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Water Quality Control and Management of Animal Wastes Through Culture with Selected Fishes

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ABSTRACT

WATER QUALITY CONTROL AND MANAGEMENT OF ANIMAL WASTES THROUGH CULTURE WITH SELECTED FISHES

This study evaluated the contributions of four Chinese carps to the biological treatments of four oxidation ponds receiving swine wastes. Carps used have specialized feeding habits: the silver carp (Hypophthalmichthys molitrix) filters suspended materials (phytoplankton, bacteria); the bighead carp (Aristichthys nobilis) filters zooplankton; the grass carp (Ctenopharyngodon idella) ingests coarse vegetation; the common carp (Cyprinus carpio) consumes benthos and detritus including fish feces. Segment I (1976) utilized different densities of carps in ponds receiving similar amounts of manure; Segment II (1977) utilized similar quantities of manure and companion fishes but different densities of silver carp; Segment III (1978) utilized ponds in series, the first containing carps, the second macrophytes; Segment IV (1979) evaluated pond aeration, in addition to fish. Prawns (Macrobrachium rosenbergii) also were stocked in 1978 and 1979. Studies of autotrophic and heterotrophic communities were intensified in 1979.

Results established that through consumption of large quantities of organic matter, both living (plankton, bacteria) and dead (detritus, feces), the carps in proper densities and combinations can significantly improve the quality of organically polluted waters and that properly designed systems would have practical applications for small communities, livestock producers, and food processers. Areas needing additional study are recommended.

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INTRODUCTION

Aerobic ponds used for the treatment of wastes are variously known as oxidation ponds, photosynthetic ponds, waste stabilization ponds, aerobic lagoons, or facultative lagoons. Regardless of the name, all use solar energy and photosynthesis as the source of oxygen utilized by bacteria in the aerobic decomposition of wastes. Such ponds are now used through much of the world for the treatment of wastes. The dynamic behavior of such ponds has been well described by Marais (1970). The advantages of utilizing such ponds have been frequently discussed (Allum and Carl 1970; Stevens 1970; Schurr 1970; Schurr and Golombek 1974; Donaszy 1974): these include economy of design and construction, simplicity of operation and management, and low operating costs. As pointed out by Martin and Schurr (1979), it has been repeatedly demonstrated that treatment of wastes in properly designed and operated oxidation ponds can meet and surpass local, state and federal water quality standards but that the use of such ponds is frequently rejected because of the biomass they produce. Such biomass most commonly consists of large quantities of algae, insects and other invertebrates which many believe to be unsightly and/or capable of degrading a receiving stream. What is viewed as a nuisance by some can be exploited by others. An obvious solution is to harvest the biomass for constructive purposes. Such purposes might include use of algae or macrophytes for cattle feed (Boyd 1968; Culley and Epps 1973; Truax et al. 1972), as a source of protein in fish feed (Liang and Lovell 1971; Stanley and Jones 1976), or as a direct food for oysters or other invertebrates (Ryther et al. 1975);

the enriched water could be used as a source of fertilizer on croplands. An additional alternative, to be examined here, is to concentrate the biomass in fish cultured in the waste treatment pond. Subsequent harvesting of the fish can remove excessive nutrients, control eutrophication, and provide a useful product.

The concept of utilizing fishes to purify wastewaters had its origin in ancient Chinese aquaculture. For centuries the Chinese farmer has placed his latrine over the fish pond, his pigsty and chicken coops on the pond bank, his ducks and geese on the pond surface--and has used such other available organic wastes as cow and horse dung, compost, or offal to enrich the pond for the production of food fish while at the same time creating an effective waste treatment system.

The success of the system is due to a highly specialized group of fishes known collectively as the Chinese carps, all of which are in the minnow family (Cyprinidae) and none of which have counterparts in our native fauna.[1] We have used four of these fishes: (1) the silver carp (Hypophthalmichthys molitrix), which has an adaptation of the gill rakers for filtering plankton algae; (2) the bighead carp (Aristichthys nobilis), a filter feeder on zooplankton; (3) the grass carp (Ctenopharyngodon idella), which consumes both filamentous algae and submerged aquatic weeds as well as many terrestrial plants, when offered; and (4) the omnivorous common carp (Cyprinus carpio), which utilizes bottom organisms and many forms of organic detritus, including the fecal pellets of the associated fishes. Because of their individual feeding habits, such

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1 The common carp has a wide distribution in the U. S. but was brought to this country from Europe in the middle of the last century; it probably reached Europe from Asia in the 15th or 16th century.

mixed species suffer a minimum of competition and in fact benefit each other through synergistic relationships. As an example, Yashouv (1971) observed the interaction between the common and silver carp wherein each produced significantly greater yields when combined than when each was cultured separately. The common carp consumed the fecal pellets, rich in partially digested phytoplankton with colonizing microfauna, of the silver carp; and the silver carp strained organic and inorganic particles from the water column, also enriched by bacteria, which were caused to be there by the rooting of the common carp in the pond bottom. Through feeding at such diverse levels of the food web, the polyculture of fishes consumes such a large percentage of available organic matter that BOD, suspended solids and fecal coliform bacteria are reduced, water quality is improved, and protein production is large.

Possibly the first to propose exploiting the feeding habits of the Chinese carps to purify wastewaters was the late, distinguished fish culturist, S. Y. Lin (1974). Dr. Lin presented evidence that the known consumptive abilities of pure plankton-feeding fishes, filamentous algae eaters, bottom feeders and scavengers could provide a biological control that could serve as an alternate to more conventional treatment systems--and that such a biological system would cost much less initially, as well as in maintenance, and would contribute to the conservation of energy and the production of protein. Dr. Lin was unable to complete his studies, but other writers (Schroeder 1975; Carpenter et al. 1974; Coleman et al. 1974; Goldshmidt 1970; Henderson 1978) have contributed supporting evidence that fish improve the waste treatment capacity of pond systems. A review of this subject has been presented by Allen and Hepher (1979).

Other studies include an effort to remove excessive nutrients from municipal wastes through incorporation into the biological systems of a series of ponds and marshes (Bahr et al. 1974) and use of a polyculture of Chinese carps to purify the domestic sewage generated by the Benton State Hospital, near Benton, Arkansas (Henderson 1978). Also, sanitary engineering conferences are giving increasing attention to aquatic systems (e.g., the International Conference on Biological Water Quality Alternatives, University of Pennsylvania, March 1975; and A Seminar on Aquaculture Systems for Wastewater Treatment, University of California at Davis, September 11-12, 1979), and a recent paper by Schroeder (1979) describes the manner by which a proper polyculture of fish can prevent catastrophic cycles in the abundance of bacteria, protozoa, and zoo- and phytoplankton, thereby maintaining suitable water quality.

The present study evolved from preliminary investigations conducted in 3-meter diameter pools in 1974 and in two small earthen ponds in 1975. The 1975 study used similar densities of fishes (4 Asian and 3 native species) in ponds receiving different amounts of swine manure. In a growing period of about 170 days the net increments in fish biomass were at the rates of 2971 kilograms per hectare (kg/ha) in pond 11 and 3834 kg/ha in pond 12 (Buck et al. 1977, 1978). Levels of dissolved oxygen were continuously adequate in both ponds for the survival of the pollution-intolerant largemouth bass (Micropterus salmoides), and final BODs (BOD_5) were 7.8 mg/l in pond 11 and 11.7 mg/l in pond 12.

Primary initial interest was in the low-cost, low-energy production of protein, but it became evident that the potential for maintenance and/or improvement of water quality was of equal importance. The studies to be reported here were conducted in four segments, beginning in 1976, each involving a special management strategy. In Segment I (1976) we measured the influence of differing densities of four species of carps on water quality in ponds which received similar amounts of swine manure. In Segment II (1977) we standardized the densities of the companion fishes and measured the influence of differing densities of the planktivorous silver carp, because this species has the greatest potential for nutrient removal. In Segment III (1978) we measured the improvements in water quality to be provided by two-stage flow-through units containing macrophytes in the second-stage ponds. In Segment IV (1979) we evaluated the contribution of a third system, namely mechanical aeration, to determine (1) whether the addition of aeration produced results superior to methods previously tested, and (2) if superior, whether the cost of aeration can be justified. The studies involved three small earthen ponds in 1976, four in subsequent years, all located at the Sam A. Parr Fisheries Research Center, a joint facility of the Illinois Natural History Survey and the Illinois Department of Conservation located near Kinmundy, Illinois.

MATERIALS AND METHODS

Description of Ponds

The four ponds used had been constructed in 1966 in relatively infertile clay; they were contiguous and had experienced similar treatments. Surface areas ranged from 0.09 to 0.18 ha; shapes were triangular for the smallest, approximately rectangular for those of intermediate size, and approximately square for the largest (Fig. 1). Initial maximum depths were approximately 2 m, average depths near 1 m, but these levels were fluctuated in different years as will be described for each study. The ponds were drainable and were gravity fed from the 237-ha Stephen A. Forbes Reservoir. Except when operated as flow-through units or when aerated, the ponds remained static, with no artificial circulation and with no addition of water except from direct rainfall and from several small trickles dropping from a perforated pipe located above each swine floor. These trickles provided drinking water for the swine, helped wash manure into the ponds, and compensated for evaporation.

Swine Management and Introduction of Manure

The swine were sheltered on the dikes which separated the ponds. Single structures served ponds 10 and 13; a two-section structure served ponds 11 and 12. The design provided a concrete floor which sloped slightly toward the pond and extended beyond the water's edge so that fresh manure could drop continuously from the lower and outer edges of the floors directly into the water. Movement of the manure was facilitated by trickles of water falling from the perforated pipes previously described. Swine were bought locally in 1978; in all other years they were provided by the Department of Animal Science at the University of Illinois. Swine were fed standard rations used in swine production at the University of Illinois. Up to a weight of about 54 kg, the swine received a ration containing 16% protein; for heavier animals the protein content was reduced to 12%. Two lots of pigs were fattened between April and October in each year. Initial weights of pigs were in the usual range of 30-35 kg; the pigs were sold and replaced at weights ranging from 90-100 kg.

Measurement of Physical and Chemical Parameters

Dissolved oxygen and water temperature were measured at 30-cm intervals from surface to bottom at the deepest part of each pond, using a YSI model 54 Oxygen Analyzer. Surface water was analyzed for pH with a Beckman Zeromatic II pH meter; turbidities (Jackson Turbidity Units, JTU) were determined with a candle turbidimeter; conductivity (micromhos/cm) was measured by means of a Dionic conductivity meter; alkalinity, biochemical oxygen demand (BOD_5), total nonfilterable residue (total suspended matter), and settleable matter were determined according to procedures outlined in the fourteenth edition of Standard Methods (American Public Health Association et al. 1975). Pond depths, Secchi disk readings, dissolved oxygen, temperature, pH, turbidity, conductivity, and alkalinity were monitored weekly between 0700 and 0900. BOD_5, total suspended matter, and settleable matter were usually measured biweekly. Surface water samples were collected biweekly and frozen for later analysis to determine hardness, ammonia, nitrate, nitrite, total Kjeldahl nitrogen, and soluble orthophosphate using a Technicon CSN-6 Autoanalyzer.

In addition to these regularly scheduled measurements, dissolved oxygen and temperature from surface to bottom (at 30-cm intervals) and surface pH were monitored in each pond every two hours over a 24-hour period on several occasions. These 24-hour analyses were performed twice a month from June through August of 1976, once a month in July and August of 1977, and once in July 1978. Temperatures were continuously read in one pond during 1978 and 1979 by a Belfort recording thermometer which had two 35 cm-long thermistors suspended vertically immediately above the bottom and just below the water surface in the deepest part of the pond.

Measurement of Biological Parameters

Zooplankton was sampled with a fine mesh (80 microns) Wisconsin Style plankton net. Each sample consisted of one vertical tow from the bottom to the surface at the deepest part of the pond. Samples were obtained biweekly from April to the first week in October during 1976, and from June through September during all other years.

Phytoplankton samples consisted of 1 liter of pond water obtained about 15 cm below the water surface plus 10 ml of Lugol's solution as preservative. These samples were obtained biweekly from mid-June to the first week in October during 1976 only.

Phytoplankton sampling during 1979 (Segment IV) was more extensive. One-half-liter samples from each pond were preserved with Lugol's solution and concentrated by sedimentation in glass hygrometer jars. The supernatant was siphoned off and the sediment volume adjusted to 50 ml; a 5-ml subsample of each sample was reserved for digestion and diatom identification.

Samples were examined using a Palmer-Maloney Nanoplankton Counting

Chamber and a Wild M-20 phase contrast compound microscope. The counting procedure followed the recommendations of Woelkerling et al. (1976). This consisted of counting two optical fields (or Whipple grids) on each of twelve separately prepared slides. A unit or clump count system was used in which unicellular and colonial organisms were tallied as single units with equal numerical weight. Diatoms were identified to genus, where possible, during the initial count, or as Centrales, Melosira and Pennales. All plants were identified to species where possible. Densities were calculated by the formula:

$$\text{Number per ml} = \frac{C}{A.D.S.F.}$$

where C = the number of each organism tallied; A = area covered by the Whipple grid (mm); D = depth of the counting cell (mm); S = the number of transects of grids counted; F = the concentration factor of the sample being counted (ml/ ml). Results are expressed as the number of phytoplankters/ml of original pond water.

Those species observed only during scanning and not in the subsamples counted, or whose densities were too low to establish an accurate count, were recorded as present.

Algal physiological condition was determined from the ratio of chlorophyll-a absorbance to phaeophytin (the degradation product of chlorophyll-a) absorbance. In a pure solution of chlorophyll-a, the absorbance ratio is 1.7 to 1, while in pure phaeophytin the ratio is 1 to 1. Thus, in rapidly growing, healthy algal cultures, the ratio would be close to 1.7, while in a senescent culture the ratio would approach 1.

Photosynthetic rates were determined utilizing the $^{\Delta}O_2$ method

(Ryther 1956) under natural conditions at 0.2-m intervals and in light-dark bottle experiments conducted in replicate 300-ml glass-stoppered BOD bottles, (two light and one dark bottle) suspended horizontally at the surface and 0.5 m.

Methodologies for phytopigments (trichromatic method), algal physiological condition, and biomass from ash-free dry weight as well as from the phytopigment samples and total suspended solids were taken directly from the fourteenth edition of Standard Methods (American Public Health Association et al. 1975).

Species diversity was determined using the Shannon-Wiener Index, (Shannon and Weaver 1949), as recommended by Pielou (1975). The form of expression used was:

$$H' = pi \ln pi$$

Where pi = the proportion of the i^{th} species to the total number of individuals in the community

An increase in the number of taxa or evenness of distribution of individuals results in an increased index value.

Benthos was sampled during 1976 and 1978 with a Standard Ekman dredge (152 mm x 152 mm x 152 mm). Three random dredge samples were taken of the pond bottom material at each 30.5-cm (1-foot) depth from 30.5 cm to 182.9 cm. Sampleable depths varied during 1976 due to water level fluctuations. The three dredge samples from each depth were combined and washed together in a 280-micron-mesh Saran bag. Organisms retained in the bag were identified, counted and weighed to the nearest 0.1 mg on a Mettler balance. During 1976 the samples were taken biweekly from April through September. In 1978 the ponds were sampled only once, in mid-September.

In 1979 the pond bottom material was sampled with a core sampler consisting of a 1.7-m long rigid plastic tube having an inside diameter of 36 mm. The core samples were taken within permanently installed, round (0.92-m diameter) wire exclosures that were dug into the pond bottom and extended above the water surface, enclosing 0.66 m^2 of bottom area. There were three types of exclosures: 3.2-mm mesh (hardware cloth), 25.4-mm mesh (chicken wire), and "open", which consisted only of a metal ring (0.92-m diameter) to mark the sampling location. Each pond had six exclosures; one exclosure of each type was situated in water that was about 1 m deep and one of each type was in 1.5-m deep water. Bird netting covers were placed over each exclosure. The purpose of the exclosures was to exclude various-sized animals to permit comparisons of the types of invertebrates present and the condition of the bottom silt when prawns and fish were excluded (3.2-mm mesh), when only the fish were excluded (25.4-mm mesh), or when nothing was excluded.

Core samples were taken biweekly from July through mid-September in 1979. On each sampling date cores were collected from three randomly selected locations within each exclosure. All liquid was decanted and the core was pushed out from the bottom until the "fluff" (soft, fluffy sediment) dropped out of the top of the sampler into a calibrated beaker. The "fluff" volume was recorded to the nearest whole cc. An additional 1-3 cm of mud-sediment was then incorporated with the fluff sample to insure that all bottom organisms were saved. The three samples from each exclosure were combined and washed through a 250-micron (0.0098-inch, Tyler Equivalent 60 mesh) sieve. All organisms retained in the sieve were identified, counted and weighed to the nearest 0.1 mg.

Fecal coliform bacteria analyses of the pond waters were performed in November 1976 by ARDL, Inc. in Mt. Vernon, IL. During all subsequent phases of this study, fecal coliform analyses were performed by using the membrane filter (MF) technique described in the fourteenth edition of Standard Methods (American Public Health Association et al. 1975). During 1977 six analyses were made: twice in June and once each month from July through October. In 1978 each pond was sampled twice in July, once in August, and once in September. Analyses during 1979 were performed twice in June, once each month in July and August, and three times in September.

In 1979 we also made preliminary studies of the non-coliform pond bacteria, with special attention to their place in the food web and their contribution to the food of fishes. We attempted to measure the densities of both aerobic and anaerobic fauna in swine manure, pond sediments, the water column, and fish guts.

Aerobic bacteria were cultured by the pour-plate method. Media were prepared by placing all media ingredients plus pond water in 1000-ml screw-cap Erlenmeyer flasks. Autoclaving was done at 121 C for 20 minutes. Fifteen to 20 ml of cooled (50 C), melted agar medium was added to each 100 x 15-mm disposable petri dish after inoculation with 0.1 or 0.5 ml of the appropriate sample dilution. The plates were then carefully swirled to mix the medium and inoculum. Plates were allowed to solidify and then either inverted and incubated at 30 C or iced down for transport and later inverted and incubated. Aerobic dilutions were done with autoclaved pond water. Anaerobic culture methods and medium preparations were similar to those described by Hungate (1950), as modified by Bryant (1972), unless stated otherwise. Incubation was at 30 C.

Water samples were taken by inserting an inverted flask or jug into the pond to a depth of 30 cm and inverting it to fill. The collecting vessels were not sterile, but they were adequately rinsed with pond water before use. A 1-ml aliquot was taken from each filled vessel and serially diluted twice by factors of 10, until the appropriate dilution was reached. (Water dilutions were done aerobically.)

Sediment samples were taken with a brass Kemmerer bottle. In the early part of this study, the bottle was washed with dishwashing liquid and tap water before use, but this led to a high level of contamination.

When gut samples were taken, the GI tracts were uncoiled and laid out on a piece of sterile aluminum foil. Three approximately 5-cm long sections were cut from the tract of each fish. The foregut section contained the caudal half of the stomach plus the anterior part of the intestine. (Although carp do not possess a well-defined stomach, there is a very thick muscular wall at that location.) The section called mid-gut was actually part of the hind gut. It was taken at mid-length of the total digestive tract. The section called hind gut contained the terminal length of the digestive tract. The gut sections were placed in a tube containing 9 ml of sterile anaerobic dilution solution. A layer of Vaspar was immediately layered on top of the liquid. Gut-containing tubes were refrigerated until processing. During processing, the tubes containing the samples were taken into the anaerobic chamber where the content of each gut segment were squeezed out into the original 9 ml of dilution solution. Exact length of the gut section was determined. If the epithelial walls of individual gut segment were to be cultured, the empty segments were placed individually into a 15-ml Corning ground-glass tissue grinder containing 9 ml of sterile anaerobic dilution solution. The segments were ground until no large pieces of tissue remained. This material was then poured into a sterile 18 x 150 mm rubber-stoppered test tube. In the first attempt to grow bacteria attached to the gut wall, gut segments were flushed with 15 ml of sterile anaerobic dilution solution using a 16-gauge hypodermic needle and 5-ml disposable hypodermic syringe, after removing the lumen contents. The gut walls were flushed to rid the wall of all unattached bacteria so that the attached population could be determined.

The fishes and prawns were sampled on an irregular basis by means of electro-fishing or seining. Each phase of this study was terminated at the end of the fish-growing season in October or November, at which time each pond was completely drained and the fishes and prawns were censused. Individual total lengths and weights were measured for a representative sample of each species; and the remaining fish were counted and weighed in groups, or, if their sizes were very uniform, their weights were calculated from a sample of several counted groups.

Gut contents were analyzed for silver carp obtained on September 26 and October 5, 1978 and on September 26, 1979. The fish were obtained by means of electro-fishing and their entire guts were dissected immediately. Fresh weights of the gut contents were obtained from measured lengths of fore-, mid-, and hindguts of each fish. Depending on the type of analyses to be done, the gut contents were either frozen, preserved in 10% formalin, preserved in Lugol's solution, or analyzed fresh.

Adenosine triphosphate (ATP) is an energy-mediating compound in all living cells, both plant and animal (bacteria, Protozoa, algal cells, etc.), but it does not occur in significant amounts in nonliving cells. Comparative measurements of cellular ATP were used to determine the relative abundance of living organic materials in the sediments and water column. Our measurements of ATP followed procedures outlined in Weber (1973) and in the fourteenth edition of Standard Methods (American Public Health Association et al. 1975).

SEGMENT I - Studies Completed in 1976

EXPERIMENTAL DESIGN and PROCEDURES

In 1976 three ponds were supplied swine manure at the maximum rate used in 1975 (about 66 swine/ha), one of which was stocked with approximately the same numbers of fish used in 1975 (our "standard" density of 5000 silver carp, 1700 common carp, 426 bighead carp, and 128 grass carp each/ha), one at one-half that density, and one at one-tenth that density. However, post-stocking mortalities changed the original ratios from 10 : 5 : 1, to approximately 7.3 : 4.1 : 1, as shown in Table 1. In addition to the carps, bluegills (*Lepomis macrochirus*) and channel catfish (*Ictalurus punctatus*) were stocked at the same approximate low density as the grass carp. These native sport fishes were used so that their rate of survival and condition might afford an indication of water quality. All fish were stocked as fingerlings over the period April 8 to 14 in the initial weights shown in Table 1.

The first lots of swine were placed over the ponds on April 15 at an initial average weight of 37 kg and were marketed on July 9 at final average weights of 87 kg. Replacement pigs were installed on July 15 at average weights of 31 kg and marketed on October 5 at average weights of 89 kg. Pond waters remained completely static throughout except as follows: between June 30 and July 2 the levels of all ponds were lowered from their initial maximum depth of 1.9 m to a maximum depth of 1.4 m until the ponds were drained and censused on October 1 and 4. Water levels were lowered in order to improve circulation and oxygenation through all levels.

RESULTS and DISCUSSION

The hypothesis to be tested was that many water quality parameters in manured ponds may be influenced by fish density. We have evaluated these influences on water quality as indicated by both biological and physical-chemical data.

Biological Parameters

Biological parameters measured included the composition and/or abundance of both zoo- and phytoplankton, benthos and fecal coliform bacteria. While the abundance of one form may not in itself be significant, it is sometimes important to consider how the abundance of one may be affected by that of another. The data are minimal in some respects but collectively can indicate character and quality of the environment.

Zooplankton

Table 2 shows the composition and relative abundance of the principal taxa of zooplankters as averages of biweekly samples collected in the three ponds over the period April-October. The principal points to be made are these:

1. Rotifers were extremely abundant in all ponds.
2. Pond 10 with the fewest fish had more than twice the total abundance of either pond having larger fish populations, with near equal numbers of rotifers, cladocerans and copepods.
3. Lesser numbers of both cladocerans and copepods in ponds 12 and 13 indicated a selective cropping of these forms by the larger numbers of fishes in these ponds.
4. The greater abundance of zooplankters in pond 10 probably contributed to the lesser abundance of phytoplankton, as described in a later section.

A number of interrelationships are apparent in this data. A numerical dominance of rotifers, as in ponds 12 and 13, signifies heavy predation of zooplankton, in this case by fish which are selective for the larger cladocerans and copepods, leaving the rotifers to multiply (Lynch 1979). The light density of fish in pond 10 permitted an increased density of zooplankton (notably cladocerans and copepods), which in turn provided for a lesser abundance of phytoplankton. It can be argued that a reduction in BOD, suspended solids, and organic N might be achieved by zooplankton in the absence of fish; however, due to the cyclic nature of zooplankton populations, they would constitute a much less dependable and continuous control than static numbers of silver carp that are daily increasing their consumption capacity. Furthermore, a fish population would in most cases be more easily harvested, would permit a greater removal of nutrients, and would have more utility or value than the zooplankton population.

Phytoplankton

The data for 1976 include identifications and counts of phytoplankton from biweekly collections from ponds 10 and 13 over the period June 16 - October 7, and from pond 12 over the period June 16 - September 20. Sampling in pond 12 was terminated prematurely due to the crash on about September 18 of a large population of a green alga (*Pyramidomonas* sp.) with subsequent loss of dissolved oxygen and suffocation of the fish populations, of which more will be said later. The data have been summarized in Table 3 which shows (1) the average number of each of six phyla of phytoplankton found in nine collections from ponds 10 and 13 and in eight from pond 12, (2) the numbers of species identified in each pond, and (3) the frequency of occurrence in individual samples.

There is special significance in the fact that green algae (Chlorophyta) were dominant in all sampling periods in ponds 10 and 12 and in four of nine periods in pond 13, while bluegreens (Cyanophyta) were dominant in only one sampling period in pond 13. Other investigators (Dunseth 1977; Henderson 1978) have observed that grazing by silver and bighead carps produced populations dominated by small green algae, whereas enriched ponds without silver carp were dominated by the larger bluegreens. It is widely recognized that dominance by green algae, with a high species diversity, in most cases signifies a healthy, stable population in terms of water quality, whereas bluegreens are considered less desirable because of their tendency to form floating mats which prevent light penetration and frequently result in die-offs. It must be noted, however, that the die-off in pond 12 is believed to have been caused by a cyclic overabundance and crash of the green alga Pyramidomonas. Such occurrences are not uncommon in late summer but are rare in the presence of an efficient population of the phytoplanktivorous silver carp.

It seems reasonable to anticipate that low densities of phytoplankton would be associated with the highest densities of silver carp, and vice versa. This seems to have been true in studies by Schroeder (1975) in Israel and Dunseth (1977) in Alabama, wherein the grazing by silver carp produced reduced but stable populations of phytoplankton. In the present study our ponds 12 and 13, with their greater numbers of fishes, had both a greater diversity of species, and a greater density of cells than our pond 10 with its reduced numbers of fishes. However, in our studies, the low density of phytoplankton in pond 10 was associated with a dominant growth of the filamentous alga Hydrodictyon which monopolized available nutrients and starved the phytoplankton. The dominance by Hydrodictyon was made possible by low numbers of grass carp. Had pond 10 contained the same densities of grass carp as pond 12 or 13, the Hydrodictyon would have been consumed and the nutrients recycled to the phytoplankton. It is therefore possible that densities of phytoplankton in ponds 12 and 13 appeared to be high only in comparison to the unusually low numbers in pond 10. It is also possible that a population heavily cropped by silver carp and dominated by smaller green algae may have a higher cell count than a population of the larger bluegreens in a pond containing no fish. Such was observed by Henderson (1978), who believed that the high density of greens signified a healthy, fast-growing, continuously expanding population experiencing a rapid rate of turnover due to continuous grazing by the silver carp, all of which provided for a maximum uptake of nutrients and control of eutrophication. This interpretation was based on the fact that the ponds containing silver carp and the dominant population of green algae had consistently lower levels of BOD_5, fecal coliforms, ammonia nitrogen and orthophosphate than the ponds containing no fish and dominated by bluegreen algae.

At this point it seems useful to consider the potential of the silver carp for harvesting plankton, the uptake of nutrients, and the control of eutrophication. Lin (1974), using data provided by Mukhamedova and Sarsembayev (1967) and Omarov (1970), has calculated that silver and bighead carps at normal summer temperatures (15-30 C) will consume plankton at rates of from 20-50%, or an average of about 35%, of their body weight per day. In calculations for pond 10 we used the seasonal mean weight of the silver carp (610 g) times a consumption rate of 35% of body weight per day times the number of silver carp in the pond (44), to yield a consumption of 9.38 kg of phytoplankton per day. Based on a growing season of 180 days, total consumption would have been 1.7 metric tons of phytoplankton, equivalent to a consumption of 18.9 metric tons/ha. For ponds 12 and 13, with their greater densities of silver carp, similar calculations provided rates of consumption of 65.8 and 87.5 metric tons/ha for ponds 12 and 13 respectively. It is recognized that rates of production would be influenced by rates of consumption, and that figures used in our computations are arbitrary, but it seems clear that differences of these approximate magnitudes would have significant effects on the oxygen demand exerted by the unharvested phytoplankton as it passes through senescence and decay. As suggested by Lin (1974) and Schroeder (1979), the principal benefit of a fish population dominated by silver carp can be to eliminate excessive peaks and subsequent crashes in the population of phytoplankton, as well as zooplankton, protozoa and bacteria.

Fecal Coliforms

Regular counts of fecal coliform bacteria in the experimental ponds were not made in 1976, as in subsequent years, but on November 1, 1976, counts were made from single samples collected in two of the experimental ponds and from a "control" pond which had received no swine wastes. The samples were collected 27 days after the swine had been removed and addition of manure terminated. In view of the limited longevity of coliform bacteria in the pond environment and the fact that only single samples were involved, the range of differences shown in Table 4 are of limited significance. They may, however, serve to illustrate the limited potential for contamination of receiving streams if the contaminated waters are ponded for a suitable period prior to drainage.

Benthos

Benthos were sampled on eight occasions in each pond between April 22 and August 26. Samples were obtained at six depths from 30.5 cm to 182.9 cm. Dipteran species dominated in all ponds, averaging 52% of the total biomass in pond 10, 59% in pond 13, and 46% in pond 12. There was no substantial difference in benthic production at the various depths, indicating that water quality was sufficient throughout each of the ponds for the production of bottom-dwelling invertebrates. This is important in waste recycling systems so that organic matter does not accumulate in one particular area and produce anoxic conditions, and so that there will be a rapid and efficient flow of nutrients from the waste material to the ultimate consumer in the system (fish).

Peaks of benthic production occurred early in the season when the fishes were small, when pond enrichment was low, and prior to the usual midsummer emergence of flying insects (Table 5). As expected, pond 10 (which had the fewest fish) had the greatest densities of benthos. Production in pond 10 probably would have been greater if such vast amounts of nutrients had not been tied up by the rank growths of *Hydrodictyon*. Also, the table does not include the invertebrates resident on the vegetation in pond 10. It was unexpected that pond 12, with its greater density of fish, would have a larger average biomass of benthos than pond 13. This may have been related to differences in the size and shape of ponds 12 and 13 (Fig. 1) but we believe that the major reason for the unexpectedly high average benthic biomass in pond 12 was the fact that it was filled thirteen days earlier than pond 13 and twelve days earlier than pond 10. Thus, the benthic community in pond 12 had considerably more time to colonize and develop. It is impossible to estimate how much larger the biomass would have been in ponds 10 and 13 had all three ponds been filled at the same time, but there is other evidence of greater predation pressure on the benthos at the heavier fish-stocking rates. For example, the average size of benthic organisms was much larger in pond 10 (36.9 mg compared to 12.3 mg in pond 13 and 19.7 mg in pond 12) indicating less predation pressure, since predators normally consume the larger, easier-to-capture prey first. Furthermore, in pond 12 only 19 different taxa were found during the experimental period while pond 10 had 24 and pond 13 had 27 taxa (Table 6). Greater species diversity usually indicates a more stable and less stressed (from predation) population.

These data seem to indicate that, even at the heaviest stocking density, this type of waste recycling system could be more efficient if greater numbers and/or additional species of benthic predators were stocked.

Fish

The experimental design called for stocking three ponds at three different densities in the ratio of 10 : 5: 1, so that pond 12 would be stocked with our "standard" density of all carps, pond 13 at one-half that density and pond 10 at one-tenth that density. As shown in Table 7 post-stocking mortalities changed the ratios of carps to approximately 7.3 : 4.1 : 1. Small numbers of channel catfish and bluegills also were stocked to provide indicators of water quality since these species normally are less tolerant than the carps to low levels of oxygen.

Mean weights of individual fishes were highest in pond 10, with its reduced density of all species, but the greatest biomass of fish was produced in pond 13 which was stocked at one-half the standard density. This apparent discrepancy, wherein the half-density population made a greater gain than the full-density population, was attributed primarily to the shortened growing season in pond 12 due to the fish kill associated with a crash of an unusually dense population of a green alga, Pyramidomonas sp., on September 18. It also is possible that there is an optimum density at which a fish population can be most efficient, due to spatial requirements and/or levels of metabolites or other inhibiting factors, and that numbers in pond 13 were closer to optimum than those in pond 12.

Attention also should be drawn to the fact that water quality was adequate in all ponds to permit reproduction by bluegill and that large numbers survived until the October census in ponds 10 and 13 and until loss of the total fish population in pond 12 on September 18.

Physical-Chemical Parameters

We had anticipated that low values of suspended solids, BOD_5, organic nitrogen, and soluble orthophosphate would be associated with the highest numbers of fishes. The relationship was as expected for soluble orthophosphate and narrowly so for BOD_5 but inconsistent for both suspended solids and organic nitrogen (Table 8). While no quantitative separations were made, higher suspended solids in the presence of the largest numbers of fishes is believed to have been due in part to the suspension of silt by greater numbers of the bottom-feeding carp. However, as previously discussed, the levels of suspended solids and organic nitrogen may actually be highest where the rate of consumption by fish also is highest. In the presence of adequate nutrients, the high rate of consumption may produce a fast-growing, continuously expanding population of green algae in which attrition is due more to predation by fish than to normal senescence and decay. The result is a continuously high number of living cells and a minimum of dead and decaying cells. This would provide for a decrease in the level of oxygen demand actually occurring in the pond that would not be reflected by samples analyzed in the laboratory, because the laboratory procedure does not differentiate between dead and living organic material. Thus, numbers of cells and levels of organic nitrogen and suspended solids may remain high while the actual in-pond level of oxygen demand, due to decomposition of algal cells, may remain low.

The combination of events described above may seem incompatible with the fact that over the weekend on September 18-19, pond 12, which contained the largest number of fish, suffered a complete kill. The fish were discovered dead on the morning of September 19; they had died in the previous 24 hours. The probable cause was the crash of an excessive bloom of the green alga Pyramidomonas sp. Such occurrences are not uncommon in late summer but rarely occur in the presence of an adequate number of silver carp.

An important phenomenon in the biology of the swine-waste fish ponds in 1976 was the nightly cooling and sinking of highly oxygenated surface waters with a consequent reoxygenation of the lower strata and disruption of stratification. This is illustrated in Table 9 which summarizes results from measurements of dissolved oxygen at two depths taken at 2-hour intervals over a 24-hour cycle on six dates in the summer of 1976. The range of readings recorded at the 0.3-m depths demonstrates both the high demand for oxygen and the high rate of recharging by daytime photosynthesis. The wide range of differences at the pond bottom reflects the effects of nightly cooling and reoxygenation. It also may be noted (Table 9) that the averages of mean levels of dissolved oxygen in the three ponds were similar at the 0.3-m depth (ranging from 9.1 for pond 12 to 11.9 for pond 10) as well as at the pond bottom (2.0 for pond 12, 2.8 for pond 10). This signifies that the five- and tenfold greater numbers of fishes in ponds 12 and 13 than in pond 10 caused no significant increase in oxygen demand.

A more graphic illustration of the influence of nighttime cooling and sinking of the surface waters is presented in Figure 2. The figure is based on readings made from pond 13 over a 24-hour period between 0800 on August 8 and 0800 on August 9 and is quite typical of conditions observed from June through August in all three ponds. The curve shows the hour at which the maximum level of dissolved oxygen was measured at each 0.3-m stratum over the 24-hour period. For example, the highest reading (9.4 mg/l) at the 0.9-m depth occurred at 0200. The figures on the curve list the level of oxygen recorded at the time and depth indicated. The numbers above the curve show temperature differentials between the depth of maximum reading and the water surface. Numbers below the curve show temperature differentials between depths of maximum reading and the pond bottom. It may be seen that by 0200 and 0400 the layer of oxygenated water had sunk to or near the bottom and the water column was essentially homothermous, with differences of only 0.1 C between top and bottom.

The significance of these data is that the daily recharging of oxygen at all levels eliminated "dead" (anaerobic) or unproductive areas, which permits utilization of the total bottom by aerobic forms of bacteria, protozoa, macrobenthos, and other food producers and permits total access to this food by fish and other consumers. This permits a continuous, high rate of oxidation of wastes, uptake of nutrients, and improvement of water quality.

SEGMENT II - Studies Completed in 1977

EXPERIMENTAL DESIGN AND PROCEDURES

The 1977 segment was designed to measure the influence of differing densities of silver carp because it was believed that the consumption of phytoplankton by this species had a major influence on water quality. Four ponds were used. Fishes used were similar to those of 1976 except that neither bluegills nor largemouth bass were included. Pond 10 received no manure, was stocked with our standard densities of carps, and served as a control. The other three ponds received manure from similar densities of swine (about 62/ha of pond area) and were stocked with our standard densities of the companion species but with differing densities of silver carp: pond 11 received the standard density (about 5200), pond 13 received 50% and pond 12 received 150% of the standard density of silver carp.

All fish were stocked as fingerlings over the period April 14 to May 2 (except for additional silver carp stocked on June 29 to compensate for earlier mortalities due to transport and handling) at the initial weights shown in Table 10.

The first lots of pigs were installed on April 18 at an initial average weight of 44 kg and were marketed on June 30 at a final average weight of 85 kg. Replacement pigs were installed on July 1 at average weights of 57 kg and marketed on September 23 at average weights of 97 kg.

Water level management differed slightly in 1977. On July 7 the levels of all ponds were lowered as in previous years, but approximately three weeks later they were raised to a point about 0.27 m higher than the original level.

RESULTS and DISCUSSION

The hypothesis to be tested was that differing densities of the filter-feeding silver carp would produce differences in water quality.

Biological Parameters

Zooplankton

Table 11 presents the composition and relative abundance of the principal taxa of zooplankton as averages of biweekly samples collected in the four ponds over the period June 1 to September 21. Pertinent points to be noted are these:

1. Pond 10, which received no swine manure, had significantly smaller populations of zooplankton than those which received swine manure.
2. Among those ponds which received swine manure, numbers were lowest in pond 12 which contained the greatest number of silver carp, signifying a higher level of predation.
3. Populations in all ponds showed a numerical dominance by rotifers, which signifies a selective cropping of the larger cladocerans and copepods by filter-feeding fishes.

Fecal Coliforms

Data are presented (Table 12) from six samples from each pond over the period June 22 - October 17. The uniformly low counts in October reflect the fact that the swine were removed and manuring terminated on September 23. The counts in pond 10, which received no manure, were continuously lower (maximum: 767) than in the three manured ponds (maximum: 6100), but the range of counts in the manured ponds exhibited a uniform level of control, presumably by fish, and were not as high as have been recorded from other waters. For example, in ponds having similar rates of organic loading, Henderson (1978) counted fecal coliforms in excess of 20,000/100 ml in ponds without fish, compared to approximately 12,000/100 ml in ponds containing fish.

Hepher and Schroeder (1974) also compared numbers of bacteria in manured ponds with and without polycultures containing silver carp. Their counts in units of 1000/ml were reduced from a range of 17-27 in manured ponds without fish to a range of 1.6-6.7 in manured ponds with fish.

Fish

The experiment was designed to measure the influences of differing densities of silver carp on water quality. Pond 10 received no manure, was stocked with our standard densities of fishes, and served as a control. The three companion ponds received manure from similar densities of swine (about 62/ha of pond area) and were stocked with our standard densities of the four companion species, but with differing densities of silver carp, as shown in Table 10. The results may be summarized as follows:

1. The maximum gain of 4585 kg/ha in 1977 was made in pond 12, which contained the greatest density of silver carp. This gain also exceeded that made in any previous year. This increased assimilation of nutrients was reflected in improved water quality, as shown in Table 13.
2. Fish production in pond 10, which received no manure, was only about 22% of that in pond 11 which received the same density of fish but a full load of manure (Table 13).
3. Greater total fish production in pond 13 than in pond 11, in spite of the lesser numbers of silver carp, was attributed primarily to

the better health of the pigs and the greater supply of manure to pond 13, and partly to a partial fish kill in pond 11 on July 18 which eliminated 99 silver, 2 common carp and 3 channel catfish.

4. Silver carp production was higher in pond 13 than in pond 11 in spite of a 50% lighter density in pond 13. This was attributed primarily to the greater production of manure over pond 13 and the greater production of plankton algae.

5. Although densities of bighead carp were similar in all ponds, their production in pond 13 was 134% greater than in pond 12, 43% greater than in pond 11. Thus, production of bighead carp was inversely correlated with that of silver carp, indicating a substantial degree of competition (Table 10).

6. Conversely, the production of the bottom-feeding common carp was directly correlated with that of the silver carp (Table 10). For example, in the three ponds enriched by swine manure, gains in biomass by the common carp were greatest when gains by silver carp were greatest (pond 12), intermediate when gains by silver carp were intermediate (pond 13), and lowest where the total gain by silver carp was lowest (pond 11). This emphasizes the importance of the partially digested feces of the silver carp as food for the common carp, and substantiates the observation of Yashouv (1971) concerning the synergism between these two species. It also emphasizes the functions of both fishes in the uptake of nutrients and recycling of wastes and the importance of combining them.

Physical-Chemical Parameters

The anticipated results in this study were that some of the most important water quality parameters would have favorably low levels in the presence of the greatest numbers of silver carp and high values in the presence of lower numbers of silver carp. The comparison will be confined to ponds 11, 12 and 13, which had similar loadings of manure and similar densities of the companion fishes, but different densities of silver carp; pond 10 received a "standard" density of all fishes but no swine manure. Table 13 shows that mean values of most parameters were indeed lowest where numbers of silver carp were highest, but the differences were not significant. There is perhaps greater value in a comparison of the peak or maximum seasonal values recorded for the various parameters because the single greatest value of the silver carp may be that it dampens or moderates the cyclic peaks and prevents catastrophic extremes. For example, if one compares only the maximum readings recorded - the high values under range - the relationship is consistent whereby the pond having the greatest number of silver carp ranks consistently low, and the ponds having the fewest silver carp were in most cases high. The differences were in all cases substantial. As an example, the highest value for suspended solids recorded in pond 12 was 80 mg/l, compared to 140 in pond 11 and 125 in pond 13. Similar differences were reflected by the standard deviations for all parameters (Table 14), wherein the deviations were consistently lowest for the pond having the greatest number of silver carp. This reflects the influence of the silver carp in moderating the "highs" for all parameters listed.

The efficiency of waste treatment in this type of oxidation pond, utilizing specialized fishes, can be illustrated by a comparison of the input of BOD with periodic measurements of BOD_5. Figure 3 plots the daily input of swine manure in terms of kg/ha of BOD (Line A) and a line tracing the biweekly measurements of BOD_5 (Line B). The sharp declination in Line A on about July 1 represents the point at which the first lot of swine was marketed and replaced by a lot of smaller pigs. The data were obtained from pond 13 in 1977 and were typical for all ponds for that year. The point to be made is that the level of pond BOD tended to ascend gradually, but more slowly than Line A, until reaching a peak of 17.3 mg/l on or about July 28, declined to a low of 4.4 on August 25, and remained below 7.3 thereafter. It is suggested that the decline in pond BOD (Line B) in August reflects the increasing level of consumption by the continuously growing fish population (primarily silver carp) and its influence on the level of unoxidized or unconsumed wastes.

Measurements of dissolved oxygen, temperature and pH over a 24-hour cycle were measured only twice in 1977, but the influence of nightly cooling and reoxygenation of the lower strata were apparent in both. There were differences, however, between ponds which received manure and the one which did not. The differences appeared related to the rates of photosynthesis and to levels of oxygen demand. For example, on July 12-13, the 24-hour range of readings for dissolved oxygen at the 0.3-m depth in pond 10 (no manure) ranged from a low of 6.1 to a high of only 10.2 mg/l, whereas the adjacent pond which received manure ranged from a low of 3.7 to a high of 19.4 mg/l. Thus, the manured pond had both a higher rate of photosynthesis and of dissolved oxygen during daylight hours due to its greater density of phytoplankton, but it had a much higher rate of oxygen demand

and much lower levels of dissolved oxygen during the night.

SEGMENT III - Studies Completed in 1978

EXPERIMENTAL DESIGN and PROCEDURES

Four ponds were again used in 1978. This segment was designed to measure the improvements in water quality to be provided by two-stage flow-through units containing macrophytes in the second-stage ponds. The experimental design involved two such flow-through units of two ponds each as shown in Figure 1. The first pond in each series received fresh manure from the swine maintained on the pond dikes at densities of about 66/ha of pond area and was stocked with silver, common, bighead and grass carps at near our "standard" density, providing a ratio of 65 : 12 : 4 : 1 (Table 15). Total density was about 5500/ha. The second pond in each series received only effluent (about 24 liter/min) from the first and was stocked with a lighter density of fish and with macrophytic plants. The lighter stockings in each second, or "polishing," pond included sufficient grass carp (10-15/ha) to partially crop, but not eliminate, the macrophytes so as to stimulate their growth and accelerate the uptake of nutrients. Each also contained light stockings of silver carp (about 650/ha) and bighead carp (about 79/ha) but no common carp. The common carp was deleted in order to minimize disturbance of the sediments and to reduce suspended solids. The niche of the common carp in the polishing ponds was at least partially filled by the freshwater prawn (Macrobrachium rosenbergii), which consumes much the same foods but with less disturbance of the bottom. The prawns, which have great commercial value, also were stocked in the first ponds in series to provide an additional consumer for the uptake of nutrients and to measure their production. The prawns were stocked at average densities of $7/m^2$ of pond bottom in each of the two ponds receiving direct applications of manure and $4/m^2$ in each of the ponds receiving only effluent from the first pond in series.

Our experimental design called for the establishment of a growth of submersed macrophytes in each of the two downstream ponds. This was to be done through the transfer of plants (primarily species of Najas, Potamogeton and Myriophyllum) in the spring or early summer, as accomplished in an earlier study (Buck et al. 1975). Unfortunately, in spite of multiple efforts involving thousands of plants, they did not become established. As a substitute the two ponds were stocked with a variety of duckweeds, primarily Spirodela polyrhiza and including Wolffia columbiana and a species of Lemna. The duckweeds thrived, but the extent to which they covered the ponds varied greatly due to windrowing. The duckweeds also were utilized by grass carp. The colonies were maintained in substantial amounts through the stocking of additional plants. The extent to which they covered the pond surfaces varied between 10 and 50% and probably averaged near 20%.

The intakes for passage of water between ponds were located so as to avoid "short circuiting" the manure directly from the first to the second pond in series. All water movement was by gravity flow. Water depth in the two upstream ponds was maintained approximately 0.2-m deeper than the second ponds in order to facilitate the movement of water. Maximum depths were approximately 1.75 m in ponds 10 and 12 and 1.94 m in ponds 11 and 13. The rates of inflow were controlled by valves to 24 l/min. Because of differences in pond sizes, the rates at which the water was exchanged in each varied from approximately 22.8 days in pond 10 to 39 days in pond 11, and from 33.4 days in pond 12 to 51.2 days in pond 13. Outflow rates were controlled by drain valves, permitting the removal of water from the pond bottoms.

The ponds had remained dry overwinter and were about one-third filled when the first lots of fish were stocked on April 19. Filling was gradual, and full levels were not achieved until May 26-27 in an effort to facilitate the establishment of macrophytes in ponds 10 and 12. The fill valves were then closed, and all ponds remained static until June 30 at which time the valves were adjusted to maintain a continuous flow-through until the ponds were drained in October.

RESULTS and DISCUSSION

The purpose of this segment was to measure the improvements in water quality to be provided by two-stage flow-through units containing macrophytes in the second-stage ponds.

Biological Parameters

Zooplankton

Table 16 presents the composition and relative abundance of the principal taxa of zooplankton as averages of biweekly samples collected over the period June 21 to September 27. Pertinent points to be made are these:

1. All ponds again showed a numerical dominance by rotifers, suggesting a selective cropping of the larger cladocerans and copepods by the filter-feeding fishes.
2. Lower totals for zooplankters in ponds 10 and 11 probably reflect the

lower input of swine manure into pond 11 than in pond 13 (57 vs. 61 swine/ha).

3. The higher total for all zooplankters in downstream pond 10 and the higher counts of copepods in both downstream ponds probably reflect lower levels of predation due to lesser numbers of fishes.

Fecal Coliforms

Fecal coliform densities in the two stage-1 ponds averaged higher than in the static ponds during 1977 (Table 13), indicating that the small amount of dilution at this stage in the flow-through systems did not reduce the coliform bacteria. Densities in the stage-2 ponds, however, averaged from 32 to 96% lower than in their respective upstream ponds during 1978 (Table 20) and from 24 to 95% lower than in the static ponds 11 and 12 during 1977 (Table 13). The reduced fecal coliform densities in the stage-2 ponds can probably be attributed to: (1) dilution in the flow-through systems, (2) increased detention time, and (3) removal by the filter-feeding fishes.

Adenosine Triphosphate

The amount of cellular adenosine triphosphate (ATP) in sediments of the study ponds (Table 17) provided no indication as to the source of the ATP, whether bacterial, algal, or from other living cells, but in view of the enrichment provided our ponds, we suspect that it was derived primarily from bacterial and algal cells. The uniquely high level of ATP in the sediments of pond 10 in 1978 reflected both the absence of common carp in that pond and the potential availability of various foods. Prawns stocked in pond 10 obviously did not exploit the full food potential of the sediments. It should be noted that all three companion ponds

(11, 12 and 13) contained both common carp and prawns, as well as extraneous crayfish. Relatively lower levels of ATP in those ponds indicate a more complete utilization of available food materials. We presume that non-living organic materials were more completely utilized as well, thereby reducing the BOD (Table 20). These conditions illustrate the advantages of stocking the common carp as a bottom feeder and synergistic partner to the filter-feeding silver and bighead carps.

Benthos

Benthos were sampled only on September 12 in 1978. Chaoborids were the most abundant form in ponds 10, 12 and 13, oligochaetes in pond 11, but oligochaetes were dominant by weight in all ponds (Table 18). The biomass and numbers of benthic organisms always decreased between the 30.5- and 91.4-cm depths and then increased at the greater depths (Table 19). The largest populations (both by biomass and numbers) usually were found at the 152.4- or 182.9-cm depths and the lightest densities at 91.4-cm. Dissolved oxygen, temperature, and light probably made this shallower depth the most heavily grazed by the fish and prawns and may have marked a transition zone where the invertebrate species composition changed. For example, chaoborids and oligochaetes usually were much more abundant at depths greater than 91.4 cm while species of Chrysops, Hexagenia, Leptoceridae, Simuliidae, and Notonectidae were never found below this depth.

Total benthic biomass and numbers (Table 18) were greater in the stage-2 ponds (10 and 12) than in the stage-1 ponds (11 and 13). This illustrates the foraging capabilities of common carp on benthic organisms. For example the benthic biomass in pond 10, which was not stocked with common carp, was 4.5 times greater than in pond 11 which contained common carp. The difference in the other flow-through unit was not as large due to the accidental presence of common carp and an unusually large number of crayfish in pond 12, both of which are benthic predators.

Benthic species diversity was greater in the stage-2 ponds (5-10 taxa) than in either of their companion ponds (4-5 taxa), but this is inconclusive due to foraging by the common carp and crayfish in pond 12. Samples from stage-2 ponds (mostly pond 10) contained seven taxa not found in stage-1 ponds, while all taxa found in stage-1 ponds were common in stage-2 ponds.

The lower standing crops of benthos in 1978 than in 1976 can be attributed to: (1) the lesser number of samples collected in 1978, (2) the fact that the 1978 samples were collected late in the growing season after predation by bottom feeders had decimated their numbers, and (3) the added predation pressure by prawns which were not present in 1976.

<u>Fish and Prawns</u>

Production data for both fish and prawns are shown in Table 21. The maximum gain by fish in 1978 (2716 kg/ha in pond 13) was substantially smaller than the maximum gain of 4585 kg/ha made in 1977 in a pond receiving a similar amount of manure (Table 10). This had several possible causes: (1) the use of fewer and smaller fish in 1978 than in previous years; (2) loss of fertility due to the flow-through of water as evidenced by lesser turbidities and lighter densities of phytoplankton; (3) shorter growing period, particularly for the common carp (104 days); and (4) competition from prawns and crayfish.

There is special interest in the notably larger gains made by the silver carp in pond 12 than in pond 10 when both were stocked and operated as replicates of the same treatment. The probable causes were the moderately large population of common carp which gained accidental entrance to pond 12 and the much larger numbers of crayfish in pond 12 than in the companion ponds. It seems probable that the filter-feeding silver carp gained bonus food in the form of organic particles, with colonized bacteria, stirred into the water column by the burrowing activities of the carp and crayfish in the fashion described for carp by Yashouv (1971) and as previously observed by the writers (Buck et al. 1978).

The fastest rate of growth by prawns occurred in pond 10 which had the lightest initial stock ($4/m^2$) and the lowest rate of competition from both fish and crayfish. The slowest prawn growth occurred in pond 13 which had the largest initial stock, the slowest water exchange, and the poorest water quality in terms of dissolved oxygen, suspended solids, and BOD5 (Table 20). The largest gain in biomass by prawns (413.8 kg/ha) occurred in upstream pond 11 which received direct applications of manure. The lowest gain in biomass occurred in downstream pond 12 which received only effluent from pond 13 and which suffered competition from larger numbers of crayfish and an extraneous population of carp.

Physical-Chemical Parameters

The points to be evaluated are the differences in water quality between (1) the first- and second-stage ponds in the flow-through series of 1978, and (2) between the first-stage ponds of 1978 and static ponds studied in previous years. Data in Table 20 show that substantial improvements were made by subjecting the wastes to the flow-through systems. For example, mean values in the second-stage ponds averaged

44% lower for BOD_5, 37% lower for suspended solids, 36% lower for organic nitrogen, 58% lower for soluble orthophosphate, and 64% lower for fecal coliforms than in first-stage ponds. The surprisingly high mean value for suspended solids in second-stage pond 12 owes to excessive numbers of crayfish and to a large population of extraneous carp. Common carp had not been stocked in this pond and probably gained entrance as larvae attached to the *Najas* and *Potamogeton* transplanted to this pond in May and June. The excessive crayfish population may have been augmented in the same way. High suspended solids were believed due to the combined burrowing activities of the crayfish and carp in the absence of sufficient silver carp to filter out the solids. This view is at least partially confirmed by the fact that this pond had the highest rates of settleable solids in three out of nine sampling periods.

In comparing the first-stage ponds (11 and 13), it may be observed that mean values for all parameters listed in Table 20 were higher in pond 13 than in pond 11. This was believed primarily due to the fact that pond 13 received a higher total input of BOD (1102 vs. 928 kg/ha). Pond 13 had a longer detention time (51.1 vs. 39.0 days) but apparently not sufficiently longer to counteract the greater input of BOD.

It is instructive to compare water quality values in the first-stage ponds of 1978 with those of static ponds of former years. The comparison emphasizes the value of greater detention time. It may be observed that water quality values were similar in first-stage flow-through pond 13 of 1978 (Table 20) and in the purely static ponds of 1977 (Table 13) which received greater loadings of BOD than the 1978 ponds. For example, the mean level of BOD_5 in first-stage pond 13 in 1978 was higher than in pond

11 of 1977, in spite of the 11% greater loading of BOD (1220 vs. 1102 kg/ha) in pond 11, and higher than in pond 13 of 1977 in spite of both a 32% greater loading of BOD (1452 vs. 1102 kg/ha) and a 50% smaller density of silver carp in pond 13 in 1977.

While the quality of final effluent produced by the two-stage flow-through system was substantially improved over that of the first-stage ponds or that of the static ponds in earlier studies, it may fairly be asked whether the improvement was sufficient to warrant the additional space and facilities involved, with attendant greater costs and labor. The data suggest that in many instances a properly stocked and managed static pond can achieve adequate results. It should also be considered that net gains by fishes were dramatically larger in the static ponds than in the flow-through systems. For example, gains in single static ponds in 1976 and 1977 were on the order of 8 to 69% larger than the combined production of both first- and second-stage ponds in 1978. It might represent a desirable trade-off to accept a less efficient level of treatment in return for a larger production of useful fish at a lesser cost and in a smaller area, providing the level of treatment achieved can fall within acceptable standards.

The influence of nighttime cooling and reoxygenation of the lower strata was observed over a single 24-hour period (July 31 - August 1) in 1978. The tendency was less strong in downstream pond 10 than in pond 11, but the sinking and mixing process was a strong force in both ponds 12 and 13. In fact, the rate of mixing proceeded at a faster rate in downstream pond 12 than in pond 13. This may have been due to the lesser volume of water in pond 12 and the faster rate of cooling.

The daily pattern of daytime stratification and nighttime cooling did not seem to be disturbed by the rate of flow through these ponds.

SEGMENT IV - Studies Completed in 1979

EXPERIMENTAL DESIGN and PROCEDURES

This final segment was projected in the same four ponds used in the earlier studies. Its purpose was to measure the contribution of a third method of treatment, namely mechanical aeration, to determine (1) whether the addition of aeration produces results superior to those previously tested, and (2) if superior, whether the cost of aeration can be justified. Two ponds were established as a flow-through system as in the previous segment, and two ponds were operated as static units with mechanical aeration. As in the previous segment, the first pond in the flow-through unit (pond 11) received the standard densities of both fish and swine and a small inflow of water from Forbes reservoir (Table 22). The second pond in series (pond 10) was stocked with duckweeds (primarily *Spirodela* and *Lemna*) and a reduced stock of fishes (no common carp). The stocking and management of both aerated ponds (ponds 12 and 13) was similar to that of the upstream pond in the flow-through unit except for aeration and the absence of flow-through water. Aeration was supplied by a 1/3 hp agitator floating over the deepest part of each pond.

Prawns were again stocked in all ponds in 1979, but at greater densities (Table 22). The prawns were flown from Hawaii in two shipments. From the first, which arrived on June 1, the two aerated ponds were stocked at densities of $36/m^2$. From the second, which arrived on June 21, the flow-through unit was stocked at densities of about $15/m^2$. The original plan had been to stock similar numbers in all ponds; but the second shipment was delayed in San Francisco, and mortalities due to excessive time en route left fewer to be stocked.

RESULTS and DISCUSSION

The purpose of this segment was to evaluate the economics of mechanical aeration and to determine if the resultant water quality was superior to that obtained with previously tested methods.

Biological Parameters

Zooplankton

Table 23 presents the composition and relative abundance of the principal taxa of zooplankters as averages of biweekly samples collected over the period June 6 to September 12. Again, rotifers were dominant in all ponds. On the whole, however, there seemed to be little relation between the numbers of zooplankters and the treatment of the ponds or differences in water quality. Higher total counts in downstream pond 10 probably reflected the lower level of predation in pond 10 than in pond 11; other differences may or may not be related to water quality and probably reflect normal ranges of variation to be found in individual ponds.

Phytoplankton

The general role of phytoplankton in the food chain of natural waters is well understood; however, in intensive polyculture ponds receiving heavy organic waste loading, the exact role of phytoplankton as a nutrient source for the fish is not clear. This question is especially important when the fish are those types that exploit the lower trophic levels, as in this study. This phase of the study was designed to determine the important species of algae in these ponds, their productivity, and the importance of algal biomass to the total nutritional value of the plankton.

Chlorophyta and Chrysophyta accounted for the bulk of the algal communities in all ponds (Table 24). Cyanophyta were of minor importance except in pond 10 during September; this pond was the least enriched and contained the fewest fish. Euglenophyta and Cryptophyta were relatively scarce in pond 10 as compared to ponds 11, 12 and 13.

Initial (June) algal concentrations were similar in ponds 10, 11 and 13 but much higher in pond 12 (Fig. 4). The percent of composition of greens in these early samples was 94 in pond 12 and from 47-61 in the companion ponds. From July through September, pond 12 maintained the highest populations of algae, exceeded only by pond 11 during a July 24 bloom of the green flagellate Chlorogonium elongatum and by pond 13 during a September 4 bloom of Euglena sanguinea. Mean concentrations of algae in the ponds ranked pond 12 as the most productive (39,499/ml); ponds 13 and 11 had means of 26,949/ml and 26,570/ml respectively, while pond 10 had a mean of 12,128/ml.

The species composition was rather uniform despite the range of organic loadings among these ponds (Table 25). Pond 10 had a total of 101 taxa, of which 15 were at one time or another a major component (more than 5 percent of the total) of the phytoplankton. Of these 15, eight were never a major component in the ponds receiving swine waste. These eight, Dictyosphaerium pulchellum, Monoraphidium tortile, M. setiforme, Coccochloris elebans, Lyngbya contorta, Dinobryon sociale, Rhizosolenia longiseta, and Synedra tenera, were evidently not suited to the higher nutrient loadings in the other ponds. Pond 13, which received the heaviest organic loading, had four species which were dominant only in it: Scenedesmus opoliensis, Euglena acus, E. sanguinea and Cyclotella meneghiniana. Overall, seven species were dominants in at least three of the ponds: Chlorogonium elongatum, Monoraphidium contortum, Scenedesmus quadricauda, Chlorochromonas minuta, Cryptomonas erosa, Cyclotella pseudostelligera and Stephanodiscus astrea v. minutula. These species seemed capable of competing successfully at the range of organic loadings experienced in the various ponds.

Algal biomass (based upon chlorophyll concentrations) generally divided the ponds into two groups. Ponds 10 and 11 had fairly low but constant algal biomass concentrations throughout, due apparently to dilution in the flow-through system; static, aerated ponds 12 and 13 had much higher biomass concentrations and exhibited greater fluctuations (Table 26).

Algal biomass indicated that pond 13 was the most productive of algae with 14.7 mg/m^3, followed by pond 12 (12.2 mg/m^3), pond 11 (4.6 mg/m^3) and pond 10 (1.9 mg/m^3). The highest biomass recorded, 54.1 mg/m^3 in pond 13 on September 4, corresponded to a Euglena sanguinea bloom of 72,088/ml, the second highest algal count recorded. The highest algal count, 90,680/ml in pond 11 on July 24, corresponded to a biomass of 20.1 mg/m^3. It should be noted that pond 13 received the highest loading of swine manure and produced the largest weight of fish. The relationship between algal biomass (based on chlorophyll) and algal counts in these ponds was not completely linear. For example, pond 13 had the greatest algal biomass (and greatest fish production), but it ranked second to pond 12 in average number of algal cells.

The swine-waste loading in each pond was reflected in the suspended solids concentrations (Table 26).[1] Suspended solids in pond 10, which received no wastes directly, averaged 53% lower than in pond 13 which received the highest waste loading. Organic suspended solids represented from 9 to 12 percent of the total suspended solids. The algal portion of the suspended organics averaged 0.01 and 0.02% in the flow-through ponds (10 and 11 respectively) and 0.03% in the two static-aerated ponds. In spite of the small fraction it represented, the phytoplankton was able to meet most of the oxygen demands of these ponds, frequently boosting oxygen concentrations above 20 mg/liter.

As with algal biomass, suspended organic matter grouped the two static ponds together and the two flow-through ponds (10 and 11) together. The relationship between suspended organic matter and algal biomass is illustrated by:

$$A = \frac{O_s - 10.4}{2.35} \times 10^{-3}$$

where A = algal biomass (mg/m^3)

O_s = suspended organic matter (mg/l)

$10^{-3} = 1/m^3$

and has a correlation coefficient of 0.86.

The autotrophic index (AI) is a measure of water quality based upon the ratio of suspended organic matter to chlorophyll-a. As explained by Weber (1973), plankton communities normally are dominated

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1 In 1979 suspended solids were measured in two separate and independent segments of the investigation (Table 26 and 29). The much higher mean values in Table 26 were caused by two unusually high levels recorded during short periods in which no samples contributed to the data in Table 29. Independent measurements were similar from all other sampling periods.

by algae, but the addition of organic wastes usually results in a greater biomass of nonchlorophyllous, heterotrophic organisms (bacteria, zooplankton, etc.) than algae, which is reflected in a higher AI. A higher AI might also be due to a larger amount of suspended, nonliving organic material. In 1979, pond 10, which had the lowest algal concentrations, had the highest AI value, indicating the poorest water quality (Fig. 5). Ponds 11, 12 and 13 were all quite similar, showing steadily declining AI values (steadily improving water quality) throughout the summer except for an increase (as did pond 10) at the end of the summer, due, we believe, to an increase in total suspended organic matter coupled with a decrease in phytoplankton abundance. However, the overall seasonal decline in AI values was attributed to a steady decrease in suspended organic matter. This decrease is attributed to an increased consumption of organic matter (bacteria, zooplankton, bits of swine manure, etc.) by an increasing biomass of silver carp. While pond 10 had the highest AI values (mean of 682), ponds 12 and 13, which received the heaviest loads of organic matter and had much larger fish populations, had the lowest values (248 and 246 respectively). These values suggest surprisingly good water quality in ponds 12 and 13, considering their level of enrichment. The significance of these data is that the AI was highest (and water quality poorest) in the pond containing the fewest fish (pond 10) and lowest in the ponds which contained the most fish but which also received the greatest load of organic waste.

Species diversity in these ponds was moderately low, averaging around 2 (Fig. 6). While the means were similar, their dynamics suggest that ponds 10 and 11 were similar as were ponds 12 and 13. Thus, ponds

10 and 11 started the study with moderate values, dropped to lows in July, were moderate in August and declined through September. Ponds 12 and 13 started low, were high in July, low in August, increased steadily through mid-September and then declined in late September. This variation of trends seems to reflect the effects of increased fertilization and/or aeration in ponds 12 and 13.

The ratio of algal chlorophyll-a to phaeophytin was used to assess the physiological condition or health of the phytoplankton. This ratio was chosen over an ATP: chlorophyll-a ratio because the chlorophyll-a: phaeophytin ratio is generally recognized as an indicator of the physiological condition of algal samples and is based solely on algal components. On the other hand, ATP analysis includes bacterial, fungal, protozoan and microcrustacean inputs as well as algal. Since the algal community in this study represented only 0.01 to 0.03% of the suspended organic matter, it seemed prudent to confine the analysis to algal products. The chlorophyll-a: phaeophytin ratios were generally high, with means ranging from 1.48 to 1.53, indicating that the algae were usually in an actively growing state, although typical dynamic surges did occur.

Photosynthesis experiments, both under natural conditions and in light bottle-dark bottle experiments, showed pond 12 to be the most productive overall (0.66 g $O_2/m^2 \cdot hr$) as well as at the surface (1.70 mg $O_2/l \cdot hr$) (Table 27). Pond 10 was the least productive, 0.25 g $O_2/m^2 \cdot hr$ overall and 0.35 mg/l·hr at the surface.

Pond 13 ranked third in overall net productivity (0.46 g $O_2/m^2 \cdot hr$) and second in surface photosynthetic rate (1.44 mg/l·hr). The low overall production rate in pond 13 probably reflected the increased oxygen demand caused by the high organic loading. Overall production of oxygen per square meter of pond surface was greatest in pond 12 which had a mean rate of 0.66 g $O_2/m^2 \cdot hr$. Ponds 11 and 13 were similar with mean rates of 0.53 and 0.46 g $O_2/m^2 \cdot hr$, while pond 10 was the lowest with a mean rate of 0.25 g $O_2/m^2 \cdot hr$ (Table 27). Pond 11 had the most consistent photosynthetic rates, while pond 10 experienced wide fluctuations throughout the study. Ponds 12 and 13 both exhibited a steady decline in productivity throughout the season and both showed a deep depression on August 21. The light-dark bottle experiments confirmed pond 12 as the most productive with a surface rate of 1.70 mg $O_2/l \cdot hr$ and pond 10 as the lowest, 0.35 mg $O_2/l \cdot hr$ (Table 27).

A primary objective in this segment of the investigation was to describe the autotrophic communities in ponds stocked with Chinese carps and receiving various rates of enrichment, so that we might identify the most desirable combination of conditions. Table 28 presents a ranking of the various ponds by water quality indicator or rate of productivity. This ranking assigned 1 to the pond having the highest value and 4 to the lowest. While high productivity and high water quality may not always be compatible, it was our desire to identify the ponds having the most desirable combination of parameters.

Pond 12 had the lowest point total (10.5), indicative of the most desirable combination of parameters. Pond 13 ranked second (15) and may have been slightly overloaded with organic matter. Ponds 11 and 12 received similar loads of manure; the more desirable conditions in pond 12 may have been influenced by aeration. Pond 10 received only effluent from pond 11 and had the poorest overall ranking. It should be noted, however, that pond 10 had the most taxa and tied for the highest index of diversity, both of which are indicative of good water quality. It should further be noted that the ponds (12 and 13) having the most desirable combination of parameters in Table 28 also had the highest rates of fish production (Table 34).

Fecal Coliforms

Fecal coliform densities in the three ponds (11, 12 and 13) which received direct applications of manure in 1979 were higher than had been recorded in these same ponds in 1977 and 1978 (Tables 13, 20 and 29). It therefore appears that the mechanical aeration in ponds 12 and 13 and the dilution in pond 11 in 1979 caused no measurable reduction of the bacteria and that the higher counts were due to either the slightly higher levels of enrichment received in that year, to a lesser reduction of bacteria by a smaller biomass of carps in these ponds in 1979, or to both. However, densities in the second-stage ponds of 1979 (pond 10) were greatly reduced, as in the second-stage ponds of 1978. Again, this is attributed to additional dilution, to longer detention, and to removal by the filter-feeding fishes.

Adenosine Triphosphate

The amount of ATP in the water column was determined during 1979 when ponds 10 and 11 comprised a flow-through unit and ponds 12 and 13 were mechanically aerated. ATP concentrations in the waters of ponds 10 and 11 were always lower than those in ponds 12 and 13, a trend apparently due to dilution in the flow-through system (Table 17). Except for the last sampling date, pond 13 had the highest levels of water-borne ATP. Such high levels were anticipated because pond 13 received a heavier load of wastes (Table 20) and produced greater densities of phytoplankton (Table 25). These factors caused pond 13 to have the greatest production of benthos, crayfish, and fish as previously described. Weber (1973) reported ATP concentrations of 300 ng/liter above a sewage treatment plant outfall on the Ohio River and 1700 ng/liter below the outfall. The low levels of ATP in ponds 12 and 13 in September, when compared with earlier levels or with those reported by Weber, indicate an increased intake of suspended biota by the filter feeders as they increased their sizes and rates of consumption.

Non-Coliform Bacteria

In 1979 we enlarged our studies to consider the place of non-coliform aquatic bacteria in the food web and their consumption by fishes. Algae and bacteria perform critical and complementary functions in aquatic food chains. Algae (phytoplankton) are the primary producers and constitute the basic food materials for aquatic animals. In balanced systems the algae are consumed in approximately the same quantities they are produced and are cycled through the food chain. In periods of imbalance they overpopulate, die, and accumulate as excess organic material which may create excessive oxygen demand. Decomposition of the algae, as well as animal wastes, by bacteria prevents the accumulation of excessive dead organic matter, controls eutrophication, and permits the biological transformation by which food supplies are made continuously available. Bacteria are of particular importance in the purification of aerobic systems receiving organic enrichment from domestic or animal wastes.

Bacteria also are important as food for other aquatic animals. Their bodies contain proteins, carbohydrates, lipids and nutrients having an assimilability of up to 83% (Sorokin 1967, cited by Kuznetsov 1977). Their value to detritivores is well recognized. Rodina (1963, 1966, 1971, cited by Kuznetsov 1977) has shown that detritus consists of mineral and organic particles containing bacteria in densities as high as 45 billion cells in each gram (wet weight) of detritus, and that the food value of detritus stems largely from this source. Bacteria constitute at least 1-5% of the weight of detritus, but Kuznetsov (1977) believes this may be greatly understated. Bacteria have been shown to be important in the food of such varied forms as _Daphnia_, chironomids[1], mussels, crabs, gephyrean worms, oysters, snails and prawns (Zobell and Feltham 1938, Newell 1965, Wood 1953, Moriarty 1977). Such marine forms as milk fish (_Chanos chanos_) and mullet (_Mugil_ sp.) are known to assimilate bacteria, and there is increasing and relatively recent evidence that bacteria may make a direct and major contribution to the food of certain freshwater fishes, primarily filter feeders and detritivores. Kuznetsov (1977) has shown that the carp consumes large quantities of bacteria along with detritus but believes that the most notable consumption of bacteria may be by the large filter-feeding cyprinids, the silver carp and the bighead carp. This same writer conducted a series of studies which permitted the following observations:

1. On an average, nearly a quarter of all cells of the bacterioplankton

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1 Chironomidae = Tendipedidae.

are in aggregates larger than 60 microns, a size vulnerable to the bighead carp, with up to 600 cells in a single aggregate.

2. Up to 80% of the planktonic bacteria in ponds having intensive polycultures of phytophagous fishes is in aggregates measuring more than 6 microns, and approximately 50% of all bacteria in such aggregations may be trapped by the filtering apparatus of the silver carp.
3. Solitary bacteria and small aggregates may be concentrated on the slime secreted by the labyrinthiform organ of the silver carp and subsequently ingested with the slime.
4. An adequate population of silver carp can stabilize the bacterioplankton at densities of 20-25 million cells/ml of water, compared to densities of 40 million or greater in similar waters not containing silver carp.

Schroeder (1978) has provided evidence that in ponds enriched with cow and chicken manure up to 50% of the net gain by a polyculture containing silver carp, Tilapia and common carp can be attributed to the consumption of bacteria. He believes that the microbial community plays an important, and perhaps the most important, role in fish growth in such ponds. Schroeder also believes, however, that the principal food for the silver carp in his ponds was the bacteria colonized on particles which originated from the sediments and were placed in suspension and made available for filtering by the burrowing of such bottom-feeding fishes as the common carp. Furthermore, silver carp commonly contain "mud" in their guts (Yashouv 1971, and personal observation by authors) that represents the filtration of silt placed in suspension by bottom feeders. This gives special significance to the observation by Wood

(1953) wherein more than 99% of the bacteria and small flagellates associated with marine sediments are adsorbed on the smallest particles. Odum (1968) has described such small particles as flourishing micro-ecosystems containing bacteria, protozoa and microalgae and has observed that the smaller the particle, the greater its relative food value. It is doubly significant that the smallest (and richest) particles are those that can most readily be placed in suspension and made available to the filter-feeding fishes. This gives rise to the synergism between the silver carp and the bottom-feeding common carp whereby each supplies food to the other, as described in an earlier section. The sum total of these observations suggests an opportunity to exploit the bacteria for the uptake of nutrients, the control of eutrophication, and the production of protein.

Research has shown that the common carp consumes large quantities of bacteria along with detritus (Kuznetsov 1977), but our primary interest is in the silver carp since it is the most abundant fish in our polyculture. The three principal components in the food of the filter-feeding silver carp are phytoplankton, suspended detritus, and zooplankton, usually in that order. The detritus consists primarily of bacteria-laden particles (both organic and inorganic) which are placed in suspension by the burrowing of the common carp in the sediments. Silver carp guts often contain up to 60% detritus by volume, and more when phytoplankton abundance is low or dominated by certain bluegreen or other less desirable forms (Kajak et al. 1977). The potential importance of the bacteria is emphasized by the fact that many forms of both zoo- and phytoplankton ingested by silver carp are not digested.

For example, studies by Spataru (1977) found that species of Euglena and Phacus, among the phytoplankton, and Rotaria and Brachionus, among the zooplankton, passed through the gut without damage. The zooplankters were in fact alive and continued to multiply after passage. Bacteria, on the other hand, are highly assimilable (from Sorokin 1971, as cited in Kuznetsov 1977), and it is known that silver carp show no loss in rate of growth when feeding primarily on detritus (Kajak et al. 1977). The sediments in our manured ponds contained only about 3-4% organic matter but contained 1.0×10^7 CFU[1]/gram dry weight, or 1.5×10^8 CFU/gram of organic matter. If these CFU were composed of aggregates of bacteria containing from 60-600 cells/aggregate, as seems likely from data provided by Kuznetsov (1977), the total number of bacteria present in the sediments was from 10^8 to 10^9 cells/gram wet weight, or 10^9 to 10^{10} cells/gram dry weight. Thus, the fish were consuming organic particles (manure, undigested feed, etc.) supporting bacterial populations at the level of 10^9/gram, which approximates the amount in the foreguts of our silver carp. While only incidentally germane to reducing the bacterial contamination in our ponds, it is interesting to consider the potential contribution of bacteria to the food of silver carp. Omarov (1970) has shown that it takes 4 hours for food to pass through the gut of silver carp. If a silver carp holds 1 gram of organic matter in its gut for four hours, the bacteria on that organic matter would undergo from 8-10 doublings during passage. If all survived, one gram of material in the hind gut would contain up to 2.5×10^{11} - 1.0×10^{12} cells/gram, or approximately 256 times the number contained in the foregut. Since

1 CFU - colony forming units of bacteria. Individual colonies may contain from hundreds to thousands of individual bacterial cells.

a 500-gram carp may consume up to 175 grams of material/day (Lin 1974) and since the hind gut in our silver carp contained no more than 12-40 times the number of cells found in the foregut (Table 30), we are provided with a measure of the massive quantities of bacteria that may be assimilated by the fish. For a 500-gram fish it could be as high as 1.75×10^{14} cells/day.

Benthos

Benthos were sampled on five occasions in each pond between July 5 and September 14 in 1979. The samples were collected from three types of "exclosures": one designed to exclude only fish (25.4-mm mesh), one designed to exclude fish, prawns and crayfish (3.2-mm mesh), and a third which was open and excluded nothing. Each "exclosure" included an area of 0.67 m^2. One of each type was located at both the 1.1-m and 1.5-m depths in each pond for a total of six "exclosures" or sampling stations in each pond. Data from the open "exclosures" were comparable to that collected in earlier studies; those from the other "exclosures" reflected the exclusion of fish or of fish, prawns and crayfish.

Table 31 presents data obtained from the open stations. Oligochaetes comprised the greatest biomass in ponds 10, 11 and 12, while oligochaetes and chironomids were dominant in pond 13. The ponds which received wastes directly (ponds 11, 12 and 13) yielded similar numbers of taxa (7 or 8), but downstream pond 10 provided only four taxa. Taxa found in upstream pond 11 but not in the downstream pond were Copepoda, Trichoptera, *Chironomus* and Chironomidae.

Both ponds in the flow-through unit had similar benthic biomasses at both sampling depths (Table 31). In the two aerated ponds, the differences in benthic biomass at the two depths were surprisingly great. Standing crops of benthos (by weight) averaged 3.0 and 2.2 times greater at the shallow stations from ponds 12 and 13 respectively than from the deeper stations. Oligochaetes in pond 12 and oligochaetes and chironomids in pond 13 were mainly responsible for the increased biomass in the shallow samples. These results are puzzling because both of these organisms are commonly abundant at greater depths. Dissolved oxygen at the 1.5-m depth averaged over 4 mg/l in both ponds and CO_2 on the pond bottom averaged only 7.7 and 9.9 mg/l in ponds 12 and 13 respectively, indicating that water quality was adequate to sustain a variety of benthic life. There was no evidence to suggest that the agitators could have physically affected the benthos at the deeper strata. Consistency of the bottom material, as indicated by our "fluff" samples, was not significantly different at the two depths. The probable cause for the decreased biomass at the 1.5-m depth was increased predation by common carp and unusually large numbers of crayfish which might have preferred feeding at these lower strata because they provided both adequate water quality and security. This is consistent with the observation by Momot and Gowing (1972) that crayfish (Orconectes virilis), especially females and yearlings, migrate to deeper water beginning in mid-summer after reproduction and maturation of yearlings in shallow water.

We had anticipated that benthic biomasses would be smallest in the ponds having the largest populations of the benthic predators, common carp, crayfish and prawns. Although all three ponds received swine wastes directly and were stocked with common carp and prawns, total benthic biomass was 1.5 to 2.9 times greater in aerated ponds 12 and 13 than in pond 11 (Table 31). Prawn survival and production was extremely low in ponds 12 and 13, but they had been replaced by vast numbers of crayfish which also are bottom feeders. Furthermore, common carp production as well as total fish production was greater in the aerated ponds. The data in Table 32 show that benthic biomass was directly correlated with crayfish production and the weight gained by the fish (correlation coefficients of r = 0.9566 and 0.9163 respectively). We suggest, however, that the greater abundance of benthos in ponds 12 and 13 was due to aeration and not to a greater abundance of their predators. While aeration seems to have had only a moderately beneficial influence on BOD and other physical-chemical parameters, as earlier described, it appears to have increased the production of benthos.

Samples from the exclosures which excluded fish as well as both prawns and crayfish (3.2-mm mesh) had 7 to 10 different taxa represented, and the exclosures which excluded only fish (25.4-mm mesh) had 5 to 8 taxa (Table 33). Ostracoda, Corixidae, and Hydrochara were found only in the 3.2-mm mesh exclosures, which indicates that the prawns and crayfish were their main predators. The abundance of copepods and the biomass of Chironomidae, Chironomus, and Ceratopogonidae decreased as the exclosure mesh size increased. Due to the invasion of ponds 12 and 13 by large numbers of crayfish, it was impossible to adequately determine the degree of competition between prawns and common carp or to assess the merits of using prawns in this type of waste recycling system.

Fish, Prawns and Crayfish

Production data for fishes, prawns and crayfish in 1979 is shown in Table 34. Production of fish was highest (3465 kg/ha) in aerated pond 13 which received the highest input of manure (Table 29), and rates of production in both aerated ponds were higher than the combined production in the two flow-through ponds (3011 kg/ha). However, production of fish in the aerated ponds in 1979 was substantially lower than rates of production in static ponds in 1976 and 1977 having similar densities of fishes and swine. We believe this had three principal causes: (1) smaller initial sizes of fishes and shorter growing season in 1979, especially for the common carp (Table 34), (2) competition from an unprecedented number of crayfish, and (3) lower water temperatures and fewer optimum growing days.

Prawn production in 1979 was far below that of 1978, due, we believe, to competition from crayfish and low water temperatures. Gains in biomass by prawns in 1979 ranged from a low of 37 kg/ha in aerated pond 12 to 193 kg/ha in second-stage pond 10. The average for four ponds in 1979 was 134.5 kg/ha, compared to an average of 320 kg/ha in 1978. Crayfish production had been negligible in 1978 but averaged 277.2 kg/ha in 1979. The larger crayfish populations - up to 616 kg/ha in pond 13 - were in direct competition with prawns for food and undoubtedly contributed to low prawn survival. We also believe that low water temperatures in 1979 severely limited prawn growth. Optimum growth temperature for prawns is in the range of 28-31 C. Recording thermometers in aerated pond 12 showed there were only six days in 1979 in which the mean daily water temperature (average of daily maximum and minimum on bottom) was 28 C or higher (compared to 30 days in 1978) and only 33 days in which it exceeded 25 C (compared to 85 in 1978). We believe that the unusually low water temperatures in 1979 were in large measure due to mixing of the water column by the mechanical aerators. The aerators were operated only at night; their agitation, with induced circulation, caused the heat stored in the water during the day to be dissipated into the cooler overlying air during the night.

Physical-Chemical Parameters

The comparisons to be made with the 1979 data are (1) the quality of water produced in a two-stage flow-through system with that maintained in static ponds receiving mechanical aeration, and (2) water quality and levels of fish production in aerated ponds with those of static ponds in earlier years that were not aerated.

By most indicators measured the quality of water produced in the flow-through unit of 1979 was similar to that produced by the flow-through units in 1978, in spite of a larger loading of BOD in 1979 (Tables 20 and 29). It also is obvious that, in both stages of the flow-through unit in 1979, the levels of all parameters measured lower and indicated better water quality than in the adjacent aerated ponds. For example, mean levels of BOD_5 were 10.99 and 11.75 in aerated ponds 12 and 13, compared to 8.32 in the first-stage flow-through pond in 1979; suspended solids were 50 and 56 in aerated ponds 12 and 13 respectively, compared to 34 in the first-stage of the flow-through unit. Differences for other parameters were of a similar pattern.

It should be pointed out that the higher levels of BOD_5 and other parameters in the aerated ponds were associated with much higher weights and densities of crayfish than in the flow-through ponds of the same year. Crayfish had been poisoned from these ponds prior to stocking with fish and installation of the swine, but the ponds were reinvaded by crayfish from a ditch which bordered pond 13 on the west. Table 34 shows that gains by crayfish were largest in pond 13 (616 kg/ha) and descended to a low of 39 kg/ha in pond 11. It probably is no coincidence that these gains (and numbers) were highest in ponds 12 and 13 which were nearest the ditch from which the crayfish are believed to have originated. The relationships are poorly understood, but it is possible that the higher levels of BOD_5 and other parameters in ponds 12 and 13 were related to the higher numbers of crayfish and to their interrelationships with the fish and other biota.

The level of aeration achieved in 1979 appears to have provided a limited improvement in the distribution of oxygen. Both mean and minimum levels in the aerated ponds of 1979 were higher than in the static ponds of 1977 but not higher than in the flow-through ponds of 1979 (Table 35). Perhaps the principal value of aeration in this study was that it reduced the danger of the type of catastrophic loss of oxygen that occurred in one pond in 1976. With regard to other important parameters, the influence appeared to be negligible or extremely limited at best. For example, mean levels of BOD_5 in the aerated ponds (Table 29) were lower than in the static ponds of 1976 (Table 8) but higher than in the static ponds of 1977 (Table 13).

For such other parameters as suspended solids, organic nitrogen and soluble orthophosphate, values in the aerated ponds were intermediate to those of the static ponds of 1976 and 1977. It should also be observed that the gains made by fish in aerated ponds (Table 34) were substantially lower than gains made in static ponds without aeration in 1976 and 1977 (Tables 7 and 10). For example, gains by fish in unaerated ponds were 3178 and 3843 kg/ha in ponds 12 and 13 in 1976 and 3527, 4585 and 3938 kg/ha in unaerated ponds 11, 12 and 13 respectively in 1977, compared to 3115 and 3465 kg/ha in aerated ponds 12 and 13 in 1979. The reasons for this lower production in aerated ponds are only partially understood because aeration normally increases fish production. Contributing factors may have included: (1) cooler temperatures and fewer growing days in 1979, especially for the common carp, and (2) smaller size of initial stock in 1979 (Table 22) than in 1976 and 1977 (Tables 1 and 10). There is evidence, however, that the production and the availability of phytoplankton to the consumers (primarily silver carp), may have been reduced by aeration. For example, a comparison of abundance of phytoplankters - especially the greens (Chlorophyta) - shows that their average numbers in samples from unaerated, static ponds in 1976 (Table 3) were much higher than in aerated ponds 12 and 13 in 1979 (Table 24). For example, green algae numbered 135,079/ml and 32,779/ml in samples from ponds 12 and 13 in 1976, compared to only 18,418 and 8175/ml in samples from aerated ponds 12 and 13 in 1979. The differences could have been influenced in part by the mixing caused by the aerators. Circulation of the phytoplankters out of the photic zone may have inhibited their rate of production or simply may have reduced their abundance in the sampling zone. In both years samples were collected from a stratum about 15-30 cm below the surface. If undisturbed, photoplankton would tend to be more concentrated in this upper photic zone than in a pond undergoing moderate mixing by an aerator. However, regardless of their true or total abundance, if the phytoplankters were concentrated they would be more available to the filter-feeding fishes and would be removed in greater quantities. This greater intake by fish would remove excess organic materials, reduce BOD, and effect a general improvement in water quality, as demonstrated here. The aerators were operated nightly from 2030 to 0730 for a total of 1595 hours over the period July 3 to September 8 in pond 12, to September 19 in pond 13. They utilized 1122 kilowatt hours at a total operating cost of $70.50, which when added to the purchase price of two aerators, gives a total cost of $663.38. The true value of aeration is difficult to evaluate. If needed to prevent anoxia and a catastrophic loss of fish, its value would be great. If, however, it provided only a moderate improvement in water quality and the danger of anoxia was small, it would be a questionable investment. The present results suggest that the levels of aeration achieved in 1979 were of limited value and probably not worth the cost.

The aerators were recommended by the manufacturer as adequate for the size of pond studied, but there is no doubt that larger or more efficient units would have proved more beneficial. Recent tests by Romaire and Boyd (1979) have shown the Japanese-style paddle-wheel aerator to have more than twice the efficiency of the spray-type surface aerator used by us, but at a considerably greater cost.

The results of the 1979 study again suggest a trade-off. While aeration can improve certain aspects of water quality, the level of improvement may not justify the additional cost. It is suggested that a properly designed and operated pond containing an adequate stock of filter-feeding, planktivorous fishes, filamentous algae eaters, bottom feeders and scavengers can in many cases provide an adequate biological treatment of organic wastes without mechanical aeration.

SUMMARY AND CONCLUSIONS

Compositions of the plankton communities were strongly influenced by filter-feeding carps (silver and bighead). When abundant, the filter-feeders selectively harvested the larger cladocerans and copepods, leaving populations dominated by smaller rotifers. When fish were less abundant, the greater numbers of the larger zooplankters tended to reduce phytoplankton abundance. Because of their cyclic nature, however, the zooplankters were less efficient in controlling excessive populations of phytoplankton than were static numbers of continuously growing fishes.

In those years in which the phytoplankters were enumerated, they were dominated by green algae, mostly in small sizes, with a high species diversity. Domination by greens normally signifies a healthy, stable population with respect to water quality and is to be expected in enriched ponds heavily grazed by the filter-feeding carps (Dunseth 1977, Henderson 1978). Populations dominated by the smaller greens and heavily grazed by carp may have a higher cell count than an ungrazed population dominated by larger bluegreens. In 1979 bluegreens were prominent only in pond 10 which received the least manure and contained the fewest fish. Our observations seemed to duplicate those of Henderson (1978) who found that high densities of greens signify a rapidly expanding population experiencing a rapid rate of turnover due to continuous grazing. This provides for a maximum uptake of nutrients and control of eutrophication.

When studied most intensively in 1979, the autotrophic communities revealed characteristics related to type of management, densities of fish and/or rates of waste loading. With relation to algal biomass and suspended organic materials, they segregated into two groups - high values in the aerated, static ponds (12 and 13), low values in the flow-through ponds (10 and 11). Also, ponds 12 and 13 received the most manure, contained both the highest cell counts and highest algal biomasses, and had the highest productions of fish.

The ratios of algal cholorophyll-a to phaeophytin usually were high, indicating the algal communities were at most times in healthy, actively growing states.

Seasonal declines in the autotrophic index (AI) in ponds having the largest biomasses of fish were attributed to the consumption of suspended materials by fish. AI was highest and water quality was generally poorest in ponds containing the fewest fish, and vice versa.

When the autotrophic communities of the ponds were analyzed and ranked on the basis of algal density, algal biomass, numbers of taxa, species diversity, autotrophic index, and O_2 production, it was found that the ponds with the highest overall rankings (ponds 12 and 13) also received the largest loads of organic wastes and produced the largest weights of fish.

High rates of suspended solids were believed due to greater numbers of bottom-feeding carp. High rates of consumption produced a fast-growing population of green algae in which attrition was due more to predation by fishes than to normal senescence and decay, resulting in large numbers of living cells and a minimum of dead and decaying cells. Thus, numbers of cells and levels of organic nitrogen and suspended solids remained high, while the in-pond level of oxygen demand remained low.

Overnight cooling and sinking of surface waters that had become highly oxygenated during daylight hours by their high densities of phytoplankton had a beneficial influence on oxygen distribution, pond metabolism, and overall water quality.

Similarities in benthic production at all depths indicated that water quality was adequate throughout for "clean water" species. This precluded formation of dead or anoxic zones, due to excessive accumulation of organic materials, and permitted a rapid, efficient flow of nutrients from the waste materials to the ultimate consumers (fish).

Fecal coliform bacteria were more abundant in manured than in non-manured ponds, but comparison with other findings evidenced a uniform level of control by fishes. Our observations support those by other investigators (Kuznetsov 1977, Schroeder 1978) that bacteria make substantial contributions to the food of fishes (both detritivores and filter feeders) and are significantly reduced by this consumption.

Comparative levels of adenosine triphosphate (ATP) in the sediments indicated the efficiency with which the fish were consuming available living organic substances, as well, presumably, as dead. ATP in sediments was lowest where numbers of bottom feeders (fish, crayfish, prawns) were largest. The seasonal decline in levels of ATP in the water columns reflected increasing rates of consumption of phytoplankton and bacterioplankton by an increasing biomass of filter-feeding fishes.

For manured ponds having similar densities of the companion fishes but differing densities of silver carp, most water quality parameters measured (BOD_5, suspended solids, organic N, soluble orthophosphate, etc.) were lowest - and water quality was best - in the pond having the most silver carp. The degrees of difference, however, were not significant. The greatest influence of silver carp was in moderating cyclic peaks and preventing catastrophic extremes. Where numbers of silver carp were largest, the seasonal "highs" were substantially lower for all important parameters measured.

BOD_5 was directly and strongly correlated with the level of waste loading, whether one considers only the static ponds during 1976 and 1977 (significant at 1.1% level) or all ponds during all segments except the second-stage ponds of the flow-through systems (significant at 1% level). Total fish production (biomass gained) also was strongly correlated with the waste loadings, indicating that wastes stimulated production of fish flesh which represents the uptake of approximately 26 g of nitrogen and 50 g of phosphorus per kilogram of fish flesh gained (Bull and Mackay 1976). The lowest levels of BOD_5 and soluble orthophosphate generally were associated with the highest fish densities, but numbers of algal cells and levels of suspended solids and organic nitrogen frequently were highest where fish densities were highest and their rate of consumption of phytoplankton also was highest.

Average BOD_5 in the stage-1 flow-through ponds was significantly higher than in their respective stage-2 ponds (0.1 to 1.0% levels), indicating substantial water quality improvement within the flow-through system. Dilution, physical settling of suspended matter, and nutrient uptake by macrophytic plants also reduced the average BOD_5 in stage-2 ponds to levels that were significantly lower (0.5 to 5.0% levels) than in static ponds 11 and 12 during 1977. There was, however, little or no significant difference (10 to 20% levels) in BOD_5 between static ponds and stage-1 flow-through ponds. While the quality of effluent from the two-stage flow-through systems was substantially improved over that of the first-stage ponds or that of the static ponds in earlier years, there is reasonable doubt that the improvement was worth the cost in labor, facilities, or reduced fish production.

The level of aeration used in 1979 did not improve (reduce) levels of BOD_5. BOD_5 in aerated ponds averaged significantly higher than in both the stage-1 ponds (1.0 to 2.5% levels) and the stage-2 ponds (0.1% level). The aerated ponds also had higher levels of BOD_5 than unaerated, static ponds 11 and 12 during 1977, although the levels of significance were low (20-40%). In terms of water quality, aeration was judged a questionable investment. Furthermore, mixing due to aeration is believed to have reduced algal production and to have caused a nighttime dissipation of heat into cooler overlying air, which reduced growth and efficiencies of prawns and fishes.

The relationship between the silver and common carp, wherein each increases the food supply of the other, was well demonstrated. Increased food intake by both contributes to the uptake of nutrients and improvement of water quality.

When sufficiently abundant, the growing fish increased their food intake (plankton, bacteria, other organic materials) at a rate which effected a decline in pond BOD (BOD_5) in spite of a continuously increasing input of manure by growing pigs.

The results establish that a polyculture of carps in the proper densities and combinations can make significant improvements in the quality of organically polluted waters. This results from the consumption by carps of massive quantities of such living components of the pond biota as zoo- and phytoplankton, benthos, bacteria, protozoans, and associated microfauna, as well as nonliving detrital materials. Futhermore, continuous grazing by the carps stimulates production and increases the rates of turnover and efficiencies of both the autotrophic and heterotrophic communities. This assures a high rate of biological activity (decomposition, assimilation, etc.), and a continuous flow of nutrients through the food web to the ultimate consumers (fish).

Variations of the system should have application for the biological treatment of organic wastes generated by small human populations, livestock facilities, or various types of meat or vegetable processing plants.

The present study was limited by time, available technology, and the number of available ponds. In terms of original goals, our principal deficiency was the control of suspended solids. In our flow-through system we failed to establish a second-stage pond having the type and density of vegetation capable of settling excessive suspended materials and effectively taking up excess nutrients. We believe that a low-volume flow through an efficient polyculture pond, such as our pond 12 in 1977, and a second-stage polishing lagoon having a proper variety and density of submerged macrophytes would provide an effluent that could meet all present water quality standards. The efficiency and stability of the second-stage pond would be enhanced by sufficient grass carp to prevent excessive densities of macrophytes and to maintain the plants in a state of rapid, continuous growth. Subsequent investigations should consider:

1. Efficiencies of the system in cold seasons with consideration of such supplemental requirements or procedures as additional pond volumes and/or aeration
2. The most efficient densities and combination of fishes, with consideration of additional species of both fishes and invertebrates
3. Optimum design of flow-through systems, with a special consideration of rates of water exchange, types of plants and densities of fish in second-stage ponds, and volume and depth of ponds
4. The role of bacteria in the biological processes, and their rate of consumption by fishes, both of which are believed to be critical elements in the success of the system
5. Practical uses of the fishes and other by-products

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APPENDIX

Table 1. Numbers per hectare (/ha) and initial average weights for fish stocked in ponds 10, 12 and 13 in 1976.

Fish Species	Number Stocked /ha[a] P 10	P 12	P 13	Initial Weight (g)
Silver carp	670	4935	2755	40
Common carp	195	1705	959	15
Bighead carp	82	526	297	35
Grass carp	22	131	77	62
Channel catfish	47	131	77	106
Bluegill	47	131	77	37
Total	1063	7559	4242	

a Represents original stock less observed initial post-stocking mortality.

Table 2. Composition and average abundance of principal taxa of zooplankters from enriched ponds having low, intermediate and high densities of fishes in 1976.

	Pond 10 Low Fish Density		Pond 13 Medium Fish Density		Pond 12 High Fish Density	
	Absolute Abundance ($/m^3$)	Relative Abundance %	Absolute Abundance ($/m^3$)	Relative Abundance %	Absolute Abundance ($/m^3$)	Relative Abundance %
Rotifera	241,760	35	246,307	78	172,536	79
Cladocera	243,110	35	23,068	7	10,149	5
Copepoda [a]	207,336	30	47,041	15	35,661	16
Insecta [b]	479	<1	252	<1	277	<1
Total	692,685	100	316,668	100	218,623	100

a Primarily immature forms.

b *Chaoborus* and Chironomidae (= Tendipedidae) in near equal numbers.

Table 3. Composition, average abundance, and frequency of occurrence of principal taxa of phytoplankters from enriched ponds having low, intermediate and high densities of fishes in 1976.

	Pond 10 Low Fish Density			Pond 13 Medium Fish Density			Pond 12 High Fish Density		
Taxa	Average Number /ml	Number of Species	Frequency[a] of Occurrence	Average Number /ml	Number of Species	Frequency of Occurrence	Average Number /ml	Number of Species	Frequency of Occurrence
Chlorophyta	26,881	29	9 of 9	32,779	40	9 of 9	135,079	37	8 of 8
Cyanophyta	1,976	7	6 of 9	7,924	5	7 of 9	5,890	7	7 of 8
Euglenophyta	1,726	3	6 of 9	2,325	8	7 of 9	956	4	6 of 8
Chrysophyta	2,757	3	9 of 9	10,878	3	9 of 9	11,004	4	8 of 8
Cryptophyta	5,833	4	9 of 9	10,878	5	9 of 9	2,024	5	7 of 8
Pyrrhophyta	171	2	3 of 9	204	2	5 of 9	22	2	2 of 8
Totals	39,344	48		64,988	63		154,975	59	

a Frequency of occurrence in 9 samples collected from each of ponds 10 and 13, and in 8 samples from pond 12.

Table 4. Fecal coliform densities in enriched and unenriched ponds containing various densities of fish during 1976.

Pond	Density of Swine	Density of Fish	FC (Colonies/100ml)
9	0	High	13
10	66/ha	Low	140
13	66/ha	High	340

Table 5. Average total biomass (g) and number of benthic organisms per m^2 (other than snails and tadpoles) present in each pond on various sampling dates during 1976.

	Pond 10 Low Fish Density		Pond 13 Medium Fish Density		Pond 12 High Fish Density	
Date	Number	Weight	Number	Weight	Number	Weight
4-22	50	2.1933	460	9.1950	1740	11.7317
5-05	742	3.8517	3972	24.6817	1550	5.6050
5-20	3852	22.4283	1257	21.6165	4596	47.0249
6-02	867	180.4917	1533	21.7967	1072	116.7588
6-16	845	39.8234	3203	31.0250	562	7.0017
7-14	1479	23.4834	602	22.4433	1445	15.3167
8-10	261	4.9167	293	10.6383	35	3.0617
8-16	637	37.5000	383	2.8017	117	12.2300
Average	1092	39.3361	1463	18.0248	1390	27.3413

Table 6. Benthic taxa sampled in 1976 in ponds having low, medium and high fish densities. Occurrence designated by X.

Fish Density	Low Pond 10	Medium Pond 13	High Pond 12
Taxa			
Annelids			
Oligochaeta (C)	x	x	x
Hirudinea (C)	x	x	x
Crustacea			
Decapoda	x	x	
Mollusks - Pulmonata			
Lymnaeidae (F)		x	
Planorbidae (F)			
Helisoma (G)		x	x
Other unidentified (G)		x	
Insects			
Coleoptera			
Hydrophilidae (F)			
Berosus (G)	x		x
Megaloptera (O)			
Sialidae (F)			
Sialia (G)	x	x	x
Trichoptera (O)			
Hydroptilidae (F)	x	x	x
Leptoceridae (F)		x	x
Other Unidentified (F)	x	x	x
Ephemeroptera (O)			
Baetidae (F)		x	
Caenidae (F)	x	x	
Ephemeridae (F)			
Hexagenia (G)	x	x	x
Other unidentified (G)	x		x
Odonata (O)			
Gomphidae (F)	x		
Libellulidae (F)			
Epicordulia (G)	x		
Other unidentified (G)	x	x	
Diptera (O)			
Ceratopogonidae (F)			
Culicoides (G)	x	x	x
Palpomyia (G)		x	
Other unidentified (G)		x	x
Culicidea (F)			
Chaoborus (G)			
albatus (S)	x		
punctipennis (S)		x	
other unidentified (S)		x	x
Other unidentified (G)	x		

Continued

Taxa	Pond 10	Pond 13	Pond 12
Tabanidae (F)		x	
Chironomidae (F)			
Chironomus (G)			
plumosus (S)	x	x	
other unidentified (S)	x		x
Pentaneura (G)		x	x
Procladius (G)	x	x	x
Tanytarsus (G)			
caracina (S)	x	x	
lugens (S)	x	x	
other unidentified	x		x
Tendipes (= Chironomus) (G)			
tentans (S)	x	x	x
Other unidentified (G)	x	x	x
Totals	24	27	19

Table 7. Initial stock in numbers per hectare, initial biomass in kilograms per hectare (kg/ha), and seasonal gains in kilograms per hectare (kg/ha) in 1976.

	Initial Number and Biomass (kg/ha)			Gain in Biomass (kg/ha)		
Fish Species	Pond 10	Pond 13	Pond 12	Pond 10	Pond 13	Pond 12
Silver carp	670 (26.7)	2755 (110.0)	4935 (197.0)	573	2582	2041
Common carp	195 (2.8)	959 (13.9)	1705 (24.7)	272	599	568
Bighead carp	82 (2.8)	297 (10.2)	526 (18.1)	163	448	335
Grass carp	22 (1.5)	77 (4.7)	131 (8.4)	23	72.3	88.6
Channel catfish	47 (6.0)	77 (7.6)	131 (14.6)	14.8	34.8	36.7
Bluegill[a]	47 (1.6)	77 (2.7)	131 (5.0)	0.1	4.5	0.6
Bluegill[b]				442.0	102.0	108.0
Total	1063 (41.4)	4242 (149.1)	7559 (267.8)	1488	3843	3178

a Initial stock.

b Age-0, spawned in pond.

Table 8. Inputs of swine manure as kilograms of BOD, plus range and mean values of selected water quality parameters in polyculture ponds receiving similar volumes of swine manure but different densities of fish in 1976.

	Pond 10		Pond 13		Pond 12	
Area of Pond, ha	0.09		0.16		0.12	
Input, kg BOD/ha						
Total	1349		1392		1221	
Daily average	8.1		8.4		8.1	
Density of fish [a]	Low		Medium		High	
Fish gain, kg/ha	1488		3843		3178	
Parameters [b]	Range	Mean	Range	Mean	Range	Mean
Suspended solids, mg/l	4 93	26	8 76	33	19 105	55
BOD_5, mg/l	4.15 25.5	11.85	4.59 25.25	11.21	5.32 22.64	11.17
Organic nitrogen, mg/l	1.44 4.78	2.54	1.41 4.34	2.22	1.32 4.80	2.38
Soluble orthophosphate mg/l	.003 .326	.114	.046 .248	.124	.036 .205	.093

a High density includes 5000 silver carp, 1700 common carp, 426 bighead carp, and 128 grass carp each/ha; medium density is one-half those numbers, low density is one-tenth those numbers.

b Suspended solids were sampled 9 times in pond 12 and 11 times in the other ponds; BOD_5 was sampled 18 times in pond 10, 17 times in pond 13, and 13 times in pond 12; organic nitrogen and soluble orthophosphate were sampled 9 times in pond 12, and 10 times in the other ponds.

Table 9. Ranges and means of dissolved oxygen in milligrams per liter (mg/l) over 24-hour periods on each of 6 dates in 1976 at each of two depths (0.3 m and bottom) in ponds which received similar amounts of swine manure but differing densities of fish.

	Pond 10 (Fish density 0.1)				Pond 13 (Fish density 0.5)				Pond 12 (Fish density 1.0)			
	0.3 m		Bottom		0.3 m		Bottom		0.3 m		Bottom	
Date	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
6-07	11.2-15.4	13.6	2.2-5.1	3.8	9.9-20.0+	15.2	1.1-1.3	1.2	7.3-20.0+	12.5	1.1-1.5	1.2
6-28	4.9-13.5	9.5	0.9-1.15	1.1	4.4-17.1	10.1	0.9-1.1	1.0	1.4-7.1	3.8	0.8-1.1	1.0
7-12	3.7-20.0+	12.1	1.2-5.8	1.8	2.9-11.7	6.7	1.1-3.2	1.7	1.5-10.8	5.7	0.8-2.0	1.1
7-26	5.6-20.0+	12.9	1.3-6.9	3.0	4.0-19.4	11.1	1.0-3.2	1.9	4.0-17.1	9.5	1.9-5.6	3.3
8-10	6.2-20.0+	13.2	2.2-8.0	3.8	4.8-14.2	9.7	2.7-7.1	5.1	4.6-17.8	11.6	1.1-6.4	2.7
8-31	4.4-17.1	10.6	1.5-7.5	3.2	3.2-10.9	6.7	2.03-6.9	3.4	5.3-18.1	11.3	1.3-4.7	2.9
Averages		11.9		2.8		9.9		2.4		9.1		2.0

Table 10. Initial stock in numbers per hectare (/ha), initial weights, and seasonal gains in kilograms per hectare (kg/ha) for fish in ponds 10, 11, 12 and 13 in 1977.

Fish Species	Number Stocked/ha [a]				Initial Weight (g)	Gain in Biomass (kg/ha)			
	P 10	P 11	P 12	P 13		P 10	P 11	P 12	P 13
Silver carp	3812	3744	5436	1889	158	603	2284	3083	2313
Silver carp	1662	1707	2471	828	2	6.1	171	168	160
Common carp	920	914	882	912	54	86.3	619	967	773
Bighead carp	288	285	274	282	28	58.0	330	202	472
Grass carp	78	75	68	72	130	28.4	91.4	138	129
Channel catfish	78	75	68	72	258	6.2	24.2	26.8	35.1
Other							6.9 [b]		55.7 [c]
Total	6838	6800	9199	4055		788	3527	4585	3938

a Represents original stock less observed initial post-stocking mortality.

b Represents 7 yellow bullheads (*Ictalurus natalis*) recovered in final census.

c Represents 176 Age-0 common carp spawned in pond.

Table 11. Composition and average abundance of principal taxa of zooplankters sampled in one unenriched pond and three enriched ponds having different densities of silver carp but similar densities of companion species in 1977.

	Pond 10		Pond 11		Pond 12		Pond 13	
Swine/ha	0		60		61		65	
Units of Silver carp[a]	1.0		1.0		1.5		0.5	
	Absolute abundance ($/m^3$)	Relative abundance %	Absolute abundance ($/m^3$)	Relative abundance %	Absolute abundance ($/m^3$)	Relative abundance %	Absolute abundance ($/m^3$)	Relative abundance %
Rotifera	28,842	76	199,776	91	109,001	91	185,196	84
Cladocera	1,373	4	1,775	<1	1,223	1	6,062	3
Copepoda	7,327	19	18,701	8	9,321	8	28,792	13
Insecta	309	1	289	<1	82	<1	174	<1
Total	37,851	100	220,521	100	119,627	100	220,224	100

a One stocking unit of silver carp was equivalent to about 5200/ha.

Table 12. Densities of fecal coliforms on various dates during 1977 in one unenriched pond and three enriched ponds having different densities of silver carp but similar densities of companion species.

	Pond 10	Pond 11	Pond 12	Pond 13
Swine/ha	0	60	61	65
Units of[a] Silver carp	1.0	1.0	1.5	0.5
Date	Number of Fecal Coliform/100 ml			
6-22	767	5500	4200	1425
6-30	317	2636		867
7-28	75	850	966	150
8-29	515	1825	4600	1067
9-19	533	6100	3300	6100
10-17	10	60	10	10
Mean	370	2828	2615	1603

a Our standard stocking unit of silver carp was equivalent to about 5200/ha.

Table 13. Inputs of swine manure as kilograms of BOD, plus ranges and mean values of various water quality parameters in polyculture ponds with and without manure, and with similar loadings of manure and differing densities of silver carp in 1977.

	Pond 10		Pond 11		Pond 12		Pond 13	
Area of Pond, ha	0.09		0.13		0.13		0.17	
Input, kg BOD/ha								
Total	0		1220		1292		1452	
Daily average	0		7.7		8.2		9.2	
Silver carp/ha	5489		5433		7879		2713	
Other carps/ha[a]	"Standard"		"Standard"		"Standard"		"Standard"	
Fish gain, kg/ha	788		3527		4585		3938	
Parameters	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Suspended solids, mg/l	17 192	51	33 140	71	20 80	43	18 125	41
BOD_5, mg/l	1.62 7.48	3.40	4.41 16.36	8.42	4.20 12.54	8.31	4.39 17.31	9.15
Organic nitrogen, mg/l	0.55 0.90	0.65	0.60 2.89	1.48	1.10 2.02	1.41	0.80 2.90	1.57
Soluble orthophosphate	0.02 0.05	0.03	0.02 0.21	0.09	0.03 0.12	0.08	0.03 0.21	0.10
Fecal coliform/100 ml	10 767	370	60 6100	2828	10 4600	2615	10 6100	1603

a Our "Standard" density includes approximately 1700 common carp, 426 bighead carp, and 128 grass carp each/ha.

Table 14. Densities of silver carp and standard deviations for various water quality parameters in polyculture ponds during 1977.

	Pond 10	Pond 11	Pond 12	Pond 13
Silver carp/ha	5489	5433	7879	2713
Parameters				
BOD_5	1.67	3.79	2.94	4.27
Suspended solids	52.51	33.42	20.04	32.86
Organic nitrogen	0.31	0.63	0.27	0.64
Soluble orthophosphate	0.01	0.06	0.03	0.06

Table 15. Numbers per hectare (/ha) and initial average weights for fish and prawns stocked in ponds 10, 11, 12 and 13 in 1978.

Fish Species	Number Stocked /ha [a] P 10	P 11	P 12	P 13	Initial Weight (g)
Silver carp	644	4371	623	4244	39
Common carp	0	871	0	844	18
Bighead carp	78	271	77	261	50
Grass carp	11	71	15	67	275
Prawns	38,889	75,000	49,231	81,978	0.085

a Represents original stock less observed initial post-stocking mortality.

Table 16. Composition and average abundance of principal taxa of zooplankters in first- and second-stage ponds in two 2-pond flow-through systems in 1978.

	Pond 11 (Stage 1)		Pond 10 (Stage 2)		Pond 13 (Stage 1)		Pond 12 (Stage 2)	
	Absolute Abundance ($/m^3$)	Relative Abundance %	Absolute Abundance ($/m^3$)	Relative Abundance %	Absolute Abundance ($/m^3$)	Relative Abundance %	Absolute Abundance ($/m^3$)	Relative Abundance %
Rotifera	86,368	83	94,879	71	310,495	93	198,070	77
Cladocera	12,147	12	5,857	4	7,404	2	12,976	5
Copepoda[a]	5,317	5	31,722	24	16,161	5	44,138	17
Insecta[b]	169	<1	339	<1	398	<1	547	<1
Total	104,001	100	132,797	100	334,458	100	255,731	100

a Primarily immature forms.

b Primarily *Chaoborus*.

Table 17. Average ATP content of sediments (dry weight) sampled on September 26, 1978, and of whole water samples collected on the dates indicated in 1979. Numbers in parentheses indicate numbers of samples taken from each pond.

Pond	Sediment ng/mg X 10^{-2} (3)	Water (ng/liter)[a] Aug. 15 (1-2)	Aug. 22 (6-12)	Sept. 12 (3)	Sept. 25 (4-5)
10	7.84	380	620	33	37
11	4.86	457	432	69	32
12	4.34	699	1016	208	181
13	3.36	799	3090	749	49

a 1 ng = 1 nanogram = 1 gram X 10^{-9}

Table 18. Average number and weight in grams (g) of benthic organisms per m^2 in ponds 10, 11 12, and 13 on September 12, 1978.

	Pond 10		Pond 11		Pond 12		Pond 13	
Taxa	Number	Weight	Number	Weight	Number	Weight	Number	Weight
ANNELIDA								
Oligochaeta	283	1.3725	186	0.4169	374	0.9925	36	0.3481
AMPHIPODA								
Hyalella	5	0.0055						
INSECTA								
Hemiptera								
Notonectidae					3	0.0053		
Odonata								
Libellulidae	8	0.0039						
Ephemeroptera								
Caenis	6	0.0036						
Hexagenia	19	0.0055						
Trichoptera								
Leptoceridae	3	0.0092						
Diptera								
Ceratopogonidae	172	0.0453	19	0.0116			8	0.0039
Simuliidae					14	0.0264	8	0.0089
Chrysops	22	0.1269						
Chironomidae	261	0.0950	11	0.0094	14	0.0139	61	0.0197
Chaoborus	880	0.6683	81	0.0839	600	0.4408	120	0.1800
Total	1659	2.3357	297	0.5218	978	1.4789	233	0.5606

Table 19. Total number and weight in grams (g) of benthic organisms per m^2 at various depths in ponds 10, 11, 12 and 13 on September 12, 1978.

Depth (cm)	Pond 10		Pond 11		Pond 12		Pond 13	
	Number	Weight	Number	Weight	Number	Weight	Number	Weight
30.5	1083	4.0217	216	0.2983	101	0.1816	167	1.6333
61.0	966	0.4066	50	0.0250	67	0.0767	283	0.3367
91.4	850	0.3699	134	0.1067	17	0.0167	83	0.0250
121.9	1533	1.7100	184	0.2667	1550	1.8317	67	0.1400
152.4	2500	4.6801	517	1.2000	2300	4.0034	249	0.2599
182.9	3034	2.8267	683	1.2350	1833	2.7633	550	0.9683

Table 20. Volume displacement, inputs of swine manure as kilograms of BOD, and mean seasonal values of various water quality parameters in first and second ponds in two flow-through systems in 1978.

	Stage in Flow-through System			
	1st Pond 11	2nd Pond 10	1st Pond 13	2nd Pond 12
Area of Pond, ha	0.14	0.09	0.18	0.13
Displacement time, days	39.0	22.8	51.1	33.3
Input, kg BOD/ha				
Total	928	205	1102	173
Daily average	6.2	2.5	7.3	2.1
Fish gain, kg/ha	2315	400	2716	1015 [a]
Crayfish, kg/ha	35	24	42	115
Prawns				
Parameters [b]	Mean	Mean	Mean	Mean
BOD_5, mg/l	5.95	3.39	9.26	5.06
Suspended solids, mg/l	43	24	67	47
Organic nitrogen, mg/l	0.77	0.55	1.17	0.66
Soluble orthophosphate, mg/l	0.04	0.02	0.06	0.02
Fecal coliforms/100 ml	2908	1977	4139	142

a Includes 190 kg/ha of extraneous carp.

b Suspended solids, organic nitrogen, and soluble orthophosphate were sampled nine times; BOD_5 was sampled six times; fecal coliforms were sampled four times.

Table 21. Initial biomass, days in pond, and gains in biomass for fish and prawns in ponds 10, 11, 12 and 13 in 1978.

Species	Initial Biomass (kg/ha)				Days in Pond	Gain in Biomass (kg/ha)			
	Pond 10	Pond 11	Pond 12	Pond 13		Pond 10	Pond 11	Pond 12	Pond 13
Silver carp	25	169	24	164	175	268	1782	504	2036
Common carp	0	16	0	15	175		224		256
Bighead carp	4	13	4	12	175	112	202	108	325
Grass carp	3	20	3	21	103,[a] 175	19	104	21	96
Other [b]						1	3	192	3
Prawn	3	6	4	9	131	320	414	264	291
Total						720	2729	1089	3007

a Grass carp were in ponds 10 and 12 for 103 days, in ponds 11 and 13 for 175 days.

b These extraneous fishes included 28 top minnows (Fundulus sp.) in pond 10, 26 small crappies (Pomoxis sp.) in pond 11, 171 carp (Cyprinus carpio) and one yellow bullhead in pond 12, and 11 small crappies and 2 small channel catfish in pond 13. Those in ponds 10 and 12 probably entered as eggs or larvae with the transplanted weeds; others possibly passed through filters.

Table 22. Numbers per hectare (/ha) and initial average weights in grams (g) for fish and prawns stocked in ponds 10, 11, 12 and 13 in 1979.

	Number stocked /ha[a]				Initial Weight
Fish Species	P 10	P 11	P 12	P 13	(g)
Silver carp	773	5915	5693	5385	5.7
Common carp	0	1676	1613	1759	9.1
Bighead carp	93	507	482	1351	11.9
Grass carp	13	127	124	132	25.3
Prawns	168,987	152,113	341,168	372,759	0.01[b]

a Represents original stock less observed initial post-stocking mortality.

b Prawns stocked in ponds 10 and 11 averaged 10.5 mg and those stocked in ponds 12 and 13 averaged 15.1 mg.

Table 23. Composition and average abundance of principal taxa of zooplankters from a flow-through system and from static ponds receiving mechanical aeration in 1979.

	Flow - through				Mechanical Aeration			
	Pond 11 Stage 1		Pond 10 Stage 2		Pond 12		Pond 13	
	Absolute Abundance ($/m^3$)	Relative Abundance %	Absolute Abundance ($/m^3$)	Relative Abundance %	Absolute Abundance ($/m^3$)	Relative Abundance %	Absolute Abundance ($/m^3$)	Relative Abundance %
Rotifera	194,297	80	247,379	71	139,439	57	302,826	83
Cladocera	16,117	7	11,262	3	25,146	10	18,164	5
Copepoda[a]	33,038	14	88,631	25	78,861	32	44,502	12
Insecta[b]	233	<1	1,001	<1	144	<1	265	<1
Total	243,685	100	348,273	100	243,590	100	365,757	100

a Primarily immature forms.

b Primarily Chaoborus.

Table 24. Average abundance of principal taxa of phytoplankters in a flow-through system and in static ponds receiving mechanical aeration during 1979.

	Stage 1	Stage 2	Mechanical Aeration	
	Pond 11	Pond 10	Pond 12	Pond 13
Taxa	No./ml	No./ml	No./ml	No./ml
Chlorophyta	14,199	3,455	18,418	8,175
Cyanophyta	573	1,380	1,394	463
Euglenophyta	3,185	438	2,358	7,923
Chrysophyta	5,083	6,511	12,712	7,733
Cryptophyta	3,106	265	4,202	2,531
Pyrrhophyta	424	79	415	124
Totals	26,570	12,128	39,499	26,949

Table 25. Composition and frequency of occurrence of principal taxa of phytoplankters in a flow-through system and in static ponds receiving mechanical aeration during 1979.

	Stage 1		Stage 2		Mechanical Aeration			
	Pond 11		Pond 10		Pond 12		Pond 13	
Taxa	Number of Species	Frequency of Occurrence	Number of Species	Frequency of Occurrence	Number of Species	Frequency of Occurrence	Number of Species	Frequency of Occurrence
Chlorophyta	38	8 of 8	38	8 of 8	45	8 of 8	44	8 of 8
Cyanophyta	7	8 of 8	6	5 of 8	7	8 of 8	8	7 of 8
Euglenophyta	7	6 of 8	10	8 of 8	8	8 of 8	13	8 of 8
Chrysophyta	32	8 of 8	38	8 of 8	25	8 of 8	18	8 of 8
Cryptophyta	5	6 of 8	6	6 of 8	8	7 of 8	6	7 of 8
Pyrrhophyta	2	3 of 3	3	5 of 8	3	4 of 8	4	6 of 8
Totals	91		101		96		93	

Table 26. Average[a] total, inorganic, and organic suspended solids and algal biomass in a flow-through system and in static ponds receiving mechanical aeration during 1979.

Parameters	Stage 1 Pond 11	Stage 2 Pond 10	Mechanical Aeration Pond 12	 Pond 13
Total suspended solids, mg/liter	234.2	150.1	285.0	321.1
Inorganic suspended solids, mg/liter	210.1	133.6	257.0	288.3
Organic suspended solids, mg/liter	21.7	16.9	34.2	33.4
Algal biomass,[b] $mg/m^3 \pm$ S.D.	4.6±1.8	1.9±0.6	12.2±10.3	14.7±14.0

a Averages are for 6 samples each of total and inorganic suspended solids and for 8 each of organic suspended solids over the period June-September.

b Algal biomass based upon chlorophyll concentrations ± 1 Standard deviation.

Table 27. Average net rates of photosynthetic oxygen production measured under natural conditions at 0.2-m intervals (overall) and in light-dark bottles at the surface and 0.5-m depth in a flow-through system and in static ponds receiving mechanical aeration during 1979.

Oxygen Production	Stage 1 Pond 11	Stage 2 Pond 10	Mechanical Aeration Pond 12	Mechanical Aeration Pond 13
Overall, g $O_2/m^2 \cdot hr$	0.53	0.25	0.66	0.46
Surface mg O_2/liter·hr	0.95	0.35	1.70	1.44
0.5 Depth, mg O_2/liter·hr	0.44	0.28	0.12	0.09

Table 28. Ranking of the 1979 swine waste disposal ponds according to various productivity and water quality indicators where 1 designates the highest productivity, or best water quality, and 4 designates the lowest.

Parameters	Stage 1 Pond 11	Stage 2 Pond 10	Mechanical Aeration Pond 12	Mechanical Aeration Pond 13
Algal density	3	4	1	2
Algal biomass	3	4	2	1
Number of taxa	4	1	2	3
Diversity index	4	1.5[a]	1.5[a]	3
Autotrophic index	3	4	2	1
Overall O_2 production	2	4	1	3
Surface O_2 production	3	4	1	2
Totals	22	22.5	10.5	15

a Ponds 10 and 12 tied for the rank of 1, so the total possible points (1 + 2) were divided equally between the two ponds.

Table 29. Volume displacement time, inputs of swine manure as kilograms of BOD, and comparison of mean seasonal values of various water quality parameters in a flow-through system and in static ponds receiving mechanical aeration in 1979.

	Flow-through		Mechanical Aeration	
	Stage 1	Stage 2	Pond 12	Pond 13
Area of pond, ha	0.14	0.08	0.14	0.17
Displacement time, days	35.7	14.2		
Input, kg BOD/ha				
Total	1334	395	1349	1579
Daily average	8.8	3.8	8.9	10.5
Parameters [a]				
Suspended solids, mg/l	34	29	50	56
BOD_5, mg/l	8.32	3.83	10.99	11.75
Organic nitrogen, mg/l	0.78	0.51	1.27	1.11
Soluble orthophosphate, mg/l	0.05	0.02	0.06	0.07
Fecal coliforms/100 ml	3565	294	3759	4308
pH	7.85	8.03	7.95	7.85

a Suspended solids and BOD_5 were sampled eight times; organic nitrogen and soluble orthophosphate were sampled 12 times; fecal coliforms were sampled five times in the stage 2 pond (pond 10), four times in the stage 1 pond (pond 11) and pond 12, and six times in pond 13; pH was measured 16 times in each pond.

Table 30. Estimates of total aerobic colony counts per gram of material from the fore, mid, and hind guts of silver carp taken from a pond receiving hog manure.[a]

Gut Section	Colony Counts x 10 Aerobic Pour Plates
Fore	7.99
Mid	53.7
Hind	312.4

a Data are estimates derived from calculating colony counts x 41.66, which was length in cm of silver carp feces/g wet weight.

Table 31. Seasonal average biomass (g/m^2) of various benthic organisms sampled in the "open" exclosures at 1.1-m and 1.5-m depths in ponds 10, 11, 12 and 13 in 1979. P indicates that the organisms were present but no weight was obtained.

	Pond 10		Pond 11		Pond 12		Pond 13	
Taxa	1.1 m	1.5 m	1.1 m	1.5 m	1.1 m	1.5 m	1.1 m	1.5 m
Copepoda				P	P		P	
Nematoda		0.0061	0.1455	1.5455	0.0061		0.3030	3.1273
Oligochaeta	2.4667	2.0061	2.1030	0.1152	5.5758	0.4121	3.6364	1.2121
Insects								
Trichoptera			P					
Diptera								
Chaoborus	0.1576	0.7818	0.4788	0.6061	0.1333	0.1576		0.3758
Chironomus			0.0545			0.2424	5.4727	
Ceratopogonidae	0.0182		0.0576	0.0121	0.0364	0.5091	0.2424	0.0485
Chironomidae			0.0303		0.0606	0.6182	0.7515	
Total	2.6425	2.7940	2.8697	2.2789	5.8122	1.9394	10.4060	4.7637
Average	2.7182		2.5743		3.8758		7.5848	

Table 32. Average total benthic biomass (g/m^2) and gains in kilograms per hectare (kg/ha) by crayfish and fish in ponds 11, 12 and 13 in 1979.

Pond	g/m^2 Benthos	kg/ha Crayfish	kg/ha Fish
11	2.5743	39.5	2532
12	3.8758	341.4	3115
13	7.5848	616.5	3465

Table 33. Benthic taxa sampled within various types of wire exclosures in ponds 10, 11, 12 and 13 in 1979.

	Pond 10			Pond 11			Pond 12			Pond 13		
	3.2mm	25.4mm	open	3.2mm	25.4mm	open	3.2mm	25.4mm	open	3.2mm	25.4mm	open
Cladocera		x		x				x		x		
Ostracoda	x						x			x		
Copepoda	x			x	x	x	x	x	x	x	x	x
Nematoda	x	x	x	x	x	x	x	x	x	x	x	x
Oligochaeta	x	x	x	x	x	x	x	x	x	x	x	x
Insects												
Trichoptera				x		x						
Ephemeroptera												
Hexagenia		x										
Hemiptera												
Notonectidae					x							
Corixidae	x						x					
Coleoptera												
Hydrochara							x					
Diptera												
Chaoborus	x	x	x	x	x	x	x	x	x	x	x	x
Chironomidae	x			x		x	x	x	x	x	x	x
Chironomus				x	x	x	x	x	x	x	x	x
Tanypodinae				x	x							
Ceratopogonidae			x	x	x	x	x	x	x	x	x	x

Table 34. Initial biomass, days fish were in the ponds and gains in biomass for ponds 10, 11, 12, and 13 in 1979.

	Initial Biomass (kg/ha)				Days in Pond	Gain in Biomass (kg/ha)			
	P 10	P 11	P 12	P 13		P 10	P 11	P 12	P 13
Silver carp	4.4	33.7	32.4	30.7	173	345	1861	2247	2043
Common carp		15.3	14.7	16.0	109		274	337	355
Bighead carp	1.1	6.0	5.7	16.1	173	111	319	428	983
Grass carp	0.3	3.2	3.1	3.3	173	23	78	103	84
Prawns	1.8	1.6	5.2	5.6	99-123 [a]	193	183	37	125
Crayfish						113	39	341	616
Other [b]							0.3		0.1
Total	7.6	59.8	61.1	71.7		785	2754	3493	4206

a Prawns were 99 days in ponds 10 and 11, 123 days in ponds 12 and 13.

b Extraneous fish recovered were 7 channel catfish from pond 11 and 3 from pond 13.

Table 35. Range and mean of dissolved oxygen (mg/l) measured at the 30.5-cm and bottom depths in selected static ponds during 1977, the flow-through units and the aerated ponds during 1979.

Pond	Year	Type	Range	Mean	Range	Mean
12	1977	static	1.30 9.45	3.78	0.40 6.00	1.56
13	1977	static	2.55 9.70	4.83	0.60 5.20	1.85
11	1979	stage-1	3.10 14.60	6.30	1.00 7.00	2.92
10	1979	stage-2	5.70 9.30	7.45	1.40 8.20	5.26
12	1979	aeration	2.50 12.30	5.80	0.90 8.60	3.06
13	1979	aeration	3.00 11.70	6.51	1.00 8.60	3.95

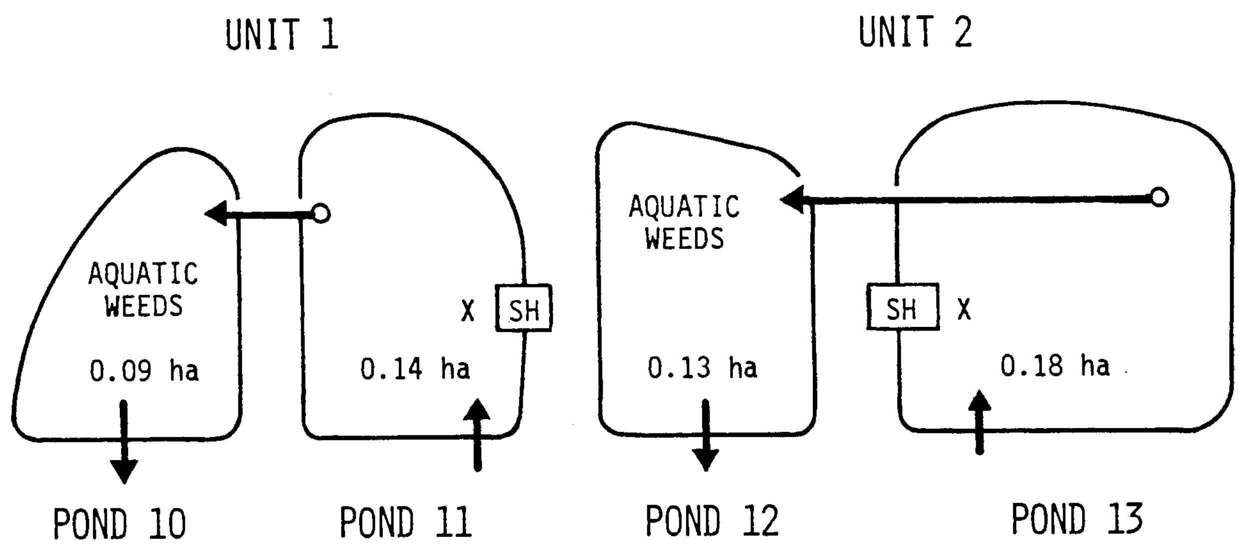

Figure 1. Shapes and sizes of ponds with diagrams of flow patterns used in two flow-through units in 1978 and in ponds 10 and 11 in 1979. SH designates swine house; X designates place where manure entered ponds.

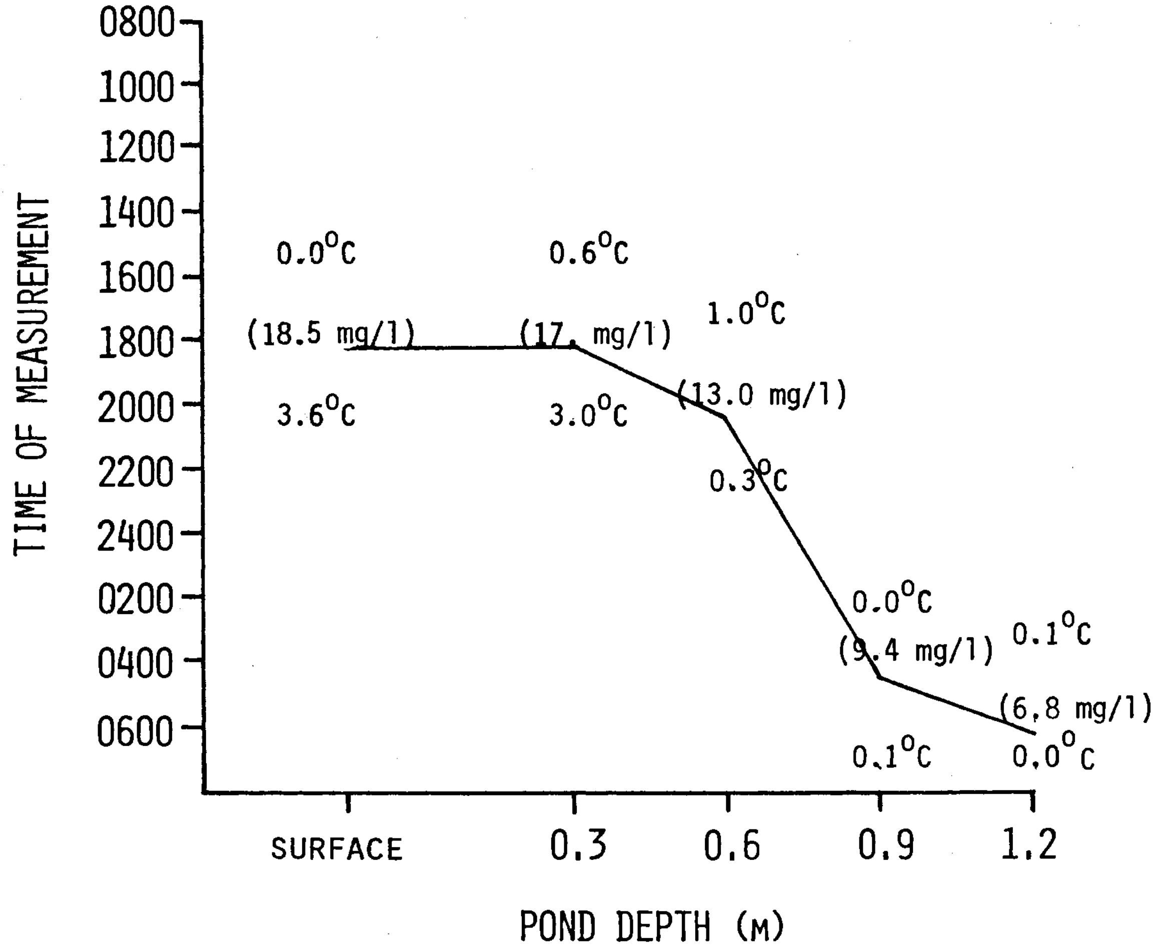

Figure 2. Typical curve demonstrating the tendency for reoxygenation of lower strata through nightly cooling and sinking of surface waters that had been highly charged with dissolved oxygen by daytime photosynthesis. Curve shows hour at which maximum level of dissolved oxygen (in parentheses) was recorded at each 0.3-m level over 24-hour period. Numbers above curve show temperature differential between depth of maximum reading and pond surface; numbers below curve show temperature differential between depth of maximum reading and pond bottom.

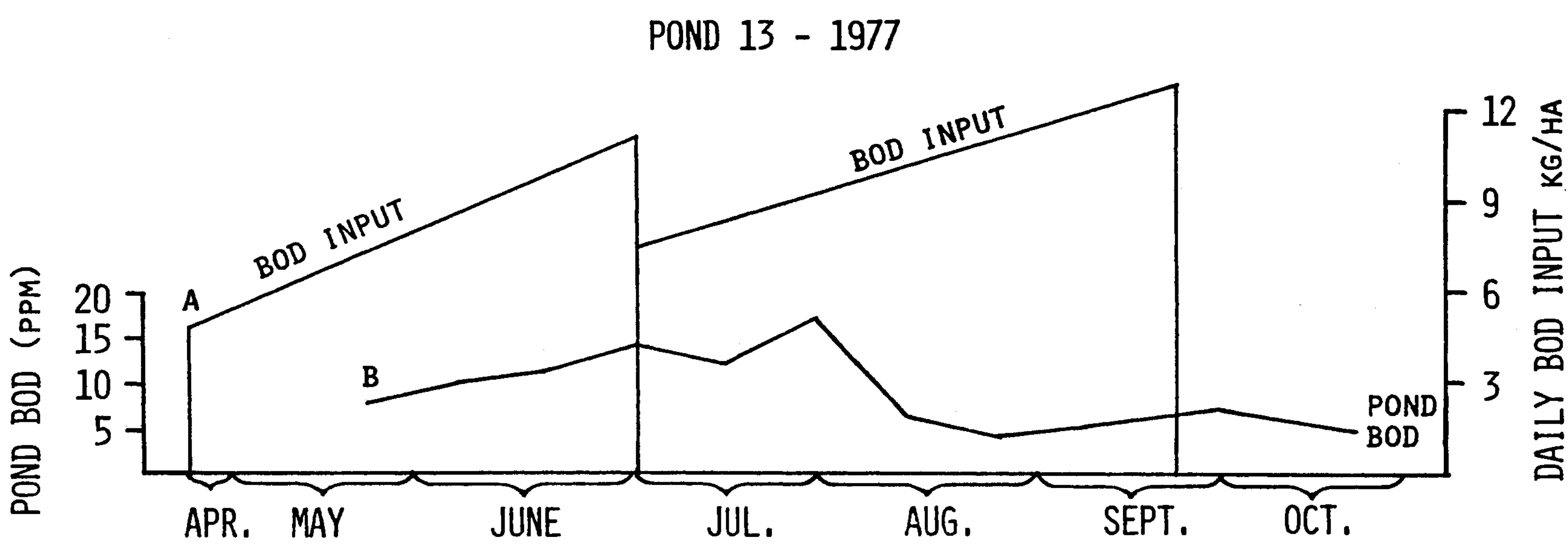

Figure 3. Daily input of swine manure in terms of kg/ha of BOD (Line A) and biweekly measurements of BOD_5 (Line B) in pond 13 during 1977.

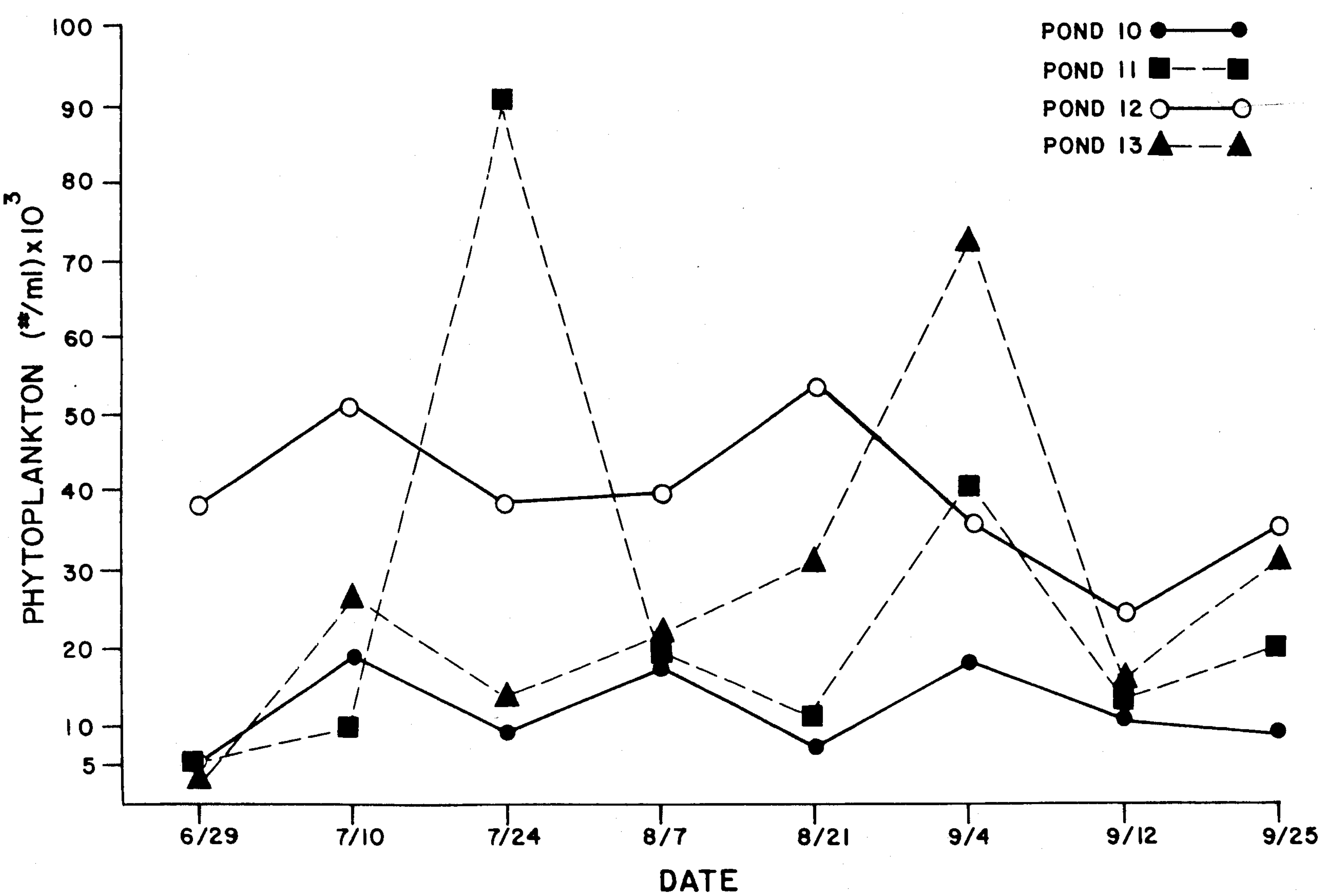

Figure 4. Phytoplankton (No./ml) in experimental ponds, 1979.

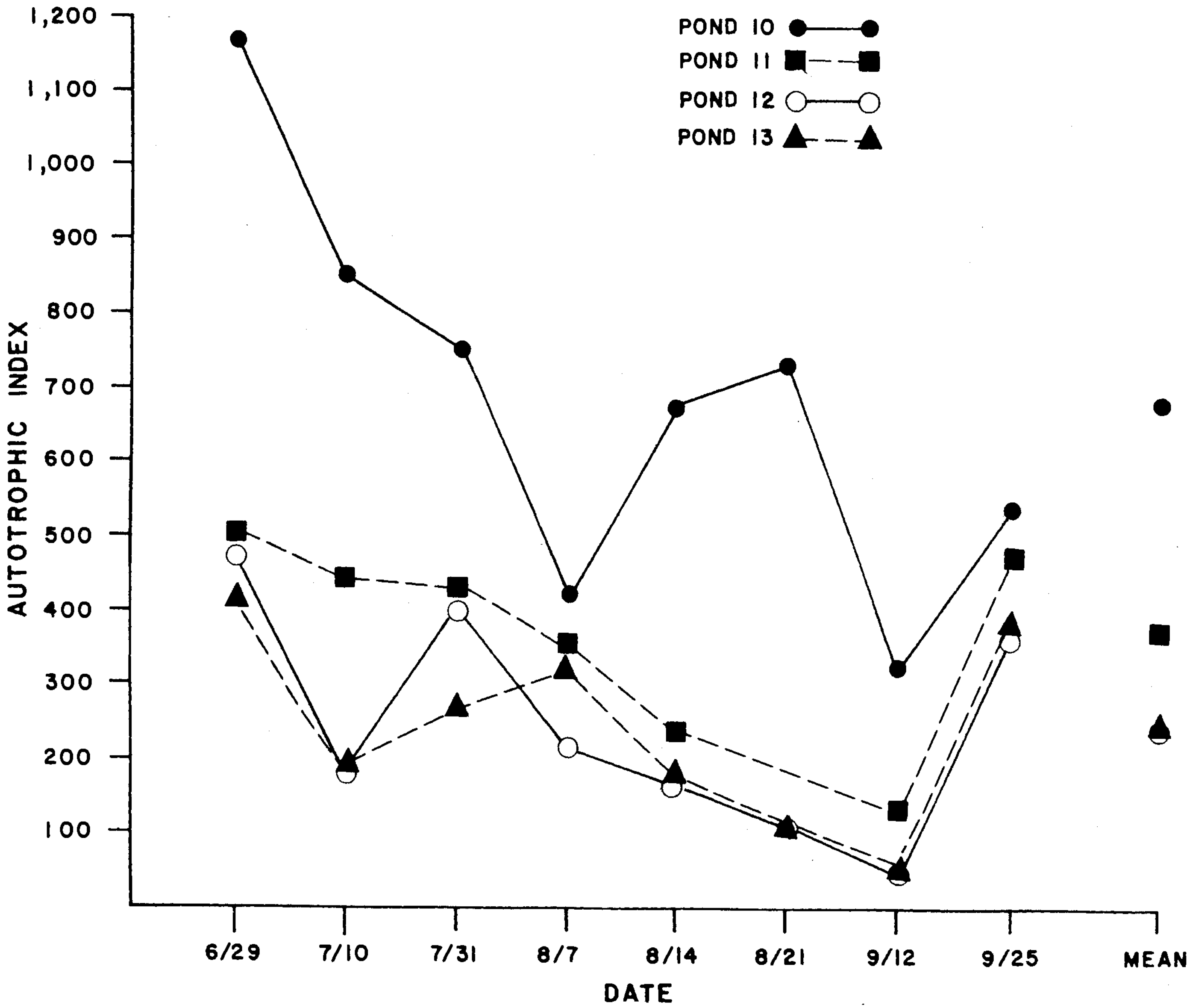

Figure 5. Autotrophic index (AI) in experimental ponds, 1979.

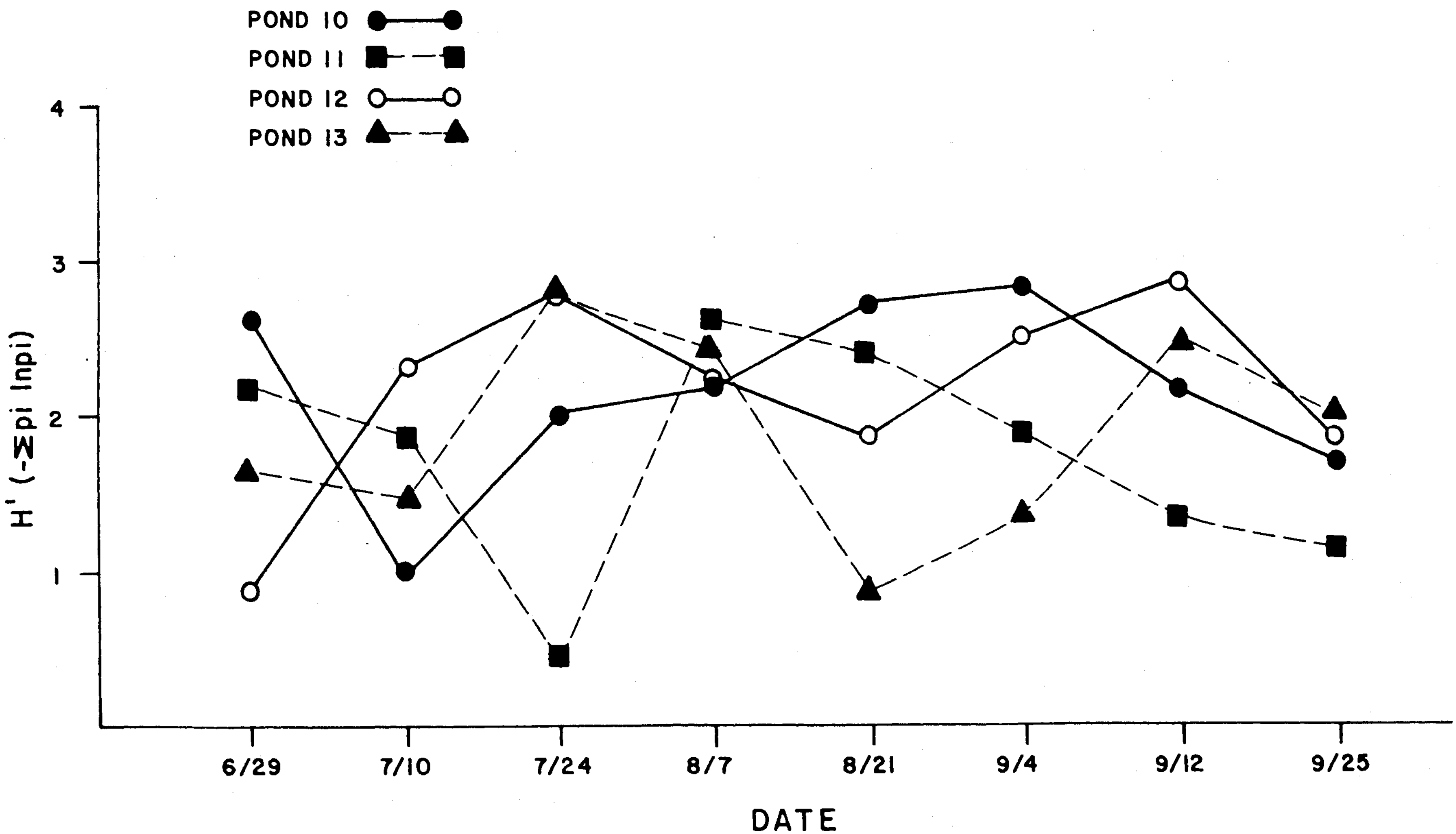

Figure 6. Shannon-Wiener Index of Diversity (H') for phytoplankton communities in experimental ponds, 1979.