visible above water off the end of the pier.

water was then used to measure the oxygen demand of water within the dome, as described for water oxygen demand (earlier). These samples were suspended for incubation near the bottom of the dome. The rate of oxygen demand within the dome was measured by a YSI D.O. probe within the dome, and by YSI meter and Rustrak recorder on shore.

The dome was normally set in late afternoon between 1700 to 2000 hours to take advantage of high initial D.O. values, and to minimize any possible light leaks since most of the incubation occurred during the night. Incubation of the dome and B.O.D. dark bottles was terminated the next morning between 0600 and 0900 hours.

The total rate of oxygen depletion within the dome was taken using the decrease in oxygen from one hour after the dome was set until one hour before the incubation ended, or if the final D.O. was zero, then the D.O. concentration one hour before it went to zero. The rate of oxygen depletion by water within the dome was estimated by the decrease in D.O. within the dark bottles. The rate of oxygen uptake by the sediments was thus calculated by subtracting the total mg of $O_2$ consumed by the water to the total mg D.O. decrease within the dome. This yields sediment oxygen consumption under the dome in mg $O_2/m^2/hr$.

Sediment Combustible Solids: Core samples for combustible solids analysis were collected around the periphery of the dome (3 samples) during each dome set, and from the whole pond on three occasions. These samples were collected by pushing a 48 mm diameter plexiglass tube into the sediment by hand. An expandable rubber stopper was then placed in the upper end of the tube, and the tube withdrawn from the sediment (Figs. 13A and 13B). A rubber stopper was then placed into the lower end of the tube, under the core sample, and the upper stopper was removed. The bottom stopper was pushed through the tube (held vertically) by a PVC pipe, and the sediment sample thus extruded through the top of the plexiglass tube. A 60 ml plastic bottle with glass tubes and stopper was used to aspirate the upper 0.5 cm of the sample into the bottle. A screw cap was placed on the bottle and it was frozen until further analysis.

The frozen sample was thawed and placed in a pre-weighed porcelain evaporating dish to dry at 105°C for a minimum of 3 days. Upon determining the dry weight, the sample was then ashed at 500°C for 4 hours. The percentage weight loss upon ashing is the ash-free dry weight, and a measure of combustible solids and organic matter.

Benthic Fauna: Benthic fauna samples were collected from the pond on three dates, at the same time as the sediment core samples. Ten dredge samples (2 from each of the 5 pond sections) were collected from each half of the pond on each date. These samples were sieved at the pond (#35 screen mesh) and preserved with 20% formalin. The samples were later sorted by sugar flotation (Anderson, 1959), separated into groups using a binocular microscope and sorting tray (Fast, 1971), and

Figure 13A. Sediment core sample collected in a plexiglass tube at Kohala Prawn Farm.

Figure 13B. Sediment being aspirated into a sample bottle. The settled sediment was pushed to the top of the tube with a rubber stopper and a piece of white PVC pipe.

then counted. After counting, each group was dried on a paper towel and weighed (wet weight).

Prawn Survival and Growth: We originally intended to harvest each half of the pond every three weeks. During the first such harvest attempt it became clear that this schedule could not be met without risking destruction of the plastic sheet separating the two halves of the pond. Consequently, the pond was not harvested until the conclusion of the experiment on March 16, 1983.

On October 31, 1982, at the beginning of the experiment the pond was thoroughly seined first, using a standard prawn harvest seine (1-inch stretch mesh), and then a smaller mesh thereafter (¼-inch stretch mesh). This resulted in the harvest of 210 lbs of market-sized, and submarket-sized prawns. The plastic barrier was then installed, and 105 lbs of prawns of all sizes were stocked into each half.

On March 16, 1983, each half was harvested separately, again using both seines. Carapace lengths were measured on 200 randomly selected prawns from each half. In addition, the total weight of market-sized prawns (12 prawns to the pound or larger) from each half was measured. The prawns were hand-sorted to market size.

Weather Data: Daily weather data was obtained from the U.S. Coast Guard Loran Station at Upolu Point. This station is about 1.5 statute miles (2.4 km) from Kohala Prawn Farm. Wind velocity observations were recorded at the station at 0800, 1200 and 1800 hours each day.

Manure Applications: Cattle manure was applied to the Kohala pond between November 29, 1982, and February 10, 1983. In all, 5,275 lbs (2398 kg) were distributed in the pond during 18 applications. Between one and five applications were made per week, and equal amounts were applied to each half of the pond during each application. The manure was broadcast into the pond in an effort to achieve even distribution. The total amount of manure added was equivalent to 0.36 $lb/ft^2$ (1.8 $kg/m^2$) of pond surface area.

There were two purposes for applying manure to the pond: (1) to evaluate its value as a low cost substitute for commercial prawn feed, and (2) to increase the oxygen fluxes in the pond, and thus create a more intensive evaluation of artificial circulation. Without manure applications, this pond had relatively small diurnal changes in oxygen concentrations, low algal densities, and low oxygen demands.

Aged cattle manure for application to the pond was collected from an abandoned manure collection sump at the Kohala Cattle Company feed lot. The sump was concrete lined, and the manure had been in the sump for about one year before we used it in the pond. We had this manure analyzed, along with freshly collected manure from grass-fed and feed lot-fed cattle.

The manure samples were analyzed by Stanley M. Ishizaki of the University of Hawaii Feed and Forage Analysis Program, Agricultural Diagnostic Service Center, University of Hawaii at Manoa. These analyses indicate that the aged manure which was applied to the pond was similar to fresh manure, with the following exceptions (Table 2): (a) crude fat was much lower in the aged manure (0.6%) compared with fresh manure (2.6%), (b) neutral detergent fiber and acid detergent fiber were higher in the aged manure (67.0% and 50.5%, respectively) compared with fresh manure (59.2% and 35.5%, respectively), (c) permanganate lignin was much higher in the aged manure (24.5%) compared with the fresh manure (8.9%), (d) phosphorus content was much lower in the aged manure (0.36%) compared with fresh manure (0.70%), and (e) iron was higher in the aged manure (8,758 ppm) compared to fresh manure (3,237 ppm).

Although these analyses indicate that the aged manure differed in many respects to fresh manure, its stimulatory effects on the pond clearly indicated that its nutrient value was more than adequate.

<u>Aquatic Farms Prawn Ponds</u>

<u>Oxygen and Temperatures</u>: D.O. and temperature with depth measurements were made weekly using techniques similar to those at Kohala Prawn Farm. Continuous oxygen measurements were not made at Aquatic Farms. Continuous temperatures were recorded using Ryan thermographs and techniques identical to those at Kohala Prawn Farm.

<u>Prawn Tagging</u>: Prawns were tagged with floats and lines during the Summer of 1982 in an effort to monitor their distribution and movement during circulated and uncirculated conditions. From 20 to 30 prawns of different sizes and sexes were selected during harvest for tagging and release to a circulated pond and an uncirculated pond. The prawns were tagged by placing small stainless steel wires (0.01 inch diameter) and clips through their rostrums. Small numbered painted corks (#7) were attached to the other ends of the wires, and the prawns were released to their respective ponds. The painted corks were clearly visible, and thus allowed us to monitor each prawn's location and movement within the pond. The locations of each prawn were monitored several times during the day over a several-day period after release.

Table 2. Nutrient and mineral composition of manure applied to Kohala Prawn pond (Kohala Cattle Company sump manure), and fresh manure samples from grass fed cattle and feed lot cattle. Analyses performed by the University of Hawaii Feed and Forage Analysis Program.

| Manure Source | % Nutrient Composition | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Dry Matter | Ash | Protein Crude | Crude Fat[1] | Neu. Deter. Fiber | Acid Deter. Fiber | Permanganate Lignin | Cellulose |
| Kohala Cattle Company | | | | | | | | |
| Surface of Sump | 24.9 | 27.3 | 16.9 | 0.7 | 64.4 | 47.4 | 23.6 | 14.3 |
| 3" - 6" below surface | 16.9 | 22.6 | 13.4 | 0.6 | 69.0 | 52.7 | 25.2 | 18.6 |
| 1' below surface | 12.5 | 22.3 | 14.2 | 0.6 | 67.5 | 51.4 | 24.8 | 19.0 |
| Fresh grass fed | 32.6 | 18.2 | 11.9 | 2.7 | 58.8 | 33.7 | 9.1 | 21.3 |
| Kukaiau Range | | | | | | | | |
| Fresh feed lot | 23.8 | 22.7 | 13.4 | 2.4 | 59.6 | 37.3 | 8.8 | 17.4 |

| Manure Source | Mineral Composition | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Phosphorus (%) | Potassium (%) | Calcium (%) | Magnesium (%) | Sodium (%) | Manganese (pom) | Iron (ppm) | Copper (ppm) | Zinc (ppm) |
| Kohala Cattle Company | | | | | | | | | |
| Surface of Sump | 0.46 | 0.48 | 1.34 | 0.39 | 0.10 | 335 | 9354 | 38 | 234 |
| 3" - 6" below surface | 0.31 | 0.22 | 0.82 | 0.23 | 0.04 | 245 | 7680 | 32 | 203 |
| 1' below surface | 0.30 | 0.21 | 0.82 | 0.22 | 0.04 | 246 | 9240 | 37 | 182 |
| Fresh grass fed | 0.63 | 0.30 | 1.11 | 0.91 | 0.09 | 398 | 2839 | 25 | 152 |
| Kukaiau Ranch | | | | | | | | | |
| Fresh feed lot | 0.77 | 0.79 | 1.81 | 0.50 | 0.19 | 235 | 3635 | 27 | 243 |

1/ Ether extract

## RESULTS

### Oxygen and Temperature

Kohala Prawn Farm: The effects of artificial circulation on the oxygen and temperature conditions in ponds are most dramatically illustrated by comparing these conditions with and without circulation on calm and windy days. Calm conditions typically existed at Kohala Prawn Farm when wind velocities were 10 knots or less when the sky was clear and sunny. The period of February 24 to 26 was such a period when wind velocities respectively averaged 10, 8 and 7 knots.

On February 24 at 0100 hours, surface and bottom temperature differences on the circulated and uncirculated halves of the pond were about 1°C (Fig. 14). About dawn (0600 hours), these temperature differences began to increase, and reached a maximum difference during the late afternoon. At 1800 hours, the bottom and surface temperatures on the circulated side were 26°C and 29°C, respectively, for a difference of 3°C. On the uncirculated side at 1800 hrs, the bottom and surface temperatures were 22.5°C and 27.5°C, respectively, for a difference of 5°C. Not only were the bottom surface differences greater on the uncirculated side, but they persisted over a longer period. On February 24-25 for example bottom and surface temperatures were nearly equal between 2000 hours on the 24th and 1000 hours on the 25th. Temperature differences on the uncirculated side during this same time ranged from 1°C to 3.5°C.

The influence of artificial circulation on bottom oxygen concentrations, as reflected by temperature conditions, is most dramatic. On February 24, bottom oxygens were about the same on each half of the pond at dawn with about 5 to 6 mg/l (Fig. 14). During the day, bottom oxygen concentrations on the circulated side increased to a maximum of 15 mg/l at 1800 hours, and then gradually declined to 7 mg/l the next morning at 0600 hours. By contrast, bottom oxygen concentrations on the uncirculated side continued to decline throughout the day on the 24th and reached a minimum of 3 mg/l at 1800 hours and then increased to 5 mg/l as convective cooling mixed surface water (with high D.O.) into the bottom water.

Bottom oxygen concentrations on the circulated half of the pond were never less than 5 mg/l during this three-day period, while maximum oxygen concentrations ranged between 15 and 18 mg/l (Fig. 14). On the uncirculated side, bottom oxygen concentrations were often less than 5 mg/l, and only once exceeded 7 mg/l.

Typical thermal stratification patterns for the circulated half of the pond on calm days was for a bottom-to-surface temperature difference of about 1 to 2°C to develop between 0600 and 1800 hours. The remainder of the day bottom/surface temperature differences was less than 1°C. Bottom oxygen values were typically at a minimum about dawn (0600 hours),

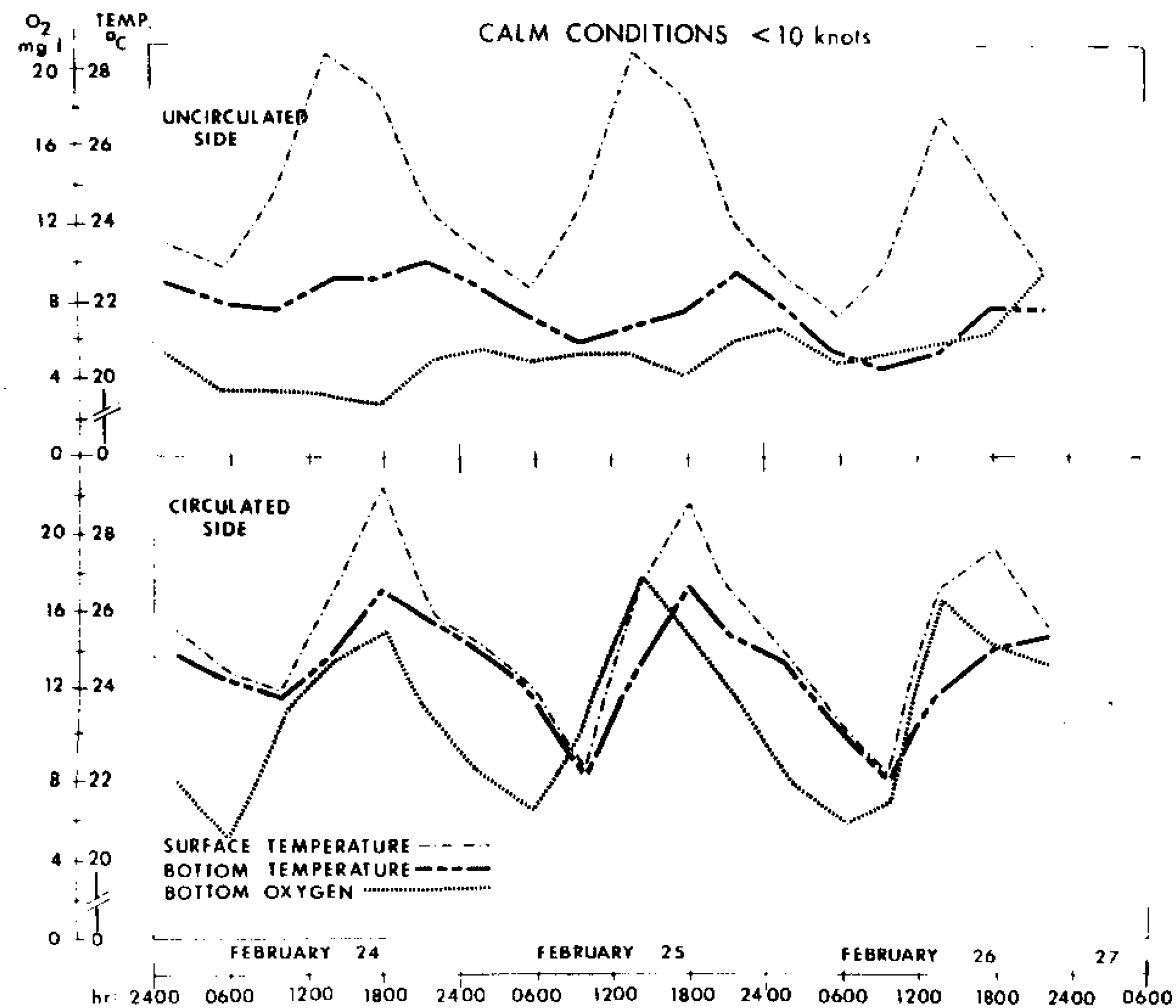


Figure 14. Surface and bottom temperatures and bottom oxygen concentrations on the uncirculated half (upper portion of figure) of Kohala Prawn Farm pond, and on the circulated half (lower portion) of the pond. Measurements were made at sample site E. This three-day interval represents a calm period where wind velocities respectively averaged 10, 8, and 7 knots.

and reached a maximum between 1200 and 1800 hours. With the exception of the pre-dawn period, bottom oxygen concentrations were almost always much greater on the circulated half of the pond.

Typical thermal stratification patterns for the uncirculated half of the pond on calm days was for bottom/surface differences of 6°C or more during the day, with persistent stratification of 1°C during much of the night. Bottom oxygen concentrations typically reached a minimum value during late afternoon, and increased thereafter as surface waters were mixed into the bottom waters by convective cooling by the wind.

On windy days, oxygen and temperature conditions on the circulated and uncirculated halves of the pond were very similar. The period January 24 to 26 was such a period when wind velocities respectively averaged 20, 15 and 11 knots (Fig. 15). Overcast and/or rainy conditions also produced little differences between circulated/uncirculated halves of the pond even if wind velocities were low.

On January 24 to 26 bottom and surface temperatures on the circulated half of the pond seldom differed by more than 0.5°C, while on the uncirculated half they ranged from 0.5 to 2.5°C. The greatest difference during windy conditions occurred on the 26th when the average wind velocity was only 11 knots (Fig. 15). When wind velocities averaged 15 knots or more, bottom/surface differences were less than 1°C.

Bottom oxygen concentrations on the two halves of the pond were very similar during the windy period of January 24 to 26 (Fig. 15). Not only were daily maxima and minima about the same value, but they occurred at about the same time. Minimum values of 5 to 6 mg/l occurred on both halves at about dawn (0600 hours), while maximum values of 12 mg/l or more occurred between 1400 and 1800 hours each day.

During windy conditions, there is almost no difference in oxygen concentrations or temperatures with depth on either half of the pond. On January 31 when wind velocities averaged 15.5 knots, oxygen concentrations were about 10 mg/l at all depths on both the circulated and uncirculated halves of the pond (Fig. 16). Likewise, temperature values were the same on both halves at the surface and bottom, with a temperature range of 1°C.

During calm conditions on February 18 (9 knots), a sharp break in both oxygen and temperature occurred at the 40 cm depth on the uncirculated half of the pond (Fig. 16). The pond bottom area below the 40 cm depth probably amounts to about 60% or more of the total bottom area. In most larger prawn ponds this percentage would be even higher. On the same date, on the uncirculated half, oxygen concentrations were uniform at 14 mg/l from the surface to the 40 cm depth, but then decreased sharply to 5 mg/l at the bottom. By contrast, the circulated half had 12 to 14 mg/l at all depths. The temperature range on the uncirculated half was from 24°C at the bottom to 27.5°C at the surface with a sharp break at

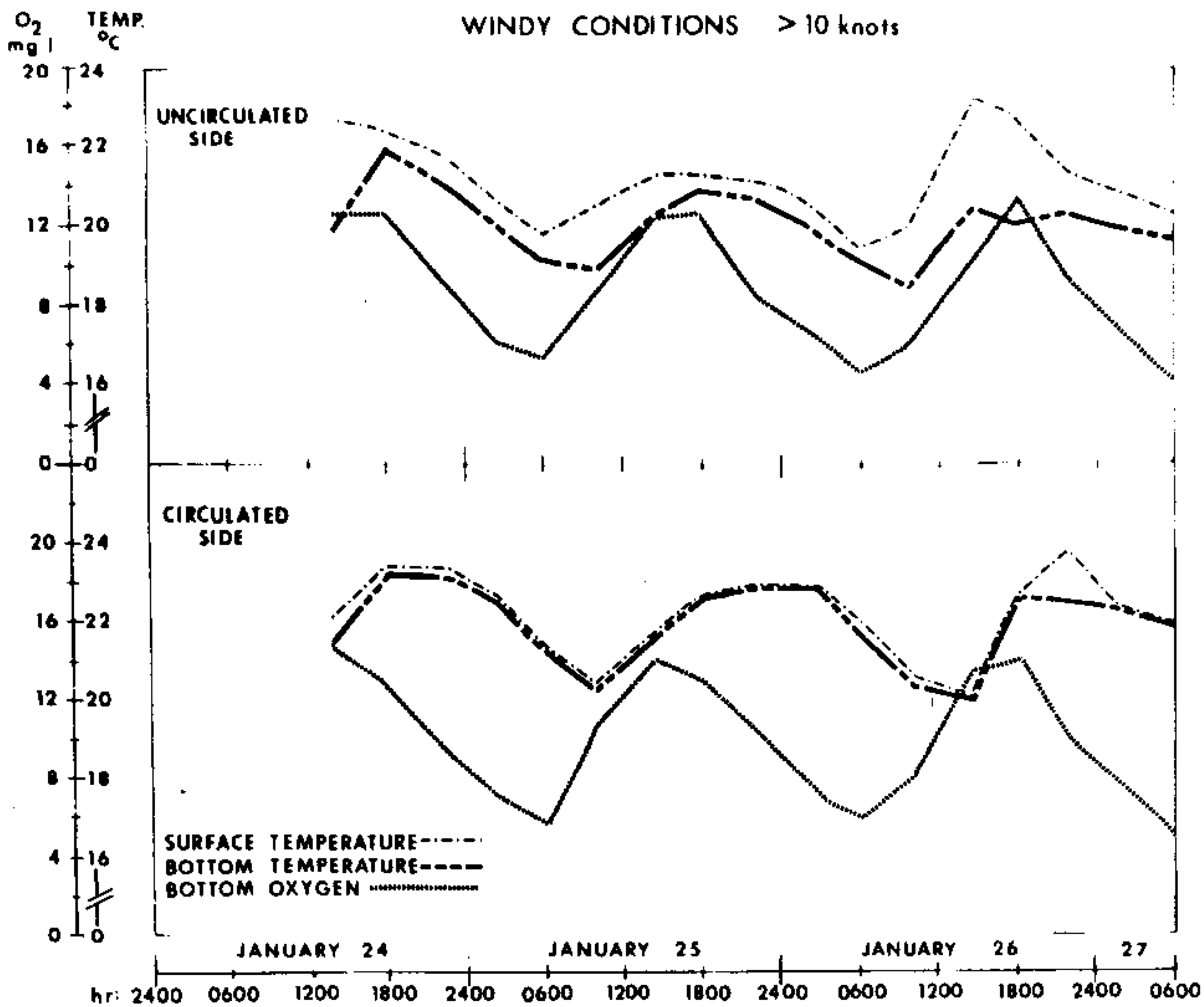


Figure 15. Surface and bottom temperatures and bottom oxygen concentrations on the uncirculated half (upper portion of figure) of Kohala Prawn Farm pond and on the circulated half (lower portion) of the pond. Measurements were made at sample site E. This three-day interval represents a windy period where wind velocities respectively averaged 20, 15, and 11 knots.

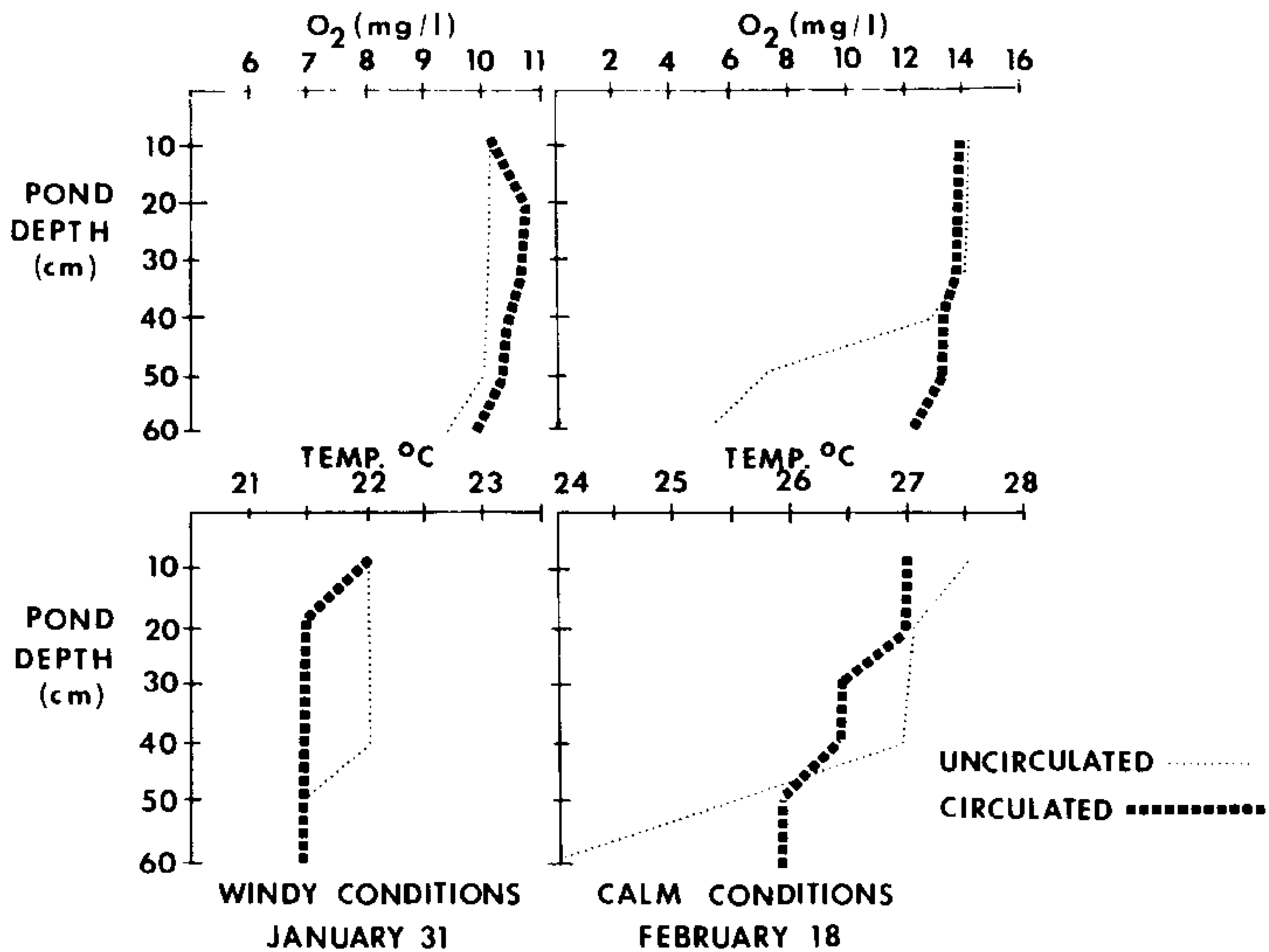


Figure 16. Mid-day oxygen and temperature with depth profiles on a windy day (January 31, 1983; 15.5 knots), and on a calm day (February 18, 1983; 9 knots) at Kohala Prawn Farm pond. These depth profiles were measured on the circulated and uncirculated halves of the pond at sampling site E.

the 40 cm depth. The circulated half ranged from 26°C at the bottom to 27°C at the surface with a gradual change from bottom to surface.

Maximum daily bottom temperatures varied greatly between the two halves of the Kohala Prawn Farm pond. Between February 21 and March 14, the maximum bottom temperatures on the circulated half averaged 26.2°C, while on the uncirculated half they averaged 23.4°C , for an average difference of 2.8°C (Fig. 17). There were relatively calm winds during this period as the average wind velocity exceeded 10 knots on only 3 of the 21 days. The least temperature differences between the two halves tended to occur on days with the greatest average wind velocity.

Also shown in Figure 17 is a warming trend from March 1 through the 14th. Bottom temperatures on both halves of the pond increased, with an increase from 23.5°C to 27.5°C on the circulated side, and from 21°C to 25.2°C on the uncirculated side.

Minimum daily bottom oxygen concentrations were nearly equal on the two halves of the Kohala Prawn Farm pond during most of January. The mean value for the month was only 0.3 mg/L higher in the circulated side although the daily oxygen concentrations were often 1 to 2 mg/L higher toward the end of the month (Fig. 18, Table 3).

Minimum daily bottom oxygen concentrations differed greatly on the two halves of the pond during February and March (Figs. 19 and 20). During these months bottom oxygen concentrations on the circulated side were always equal to, or greater than, the concentrations on the uncirculated sides. In many cases, the uncirculated side had a minimum of 2 mg/l, while on the average the circulated side was 1.5 mg/l higher during February, and 1.0 mg/l higher during March (Table 3).

Minimum bottom oxygen concentrations were below 3 mg/l on 7 dates on the circulated side, and on 11 dates on the uncirculated side (Figs. 18, 19 and 20). The numbers of days measuring below 2 mg/l were 4 for the circulated and 5 for the uncirculated. Both sides had very low minimum concentrations during March 9 to 13 when algal populations deteriorated.

Maximum daily bottom oxygen concentrations were usually much greater on the circulated half of the Kohala Prawn Farm pond. The average for the circulated side during January was 2.2 mg/l higher than the uncirculated, with a maximum difference of 6.2 mg/l on the 21st (Fig. 21, Table 3). This trend continued during February and March (Figs. 22 and 23). The maximum bottom D.O. was higher on the uncirculated side for only six days during the three-month period. The largest difference occurred on February 8 when the uncirculated side had a D.O. value of 6.3 mg/l compared with 18.8 mg/l for the circulated side. The three-month average for the circulated side was 4.0 mg/l higher than the average for the uncirculated side (Table 3).

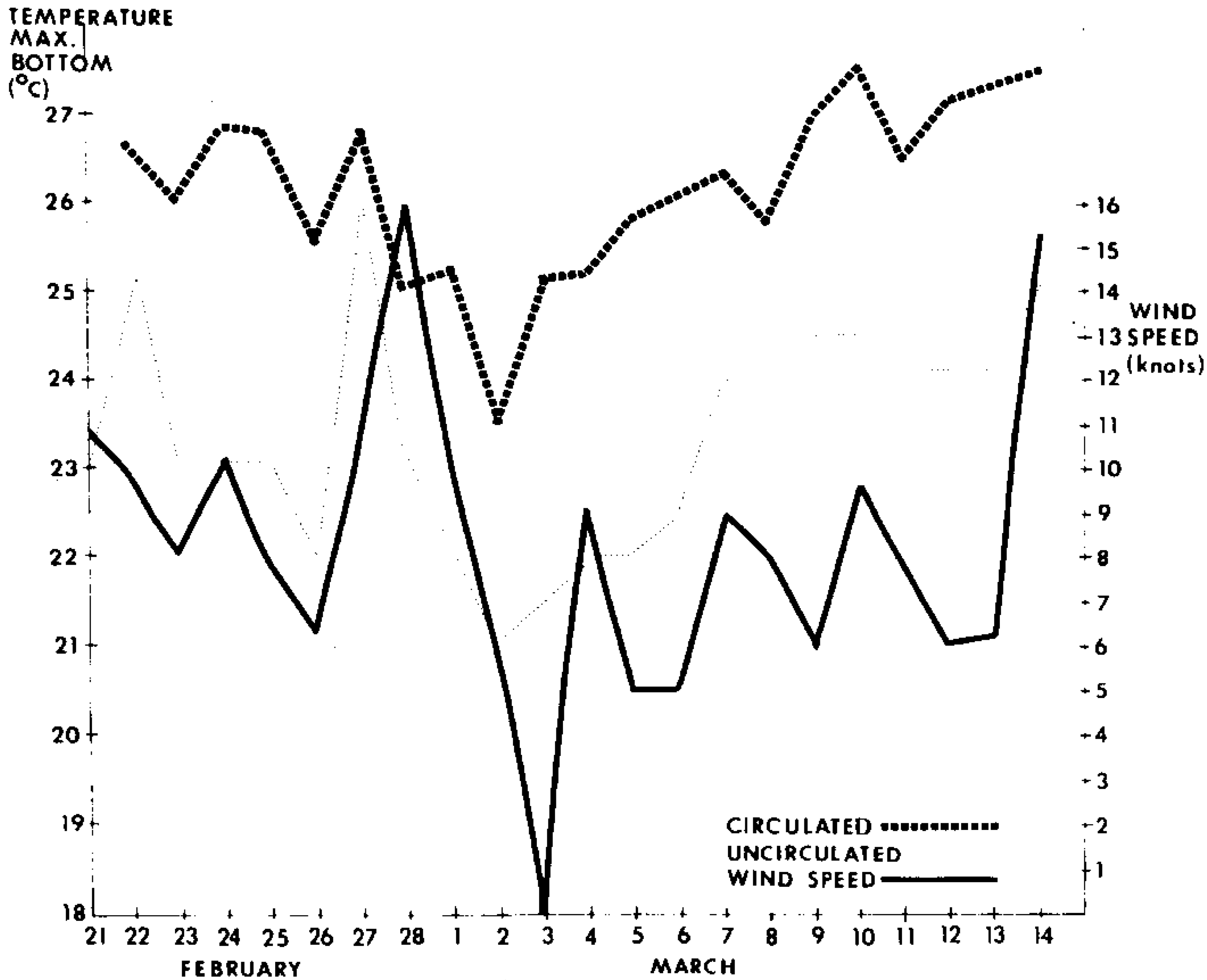


Figure 17. Daily maximum bottom temperatures on the circulated and uncirculated halves of the Kohala Prawn Farm pond during February and March 1983. Temperatures were measured at sampling site E. Average daily wind velocities are also shown.

Table 3. Average daily bottom, maximum, and minimum oxygen concentrations for January, February, and March 1983 at Kohala Prawn Farm pond on the circulated and uncirculated halves.

| Month | Circulated Half | | Uncirculated Half | |
|---|---|---|---|---|
| | Max. $O_2$ (mg/1) | Min. $O_2$ (mg/1) | Max. $O_2$ (mg/1) | Min. $O_2$ (mg/1) |
| January | 13.7 | 4.8 | 11.5 | 4.5 |
| February | 14.8 | 5.1 | 9.7 | 3.6 |
| March | 12.4 | 3.6 | 6.3 | 2.6 |
| All dates | 14.0 | 4.8 | 10.0 | 3.8 |

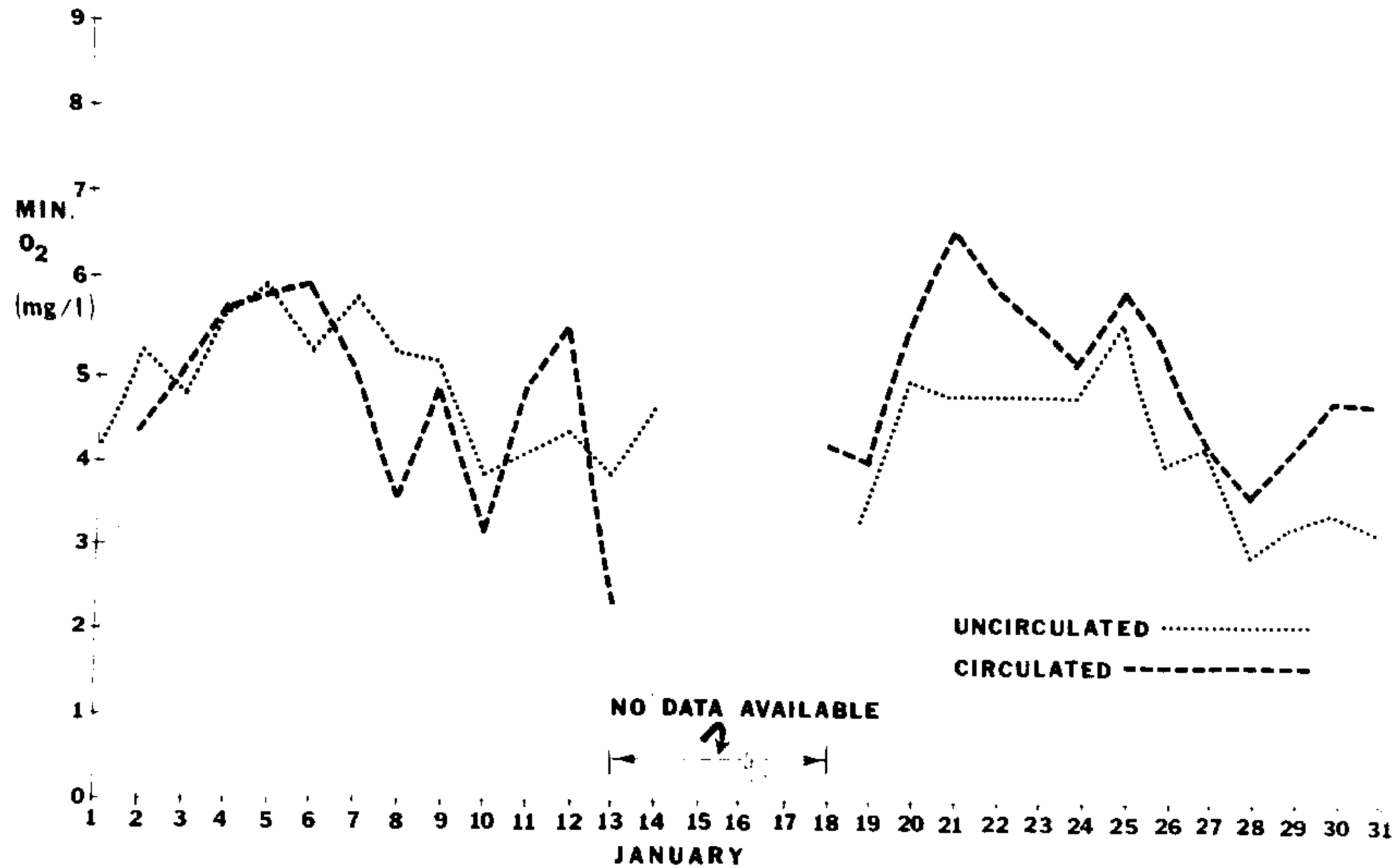


Figure 18. Minimum bottom oxygen concentrations on the circulated and uncirculated halves of Kohala Prawn Farm pond during January 1983

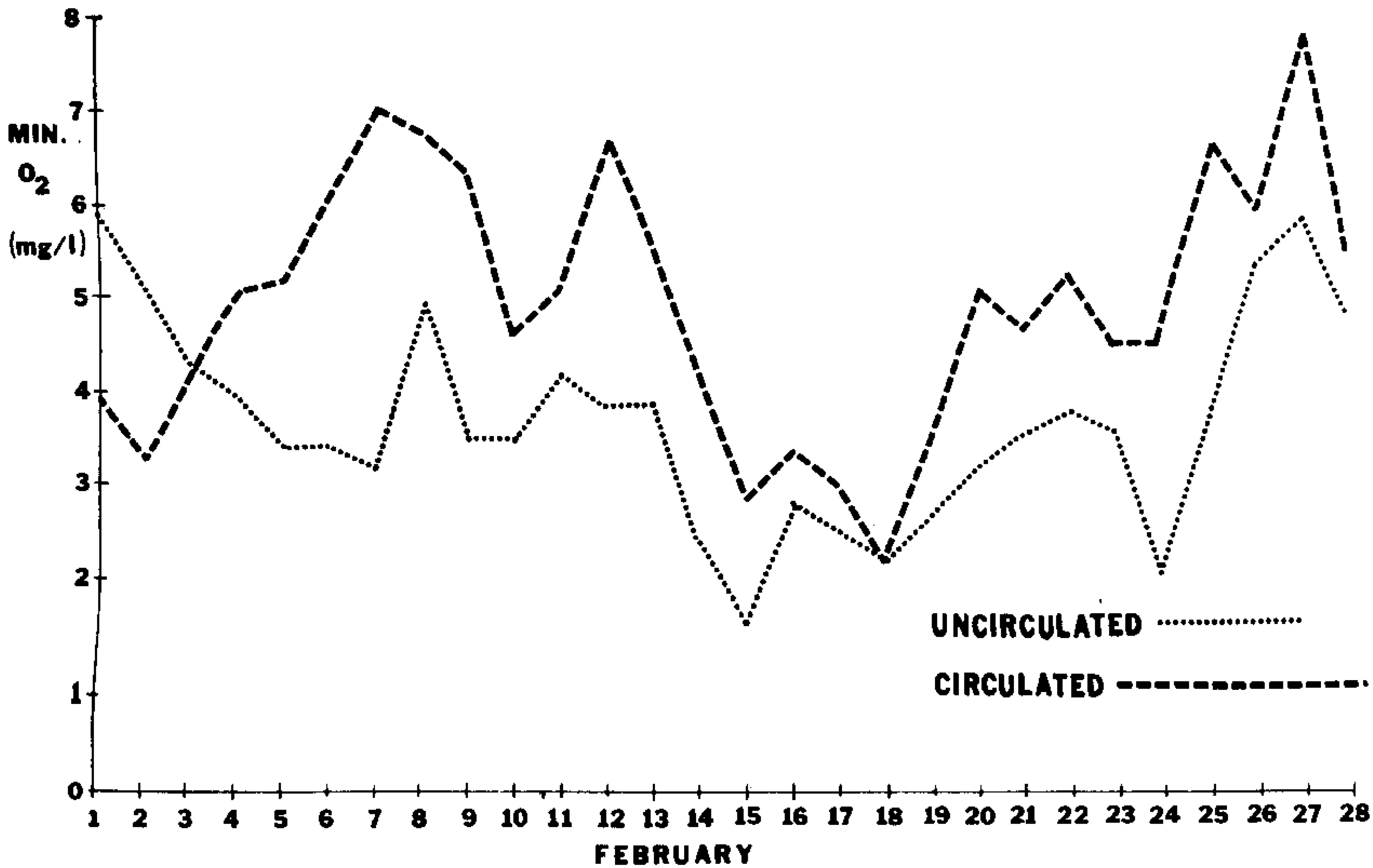


Figure 19. Minimum bottom oxygen concentrations on the circulated and uncirculated halves of Kohala Prawn Farm pond during February 1983.

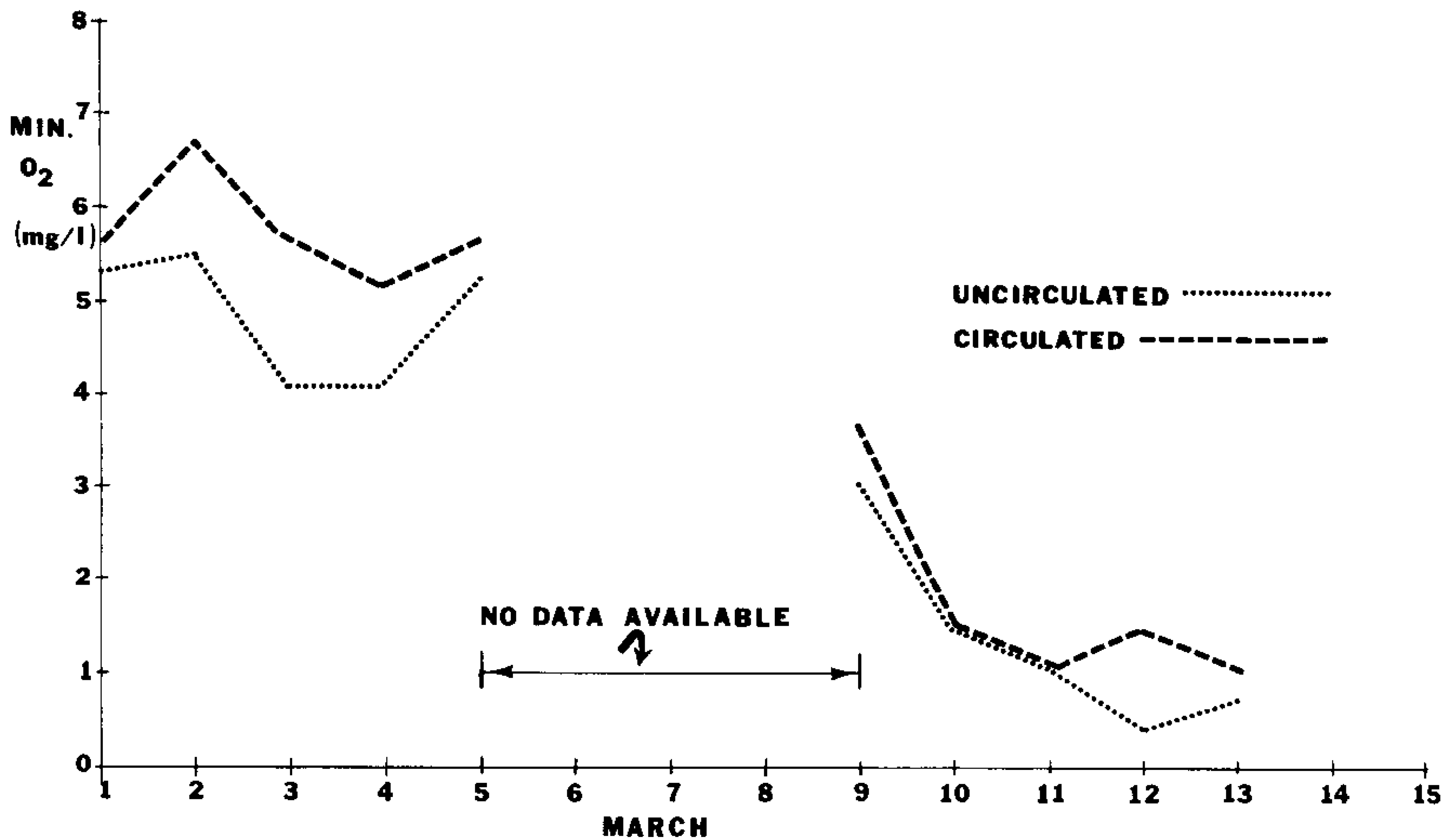


Figure 20. Minimum bottom oxygen concentrations on the circulated and uncirculated halves of Kohala Prawn Farm pond during March 1983

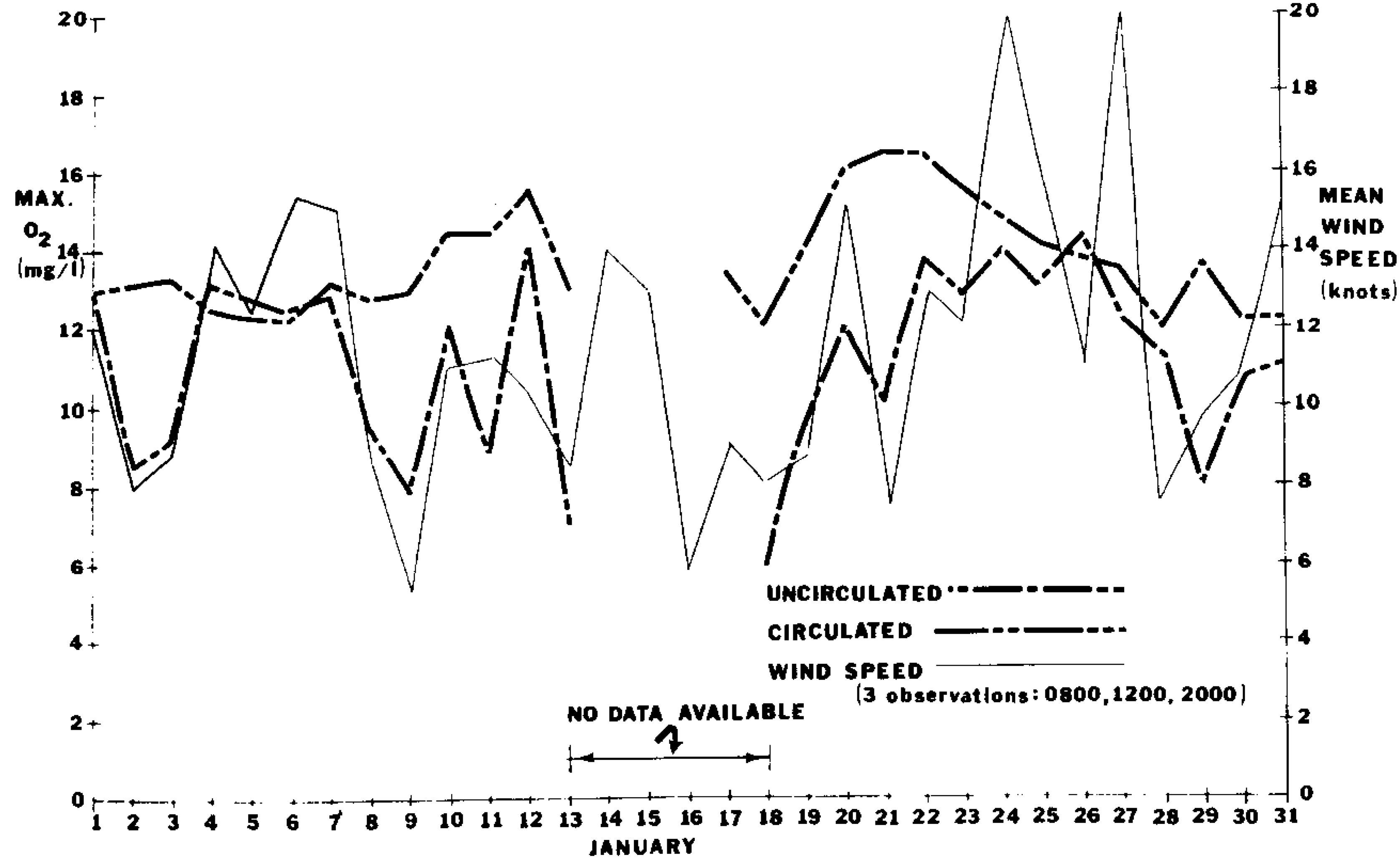


Figure 21. Maximum bottom oxygen concentrations on the circulated and uncirculated halves of Kohala Prawn Farm pond during January 1983. Average daily wind velocities are also shown.

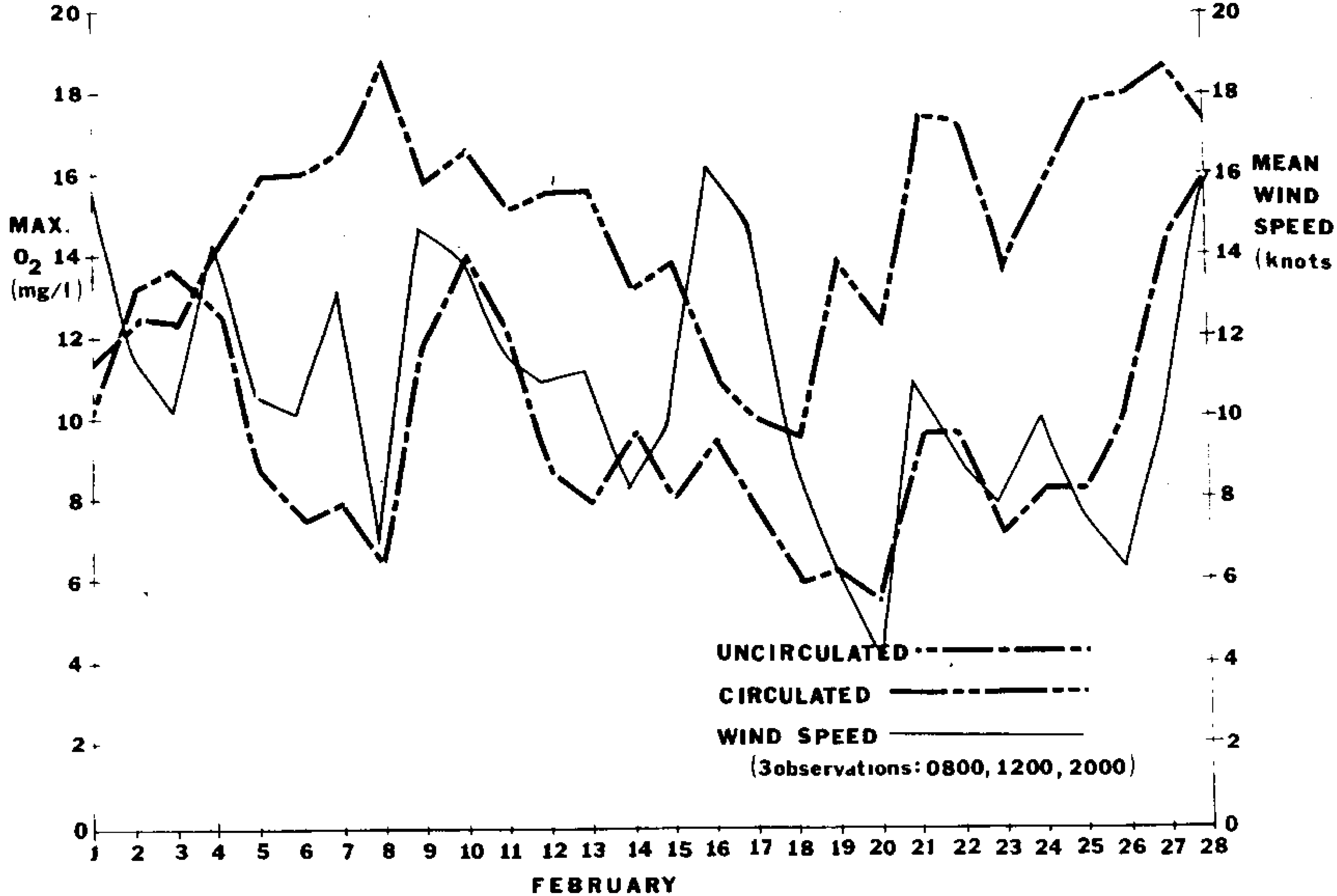


Figure 22. Maximum bottom oxygen concentrations on the circulated and uncirculated halves of Kohala Prawn Farm pond during February 1983. Average daily wind velocities are also shown.

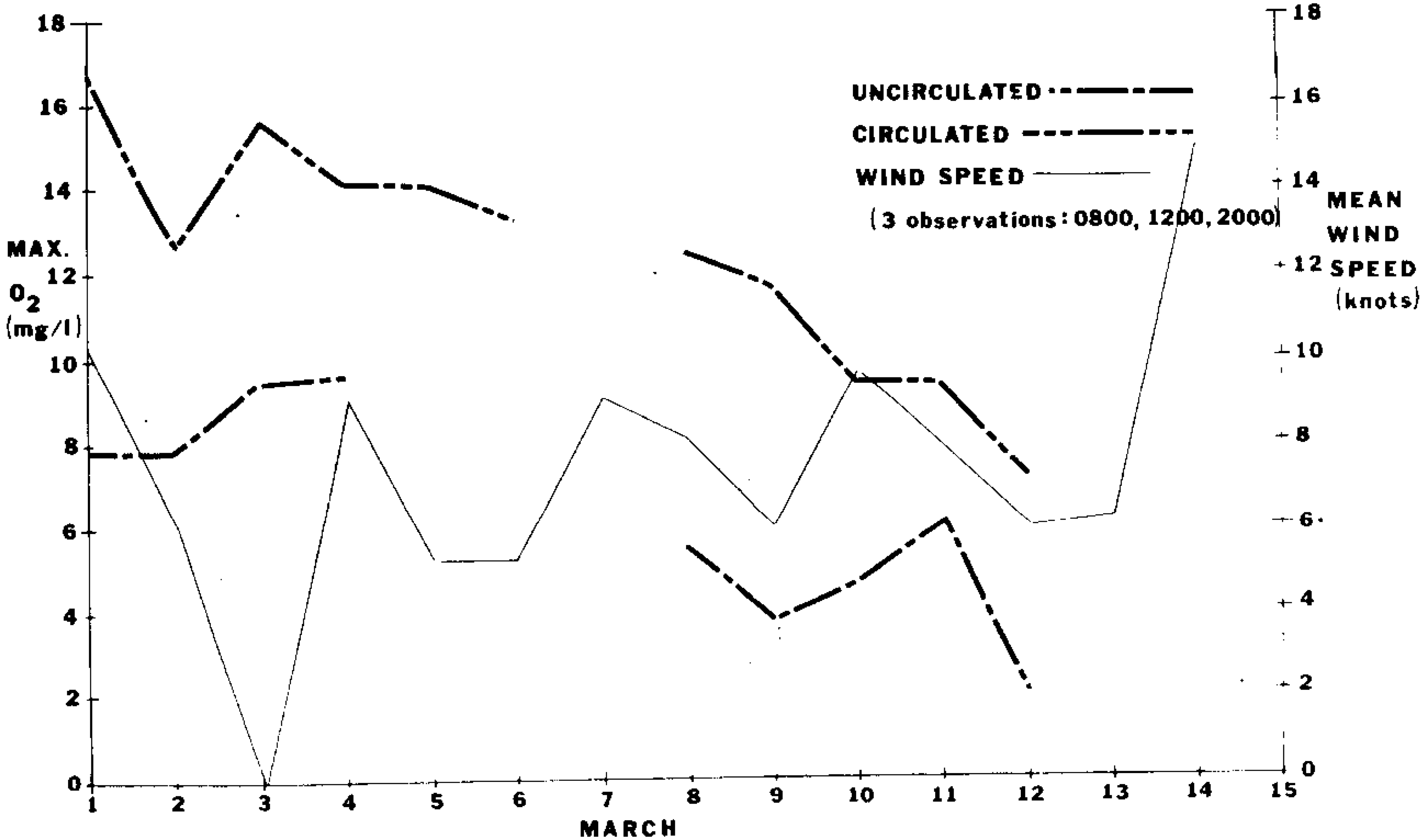


Figure 23. Maximum bottom oxygen concentrations on the circulated and uncirculated halves of Kohala Prawn Farm pond during March 1983. Average daily wind velocities are also shown.

Aquatic Farms: Oxygen and temperature stratifications at Aquatic Farms followed similar trends to those described for Kohala Prawn Farm, although the number of days per year when intense stratification exists is probably greater for the Aquatic Farms site because of its sheltered location. We will show only a few graphs here to illustrate summertime stratification at Aquatic Farms.

During June 18-20, 1982, thermal stratification in an uncirculated, 1-m deep pond was intense. Stratification developed each day at about 0900 hours and surface temperatures reached a maximum of 35°C (95°F), while bottom temperatures showed little dinural variation (Fig. 24). Bottom temperatures reached a 28°C (82°F) maximum during this three day period. These temperatures are considerably higher than those observed at Kohala Prawn Farm, and reflect seasonal as well as site differences. Although oxygen concentrations were not measured along with temperature (Fig. 24), other observations indicate that they probably reached a minimum during late evening, and were probably less than 3 mg/l at the bottom.

Oxygen and temperature in an uncirculated pond (No 4) and a circulated pond (No 5) during August indicate substantial differences (Fig. 25). In the uncirculated pond, the temperature and oxygen differences between the surface and bottom were 4.7°C and 12.6 mg/l respectively. In the circulated pond, these differences were greatly reduced to 1.2°C and 0.6 mg/l respectively. Compared with the uncirculated pond, the temperature and oxygen at the bottom of the circulated pond were 2°C higher and 3.4 mg/l higher respectively. Bottom oxygen concentrations in the uncirculated pond undoubtedly dropped further before stratification was eliminated later in the evening.

Alkalinity and Conductivity: There was little difference in alkalinity or conductivity between the circulated and uncirculated halves of the Kohala Prawn Farm pond. On any given date, values between the two halves were within the normal range of collection and analysis error. During January 24, 1983, for example, alkalinities for the circulated and uncirculated halves averaged 38.0 and 37.8 mg/l respectively, while conductivity averaged 140 and 133 μmhos/cm respectively (Table 4). Although circulation did not appreciably affect these parameters, manure application apparently did. The November and December values averaged 23.1 mg/l for alkalinity and 89 μmhos/cm for conductivity. The values for January through March show almost a two-fold increase compared with the November values. The respective values for March are 44.6 mg/l and 140 mho/cm. Alkalinity values above 20 mg/l are generally associated with high productivity potentials in catfish ponds (Boyd, 1973). This relationship in Hawaiian prawn ponds is unknown, but it should more than likely be very similar. Alkalinity values in the range of 40 to 50 mg/l should assure even higher production potentials, although values above this range may not contribute much more to the potential production.

Nutrients: Inorganic phosphorus ($PO_4$-P) and total phosphorus (inorganic plus organic) show no consistent patterns with regard to

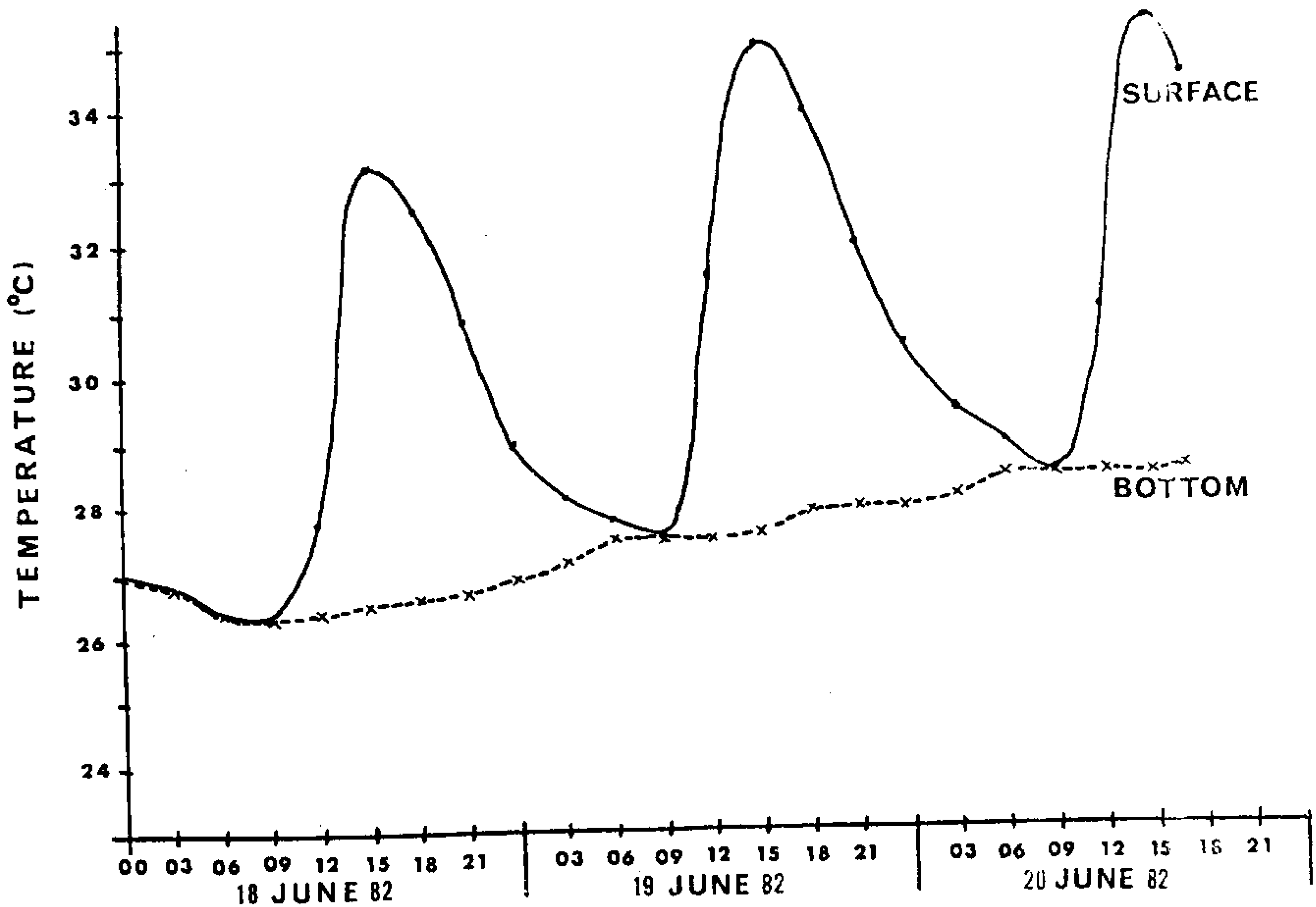


Figure 24. Surface and bottom temperatures in an uncirculated pond at Aquatic Farms during June 18-20, 1982. This was a calm, sunny period.

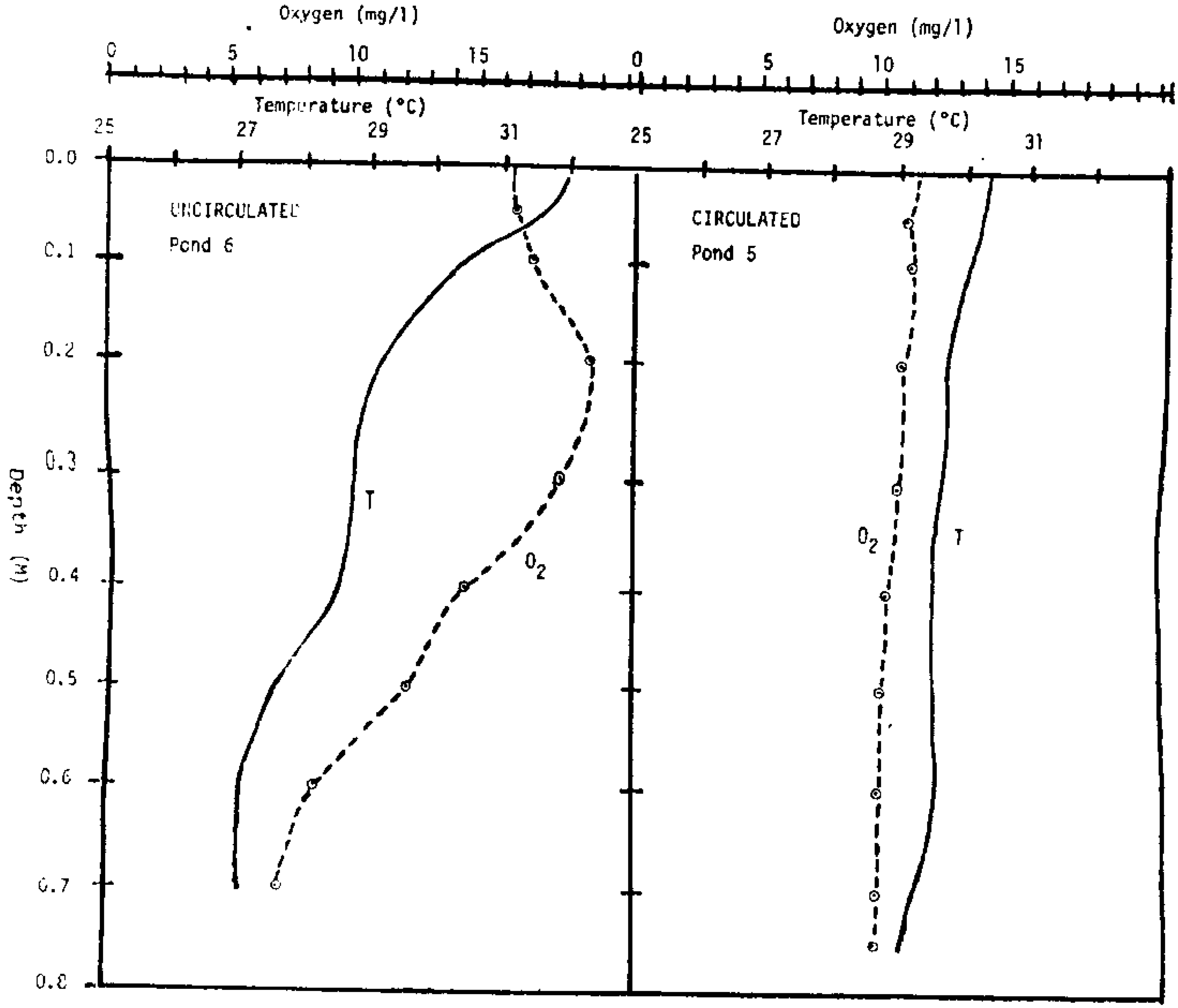


Figure 25. Comparison between oxygen and temperature values with depths in an artificially circulated pond (pond 5) and an uncirculated pond (pond 4) at Aquatic Farms during August 1982. Measurements were made during mid-afternoon.

Table 4. Alkalinity and conductivity of water collected at the influent (I) and effluent (E) ends of the Kohala Prawn Farm pond between October 1982 and March 1983

| Collection Site Date and Side | Alkalinity (mg/l) | | Conductivity (μmhos/cm) | |
|---|---|---|---|---|
| | I | E | I | E |
| Nov. 22, 1982 | | | | |
| Circulated | 24.0 | 26.3 | 75 | 70 |
| Uncirculated | 27.5 | 27.5 | 105 | 105 |
| Dec. 21, 1982 | | | | |
| Circulated | 21.8 | 20.0 | 95 | 100 |
| Uncirculated | 19.0 | 18.8 | 85 | 80 |
| Jan. 24, 1983 | | | | |
| Circulated | 38.0 | 38.0 | 151 | 130 |
| Circulated | 38.0 | 37.5 | 135 | 132 |
| Feb. 21, 1983 | | | | |
| Circulated | 37.0 | 37.0 | 132 | 134 |
| Uncirculated | 38.5 | 36.5 | 133 | 135 |
| Mar. 14, 1983 | | | | |
| Circulated | 45.0 | 45.0 | 140 | 141 |
| Uncirculated | 44.0 | 44.5 | 138 | 140 |

either manure application or artificial circulation (Table 5). The highest value for inorganic phosphorus was 0.037 mg/l, while the highest for total-P was 0.108 mg/l. Total-P was generally less than 0.055 mg/l. These values are well below the 1.0 mg/l-P sometimes considered optimum for phytoplankton growth (Hora and Pillay 1962). Our measurements do not however, include the phosphorus which was retained by the filterable materials (e.g. phytoplankton) and thus underestimates total phosphorus in the water. Algal densities clearly indicate that sufficient phosphorus was available to promote dense algal growth (Fig. 26A).

With the exception of the last sample date, inorganic nitrogen ($NO_3$, $NO_2$ and $NH_4$) were always much lower in the pond than in the influent water (Table 5). On the last date, ammonia values increased greatly in the pond water, most likely as a consequence of a deterioration in the phytoplankton population during this period. Total-N also increased substantially on the last date, although some increases occurred earlier probably as a result of manure applications (Fig. 26A).

Silica showed its largest increase during the December 6 measurements (Table 5). This is most likely due to the manure application since a trend of increasing silica occurs throughout the study period.

Chlorophyll, Suspended Solids and Secchi Disc Transparencies: Before manure applications began at Kohala Prawn Farm on November 29, 1982, Secchi disc transparencies normally averaged between 35 and 45 cm (Fig. 26B). Soon thereafter, and continuing until March 14, 1983, transparencies never exceeded 25 cm, and values as low as 8 cm were observed during January. The change was most dramatic, and even casual observations revealed a change in the pond from a greenish-grey color to a bright green with floating green "scum". There were no differences between transparencies on the circulated and uncirculated halves of the pond, and the values were nearly equal on all dates.

Total chlorophyll a values show a similar but inverse trend following manure treatment. Chlorophyll a values increased from 50 mg/m$^3$ before manure application, to a maximum of more than 500 mg/m$^3$ during January (Fig. 26, Table 6). There was a sharp decrease in total chlorophyll a values during late January, which was reflected to a lesser degree in Secchi disc transparencies. The largest change in total chlorophyll a occurred during the last week, when values plunged to less than 50 mg/l. This crash was accompanied by very low dissolved oxygen concentrations, increased tranparencies, decreased suspended solids, and increased ammonia concentrations. There were no differences in chlorophyll concentration attributable to artificial circulation, and concentration on both halves of the pond responded in a remarkably similar fashion. The similarities were so strong that we suspected a break in the plastic sheet separating the two halves. No such break was found although small amounts of exchange undoubtedly occurred. We conclude that the nearly equal response by both halves of the pond was caused primarily by similarities of sediment, influent water and manure treatment.

Table 5. Nutrient concentrations of irrigation inflow water, and water collected from site I (influent end of pond) and site E (effluent end of pond) at Kohala Prawn Farm pond. See Figure 8 for site location.

| Sample Date | Sample Site and Source | ppb (μg/l) | | | | | ppm (μg/l) |
|---|---|---|---|---|---|---|---|
| | | $PO_4$-P | N03 + N02 (N) | NH (N)4 | Total P[2/] | Total (N) | Silica (Si) |
| 10/30/82 | Inflow[1/] | 18 | 150 | 157 | 36 | 517 | 2.14 |
| | I-bottom | 20 | 3 | 8 | 49 | 451 | 1.00 |
| | I-surface | 10 | <1 | 5 | 36 | 331 | 1.75 |
| | E-bottom | 37 | <1 | 33 | 108 | 699 | 0.05 |
| | E-surface | 10 | <1 | 10 | 29 | 147 | 0.04 |
| 12/06/82 | I-uncirculated | 12 | <1 | 5 | 34 | 324 | 6.43 |
| | I-circulated | 11 | <1 | 7 | 33 | 349 | 7.46 |
| | E-uncirculated | 21 | <1 | 7 | 53 | 433 | 6.60 |
| | E-circulated | 17 | <1 | 6 | 48 | 389 | 3.18 |
| 01/03/83 | Inflow | 17 | 220 | 99 | 30 | 539 | 3.15 |
| | I-uncirculated | 16 | <1 | 7 | 54 | 612 | 8.26 |
| | I-circulated[2/] | -- | -- | -- | -- | -- | -- |
| | E-uncirculated | 16 | 5 | 8 | 59 | 582 | 7.60 |
| | E-circulated | 35 | 3 | 16 | 95 | 956 | 8.31 |
| 02/07/83 | Inflow | 26 | 100 | 320 | 90 | 1,318 | 3.42 |
| | I-uncirculated | 15 | 1 | 11 | 50 | 931 | 11.03 |
| | I-circulated | 25 | 1 | 16 | 73 | 1,138 | 9.32 |
| | E-uncirculated | 15 | <1 | 36 | 53 | 1,000 | 10.52 |
| | E-circulated | 16 | 1 | 14 | 55 | 943 | 10.01 |
| 03/14/83 | Inflow | 15 | 57 | 65 | 24 | 303 | 17.75 |
| | I-uncirculated | 21 | 3 | 949 | 47 | 1,627 | 9.00 |
| | I-circulated | 20 | 6 | 755 | 35 | 1,515 | 12.17 |
| | E-uncirculated | 18 | 3 | 1,005 | 36 | 1,817 | 9.25 |
| | E-circulated | 20 | 7 | 875 | 25 | 1,509 | 8.24 |

1/ Fresh irrigation water inflow
2/ Sample lost

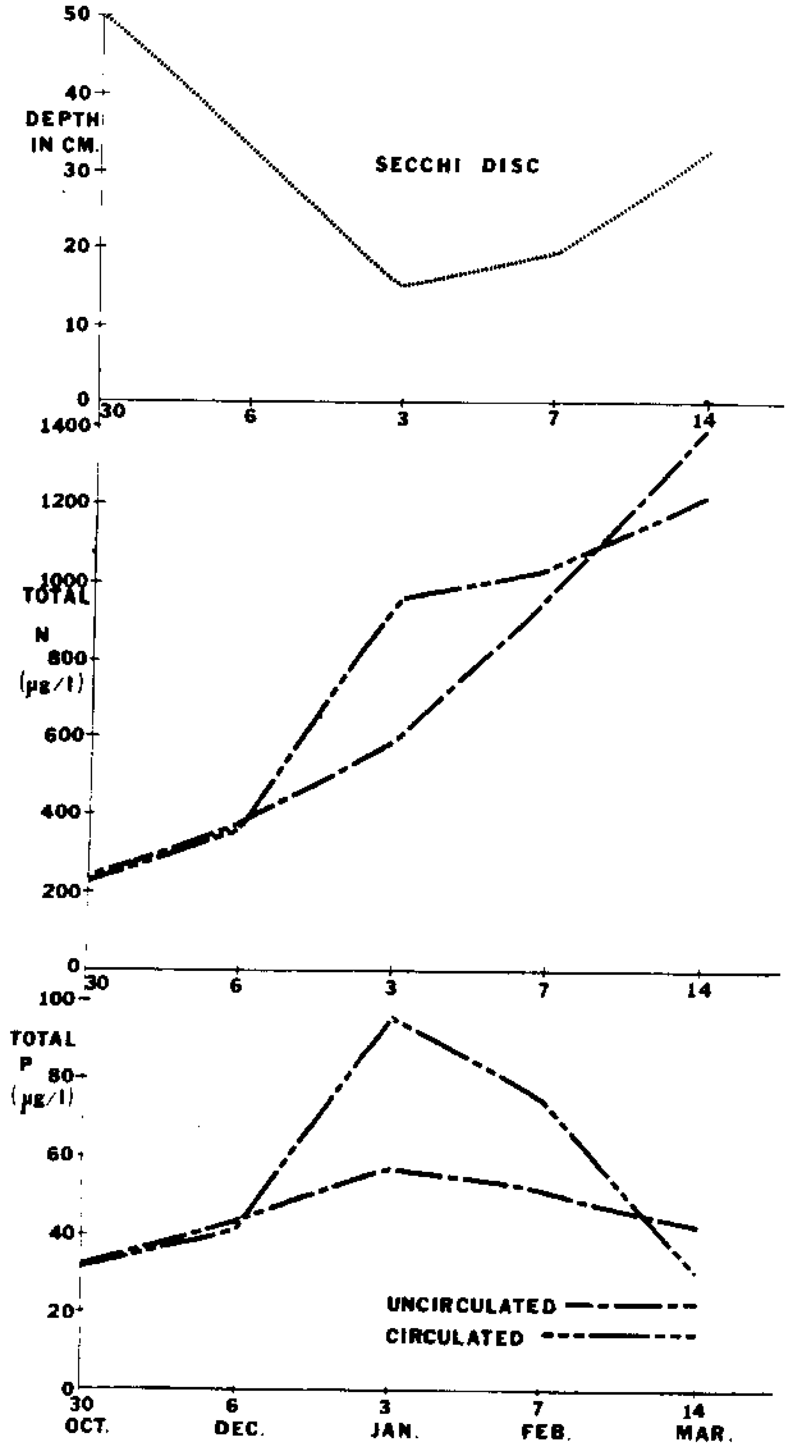


Figure 26A. Secchi disc transparencies. Total nitrogen and total phosphorus concentrations at Kohala Prawn Farm pond from November 1982 through March 1983. Values for the circulated and the uncirculated halves of the pond are shown. Each data point is the average of sampling sites I and E values for the respective half.

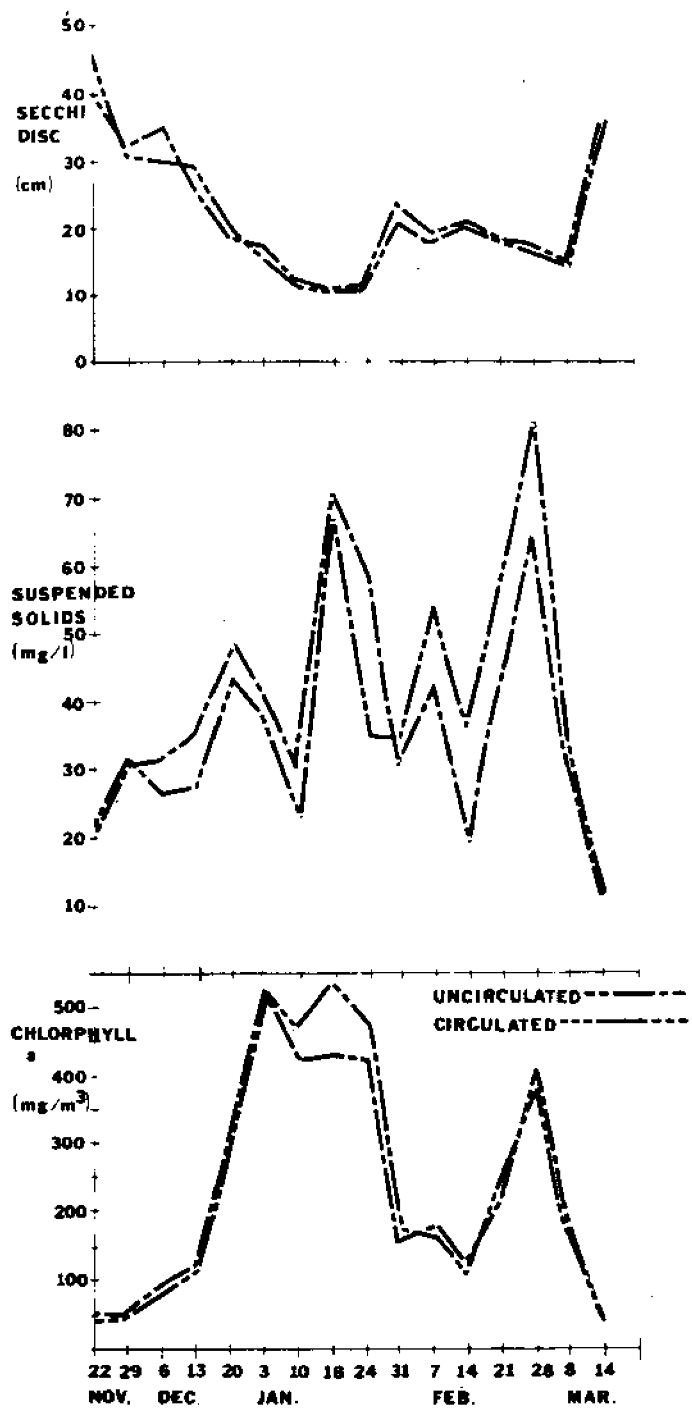


Figure 26B. Secchi disc transparency, suspended solids, and total chlorophyll a concentrations, Kohala Prawn Farm pond, from November 1982 through March 1983. Values for the circulated and uncirculated halves of the pond are shown. Each data point is the average of sampling sites I and E values for the respective half.

Table 6. Total chlorophyll a, chlorophyll c, carotenoid, active chlorophyll a, and phaeophytin a values (μg/l or $mg/m^3$) for Kohala Prawn Farm pond. Sample designations are: EC = sample site E on circulated half, EU = sample site E on uncirculated half, IC = sample site I on the circulated half, IU = sample site I on the uncirculated half.

| Date | Sample | | Kohala Pond Pigments (in μg/l = $mg/m^3$) | | | | |
|---|---|---|---|---|---|---|---|
| | | | CHLA | CHLC | CAROT | ACHLA | Phaeo |
| 11-22-82 | Kohala | EC | 65.2 | 4.8 | 27.3 | 58.7 | 9.1 |
| | | EU | 69.9 | 6.3 | 28.1 | 65.4 | 5.9 |
| | | IC | 33.0 | 4.1 | 12.8 | 29.9 | 4.6 |
| | | IU | 44.2 | 5.5 | 18.1 | 39.9 | 6.6 |
| 11-29-82 | Kohala | EC | 50.0 | 5.6 | 19.9 | 45.6 | 6.1 |
| | | EU | 23.3 | 2.8 | 7.4 | 20.8 | 3.7 |
| | | IC | 48.1 | 4.4 | 17.2 | 43.8 | 5.7 |
| | | IU | 58.2 | 5.8 | 20.3 | 56.4 | 1.3 |
| 12-06-82 | Kohala* | EC | 88.3 | 6.7 | 36.6 | 71.9 | 25.0 |
| | | EU | 99.4 | 4.8 | 49.6 | 83.9 | 22.0 |
| | | IC | 65.6 | 4.4 | 27.8 | 51.3 | 21.8 |
| | | IU | 88.4 | 5.1 | 38.0 | 75.4 | 18.5 |
| 12-13-82 | Kohala | EC | 110.6 | 6.8 | 31.8 | 104.5 | 5.5 |
| | | EU | 189.0 | 9.7 | 79.6 | 189.7 | 0 |
| | | IC | 129.4 | 7.2 | 44.6 | 129.9 | 0 |
| | | IU | 68.0 | 4.6 | 22.0 | 66.0 | 0.8 |
| 12-20-82 | Kohala | EC | 305.8 | 16.4 | 94.8 | 295.2 | 2.7 |
| | | EU | 293.2 | 9.7 | 87.8 | 301.1 | 0 |
| | | IC | 279.4 | 11.4 | 84.7 | 280.9 | 0 |
| | | IU | 303.9 | 15.5 | 91.8 | 309.4 | 0 |
| 01-03-83 | Kohala | EC | 532.8 | 3.6 | 136.0 | 672.2 | 0 |
| | | EU | 525.1 | 0.5 | 149.6 | 663.3 | 0 |
| | | IC | 489.0 | 2.7 | 152.6 | 604.7 | 0 |
| | | IU | 531.0 | 0 | 189.1 | 668.9 | 0 |
| 01-10-83 | Kohala | EC | 560.7 | 25.8 | 212.5 | 584.4 | 0 |
| | | EU | 417.2 | 17.3 | 105.5 | 414.9 | 0 |
| | | IC | 409.7 | 19.6 | 103.8 | 414.3 | 0 |
| | | IU | 426.0 | 15.2 | 146.0 | 450.0 | 0 |

*Filter samples were visibly wet and low $mgCO_3$

Table 6. Total chlorophyll a, chlorophyll c, carotenoid, active chlorophyll a, and phaeophytin a values (μg/l or mg/m$^3$) for Kohala Prawn Farm pond. Sample designations are: EC = sample site E on circulated half, EU = sample site E on uncirculated half, IC = sample site I on the circulated half, IU = sample site I on the uncirculated half. (continued)

| Date | Sample | | Kohala Pond Pigments (in μg/l = mg/m$^3$) | | | | |
|---|---|---|---|---|---|---|---|
| | | | CHLA | CHLC | CAROT | ACHLA | Phaeo |
| 01-18-83 | Kohala | EC | 592.4 | 19.0 | 250.5 | 623.4 | 0 |
| | | EU | 399.8 | 20.2 | 96.5 | 393.8 | 0 |
| | | IC | 487.3 | 21.6 | 185.1 | 500.9 | 0 |
| | | IU | 453.9 | 21.2 | 151.0 | 465.2 | 0 |
| 01-24-83 | Kohala | EC | 476.8 | 18.9 | 207.6 | 489.9 | 0 |
| | | EU | 394.1 | 14.8 | 176.4 | 398.1 | 0 |
| | | IC | 447.5 | 20.6 | 192.1 | 460.6 | 0 |
| | | IU | 448.4 | 35.4 | 208.1 | 459.3 | 0 |
| 01-31-83 | Kohala | EC | 210.4 | 9.5 | 87.1 | 216.8 | 0 |
| | | EU | 154.1 | 8.6 | 35.7 | 162.9 | 0 |
| | | IC | 145.4 | 7.6 | 46.1 | 150.3 | 0 |
| | | IU | 167.7 | 7.1 | 62.0 | 168.7 | 0 |
| 02-07-83 | Kohala | EC | 139.6 | 6.6 | 38.9 | 148.4 | 0 |
| | | EI | 226.4 | 12.8 | 58.5 | 226.4 | 0 |
| | | IC | 183.7 | 9.0 | 54.3 | 185.3 | 0 |
| | | IU | 135.8 | 9.1 | 42.1 | 136.6 | 0 |
| 02-14-83 | Kohala | EC | 109.9 | 9.5 | 42.3 | 116.6 | 0 |
| | | EU | 108.2 | 4.8 | 42.9 | 105.4 | 0 |
| | | IC | 116.9 | 6.6 | 50.8 | 121.1 | 0 |
| | | IU | 101.0 | 6.2 | 38.9 | 97.4 | 0.2 |
| 02-21-83 | Kohala | EC | 254.9 | 10.0 | 92.1 | 258.1 | 0 |
| | | EU | 234.9 | 8.9 | 68.5 | 248.6 | 0 |
| | | IC | 270.2 | 14.3 | 71.7 | 285.0 | 0 |
| | | IU | 235.0 | 9.8 | 54.8 | 237.1 | 0 |
| 02-28-83 | Kohala | EC | 412.3 | 5.7 | 85.6 | 517.9 | 0 |
| | | EU | 411.4 | 18.9 | 106.6 | 417.7 | 0 |
| | | IC | 349.1 | 16.8 | 83.9 | 355.3 | 0 |
| | | IU | 399.1 | 16.7 | 87.1 | 410.3 | 0 |

Table 6. Total chlorophyll a, chlorophyll c, carotenoid, active chlorophyll a, and phaeophytin a values (μg/l or $mg/m^3$) for Kohala Prawn Farm pond. Sample designations are: EC = sample site E on circulated half, EU = sample site E on uncirculated half, IC = sample site I on the circulated half, IU = sample site I on the uncirculated half. (continued)

| Date | Sample | | Kohala Pond Pigments (in μg/l = $mg/m^3$) | | | | |
|---|---|---|---|---|---|---|---|
| | | | CHLA | CHLC | CAROT | ACHLA | Phaeo |
| 03-08-83 | Kohala | EC | 137.2 | 6.6 | 41.9 | 138.9 | 0 |
| | | EU | 213.5 | 12.4 | 54.8 | 205.7 | 0.3 |
| | | IC | 206.5 | 8.7 | 66.9 | 206.5 | 0 |
| | | IU | 189.4 | 11.0 | 69.3 | 194.3 | 0 |
| 03-14-83 | Kohala | EC | 35.5 | 3.8 | 13.9 | 34.9 | 0 |
| | | EU | 35.1 | 3.4 | 24.2 | 33.5 | 1.1 |
| | | IC | 34.2 | 3.9 | 1.9 | 30.3 | 4.8 |
| | | IU | 27.3 | 3.2 | 13.1 | 24.0 | 4.3 |

Most of the chlorophyll in our samples was in the active form. Only on December 6 did phaeophytin a (inactive form) exceed 10 mg/l, and this was probably due to improper sample handling (Table 6). Chlorophyll c was usually about 5% of total chlorophyll a. Carotenoids followed the same basic trend as chlorophyll a.

A strong, curvilinear relationship exists between total chlorophyll a values and Secchi disc transparencies (Fig. 27). There are no obvious differences in this relationship between the circulated and uncirculated halves of the pond.

Suspended solids followed trends similar to those for chlorophyll and Secchi disc transparencies (Fig. 28), but the relationship between suspended solids and chlorophyll is not as good as between chlorophyll and transparencies (Fig. 27). This relationship would be improved if the suspended solids data between January 10-24, 1983, were eliminated.

There are no differences in suspended solids attributable to artificial circulation.

Water Respiration: Water respiration rates, (water BOD) averaged 0.52 mg/l/hr for the circulated half of the pond, and 0.50 mg/l/hr for the uncirculated half (Table 7). The range in values was from some negative values (final D.O. exceeded initial) to 2.80 mg/l/hr. In all, 8 negative values were observed, which is an impossibility. We were unable to determine the source of these errors, and for that reason will not attempt to interpret these data. These data points have been eliminated from Table 7.

Sediment Respiration Rates: Sediment respiration rates at Kohala Prawn Farm pond ranged from 24 to 341 mg $O_2/m^2/hr$ (Table 8). The averages for the circulated and uncirculated halves are 236 and 205 mg $O_2/m^2/hr$ respectively. These average values are not significantly different at the 0.05 confidence level. Since we began these measurements after manure applications began, we cannot evaluate the influences of manure on sediment respiration. There is no relationship between sediment respiration and the ash-free dry weight (combustible solids fraction) of sediment core samples collected from outside the periphery of the dome (Fig. 29).

Water respiration rates within the dome were more consistent than those measured outside the dome. Water respiration rates within the dome were 0.30 mg/l/hr for the circulated side, and 0.34 mg/l/hr for the uncirculated side (Table 8).

Sediment Ash-Free Dry Weight: Ash-free dry weight (combustible solids fraction) of sediment collected from each half of the pond on three dates indicates no significant difference between dates, but a significant difference between the circulated and uncirculated halves on March 6, 1983 (Table 9).

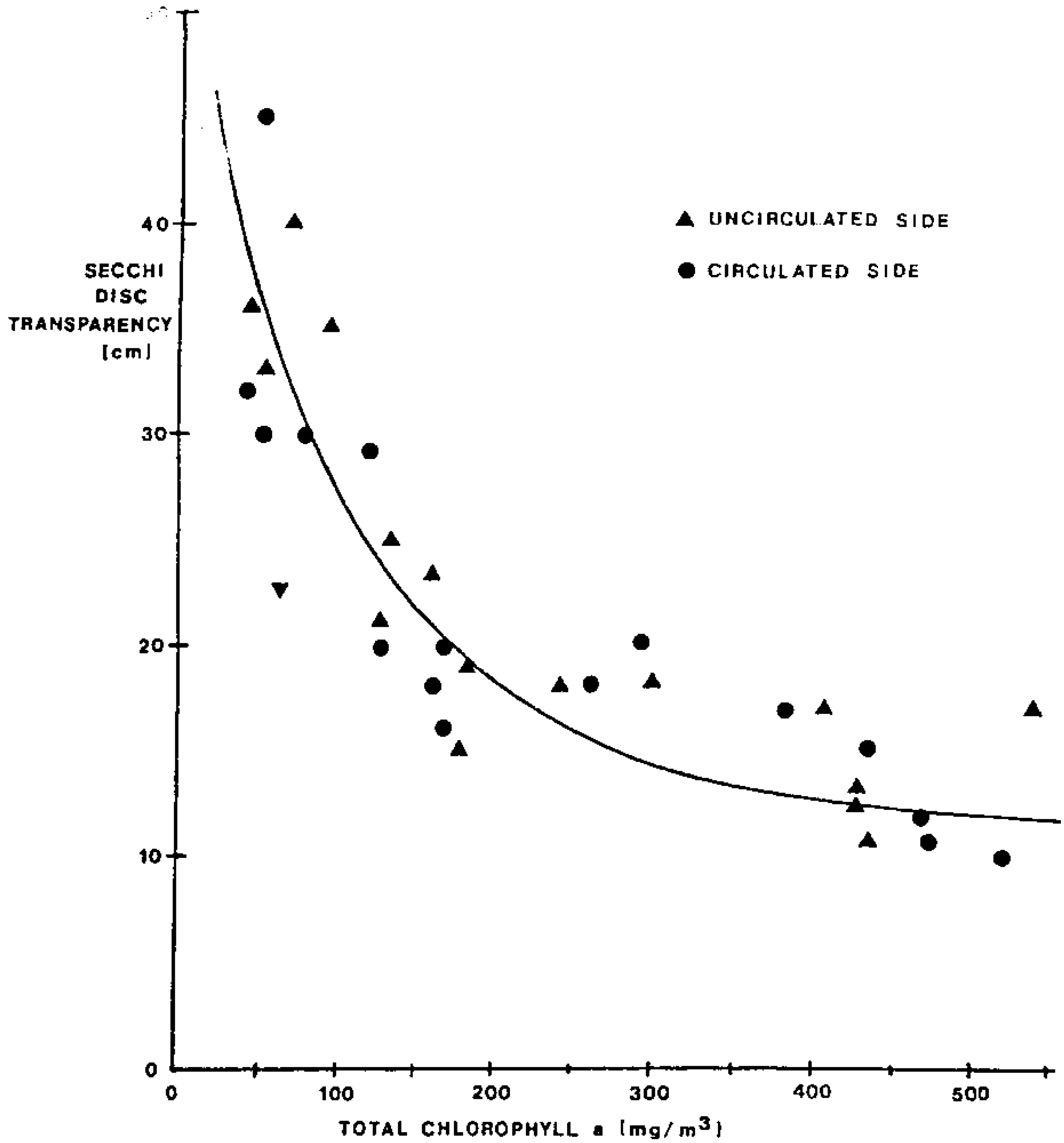


Figure 27. Relationship between total chlorophyll a concentrations and Secchi disc transparencies at Kohala Prawn Farm pond between November 1982 and March 1983. Data points for each half of the pond are indicated. The curve is hand drawn. Each data point is the average of two observations (sample sites I and E) on each date.

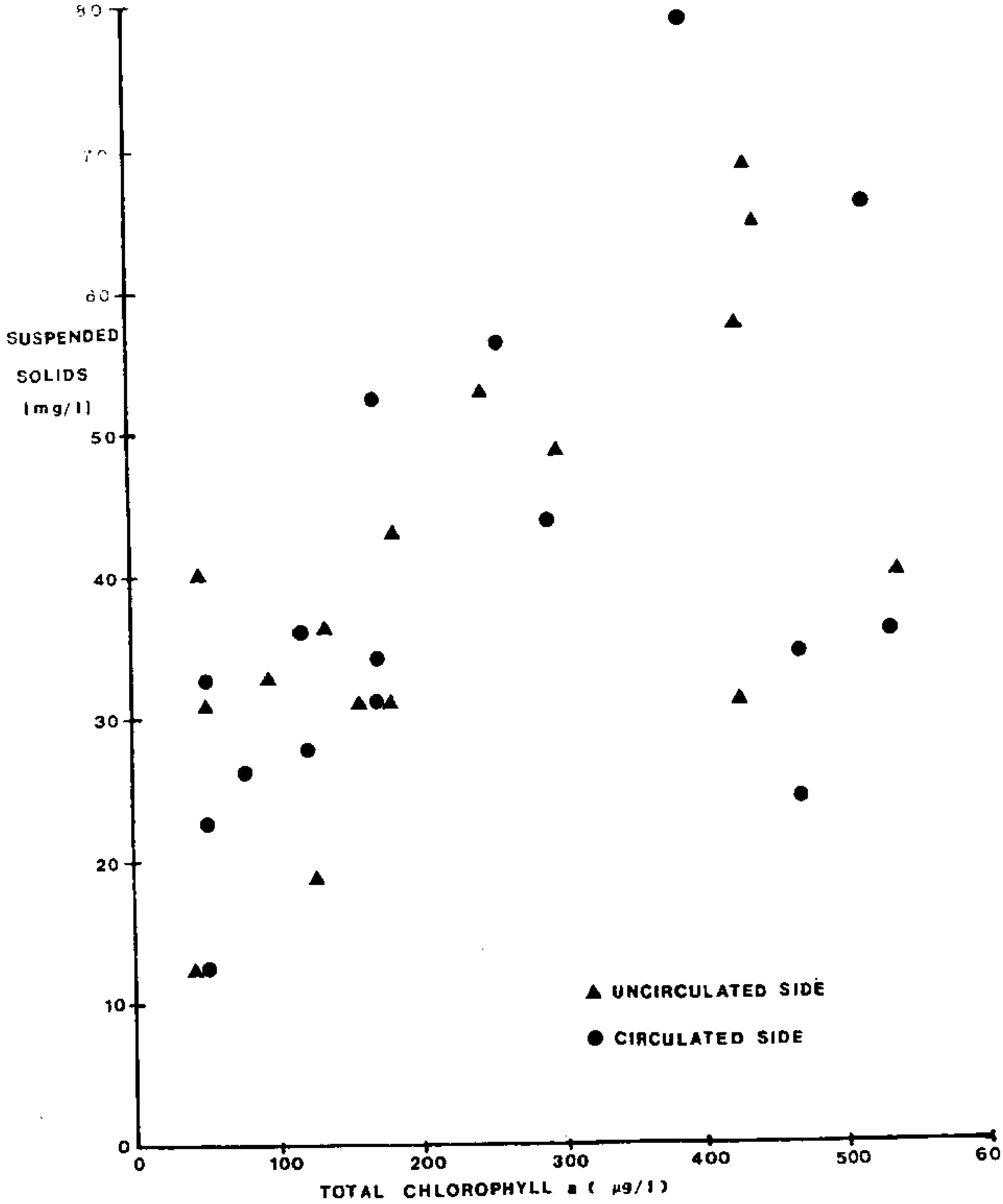


Figure 28. Relationship between total chlorophyll a concentrations and suspended solids concentrations at Kohala Prawn Farm pond between November 1982 and March 1983. Data points for each half of the pond are indicated. Each data point is the average of two observations (sample sites I and E) on each date.

Table 7. Water respiration rates in mg/1/hr at four sample sites in the Kohala Prawn Farm pond between November 1982 and March 1983. Sample designations are: EC = sample site E on circulated side, IC = sample site I on circulated side, IU = sample site I on uncirculated side, EU = sample site E on uncirculated side. Lined out values were when the final oxygen determination exceeded the initial.

| | Sample Sites | | | |
|---|---|---|---|---|
| Date | EC | IC | IU | EU |
| 11/22 | 0.32 | 0.48 | 0.43 | 0.39 |
| 11/29 | 0.13 | 0.18 | 0.11 | 0.32 |
| 12/6 | 0.13 | 0.02 | 0.13 | ---- |
| 12/13 | 0.82 | 0.65 | 0.06 | 0.03 |
| 12/20 | 0.79 | 0.72 | 0.06 | 1.14 |
| 1/3 | 1.70 | 2.10 | 2.80 | 1.40 |
| 1/10 | 0.45 | 0.57 | 0.37 | 0.39 |
| 1/18 | 0.25 | ---- | ---- | 0.39 |
| 1/24 | 0.47 | ---- | ---- | 0.94 |
| 1/31 | 0.70 | 0.90 | 0.90 | 0.90 |
| 2/7 | 0.65 | 0.42 | 0.06 | 0.44 |
| 2/14 | 0.39 | 0.41 | 0.37 | 0.16 |
| 2/21 | 0.26 | 0.34 | 0.19 | 0.08 |
| 2/28 | 0.47 | 0.05 | 0.05 | ---- |
| 3/8 | 0.50 | ---- | ---- | 0.18 |
| 3/14 | 0.16 | 0.06 | 0.05 | 0.18 |

Average: Circulated = 0.52 Uncirculated - 0.50

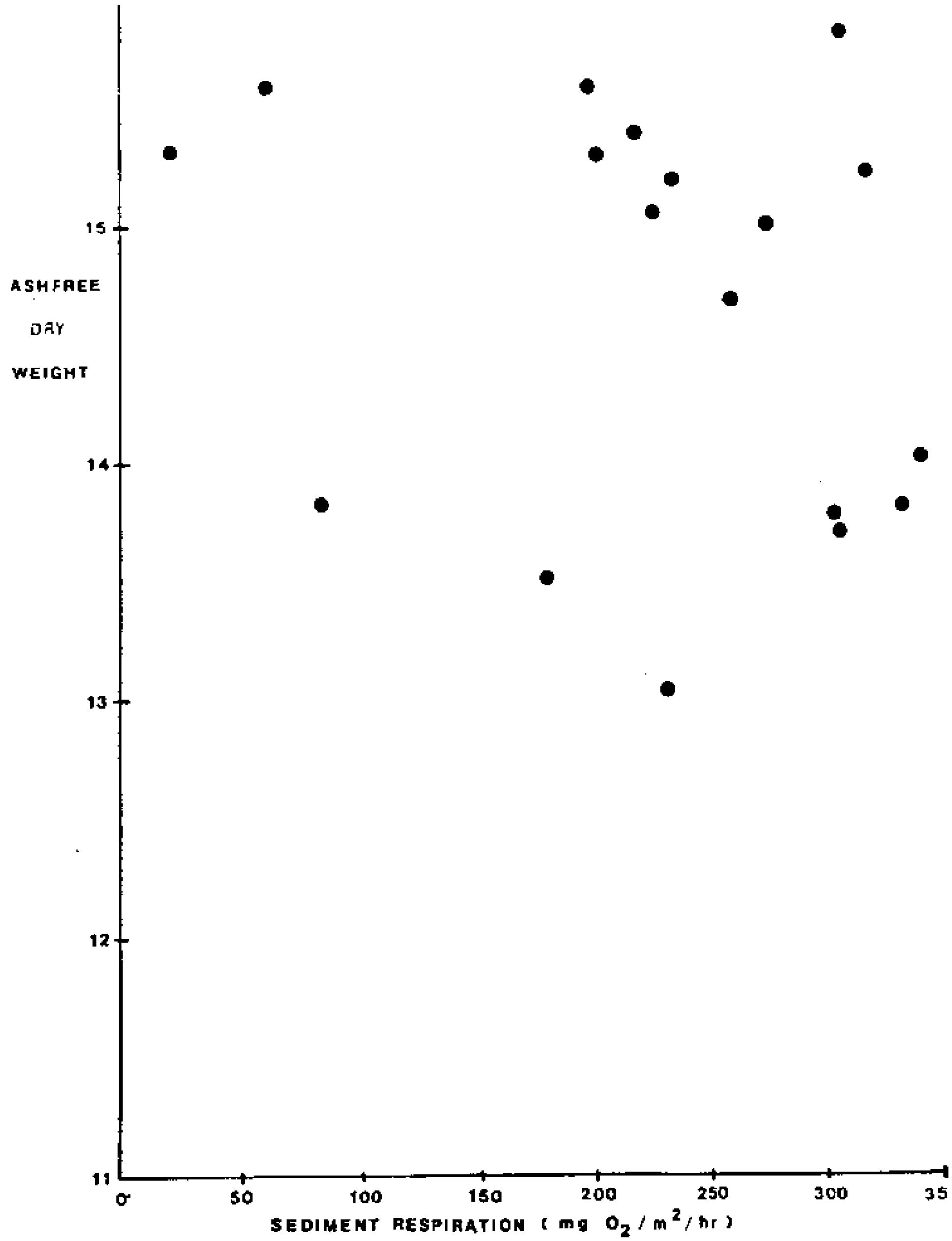


Figure 29. Relationship between sediment respiration values shown in Table 9 and ash-free dry weight of sediment samples collected around the perihpery of each dome set at Kohala Prawn Farm pond. Each ash-free dry weight is the average of three core samples on each dome measurement.

Table 8. Sediment respiration rates at Kohala Prawn Farm pond measured with a one meter diameter plexiglass dome. Measurements were made during January, February, and March 1983 from both the circulated and uncirculated halves of the pond. Water respiration within the dome and sediment respiration under the dome are shown. Sample location identifications are: C = circulated half, U = uncirculated half, numbers = pond section (see Figure 28).

| Sediment on Circulated Side | | | | Respiration on Uncirculated Side | | | |
|---|---|---|---|---|---|---|---|
| Date/Location | | mg/1/hr Water Respiration | $mg/m^2/hr$ Sediment Respiration | Date/Location | | mg/1/hr Water Respiration | $mg/m^2/hr$ Sediment Respiration |
| 1/18 | 4C | 0.25 | 340 | 1/26 | 5U | 0.58 | 239 |
| 3/1 | 4C | 0.24 | 306 | 3/4 | 5U | 0.23 | 225 |
| 1/30 | 5C | 0.33 | 188 | 2/1 | 4U | 0.37 | 315 |
| 3/2 | 5C | 0.48 | 78 | 2/3 | 4U | 0.33 | 308 |
| 2/9 | 3C | 0.21 | 302 | 3/9 | 4U | 0.42 | 275 |
| 2/28 | 3C | 0.13 | 341 | 311 | 3U | 0.25 | 200 |
| 2/14 | 2C | 0.38 | 221 | 3/20 | 3U | 0.43 | 24 |
| 2/23 | 2C | 0.30 | 258 | 3/13 | 2U | 0.15 | 198 |
| 2/17 | 1C | 0.29 | 93 | 3/14 | 2U | 0.26 | 60 |
| 2/20 | 1C | 0.34 | 234 | | | | |
| Average: | | 0.30 | 236 | | | 0.34 | 205 |
| Standard Deviation | | | 94.3 | | | | 102 |
| 95% Confidence Interval | | | 303/168 | | | | 283/126 |

Table 9. Sediment core samples (% ash-free dry weight) collected on three dates from Kohala Prawn Pond and on each half (circulated and circulated) of the divided pond. Fifteen samples were collected from each side on each date. The mean (x), standard error (S.E.), range, and 95% (C.I.) are shown for each data set. The November set is before manure was applied to the pond, while the later dates were during and after manuring.

| Sampling Date | Circulated Half of Pond | Uncirculated Half of Pond |
|---|---|---|
| I | | |
| Nov. 18, 1982 | $\bar{x}$ = 14.53 | $\bar{x}$ = 15.55 |
| | S.E. = 0.48 | S.E. = 0.33 |
| | Range = 12.02∿17.33 | Range = 13.21∿17.42 |
| | 95% C.I.(13.51-15.55) | 95% C.I.(14.85-16.25) |
| II | | |
| Jan. 15, 1983 | $\bar{x}$ = 13.94 | $\bar{x}$ = 14.81 |
| | S.E. = 0.22 | S.E. = 0.27 |
| | Range = 12.72-15.77 | Range = 12.64∿16.03 |
| | 95% C.I.(13.54-14.41) | 95% C.I.(14.23-15.39) |
| III | | |
| March 6, 1983 | $\bar{x}$ = 14.29 | $\bar{x}$ = 15.27 |
| | S.E. = 0.28 | S.E. = 0.28 |
| | Range = 12.72∿17.21 | Range = 13.56∿16.16 |
| | 95% C.I.(13.69-14.89) | 95% C.I.(14.89-15.65) |

Ash-free dry weight samples do not show any consistent response to manure treatment, nor to artificial circulation. As previously noted, there is no relationship between sediment respiration and ash-free dry weight of the sediments.

Benthic Fauna: Benthic fauna (Macrobenthos) at Kohala Prawn Farm pond consisted almost entirely of two groups of organisms: oligochaete worms, and chironomid midge larvae. The former was by far the most numerous and represented the largest biomass.

During November, the pond had average densities of oligochaete worms of 17,000/ $m^2$ and 13 $mg/m^2$ (Fig. 30). They increased to more than 20,000/$m^2$ and 20 $mg/m^2$ during January. They again increased substantialy during March to a maximum density of 34,000/$m^2$ and 56 $mg/m^2$. This doubling in number, and 4.3-fold increase in weight, is undoubtedly due to manure applications beginning November 29th.

Chironomid larvae density was only 1% by number or weight of the oligochaete worms during November (Fig. 31). On that date, chironomid numbers were less than 300/$m^2$, while biomass was less than 0.15 $mg/m^2$. Chironomid densities increased greatly during January to more than 1,000/$m^2$ and more than 1.3 $mg/m^2$. Their density then decreased sharply during March to less than the November levels. The January increases may be due to manure applications during November, while the March decrease may be due to the discontinuation of manure application in early February.

On any of the three sampling dates, oligochaete worm densities were not significantly different on the circulated and uncirculated halves of the pond (Figs. 32 and 33). The means in numbers and biomass are about the same for the two halves, except for biomass during March. On that date, however, the 95% confidence intervals overlap. There is a significant difference between both mean numbers and biomass of worms on the uncirculated half of the pond during March, compared with either half of the pond on the two earlier dates.

Chironomid midge larval densities (numbers and biomass) are not significantly different from each other on any sampling date, in comparing the circulated with the uncirculated halves of the pond (Figs. 34 and 35). There are significant differences between the January and March densities, with significantly lower numbers and biomass on the latter date. Comparing the December and January densities, chironomid larval numbers and biomass were significantly higher on the uncirculated side on the two dates, but densities on the circulated side were not significantly different.

Prawn Distribution Within Circulated and Uncirculated Ponds: The distribution of prawns within a pond is substantially influenced by the degree of stratification. A comparision between prawn distribution in an artificially circulated pond and a noncirculated pond clearly indicates this influence. At Aquatic Farms, during mid-afternoon in an uncirculated

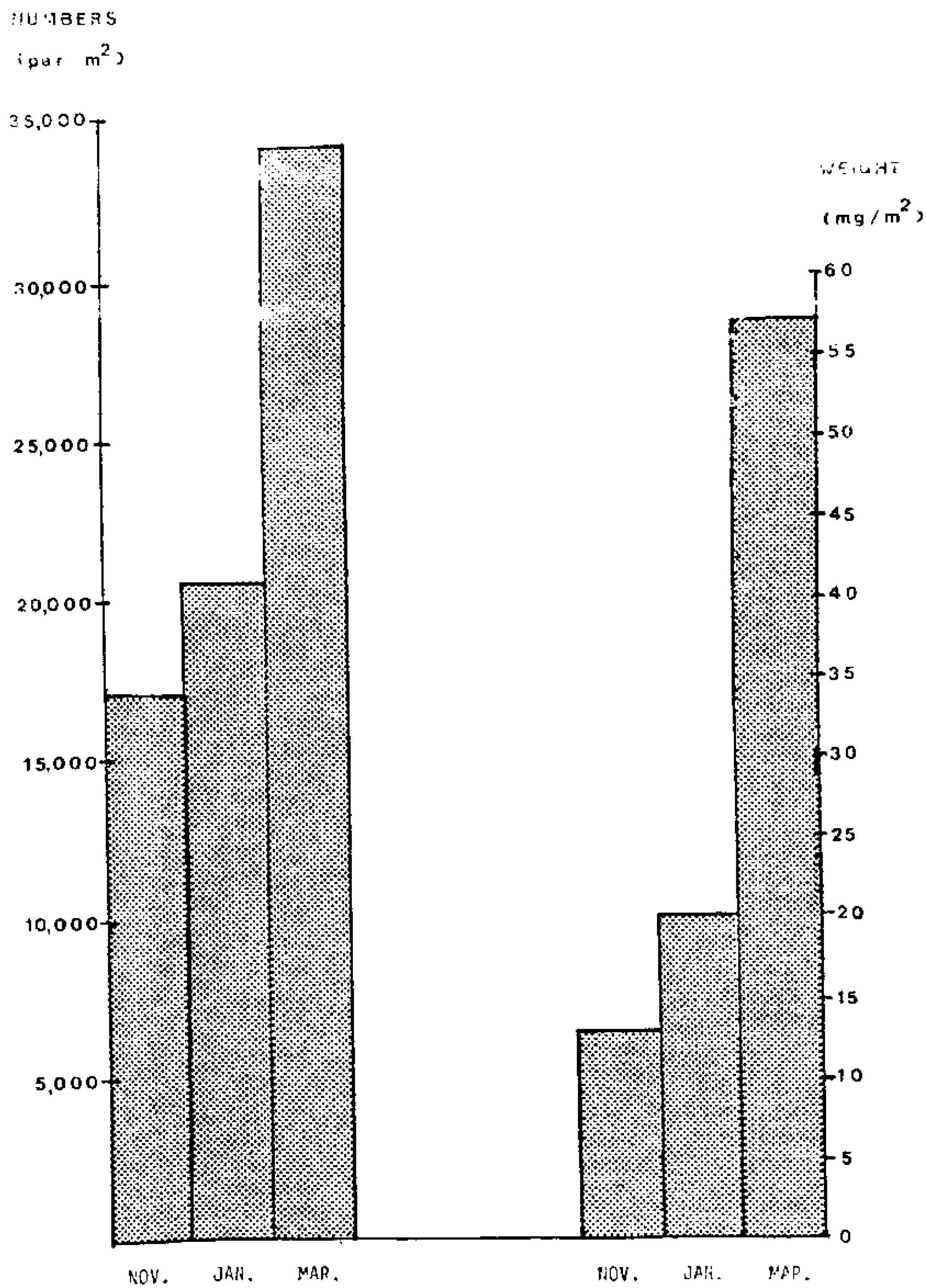


Figure 30. Oligochaete worm densities in Kohala Prawn Farm pond during November 1982, January 1983, and March 1983. Densities are for both the circulated and uncirculated samples combined.

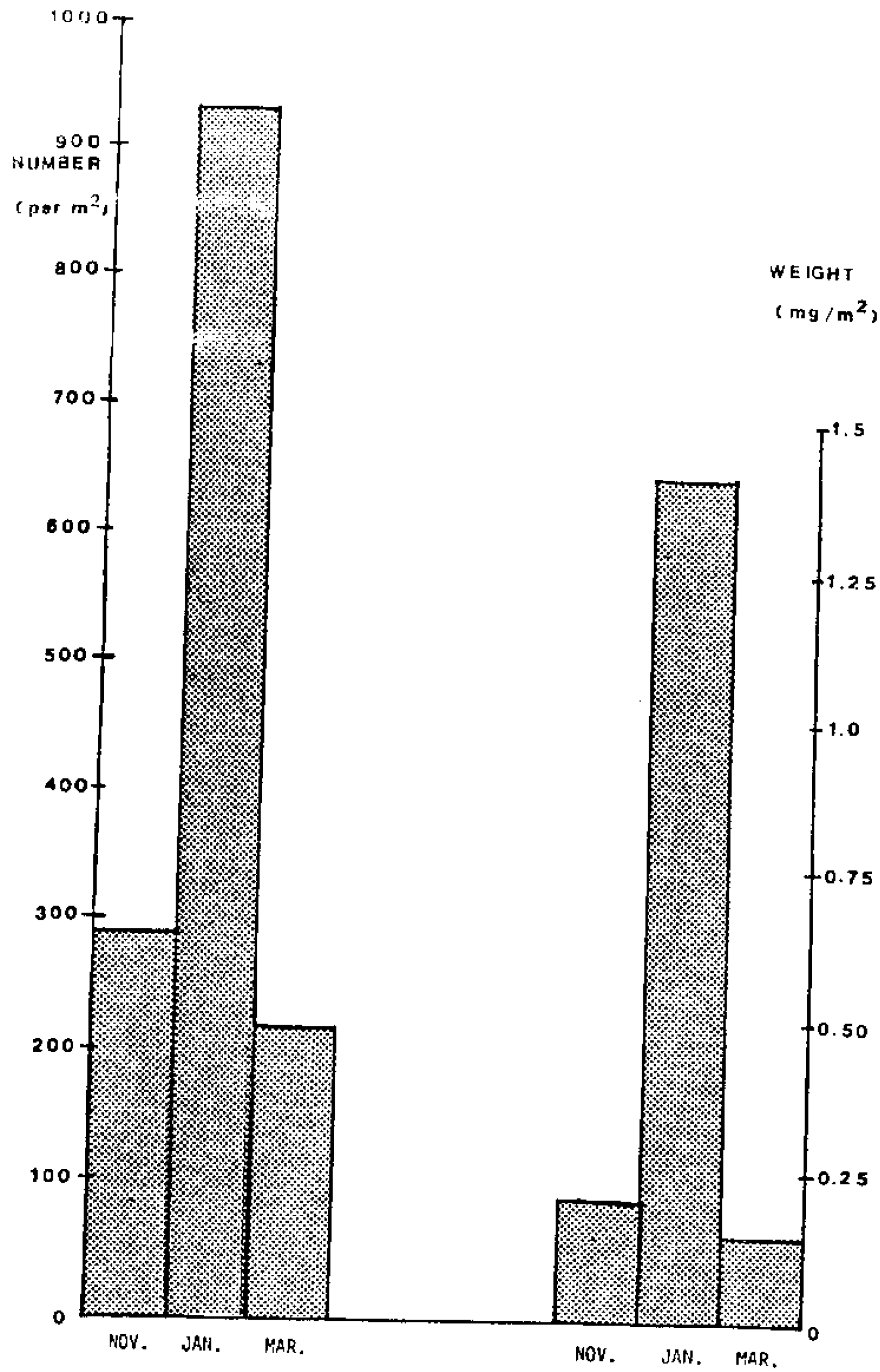


Figure 31. Chironomid midge larvae densities in Kohala Prawn Farm pond during November 1982, January 1983, and March 1983. Densities are for both the circulated and uncirculated samples combined.

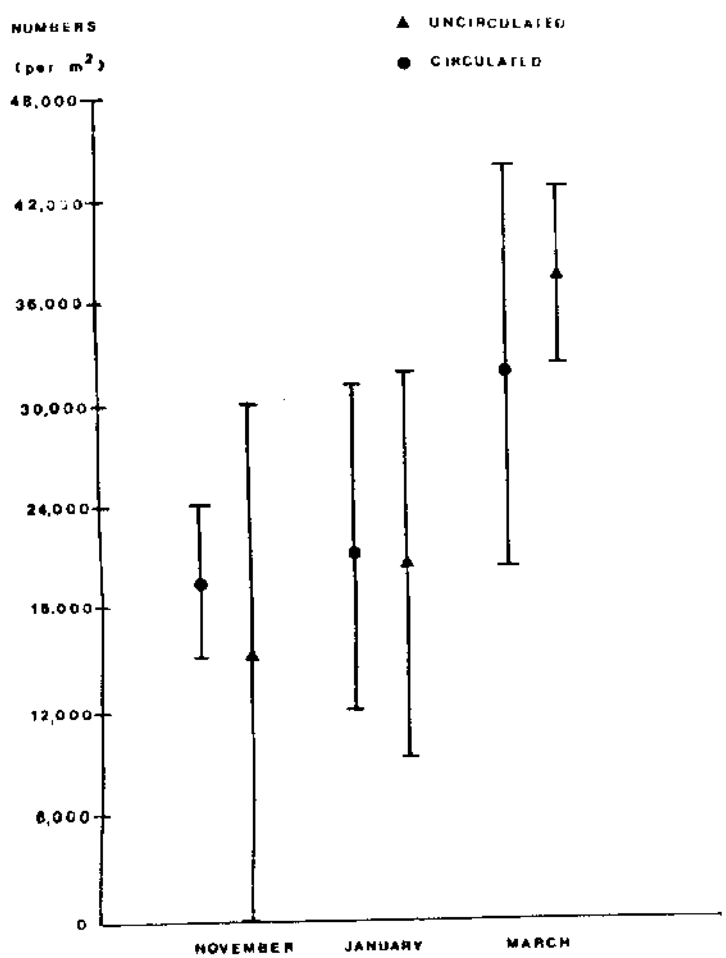


Figure 32. Oligochaete worm densities (numbers/$m^2$) at Kohala Prawn Farm pond on three sampling dates. The respective mean densities with 95% confidence intervals for the circulated and uncirculated halves of the pond are shown.

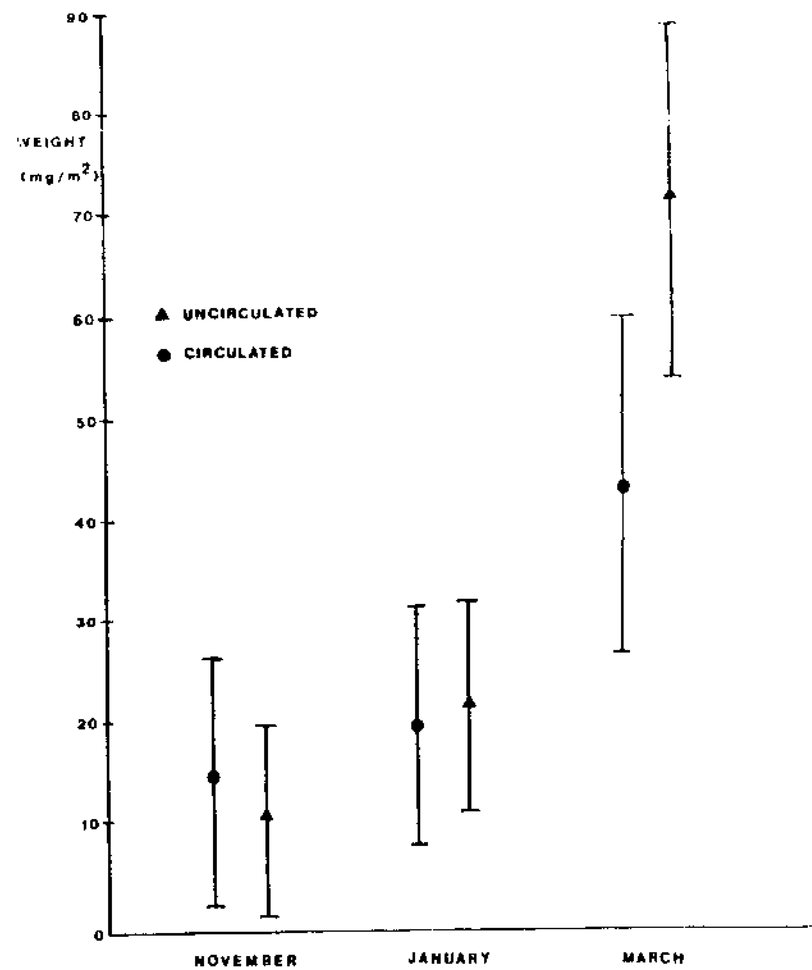


Figure 33. Oligochaete worm density (mg/$m^2$) at Kohala Prawn Farm pond on three sampling dates. The respective mean densities with 95% confidence intervals for the circulated and uncirculated halves of the pond are shown.

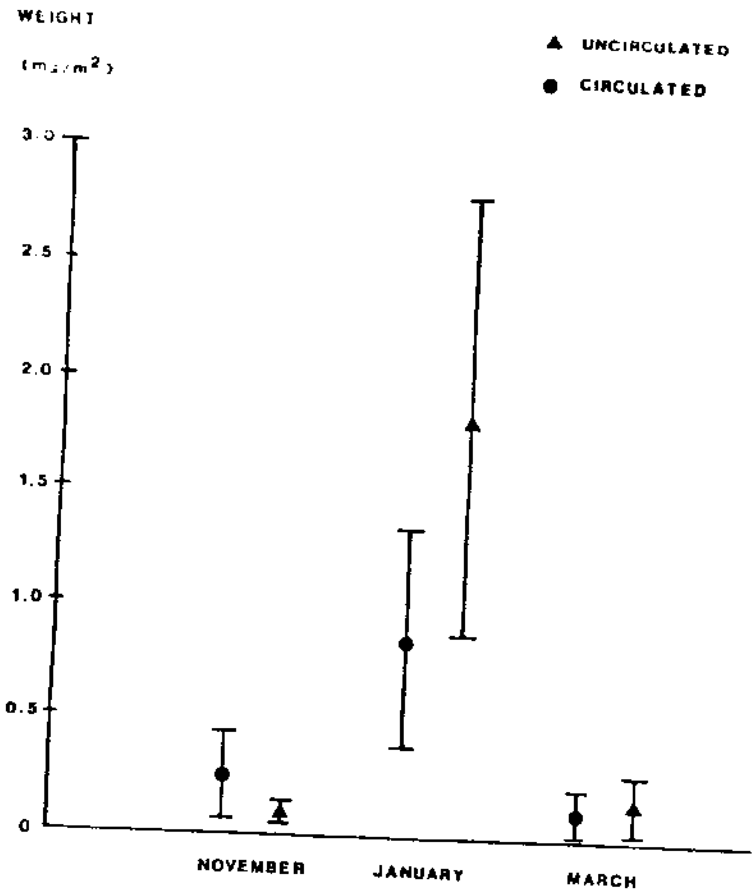


Figure 34. Chironomid midge larvae density (numbers/m2) at Kohala Prawn Farm pond on three sampling dates. The respective mean densities with 95% confidence intervals for the circulated and uncirculated halves of the pond are shown.

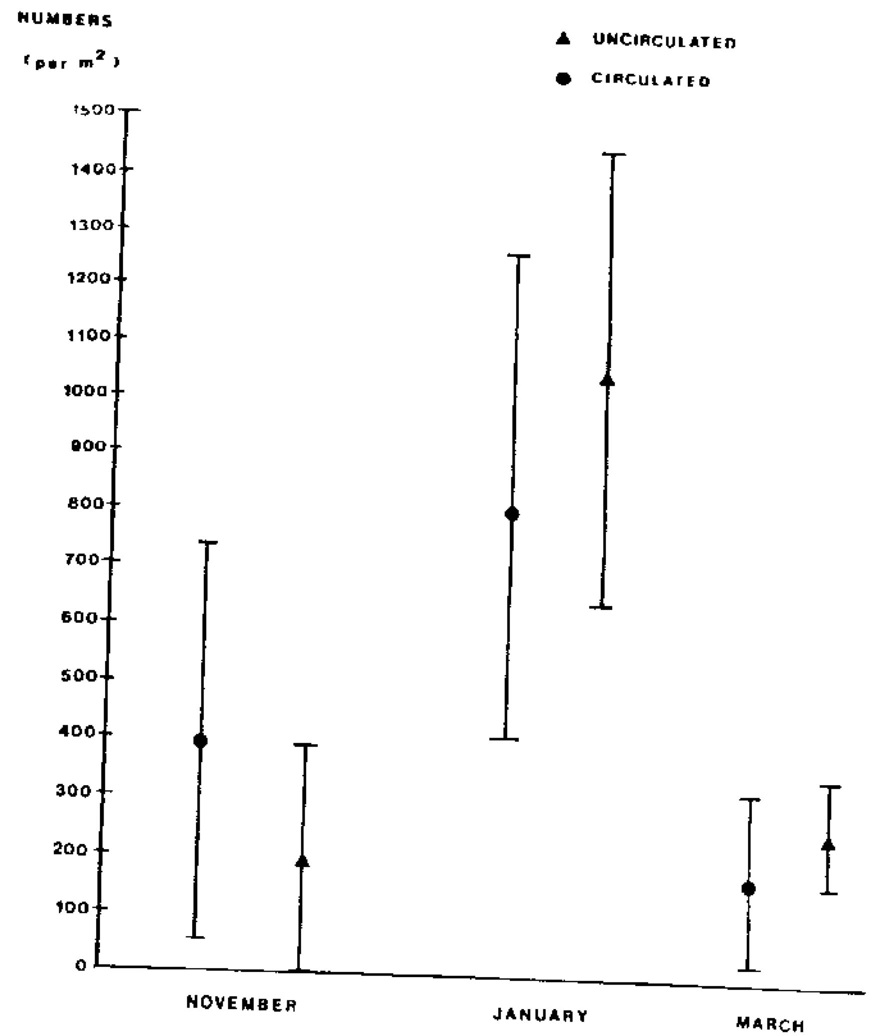


Figure 35. Chironomid midge larvae density (mg/$m^2$) at Kohala Prawn Farm pond on three sampling dates. The respective mean densities with 95% confidence intervals for the circulated and uncirculated halves of the pond are shown.

pond, all of the tagged prawns were located in the shallow, weedy area around the periphery of the pond (Fig. 36). None of these tagged prawns were found away from the shore. By contrast, a large percentage of the tagged prawns in the circulated pond were found away from the banks (Fig. 37). In both cases, more prawns were found nearer one end of the pond than the other as a consequence of being released at one location in each pond.

The prawn distributions shown in Figures 36 and 37 represent only one point in time in each pond. We conducted numerous other surveys of prawn distributions during the summer and generally found the same distributional differences between circulated and uncirculated ponds on calm days. We never observed the reverse pattern with more prawns near the banks in circulated ponds. On windy days, we observed more prawns away from the banks in the uncirculated ponds. During windy conditions the distribution in circulated and uncirculated ponds was more similar.

We did not measure prawn distribution at Kohala Prawn Farm.

Prawn Growth: At harvest at Kohala Prawn Farm on March 16, 1983, a substantial prawn size difference existed between the circulated and the uncirculated halves of the pond. The average carapace size on the circulated side was 1.46 cm, compared with 1.37 cm for the uncirculated side. More importantly, a much greater proportion of the prawns on the circulated side had reached market size. Market size generally means prawns equal to or larger than 12 prawns per pound (38g/prawn). This is equivalent to prawns with an average carapace length of 3.8 cm. Of those prawns harvested on March 16, 49.0% were this size or larger on the circulated side of the pond, compared with only 33.5% on the uncirculated side (Fig. 38).

On March 16, a total of 21 lbs of prawns were harvested from the circulated side of the Kohala Prawn Farm ponds, compared to 18 lbs from the uncirculated side.

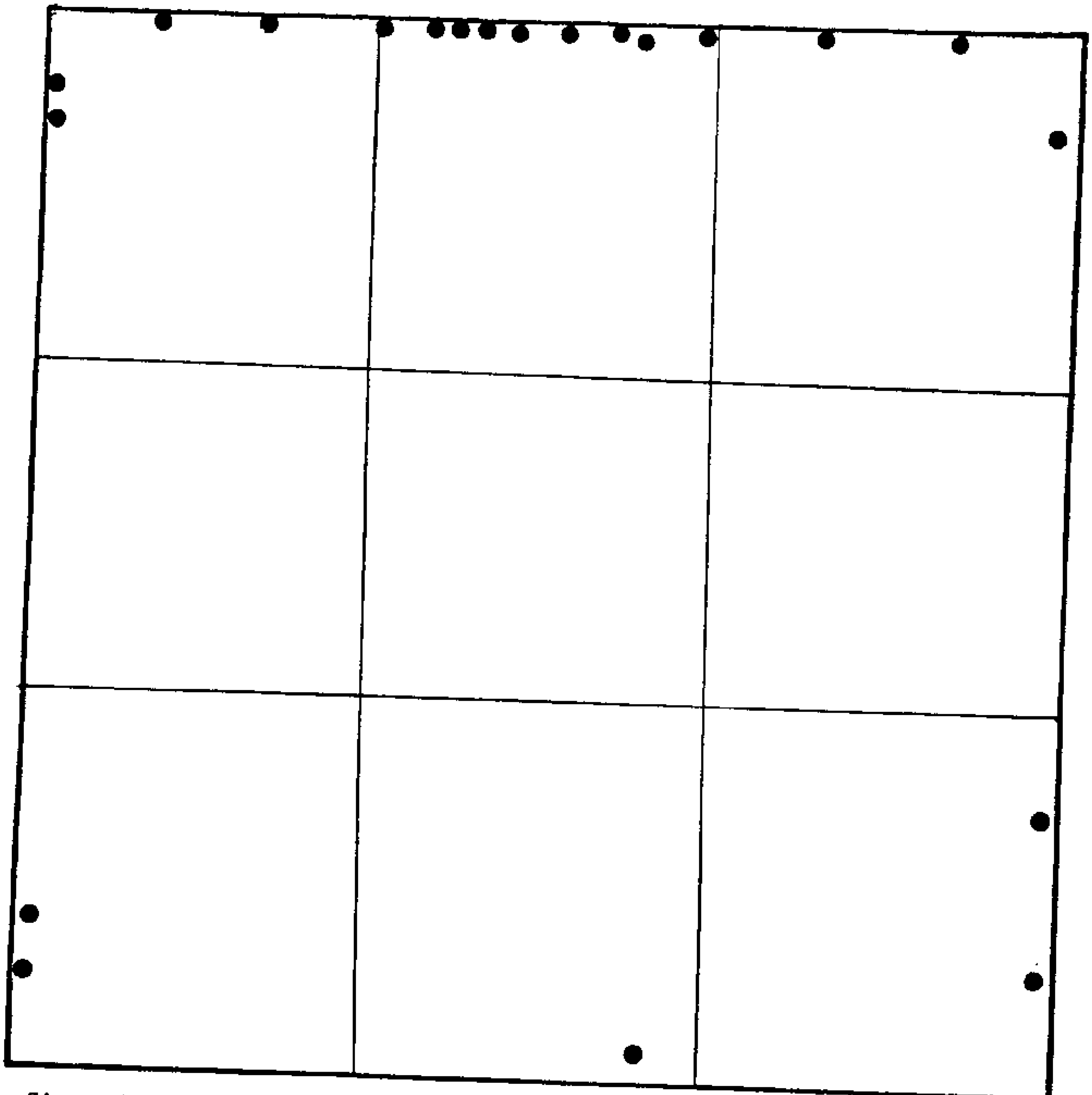

Figure 36. Distribution of tagged prawns in Aquatic Farms pond No. 6 on July 20, 1982. The pond was not artificially circulated. Each dot represents one prawn. The distribution is at 1500 hours, while they were tagged and released into the pond about five hours earlier.

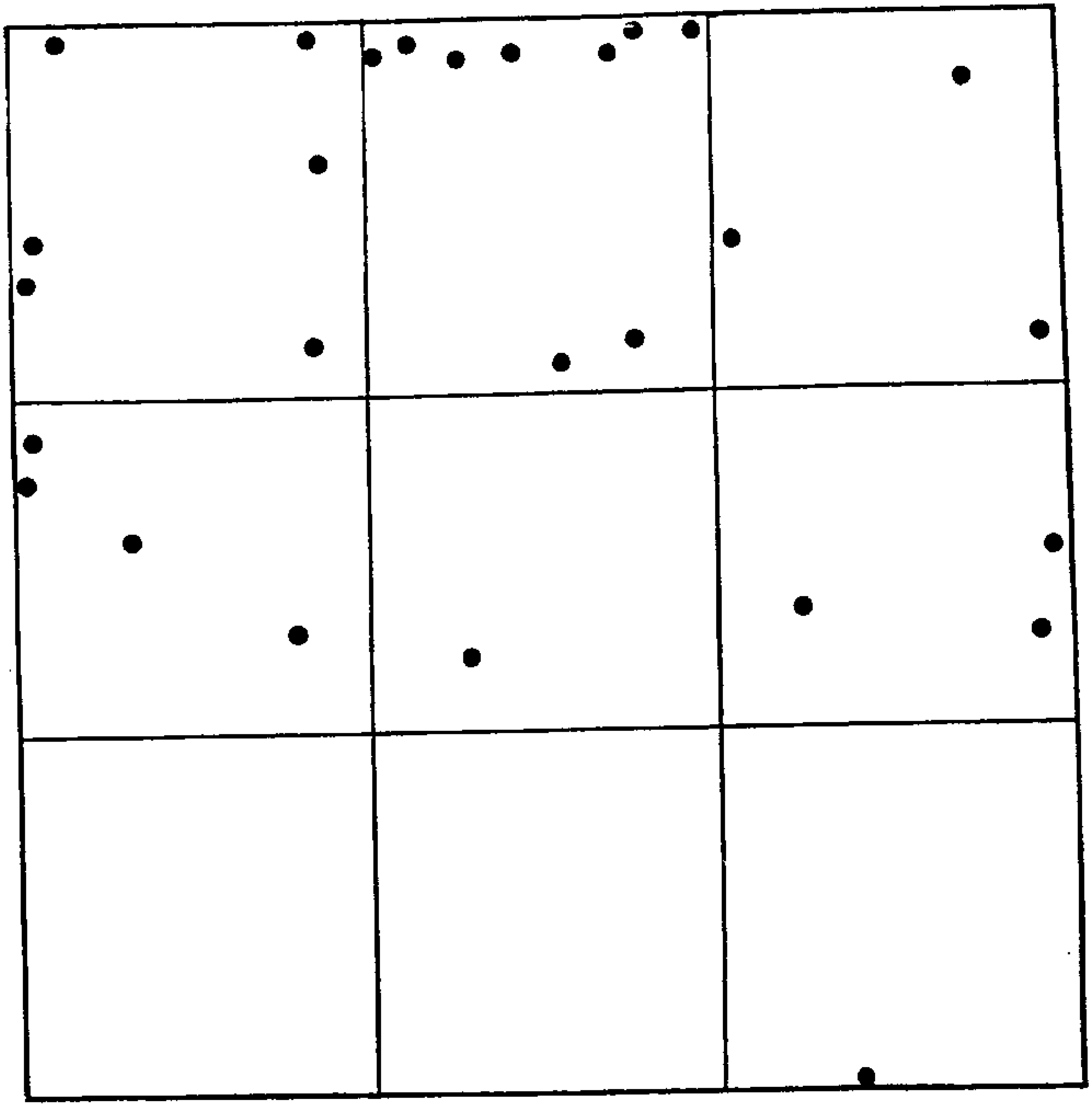

Figure 37. Distribution of tagged prawns in Aquatic Farms pond No. 5 on July 20, 1982. The pond was artificially circulated by a one-pond circulator (PC-I). Each dot represents one prawn. The prawn distribution is at 1625 hours, while they were tagged and released into the pond about 6½ hours earlier.

| | CIRCULATED | UNCIRCULATED |
|---|---|---|
| DESIGNATION | (shaded box) | (open box) |
| NUMBER OF PRAWNS MEASURED | 200 | 200 |
| MARKET SIZE PRAWNS | 49.0% | 33.5% |
| SUB-MARKET SIZE PRAWNS | 51.0% | 66.5% |

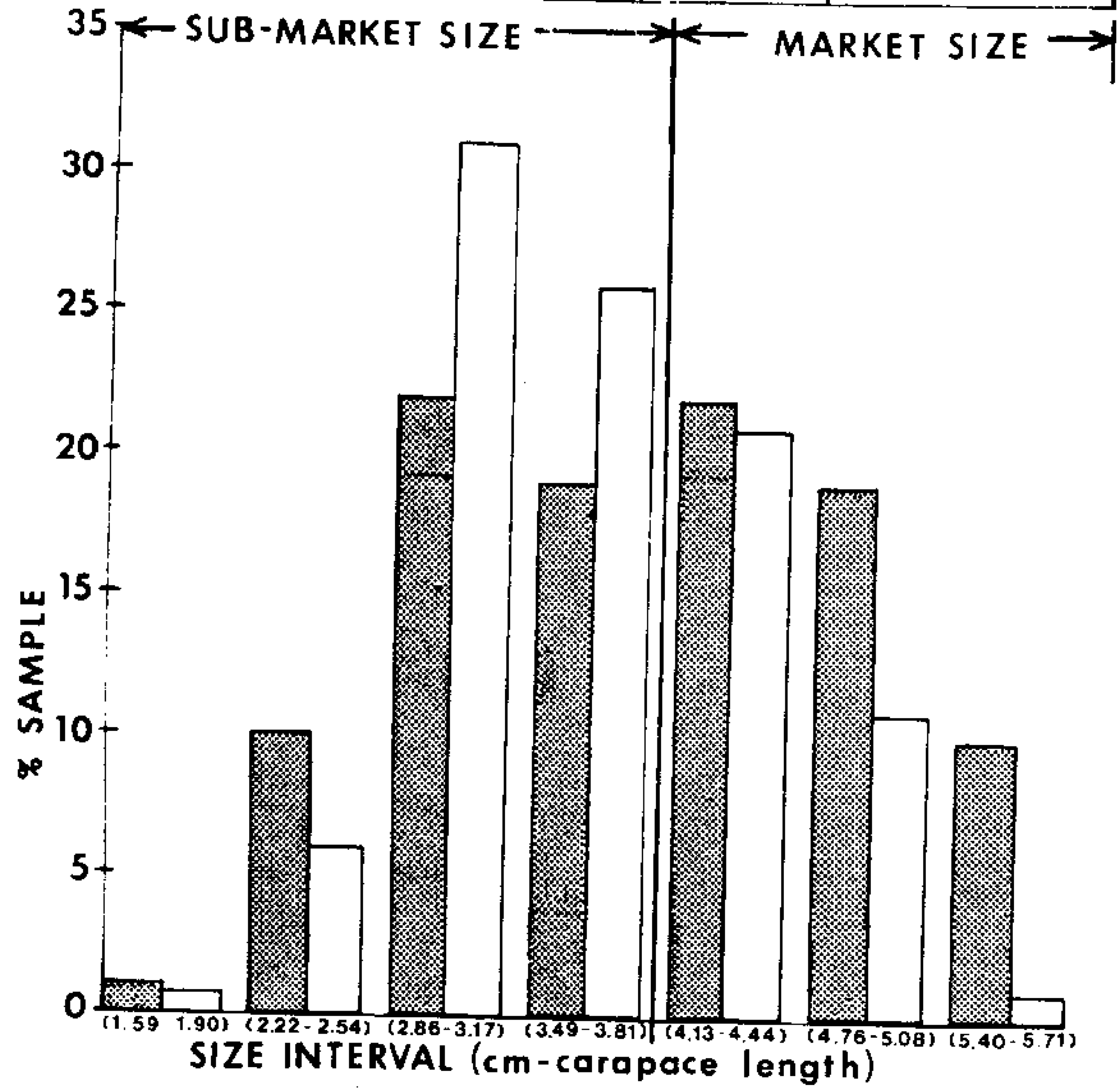


Figure 38. Prawn Harvest Data from Kohala Prawn Farm on March 16, 1983.

## DISCUSSION

Quite clearly, artificial circulation can create both higher oxygen and higher temperature values on the bottoms of Hawaiian prawn ponds. Prawns are bottom dwelling animals, and are therefore most sensitive to any improvement or deterioration of these or other water quality conditions at the pond's bottom.

Artificial circulation caused an average increase in daily maximum bottom temperatures of 2.8°C compared with uncirculated conditions. Although this is a difference in maximum temperature, the average increase, integrating over the day is probably closer to 1.5°C. It could be higher during the summer months at a calm site. According to McSweeny (Personal Communications, 1983), prawn growth is increased 6% to 7% for every degree rise in temperature in the range of about 23° to 30°C. If this relationship is valid, then we might expect growth increases due to temperature elevation alone in circulated ponds, at a calm site, to exceed 10%.

Artificial circulation not only increased bottom temperatures, it also increased minimum bottom oxygen concentrations by an average 1.0 mg/l, and maximum bottom oxygen concentrations by 4.0 mg/l. These averages are for all conditions, including windy and calm days. These increases are even more pronounced during calm conditions when bottom oxygen concentrations without artificial circulation can reach stressful, if not lethal, levels.

Spotts (in press) observed physiological stress in *Macrobrachium rosenbergii* when oxygen values dropped below 2.0 mg/l during the day, or below 3.3 mg/l during the night. Higher temperatures, higher activity levels, greater prawn densities, or aggressive interactions might raise minimum oxygen requirements even higher. Our observations at Kohala Prawn Farm indicate that on the average, minimum oxygen concentrations of less than 3.0 mg/l occur more frequently during uncirculated conditions (by 57%) compared with circulated conditions. The conclusion then, is that circulation will reduce stress caused by low oxygen concentrations.

Prawns are aggressive, cannibalistic animals (Peebles, 1977). Large males are particularly aggressive. Most management strategies in prawn grow-out ponds attempt to minimize the deleterious effects of these larger animals by frequent harvesting and cropping of the larger prawns, especially the males. If this strategy is successful, then aggressive interactions will be reduced and the small prawns will be allowed to grow more rapidly to market size. If harvests are too infrequent or unsuccessful in cropping the larger animals, then aggressive interactions increase, with the result that the overall growth of the prawn population is suppressed. Survival may also decrease, and heterogenous growth is promoted.

The evidence thus far indicates that artificial circulation will reduce aggressive interaction and thus promote more uniform growth of the population. During calm conditions in uncirculated ponds, prawns will seek the narrow area around the pond banks. It is unclear whether this is an avoidance of unacceptable conditions in deeper water, or an attraction to more desirable conditions in shallow water. Whatever the case, the result is a crowding of the population into a very small portion of the pond during these condtions. Artificial circulation causes more uniformity of oxygen, temperature and possibly other conditions, and thus allows the prawns to utilize the entire bottom area. The avoidance or attraction response is thus overcome with the result that more habitat is available to the prawns with reduced danger of aggressive interactions.

Fast and Momot (1973), Momot (1967) and Momot and Gowing (1972) found a similar situation with the crayfish Orconectes virilis in Michigan lakes. Large male crayfish of this species preferentially selected shallow water depths in normally stratified lakes because these areas had the highest water temperatures. The less aggressive females and small males were forced out of the warm shallows and into the cooler deep water by the large aggressive males. In these cases temperature, and not oxygen, was the selective factor since oxygen was plentiful in the deeper, cold water. When a thermally stratified lake was artificially destratified by compressed air injection, both male and female crayfish distributed uniformly throughout the isothermal lake. A parallel situation appears to occur in Hawaiian prawn ponds, albeit on a very reduced vertical scale.

Because of the relatively short experimental time period, we were unsuccessful in conclusively documenting the effects of artificial circulation on yearly production rates of prawns. Preliminary results indicate a substantial increase in total production is likely, based on total pounds of market-sized animals at Kohala Prawns, and on the size distribution of prawns reared under circulated and uncirculated conditions. Although these findings are encouraging, they are not definitive. Additional growth and production observations are needed from a larger number of production ponds over a longer period of production. Production figures vary greatly from pond to pond, and even for a given pond through time. Consequently, further observations are needed on prawn production within circulated and uncirculated ponds before we can confidently quantify the effect of this treatment. We are highly optimistic that circulation will cause a substantial increase in prawn production, not only from the limited production data gathered thus far at Kohala Prawn Farm and at Aquatic Farms during artificial circulation, but also from the limnological effects of circulation. Taken together, these observations lead us to the conclusion that artificial circulation removes certain important barriers to prawn growth and survival.

We originally hypothesized that artificial circulation would reduce or eliminate the need for emergency aeration. The rationale for this hypothesis was that most lethal dissolved oxygen conditions are caused by one of two conditions. One situation develops due to massive algal die-offs which occur when blue-green algae float to the surface of the pond during calm, sunny conditions. The algae are then killed by intensive ultraviolet light (Boyd, et al, 1975). Photosynthetic oxygen production is thus greatly reduced, while at the same time oxygen is depleted by the decomposition of the dead algae. A second condition causing massive die-offs of algae occurs as a result of intensive thermal stratification, followed by sudden destratification and the upwelling of algal toxicants (Swingle, 1968). In the first case, artificial circulation may prevent the UV death of blue green algae during calm, sunny conditions, while in the second case circulation should prevent the establishment of intensive thermal stratification. Although our original hypothesis may still be valid for these conditions, algal crashes and oxygen depletions can also occur during other conditions. We observed one such algal crash during the last week of our evaluations at Kohala Prawn Farm. This situation occurred in both the circulated and uncirculated sides of the pond, and was probably a result of nutrient starvation. The pond had not been manured or "fed" for at least three weeks when the crash developed.

Oxygen depletions can also occur with healthy algal populations. Respiration values for extremely dense algal populations can range between 0.8 and 1.0 m/l/hr (A.W. Fast, unpublished data; Barry Costa-Pearce, personal communcation, 1982). This condition occurred at several Hawaiian prawn farms during the Summer of 1982, and a number of massive kills occurred. The high algal respiration rates were more often associated with dense populations of dinoflagellates. At least three ponds experienced major kills at Aquatic Farms during 1982 because of these conditions. Even with a respiration rate of 0.8 mg/l/hr, the whole pond must have more than 8 mg/l at nightfall just to accommodate algal respiration during 10 hours of darkness. With high sediment B.O.D., dense prawn populations, and/or longer hours of darkness, the D.O. at nightfall should be much higher to prevent lethal oxygen levels before dawn.

Previous work at Auburn University indicated that artificial circulation is a substitute for emergency aeration (Busch and Goodman, 1981; Busch, 1980). At least one paper even compared energy savings associated with circulation with emergency aeration. More recent, unpublished work at Auburn indicates that these predictions were overly optimistic, and that circulation is not a substitute for emergency aeration (Randal Goodman, personal communications, 1983).

Although circulation is not a substitute for emergency aeration, it does have a major role to play in the management of prawn grow-out ponds. The benefits and application of each technique should be clearly understood, and criterion for when and how to apply each technique should be developed. Circulation and aeration are complementary and necessary if production is to be maximized.

Since circulation is not a substitute for emergency aeration, Hawaiian prawn farmers must develop (1) predictive procedures for determining when lethal oxygen concentrations will occur in their ponds; and (2) emergency aeration techniques tailored to their situation and needs. We intend to include the development of these techniques and tools in our future research efforts.

Future research efforts should also include model development for the on/off operation of pond circulators. Clearly, full-time operation is not necessary. Most likely, operation need only occur during daylight hours, and then only when the combination of wind, solar irradiance and rainfall conditions lead to thermal stratification. The percent of time that circulators must operate could vary greatly between windy and calm sites. Optimum operation time may be as little as 15% at some locations, and as much as 30% at other sites. We do not have enough information now to determine under what set of conditions the circulators should operate, and what percentage of time this represents at different sites. This too will be part of our future research efforts.

Optimization of operating time for circulators can result in substantial savings. Table 10 lists the cost to operate circulators at a 100-acre farm, assuming one ¼ h.p. circulator per acre (amperage draw of 3.9/circulator), and power cost of $.13/kw-hr. Relative to full-time operation, a 50% operating schedule saves $25,608 per year in electricity, while 20% operation saves $40,972.

Optimization of circulator operation will require (a) establishment of a definitive relationship between meteorological parameters and thermal stratification in ponds; (b) mathematical model and software development for small, personal computers; (c) meteorological data inputs into a personal computer; and (d) on/off control of pond circulators. Optimization of operation should proceed simultaneously with further evaluations of the efficacy of circulation, and with circulation hardware development.

Capital and operating costs for artificial circulation are not fully known, but can be estimated. In kit form circulators will probably retail for about $800 each, and have a life expectancy of 5 years. Yearly depreciation, plus minor maintenance may thus run about $225. Operating costs, on a 20% operating schedule will run about $103/yr in electricity. These figures give a yearly cost of circulating a one-acre pond of about $328. This is equivalent to 82 lbs of prawns @ $4.00/lb. Thus a 4.1% increase in a pond which produces 2,000 lbs/yr. will pay for the circulator, while a 8.2% increase in a pond which produces 1,000 lbs/yr. will cover the circulator costs. We anticipate increases substantially greater than 10% resulting from the appropriate application of circulation equipment and techniques.

Windbreaks, used in conjunction with artificial circulation, could result in substantial increases in prawn production at windy sites.

Table 10. Operating cost for pond circulators at a 100-acre prawn farm, assuming one ¼-h.p. (3.9 amps) circulator per acre and power cost of $.13/KW-hr

| Percent of Time Circulators Operate | Total KW-Hr | Yearly Costs |
|---|---|---|
| 100 | 393,962 | $51,215 |
| 50 | 196,981 | 25,608 |
| 40 | 157,584 | 20,486 |
| 30 | 118,189 | 15,364 |
| 20 | 78,792 | 10,243 |
| 15 | 59,094 | 7,682 |

Klemetsan and Rogers (in press) have demonstrated that windbreaks at windy sites could increase water temperatures by 2°C or more by reducing evaporative cooling. Besides increasing temperature, windbreaks also promote thermal stratification since the mixing influence of the wind is reduced. Consequently, artificial circulation may be needed to ensure that the bottom-dwelling prawns will realize the benefits of increased temperatures in the pond. An average temperature increase of 2°C could alone increase prawn production by 10% or more (McSweeney, personal communication, 1983). In a pond which produces 1500 lbs of prawns per year, this amounts to an increase of 150 lbs of prawns, or $600/acre/yr. This should more than pay for the circulator and the windbreak over the five-year life expectancy of the circulator. The additional benefits of circulation could increase production well above the 10% level, in which case profits would soar.

Manure applications at the Kohala Prawn Farm caused a substantial increase in primary and seconday production within the pond. Chlorophyll a values increased as much as 10-fold, while the standing crop of oligochaete worms and chironomid midge larvae increased 60% by weight after 1½ months of manure application, and 325% after 3 months of manure application. The worms showed the most consistent increase even after manure applications ceased. The chironomids increased greatly during manure application but decreased to below initial levels after manure applications ceased. These data, plus the algal population crash in March, suggest that continuous manure treatment is necessary to sustain high densities of both oligochaetes and chironomids, as well as a healthy algal population.

The effect of increased primary production and benthic fauna standing crop on prawn production is not well known, but most researchers would probably agree that these increases should improve prawn production, provided that the increased primary production is not excessive and does not lead to oxygen depletion crises and prawn deaths. Although the relationship between primary productivity and prawn production is not presently defined, complementary evidence from tropical lakes show positive correlations between primary production and fish production (Melack, 1976). Almazan and Boyd (1978) found highly significant correlations between Tilapia yields in fish ponds and chlorophyll a ($r^2 = 0.89$) as well as Secchi disc transparency ($r^2 = -0.71$). Although fish have a different trophic niche than prawns, we expect prawn production to behave similarly to fish production with regard to its relationship to primary and secondary production. In other words, increased primary and secondary production associated with manure applications should cause increased prawn production. The presently unanswered question is whether manure applications alone can substitute for the application of commercial prawn pellets and feeds.

All commercial prawn farms in Hawaii utilize commercial prawn feed (or some other prepared feed) at rates ranging from 15 lbs of feed/day to more than 30 lbs of feed/day. At an average feeding rate of 20 lbs/day, this amounts to 7,300 lbs of feed per acre per year, or $1,095/acre/yr at $.15/lb of feed. Average prawn production of about 2,000 lbs/acre/yr would give a "feed conversion" rate of 3.65:1, or $.55 of feed for each pound of prawn produced. If some or all of the prawn pellets could be replaced with manure applications, then considerable savings might occur with the use of the lower cost manure. Our study was the first that we know of where cattle manure was applied to commercial size Macrobrochium grow-out ponds as a possible substitute for commercial pellets. Although we did not determine whether manure can be substituted wholly for pellets, we feel that our observations, as well as the findings of other researchers on this topic, are encouraging and indicate that manure can be at least a partial substitute for commercial pellets.

Studies at Oceanic Institute, Hawaii (Anonymous, 1982) on manure applications to marine shrimp ponds (Peneids) indicate that manure alone can be an effective, low cost substitute for prepared feeds. More directly, recent feeding studies on Macrobrachium rosenbergii in small experimental ponds in Hawaii have shown that agricultural byproducts such as green chop (pineapple plant), corn silage, or bagasse (sugar cane stalk waste) in 50% combination with prepared feeds produced prawn growth equal to prepared feed applications alone (Lori Moore, personal communications, 1983). Prawn production with these agricultural byproducts alone was lower than with prepared feeds alone. In another related study, Stahl (1979) found that prawns grew almost as well in experimental tanks containing a mixture of organic debris (manure or other materials) and soil, as with tanks providing a prepared feed and containing soil. These studies, taken together, indicate that manure and other low cost plant waste or byproducts may be as good as, or almost as good as, prepared prawn feeds.

Manure is routinely applied to many fish ponds around the world as the sole source of nutrient input with resultant substantial rates of fish production (Schroeder, 1978, 1980; Tang, 1970; Noriega-Curtis, 1979). These studies have also shown that the resultant fish production cannot be accounted for by the rate of primary production alone, but must also be due to other nutritional aspects of the manure.

Nutritional aspects of manure, which can ultimately culminate in prawn or fish biomass production, include the following: (1) The stimulatory effect of primary nutrients such as phosphorus, nitrogen and potassium on plant production. The plants are then either consumed directly by the cultured species, or by other organisms which may then be consumed directly or indirectly by the cultured species; (2) Direct consumption and assimilation of manure by the cultured species: manures of many types contain considerable food value, even when they are the sole source of food for certain other species; (3) The manure provides an organic substrate on which heterotrophic bacteria, fungi, protozoa and other organisms flourish. This complex is then ingested and assimilated by the cultured species.

From the above studies, we are convinced that manure treatments alone, or in some combination with prepared feeds, can result in prawn production levels equal to prawn production levels with prepared feeds alone, but at a lower overall cost to the prawn farmer. This problem will require further investigation, preferably on commercial sized prawn ponds using a factorial experimental design where the treatments will include manure, prepared feed and artificial circulation. Without replication of treatments, a minumum of six ponds will be needed. The treatments per pond will thus be (1) manure only with circulation; (2) manure only without circulation; (3) feed only with circulation; (4) feed only without circulation; (5) feed and manure with circulation; and (6) feed and manure without circulation.

Since artificial circulators increase sediment oxygen and temperature conditions significantly, we believe that their use can enhance the success of manure usage. The circulators would offset the effects of increased sediment respiration rates which is likely to occur with manure application since more than 90% of the manure applied to a pond will settle to the bottom within a few hours (Schroeder, 1978). If more than a few millimeters of manure accumulate in the absence of sufficient oxygen, anaerobic conditions will develop within the sedimentary manure layer. This layer may then generate toxic substances which, particularly if disturbed, can lead to mortality of the cultured species. In Israel, the safe rate of manure application is generally less then 125 lbs/day/acre. Perhaps this manure loading can be increased through the use of artificial circulation and aeration techniques. The main objective is to maintain aerobic conditions so that the manure may be digested rapidly without the production of toxicants.

Whether prepared feed and/or manure is applied to a pond, artificial circulation should increase its direct utilization by the prawns. If the pond is not circulated, the prawns will crowd into the banks during calm spells. Feed or manure applied to the main body of the pond will not be available to the prawns until stratification is diminished. By then, much of the prepared feeds will have dissolved and their nutrient content leached out. Artificial circulation will allow immediate access to feeds and manures whenever and wherever they are applied.

The largest prawn pond that we tested our circulators in was 0.5 acres. Based on our observations in this sized pond, we believe that a ¼-h.p. circulator such as the PC-II can handle a one acre Hawaiian prawn pond under most conditions. This may not result in isothermal conditions, nor uniform oxygen throughout during intense periods of solar irradiation and calm winds, but it should greatly increase bottom and oxygen conditions even during these "worst case" conditions.

# SUMMARY AND CONCLUSIONS

## SUMMARY

1. Under calm conditions, without artificial circulation, prawn ponds develop thermal and oxygen stratification soon after sunrise, a condition which can persist most of the night as well. Bottom oxygen concentrations normally reach a minimum of less than 5 mg/l during late afternoon and then increase after sunset as thermal stratification is disrupted by natural convective cooling.

2. With artificial circulation, thermal stratification is much less pronounced and does not persist as long each day. Bottom oxygen concentrations normally reach a minimum at dawn of about 4 to 5 mg/l and then increased greatly until afternoon when values often exceeded 12 mg/l. Oxygen decreases after sunset.

3. On windy days, oxygen and temperature values at all depths are similar with or without artificial circulation, although circulation resulted in higher oxygen and temperature values at the bottom even during windy conditions.

4. The degree of natural mixing, and thus the bottom oxygen and temperature values, is related to wind velocity, solar irradiance, air temperature and rainfall. The relationship between these parameters and pond stratification is not now well defined, but needs to be for optimization of artificial circulation. Optimization includes maximizing oxygen and temperature conditions on the pond bottom, while at the same time minimizing hours of operation (i.e. energy consumption) by the pond circulators.

5. Artificial circulation caused an average increase in daily maximum bottom temperatures of 2.8°C, compared with uncirculated conditions.

6. Minimum daily bottom oxygen concentrations averaged 1.0 mg/l higher during artificial circulation, compared with uncirculated conditions.

7. Maximum daily bottom oxygen concentrations averaged 4.0 higher during artificial circulation, compared with uncirculated conditions.

8. Alkalinity and conductivity doubled during the study period apparently due to manure applications. Artificial circulation had no apparent effect on these parameters.

9. Most of the plant nutrients, phosphorus and nitrogen were present as organic, rather than inorganic, fractions. Both levels were rather low and did not show consistent patterns with regard to either manure applications or artificial circulation.

10. Chlorophyll a concentrations increased greatly as a result of manure application. Chlorophyll a increased from 50 $mg/m^3$ before manure

treatment to 500 $mg/m^3$ during treatment. At the same time, Secchi disc transparencies decreased from about 40 cm before manure treatment to 10 to 12 cm during treatment. There was a close, curvilinear relationship between chlorophyll a concentrations and Secchi disc transparencies.

11. Sediment respiration rates averaged 222 $mg/m^2/hr$, and did not differ significantly between the circulated and uncirculated halves of the ponds.

12. Benthic fauna consisted almost entirely of oligochaete worms and chironomid midge larvae, and these populations increased greatly during manure treatment. Benthic fauna densities increased from 13.2 $mg/m^2$ before manure treatment to 21.3 $mg/m^2$ after 2½ months of manuring. The total increased further to 56 $mg/m^2$ after 3½ months. Circulation did not seem to have much effect on benthic fauna densities, compared with manure treatment.

13. Thermal and oxygen stratification causes prawns to restrict their distributions to the shallow water and bank areas. This almost certainly leads to aggressive interactions, reduced survival, heterogenous growth and a negative effect on prawn production. Artificial circulation reduced stratification and resulted in a more even distribution of prawns within the pond.

14. Prawns harvested from the circulated half of the pond were larger than those on the uncirculated side. On the circulated side 49.0% were market sized, compared with only 33.5% on the uncirculated side.

15. Although definitive prawn production data is not available, the preliminary results indicate greater production due to artificial circulation.

## CONCLUSIONS

16. Prawn growth and production would be increased, perhaps by 10% or more, due to temperature increases on the pond bottom caused by artificial circulation.

17. Prawn growth and production would be increased by some unknown amount due to an unrestricted distribution within the pond caused by artificial circulation. An unrestricted distribution will lessen aggressive interactions, and should therefore promote increased survival and growth.

18. Artificial circulation substantially increases oxygen concentrations on the bottom.

19. Although artificial circulation results in higher minimun oxygen concentrations, it is not a substitute for emergency aeration. Both forms of oxygen management should be used as appropriate.

20. Artificial circulation is not needed full time, but criteria for optimization of operation time have not yet been developed. Development of these criteria and methods of application could reduce circulation costs by 75% to 80%, or more.

21. One ¼-h.p. pond circulator with a 24-inch fan blade should adequately circulate a one-acre prawn pond. The yearly cost to operate the circulator continuously is $512.16 (at 13¢/Kw-hr). Optimization of operation could reduce this cost to $100/yr or less.

22. Maximizing prawn production will require a simple and reliable system of oxygen management within the grown-out ponds. Elements of this system include (a) methods of predicting oxygen depletion well before the depletion occurs; (b) low cost circulation equipment and techniques, and (c) reliable emergency aeration equipment and techniques. With the exception of item (c), little has been done in Hawaii to develop such a system of oxygen management.

23. Windbreaks can cause a substantial increase in pond water temperatures by reducing evaporative cooling, but they can also promote stratification. A combination of windbreaks and artificial circulation could substantially increase prawn growth and production in windy areas.

24. Manure applications can greatly increase primary and secondary production in a prawn pond. While these should increase prawn growth, it is not clear whether manure application can substitute entirely for prepared feed applications. Other research indicates that a combination of manure (or agricultural byproduct) treatments and prepared feeds will give the best growth at the lowest cost.

## FUTURE RESEARCH NEEDS

1. Circulator operation must be optimized to reduce operating expense. Optimization will require mathematical model development to link meteorological conditions such as wind speed, wind direction, solar irradiance, air temperature and rainfall with pond stratification. Optimum use of the circulators will most likely require (a) mathematical model development and adaptation; (b) meteorological inputs to a personal computer; and (c) on/off control of the circulators by the computer.

2. Oxygen prediction techniques need to be developed such that a pond operator can easily predict from a few simple observations on his ponds when oxygen depletions will occur. These predictive procedures have been developed for catfish ponds but they are not widely used, in large part because they are not convenient. With the widespread acceptance of low cost personal computers, these predictive procedures can be "conveniently" adapted to Hawaiian prawn ponds.

3. Emergency aeration equipment and techniques need to be developed and adapted to Hawaiian prawn ponds. These equipment and techniques have been developed for other aquaculture ponds, as well as lake, stream and sewage aeration. The most appropriate ones should now be adapted to Hawaiian prawn ponds.

4. The effects of artificial circulation on prawn production need further verification. Although preliminary results indicate substantial increases in prawn production are possible, these need to be verified by observing prawn production in a number of ponds, compared with uncirculated ponds managed in an otherwise similar manner. Production should be observed for at least one year.

5. The effects of artificial circulation on other pond systems should be evaluated. Other types of aquaculture production that could be benefited include catfish, milkfish, mullet, tilapia and peneid shrimp. Tests in these different pond situations would include both freshwater and seawater sites.

6. Engineering design work should be done on different sized circulation devices. A range of sizes for blades from perhaps 10 inches through several feet in diameter should result in an array of circulation devices for different sized ponds.

7. The cost effectiveness of operating a larger circulator less time should be evaluated. For example, if a ¼ h.p. circulator must be circulated continuously on a given day to achieve adequate mixing, perhaps a ½ h.p. circulator may only need to be operated 1/3 of the time, with a resultant savings in operating costs.

8. The benefits of manure applications in lieu of prepared feed should be evaluated more thoroughly. This evaluation should include a

factorial design with different combinations of the following treatments: manure, prepared feed, and artificial circulation.

9. Pond circulator design and construction should be improved such that the circulators can be sold in kit form, at a resonable cost, and have a reasonable life expectancy. Reasonable cost and life expectancy for a circulator might be $700 and 7 years respectively.

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