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Modeling *Daphnia* Populations in Wastewater Stabilization Ponds in Minnesota

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Abstract

A two-year study of physical, biological, and chemical aspects of Minnesota wastewater treatment ponds was conducted. As a part of this study, the one-dimensional unsteady advection/diffusion lake model MINLAKE was adapted for simulation of pond processes. A special sub-routine to track the ponds' *Daphnia* population was developed. Toxic effects of ammonia, low dissolved oxygen, and hydrogen sulfide were included in the model. The model and sub-routine were calibrated, and showed reasonable agreement with population data collected during the study. Development of the *Daphnia* sub-routine and its performance in the overall pond model are discussed herein.

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I. Introduction

Stabilization Ponds - General Information

Many ways of purifying domestic, agricultural, and industrial wastewater have evolved over the past century. Probably the simplest of these involves pumping the water into large basins and allowing it to rest there for a variable period of time. Through a complex combination of chemical and biological processes, these basins - called wastewater stabilization ponds - are able to purify the water to the point where it can be safely returned to local streams or rivers.

Wastewater stabilization ponds represent a low-cost, low-energy, low-technology method of treating sewage. They require little maintenance, and usually demand relatively little human attention in order to provide a high quality treated effluent. Stabilization ponds are effective in a wide range of climatic settings (Gloyna, 1971; Shelef, 1979; Oleszkiewicz and Sparling, 1987), and therefore are employed in wastewater treatment worldwide. Domestic, agricultural, and even industrial wastes are currently being treated successfully using such ponds (Srivastava et al., 1986; Mara, 1987). Wastewater stabilization ponds are particularly well suited to the needs of small rural communities where land is readily available and total sewage flow volumes are moderate. Minnesota communities make good use of this treatment method; approximately 250 such ponds are in operation, primarily in rural areas of the state (Sexauer and Karn, 1979).

Treatment ponds such as those used in Minnesota have been described as being fundamentally a two-component ecosystem. Here, algae flourish and, through photosynthesis, provide oxygen to allow the growth of bacteria which consume the detritus or carbon load. While this analysis does provide the barest skeleton of the pond water purification process, the actual situation is much more complex. Wastewater treatment ponds represent an intricate and dynamic layering of plant and animal species - including many algal species, macrophytes, a host of aerobic and anaerobic bacterial species, several zooplankton species, a variety of representatives from the insect kingdom, and at times vertebrate inhabitants such as frogs, shore birds, and ducks. In concert with this complex biological system is a fluctuating chemical environment that changes constantly with varying loads, biological activity, and climatic conditions; and a continually shifting hydrodynamic mixing regime which may vary even hourly with changing weather conditions.

Problems with Excessive Algae

The ability of ponds to substantially improve wastewaters has been well documented (see for example Middlebrooks et al., 1982). After sufficient detention time, wastewaters show greatly reduced BOD, COD, total nitrogen, phosphorus, and coliform counts.

Often, however, treatment ponds have difficulty meeting regulatory standards for suspended solids due to the presence of algae in the water. Excessive algal presence is a common and often-cited problem in ponds throughout the world (e.g. Brockett, 1977b). Several methods may be used for removing algae prior to discharging finished water to receiving streams, including the use of herbicides (commonly, copper sulfate), coagulating agents such as alum, and even filtration of the effluent. Alternatively, schemes have been developed to preclude algal growth while still providing necessary oxygen by promoting the growth of floating macrophytes such as water hyacinths or duckweed (Ehrlich, 1966; Thomas and Phelps, 1987).

Daphnia and Ponds

At the same time, it has often been observed that wastewater treatment ponds are often capable of producing an effluent that is nearly free of algae without human intervention. The capacity of the ponds to intermittently remove algae has been noted and documented in many locations worldwide (see Dinges, 1973). As this clear-water state ("Klarwasserstadium", as it was originally described - Uhlmann, 1967) is a desirable condition for pond water when it is to be discharged, the cause of the decline of the algal population has been extensively studied. The decline has been widely attributed to consumption of the algae by filter-feeding herbivorous zooplankton.

In particular, members of the microcrustacean *Daphnia* genus - distributed widely in fresh water bodies worldwide - are held to be primarily responsible for the successful generation of a clear pond effluent. Though pond waters support a wide range of animal life, attention is focused on *Daphnia* since they are among the largest of the herbivorous zooplankton and therefore best suited for consuming large quantities of algae. Characteristics of *Daphnia*, and its relationship to pond processes are examined in detail in this report.

The LCMR Study

Minnesota treatment ponds are not immune to the problems of excessive algae. The Minnesota Pollution Control Agency requires the communities operating to keep the measured "total suspended solids" (TSS) below 45 milligrams per liter of water discharged from their ponds. Because of dense algal growth, at times this requirement cannot be met.

One possibility for solving this algal problem is to encourage the growth of a healthy *Daphnia* population that could control the algae by grazing. At the instigation of Dr. Ed Swain, then of the MPCA Water Quality division, and Dr. Heinz Stefan of the University of Minnesota, the present study was undertaken in May, 1989, to examine treatment pond processes. With funding from the Legislative Committee for Minnesota Resources, the goal was to develop a computerized mathematical model that could simulate pertinent chemical, biological, and physical effects. Such a model would help to show why some ponds are able to keep algae in check by maintaining thriving *Daphnia* populations.

The successful prediction of water quality parameters requires field data to use in model formulation, and against which modeling results can be compared. For this project, field data was collected primarily from the stabilization ponds at Harris, Minnesota. The Harris site was selected because of its history of successful operation and to its relative proximity to the University of Minnesota. During the two-year study period, the physical limnology, biology, and chemistry of these ponds were monitored closely.

Three agencies contributed to this study. The Minnesota Pollution Control Agency Water Quality Division did all of the field work involving biological sampling of the ponds studied, in addition to doing a large amount of data analysis. The University of Minnesota's Civil Engineering Environmental group performed the majority of the chemical analyses, and did much of the chemical sampling. The development of the computer model for the pond simulations was the responsibility of the Saint Anthony Falls Hydraulic Laboratory (SAFHL) at the University of Minnesota. Collection and analysis of the physical and weather data pertinent to the study was also done by members of SAFHL.

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This report summarizes the research done with respect to the modeling of *Daphnia* in Minnesota ponds. It tells what work had been done previously, gives an overview of the life cycle of *Daphnia* and its relationship to the stabilization pond environment, and explains the development of the model. It also relates the modeling work to the sampling and biological analysis conducted by the MPCA. Finally, it provides recommendations for pond operation and for future study.

II. Review of Literature

Daphnia

Daphnia are common inhabitants of non-saline water bodies worldwide. Their role in lakes and natural ponds has been well-studied, and much is known about their habits in those situations (see for example Wetzel, 1983; Peters and De Bernardi, 1987; George et al., 1990; etc.). In addition, plentiful information may be found about *Daphnia* in controlled laboratory experiments (e.g. Haney, 1985; Helgen, 1987). Much less is known, however, about their behavior and adaptations in the unusual environment of the wastewater treatment pond.

Only scant information is available concerning the precise nature of the interactions of *Daphnia* with the stabilization pond environment. The most comprehensive work on this topic is the publication: *Ecology of Daphnia in Stabilization Ponds* by Ray Dinges (Dinges, 1973). Dinges discusses many aspects of the biology of *Daphnia*, and their distribution in Texas stabilization ponds. Several articles pertaining to treatment ponds point to *Daphnia* as playing a role in successful pond operation, but few go beyond that simple assertion (Dinges, 1973; Daborn et al., 1978).

Stabilization Pond Modeling

Several modeling schemes have previously been devised for wastewater stabilization ponds. Many of these are relatively simple models designed primarily to predict biochemical oxygen demand (BOD), treating pond hydrodynamics in a very simplified manner (see review in Ferrara and Harleman, 1980; also Fritz, 1985, and Middlebrooks, 1987).

More complicated models attempt to predict a wide variety of chemical, biological, and physical variables; such as pH, BOD, dissolved oxygen (DO), ammonia, phosphorus, and chlorophyll-a (representing algae). Fritz (1979), for example, reports success in treating twelve state variables in his model. Moreno (1988) describes a simulation which attempts to predict several pond parameters, including zooplankton. In a 1987 Ph.D. thesis (New, 1987), George New presents an "Ecological Model of Wastewater Treatment Ponds". New attempted to adapt a fast-flushing reservoir model (RESEN) to the modeling of continuous flow pond systems in Corrine, Utah. His comprehensive model incorporates many features of the above models, contains a zooplankton compartment, and attempts to predict seasonal variations in two algal species: Microcystis, a blue-green, and Scenedesmus, a green. (This thesis is also noteworthy for its excellent summary of the history of stabilization ponds, and its comprehensive review of treatment pond modeling literature.)

(It should also be mentioned that many other lake and reservoir models exist that attempt to predict physical, biological, and chemical changes occurring in these larger water bodies. Some of the better known of these are the U.S. Army Corps of Engineers' QUAL R1 and QUAL R2, and the U.S. EPA's WASP models.)

The zooplankton compartments in these and other water quality models simulate population dynamics by modeling zooplankton growth, respiration, and death. Growth is predicated on temperature and food supply, respiration is linked to ambient temperature, and mortality is dependent upon temperature, and possibly, predation. But none of the existing schemes account for the rapidly fluctuating chemical and physical environments - see Luck and Stefan, 1990 - typical of many wastewater stabilization ponds. These effects must be taken into account if one is to accurately model the *Daphnia* population in stabilization ponds such as those found in Minnesota.

III. Biology of Daphnia

Daphnia in Natural Systems

A brief description of the biology of *Daphnia* as encountered in naturally occurring lakes and ponds follows:

Daphnia in General

Daphnia is a member of the Cladoceran order of microcrustaceans (kingdom: Animalia, class: Crustacea, sub-class: Branchiopoda), its classification within the animal kingdom based on its physical characteristics. A tiny relative of shrimp, it thrives in fresh water bodies throughout the world. *Daphnia* is a filter-feeder, straining algae, bacteria and bits of detritus for food from the water in which it lives. *Daphnia* are visible to the naked eye; they range in size from about one to four millimeters long. For locomotion it uses frequent and sudden thrusting motions of its pair of forward-mounted antennae. The peculiar hopping motion that results from this spasmodic paddling caused it to be given the nickname "water flea." (For a good general introduction to the basic biology of *Daphnia*, the reader is directed to the appropriate section in Wetzel's Limnology, or to the comprehensive review of *Daphnia* research by Peters.)

Several species and sub-species of the *Daphnia* genus may exist in wastewater treatment ponds, and the various species show some differences with respect to feeding rates, longevity, susceptibility to toxic chemicals, vulnerability to predators, etc. (Wetzel, 1983; U.S. EPA, 1984). However, the basic life history of *Daphnia* is the same throughout the genus. One must examine the life cycle of this zooplankter in order to understand the dynamics of its interaction with the treatment pond environment.

Life Cycle

Daphnia may be born either through the hatching of the so-called "resting" eggs (see below), or they may be hatched live after incubation in the female's brood pouch. Newborn are approximately one-eighth the size of the adults, but grow and develop rapidly under favorable conditions of temperature and food supply (see life cycle schematic, Figure 1). Growth stages, or "instars", are bracketed by the periodic shedding of the chitinous exoskeleton called the carapace. The number of instars varies between species, and ranges from about eight to over thirty (Wetzel, 1983). The duration of each instar is also highly variable, depending primarily on temperature conditions. Time between molts varies from a few days up to a period of weeks.

It follows that if one excludes death due to toxic events or predation, the life span of *Daphnia* will depend on the presence of an adequate food supply and will be a function of pond temperature. "Life tables" have been constructed for *Daphnia* relating life span to ambient temperature (e.g. Korpelainen, 1986). In general terms, provided food is plentiful, *Daphnia* will live from 25 to 110 days. If food is scarce, starvation will result. Young *Daphnia*, having a higher metabolic rate due to the requirements of their growth processes, would be expected to be more susceptible to the effects of nutritional deficits.

Under favorable conditions, *Daphnia* may achieve reproductive age in as little as six days after hatching (Dinges, 1973). Normally, when ambient conditions are favorable, fertile eggs are produced by the female through parthenogenesis - without the services of the male. The number of eggs per brood is highly variable, ranging from 2 to 70 (Daborn et al., 1978). Fertile eggs are released from the ovaries and deposited in the brood pouch for incubation, which may take many days or as few as two (Dinges, 1973). Both the number of eggs per brood and the time of incubation relate to the ambient conditions, with accelerated reproduction occurring during periods of warm temperatures and plentiful food supplies (Wetzel, 1983). One female is capable of producing as many as 20 broods during her lifetime. The eggs hatch within the brood pouch of the mother, and soon after, the mother sheds her carapace and the young are released into the surrounding water.

As long as ambient conditions remain favorable, only females are produced through this brood hatch process. And since normally the eggs are auto-fertilized, no mixing of genetic strains takes place. It can be seen that this reproductive strategy rapidly produces a set of large numbers of genetically identical female clones - presumably well-suited to the particular pond environment in which they were born.

When the population is under stress - i.e. when the population is declining due to predation, declining temperatures, inadequate food supplies, or adverse pond chemistry - males begin to be produced by the brood hatch process (which normally only produces exclusively females). The existence of male *Daphnia* is thus an indication that the population is under stress and preparing to adapt to changing conditions. With the presence of males, sexual reproduction takes place, and there is the opportunity for genetic mixing between the clones.

Sexual reproduction, however, produces only two eggs in the female. These eggs become encased in a resistant shell known as the ephippium, which is shed with its enclosed eggs at the next molt. Ephippia released into the water may either sink to the sediment or float to the surface. The shell provides a protective seal for the enclosed eggs, allowing them to endure extremes of temperature, drying, or adverse chemical environments. The protected eggs lay dormant for a variable period, later hatching under the influence of environmental cues. Through this supply of resting eggs, *Daphnia*

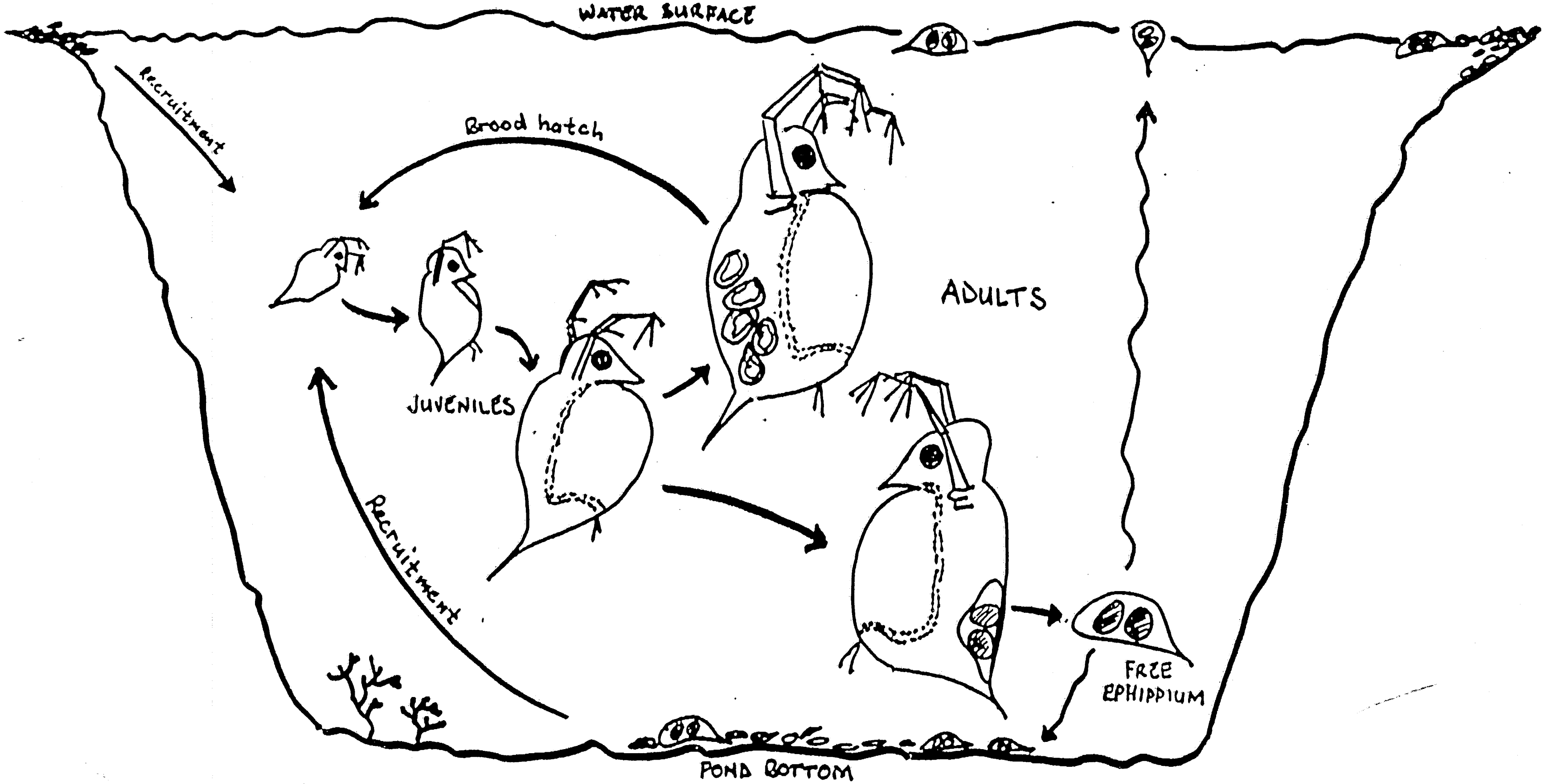

Figure 1: Life cycle of *Daphnia*, the "water flea"

have a means of surviving periodic adverse events which would otherwise be catastrophic to the population, and a means of re-starting the population when conditions once again become favorable. This adaptation is particularly useful in the pond environment, where temperature, mixing, and chemical conditions may fluctuate greatly.

Not all of the ephippial eggs survive and develop into mature *Daphnia*. Some are likely to be consumed by insects and birds. Some may succumb to extremes of temperature, or prolonged desiccation. Still others may be killed by toxic chemical environments likely to exist at the pond bottoms. The survival rate of the ephippial eggs is difficult to assess, and as such is not defined in the literature.

Information on ephippial hatching rates in wastewater treatment ponds is apparently non-existent, but even data on resting egg populations in lakes is almost impossible to come by. One noteworthy study by Carvalho and Wolf (1989), tracked ephippial egg populations and hatching rates in two glacial lakes in Germany. They found that while ten to fifteen percent of the ephippia appeared viable, only a tiny fraction (less than 1%) of the sediment eggs actually hatched under natural conditions. It is obvious, however, that in wastewater treatment ponds, many eggs do survive to hatch and allow the population to re-establish itself when conditions once again become favorable.

The precise nature of the environmental cues necessary to stimulate hatch of the ephippial eggs is not well understood either. Proper temperature and adequate photoperiod have been studied as the environmental triggers that may allow hatching (Peters and De Bernardi, 1987, Carvalho and Wolf, 1989a). It is known that a waiting period, or "diapause" is required before the sexually produced young can hatch - the eggs are unable to open immediately after being released to the water. But the exact time of the wait is not known with precision, and appears to vary with environmental conditions. The time required for diapause appears to vary from 3 weeks to 6 months (Wetzel, 1983). Only female *Daphnia* are generated from the resting eggs.

Daphnia and Algae

Daphnia in the wastewater stabilization ponds consume algae; for this reason alone they are given special attention in treatment pond modeling. *Daphnia* may also feed on bacteria and detritus in the ponds, but algae is the preferred source of nutrition.

This picture is complicated somewhat by the fact that *Daphnia* can only consume certain types of algae. *Daphnia* are filter-feeders, using their ciliated thoracic legs to draw water into their food slot where edible particles are removed for consumption. Certain algal particles are too large to be taken into the food slot and are rejected by *Daphnia*; the majority of the ingested algae are protococcal algae, small greens or diatoms and flagellates (various; Porter, 1981; Peters and De Bernardi, 1987, p.177) Blue-green algae are of limited value as a food source for *Daphnia*. Blue-green algae tend to coalesce into long strings, making them too large and unwieldy for the tiny microcrustaceans. Certain blue-greens may also secrete toxic or gel-like substances, making them unpalatable. Hence successful *Daphnia* modeling in wastewater stabilization ponds must take into account the presence of different species of algae which may vary in their usefulness to *Daphnia* as a food source. [It bears mentioning at this point that despite the efforts of many researchers, the reasons for the dominance of a particular class of algae in a particular water body remains a mystery (see Shapiro, 1990). As a consequence, modeling of algal speciation remains tenuous and unreliable (Smith, 1987). This presents a hindrance to successful *Daphnia* modeling.]

The rate of consumption of algae by a *Daphnia* population will depend on several factors. As water temperature increases, the metabolic rate of *Daphnia* will also increase, requiring increased caloric intake. Larger *Daphnia* species will require larger daily food supplies - the rate of intake being proportional to the cube of the body length in larger species such as *D. magna* and to the square of body size for smaller species such as *D. rosea* (Burns, 1968; Peters and Downing, 1984; Haney, 1985). Similarly, younger, smaller members of a given species will consume less - though their small size would be expected to be compensated for somewhat by their higher metabolic rate.

Population Dynamics

When toxic effects are ignored, the interaction between *Daphnia* and those algae upon which they feed is typical of "grazer - grazed upon" (or "predator-prey") relationships described by population ecologists. Represented in graphical fashion (see Figure 2 in this report, from Whittaker, 1975) with time as the ordinate axis and population density as the abscissa, the relationship may be understood through the population traces.

First, the algal population (prey) will rise owing to the beneficial influences of adequate nutrients, abundant sunlight, and sufficient warmth (if other environmental factors are favorable). As the algal population increases, the small numbers of surviving *Daphnia* (predators) will find their environment enhanced by the newly plentiful algal food source and their reproduction rate will increase. Losses to the algal population through grazing become more significant as the *Daphnia* become more abundant, and soon the rate of algal population increase will diminish. When the *Daphnia* population rises to the point where it is able to consume algae as fast as it is produced, the algal population curve will peak. This relative decline in net algal production will not be immediately recognized by the *Daphnia* population, however, and it will continue to increase its numbers. The algal population thus begins to decline as consumption by the still increasing *Daphnia* outstrips its own reproduction.

Soon the numerous *Daphnia* begin to feel the effects of the relative scarcity of food,and the rate of population increase begins to level off. Still, however, numerous

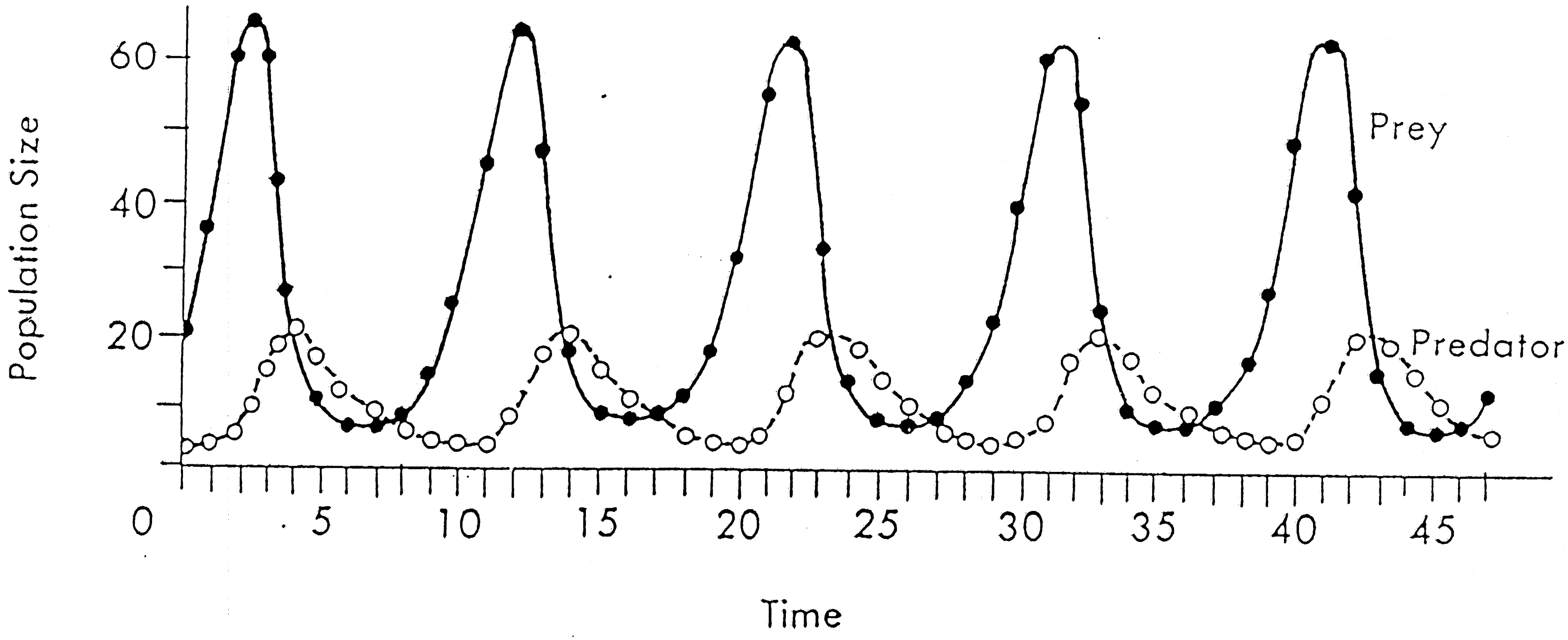

Figure 2: Population cycles for a hypothetical predator and prey

Daphnia will be combing the waters for algae, further reducing algal concentrations. (It is when the still numerous Daphnia reduce the algal concentration to a very low level that the "clear water state" is presumed to occur.) Finally the algae is effectively depleted and the *Daphnia* become stressed by inadequate food supplies. Population levels drop rapidly, while resting eggs are produced. This pattern of an algal peak and decline followed soon after by a similar peak and decline in the
Daphnia population may be repeated periodically throughout the year.

***Daphnia* in Stabilization Ponds**

As has been mentioned, little is known about *Daphnia* dynamics in the unusual environment of wastewater stabilization ponds. While it may be assumed that these creatures will generally behave and react much as they would in any freshwater habitat, there is little data available with which to either prove or disprove this assertion. However, even after allowing that most life cycle parameters will remain the same, it is clear that the pond environment presents conditions that require re-thinking of zooplankton modeling.

Migration

In deep fresh water bodies such as lakes, *Daphnia* are known to traverse relatively great distances on a daily basis, traveling from deeper refuges at dusk to overnight in shallow waters and then return to the depths at dawn. This phenomenon, known as daily vertical migration (DVM), has been well documented. Migratory rates of up to 10 meters per hour have been observed (McNaught and Hasler, 1964). The migrations are thought to demonstrate an adaptation to the lake environment, allowing the *Daphnia* to feed in the algae-rich epilimnetic waters during the darker hours when predators such as fish will be unable to see them as readily. The *Daphnia* then return to the less well-lit deep refuges during the daylight hours.

It is reasonable to expect that *Daphnia* will respond to light, no matter what its habitat. However, in the shallow (depths of 1/2 to 2 meters) treatment pond environment the adaptive advantage of vertical migration is doubtful. Furthermore, fish are unlikely to be present in the ponds, so that escape from visual predators may not be necessary. It is not known whether *Daphnia* in these ponds actually do migrate on a daily basis (though observations of ponds studied for this project - see Helgen, 1992 - suggest that some migration does take place). However, the well-known migratory ability of *Daphnia* in freshwater lakes suggests that they are capable of seeking out and remaining in regions of the pond that are conducive to their survival. Work done by Haney using toxins produced by blue-green algae (Haney, 1980) indicated that *Daphnia* actively avoid hostile environments and seek out more hospitable aquatic regions.

In addition to moving vertically, *Daphnia* may be assumed to travel and become unevenly distributed in the horizontal plane. This aspect of *Daphnia* population dynamics has been less well studied, and little has been written documenting lateral movements or seeking to explain them. Possible reasons for *Daphnia* developing a "patchy" horizontal distribution would include shade-seeking behavior, or congregating in cooler areas or areas of relative oxygen or food abundance.

Predation

While fish are generally not found in these smaller water bodies, *Daphnia* are nonetheless a target of predation in wastewater stabilization ponds. Ducks and shorebirds may feed on the *Daphnia* and their eggs. And at least at certain times of the year, the rise of a population of predatory invertebrates within the pond, or the immigration of predatory insects to the pond may diminish the *Daphnia* population. The larval form of the midge *Chaoborus* appears frequently in treatment ponds and is known to consume *Daphnia* in large numbers. Various swimming insects and beetles which are known to prey on *Daphnia* are often seen in ponds. In addition, various protozoan species exist in the ponds as parasites on *Daphnia* and may further diminish the population.

Quantifying any sort of predation on *Daphnia* in the ponds is extremely difficult. To do so requires both an accurate estimation of the numbers of the predatory species and knowledge of their rates of *Daphnia* consumption. Tracking the populations of transient invertebrate pond inhabitants would require continuous sampling or accurate modeling. And, the *Daphnia* consumption rates for these transient predators have not been established.

Further complicating the situation is the fact that predation would, to some extent, be dependent on the size of the prey; each predator will feed selectively on *Daphnia* of a certain size. Thus, whether a particular individual is eaten or not would depend on the maturation stage of the individual, and predatory rates would fluctuate with the relative maturity of the *Daphnia* population as a whole.

In addition to being difficult to quantify and model, predation may not be extremely significant. Several authors question the significance of invertebrate predation as a control on *Daphnia* populations (Neill, 1981; Peters and De Bernardi, 1987).

Temperature Effects

Zooplankton in Minnesota must contend with a climate that changes drastically throughout the four seasons. Fortunately, *Daphnia* are adapted to endure a wide range of temperatures, from near freezing to over 35 degrees centigrade (Dinges, 1973). Except occasionally at the surface, pond temperatures measured for this project (Luck and Stefan, 1990) were uniformly within the ranges in which zooplankton may be expected to survive and thrive. At no time was a cool water refuge unavailable. It is concluded that *Daphnia* populations in Minnesota ponds will not suffer mortality due to temperature effects alone.

Toxicity

Daphnia in wastewater stabilization ponds must also contend with frequent fluctuations in the chemical environment, some of which may affect them adversely. Some of the chemical components of the pond waters (e.g. dissolved oxygen, hydrogen sulfide, and ammonia) occur commonly and are intrinsic to the ponds' digestive processes (Mackenthun and McNabb, 1961; Brockett, 1977a). At times, however, the ponds may also carry toxic concentrations of chemicals which are not normally a part of the treatment environment, such as pesticides or metal ions. A discussion of those factors thought to influence the *Daphnia* population follows:

Oxygen - Since it is a gas, oxygen is able to become dissolved in water bodies that are exposed to it. Oxygen enters waters by one of two methods - either by diffusion from the atmosphere, accelerated by surface turbulence and wave action; or as a result of the exhalation of oxygen by algae or larger plants during photosynthesis. In turn, the oxygen leaves the water either by diffusion into the air or by being consumed by respiring plants and animals (plankton, bacteria, and macrophytes) in the water.

Levels of dissolved oxygen (DO) may vary greatly during a single day in the intense environment of the treatment pond. Furthermore, a large difference in DO may develop between the surface and deep pond waters. DO levels in Minnesota wastewater stabilization ponds range from nearly zero (0.1 mg/l) to well over twice the saturation level for oxygen in water - DO values of more than 25 mg/l are not uncommon (Luck and Stefan, 1990).

Daphnia are quite tolerant of fluctuations in oxygen levels (owing in part to their ability to produce oxygen-carrying hemoglobins - Peters and De Bernardi, 1987), although they must have some oxygen to survive. While they seem to prefer environments having DO levels above at least 0.5 mg/l, they are able to survive in waters of very low dissolved oxygen - 0.1 mg/l (Scheithauer and Bick, 1964), and can do quite well at 2 mg/l. Very high DO levels do not seem to be a problem for *Daphnia*, although extremely high DO levels in ponds will typically be accompanied by high levels of other substances that *Daphnia* find intolerable.

Hydrogen Sulfide - Obligate and facultative anaerobic bacteria present at the bottom of the ponds produce hydrogen sulfide gas (H_2S) as a by-product in their consumption of organic material through the reduction of sulfates. Sulfate-reducing bacteria are favored by warm water temperatures. H_2S gas is produced under anaerobic conditions (which are commonly found in the lower regions of wastewater treatment ponds), but may be oxidized to sulfate when oxygen becomes available.

Sulfide in water is toxic to many aquatic organisms, *Daphnia* included. It has been reported that *Daphnia* do best when sulfide concentrations are below 0.4 mg/l, but can survive at H_2S levels of as high as 3.0 mg/l. Toxicity also seems to be directly related to increased pH (Scheithauer and Bick, 1964).

Ammonia - Ammonia is a common constituent of domestic sewage, its presence in wastewater stabilization ponds primarily owing to the breakdown of urea and nitrogen-bearing organic compounds. The concentration of ammonia in raw municipal wastewater is frequently in the range of 9 to 30 mg/l (Metcalf & Eddy, 1972), but may be in excess of 50 mg/l, and higher still in industrial wastes.

The toxicity of ammonia to aquatic organisms is well known. The neutral NH_3 species of ammonia is generally held to be much more toxic than the positively charged NH_4^+ ("ammonium") ion. The heightened toxicity of the un-ionized form is linked to its ability to traverse cell membranes more easily than the charged and hydrated NH_4^+ form (Barndthouse and Suter, 1986).

Un-ionized ammonia concentration in the ponds depends on the total concentration of ammonia species (NH_3 plus NH_4^+), but also on the temperature of the water and the pH. Increasing temperature and pH will increase the amount of the electrically neutral form; a 10 degree C rise in the temperature will double the amount of NH_3 in solution, and while virtually all of the ammonia is in the NH_4^+ form at pH 7, fifty percent is in the un-ionized form at pH 9.2 (Thurston et al., 1977).

Precise data relating *Daphnia* mortality to actual ammonia levels in the treatment pond milieu are not available. However, sampling of pond populations when pH and total ammonia have been measured (Dinges, 1973) suggests that *Daphnia* are able to thrive in situations where the concentrations of un-ionized ammonia is less than about 0.15 mg/l, but will not be present when ponds develop concentrations in excess of about 0.7 mg/l. In addition, larger species of *Daphnia* (such as *Daphnia* magna) seem to be better able to tolerate higher ammonia levels. Similarly, the toxic effects of ammonia would be expected to bear more heavily on the younger, smaller members of a population.

It has often been noted that the presence of *Daphnia* in wastewater treatment ponds is frequently associated with conditions of relatively low pH. This lends support to the idea that *Daphnia* cannot exist in ponds where the high pH levels promote high levels of the ammonium ion.

Pesticides - While pesticides would not normally be applied directly to wastewater stabilization ponds, it is possible that they may find their way into the pond waters. Pesticides may be employed in the immediate area for control of mosquitoes, blackflies, and midge larvae. As a result of overspray, or improper domestic disposal, pond waters may become contaminated with toxic organochlorines such as DDT, methoxychlor, or temephos.

Even very low dosages of certain pesticides can be lethal to *Daphnia* populations. Cladocerans such as *Daphnia* are especially sensitive to pesticides, and pesticide levels of less than 1 microgram per liter can have disastrous effects on the population (Helgen et al., 1988). Again, due to their higher metabolic rates and lesser maturity, the youngest members of the population would be expected to be the most severely affected.

Herbicides - Certain herbicides such as "Round-Up", "Pramitol", "Vegetrol", and 2,4-D are used periodically by Minnesota stabilization pond operators to control vegetation growth on the surrounding dikes, and on occasion, in the ponds themselves. Such chemicals may have direct, and indirect effects (for example, by killing aquatic macrophytes and thus diminishing shade or oxygen production) on the zooplankton population. (However, since the aquatic effects of such herbicide applications has not been well examined by researchers, and such applications are generally infrequent, herbicide toxicity is not considered in the present model.)

Metal Ions - Metals such as copper, cadmium, lead and zinc are known to be toxic to zooplankton when they occur in wastewaters in their ionic form. Cadmium, in particular, seems to have been well studied with respect to its effects on *Daphnia* - both adult and embryonic forms are affected at concentrations of approximately 1 mg/l (Bodar et al., 1989). When food supplies are plentiful, *Daphnia* seem to be less susceptible to the harmful effects of metal ions (Gerasimov, 1987). While metals are not likely to be present in large quantities in domestic wastes, certain industrial wastes may carry high concentrations.

Copper is of particular interest with respect to wastewater stabilization ponds, since copper sulfate (as an algicide) may be periodically applied to ponds for the reduction of algal concentrations in order to meet discharge requirements. After applications of copper sulfate, copper concentrations in larger water bodies has been observed to drop off quickly (Tseng and Wang, 1986). However, the situation in shallow, more frequently mixed water bodies such as treatment ponds is likely to be quite different. The recycling of copper from the sediments in the stabilization ponds has not been studied. Adverse effects are likely: in concentrations as low as 0.01 mg/l, copper is known to affect *Daphnia* survival (Gerasimov, 1987; also see Hawkins and Griffiths, 1987). Copper sulfate applications are virtually certain to harm the *Daphnia* population, though the extent of the damage is difficult to predict.

Toxic effects of metal ions (as well as other chemical constituents such as ammonia) on zooplankton have been examined in many laboratory experiments. The U.S. Environmental Protection Agency gives information on zooplankton mortality with respect to metal ions in various forms, including: median lethal concentration (LC50), median lethal dose (LD50), median effective concentration (EC50), lethal threshold concentration (LC1), no observed effect level (NOEL), lowest observable effect level (LOEL), and the MATC - maximum acceptable toxicant concentration (Barndthouse and Suter, 1986). Using these bench marks to develop modeling equations would be possible if several points along a mortality curve could be obtained; presumably, the model would also show varying effects as the pH fluctuated within the water body.

It should be noted that the assessment of the toxic qualities of wastewater is complicated and uncertain. Owing to the cost and labor involved, it is impractical to thoroughly analyze pond water chemistry with great frequency. As a result, the exact chemical nature of the water is rarely known. And even the best chemistry models will be limited in scope and thus unable to predict concentrations of all constituents which may influence toxicity. Hence, any listing of the makeup of the water will necessarily be incomplete and uncertain.

But even if the exact composition of the water were able to be known, problems would remain. The precise effects of the chemicals themselves have not been well-characterized. Chemicals in ambient water may have both short-term (acute) and long-term (chronic) effects on the *Daphnia* population; how these effects would combine to bear on a population is not known.

In addition, the interactions of the chemical components of wastewater which produce varying toxic effects are not well understood. Most studies that assess toxicity to aquatic organisms focus on one chemical in isolation, and consider its effects under well-controlled and constant laboratory conditions. But it is known that in combination, toxicity-producing components may interact to produce effects quite different from those produced by a single chemical in isolation. (See U.S. E.P.A, 1985.) Components may interact synergistically, enhancing the toxic effects of each other; or antagonistically - canceling the effects of each other to some degree. In the complex and fluctuating stabilization pond environment it becomes very difficult to assess the likely effects of the water at any given moment. Ideally, toxicity modeling would determine the combined effect of a multi-dimensional matrix of pond chemicals in order to determine the overall resulting toxicity.

Further complicating the assessment is the fact that *Daphnia* does not respond uniformly to toxic stress. Juveniles, for instance, are known to be generally more sensitive to toxic stress than adult forms. Even within a particular life stage, the condition of the *Daphnia* with respect to temperature and food satiation will determine (at least to some extent) what its response to chemical stress will be.

Effects of Water Transfer on *Daphnia*

The typical waste stabilization pond system in Minnesota consists of two, three, or more ponds in series. The wastewater being treated is moved from one pond to the next in sequence, and the water is detained in each pond for a period of weeks or months before being moved to the next pond (see previous discussion). When the treated water in the last pond is judged to be of sufficient quality it is discharged into the receiving stream. Typically, discharges occur in the spring (April or May) and fall (September or October); operating conditions may necessitate supplementary discharges as well. The last pond is then refilled from the next pond up in the series.

A pond system operated in this way presents a sequence of differing chemical and biological environments. The uppermost pond in such a series will generally show the highest BOD loads, the greatest tendency toward anaerobic conditions, and the most H_2S production and release. Following ponds will show an amelioration of these harsh conditions, and thus a greater likelihood of supporting *Daphnia* populations. If the system is operating effectively, the last pond's water will be much less concentrated than those preceding it, and will be most likely to be able to generate the clear water state resulting from a thriving *Daphnia* population.

When communities of zooplankton exist in ponds upstream from the last one, pond water transferred sequentially will carry some *Daphnia* - both young and adults, and possibly even resting eggs - from upper ponds to lower ones in the sequence. One would expect the highest population densities in the downstream ponds; rigorous modeling would require accounting for the periodic immigrations and emigrations of *Daphnia* in each pond.

IV. Development of the *Daphnia* Model

General Concepts

Devising a mathematical model that describes the complex processes that take place in wastewater treatment ponds serves several purposes. First, it provides a vehicle by which a comprehensive study and analysis of the myriad hydrodynamic, biological, and biochemical pond processes may be accomplished. It allows this analysis to take place in an orderly, step-wise fashion, and allows some means for an evaluation of the accuracy of the analysis.

Second, if the modeling effort produces a system that seems to function well in simulating the changes that occur in the pond environment, the model may serve as a useful tool in predicting consequences of disturbances to the ponds. The effects of periodic discharges or of changes in loading rates, possible consequences of unusual climatic events, or long and short term effects of applications of copper sulfate or alum may be able to be predicted and planned for. This would have value in allowing more effective management by pond operators, serving as an aid in decision making processes.

Similarly, an effective model may have value in diagnosing problems with "problem ponds" - ponds that frequently have difficulty meeting regulatory effluent standards. Model simulations have the potential of being able to track down the underlying cause of the problem, and suggest possible means for its correction. Design alterations may be suggested as well by an examination of model results. Such possibilities make the modeling effort seem worthwhile.

Worthwhile as the effort may be, wastewater treatment pond systems present a dauntingly numerous and complicated array of interlocking mechanisms. The impossibility of actually defining and elucidating all of these, and describing the methods of their interactions soon becomes apparent. Hence the modeler is forced to reduce the processes considered to a manageable number, attempting to select those which seem to be most important. It is hoped that the processes selected and described will be sufficient to "capture" enough of the actual situation to make the resultant model sufficiently valid and useful.

Assumptions for the Daphnia Sub-model

The proposed *Daphnia* sub-model which follows makes several simplifying assumptions in order to bring the processes considered down to a manageable number. These assumptions and their rationales are described below:

1) The model assumes that inter-species differences within the *Daphnia* group will not be critical in assigning values to the calibration coefficients. Many of the coefficients used are for *Daphnia pulex*, despite the fact that Minnesota's treatment ponds carry other species as well - notably *Daphnia magna* and *Daphnia similis*. The *D. pulex* (along with *D. magna*) species is abundant and common, and it is hoped that the other species will be accounted for accurately enough by the parameters used for this one representative.

2) While it is known that *Daphnia* of different ages and sizes have different nutritional requirements, filtering rates, growth rates, and susceptibilities to noxious agents or starvation, the model treats the population as though it were homogeneous. This is done with the expectation that an "average *Daphnia*" may be used to represent the population effectively.

3) The model does not track the resting egg population. The existence of a standing supply of resting eggs is assumed, however, in order to start the population after the winter die-off, and to restart the population should toxic effects destroy a stable population. Apart from these contributions, the hatch from resting eggs is held to be insignificant by comparison to prolific brood hatching under favorable conditions.

4) Predation on *Daphnia* is not expected to be significant. To date, biological sampling of the ponds indicates that invertebrate predators do not exist in numbers large enough to significantly affect the *Daphnia* populations. Fish are likewise assumed to be absent from the treatment pond environment. If predators are found to be present, their effect can be accounted for by the predation sink term provided in the model.

5) Immigration of *Daphnia* to the ponds is assumed to be insignificant, despite the periodic transfer of water between ponds. Sampling has shown that *Daphnia* numbers increase from the upstream ponds to the downstream ones (MPCA Studies). It is thus assumed that the relatively low numbers of *Daphnia* brought in by the transfers of water will not greatly alter the population dynamics established by the existing physical, chemical and biological conditions. Pond drainage, however, may reduce the population significantly and must be accounted for; subsequent transfer of water into the pond will dilute the resulting population.

6) Diurnal migration, a well-examined feature of *Daphnia* in large water bodies, is ignored by the pond model. Migratory distances would be small, and frequent mixing of the ponds tends to make the migratory effects less significant. In addition, there is not likely to be adaptive advantage in migrating in the pond environment - consumption and predation will not be affected greatly by daily vertical migration.

7) Only acute toxic effects are represented by the model. It may be surmised that chronic toxicity of the pond water may indeed adversely affect the *Daphnia* population. However, it is assumed that the acute effects will be more significant, and sufficient to represent the changes in the population resulting from chemical effects.

8) The model assumes that *Daphnia* will find their way to layers of the pond in which the chemical environment is favorable. This assumption forces the model to predict that the pond's population will at times tend to concentrate in only some of the strata. Perhaps more significantly, this assumption allows the *Daphnia* population to be unaffected by toxic chemical environments existing in only some of the layers. The result is that very low levels of dissolved oxygen, or high concentrations of ammonia or hydrogen sulfide, will only diminish the population if such levels are present throughout the entire depth of the pond.

9) Pesticides, herbicides, and toxic metals, all of which are capable of having significant effects on *Daphnia* populations, are assumed to be absent from the treatment ponds. The validity of this assumption may be called into question by unexplainable or precipitous population declines, or failure of the species to establish itself under apparently favorable conditions. A model for metal toxicity might be developed similar to that used for other toxic substances (see below), but without field data the validity of such a model would be impossible to determine. (If copper sulfate were applied to the pond, one could simply assume one hundred percent mortality for a period of several days. The population could then be re-started from the supply of resting eggs.)

10) Hydrogen ion concentration in itself is unimportant in the model. *Daphnia* are known to be sensitive to acidic conditions (Dinges, 1973), but Minnesota treatment ponds characteristically support moderate to high concentrations of hydrogen ion (pH 7.0 to 10.0). Pond pH will be important through its effect on ammonia speciation, however.

11) Only two types of algae need consideration in order to successfully model *Daphnia*: edible and non-edible species. The distinction between the two would be made on the basis of size, and possibly other characteristics such as filamentous nature or toxicity. A variety of algal species would be grouped under each category.

Mathematical Relationships for *Daphnia* Model

The actual mathematical relationships used to describe the relevant physical, chemical, and biological processes are described in the sections that follow.

Movement of *Daphnia* between Pond Layers

In contrast to the other variables in the MINLAKE model, the *Daphnia* concentrations are not modeled using the one-dimensional, unsteady transport equation. The *Daphnia* population is treated as though it were capable of independent migration between pond layers, and is not subject to advective/diffusive forces acting on the other pond variables such as heat, algae, and chemical components. Hence, as mentioned earlier, the model will show the *Daphnia* uniformly concentrated in those layers of the pond that present a suitable chemical environment. The toxic factors ammonia, hydrogen sulfide, and low dissolved oxygen, will not have a detrimental effect on the population unless they are determined by the model to be present at toxic levels throughout the depth of the pond.

Vertical distribution of the *Daphnia* is thus determined by the toxic situation. Subsequent population modeling effects will depend upon the conditions found in those pond layers in which toxic determinations place the *Daphnia*.

The model evaluates each layer of the pond for the total toxicity resulting from low DO, high ammonia or hydrogen sulfide concentrations. If none of the pond layers show a combined death rate due to toxicity greater than 0.005 (arbitrarily set to a low value), the *Daphnia* remain evenly distributed throughout the depth of the pond. If only some of the pond layers are shown to be toxic, the *Daphnia* are re-distributed evenly throughout the non-toxic layers. They are thus allowed to escape the deleterious chemical effects that may be present in only some portions of the pond.

If all of the pond layers are determined by the model to be toxic, all of the *Daphnia* are placed in that layer which is found to be the least toxic. Then the combined death rate owing to the toxic substances in that layer is allowed to take its toll on the population.

The *Daphnia* population in a stabilization pond may be increased or diminished through a large and complex array of physical, chemical, and biological mechanisms. However, to keep the model practical, only those sources and sinks judged to be most important are explicitly included. The overall equation used for tracking the changes in the *Daphnia* population is:

$$\frac{\partial D_{TOTAL}}{\partial t} = \sum_{i=1}^{MBOT} (D_i * REPRO_i) + EGDENS * A_{BOT} * RHATCH$$
$$- \sum_{i=1}^{MBOT} (C_{D_i} * DSRATE_i) - \sum_{i=1}^{MBOT} [D_i * (TOXDO_i + TOXNH_i + TOXHS_i)] \quad (1)$$
$$- \sum_{i=1}^{MBOT} (D_i * AGE_i) - \sum_{i=1}^{MBOT} (D_i * DRESP_i)$$

The left-hand side of equation 1 is the rate of change of the *Daphnia* population in time. The right-hand side has six additive terms which represent, respectively: a) live or brood hatching, b) resting egg hatching, c) loss through pond drainage, d) population losses due to toxic effects, e) losses due to aging, and f) losses by endogenous respiration. The summation term (Σ, from i=1 to MBOT) indicates the addition of all the pond layer source or sink values from the pond surface to the pond bottom.

In equation 1,

D	is the number of *Daphnia* in the pond or layer
EGDENS	is the sediment ephippial density (eggs per meter squared)
A	gives pond bottom area (square meters)
BOT	is the pond bottom index
RHATCH	is the rate of ephippial hatch (*Daphnia* per day)
MBOT	represents the index for the bottom layer of the pond
i	is the index for the pond layer in question
REPRO	gives the rate of parthenogenetic reproduction (per day)
DAPHNIA	is the *Daphnia* concentration (individuals per m^3)
DSRATE	is the rate of pond water discharge from the layer in question (m^3 per day)
TOXDO	is the death rate due to inadequate oxygen (per day)
TOXNH	is the death rate due to un-ionized ammonia (per day)
TOXHS	gives the death rate due to the presence of hydrogen sulfide (per day)

AGE — represents age-mediated mortality (per day)

DRESP — is the rate of population decline due to respiration/starvation (per day)

Movement of *Daphnia* between layers is treated separately. A discussion of the source and sink terms follows.

Sources

The model ignores the contribution of incoming *Daphnia* from upstream ponds, and considers reproduction as the only source of new population members. Significant population increases will depend on the live hatch from the parthenogenic female. A small contribution is also made from the resting egg population. "New" *Daphnia* are distributed evenly throughout hospitable pond layers.

Parthenogenic Reproduction - *Daphnia*'s reproduction rate depends upon ambient temperature and nutritional status (Hall, 1964). Other factors also play a role, but are not considered by the model.

The rate of population growth owing to viviparous reproduction is modeled using a Monod-type equation. Under ideal conditions, growth rates may be as high as 10 per day (assuming mean brood size of 20, and a molting rate of once every two days - see Dinges, 1973). *Daphnia* show maximum reproduction rates at water temperatures between 15 and 25 degrees C (Goss and Bunting, 1983); a ramp function gives the maximum rate possible under existing temperature conditions.

Although a minimum nutrient level of 0.08 mg/l (as carbon) is required to allow reproduction to take place (Lampert and Schober, 1980), and rates will depend on the amount of food available above these levels, it is assumed that carbon levels will always be above the low threshold required.

Hence,

$$REPRO_i = GMAX * \frac{EDALG_i}{HSCZP + EDALG_i} \qquad (2)$$

and

$$GMAX = GMAX * T2/15 \qquad \text{IF } (0 < T2 < 15)$$
$$GMAX = GMAX \qquad \text{IF } (15 \leq T2 \leq 25)$$
$$GMAX = GMAX * \{1 - (T2-25)/30\} \qquad \text{IF } (25 < T2 < 40)$$

where

REPRO	is the *Daphnia* parthenogenic reproduction rate (per day)
GMAX	is the maximum rate, under ideal conditions (per day)
EDALG	is the chlorophyll concentration of edible algae (mg/l)
HSCZP	is the half saturation coefficient for zooplankton (mg/l)
T2	is the pond temperature (degrees C)

Hatch from Resting Eggs - A small, finite contribution from the resting egg population (which may be as high as 800,000 per square meter - MPCA studies) is set to provide a start-up population at any time, should that be necessary. The hatch will be photoperiod dependent, however, and will only take place if the amount of daylight hours exceeds 12 (reflecting the observation that *Daphnia* do not normally appear in Minnesota water bodies before the end of March). This corresponds (in Minnesota) approximately to the period between March 20 and September 21, or the Julian days between 80 and 260.

Information regarding *in situ* ephippial hatch rates in wastewater treatment ponds is not available; apparently these rates have not been characterized. In addition, the viability of eggs found in sediment samples is difficult to determine. Using a fairly conservative estimate of the hatch rate (compare, for example, Carvalho and Wolf, 1989b), one may assume that only 0.1% of the eggs present will hatch. Then, allowing that the period of hatching extends over a period of roughly 180 days, the rate per day will equal 1/180 * 0.001, or approximately 5x10-7.

Therefore, if { 80 < DY < 260 }

$$RHATCH = 5*10^{-7} \quad (3)$$

and

$$EPHATCH = RHATCH*EGDENS*A_{BOT} \quad (4)$$

where

RHATCH	is the rate of ephippial egg hatching (per day)
EPHATCH	is the number of *Daphnia* released per day from ephippia
EGDENS	is the measured (or estimated) egg density (number per meter squared)
A_{BOT}	the area of the pond sediment (square meters)
DY	is the Julian day modeled

The number of ephippia would be determined by core sampling and egg counting. Alternatively, or if a sediment count is not practical, a small "feed" of *Daphnia* may be allowed:

$$EPHATCH = 10{,}000 \tag{5}$$

Hatch from resting eggs is added to the bottom layer. However, the newborn are assumed to become distributed quickly throughout the water column owing to the mobility of the *Daphnia* even at birth.

Sinks

Reductions of the population will be a result of several factors: a) natural death due to aging, starvation when food supplies are critically low, b) anoxia if pond oxygen supplies fail, c) the toxic effects of either ammonia or hydrogen sulfide, d) predation by invertebrates (if present in the pond) that feed on *Daphnia*, and e) periodic drainage of the ponds.

As there are several ways in which the *Daphnia* population may be depleted, the model must sum these effects for the time period in question. Losses will be the sum of outflow losses, and death due to predation, starvation, toxicity, and aging.

A ceiling is placed on the loss rates; the sum of the losses is allowed to reach no more than 90% per day. This prevents the model from generating negative values for the *Daphnia* population, and follows the expectation that not all of the population could be killed off in one single day.

Pond Drainage

At the treatment pond site, when water quality in the last pond of the series is judged to be of adequate quality, or when total pond capacity is reached, water from the last pond is discharged to the receiving body. Later the pond is re-filled by allowing inflow from "upstream" ponds.

Since more than half of the pond volume may be lost when water is discharged, more than half of the *Daphnia* population may be flushed out in the process. These losses must be accounted for.

One way of modeling the losses is to use the average *Daphnia* concentration in the pond at the time of discharge. The outflow rates and times, or the change in pond depth can be used to compute a discharge volume. *Daphnia* losses, then, will equal the average *Daphnia* concentration multiplied by the discharge volume, or:

$$OUTLS_i = C_{D_i} * DISCHRATE_i \qquad (6)$$

where

OUTLS	is the population loss due to outflow (individuals)
DSRATE	is the rate of pond water discharge (m^3 per day)
C_D	is the average *Daphnia* concentration at the time of discharge (individuals per m^3)

Total outflow losses would be divided by the number of layers actually containing *Daphnia*, and subtracted equally from each of those layers.

The pond outflow in the model should mimic the actual situation in the ponds; in the model, water should leave from the same layer as it would in the actual pond itself. Presently, the model withdraws water from the layer in which the outflow aperture is located. This seems to be a reasonable approximation of what would be expected to occur during discharge.

The present modeling scheme accounts for this selective withdrawal in accounting for population losses due to pond discharge. *Daphnia*, then, are lost from the pond according to the volume of water withdrawn from a particular layer, and the concentration of *Daphnia* within that layer:

$$OUTLS_i = DAPH_i * DSRATE_i \tag{7}$$

where

DAPH	is the *Daphnia* concentration (number per m^3)
DSRATE	is the withdrawal rate (m^3 per day)
i	is the layer index

The withdrawal volume will normally be zero in each of the layers. *Daphnia* is thus withdrawn only from the layers from which water is taken.

Predation

Through sampling done on the Minnesota ponds for this study, it was determined that invertebrate predation probably would not often play a role in diminishing the *Daphnia* population. However, invertebrate predators (in particular, Chaoborus species, "water boatmen," diving beetles, and Chironomid larvae) have been found in the ponds studied. At times they may be present in numbers large enough to have a significant impact on the *Daphnia*. When this is the case, predatory effects could be accounted for in the model only if the predator concentrations and predatory rates are known. Losses due to predation would be summed for each predatory species present. A typical modeling scheme would be as follows:

$$PREDLOSS_{i,j} = \sum_{n=1}^{k} PRED_{i,j,k} * PMAX_k * \frac{DAPH_{i,j}}{HSCPRED_k + DAPH_{i,j}} \tag{8}$$

where

PREDLOSS	is the overall loss due to predation (indiv. per m^3 per day)
PRED	is the concentration of the predatory species present (indiv. per meter cubed)

PMAX	is the maximum rate of predation for the given predatory species (indiv. per indiv. per day)
DAPH	is the *Daphnia* concentration in the layer (ind. per m^3)
HSCPRED	is the half saturation constant for predation for the predatory species (ind. per m^3)
i,j,k	indices for the pond layer, time step, and predatory species concerned, respectively

The above predation scheme was deemed to be impractical for the pond model in its present form because of the absence of detailed information about the likely predators. However, in order to provide some means for simulating such effects, a simple predation model is included. This scheme allows the user to specify an estimated minimum and a maximum overall predation rate, and dates for the onset of predation and the peak predation rate. A ramp function simulates intermediate changes in predation rates.

The index I is first created to define the fraction of predation allowed at the Julian day modeled:

Then if $\{I \leq 0\}$ or $\{I \geq 2\}$,

$$I = \frac{DY-(MAXDAY-0.5*LENPRED)}{0.5*LENPRED} \tag{9}$$

$$PRED = PRMIN \tag{10}$$

Or if $\{I>0\}$ and $\{I \leq 1\}$,

$$PRED = PRMIN+I*(PRMAX-PRMIN) \tag{11}$$

Or, finally, if $\{I>1\}$ and $\{I<2\}$

$$PRED = PRMIN+(2-I)*(PRMAX-PRMIN) \tag{12}$$

where

I	is the dimensionless index created to indicate the position within the ramp function
DY	is the Julian day modeled
MAXDAY	indicates the day on which the maximum predation occurs
LENPRED	is the length (in Julian days) over which the predation peak occurs
PRED	is the resultant predation death rate for *Daphnia* (per day)
PRMAX	the maximum (user-specified) predation rate
PRMIN	the minimum predation rate; may be set to zero if the user estimates that no predation occurs outside the peak season

A graph of a predation scheme modeled as described above may be found in Figure 3.

Respiration and Starvation

When *Daphnia*'s algal food supply in the ponds becomes extremely low, metabolic demands exceed caloric consumption, and starvation results. Here, starvation - represented as a decline in the population - would occur when food supplies (edible algae) become so scarce that the population growth rate drops below the predicted respiratory mortality rate.

Zooplankton respiration is known to be a function of several factors, including life stage, body size, and temperature. Nevertheless, for simplicity, most authors model zooplankton respiration as a constant, or as a straight line function of temperature. Respiration rates (in ml O_2 per minute) may be converted to loss in body weight and to population mortality by means of appropriate conversion factors.

The resultant "respiratory mortality" rates cited by modelers vary widely: the U.S. EPA (Zison et al., 1978) gives values from 0.001 to 0.36 per day that have been used in various modeling schemes. DiToro (DiToro et al., 1971) shows data indicating that *Daphnia* respiratory mortality may be approximated by a straight line function with slope of 0.02 ± 0.01 (per day per degree C). This function is adapted for the present model as follows:

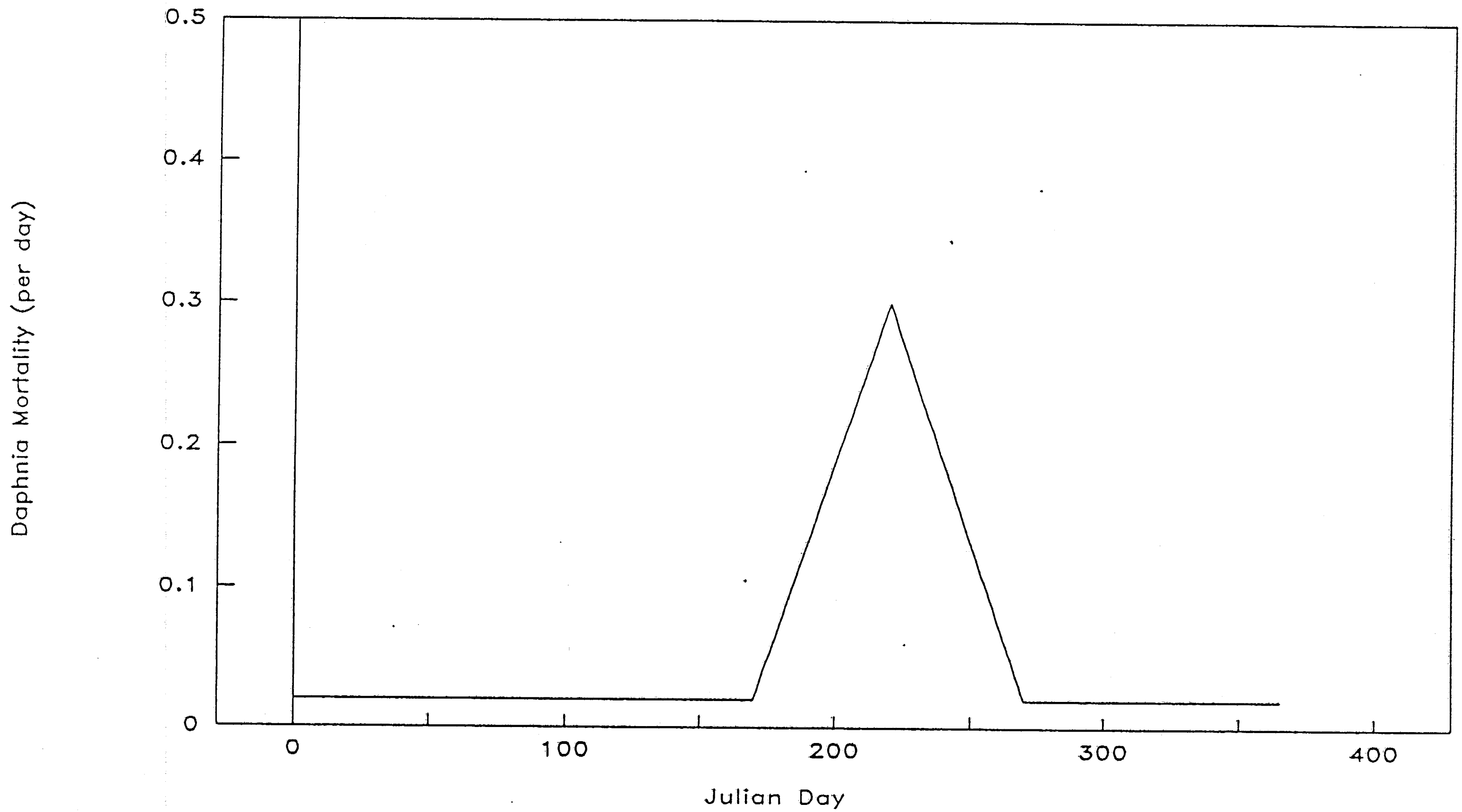

Figure 3: Typical predation scheme
(with PMIN = 0.02, PMAX = 0.3, LENPRED = 100, MAXDAY = 220)

$$DRESP = TRESP*T2 \qquad (13)$$

where

DRESP	is the temperature-related respiratory mortality rate for *Daphnia* (per day)
TRESP	is the calibration constant for the respiration function (per day per degree C)
T2	is the water temperature (degrees C)

(It should be noted that DiToro's value for the slope of the function gives relatively high values for the respiratory mortality rate; most authors appear to use daily rates of less than 0.1 per day.)

Toxicity

High BOD loads, high levels of nutrients, and high nitrogen levels in the pond combine to create a situation in which toxic conditions may develop throughout the ponds, or in certain pond layers. In particular, *Daphnia* are adversely affected by metal ions, high levels of ammonia (in the dissociated, NH_3 form which is favored at high pH values), high levels of hydrogen sulfide (H_2S) which is favored by anoxic environments, and very low levels of dissolved oxygen (DO). As mentioned previously, copper is not represented in the present model. Also, the model assumes that the *Daphnia* population will not be affected by these toxic factors unless toxic levels are reached in all pond layers.

While toxic effects may be synergistic (as discussed previously), for the purposes of this model the toxic effects of each substance modeled are simply added. More complex schemes exist for predicting the toxic effects of several chemicals in combination, but the assumption of simple additivity of toxic effects is often made in modeling toxicity (see for example Erickson, 1985, or Parkhurst et al., 1979) Overall toxicity will thus be the sum of the toxicity resulting from each of the factors in consideration:

$$TOX = TOXNH+TOXHS+TOXDO \qquad (14)$$

where

TOX	is the overall toxic death rate (per day)
TOXNH	is the death rate due to ammonia toxicity (per day)
TOXHS	represents the death rate due to the presence of hydrogen sulfide (per day)
TOXDO	is the rate of oxygen deficit toxicity (per day)

(Again, a cap is put on the overall toxicity so that it may not exceed 1.0)

Each of the three dissolved substances is modeled separately from the *Daphnia* sub-model. In each case, a toxicity dose-response curve is fitted to available data to relate *Daphnia* mortality to predicted chemical levels in the ponds. The curve is sigmoidal, in accord with commonly held notions that toxicity will approach both zero and one hundred percent asymptotically (see for example Barndthouse and Suter, 1986). The mortality functions for each are considered separately below, but the sigmoidal function used in each case is:

$$P = \frac{e^{\alpha * C}}{\beta + e^{\alpha * C}} * 100 \tag{15}$$

where

P	is the expected percent mortality (per day)
C	is the toxicant concentration (mg/l)
α, β	are fitting parameters (dimensionless) which regulate the slope and form of the sigmoidal curve

(It should be noted that for each of the three toxic substances modeled, the toxicity function developed is based on estimated 24-hour mortality rates. However, since the pond model employs a 12-hour time step, the derived 24-hour rates are simply halved to compute mortality during the time step. This is done for want of toxicity data for such short time periods, and in full realization that such an approach is not in complete accord with what is known about toxicology.)

Ammonia - The toxicity formulation for ammonia is based on a sigmoid-shaped toxicity function (as mentioned above), and the concept of a discernable LC50 (the concentration at which 50% of the population is killed within a given time period). Given the ambient pH and temperature by other sub-routines, the model uses the formulation of Erickson (Erickson, 1985) to determine the LC50 for ammonia in each water layer. Erickson, while allowing for a toxic effect of both the ionized and the un-ionized form of ammonia (with the ammonium ion being more strongly toxic), computes an LC50 value based on the concentration of un-ionized ammonia alone:

$$LC_{50} = \frac{LCU}{1+REL*10^{pK_a-pH}} \tag{16}$$

with

LC_{50}	the concentration at which 50% of the population is killed (mg/l)
LCU	50% lethal concentration when only un-ionized ammonia is present (mg/l)
REL	relative toxicity of ammonium ion and un-ionized ammonia (dimensionless)
pK_a	negative $\log_{10}$ of the acid dissociation constant for ammonia (dimensionless)
pH	negative $\log_{10}$ of the hydrogen ion concentration (dimensionless)

The formulation is thus sensitive to both pH and temperature (since the pK_a is a function of temperature); the pH and pKa are computed independently elsewhere within the pond model.

Using additional data given by Gersich (Gersich and Hopkins, 1986), the slope and shape of the sigmoidal toxicity function was approximated by trial and error; the parameters α and β for the sigmoidal function were determined for the case where pH = 8 and temperature = 20 degrees C. Assuming that the general configuration of this curve will be similar to that of ammonia toxicity curves for all other pH and temperature combinations, the β parameter value is held constant and the α parameter is found using predicted 50% mortality (P = 50) ammonia concentrations at the ambient temperature and pH as per Erickson, above. To generate the necessary alpha values, the sigmoidal function (see equation 15) is re-formulated as follows:

$$\alpha_{amm} = \frac{\left(\ln\frac{P}{100-P}\right)+\ln\beta_{amm}}{LC50_{amm}} \tag{17}$$

Then, with the assumed β value, and a calculated α value based on the computed LC50 for ionized ammonia, the mortality rate may be estimated using the predicted ammonia level for the layer:

$$AMTOX = \frac{\exp(\alpha_{amm}*XUNH2)}{\beta_{amm}+\exp(\alpha_{amm}*XUNH2)} \tag{18}$$

In these equations,

α and β	are the curve fitting parameters used to regulate the shape of the sigmoidal toxic mortality function (dimensionless)
P	is the mortality rate (per day) at the LC50 concentration (P=0.5)
LC50	is the predicted concentration at which 50% mortality occurs over a 48-hour period (mg/l)
AMTOX	is the resultant 48-hour mortality rate (per day) due to ammonia
XUNH2	is the un-ionized ammonia concentration (mg/l)

Resultant toxic mortality will thus depend, in effect, on where the ionized ammonia levels (as predicted by the model) intersect with the sigmoidal toxicity curve.

Data relating varying *Daphnia* mortality to varying ammonia levels is notably scarce. While 48-hour LC50's for ammonia at certain temperature and pH combinations may be fairly easily obtained for *Daphnia*, information about mortality within shorter time frames (and about mortality of other than 50%) is practically non-existent. Scant data from Tabata (Tabata, 1962) was used to make the necessary conversion from 48-hour LC50's to 24-hour values. 24-hour values appear to be approximately 1.4 times those for 48 hours; this conversion factor was used in all cases to extrapolate to the shorter time frame.

(A representative ammonia toxicity function is depicted in Figure 4.)

Hydrogen Sulfide - *Daphnia* show "tolerance" of H_2S concentrations up to 3.0 mg/l, but thrive only if concentrations are below 0.4 mg/l (Scheithauer and Bick, 1964). This was interpreted to indicate a situation with minimal mortality at concentrations below about 0.5 mg/l, and significant mortality at 3.0 mg/l (used as a best guess for the 24-hour H_2S LC50).

As in the case of ammonia, the mortality function is forced through the estimated LC50. With the LC50 supplied, the alpha value for the function is computed using a re-formulation of equation 15 and setting P to 50 (for 50 percent mortality):

$$\alpha_{H_2S} = \frac{\ln\left(\frac{50}{100-50}\right) + \ln \beta_{H_2S}}{SLC50_{24}} \qquad (19)$$

The function is then described using the following formulation and a beta value found by curve fitting:

$$TOXHS = \frac{\exp(\alpha_{H_2S} * [H_2S])}{\beta_{H_2S} + \exp(\alpha_{H_2S} * [H_2S])} \qquad (20)$$

here,

SLC50	is the estimated 24-hour 50% mortality level for hydrogen sulfide (mg/l)
TOXHS	is the death rate due to H_2S toxicity (per day)
α, β	are calibration parameters (dimensionless)
$[H_2S]$	is the concentration of hydrogen sulfide (mg/l)

(A depiction of the sulfide toxicity function may be found in Figure 5.)

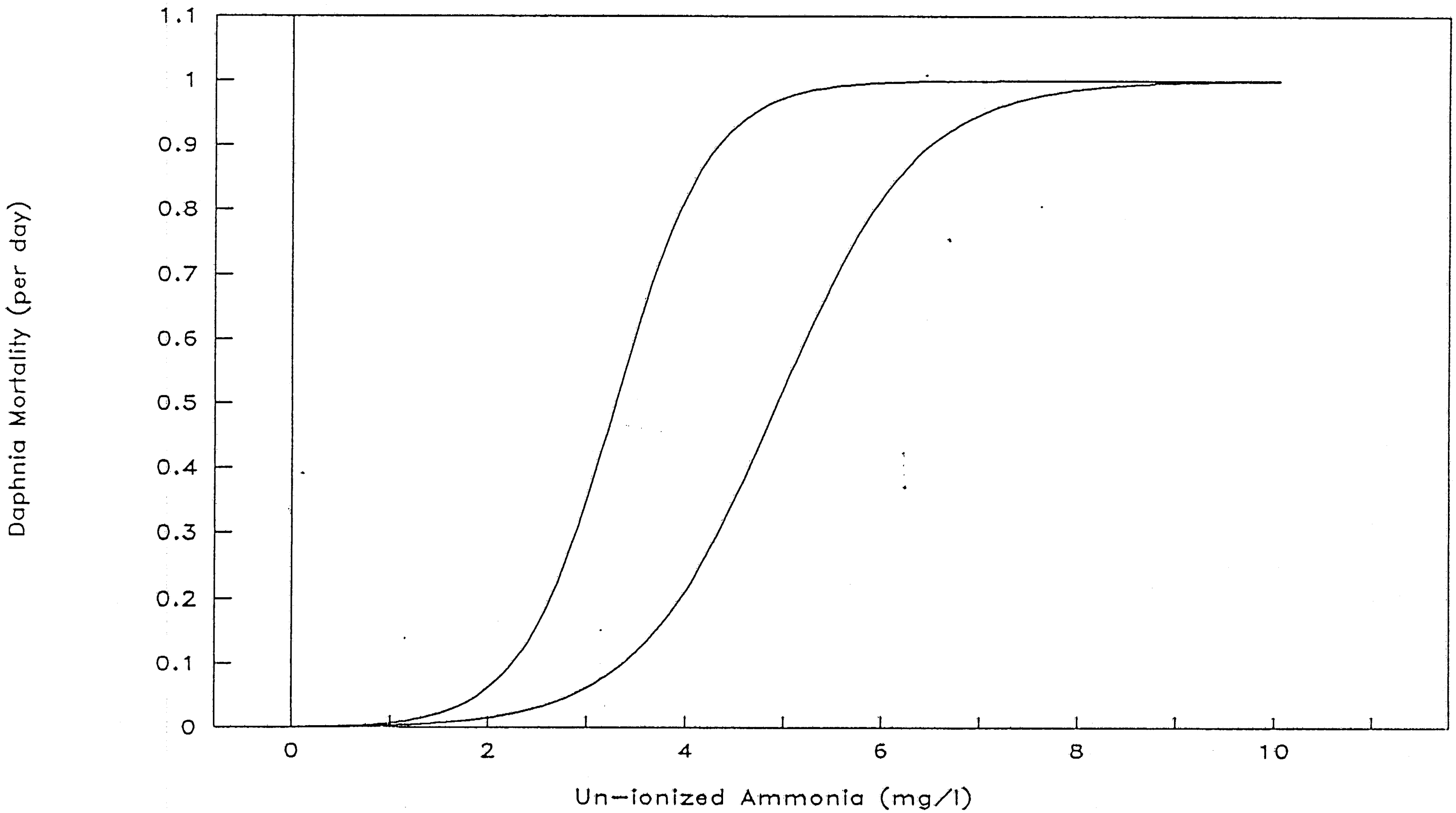

Figure 4: Mortality due to Ammonia, for 24 and 48 hour periods
(for *Daphnia* at pH = 8, Temperature = 25 degrees C)

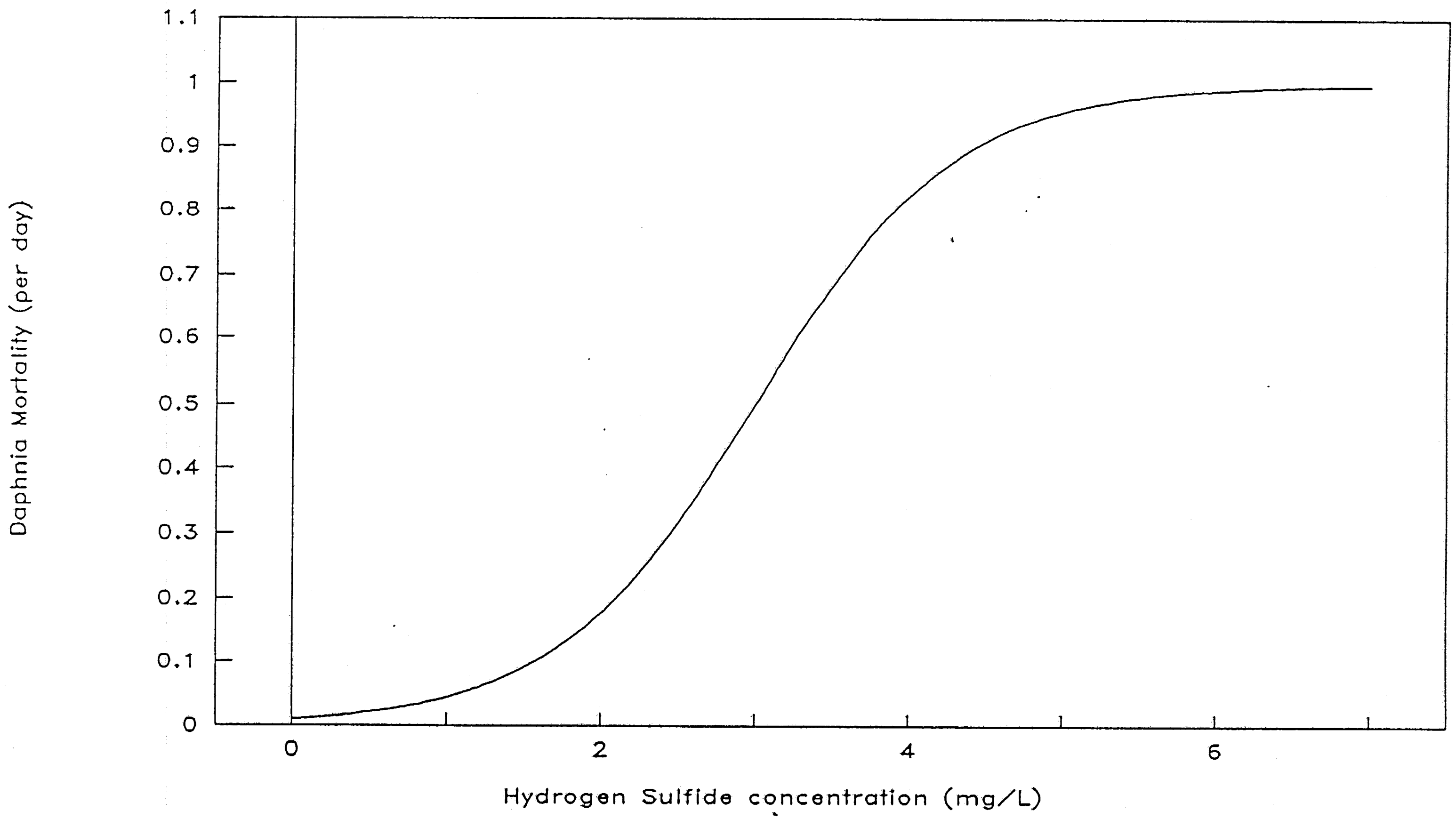

Figure 5: Mortality due to Hydrogen Sulfide
(for *Daphnia* - estimated 24-hour values)

<u>Dissolved Oxygen</u> - *Daphnia* cannot survive (except very briefly) in the absence of oxygen, but they are able to exist in environments having DO levels as low as 0.1 mg/l (Scheithauer and Bick, 1964). They can thrive when the DO is above 0.5 mg/l. While ponds supporting *Daphnia* populations rarely demonstrate extremely low oxygen levels (our observations), provision is made in the model for anoxic toxicity. The mortality function that describes this situation is sigmoidal, but reversed as compared to the previous two functions; most of the toxic effect is expected to occur near DO levels of 0.1 mg/l or less.

As with the previous two toxicity formulations, an estimation of the 24-hour LC50 concentration is first made, and a beta value for the sigmoidal curve is provided to give the curve appropriate form. The alpha value is then computed, forcing the function through the LC50 point (again using a reformulation of equation 15, with P=50):

$$\alpha_{DO} = \frac{\ln\left(\frac{50}{100-50}\right) + \ln \beta_{DO}}{OLC_{50}} \tag{21}$$

And the resulting 24-hour toxicity function becomes:

$$TOXDO = 1 - \frac{\exp\left(\alpha_{DO} * DSO2\right)}{\beta_{DO} + \exp\left(\alpha_{DO} * DSO2\right)} \tag{22}$$

wherein

OLC50	is the estimated 24-hour LC50 for *Daphnia* anoxic mortality
TOXDO	is the toxicity due to low oxygen levels (per day)
α, β	are calibration parameters (dimensionless)
DSO2	is the concentration of dissolved oxygen (mg/l)

(A graph of the toxicity function for oxygen may be found in Figure 6.)

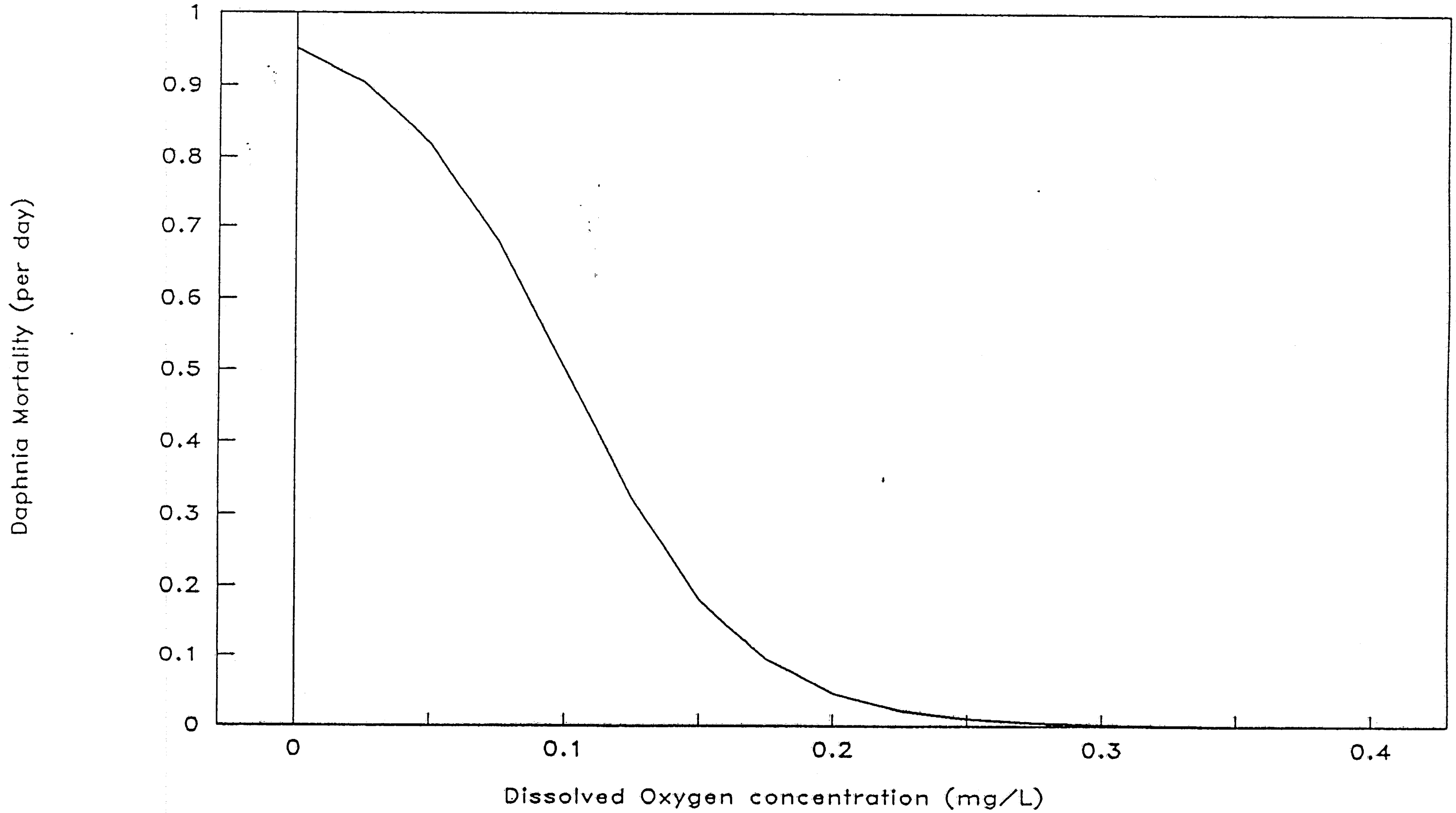

Figure 6: Mortality due to Anoxia
(for *Daphnia* - estimated 24-hour values)

Death due to Aging

Since *Daphnia* are not immortal, a fraction of the population will be lost each day as a result of natural aging processes. Because of increased metabolic rates, higher temperatures tend to reduce the longevity of any zooplankton. "Life tables" are available for *Daphnia* (e.g. MacArthur and Baillie, 1929; Korpelainen, 1986), providing a means of estimating life span throughout the range of pond temperatures. From such tables it can be estimated that each seven degree (C) rise in temperature results in a one percent rise in mortality:

$$AGE = \frac{T2}{7^{\circ}} * TMORT \qquad (23)$$

where

AGE	is the death rate due to aging (per day)
T2	is the pond temperature (degrees C)
TMORT	is the temperature-related mortality coefficient (per day per degree C)

(The age function may be seen depicted graphically on Figure 7.)

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Table 1 details the coefficients used in the *Daphnia* sub-model along with the reference literature upon which they are based.

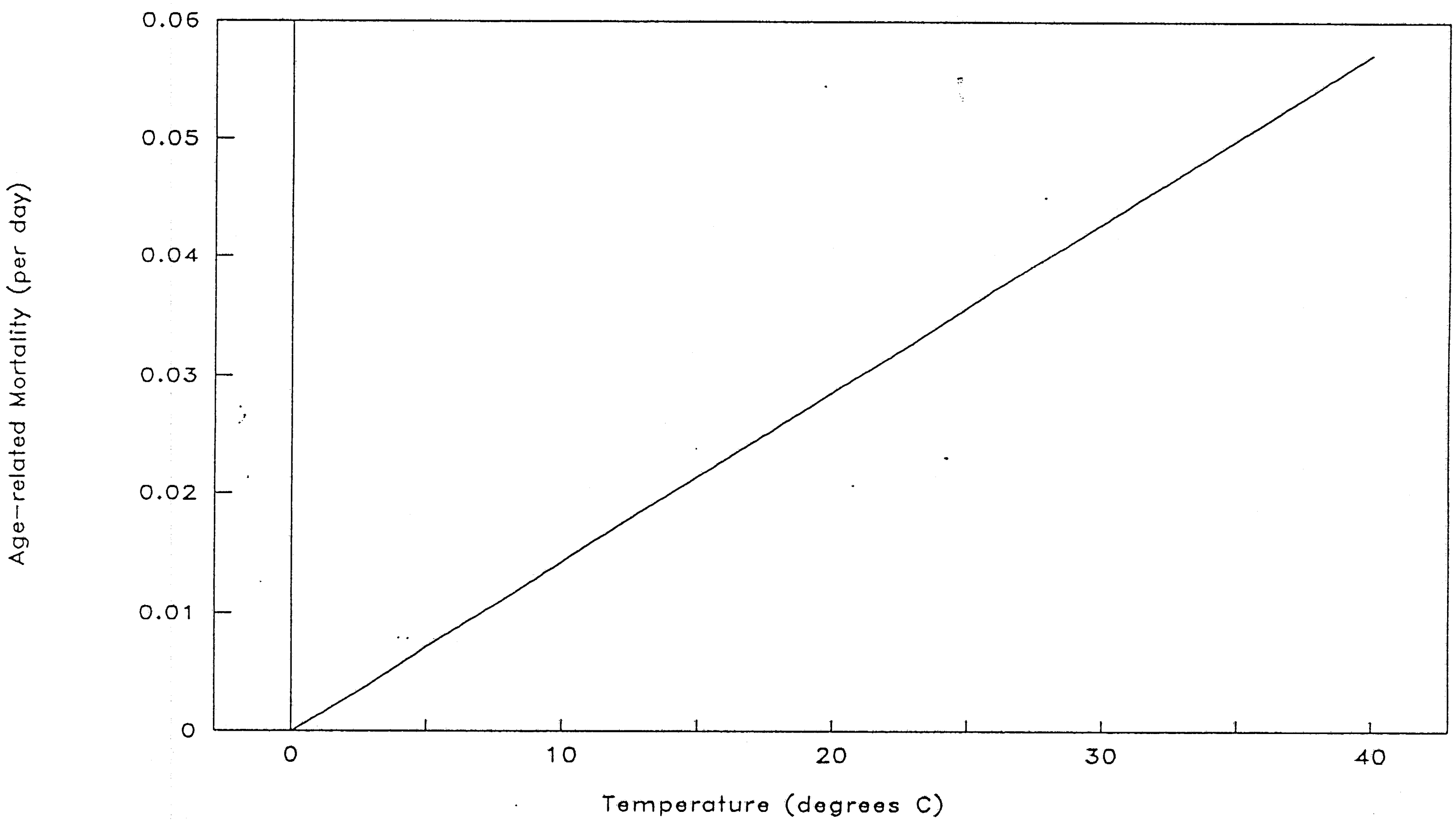

Figure 7: Age-related Mortality
(for *Daphnia* - estimated 24-hour values)

Table 1 - Suggested Values for Coefficients

	Value	Units	Source
Growth:			
GMAX	0.3-0.5	per day	McNaught & Scavia
HSCZP	0.0-1.0	dim'less	calibration
RHATCH	5.5 E-4	per day	estimate based on data from Carvalho and Wolf
Predation:			
PRMIN	0-0.2	per day	supplied by user
PRMAX	0-0.4	per day	supplied by user
Respiration/Starvation:			
TRESP	0.01-0.03	per degree C per day	DiToro
Toxicity			
Ammonia			
LCU	4.24	dim'less	Erickson
REL	0.0178	dim'less	Erickson
α	--	dim'less	calculated by model
β	1000	dim'less	calibration
Hydrogen Sulfide			
LC50 (est.)	3.0	mg/l	based on data from Scheithauer, Dinges
Detriment	>0.4	mg/l	Scheithauer, Dinges
α	--	mg/l	calculated by model
β	100	mg/l	calibration
Dissolved Oxygen			
LC50 (est.)	0.1	mg/l	based on data from Scheithauer, Dinges
Detriment	<0.5	mg/l	Scheithauer, Dinges
α	--	mg/l	calculated by model
β	20	mg/l	calibration
Age-related Mortality			
TMORT	0.01	per degree C per day	Korpelainen

(All other values for the modeling equations detailed above are either calculated by the model or require measurements for their estimation.)

Testing the Sub-routine with Stella Software

A preliminary version of the above *Daphnia* sub-routine was tested on a microcomputer using Stella for Academia® modeling software. Charts and tables shown below (see Figures 8, 9 and 10 on the pages following) were generated using the Stella program.

For purposes of the test run, the system was modeled as a well-mixed reactor, with required temperatures, chemical concentrations, and predatory effects entered simply as functions of the Julian day. (Normally these values would be calculated by the MINLAKE model.) A small module was set up within the Stella model to model the changes of the algal population as the *Daphnia* population waxes and wanes.

The time step for the simulation was set at one day. Both longer and shorter periods were attempted; a one-half day time period gave results nearly identical to the one day simulations. Time steps of greater than one day resulted in erratic model performance, as extrapolations became less accurate. Total time of the run was set at 360 days, or approximately one year.

The Stella program offers three extrapolation methods for its simulations: Euler's method, second degree Runge-Kutta, and fourth degree Runge-Kutta. All of these options were tested during the trial simulations. As might be expected, the Euler's method proved to be slightly faster in completing the simulation runs. However, it also gave more erratic and less satisfactory results than the Runge-Kutta methods. For final simulations, the Runge-Kutta 4 method of calculation was used.

The first of the three figures on the previous pages shows a comprehensive modeling scheme wherein life stages and the influence of many factors would be considered. The second shows a pared-down version in which a more manageable set of controlling factors is taken into account. In the second diagram, the *Daphnia* rectangle in the center represents the sum of the *Daphnia* in the pond at a given time - this sum is added to or taken from by any of the four large lines leading to it. Lines with arrows pointing to the rectangle represent sources; lines leading away represent sinks. The "valves" on these source lines represent the rates of flow into or out of the *Daphnia* pool. The rest of the circles shown on the diagram are the various factors affecting those rates, either directly or indirectly.

Results of the simulation are presented in graphical form in the third of the Stella diagrams. The simulation predicts two peaks for the *Daphnia* population, one in early April

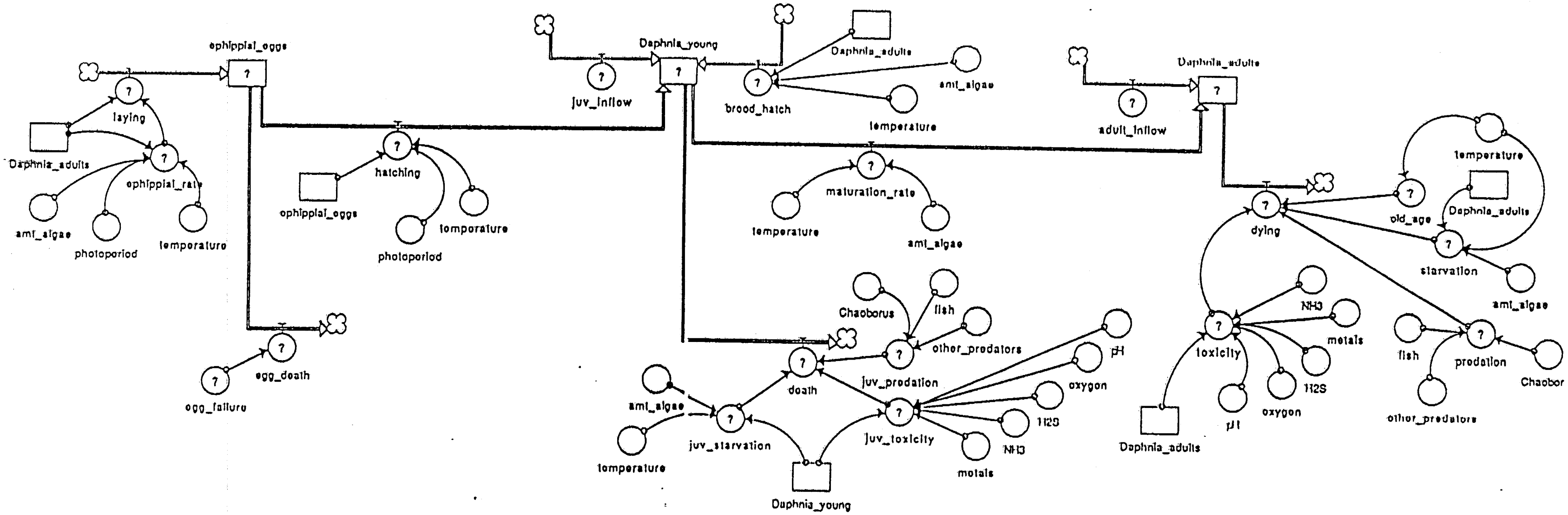

Figure 8: Overall *Daphnia* flow scheme for stabilization pond modeling

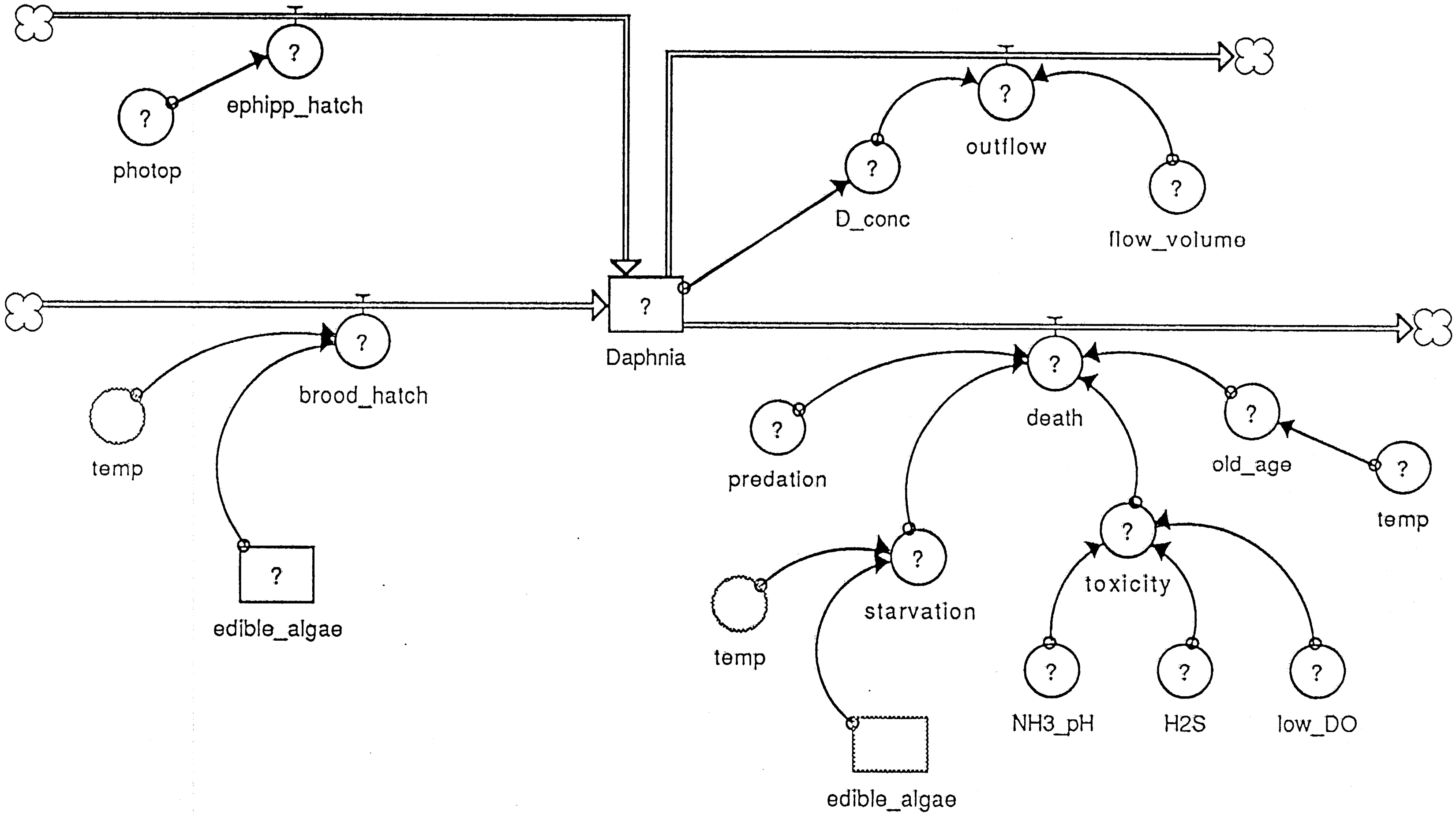

Figure 9: Simplified *Daphnia* flow scheme for stabilization pond modeling

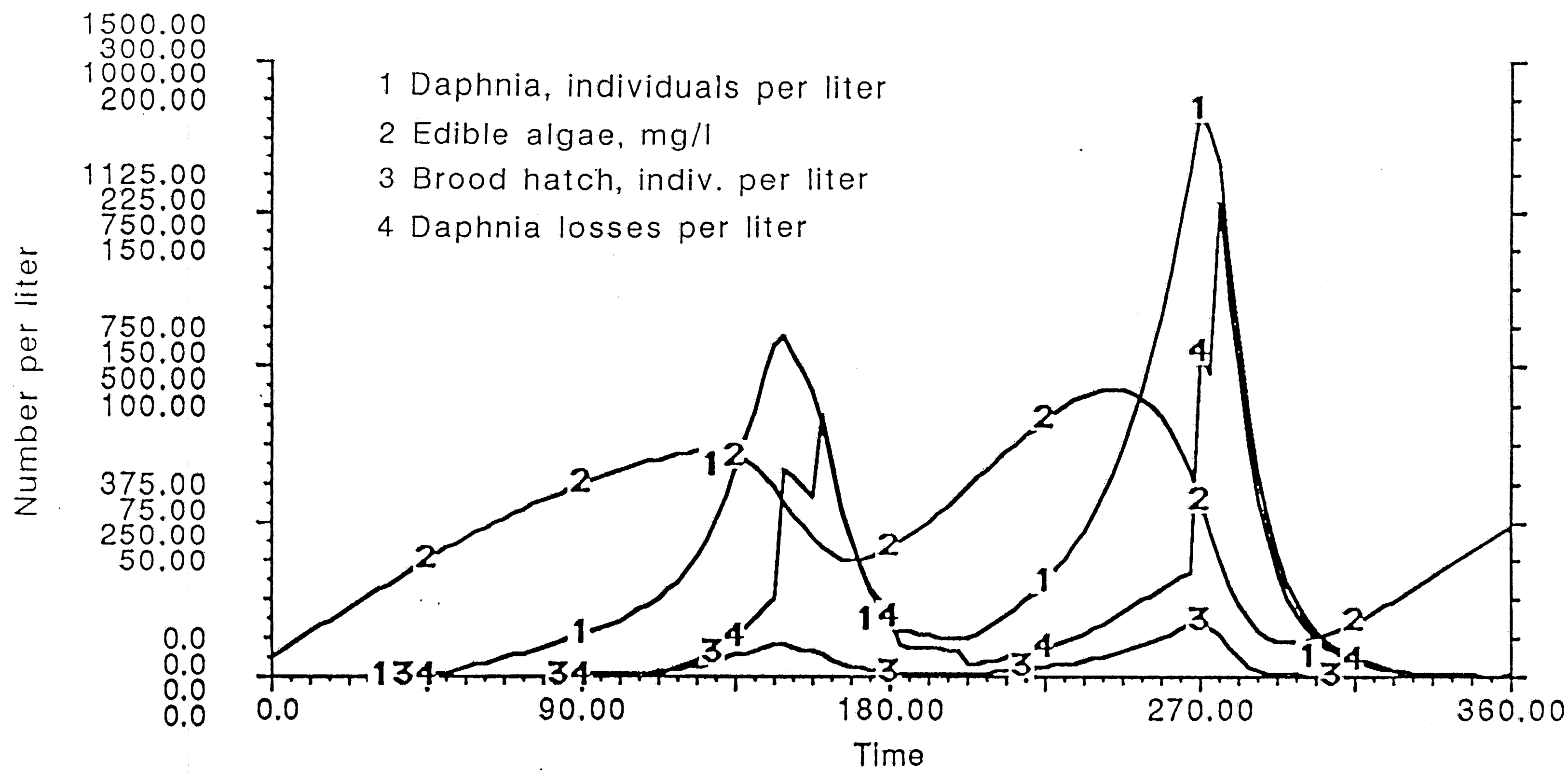

Figure 10: Stella© modelling results

(approximately day 100) and another smaller peak in late September (near day 260). The *Daphnia* population reaches concentrations of approximately 2000 per liter - which seems to conform roughly to sample values taken during peak *Daphnia* periods. Similarly, the fluctuations in the algal concentrations predicted by the model seem to conform to sample values for algal levels in the ponds being studied. Predictions of algal concentrations range from 20 to approximately 120 milligrams per liter, which is within the range of sample values.

V. Pond Modeling by Modification of MINLAKE

Rationale for Use of the MINLAKE Model for Minnesota Ponds

While all of the modeling schemes mentioned in the review of literature have merit in the situation for which they were developed, they are not directly applicable to the unusual situation characteristic of Minnesota ponds. Many ponds worldwide operate on a continuous-flow basis, where water is allowed to move continuously from one pond to the next, and is discharged continuously from the last pond in series. However, in regions such as Minnesota where winter weather brings extended periods of ice cover, ponds are often operated on a "draw-and-fill" basis. This method of operation permits only periodic discharge, when conditions are favorable and ice cover has been absent long enough to allow re-oxygenation of the pond waters.

Previously developed pond models assume continuous flow and well-mixed conditions - a hydrodynamic regime that does not prevail in Minnesota's draw-and-fill systems. In addition, other models do not represent the dynamics of stratification and de-stratification processes, mixing by inflow, or the effect of weather on algal growth. For these reasons, the one-dimensional, unsteady advection-diffusion lake model MINLAKE (Riley and Stefan, 1987) was adapted in an attempt to better simulate the biological and hydrodynamic conditions prevailing in these stabilization ponds.

The MINLAKE model divides the water body into a series of horizontal water layers, initially of equal thickness. The effects of weather (solar radiation, wind, and air temperature) are felt initially in the uppermost layer, but are transmitted throughout the water column by mixing processes. The model represents oxygen, nitrogen, and phosphorus in each of the layers as dissolved substances with appropriate source and sink terms; the dissolved materials are transported by inter-layer diffusion. Three classes of algae (measured as chlorophyll-a), and zooplankton are also modelled in MINLAKE (see Figures 11 and 12 for a pictorial representation of limnological process represented in MINLAKE, and a schematic of the MINLAKE model operation).

MINLAKE offers several advantages for modeling Minnesota wastewater ponds. Being a lake model, it is more readily able to simulate the hydrodynamics of pond systems that are usually closed to inflow and outflow. It has been shown to be effective in simulating temperature and DO in natural water bodies. Unaltered, it simulates many of the chemical and physical variables deemed necessary to predict pond performance with respect to suspended solids: temperature, DO, ammonia, BOD, and three algal classes. With modifications to the zooplankton compartment, the inflow regime, and the addition of pH and hydrogen sulfide (H_2S) subroutines, it provides a reasonable starting point from which to develop an effective stabilization pond model.

Modifications to the MINLAKE Model

Although the existing MINLAKE model was judged to be well-suited for use in pond modeling, MINLAKE is nevertheless a lake/reservoir model. Since stabilization ponds are significantly different from lakes in many respects, it was necessary to modify the original MINLAKE program code significantly to make it suitable for treatment pond modeling.

Using the pre-existing MINLAKE model as a base, adaptations were required in order to:

- Simulate the day/night stratification cycle that became apparent through temperature measurements (see Luck and Stefan, 1990).

- Model toxic effects deemed to have a strong and frequent effect on the *Daphnia* population

- Predict chemical concentrations responsible for those toxic effects

- Handle pond inflow and outflow regimes that differ considerably from the situation in lakes

- Model *Daphnia* growth kinetics in such a way as to emphasize their strong dependence on algal populations

- Track phytoplankton growth in an environment where nutrients are not generally growth-limiting; and predict the growth of those species suitable for food for *Daphnia*.

Important aspects of some of the changes made in adapting the MINLAKE model for pond service are discussed in the sections that follow.

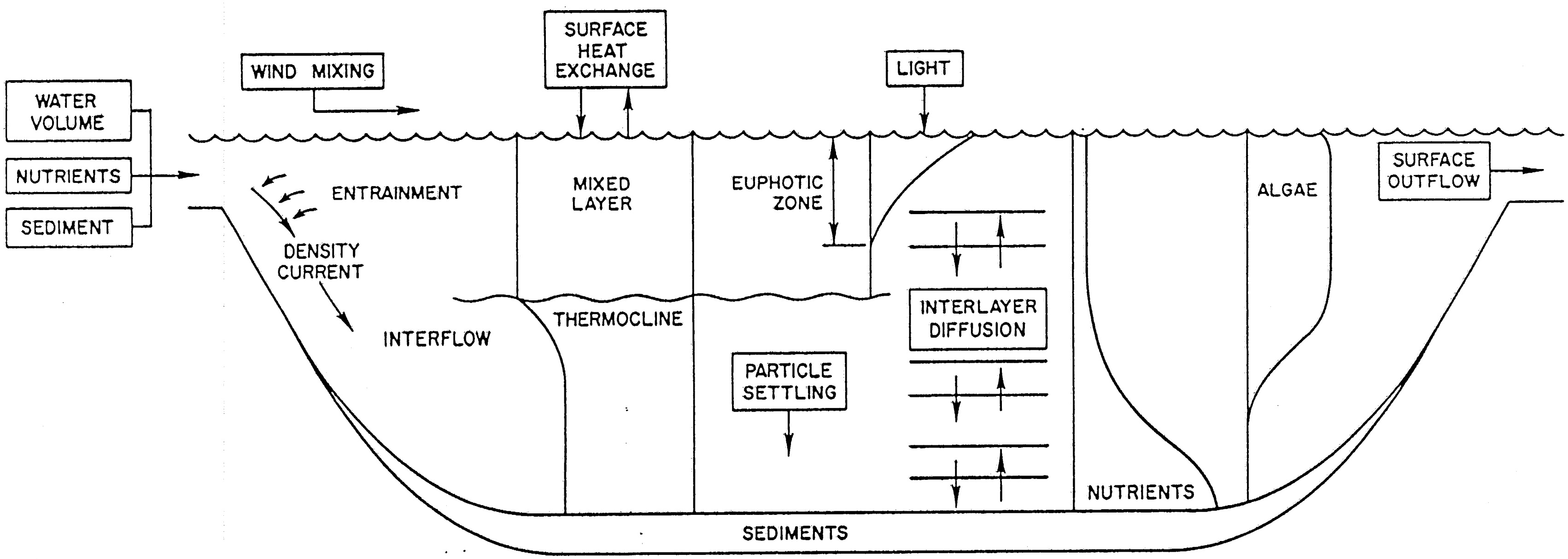

Figure 11: Limnological Processes Represented in MINLAKE
(from Riley and Stefan, 1987)

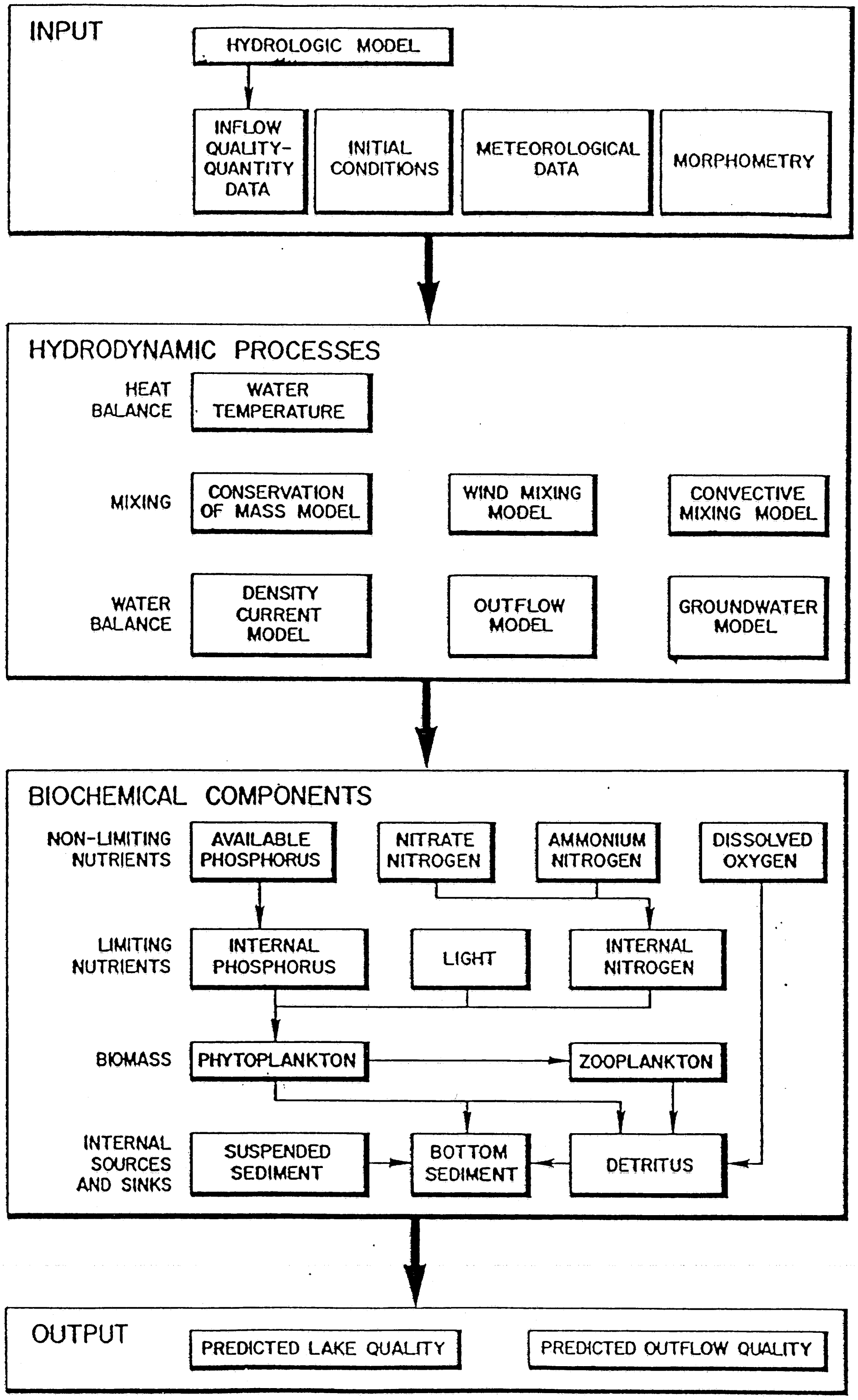

Figure 12: MINLAKE Process Schematic (from Riley and Stefan, 1987)

Daphnia Subroutine

As was previously mentioned, the original zooplankton scheme contained in MINLAKE was judged to be inadequate for the pond environment. As a result, MINLAKE's existing zooplankton model was removed, and replaced with the scheme described above. The difference in the way in which the two systems handle the vertical distribution of *Daphnia* meant that corresponding modifications had to be made to the chlorophyll and dissolved solids subroutines. Input files were also adjusted to accommodate new user-supplied coefficients.

New Water Quality Variables

It should be noted that accurate prediction of the zooplankton population in the ponds is to a large extent dependent on the model's ability to predict such water quality (state) variables as temperature, chlorophyll-a, and dissolved oxygen. Furthermore, in order to model *Daphnia*'s response to toxic qualities of the pond water, additional water quality (state) variables were needed. The computation of pond pH and hydrogen sulfide concentration was judged to be necessary to allow accurate forecasting of toxicant-induced mortality. To this end, subroutines for the estimation of pH were developed and incorporated into the model (see Deutschmann, 1992). To date, no method has been developed to predict hydrogen sulfide levels in the ponds; the model currently sets H_2S concentrations to zero except in the lowest four layers if modeled DO is below 0.1 mg/l. The modeling of sulfur chemistry will eventually be required if the model is to reliably predict toxic effects resulting from varying sulfide concentrations.

Shorter (1/2-day) Time Step

Through analysis of the stratified temperature data collected for this study, it became obvious that modifications to MINLAKE would be required in order to accurately simulate the rapid changes in pond stratification that occur in these shallow water bodies. The model was re-formulated (see Gu and Stefan, 1991) to operate on a 12-hour time step in order to allow it to capture the diurnal cycles of stratification and de-stratification. These changes required modifications in several subroutines to accommodate the new, shorter time step.

Field studies of the Harris ponds also revealed dramatic day-night shifts in physical and biological parameters (see Helgen, 1992; and Luck and Stefan, 1991). For example, dissolved oxygen profiles as measured during one diel survey showed near-surface oxygen levels in pond 1 moving from less than 1 mg/l at dawn to over 20 mg/l by late afternoon. By the following dawn, dissolved oxygen concentrations had returned to approximately zero. (See Figure 13.)

Such rapid and extreme fluctuations in pond characteristics create many difficulties in attempting to model pond processes and the effects of such fluctuations on pond biota.

The shortened time step provided a means of better representing the actual pond dynamics. With this modification, the model was better equipped to accurately track (and predict the effects of) day/night shifts in chemical and biological parameters.

Water Inflow and Outflow

Sewage normally is pumped through a pipe to stabilization ponds, where it enters the first pond from a submerged horizontal or vertical outlet. The behavior and eventual distribution of this incoming flow was evaluated through temperature measurements conducted by Fred Luck and Chris Ellis of SAFHL (Luck and Stefan, 1990). Since this inflow situation is quite different from those which a lake model would normally need to handle, a separate subroutine was developed to model the pumped inflow and its entrainment of the ambient waters. The current model deals with vertical inflow only. The effects of this vertical inflow on the temperature structure, and on the distribution of chemical concentrations have been accounted for by the modified MINLAKE model (Gu and Stefan, 1991).

Similarly, the manner in which water is transferred from one pond to the next is unlike the flow of water from a lake; the difference required modifications in the model's outflow simulation. In the ponds, outflow occurs through a submerged outlet (at the Harris, Minnesota ponds, this outlet is directed upward, and is located approximately two feet from the pond bottom). The MINLAKE model was therefore modified to remove water at the level of the outlet. The water is taken from the layer in which the outlet is located.

The next pond in series receives this outflow from the upstream pond through a submerged inlet. In the second and third ponds, the inflow water is added directly to the water layer in which the inlet is located. If the inflow volume is such that the resultant layer volume exceeds the limits specified by the user, the model splits the water layer into two, in accord with standard MINLAKE operation.

Since the chemistry of the water transferred from one pond to the next will have an impact on the downstream pond, the characteristics of the incoming water must be taken into account. This is done by the creation of an outflow file during the modeling of the first pond in series. This outflow file contains data regarding the flow amounts, water temperature, and water biology and chemistry for each day on which the simulation indicates that water is transferred. Modeling of a series of ponds must be done in sequence; the outflow file from the first pond becomes the inflow file for the second pond, and the outflow file from the second pond will be the inflow file for the third pond. Inflow chemistry and physical data from the inflow file are used to adjust the water characteristics of the water layer into which the inflow is inserted. This occurs during each time step for which water transfer is indicated in the outflow/inflow file.

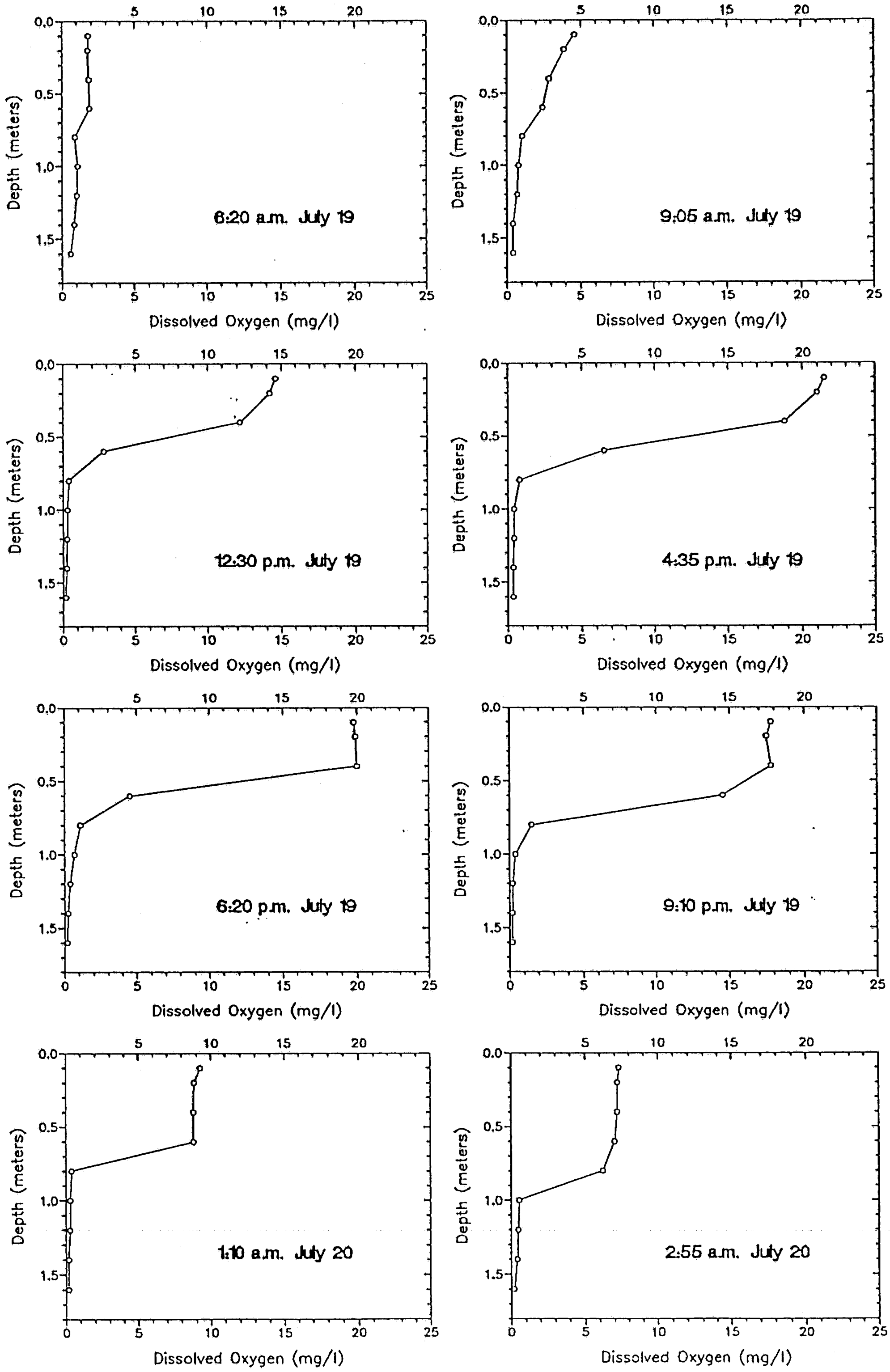

Figure 13: Diel Dissolved Oxygen Fluctuations, Harris Pond 1
(from Luck and Stefan, 1991)

The volume of water transferred is calculated using the relationship between water level (stage) and pond volume, and inflow volume data supplied. If the previous time step's volume plus the inflow volume exceeds the volume indicated by the stage measurement for the time step, an outflow volume is indicated and will be recorded in the outflow file. For the first pond, the inflow amount can be determined from pumping records; the subsequent ponds will receive inflow only via water transfer as indicated in the outflow/inflow files generated by the model, and in accordance with the pond operators' selection of water transfer dates and volumes.

Miscellaneous and Associated Program Changes

In association with the general changes described above, many minor alterations were required in order to convert the original MINLAKE program for stabilization pond operation. Many of the changes have to do with conversions to the shorter time step, the integration of new state variables and subroutines, or the new water transfer/balance schemes. A listing of these changes is provided in Appendix C for the benefit of those dealing directly with the program code.

VI. Model Calibration and Application

Data Collection and Analysis

The Stella© model aided in the preliminary development of the *Daphnia* sub-routine. In order to adapt and make the MINLAKE model applicable to pond modeling, much data was needed to guide the formulation and to allow calibration of the simulations of Minnesota wastewater stabilization ponds. For this purpose, the Harris, Minnesota ponds were monitored closely for a period of over more than one year by members of SAFHL. Weather conditions (including wind speed, wind direction, rainfall, solar radiation, relative humidity and air temperature), pumped inflow rates and temperatures, and pond temperatures at six depths were monitored continuously and automatically. As a result, one of the most complete and extended physical data sets for a stabilization pond has been compiled and analyzed. The data appears in the SAFHL report by Luck and Stefan (1990).

The Minnesota Pollution Control Agency was responsible for the collection and analysis of the biological and chemical data required for this study. MPCA workers, led by Dr. Judy Helgen, collected and analyzed sediment samples for egg counts, determined zooplankton numbers and species, collected samples for chlorophyll analysis, and assembled temperature and pH data for correlation with their biological analyses. The Harris, Minnesota, site was the main focus of this sampling, but substantial information was also collected from ponds at St. Peter and Janesville. Additional samples were collected and analyzed from several other outlying sites in the state. The MPCA group also conducted statistical analyses and completed a survey of pond operators in selected statewide sites to assess pond conditions and performance. (For further information, the MPCA report submitted as a part of this study can be consulted.)

The University of Minnesota's Environmental Engineering group in the Department of Civil and Mineral Engineering was sub-contracted by the MPCA to conduct chemical and chlorophyll analyses. The CE group was also responsible for the field work necessary for the collection of the water samples for the chemical analyses. In addition to the chlorophyll-a determinations, samples were analyzed for nitrogen, phosphorus, sulfides, iron, cations and anions. These findings may be found within the MPCA report (Helgen, 1992).

To illustrate the nature of the data collected by the three groups, Table 2 was prepared. The table gives the ranges of the recorded field data for each of the three ponds

Table 2 - Field Data Summary
(Harris, Minnesota 1989 - 1991)

Field Data Item	Field Data Ranges[1]		
	Pond 1	**Pond 2**	**Pond 3**
Temperature (degrees C)	0 - 35	0 - 33	0 - 32
Dissolved Oxygen (mg/l)	0 - 20+[2]	0 - 18	0 - 19
Total Chl-A (ug/l)	0 - 729	10 - 273	2 - 125
Daphnia (indiv./l)	0 - 0.1	0 - 0.8	0 - 250
Total Susp. Solids (mg/l)	8.3 - 63	2.4 - 72	1.0 - 41
pH (dim'less)	6.3 - 9.7	7.3 - 9.8	7.0 - 9.7
Alkalinity (ueq/l)	240 - 480	240 - 440	230 - 380
Total Phosphorus (mg/l)	3.0 - 4.6	1.1 - 5.0	1.4 - 4.2
Ortho-Phosphate (mg/l)	0.9 - 4.8	0.6 - 4.2	0.5 - 4.5
Total Nitrogen (mg/l)	5.5 - 39.4	1.9 - 48.8	0.1 - 17.4
Total Ammonia (mg/l)	0.1 - 32	0.1 - 20.2	0.1 - 6.6

[1]Data was compiled from Luck and Helgen reports. Helgen report includes data compiled by University of Minnesota Environmental Engineering program.

[2]Value taken on site exceeded range (0-20 mg/l) of YSI dissolved oxygen meter.

throughout the study period. Data extremes were culled from the reports of SAFHL, the MPCA, and the U of MN Environmental group.

Model Calibration

General Considerations

Calibration of the stabilization pond model proved to be difficult, owing to a variety of reasons both external and internal to the model itself. In retrospect, the sampling regimen that had been devised for biological and chemical analyses was less than ideal for modeling purposes. The manner in which chemical and biological parameters varied with depth was not routinely analyzed for the modeled period. This forced the estimation of target chemical and biological profiles based on a single value for one depth only. As a result, it was difficult to assess the results of the modeling effort with a large degree of confidence.

In addition, chemical and biological sampling for the study occurred at approximately 2-week intervals. While this is appropriate for modeling studies for more stable systems such as lakes or reservoirs, a much smaller sampling interval would be desirable for the dynamic and labile stabilization pond environment. The relative infrequency of the sampling made accurate characterization of the pond environment impossible. Model output for the periods between sampling dates was thus difficult to evaluate.

In addition to the high rate of change in pond characteristics, it was noted during the study that the frequently reported "patchy" distribution of both algal and zooplankton species put the representativeness of the sampling results in question. During one diel study, dissolved oxygen values, almost certainly reflecting algal densities, were seen to vary greatly from one end of a pond to the other (MPCA data).

The mobility of the zooplankton population also contributed to uncertainty of the accuracy of the sampling results. (Other researchers, for example Horn and Benndorf, 1980, have commented on the "ill effects of spastial heterogeneity in zooplankton distribution" on field data.) One diel sampling of the Harris ponds zooplankton community (measured at three different depths) showed remarkably different population densities from daytime to night (MPCA studies). This difference suggests the existence of daytime refuges within the pond, and calls into question the accuracy of our *Daphnia* population estimates made exclusively from daytime pond water samples.

The model was able to accurately predict temperature changes in the ponds (see Gu and Stefan, 1991), and to predict for how often and for how long the ponds would be stratified or well-mixed. The prediction of the fluctuations of the biological and chemical parameters modeled for the ponds proved to be more difficult.

As has been mentioned, some problems existed with the sampling and analysis of the pond environment. But in large part the problems encountered with calibrating the model are more basic. The state of understanding of the complex processes governing the rise and fall of aquatic populations, and governing the associated chemical environment, are simply not thoroughly understood. This fact is demonstrated by the wide range in the values suggested by various authors for the coefficients to be used in modeling formulations.

The rapidly fluctuating aquatic environment of stabilization ponds has received less attention than natural water bodies, and its ecology is therefore even less well understood. Even in lakes and reservoirs, it remains quite difficult to make predictions for the behavior of phytoplankton and zooplankton communities. Such predictions become even more difficult in the case of stabilization ponds. The effects, for example, of the high ammonia concentrations on algal growth and speciation (see Abeliovich and Azov, 1976; Konig et al., 1987; Pearson et al., 1987) in the ponds have not been evaluated. Though ammonia almost certainly does play a role in regulating pond populations, there is currently insufficient information to characterize such effects in modeling equations.

Calibration

The present pond model was calibrated for zooplankton using successive iterations, adjusting input parameters until model output was satisfactory. Since the status of the *Daphnia* population depends in large part on the availability of edible algae, it was necessary to attempt to calibrate for *Daphnia* and for chlorophyll-a concentrations concurrently. This in turn required simultaneous attention to the available phosphorus and ammonia modeling results, since these affect the phytoplankton growth equations. Oxygen is involved in another control loop, its levels being strongly dependent on algal concentrations, which are controlled by *Daphnia* grazing. In turn, the oxygen concentrations affect the *Daphnia* population through anoxic toxicity. Because of these feedback loops, the calibration for zooplankton necessitates the coordination of many modeling parameters.

For more effective use and calibration of the pond model, further work remains to be done. At present, a subroutine that would predict the concentration of hydrogen sulfide has not yet been devised; the concentration of hydrogen sulfide was therefore simply set to an arbitrarily low value within the simulation program. Similarly, the pH/alkalinity subroutine is still under development. For the simulations reported herein, the pH/alkalinity subroutine was circumvented by artificially setting the pH constant throughout the simulation period. While the above contrivances would not be expected to greatly affect the outcome of the simulations, it should be kept in mind that the calibration of the model was effected without the benefit of these model components.

The average *Daphnia* concentrations resulting from the simulations proved to be sensitive to several of the zooplankton model parameters. The value of EPHIP, representing the number of sediment ephippial eggs, played a role in determining the rapidity with which the population could recover from near-zero levels. Similarly, the values of MINEPH and MAXEPH set the bounds within which the population could be expected to thrive. The temperature-sensitive respiration rate parameter TRESP affected the timing of the *Daphnia* growth peaks. The model also proved very sensitive to the half-saturation coefficient for growth (HSCZP), which affected both the steepness of the growth curves and the height of the predicted population peaks.

In addition to being strongly controlled by grazing by *Daphnia* (see GRAZMAX in the MINLAKE formulation), the algal populations proved to be sensitive to several of the model's phytoplankton parameters such as the fall velocity (FVEL), the mortality rate (XKM) and in particular, the maximum growth rate (GMAX). Available phosphorus concentrations were particularly sensitive to the benthic release coefficient, BRR.

Regulation of the model's dissolved oxygen predictions was particularly difficult. The part of the dissolved solids subroutine that deals with dissolved oxygen in the water was entirely reformulated to bring it into accord with recent work on gas transfer, and to adapt it for the stabilization pond situation. While the oxygen concentrations were sensitive to algal population fluctuations, they showed remarkably little sensitivity to the major oxygen modeling parameters SB20, BODK20, YZDO, and WS (the benthic uptake rate, the oxygen uptake rate for BOD, the uptake by respiring zooplankton, respectively). The model did show some sensitivity to algal oxygen uptake and release parameters (YCHO2 and Y2CHO2), but the effects of altering these coefficients were somewhat unpredictable.

For comparison with recommended values (see Table 1), Pond 3 coefficient values obtained by calibration are given in Table 3. The period of ephippial hatching was taken as April 10 to September 7, and the period during which the predatory effect was allowed was May 15 to September 20.

Further information regarding calibration values for pond 3, and calibration values for ponds 1 and 2 may be found in Appendix 2.

Simulation Results

Simulation results for Harris pond 3 for the period April 7, 1990 through October 31, 1990 are shown on pages 65-70. All simulation results and field data given are for the sampling depth of 0.3 meters; field data are indicated with a square, and simulation results are shown as a continuous line. (Simulation results for ponds 1 and 2 contributed to the inflow and thus the simulation of pond 3; these intermediate results for ponds 1 and 2 are presented in Appendix A. In Appendix B may be found the parameter input files used for the final simulation.)

Table 3 - Coefficient Values used for Pond 3 Simulation

	Value	Units	Source
Growth:			
GMAX	0.80	per day	Calibrated Value
HSCZP	0.004	dim'less	Calibrated Value
RHATCH	5.5 E-4	per day	estimate based on data from Carvalho and Wolf
Predation:			
PRMIN	0.05	per day	Calibrated Value
PRMAX	0.08	per day	Calibrated Value
Respiration/Starvation:			
TRESP	0.015	per degree C per day	Calibrated Value
Toxicity			
Ammonia			
LCU	4.24	dim'less	Erickson
REL	0.0178	dim'less	Erickson
α	--	dim'less	calculated by model
β	1000	dim'less	calibration
Hydrogen Sulfide			
LC50 (est.)	3.0	mg/l	based on data from Scheithauer, Dinges
Detriment	>0.4	mg/l	Scheithauer, Dinges
α	--	mg/l	calculated by model
β	100	mg/l	calibration
Dissolved Oxygen			
LC50 (est.)	0.1	mg/l	based on data from Scheithauer, Dinges
Detriment	<0.5	mg/l	Scheithauer, Dinges
α	--	mg/l	calculated by model
β	20	mg/l	calibration
Age-related Mortality			
TMORT	0.01	per degree C per day	Korpelainen

(All values given are those actually used in the simulation; "Calibration Value" indicates those *Daphnia* modeling coefficients found as a result of the simulation process.)

Normally, water quality modeling involves both *calibration*, using field data for one simulation period to adjust input parameters; and *verification*, testing the calibrated model against a second set of field data from a separate time period. For the Harris pond studies, the verification phase was not possible since the time frame of the study allowed the collection of only one season's field data.

The model was able to simulate pond processes with a fair degree of accuracy. Temperature modeling (Figure 14) was remarkably successful - see also Gu and Stefan, 1991. The simulations of both phosphorus (Figure 16) and nitrogen (Figure 18) showed results within the range of the field data, however, the calibrated model was unable to mimic the field data variations with great accuracy. Despite this, since the algal simulations did not show extreme sensitivity to small changes in the phosphorus or nitrogen concentrations, the other simulation parameters were apparently not adversely affected.

Algal simulations (Figure 15), while generally remaining within the bounds of the field data ranges, were unable to successfully mimic all of the rapid chlorophyll-a concentration changes identified through field studies. Inparticular, early population spikes proved troublesome: adjusting the growth rates high enough to allow an early growth spurt resulted in the algal population growing to unacceptably high levels later in the season.

Simulation of dissolved oxygen (Figure 17), as has been mentioned, proved to be particularly difficult. Nevertheless, the calibrated model showed predicted dissolved oxygen concentrations remaining within reasonable ranges throughout the simulation period. The simulations showed reasonable similarity to the field data patterns.
Since in ponds 1 and 2 the *Daphnia* populations apparently were virtually nonexistent, no firm conclusions can be made with respect to the zooplankton simulations in those ponds. In pond 3, the *Daphnia* simulations (Figure 19) show reasonable agreement with both the timing and magnitude of the June population peak. The late-season population rise is apparently due to the decline in the temperature-mediated respiratory mortality, and the decline in predation pressure.

Modeled Toxic Effects - Model results showed that toxicity did not seem to play a large role in the regulation of the *Daphnia* population in the Harris ponds. This may be one of the reasons why the Harris ponds maintain a healthy *Daphnia* population and consistently produce a high quality effluent. According to the model, the zooplankton migrated out of, and thereby escaped, layers of the pond which would otherwise cause mortality. In relatively few situations was the modeled pond environment seen to cause toxic mortality by denying the population a refuge. Modeled toxic mortality occurred in pond 1 only in the period from April 7 to April 28, and was primarily due to low oxygen levels. Pond 2 showed toxic mortality only within the first week of simulation.

Even in the case of ammonia, which was expected to demonstrate significant toxic effects, predicted toxic mortality rates remained at the low level of approximately 0.1 percent per 12-hour period in nearly all layers of every pond throughout the modeled period. Pond 1 demonstrated the highest modeled ammonia toxicity, but even in the most toxic layers of that pond in April, ammonia toxicity rarely reached 5 percent per day.

Though modeled total ammonia levels were high during April and early May, especially in pond 1 (where they were in the 20-30 mg/l range), these high levels were insufficient to cause significant mortality. This relates to the LC50 for un-ionized ammonia being higher for conditions of elevated pH (see previous discussion) and the fact that the pond pH generally decreases with depth. In addition, due to algal uptake of ammonia, the model generally showed relatively lower concentrations of total ammonia near the pond surface. Thus, near the surface, despite the higher pH causing a greater percentage of the total ammonia to exist in the un-ionized form, the smaller total ammonia concentration in combination with the higher LC50 resulted in predictions of low mortality. Near the bottom, although total ammonia concentrations were higher and the un-ionized LC50 lower, the lower pH caused much less of the total to exist in the more toxic un-ionized form. Toxic mortality was therefore again minimized.

As has been discussed, at present the model contains no hydrogen sulfide sub-routine, and sulfide toxic mortality rates are based on concentrations arbitrarily set within the model. Since little is known about pond sulfide levels, in all ponds each layer's sulfide concentration was set to zero except in the lowest 4 layers. In these layers, if the modeled dissolved oxygen concentration was below 0.1 mg/l, the H_2S concentration was made to rise from 0.75 mg/l to 3.0 mg/l at the pond bottom. This manner of handling hydrogen sulfide precluded its having a significant toxic effect on the *Daphnia* population.

While the low values for toxic mortality were unexpected, data with which to evaluate their validity are currently unavailable. Future improvements to the model, such as the implementation of a functional pH/alkalinity sub-model and a method for predicting hydrogen sulfide concentration, should maximize the model's ability to predict toxic mortality.

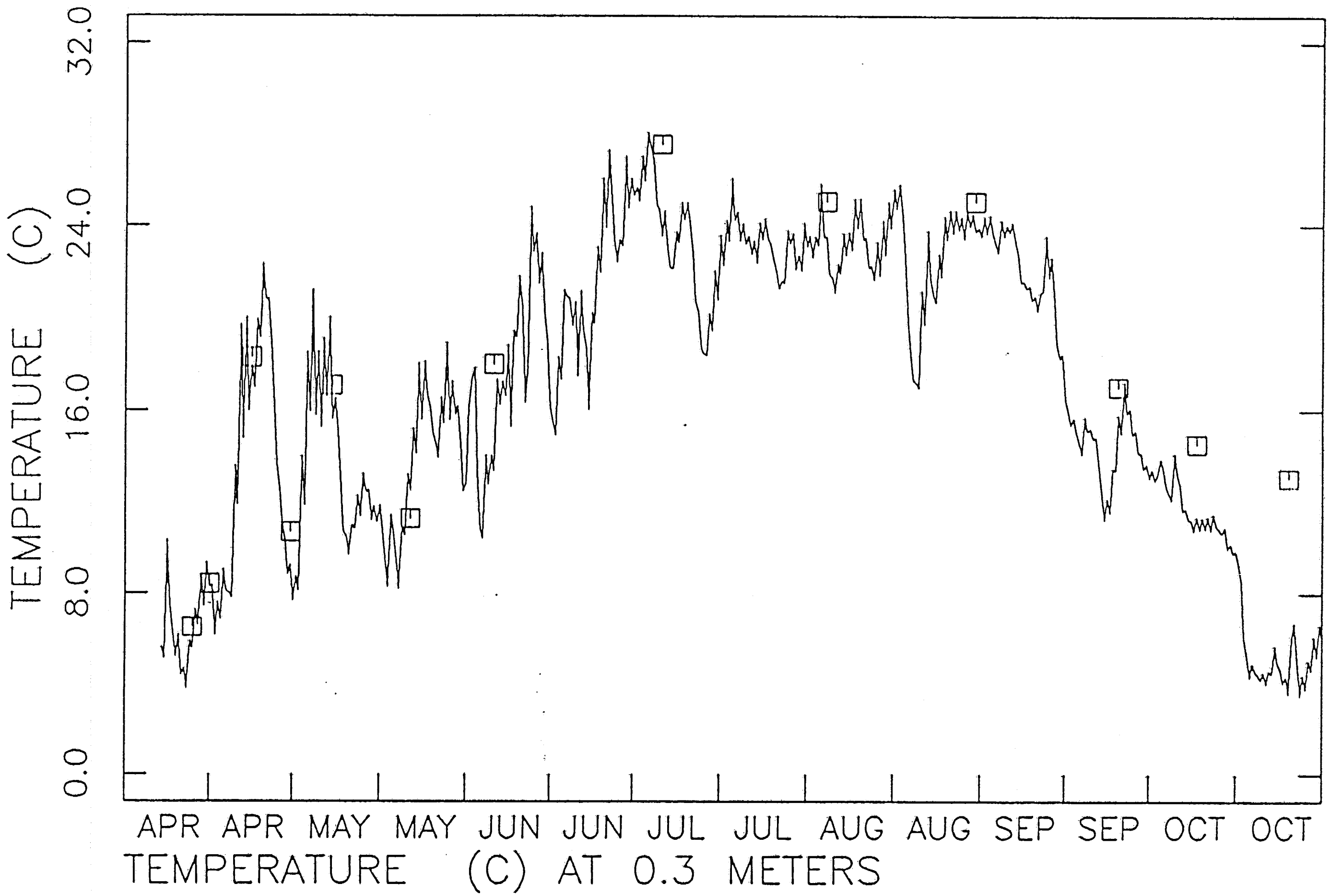

Figure 14: Pond 3 temperature simulation; Harris, MN, 1990

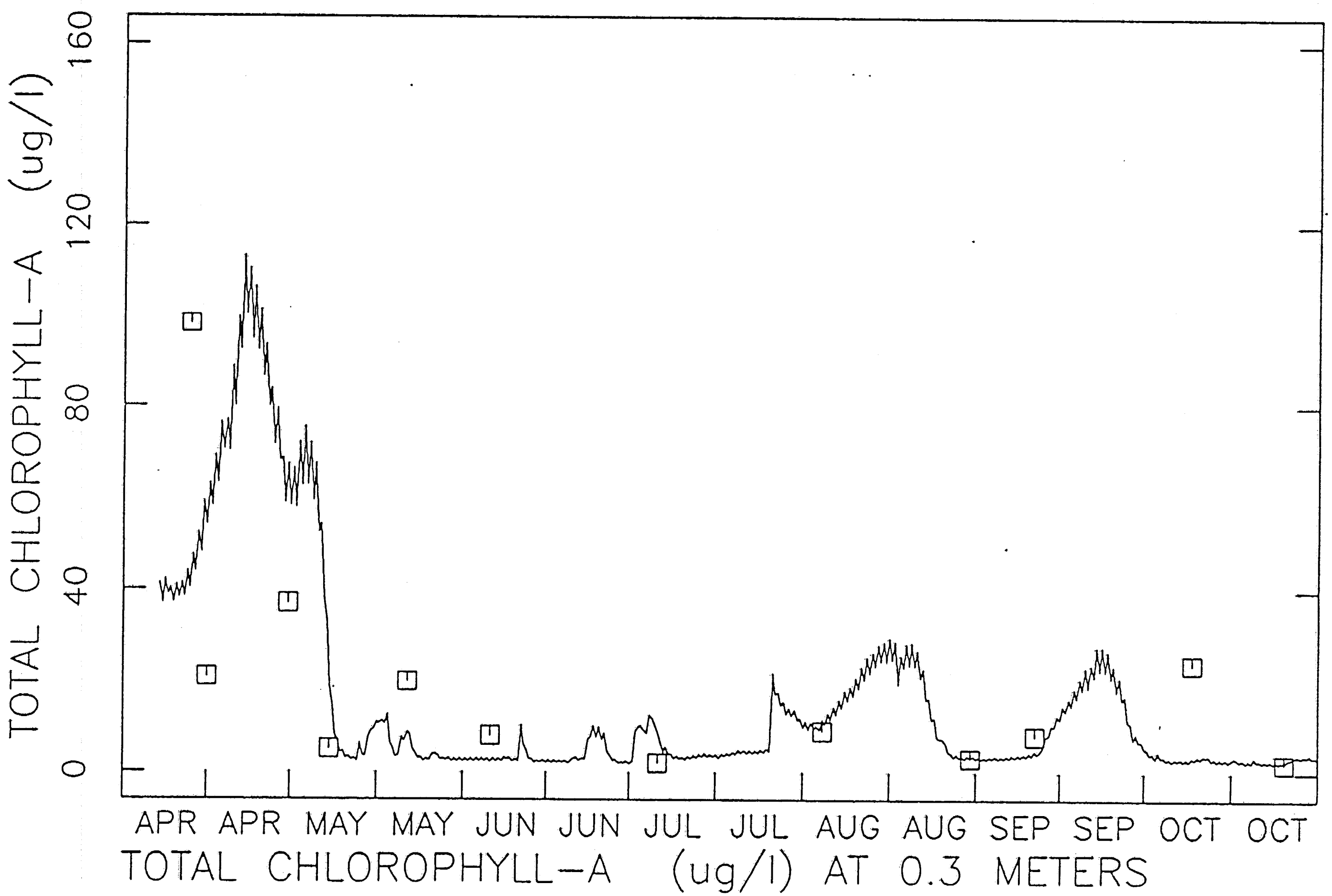

Figure 15: Pond 3 total chlorophyll-A simulation; Harris, MN, 1990

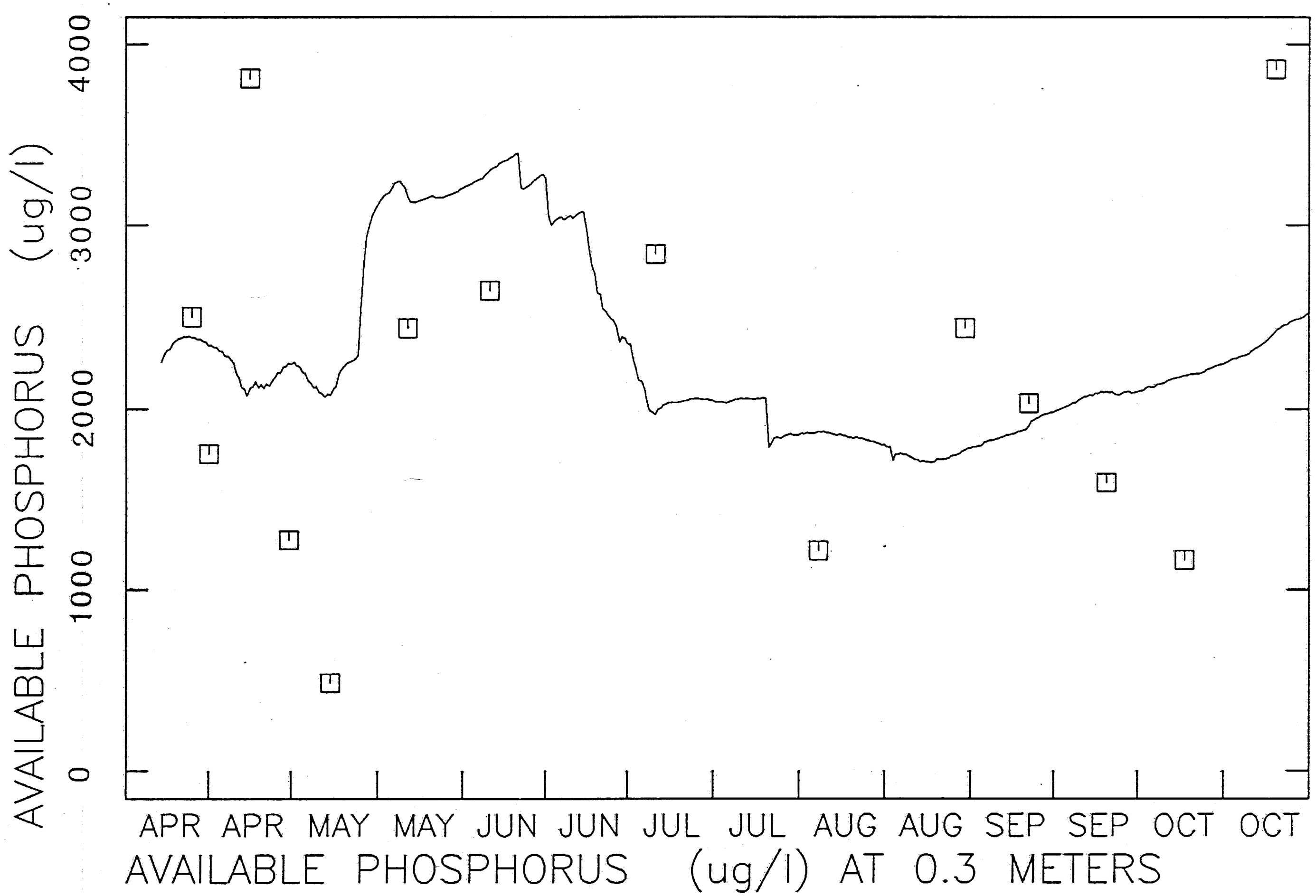

Figure 16: Pond 3 available phosphorus simulation; Harris, MN, 1990

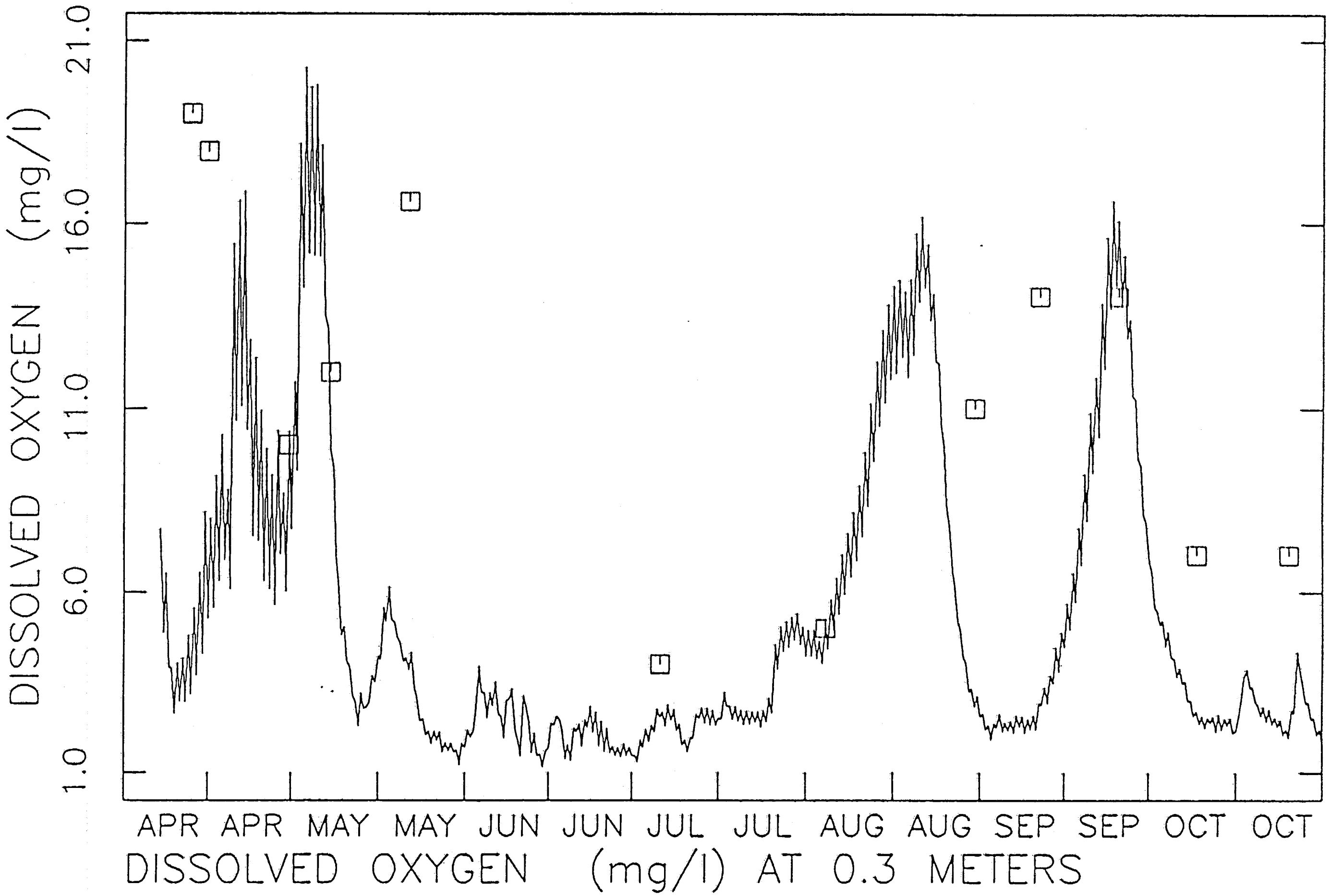

Figure 17: Pond 3 dissolved oxygen simulation; Harris, MN, 1990

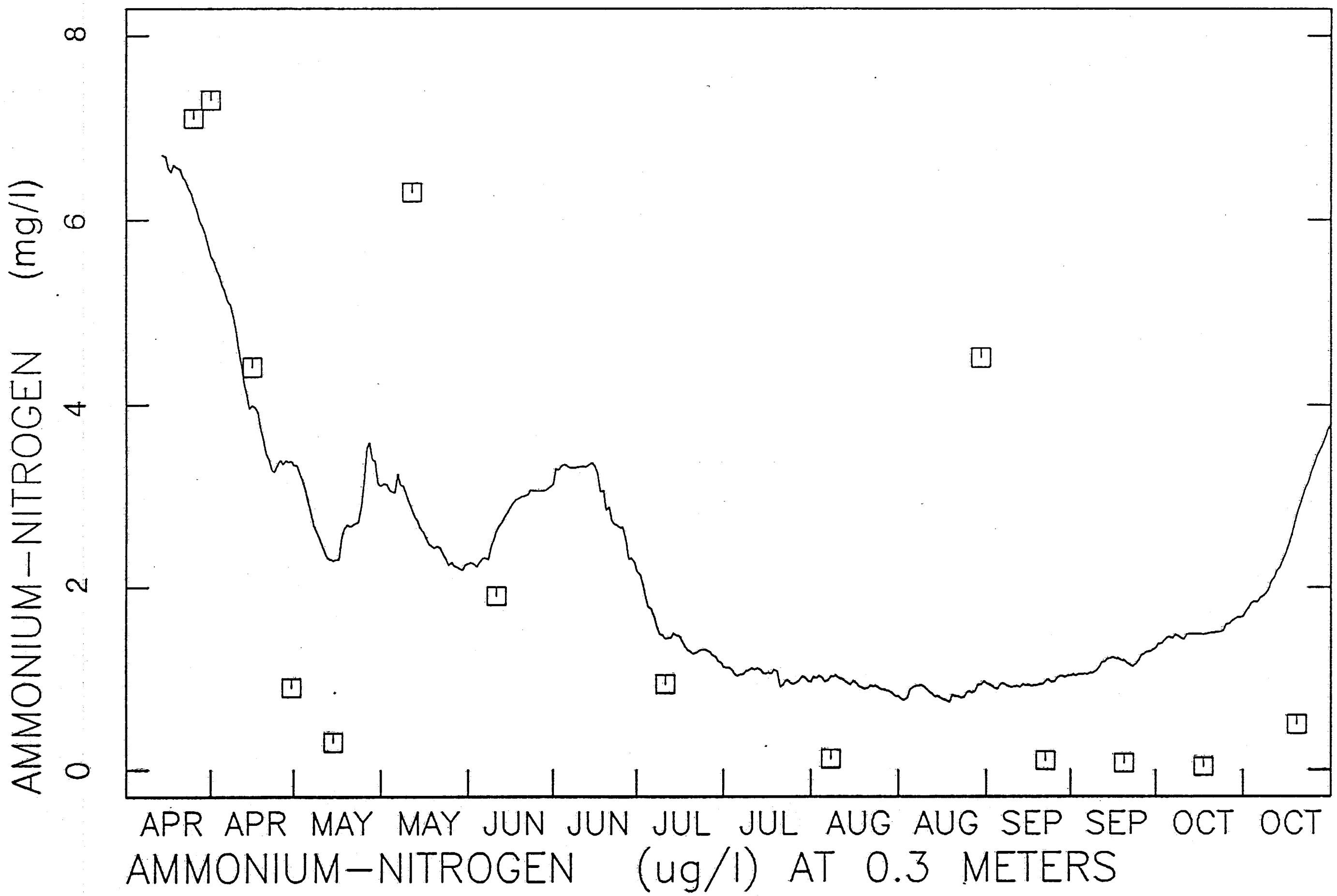

Figure 18: Pond 3 total ammonia simulation; Harris, MN, 1990

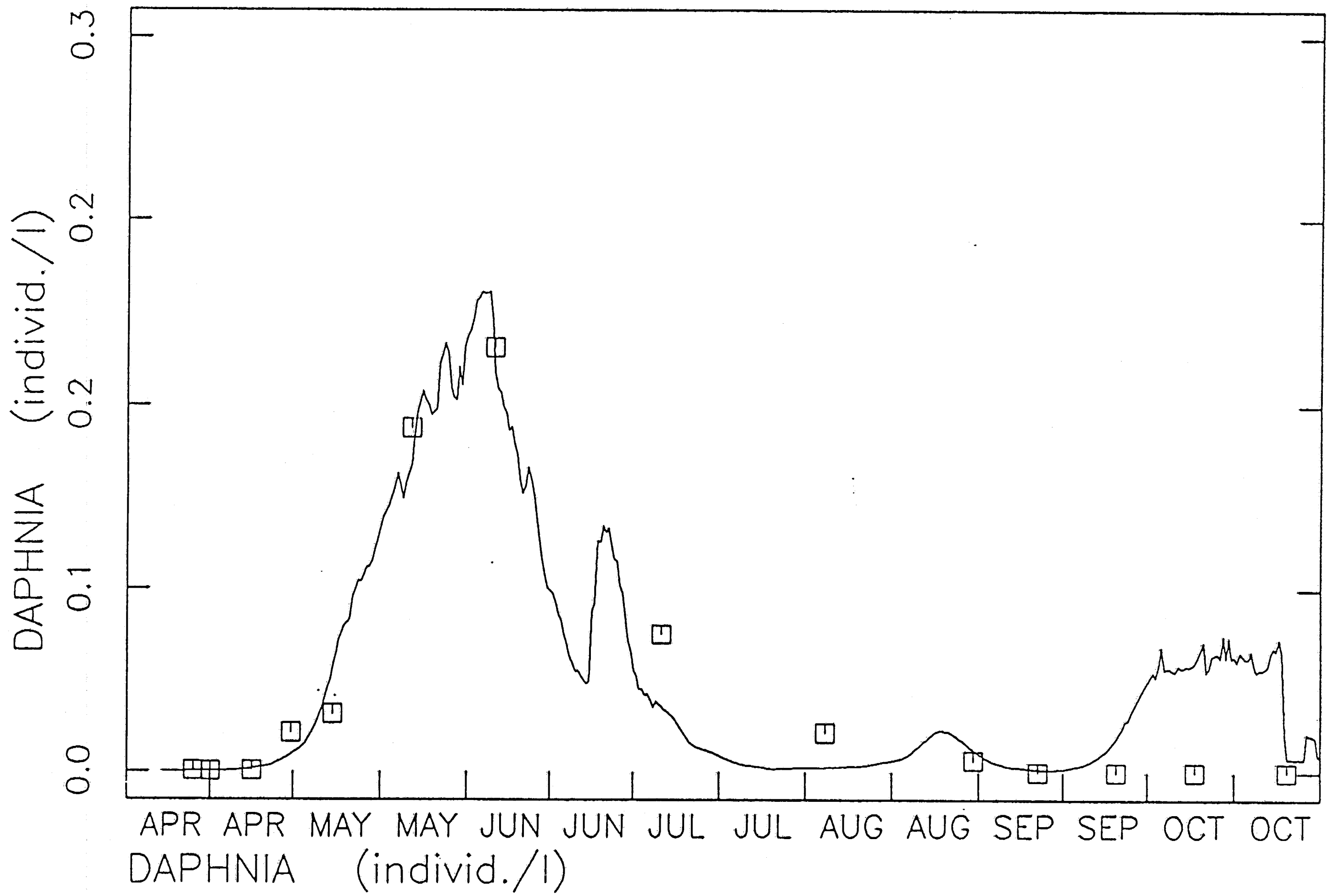

Figure 19: Pond 3 *Daphnia* simulation; Harris, MN, 1990

VII. Recommendations for Future Study

For the purposes of calibrating a one-dimensional water quality model such as MINLAKE, one should have chemical and biological information with respect to depth for the water body being modeled. In this respect we found ourselves somewhat hampered. Apart from temperature data, depth-dependent information was quite limited. Future work should make a more concerted effort to collect data at several depths over the study period. In this way, the results of the modeling could be more effectively evaluated, and a more complete picture of the pond processes could be drawn.

In addition, for the present study, samples were collected over only one season. Future studies would be aided by the existence of a second data set with which the calibrated model could be verified.

Similarly, the pond influent chemistry was not well characterized during this study. Future work should include regular, frequent sampling of the pond influent so that its chemical nature can be better characterized, and any fluctuations can be charted. One would thus be in a better position to judge and model the effects of varying inflow concentrations on the ponds' behavior.

After consideration of several alternatives, (see the Luck report for the reasons behind the selection the monitoring site), the focus of our study was the Harris, Minnesota ponds - which have a history of functioning quite well over an extended period. This was appropriate for the purposes of developing a model for ponds operating normally. However, the intense focus on a single pond system provides little opportunity for comparison with other pond systems that do not function as well. Therefore, it was difficult to contrast our findings with those of other ponds, and thereby identify potential sources of problems with less healthy systems. A more ample supply of physical, chemical, and biological data from several pond systems and their influents might allow insight into the sources of problems for treatment ponds in general.

Despite the extensive use of *Daphnia* in toxicity assessments, relatively little is known about the toxic effects of waste waters on *Daphnia* growth, reproduction, or short term mortality (similarly, toxic effects on algal populations are not understood). The situation is admittedly complex; many chemical constituents may interact to produce an effect on a given zooplankton species. Yet successful deterministic modeling of stabilization pond zooplankton populations will require more information regarding toxicity.

The resurgence of the *Daphnia* population in the spring, and the restoration of the population following toxic events or starvation depends on the contributions of the resting egg population. Unfortunately, little is known about the viability of the resting eggs, or the controls on the hatching rates of this important constituent of the population. Further work is needed to bring the needed rates and timing mechanisms to light.

Daphnia growth rates depend heavily on the available food supply; as has been discussed, the assessment of the available food supply requires knowledge of the types of algae comprising the phytoplankton population. Water quality models are not yet at a point where algal speciation can be predicted with confidence. *Daphnia* modeling remains hampered by this problem. Not until shifts from green algae to blue-greens can be predicted accurately will reliable assessment of *Daphnia* population dynamics be possible.

As mentioned previously, both the hydrogen sulfide and pH subroutines are not yet functioning. Further work will be required in the development of these subroutines in order to allow the prediction of the concentration of these pond constituents. Such work should enhance the ability of the model to accurately project fluctuations in the zooplankton compartment.

VIII. Conclusions

Many changes were required in adapting the water quality model MINLAKE for use with stabilization ponds. Among these changes is a new *Daphnia* subroutine formulated to take into account the peculiar chemical and hydrodynamic characteristics of these ponds. In the model, growth of the *Daphnia* requires the presence of edible species of algae - excluding blue-greens as a food source. The subroutine incorporates novel adaptations for the modeling of ammonia, hydrogen sulfide, and low dissolved oxygen toxicity. It provides for avoidance behavior of the *Daphnia* population to toxic pond water environments. Provision is made for predatory depletions of the population, if indicated.

In spite of the many uncertainties remaining with respect to the chemical and biological inter-relationships within wastewater stabilization ponds, the modeling and calibration effort provided insight into pond dynamics. The modeling process confirmed the importance of the balance between dissolved oxygen levels, algal growth, and the *Daphnia* population. Simulations showed each of these parameters influencing, and being strongly influenced by, each of the others. The balance between the algal and *Daphnia* populations also controls, to some extent, pond phosphorus, nitrogen, and suspended solids levels.

Our studies seem to confirm the impression that a healthy *Daphnia* population in stabilization ponds will serve as a check on algal overabundance and help reduce effluent suspended solids. As can be seen from the example of the Harris, MN, pond system, this occurs even if only the last pond in the series supports a significant *Daphnia* population. Indications from the modeling process suggest that maintaining a strong contingent of these algal grazers depends on the presence of a suitable and adequate food supply, adequate oxygen, and low toxic levels.

Discouraging the growth of the generally unpalatable or inedible blue-green algal species will benefit the *Daphnia* population. The method by which selective promotion of algal classes might be accomplished, unfortunately, remains a mystery. Such a method may be encountered through further study. Selective promotion already occurs in natural systems - the Harris, MN, ponds had remarkably little blue-green growth despite the continual elimination of competing classes by the grazing *Daphnia*.

Despite their relatively high tolerance for low oxygen levels, the model indicated that *Daphnia* were adversely affected by recurring near anoxic conditions. To counter such effects, promotion of algal growth, BOD loading reduction, and possibly aeration may be used to maintain pond oxygen levels. Adequate oxygen will prevent high rates of anoxic toxicity for the zooplankton population. It may also play a role in allowing the successful preservation and hatching of *Daphnia* resting eggs.

Similarly, adult, juvenile, and resting egg portions of the *Daphnia* population will benefit from keeping the ponds relatively free of toxic stresses. Simulations for the Harris, Minnesota ponds showed minimal toxic mortality throughout the modeled period (see results section); perhaps low toxicity is one of the factors contributing to the continued success of that pond system. In general, ammonia and hydrogen sulfide levels should be kept low, presumably through controlling oxygen levels and BOD loading. In addition, high levels of the more toxic un-ionized ammonia form may be kept low by avoiding conditions of high pH. Pesticide use on or near the ponds should be avoided in order to prevent lethal effects on *Daphnia*.

The model performs with reasonable accuracy under the conditions for which it was tested. However, much work remains to be done before such modeling can be expected to be of value in the day-to-day management of stabilization ponds. In particular, more research is needed to elucidate the mechanisms by which algal populations wax and wane, and to understand the conditions by which certain algal groups become dominant in these waters. Such understanding will be crucial for the accurate prediction of *Daphnia* populations, and for the prediction of resultant pond "health".

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Fred Luck, with his thorough and extensive work in collecting and analyzing the physical data, laid the foundations for the study. Special thanks is in order to Chris Ellis of SAFHL, who was responsible for the development and installation of the automated weather and pond temperature equipment. He also coordinated the data retrieval and provided invaluable advice and assistance throughout the project. Many other members of the SAFHL research community provided support and assistance in solving the minor problems that developed along the way; we extend our gratitude to them as well.

Note on Annotated Bibliography

In association with the research done for this project, an annotated bibliography containing over two hundred and fifty references was prepared. These references pertain to pond operation and processes, *Daphnia* life history and toxicology, modeling formulations, and a variety of associated topics. The bibliography was prepared using PAPYRUS™ software, which allows searching by title, author, keyword, date, journal, or phrase. Since the "List of References Cited" prepared for this report does not include all of the references collected for the study, a copy of the complete bibliography is appended to the report (Appendix D).

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(This is a listing of references actually cited in the text; the complete bibliography listing appears in Appendix D.)

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Appendix A - Ponds 1 and 2 Modeling Results

The following pages present the intermediate modeling results for ponds 1 and 2 at Harris, Minnesota, for the period April, 1990 through October, 1990. Temperature, total chlorophyll-a, available phosphorus, dissolved oxygen, ammonia, and *Daphnia* simulations are shown for each pond. All simulation and field data presented is at the sampling depth of approximately 0.3 meters. In all cases, the graphs show field data with a square, and simulation results as a continuous line.

Field data for the *Daphnia* simulations are not presented, since sampling results showed negilgible population levels throughout the modeled period in ponds 1 and 2.

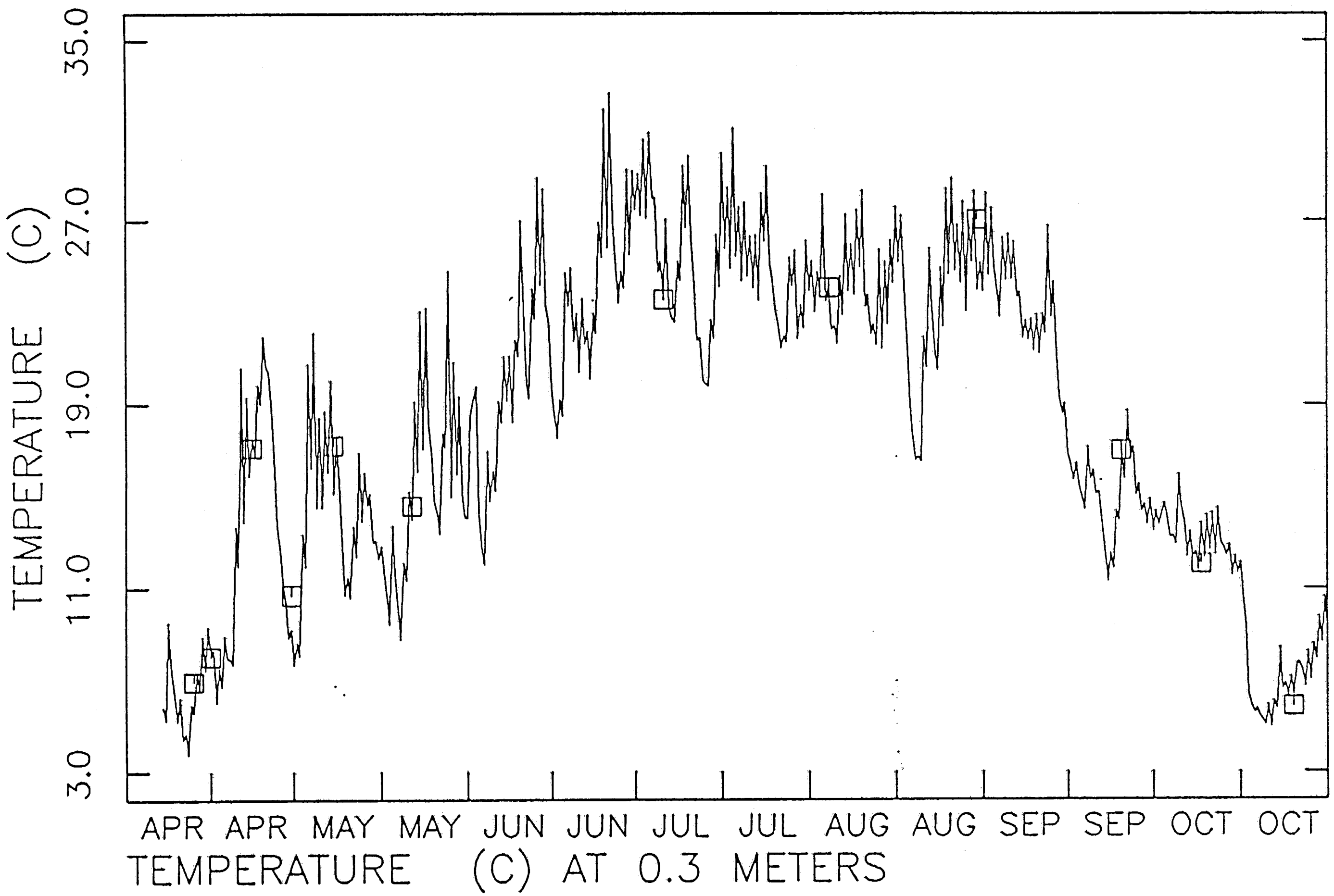

Figure 20: Pond 1 temperature simulation; Harris, MN, 1990

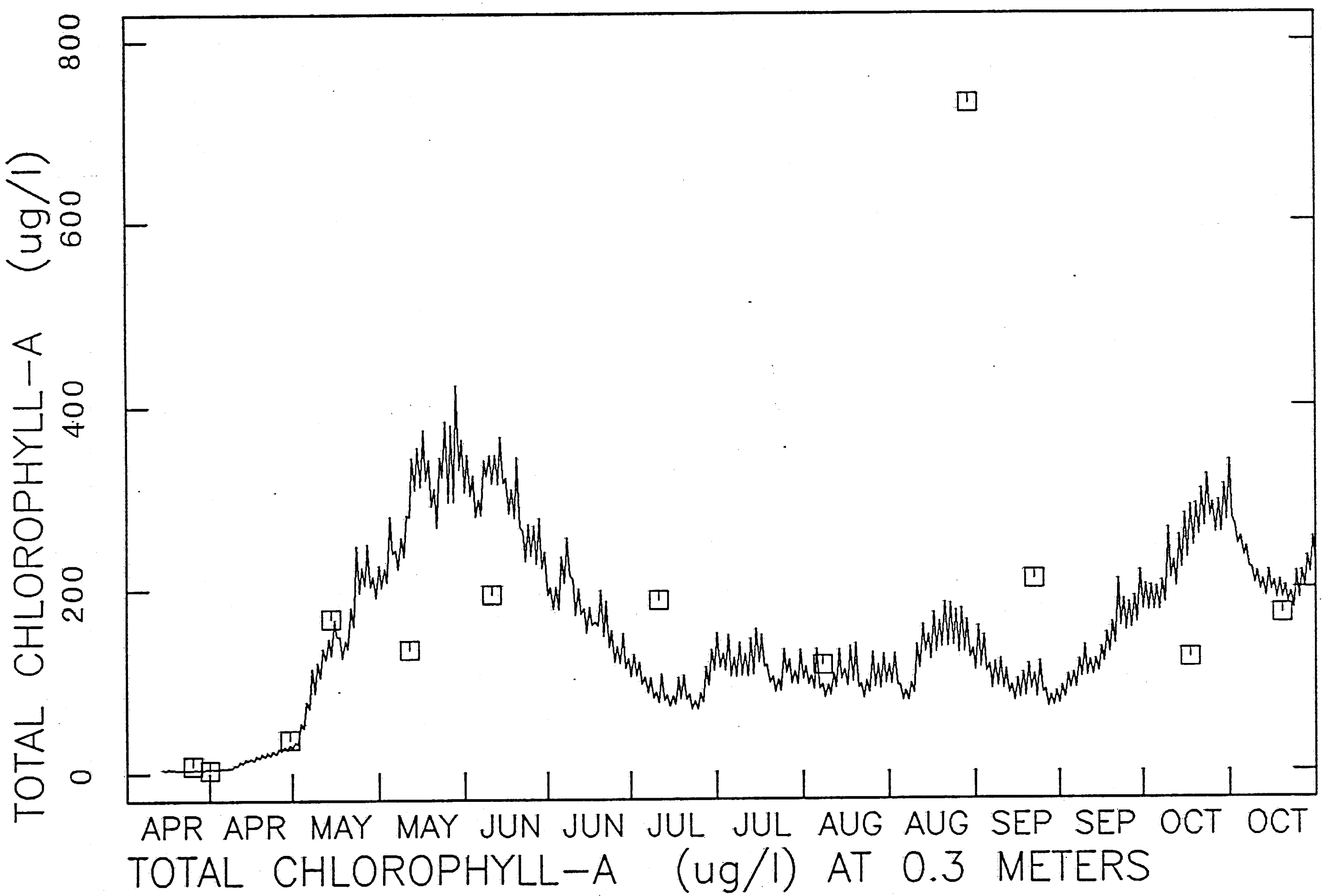

Figure 21: Pond 1 total chlorophyll-a simulation; Harris, MN, 1990

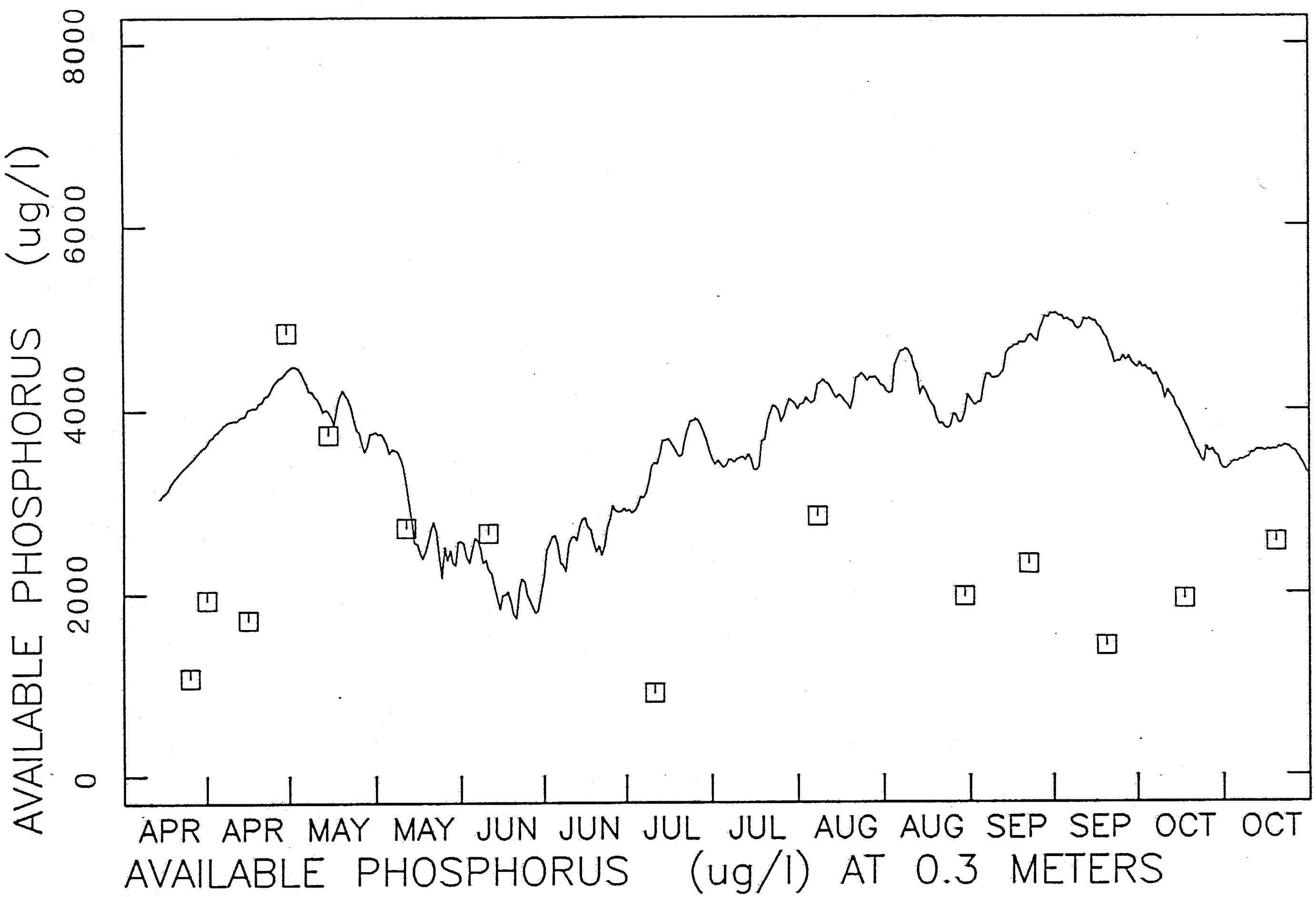

Figure 22: Pond 1 available phosphorus simulation; Harris, MN, 1990

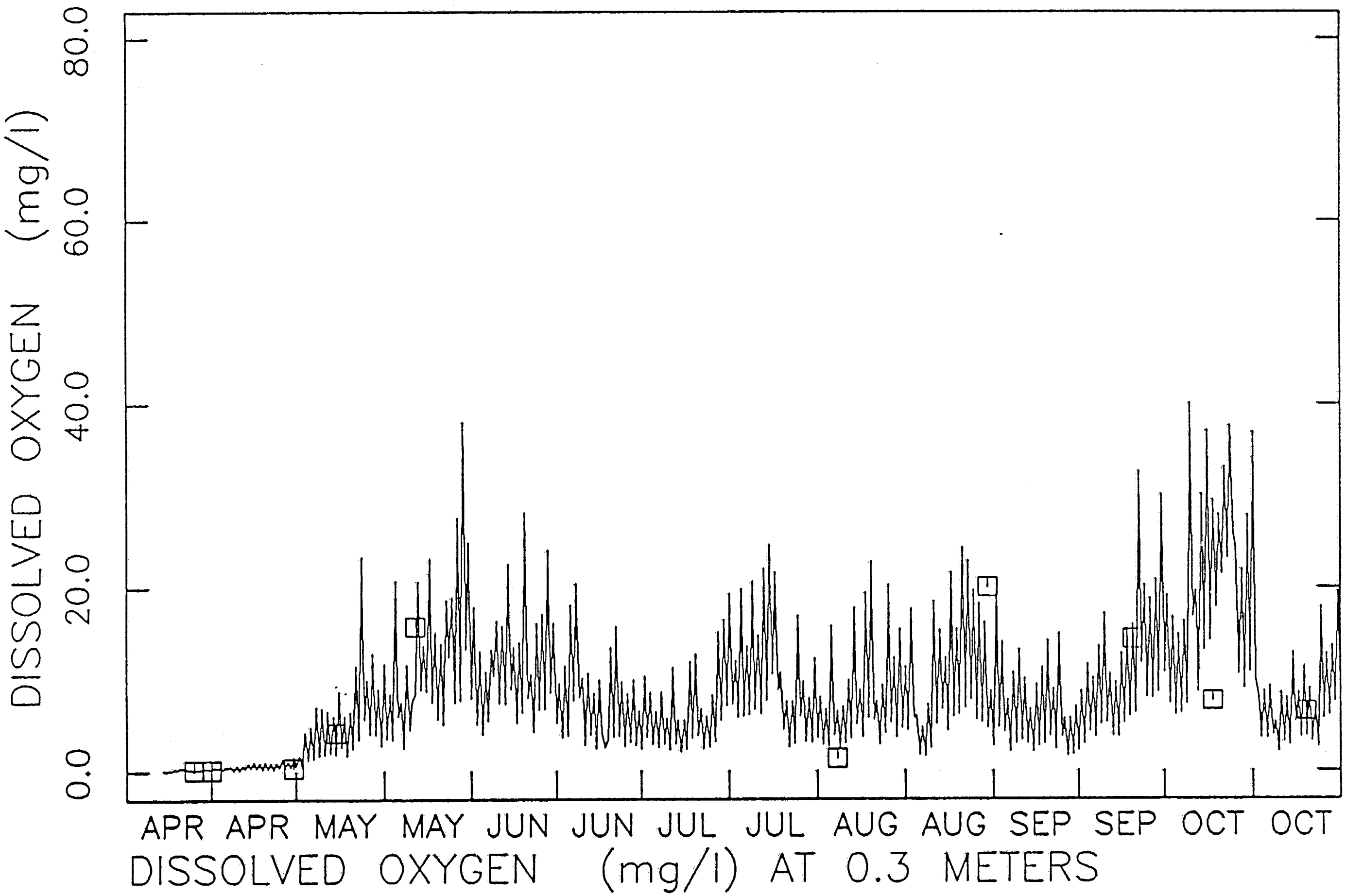

Figure 23: Pond 1 dissolved oxygen simulation; Harris, MN, 1990

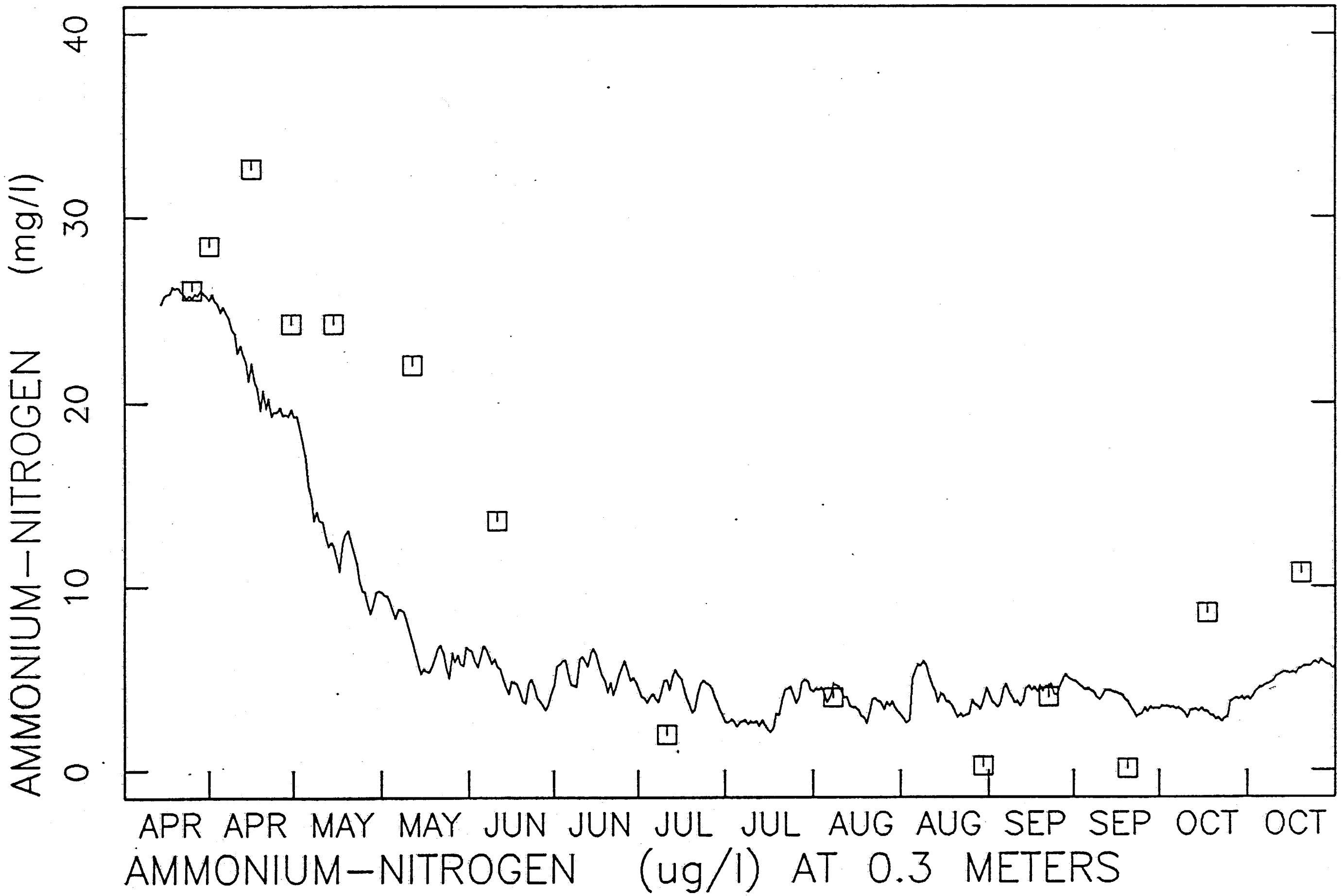

Figure 24: Pond 1 total ammonia simulation; Harris, MN, 1990

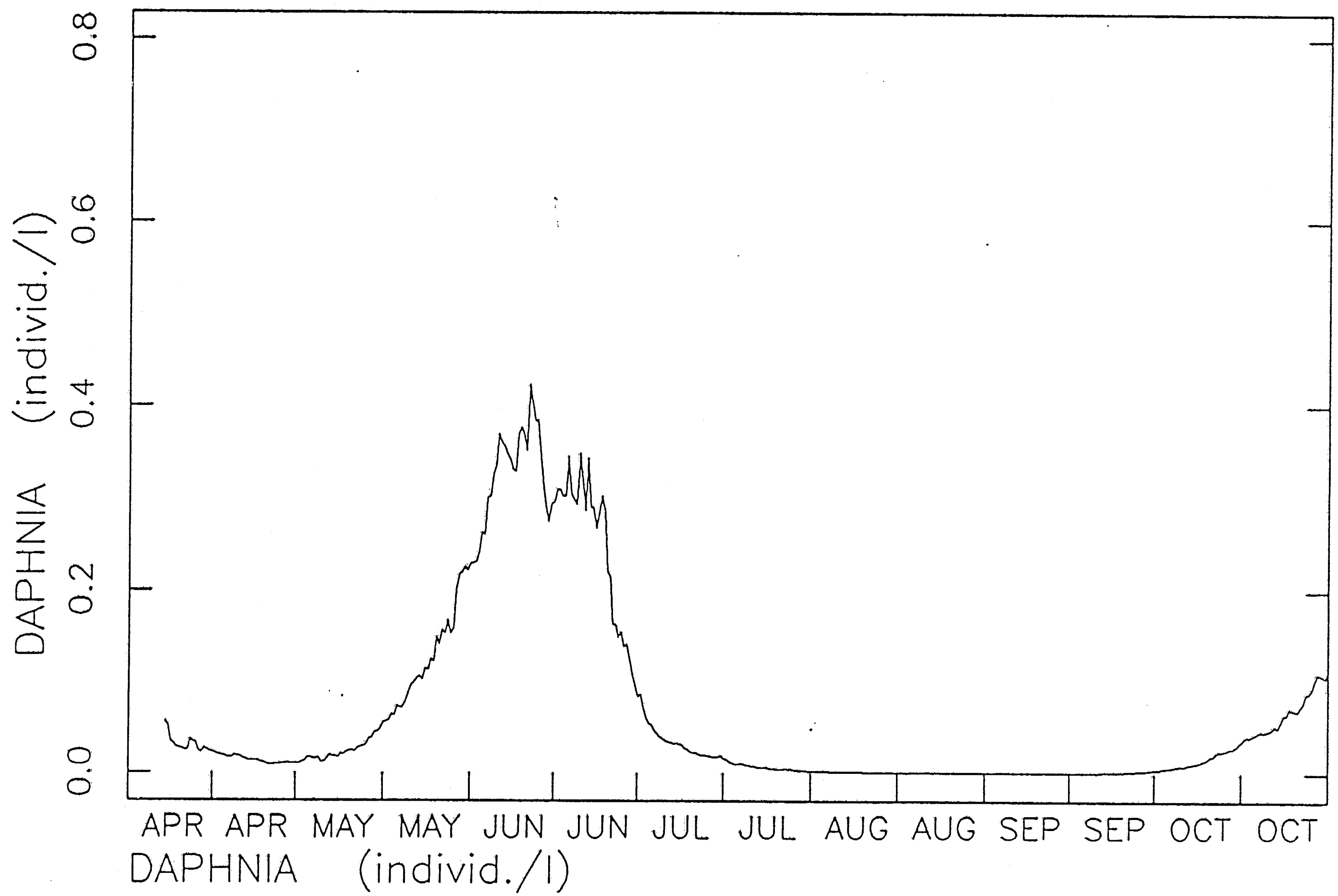

Figure 25: Pond 1 *Daphnia* simulation; Harris, MN, 1990

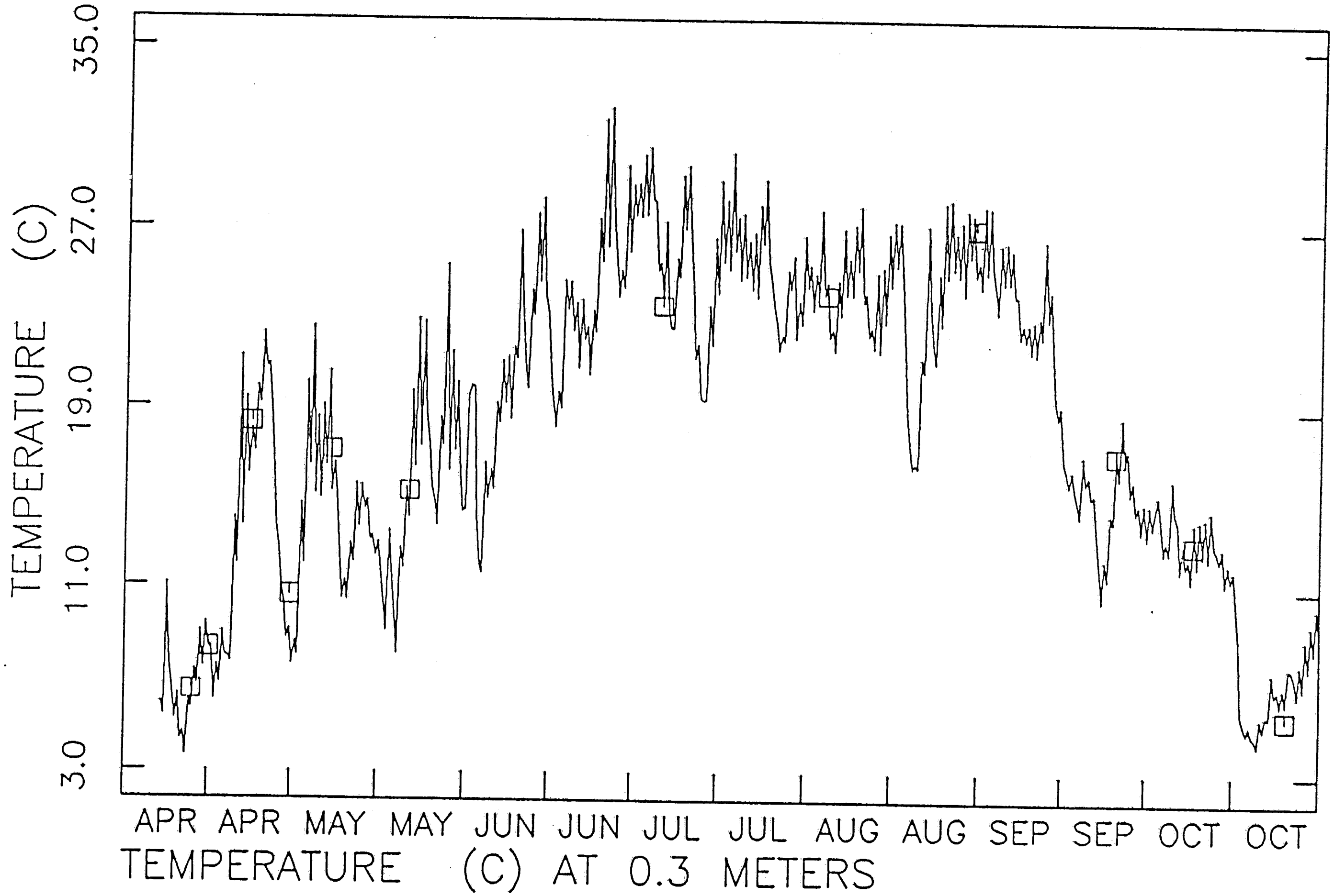

Figure 26: Pond 2 temperature simulation; Harris, MN, 1990

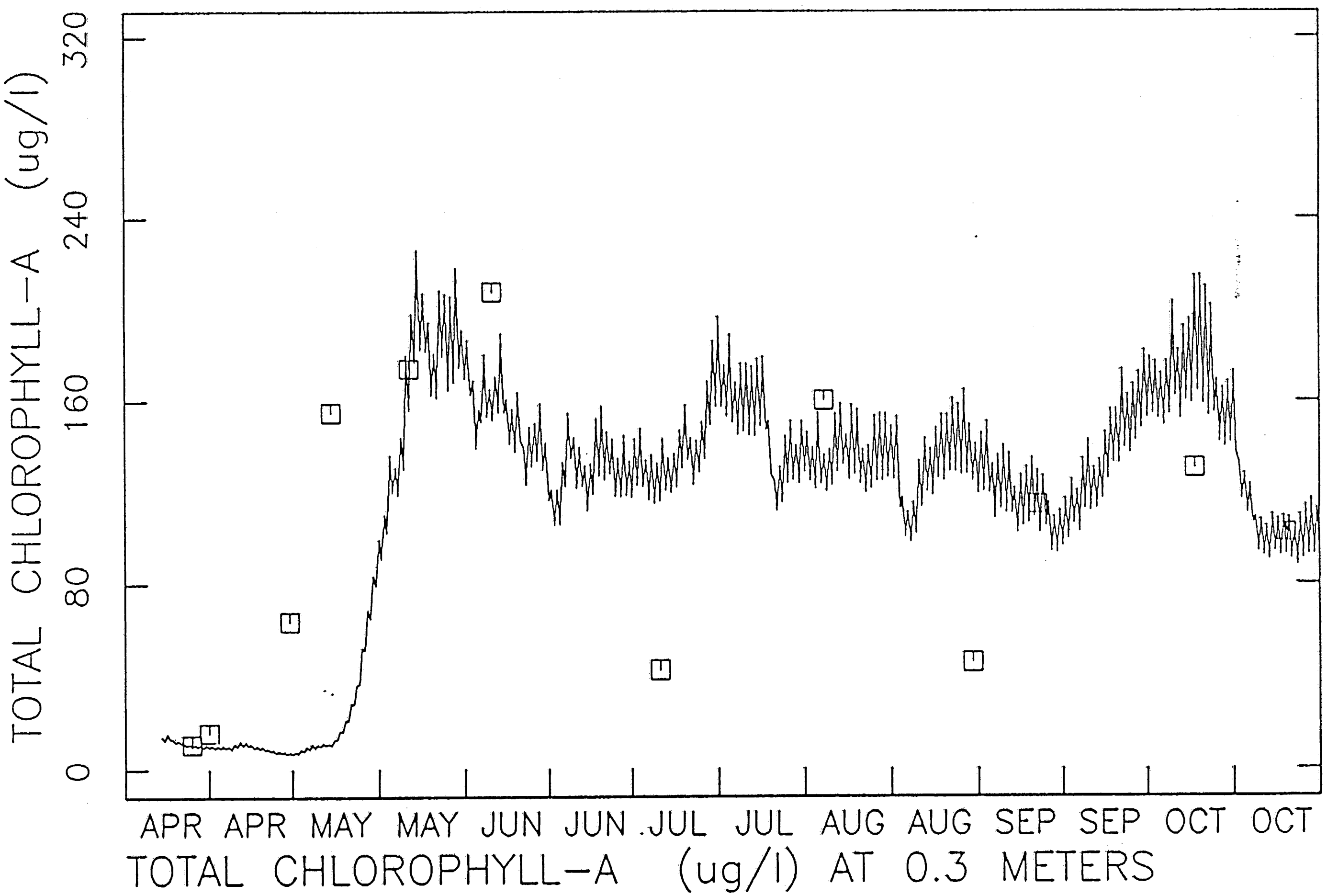

Figure 27: Pond 2 total chlorophyll-A simulation; Harris, MN, 1990

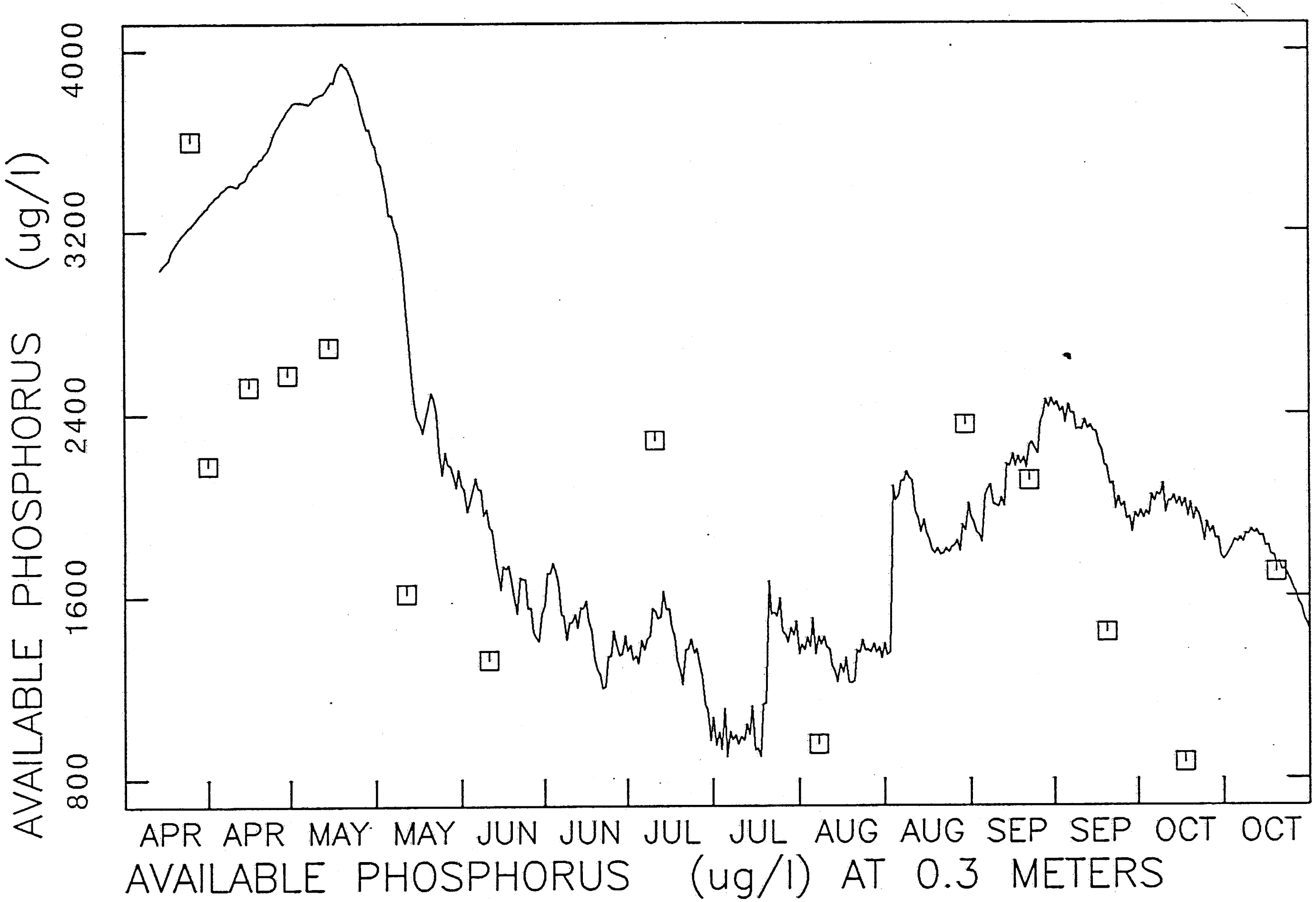

Figure 28: Pond 2 available phosphorus simulation; Harris, MN, 1990

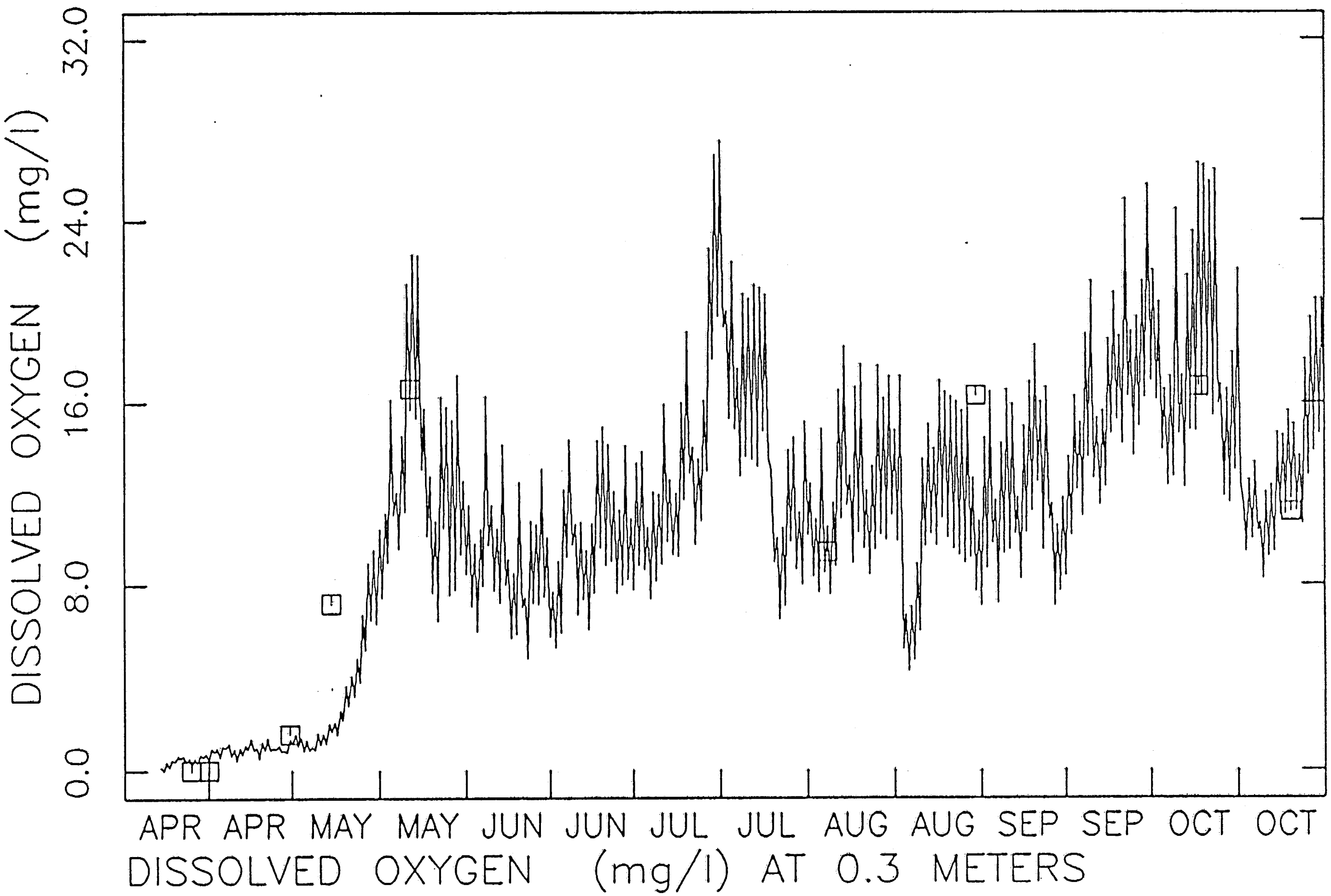

Figure 29: Pond 2 dissolved oxygen simulation; Harris, MN, 1990

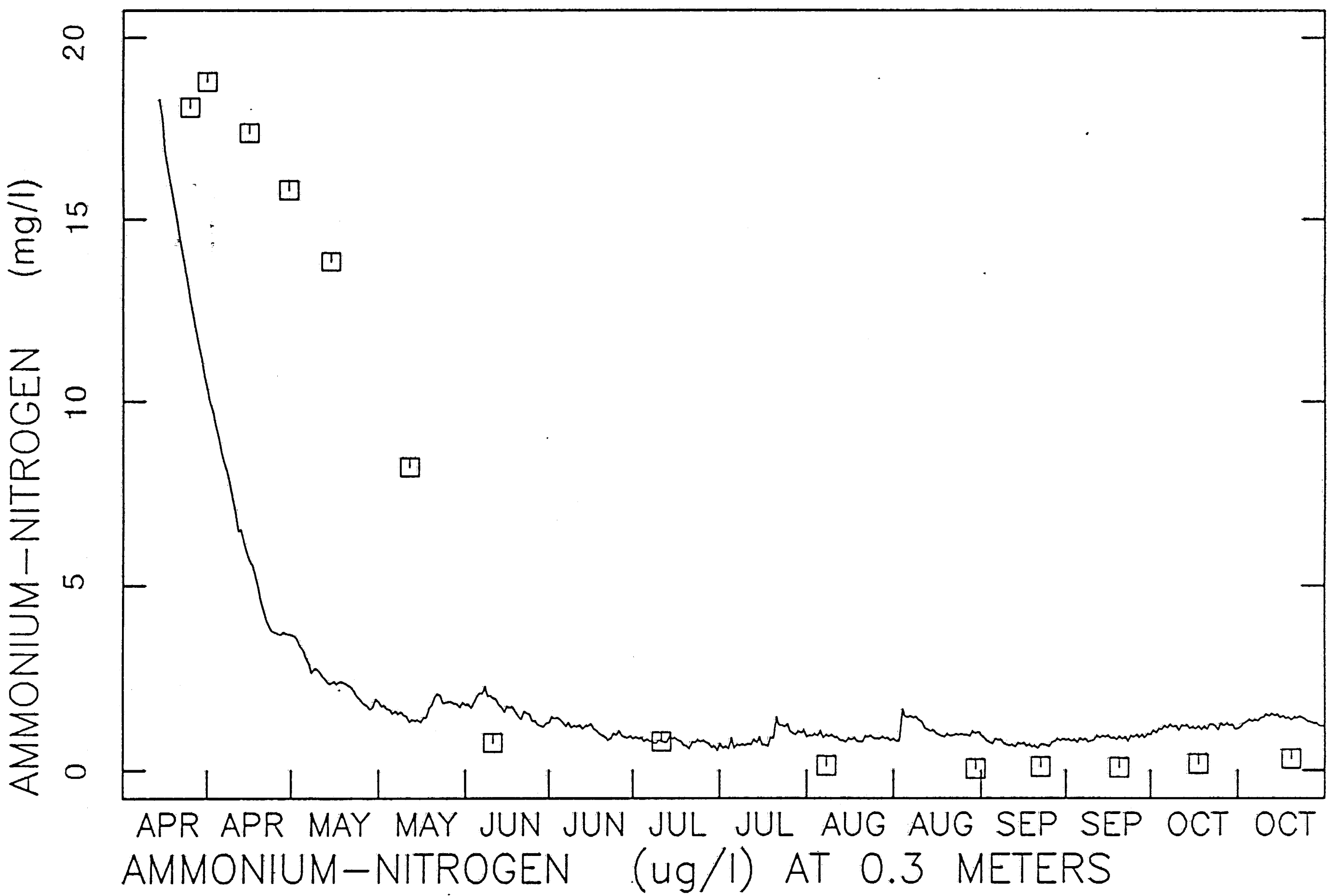

Figure 30: Pond 2 total ammonia simulation; Harris, MN, 1990

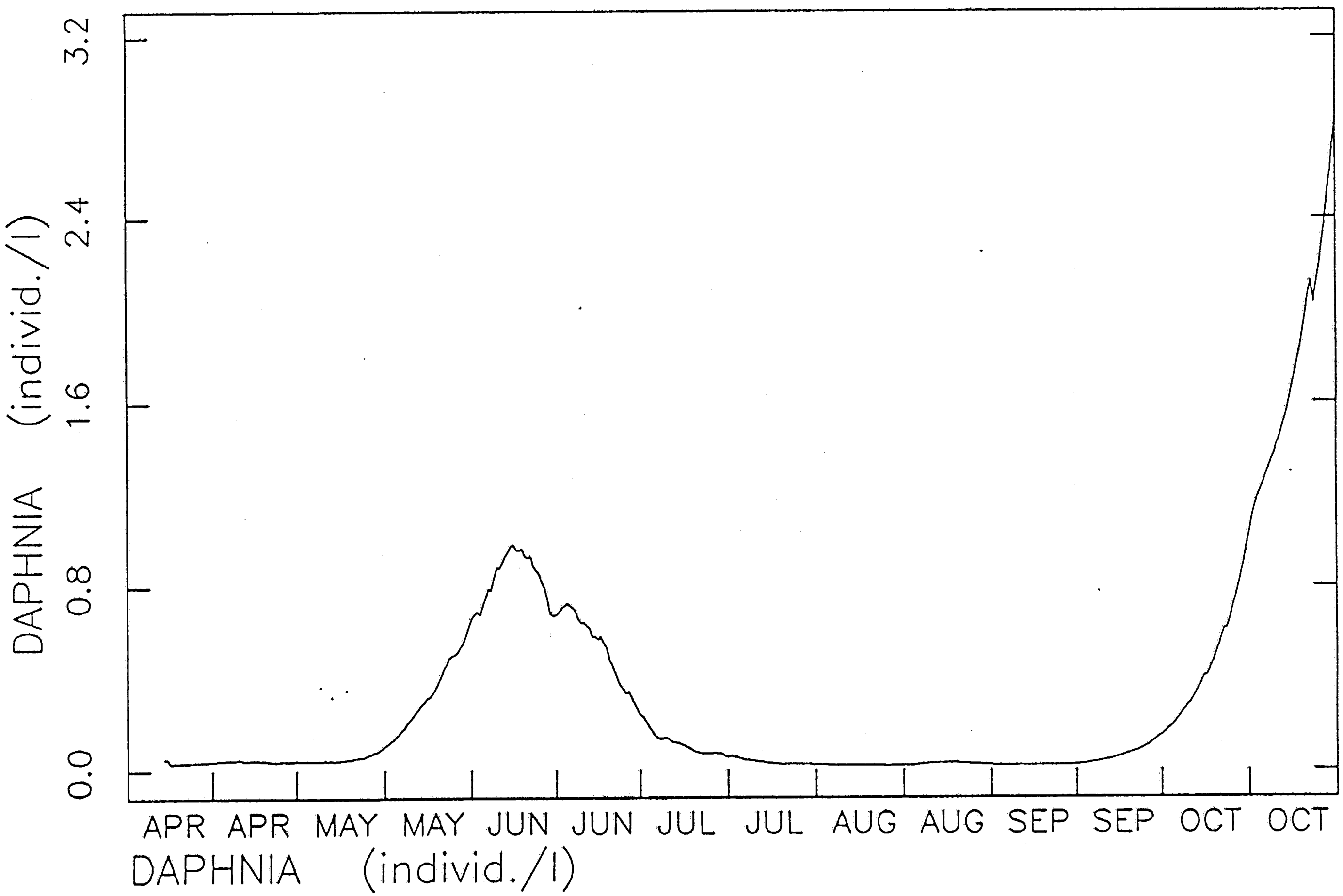

Figure 31: Pond 2 *Daphnia* simulation; Harris, MN, 1990

Appendix B - Input Files

The "ICE" and "INDP" input files used with the MINPOND model are given in this appendix for the benefit of those working closely with the model. Detailed information regarding the operation of the original MINLAKE model and the use of these files may be found in the MINLAKE project report (Riley and Stefan, 1988). In the program, the ICE file is read from within the Lake Specific subroutine.

Table 4 - ICEP1 Input File for Pond 1

Jet Inflow Parameters:

1.0 15.0 16 3 .03974 6.5 .25 1
.0 2.6 .45 50.250 1.0 .50 7 12 22 16
0.20 20. .3 .2 20. .3 .003
0.20 20. .3 .0505 .0 0.0
.37 .5 5. .17 0.4 40.
2.5 -2. 12.
18 14 200
.01167 0.111 0.1016

Alkalinity and pH Data:

7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5
15 15 15 15 15 15 15 15 15 15 15 15 15 15 15
0.0000028 .000111 .000016 .000181 .000486 .00000 1
.2 .2 0.2
.145 .35 1.05

***Daphnia* Information:**

Daphnia and H_2S Initial Conditons:
0 1 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 .001 .002 .045

HSCZP, GMAX, LENPRED, TRESP
.005 .500 260 .015

EPHIP, MINEPH, MAXEPH
10000 200 500

Table 5 - INDP1 Input File for Pond 1
(field data omitted)

HARRIS POND 1, MODEL 3, 3 CLASSES, N2 LIMIT.

Preliminary Information:
3 1 3 1 1 1

15
724 730 815 829 914 1011 1110 1310 1507 1629 1721 1819 1917 2019 2208

.08 .15 .4 .970 8.0 40.0 0.20 20.0 .3
5. 50. 200. 201.82 .001 .035
203.2 10 5.
15 14 100 193 7 13 1990

Initial Conditions:
.025 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.0
1.2 1.4 1.6 1.8
3.0 3.5 3.8 3.7 3.6 3.8 3.9 3.8 3.9 3.9
3.9 3.9 3.9 4.0 4.0
20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0
25.0 25.0 25.0 25.0 25.0
1.8 1.8 1.8 1.8 1.8 1.8 1.8 1.8 1.8 1.8
1.8 1.8 1.8 1.8 1.8
.001 .001 .001 .001 .001 .001 .001 .001 .001 .001
.001 .001 .001 .001 .001
.003 .003 .002 .002 .002 .002 .001 .001 .001 .001
.001 .001 .001 .001 .001
.001 .001 .001 .001 .001 .001 .001 .001 .001 .001
.001 .001 .001 .001 .001
3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0
3.0 3.0 3.0 3.0 3.0
29.0 29.0 29.0 29.0 29.0 29.0 29.0 29.0 29.0 29.0
29.0 29.0 29.0 29.0 29.0
0. 0. 0. 0. 0. 0. 0. 0. 0. 0.1
0. 0. 0. 0. 0.1
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0
24.0 24.0 24.0 24.0 24.5 24.5 25.0 25.1 25.2 25.5
25.8 26.5 27.0 27.4 28.4
.010 .009 .007 .006 .006 .006 .006 .006 .006 .006
.006 .006 .006 .006 .006

Table 5 - INDP1 Input File for Pond 1 - continued
(field data omitted)

Benthic and BOD Parameters:
0.1 .05 0.04 .45

Algae - Phosphorus Uptake, Growth, and Mortality:
8.5 1.08 .15 10. 3. .1 .1 1.045 .1 1.04
4.5 1.08 .12 30. 15. .1 .1 1.045 .1 1.1
8.5 1.08 .05 37. 33. .1 .1 1.045 .1 1.04

Algae - Phosphorus Uptake, and Light:
.0 250. 500. 1.0 9.0 9.0 .05
.02 10. 1400. 1.0 9.0 9.0 .05
.01 140. 1000. 1.0 9.0 9.0 .05

Algae - Nitrogen Uptake:
8. .02 6. 8.0 1. .4 .1
8. .02 6. 14.5 1. 0.04 .025
8. .02 6. 8.0 1. .2 .1

Benthic Nitrogen Release:
.05 .1 .1 1.06

Zooplankton Parameters as in Original MINLAKE Model:
000. 100. .02 .1 .05 2. 5.
430 400 .001 1. .0 .5

Zooplankton Grazing Coefficients:
.003 1.0 .005 .001
.002 1.0 .005 .001
.0005 1.0 .005 .001

Yield Coefficients:
.0025 .01 .0083 .01 .05 1.0 1.0 .003 0.0

Table 6 - ICEP2 Input File for Pond 2

Jet Inflow Parameters:

```
 1.0 15.0  16   3  .03974   6.5  .25  1
 .0  2.6  .45   50.250  1.0  .50  7  12  22  16
 0.20  20.  .3  .2        20.  .3  .003
 0.20  20.  .3  .0505   .0  0.0
 .37  .5   5.  .17  0.4  40.
   2.5  -2.  12.
 18  14  200
.01167  0.111  0.1016
```

Alkalinity and pH Data:

```
7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5
15 15 15 15 15 15 15 15 15 15 15 15 15 15 15
0.0000028  .000111  .000016  .000181  .000486  .00000  1
.2   .2   0.2
.145  .35  1.05
```

***Daphnia* Information:**

Daphnia and H_2S Initial Conditons:

```
0 1 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 .001 .002 .045
```

HSCZP, GMAX, LENPRED, TRESP
.005 .500 260 .015

EPHIP, MINEPH, MAXEPH
275000 200 500

Table 7 - INDP2 Input File for Pond 2

(field data omitted)

Preliminary Information:

HARRIS POND 2, MODEL 3, 3 CLASSES, N2 LIMIT.
3 1 3 1 1 1

15
724 730 815 829 914 1011 1110 1310 1507 1629 1721 1819 1917 2019 2208

.08 .15 .4 .970 8.0 50.0 0.20 20.0 .3
5. 50. 200. 201.68 .001 .035
203.2 10 5.
15 14 100 193 7 13 1990

Initial Conditions:

.025 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.0
1.2 1.4 1.6 1.8
3.0 3.5 3.8 3.7 3.6 3.8 3.9 3.8 3.9 3.9
3.9 3.9 3.9 4.0 4.0
20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0
25.0 25.0 25.0 25.0 25.0
1.8 1.8 1.8 1.8 1.8 1.8 1.8 1.8 1.8 1.8
1.8 1.8 1.8 1.8 1.8
.001 .001 .001 .001 .001 .001 .001 .001 .001 .001
.001 .001 .001 .001 .001
.013 .013 .012 .012 .012 .012 .011 .011 .011 .011
.011 .011 .011 .011 .011
.001 .001 .001 .001 .001 .001 .001 .001 .001 .001
.001 .001 .001 .001 .001
3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0 3.0
3.0 3.0 3.0 3.0 3.0
29.0 29.0 29.0 29.0 29.0 29.0 29.0 29.0 29.0 29.0
29.0 29.0 29.0 29.0 29.0
0. 0. 0. 0. 0. 0. 0. 0. 0. 0.1
0. 0. 0. 0. 0.1
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0
18.0 18.0 18.0 18.0 18.5 18.5 19.0 19.1 19.2 19.5
19.8 20.5 21.21.4 22.4
.010 .009 .007 .006 .006 .006 .006 .006 .006 .006
.006 .006 .006 .006 .006

Table 7 - INDP2 Input File for Pond 2 - continued
(field data omitted)

Benthic and BOD Parameters:
0.1 .05 0.02 .35

Algae - Phosphorus Uptake, Growth, and Mortality:
8.5 1.08 .15 10. 03. .1 .1 1.045 .1 1.04
8.5 1.08 .06 30. 10. .1 .1 1.045 .1 1.04
8.5 1.08 .05 37. 33. .1 .1 1.045 .1 1.04

Algae - Phosphorus Uptake, and Light:
.0 250. 500. 1.0 9.0 9.0 .05
.02 10. 1400. 1.0 9.0 9.0 .05
.01 140. 1000. 1.0 9.0 9.0 .05

Algae - Nitrogen Uptake:
8. .02 6. 8.0 1. .4 .1
8. .02 6. 14.5 1. 0.04 .025
8. .02 6. 8.0 1. .2 .1

Benthic Nitrogen Release:
.5 .1 .1 1.06

Zooplankton Parameters as in Original MINLAKE Model:
000. 100. .02 .1 .05 2. 5.
430 400 .001 1. .0 .5

Zooplankton Grazing Coefficients:
.003 1.0 .005 .001
.003 1.0 .005 .001
.0005 1.0 .005 .001

Yield Coefficients:
.005 .1 .0083 .01 .05 1.0 1.0 .003 0.0

Table 8 - ICEP3 Input File for Pond 3

Jet Inflow Parameters:

1.0 15.0 16 3 .03974 6.5 .25 1
.0 2.6 .45 50.250 1.0 .50 7 12 22 16
0.20 20. .3 .2 20. .3 .003
0.20 20. .3 .0505 .0 0.0
.37 .5 5. .17 0.4 40.
2.5 -2. 12.
18 14 200
.01167 0.111 0.1016

Alkalinity and pH Data:

7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5
15 15 15 15 15 15 15 15 15 15 15 15 15 15 15
0.0000028 .000111 .000016 .000181 .000486 .00000 1
.2 .2 0.2
.145 .35 1.05

***Daphnia* Information:**

Daphnia and H_2S Initial Conditons:
0 1 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 .001 .002 .045

HSCZP, GMAX, LENPRED, TRESP
.004 .80 260 .015

EPHIP, MINEPH, MAXEPH
450000 200 500

Table 9 - INDP3 Input File for Pond 3

(field data omitted)

Preliminary Information:

HARRIS POND 3, MODEL 3, 3 CLASSES, N2 LIMIT.
3 1 3 1 1 1
15
724 730 815 829 914 1011 1110 1310 1507 1629 1721 1819 1917 2019 2208
.08 .15 .4 .970 2.0 30.0 0.20 20.0 .3
5. 50. 200. 201.96 .001 .035
203.2 10 5.
15 14 100 193 7 13 1990

Initial Conditions:

.05 .17 .3 .44 .6 .75 .9 1.05 1.2 1.35 1.5
1.6 1.7 1.8 1.9
3.0 3.5 3.8 3.7 3.6 3.8 3.9 3.8 3.9 3.9
3.9 3.9 3.9 4.0 4.0
20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0 20.0
25.0 25.0 25.0 25.0 25.0
1.8 1.8 1.8 1.8 1.8 1.8 1.8 1.8 1.8 1.8
1.8 1.8 1.8 1.8 1.8
.021 .021 .021 .021 .021 .010 .010 .010 .010 .015
.025 .025 .022 .022 .022
.025 .025 .025 .025 .025 .015 .015 .011 .011 .011
.021 .021 .021 .021 .021
.001 .001 .001 .001 .001 .001 .001 .001 .001 .001
.001 .001 .001 .001 .001
2. 2. 2. 2. 2. 2.0 2.0 2. 2. 2.2
2.2 2.3 2.3 2.3 2.6
29.0 29.0 29.0 29.0 29.0 29.0 29.0 29.0 29.0 29.0
29.0 29.0 29.0 29.0 29.0
10.0 10.0 11.0 11.0 11.0 10.0 10.0 10.0 9.9 9.8
9.4 9.3 9.2 9.0 8.5
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0
6.5 6.5 6.5 6.5 6.6 6.6 6.8 7.0 7.0 7.5
7.8 7.9 8.0 8.3 8.8
.120 .120 .122 .120 .115 .112 .110 .105 .100 .090
.085 .080 .070 .060 .050

Table 9 - INDP3 Input File for Pond 3 - continued
(field data omitted)

Benthic and BOD Parameters:
0.05 .05 .01 .45

Algae - Phosphorus Uptake, Growth, and Mortality:
8.5 1.08 .12 10.0 03. .1 .1 1.045 .05 1.04
8.5 1.08 .10 30. 13. .1 .1 1.1 .1 1.1
8.5 1.08 .05 37. 33. .1 .1 1.045 .1 1.04

Algae - Phosphorus Uptake, and Light:
.0 250. 500. 1.0 9.0 9.0 .05
.005 200. 1000. 1.0 2.0 10.0 .05
.01 140. 1000. 1.0 9.0 9.0 .05

Algae - Nitrogen Uptake:
8. .02 6. 25.0 1. .4 .1
2. 1. 2. 25.5 1. 0.04 .025
8. .02 6. 8.0 1. .2 .1

Benthic Nitrogen Release:
.50 .1 .05 1.06

Zooplankton Parameters as in Original MINLAKE Model:
000. 100. .05 .08 .05 2. 5.
430 400 .000001 1. .0 .5

Zooplankton Grazing Coefficients:
.002 1.0 .005 .001
.001 1.0 .005 .001
.002 1.0 .005 .001

Yield Coefficients:
.0025 .01 .0083 .0100 .05 1.000 1.0 .003 0.0

Appendix C - Program Changes

The following is a listing of the program changes made in converting the MINLAKE code for stabilization pond operation. The changes are listed according to the subroutine in which they appear. The altered subroutines are listed in alphabetical order.

Program Changes

General — The amount of storage space allocated for the integer variables was increased; the FORTRAN metacommand $STORAGE:4 was added to all program segments. This was necessary to allow generation of time series plots with the increased total number of time steps.

A separate file (COMMON.BLK) containing a collection of essential common block variables was created. This allowed simplification of program code.

The variable TIME was created to work in association with equations utilizing a per day rate formulation. This allows the changes predicted by the model to align more closely with what would be expected during the new, shorter 12-hour time step.

ADVECT — This subroutine was altered for the new inflow/outflow situation. Note that the ADVECT subroutine is no longer identical for each pond - the pond 1 condition requires ADVECT to provide information that forces WDEPTH to show zero outflow when the water balance is negative.

CHLORO — The section in which BOD is augmented by the death of zooplankton was removed.

CONMIX — The variable NFLOW is set back to its original value after having been altered in the pond-specific subroutine.

DISSOLID — Extensive changes were made to this subroutine. New common block variables were added. A new dissolved oxygen section was incorporated to reflect recent research in air-water gas exchange. The nitrification and ammonia sections were re-written, with reaction progress now reflecting the water oxygen content. Since the zooplankton interactions with ammonia and oxygen concentrations are considered differently in the pond situation, sections treating those interactions were corrected.

PONDSS The "pond-specific subroutine" (originally the "lake-specific subroutine) was extensively modified for pond modeling. Several new common block variables are included. The jet inflow routines developed for pond 1 by Dr. Ruochan Gu operate here. An associated JNTRAIN subroutine alters pond water chemistry in accord with the jet entrainment mechanisms. For ponds 2 and 3 the jet inflow mechanisms are inoperative, but the water balance calculations are re-worked to accommodate inflow from the upstream ponds. This requires the opening and use of different inflow files for each pond. The new water balance sections work in coordination with the ADVECT, WDEPTH, and CONMIX subroutines.

The new subroutines (CARBON, DICINIT, ROOT, IONBAL, FUNCD) developed by Mark Deutschman for modeling pH and alkalinity are located in the pond-specific subroutine. A mechanism for computing the un-ionized ammonia concentration (important for toxicity calculations) based on both temperature and pH was included. As the new subroutines are not yet fully operative, pH is temporarily programmed to decline linearly from 9.0 (pond surface) to 7.5 (pond bottom) under all conditions.

The ICEP1, ICEP2, and ICEP3 files, which contain the new parameters and initial conditions required for *Daphnia* and pH modeling, are read by the pond-specific subroutine. The subroutine immediately converts *Daphnia* initial conditions from units of individuals-per-liter to individuals-per-m^3.

FPLOT This plotting subroutine was altered to allow the writing of *Daphnia* field data to the plot file. Common blocks were also re-dimensioned for this purpose.

MAIN In the MAIN program, the common blocks for the new zooplankton and pH variables are included for communication with program subroutines. Other common blocks were re-dimensioned to allow the plotting of *Daphnia* field data. The program is also altered to read in pH and alkalinity data from the inflow files in the cases of ponds 2 and 3.

The use of a half-day time step required alterations: the generation of the variable TD (hours of daylight in the current time step) had to be changed to reflect the fact that every other time step modeled a nighttime period. Similarly, flow rate conversions were changed to compute the total inflow per half-day rather than the original 24-hour period.

Corrections were also made to the original code. The benthic silica yield, fixed in the MAIN program, was greatly reduced to avoid proliferation of silica in the pond waters. A statement defining the time step's solar radiation input was moved to provide correct information to concerned subroutines.

PTABLE	The zooplankton plotting section was removed from this plotting subroutine.
RESSETL	While the pond waters typically contain a large quantity of organic suspended solids, the MINLAKE model considers only suspended inorganic sediments. To reflect the varying turbidity of the pond waters, the suspended sediment concentration is artificially set in this subroutine. This alteration allows the suspended material to play a more realistic role in the calculation of the light extinction coefficient. For pond 1, the concentration is set at 20 mg/l; for pond 2, 12 mg/l. In the case of pond 3 the original MINLAKE formulation is allowed to operate normally; the concentration soon drops to near zero.
START	A correction was made here to allow the simulation of Class 1 algae (diatoms) in accord with the original intentions of the model. Similarly, a READ statement was changed to read YNZP rather than (the erroneous) YNHZP.
SUBLAY	This subroutine had to be modified to permit the correct handling of the relatively small-volume water layers in the pond situation.
TIMEPLOT	The conversion to half-day modeling in the ponds necessitated the expansion of variable dimensions in this time-series plotting subroutine. In addition, one of the DO loops had to be enlarged. The title for the zooplankton plot was changed. To allow for the plotting of zooplankton field data, common blocks were re-dimensioned. Units conversion of zooplankton field data was eliminated.
ZPLKTN	A new *Daphnia* subroutine replaces Mike Riley's original MINLAKE zooplankton formulation. See main document for details.

Appendix D - Bibliography

Appendix D gives the complete bibliography compiled as a result of this study. The authors are particularly indebted to Dr. Ed Swain of the MPCA for his work in assembling much of this listing during the early stages of the project. At his suggestion, the bibliography was kept and indexed using PAPYRUS^{TM} computer software, which we found to be particularly helpful.

References are listed by author in alphabetical order. Keywords are provided and allow for bibliography searching within the computerized bibliography. In most cases, short comments are appended to the reference listing.

Annotated Bibliography Listing

1. Abeliovich A. (1986) Algae in wastewater oxidation ponds. In *CRC Handbook of Microalgal Mass Culture*, (ed. Richmond A.), pp. 331-338. CRC Press, Boca Raton, Florida.
Keywords: ALGAE, AMMONIA, CHLOROPHYLL, COPY, LAGOONS, PH, SWAIN

2. Abeliovich A., and Azov Y. (1976) "Toxicity of ammonia to algae in sewage oxidation ponds." *Appl. Environ. Microbiol.* **31**(6), 801-806.
Keywords: ALGAE, AMMONIA, ANACYSTIS, CHLORELLA, COPY, LAGOONS, PH, PLECTONEMA, SCENEDESMUS, SWAIN, TOXICITY
Comments: Ammonia, at concentrations over 2 Mm and at pH over 8.0, inhibits photosynthesis and growth of Scenedesmus.

3. Allan J. D. (1976) "Life history patterns in zooplankton." *Am. Nat.* **110**(971), 165-180.
Keywords: COPEPODS, COPY, DAPHNIA, FEEDING, GROWTH, HATHAWAY, PREDATION, TEMPERATURE
Comments: Gives information on growth rates and lifespan as functions of temperature

4. Allen M. B. (1955) *General features of algal growth in sewage oxidation ponds*. State Water Pollution Control Board, Sacramento, California.
Keywords: ALGAE, BACTERIA, CHLAMYDOMONAS, CHLORELLA, CO2, COPY, FUNGI, LAGOONS, LIGHT, SCENEDESMUS, SUCCESSION, SWAIN, TEMPERATURE
Comments: Unicellular green algae Chlorella and Scenedesmus are algae most important in the functioning of the ponds. Limited by nitrogen and carbon. When oxidation is well advanced, Chlorella is succeeded by a mixed flora in which Scenedesmus and Chlamydomonas are important.

5. Assenzo J. R., and Reid G. W. (1966) "Removing nitrogen and phosphorus by bio-oxidation ponds in central Oklahoma." *Water Sewage Works* **8**, 294-299.
Keywords: COPY, LAGOONS, NITROGEN, PHOSPHORUS, SWAIN
Comments: volume number (for August) is fictitious.

6. Azov Y., and Shelef G. (1982) "Operations of high-rate oxidation ponds: theory and experiments." *Water Res.* **16**, 1153-1160.
Keywords: AREA, COPY, DEPTH, EXPERIMENT, LAGOONS, LIGHT, OPERATION, SWAIN, TEMPERATURE, THEORY

7. Banerji S. K., and Ruess B. (1987) "Evaluation of waste stabilization pond performance in Missouri and Kansas, U.S.A." *WST* **19**(12), 39-46.
Keywords: BOD, COPY, DESIGN, H2S, LAGOONS, LUCK, MODEL, PH, SS, TREATMENT, WASTEWATER
Comments: Checked pond performance against state standards; found that many ponds were in violation, esp. for BOD and SS. Looked for answers in pond design equations. Suggested "polishing methods" for eliminating algae from the effluent during summer months.

8. Barker L. S. (1979) A case history examination of lagoon upgrading techniques. In *Performance and Upgrading of Wastewater Stabilization Ponds*, (eds. Middlebrooks E. J., Falkenborg D. H., and Lewis R. F.), pp. 63-74. U.S. EPA, EPA-600/9-79-011, Cincinnati, Ohio.
Keywords: ALGAL REMOVAL, COPY, LAGOONS, MICROSCREEN, SWAIN

9. Barndthouse L. W., and Suter G. W., eds. (1986) *Environmental Sciences Division User's Manual for Ecological Risk Assessment*. Oak Ridge National Laboratory, Oak Ridge, TN, prepared for the Office of Research and Development, U.S. Environmental Protection Agency.
Keywords: AMMONIA, COPY, HATHAWAY, RISK ASSESSMENT, TOXICITY
Comments: Discusses many toxicity measures (e.g. MATC, LD50, LC50) and their applications. Shows sigmoidal toxicity/response curves.

10. Barsom G. M., and Ryckman D. W. (1970) Evaluation of lagoon performance in light of 1965 Water Quality Act. In *2nd International Symposium for Waste Treatment Lagoons*, (ed. McKinney R. E.), pp. 63-80. Missouri Basin Engineering Health Council & Federal Water Quality Administration, Kansas City, Missouri.
Keywords: ALGAE, BACTERIA, BOD, COPY, HISTORY, LAGOONS, PHOSPHORUS, REVIEW, SS, SWAIN
Comments: "The elements contained in organic matter are repeatedly oxidized and synthesized, gaining energy through the combination of light energy. This cyclic process is known as the Law of Recycle." (p. 75). Researchers have verified that this cyclic bacteria-algae symbiosis as the dominant treatment process operative in lagoons."(p. 76)

11. Bartsch A. F. (1961) "Algae as a source of oxygen in waste treatment." *J. Water Pollut. Control Fed.* **33**, 239-249.
Keywords: ALGAE, BOD, COPY, GREAT REFERENCE, LAGOONS, OXYGEN, SWAIN
Comments: Thoughtful paper that balances the advantages of oxygen production against the disadvantages of BOD production (algal growth).

12. Bartsch A. F., and Allum M. O. (1957) "Biological factors in treatment of raw sewage in artificial ponds." *Limnol. Oceanogr.* **2**, 77-84.
Keywords: ALGAE, BOD, COLIFORMS, COPY, GREAT REFERENCE, LAGOONS, LIGHT, PHOTOSYNTHESIS, RESPIRATION, SS, SWAIN
Comments: Cited in 504; 99 ponds in 1957 in northern plains; 5 studied intensively for this study.

13. Bhattari K. K., Polprasert C., and Lohani B. N. (1987) "Models for aquacultural treatment of septage." *WST* **18**(7/8), 103-112.
Keywords: ALGAE, BACTERIA, CO2, COD, D.O., FISH, HATHAWAY, LAGOONS, MODEL, NEED
Comments: Models single-stage, non flow-through ponds producing algae and herbivorous fish. Uses a previously developed model system: Continuous System Modeling Program available from the Asian Institute of Technology (Bangkok).

14. Bodar C. W., Zee A. V., Voogt H. W., and Zandee D. I. (1989) "Toxicity of heavy metals to early life stages of Daphnia magna." *EESADV* **17**(3), 333-338.
Keywords: CADMIUM, COPPER, DAPHNIA, HATHAWAY, LEAD, METALS, NEED, TOXICITY, ZINC
Comments: Finds that D. eggs are less susceptible to metals than are the adults!

15. Borgmann U., Millard E. S., and Charlton C. C. (1988) "Dynamics of a stable, large volume, laboratory ecosystem containing Daphnia and phytoplankton." *J. Plankton Res.* **10**(4), 691-713.
Keywords: ALGAE, CHLOROPHYLL, COPY, DAPHNIA, FEEDING, FOOD, GROWTH, HATHAWAY, MAGNA, MODEL, MORTALITY, PHOSPHORUS, POPULATION, PULEX, SCENEDESMUS
Comments: Grew Daphnia in large containers along with algae, and studied population oscillations. Claimed to be able to model the oscillations. Estimated growth and death rates

16. Breskhovskikh V. F., Bagotskii S. V., and Zolotareva N. S. (1987) "Effect of artificial aeration of a stratified water body on its primary production." *W. Res. Bull.* **14**(1), 51-59.
Keywords: AERATION, ALGAE, HATHAWAY, LIMNOLOGY, MIXING, NEED, PRODUCTION, STRATIFICATION
Comments: Discusses the effects of mixing and de-stratification on primary productivity in water bodies: lakes in this case. Russia.

17. Bridgham S. D. (1988) "Chronic effects of 2,2-dichlorobiphenyl on reproduction mortality, growth, and respiration of Daphnia pulicaria." *Arch. Env. Cont. Tox.* **17**, 731-740.
Keywords: COPY, DAPHNIA, GROWTH, HATHAWAY, LIFE TABLES, PCBS, PULEX, REPRODUCTION, RESPIRATION, TOXICITY
Comments: Ran lab experiments on D. pulex to observe effects of PCB's. Found significant effects at concentrations of 50-100 ng/l. Suggests that the Great Lakes are affected.

18. Brockett O. D. (1977a) "Nitrogenous compounds in facultative oxidation pond sediments." *Water Res.* **11**, 317-321.
Keywords: AMMONIA, COPY, LAGOONS, NITROGEN, PROTEIN, SEDIMENT, SWAIN

19. Brockett O. D. (1977b) "Nitrogenous compounds in facultative oxidation pond sediments." *Water Res.* **11**, 317-321.
Keywords: AMMONIA, COPY, LAGOONS, NITROGEN, PROTEIN, SEDIMENT, SWAIN

20. Brockett O. D. (1977c) "Some causes of biological instability and their effect on algal population levels in waste treatment lagoons." *Prog. Wat. Tech.* **9**, 941-948.
Keywords: ALGAE, BIOASSAY, CHLORELLA, COPY, FACULTATIVE, LAGOONS, NEW ZEALAND, SEASONS, SWAIN

21. Broderius S. J., and Smith L. L. Jr. (1977) "Direct determination and calculation of aqueous hydrogen sulfide." *Anal. Chem.* **49**(3), 424-428.
Keywords: COPY, H2S, #LAGOONS, LAKE, METHOD, SWAIN
Comments: cited in 657

22. Bryant C. W. (1987) "Lagoons, ponds and aerobic digestion." *J. Water Pollut. Control Fed.* **59**(6), 401-403.
Keywords: HATHAWAY, LAGOONS, MODEL, NEED, REVIEW, SURVEY, WASTEWATER
Comments: Literature review of pond literature; 59 references cited.

23. Buhr H. O., and Miller S. B. (1983) "A dynamic model of the high-rate algal-bacteria wastewater treatment pond." *Water Res.* **17**, 29-37.
Keywords: ALGAE, BACTERIA, COPY, HROP, LAGOONS, MODEL, SWAIN

24. Burns C. W. (1968) "The relationship between body size of filter-feeding Cladocera and the maximum size of particle ingested." *Limnol. Oceanogr.* **13**, 103-106.

Keywords: ALGAE, BLUEGREENS, COPY, DAPHNIA, EDIBLE ALGAE, FEEDING, FILTERING, FOOD, GREENS, HATHAWAY, MAGNA, PULEX, SIZE-EFFICIENCY
Comments: Cited in Wetzel. Compares body size to filtering rates. Fitted a regression curve to the length-rate data. Temperature also important.

25. Burns C. W. (1969) "Particle size and sedimentation in the feeding behavior of two species of Daphnia." *Limnol. Oceanogr.* **14**, 392-402.
Keywords: ALGAE, DAPHNIA, FOOD, HATHAWAY, NEED, SIZE-EFFICIENCY
Comments: Cited in Wetzel.

26. Canale R. P., ed. (1976) *Modeling Biochemical Processes in Aquatic Ecosystems.* Ann Arbor Science, Ann Arbor, Michigan.
Keywords: COPY, #LAGOONS, LAKE, MODEL, SWAIN
Comments: Have table of contents copied. St. Paul library 574.5263 m72

27. Carvalho G. R., and Wolf H. G. (1989a) "Resting eggs of Daphnia - I. Distribution, abundance and hatching of eggs collected from various depths in lake sediments." *Fresh. Bio.* **22**, 439-470.
Keywords: COPY, CUCULLATA, DAPHNIA, DIAPAUSE, EPHIPPIA, GALATEA, HATCHING, HATHAWAY, HYALINA, PHOTOPERIOD, SEDIMENT, TEMPERATURE
Comments: Very nice paper on Daphnia ephippia: why, when, and how they hatch. Also presents interesting information on the distribution of ephippial eggs in a large water body.

28. Carvalho G. R., and Wolf H. G. (1989b) "Resting eggs of Daphnia - II. In situ observations on the hatching of eggs and their contribution to population and community structure." *Fresh. Bio.* **22**, 471-478.
Keywords: COPY, DAPHNIA, EPHIPPIA, HATCHING, HATHAWAY, PHOTOPERIOD, POPULATION, SEDIMENT
Comments: Second part of a two-part report on Daphnia ephippial egg hatching. This part focuses on hatching as it actually takes place in a lake. Interesting. Found that hatching was highly synchronized, most of it occurring in late April and early May. Just what the environmental cues for hatching were was not obvious. And, though egg counts found 20,000 eggs/m2, only 36 and 91 hatchlings per m2 were counted!

29. Chow-Fraser P., and Knoechel R. (1985) "Factors regulating in situ filtering rates of cladocera." *Can. J. Fish. Aquat. Sci.* **42**, 567-576.
Keywords: BOSMINA, C14, CERIODAPHNIA, COPY, DAPHNIA, DIAPHANOSOMA, FILTERING RATE, GREAT REFERENCE, HOLOPEDIUM, IN SITU, LAGOONS, SWAIN, TEMPERATURE, ZOOPLANKTON, ZOOPLANKTON VOLUME
Comments: Carapace length emerged as the most important predictor of in situ filtering rate in our study. "We suggest that zooplankton in these lakes filter-feed in proportion to their volume..." Used C-14 labeled Scenedesmus for in situ 15 minute incubation with Haney chamber.

30. Coveney M. F., Cronberg G., Enell M., Larsson K., and Olofsson L. (1977) "Phytoplankton, zooplankton, and bacteria--standing crop and production relationships in a eutrophic lake." *Oikos* **29**, 5-21.
Keywords: ALGAE, AMMONIA, APHANIZOMENON, BACTERIA, BROOD SIZE, COPY, DAPHNIA, EUDIAPTOMUS, EUTROPHIC, FOOD CHAIN, GRAZING, LAGOONS, LONGISPINA, MAGNA, NITROGEN, PHOSPHORUS, PRIMARY PRODUCTION, PULEX, SILICA, STEPHANODISCUS, SWAIN, SWEDEN, ZOOPLANKTON
Comments: Cited in pap 533. Not a stabilization pond, but an ecosystem level study of a eutrophic (about .5 ppm TP) lake with Daphnia.

31. Cowgill U. M., Emmel H. W., Hopkins D. L., Applegath S. L., and Takahashi I. T. (1986) "Influence of water on reproductive success and chemical composition of laboratory reared populations of Daphnia magna." *Water Res.* **20**(3), 317-323.
Keywords: BROOD SIZE, DAPHNIA, HATHAWAY, LIFE TABLES, NEED, POPULATION, REPRODUCTION, WASTEWATER, ZOOPLANKTON
Comments: tests done on Daphnia using different waters and studying reproduction rate changes

32. Daborn G. R., Hayward J. A., and Quinney T. E. (1978a) "Studies on Daphnia pulex Leydig in sewage oxidation ponds." *Can. J. Zool.* **56**, 1392-1401.
Keywords: COPY, D.O., DAPHNIA, EPHIPPIA, FECUNDITY, FILTERING, KLAREWASSERSTADIUM, LAGOONS, PULEX, SWAIN, TEMPERATURE
Comments: Females as large as 4.4 mm. Brood up to 70, averaging 29.5. Density as high as 932/L.

33. Daborn G. R., Hayword J. A., and Quinney T. E. (1978b) "Studies on Daphnia pulex Leydig in sewage oxidation ponds." *Can. J. Zool.* **56**, 1392-1401.
Keywords: COPY, DAPHNIA, EPHIPPIA, FISH, FOOD, HATHAWAY, LAGOONS, OXYGEN, TEMPERATURE
Comments: Points to food availability as the control on Daphnia populations. Showed up to 70 eggs per brood!! Abundance was inversely related to oxygen levels. Max density was 932/l. Points to Daphnia as being major players in pond health.

34. Davis C. S. (1987) "Components of the zooplankton production cycle in the temperate ocean." *J. Mar. Res.* **45**(4), 947-983.
Keywords: ALGAE, FOOD, GRAZING, GROWTH, HATHAWAY, MODEL, NEED, PRODUCTION, REPRODUCTION, TEMPERATURE, ZOOPLANKTON
Comments: Examines the planktonic structure of George's Bank using ecological models. Claims that temperature is the most important factor in determining zooplankton population - food limitations said to be not critical

35. DeGraeve G. M., Overcast R. L., and Bergman H. L. (1980) "Toxicity of underground coal gasification condenser water and selected constituents to aquatic biota." *Arch. Env. Cont. Tox.* **9**, 543-555.
Keywords: AMMONIA, COPY, DAPHNIA, HATHAWAY, MORTALITY, PH, PULEX, TOXICITY
Comments: Discusses bioassays done on Daphnia and other critters. Suggests that Daphnia may be fairly tolerant to organic compounds, though sensitive to ammonia. Cited in the EPA ammonia report.

36. deNoyelles F. Jr. (1967) "Factors affecting phytoplankton distribution in a double-cell sewage lagoon." *J. Phycol.* **3**, 174-181.
Keywords: ALGAE, ANKISTRODESMUS, BRACHIONUS, GRAZING, LAGOONS, NEBRASKA, ROTIFER, SWAIN
Comments: Ankistrodesmus is dominant. Good mixing. Some control by D. magna and Brachionus.

37. deNoyelles F. Jr., and O'Brien W. J. (1978) "Phytoplankton succession in nutrient enriched experimental ponds as related to changing carbon, nitrogen and phosphorus conditions." *Arch. Hydrobiol.* **84**(2), 137-165.
Keywords: ALGAE, BLUEGREENS, CARBON, COPY, GREENS, LAGOONS, NITROGEN, PHOSPHORUS, SUCCESSION, SWAIN

Comments: Some greens became dominant over colonial bluegreens as pH rose above 10.5.

38. DeWitt J. W., and Candland W. (1971) "The water flea." *Amer. Fish Farmer* **12**, 8-?
Keywords: DAPHNIA, LAGOONS, NEED, SWAIN
Comments: Cited in 578.

39. DiGiano F. A., Middlebrooks E. J., and Ferrara R. A. (1982) "Discussion of: Ammonia nitrogen removal in facultative wastewater stabilization ponds and nitrogen dynamics in waste stabilization ponds." *J. Water Pollut. Control Fed.* **54**(12), 1617-1618.
Keywords: AMMONIA, HATHAWAY, LAGOONS, NEED, NITROGEN
Comments: Here is the big argument as to whether the ammonia leaves the ponds via loss to the atmosphere or loss to the sediments. DiGiano says atmosphere; Ferrara says it's through biological uptake and sedimentation.

40. Dillaha T. A., Zolan W. J., and Sherrard J. H. (1986) "Design of saline waste stabilization lagoons in tropical areas." *Civ. Eng. Pract. Des. Eng.* **5**(4), 281-303.
Keywords: DESIGN, HATHAWAY, LAGOONS, MODEL, NEED, SALINITY, SODIUM, WASTEWATER
Comments: Bench-scale lagoons were operated on a draw-and-fill basis to see how salinity would affect kinetics. May be interesting in light of the elevated salinity seen in the St. Peter and Janesville ponds.

41. Dinges R. (1972) "New developments in wastewater stabilization ponds." *Deeds and Data (Water Pollution Control Federation)* **12**, 6-?
Keywords: BOD, CHLORINE, COPY, DAPHNIA, LAGOONS, SWAIN
Comments: Volume number (for December) is fictitious! An extensive survey of wastewater stabilization ponds in Texas during 1969-70 revealed 5 percent support populations of Daphnia (water fleas) during winter and spring. Most of these ponds have low populations of Daphnia and seem normal, that is, the water is green. A few ponds have high Daphnia populations, the pond water being very clear.

42. Dinges R. (1973) *Ecology of Daphnia in stabilization ponds.* Texas State Department of Health (NTIS PB 226273), Austin.
Keywords: COPY, DAPHNIA, LAGOONS, SWAIN
Comments: MPCA library has this on microfiche also.

43. Dinges R. (1974) The availability of Daphnia for water quality improvement and as an animal food source. In *Wastewater use in the Production of Food and Fiber--Proceedings. EPA-660/2-74-041*, pp. 142-161. U.S. Environmental Protection Agency, Washington, D.C.
Keywords: COPY, DAPHNIA, HARVEST, LAGOONS, LIGHT, SWAIN, TEMPERATURE

44. Dinges R. (1976) Proposed integrated biological wastewater treatment system. In *Biological Control of Water Pollution*, (eds. Tourbier J. and Pierson R. W. Jr.), pp. 225-230. University of Pennsylvania Press, .
Keywords: INCOMPLETE, AMMONIA, COPY, DAPHNIA, FISH, LAGOONS, LEMNA, SWAIN, WATER HYACINTH, ZOOPLANKTON
Comments: Describes plans rather than results.

45. Dinges R. (1982) *Natural Systems for Water Pollution Control.* Van Nostrand Reinhold Co., New York.

Keywords: ANAEROBIC, CHAOBORUS, COPY, DAPHNIA, EARTHWORM, FACULTATIVE, FISH, HISTORY, INFILTRATION, LAGOONS, SLUDGE, SWAIN, WETLAND
Comments: UNIV. ENGINEERING LIBE: TD 743 .D56.

46. Dinges R., and Rust A. (1972) "The role of Daphnia in wastewater oxidation ponds." *Pub. Works* **10**, 89-91,128.
Keywords: BRACHIONUS, COPY, DAPHNIA, LAGOONS, MOINA, SWAIN, TEXAS
Comments: Volume number (for October) is possibly wrong. Talks about Daphnia in Texas ponds. Looks like the same material handled more in depth in his Ecology of D ...

47. Dinges W. R. (1979) Stabilization Ponds. In *Texas Manual of Wastewater Operations*, pp. 1-38. Texas Water Utilities Association, Austin.
Keywords: INCOMPLETE, ALGAE, BACTERIA, COPY, DAPHNIA, FACULTATIVE, INSECT, LAGOONS, SWAIN

48. DiToro D. M., Thomann R. V., and O'Connor D. J. (1971) A dynamic model of phytoplankton population in the Sacramento-San Joaquin Delta. In *Advances in Chemistry*, 106, *Nonequilibrium Systems in Natural Water Chemistry*, (ed. Gould R. F.), pp. 131-180. American Chemical Society, Washington, DC.
Keywords: ALGAE, DAPHNIA, FOOD, GRAZING, GROWTH, HATHAWAY, MODEL, NEED, NITROGEN, PHOSPHORUS, RESPIRATION, ZOOPLANKTON
Comments: Nice, old model of phytoplankton/zooplankton growth used for a river delta. Shows Lotka-Volterra predator-prey interactions in the zoo- and phyto- plankton tracings

49. Dodson S. I. (1972) "Mortality in a population of Daphnia Rosea." *Ecology* **53**, 1011-1023.
Keywords: CHAOBORUS, DAPHNIA, HATHAWAY, LIFE HISTORY, MORTALITY, NEED, PREDATION
Comments: Cited in Wetzel. He maintains that predation pressure (from Chaoborus) exerts a significant pressure on the population, at least in the lake population that he studied.

50. Dodson S. I. (1974) "Zooplankton competition and predation: An experimental test of the size-efficiency hypothesis." *Ecology*, 605-613.
Keywords: INCOMPLETE, ALGAE, DAPHNIA, FEEDING, HATHAWAY, NEED, SIZE-EFFICIENCY
Comments: Cited in Wetzel

51. Downing J. A., and Rigler F. H. (1984) *Secondary productivity in fresh waters. IBPP Handbook 17, 2nd edition.* Blackwell, ?
Keywords: COPY, DAPHNIA, #LAGOONS, SWAIN, ZOOPLANKTON
Comments: Table 7.2: length-biomass.

52. Ehrlich S. (1966) "Two experiments in the biological clarification of stabilization-pond effluents." *Hydrobiologia* **27**, 70-80.
Keywords: ALGAE, COPY, DAPHNIA, ISRAEL, LAGOONS, LEMNA, OXYGEN, SWAIN, TOXICITY
Comments: In order to use Daphnia in the clarification of stabilization pond effluents it was necessary to devise means for reducing the amplitude of the diurnal oxygen curve: Lemna.

53. Ellis K. V (1983) "Stabilization ponds: design and operation." *CRC Crit. Rev. Env. Control* **13**, 69-102.

Keywords: COPY, DESIGN, LAGOONS, OPERATION, SWAIN

54. Elser J. J., Elser M. M., and Carpenter S. R. (1986) "Size fractionation of algal chlorophyll, carbon fixation, and phosphatase activity: relationships with species-specific size distribution and zooplankton community structure." *J. Plankton Res.* **8**, 365-383.
Keywords: ALGAE, COPY, GRAZING, #LAGOONS, PHOSPHATASE, SIZE FRACTIONATION, SWAIN, ZOOPLANKTON

55. Erickson R. J. (1985) "An evaluation of mathematical models for the effects of pH and temperature on ammonia toxicity to aquatic organisms." *Water Res.* **19**(8), 1047-1058.
Keywords: AMMONIA, COPY, DAPHNIA, HATHAWAY, MORTALITY, PH, TEMPERATURE, TOXICITY
Comments: Erickson demonstrates predictive relationships between un-ionized ammonia concentration and 50% mortality rates (LC50) for a variety of aquatic species. He determined that a model that allows for the additive effects of both ammonia species gives the best fit to experimental data. I based my ammonia toxicity curves on his results.

56. Ferrara A. M., and Harleman M. (1980) "Dynamic nutrient cycle model for waste stabilization ponds." *J. Env. Eng. Div.* **106**(EE1), 37-54.
Keywords: AMMONIA, BOD, CARBON, COLIFORMS, DESIGN, LAGOONS, LUCK, MODEL, NEED, NITROGEN, NUTRIENTS, PHOSPHORUS, WASTEWATER
Comments: Model attempts to simulate BOD and coliform removal; tested against some Utah ponds

57. Ferrara R. A., and Avci C. B. (1982) "Nitrogen dynamics in waste stabilization ponds." *J. Water Pollut. Control Fed.* **54**(4), 361-369.
Keywords: AMMONIA, DEUTSCHMAN, HATHAWAY, LAGOONS, MODEL, NITROGEN, NITROGEN REMOVAL, TREATMENT, WASTEWATER
Comments: Model to simulate nitrogen removal in ponds. Found that biological activity is the primary mechanism for ammonia removal (uptake, then sedimentation), though ammonia volatilization may contribute. Denitrification not important.

58. Finney B. A., and Middlebrooks E. J. (1979) Evaluation of facultative waste stabilization pond design. In *Performance and Upgrading of Wastewater Stabilization Ponds*, (eds. Middlebrooks E. J., Falkenborg D. H., and Lewis R. F.), pp. 18-36. U.S. EPA, EPA-600/9-79-011, Cincinnati, Ohio.
Keywords: BOD, COLIFORMS, COPY, DESIGN, LAGOONS, MODEL, SWAIN

59. Finney B. A., and Middlebrooks E. J. (1980) "Facultative waste stabilization pond design." *J. Water Pollut. Control Fed.* **52**(1), 134-147.
Keywords: BOD, CLIMATE, DESIGN, EPA, FLOW, HATHAWAY, LAGOONS, LOADING, MODEL, NEED, TREATMENT, WASTEWATER
Comments: Evaluated models for ponds considering three ponds in the USA; found that the models were generally inadequate to accurately describe performance. Design criteria were often met though the pond was in violation of federal discharge standards.

60. Fitzgerald G. P. (1964) "The effect of algae on BOD measurements." *J. Water Pollut. Control Fed.* **36**(12), 1524-1542.
Keywords: ALGAE, BOD, CHLORELLA, COPY, LAGOONS, SWAIN
Comments: Dead algae consumed 4x more oxygen than live algae in BOD test.

61. Fitzgerald G. P., and Rohlich G. A. (1958) "An evaluation of stabilization pond literature." *Sewage Ind. Wastes* **30**, 1213-1224.
Keywords: ALGAE, BACTERIA, BOD, COPY, LAGOONS, NUTRIENTS, OXYGEN, PHOSPHORUS, REVIEW, SWAIN

62. Fontes A. G., Angeles Vargas M., Moreno J., Guerrero M. G., and Losada M. (1987) "Factors affecting the production of biomass by a nitrogen-fixing blue-green alga in outdoor culture." *Biomass* **13**(1), 33-43.
Keywords: ALGAE, ANABAENA, BLUEGREENS, HATHAWAY, NEED, NITROGEN, NUTRIENTS, PRODUCTION
Comments: Discusses commercial production of blue-green algae; claims growth is not dependent on additional CO2 or nitrogen beyond that supplied by air in an aerated system.

63. Foree E. G., and Scroggin C. R. (1973) "Carbon and nitrogen as regulators of algal growth." *J. Env. Eng.* **99**(EE5), 639-652.
Keywords: ALGAE, ANABAENA, BLUEGREENS, CARBON, CHLAMYDOMONAS, CHLORELLA, CLADOPHORA, CO2, COPY, KENTUCKY, LABORATORY, LAGOONS, NITROGEN, OSCILLATORIA, SWAIN
Comments: Bluegreen algae were found to be dominant in CO2 deficient conditions but in low biomass because of carbon limitation. When algal growth was supported by diluted sewage effluent and excess CO2 was supplied, then nitrogen became limiting factor, and bluegreens dominant.

64. Fox M. G. (1989) "Effect of prey density and prey size on growth and survival of juvenile walleye (Sizostedion vitreum vitreum)." *Can. J. Fish. Aquat. Sci.* **46**, 1323-1328.
Keywords: CHIRONOMID, COPEPOD, COPY, #LAGOONS, SWAIN, WALLEYE

65. Fritz J. J. (1985) Mathematical models for waste stabilization ponds. In *Mathematical Models in Biological Waste Water Treatment*, (eds. Jorgensen S. E. and Gromiec M. J.), pp. 171-241. Elsevier, Amsterdam.
Keywords: ALGAE, BACTERIA, CARBON, COPY, DETRITUS, HEAT, LAGOONS, LIGHT, MODEL, NITROGEN, OXYGEN, PHOSPHORUS, REVIEW, RUNGE-KUTTA, SWAIN, TEMPERATURE
Comments: Reviews models of Marais, Thirumurthi, Gloyna, Oswald, Larsen.

66. Fritz J. J., Middleton A. C., and Meredith D. D. (1979) "Dynamic process modeling of wastewater stabilization ponds." *J. Water Pollut. Control Fed.* **51**(11), 2724-2743.
Keywords: ALGAE, AMMONIA, BACTERIA, CARBON, COPY, DETRITUS, LAGOONS, LIGHT, MODEL, NITRATES, NITRIFICATION, NITROGEN, OXYGEN, PHOSPHORUS, PHOTOSYNTHESIS, SWAIN
Comments: Cited in 536.

67. Gentil S. (1984) "Predictive or explanatory models for aquatic ecosystems." *WST* **16**(5-7), 571-578.
Keywords: ALGAE, FRANCE, HATHAWAY, LIGHT, MODEL, NEED, ZOOPLANKTON
Comments: A linear (?) model was used to track changes in a eutrophic lake in the alps. CAD was used to develop models describing the plankton systems. This model predicates phytoplankton behavior on K and grazing.

68. George D. B. (1981) "Lagoons and oxidation ponds." *J. Water Pollut. Control Fed.* **53**(6), 709-711.

Keywords: HATHAWAY, LAGOONS, MODEL, NEED, REVIEW
Comments: Literature review of pond articles published in 1980.

69. George D. G., Hewitt D. P., Lund J. W. G., and Smyly W. J. P. (1990) "The relative effects of enrichment and climate change on the long-term dynamics of Daphnia in Esthwaite Water, Cumbria." *Fresh. Bio.* **23**, 55-70.
Keywords: ALGAE, APHANIZOMENON, BLUEGREENS, COPY, DAPHNIA, DIATOMS, EDIBLE ALGAE, ENGLAND, FEEDING, FOOD, GREENS, GROWTH, HATHAWAY, MICROCYSTIS, NITROGEN, PHOSPHORUS, POPULATION, TEMPERATURE
Comments: Discusses population swings in the D. population; relates this to temperature and algae. Proposes that "edible algae" must be present for the population to thrive. Relates bluegreen growth to stable stratification. Showed a two peak (May, September) Daphnia population pattern.

70. Gerasimov Y. L. (1987) "Toxic effect of copper on Daphnia magna (crustacea, cladocera) with varying food concentrations." *DKBSAS* **293**(1-6), 174-176.
Keywords: CHLORELLA, COPPER, DAPHNIA, FOOD, HATHAWAY, METALS, NEED, TOXICITY
Comments: Shows effects on D. at very low levels of Cu. Laboratory experiments with varying copper and food levels.

71. Gersich F. M., and Hopkins D. L. (1986) "Site-specific acute and chronic toxicity of ammonia to Daphnia magna Straus." *Environmental Toxicology and Chemistry* **5**, 443-447.
Keywords: AMMONIA, COPY, DAPHNIA, HATHAWAY, MAGNA, PH, TOXICITY
Comments: Did bioassays using river water - got ammonia toxicity values near the EPA numbers. Gives some limited information about upper and lower limits for toxicity. I used this for the rough toxicity "curves" for ammonia in the pond model.

72. Gloyna E. F. (1968) Basis for waste stabilization pond designs. In *Advances in Water Quality Improvement*, (eds. Gloyna E. F. and Eckenfelder W. W. Jr.), pp. 397-408. University of Texas Press, Austin.
Keywords: AEROBIC, ALGAE, ANAEROBIC, COPY, DESIGN, FACULTATIVE, GREAT REFERENCE, LAGOONS, LIGHT, NUTRIENTS, OPERATION, SLUDGE, SWAIN, TEMPERATURE

73. Gloyna E. F. (1971) *Waste Stabilization Ponds.* World Health Organization, Geneva.
Keywords: AEROBIC, ALGAE, ANAEROBIC, COPY, FACULTATIVE, LAGOONS, OXYGEN, REVIEW, SWAIN

74. Gloyna E. F., and Aguirre J. (1970) New experimental pond data. In *2nd International Symposium for Waste Treatment Lagoons*, (ed. McKinney R. E.), pp. 200-210. Missouri Basin Engineering Health Council & Federal Water Quality Administration, Lawrence, Kansas.
Keywords: ANAEROBIC, BOD, COPY, EXPERIMENT, FACULTATIVE, LABORATORY, LAGOONS, SWAIN

75. Gloyna E. F., and Hermann E. R. (1957) "Algae in waste treatment." *J. Water Pollut. Control Fed.* **29**(4).
Keywords: INCOMPLETE, ALGAE, LAGOONS, NEED, SWAIN
Comments: Requested mpcal 89.3.23

76. Gloyna E. F., and Tischler L. F. (1979a) "Design of waste stabilization pond systems." *Prog. Wat. Tech.* **11**(4/5), 47-70.
Keywords: ALGAE, BOD, DESIGN, ECOLOGY, LAGOONS, LOADING, LUCK, MODEL, NEED, SS, TREATMENT, WASTEWATER
Comments: Examined several pond systems thoroughly to evaluate performance. Has nice summary of pond biota. Discusses design criteria and SS violations.

77. Gloyna E. F., and Tischler L. F. (1979b) Waste stabilization pond systems. In *Performance and Upgrading of Wastewater Stabilization Ponds*, (eds. Middlebrooks E. J., Falkenborg D. H., and Lewis R. F.), pp. 37-50. U.S. Environmental Protection Agency, EPA-600/9-79-011, Cincinnati, Ohio.
Keywords: AEROBIC, ALGAE, ANAEROBIC, BOD, COPY, DESIGN, FACULTATIVE, INDUSTRIAL WASTE, LAGOONS, SWAIN, WATERWAY IMPACT

78. Gloyna E. F., and Tischler L. F. (1981) "Recommendations for regulatory modifications: the use of waste stabilization pond systems." *J. Water Pollut. Control Fed.* **53**, 1559-1563.
Keywords: ALGAE, COPY, LAGOONS, REGULATION, SS, SWAIN
Comments: Study supports the position that generally algal cells should be excluded from TSS limitations.

79. Goldman J. C., Oswald W. J., and Jenkins D. (1974) "The kinetics of inorganic carbon limited algal growth." *J. Water Pollut. Control Fed.* **46**(3), 554-574.
Keywords: ALGAE, CARBON, CO2, COPY, KINETICS, LAGOONS, SWAIN

80. Gomez-Parra A., Forja J. M., and Cantero D. (1987) "New device for sampling waters in shallow ecosystems." *Water Res.* **21**(11), 1437-1443.
Keywords: D.O., ECOLOGY, HATHAWAY, HELGEN, NEED, SAMPLING, TEMPERATURE
Comments: This thing deserves a look - claims to make stratified sampling simple, from a boat or from the shore.

81. Gordon D. M., and McComb A. J. (1989) "Growth and production of the green alga Cladophora montagneana in a eutrophic Australian estuary and its interpretation using a computer program." *Water Res.* **23**(5), 633-645.
Keywords: ALGAE, COPY, HATHAWAY, LIGHT, MODEL, NUTRIENTS, TEMPERATURE
Comments: Examined growth of just one species of algae, apparently modeled it using a few factors only.

82. Goss L. B., and Bunting D. L. (1983) "Daphnia development and reproduction: responses to temperature." *J. Therm. Biol.* **8**, 375-380.
Keywords: DAPHNIA, GROWTH, HATHAWAY, NEED, OPTIMA, PETERS, REPRODUCTION, RESPIRATION, TEMPERATURE
Comments: Gives optimum temperatures for reproduction in lab cultures. Cited in Peters (p 213), where temp of 15-25 C is also given as being optimal for assimilation, growth, and filtering.

83. Goudey J. S. (1987) "Modeling the inhibitory effects of metals on phytoplankton growth." *Aq. Tox.* **10**(5-6), 265-278.
Keywords: ALGAE, GROWTH, HATHAWAY, METALS, MODEL, NEED, TOXICITY
Comments: May be useful in generating toxicity functions - and possibly in considering toxic effects in ponds

84. Grobbelaar J. U. (1982) "Potential of algal production." *Water* **8**(2), 79-85.

Keywords: ALGAE, DEPTH, GREENS, HATHAWAY, LAGOONS, LIGHT, MODEL, NEED, PRIMARY PRODUCTION, SOUTH AFRICA, TEMPERATURE, TREATMENT, WASTEWATER, ZOOPLANKTON
Comments: Algal production model, incorporating temp, light, depth to predict biomass changes. Protozoans and rotifers listed as culture parasites.

85. Grobbelaar J. U., Soeder C. J., Groeneweg J., Stengel E., and Hartig P. (1988) "Rates of biogenic oxygen production in mass cultures of microalgae, absorption of atmospheric oxygen and oxygen availability for wastewater treatment." *Water Res.* **22**(11), 1459-1464.
Keywords: ALGAE, COPY, LAGOONS, MODEL, OXYGEN, SWAIN

86. Grobbelaar J. U., Soeder C. J., and Stengel E. (1990) "Modeling algal productivity in large outdoor cultures and waste treatment systems." *Biomass* **21**, 297-314.
Keywords: ALGAE, COELASTRUM, COPY, HATHAWAY, LIGHT, MODEL, PRODUCTION, RESPIRATION, SCENEDESMUS, TEMPERATURE, WASTEWATER
Comments: Production was based on light and temperature. Light and photo-inhibition were included. Predicted biomass only; no speciation. Interestingly, a CO2 sparger was used to keep the pH down.

87. Gu R., and Stefan H. G. (1991) *Numerical simulation of stratification dynamics and mixing in wastewater stabilization ponds.* Saint Anthony Falls Hydraulic Laboratory, Minneapolis, MN, Project Report No. 316.
Keywords: HATHAWAY, HYDROLOGY, LAGOONS, MIXING, MODEL, STRATIFICATION, TEMPERATURE
Comments: Methods and results of temperature simulations conducted for the Harris MN ponds by Ruochuan Gu. Work was conducted as part of the overall pond study. Generally good agreement with field data was demonstrated.

88. Guterman H., and Ben-Yaakov S. (1987) "Exchange rates of O2 and CO2 between an algal culture and atmosphere." *WATRAG* **21**(1), 25-34.
Keywords: ALGAE, BLUEGREENS, CARBON, CO2, D.O., DEUTSCHMAN, GAS EXCHANGE, HATHAWAY, LAGOONS, LIGHT, NEED, OXYGEN PRODUCTION, PH, PHOTOSYNTHESIS, SPIRULINA, TEMPERATURE, TURBIDITY
Comments: Gas exchange model; studied and monitored a mini-pond containing the blue-green Spirulina.

89. Gyunter L. I., Grebenevich E. V., Vavilin V. A., and Vasil'ev V. B. (1982) "Additional treatment of wastewaters to remove nitrogen compounds in aerated oxidation ponds." *Water Resources (English translation)* **9**(1), 104-109.
Keywords: ALGAE, DAPHNIA, GRAZING, GREENS, GROWTH, HATHAWAY, LAGOONS, NEED, NITROGEN, POPULATION, PRODUCTION, WASTEWATER, ZOOPLANKTON
Comments: Experimented to determine the ideal concentrations of algae for optimal Daphnia growth - found that algae at 150-300 mg/l was best. Population of Daphnia found to be highly dependent on algae . . . no big surprise here. But it's interesting in the light of observations that Daphnia is rarely found in association with intense algal growth.

90. Hall D. J. (1964) "An experimental approach to the dynamics of a natural population of Daphnia galeata mendotae." *Ecology* **45**, 94-112.
Keywords: DAPHNIA, FOOD, GALEATA, GROWTH, HATHAWAY, LIFE TABLES, NEED, POPULATION, REPRODUCTION, TEMPERATURE

Comments: Shows relationships between population growth, food supply, and temperature. Table presented in Wetzel, p433.

91. Hall D. J., Thelkeld S. T., Burns C. W., and Crowley P. H. (1976a) "The size-efficiency hypothesis and the size structure of zooplankton communities." *Ann. Rev. Ecol. Syst.* **7**, 177-208.
Keywords: COPY, FILTERING RATE, LAGOONS, RESPIRATION, SIZE-EFFICIENCY, SWAIN, ZOOPLANKTON

92. Hall D. J., Threlkeld S. T., Curns C. W., and Crowley P. H. (1976b) "The size-efficiency hypothesis and the size structure of zooplankton communities." *Ann. Rev. Ecol. Syst.* **7**, 177-208.
Keywords: ALGAE, DAPHNIA, FEEDING, FILTERING, HATHAWAY, NEED, SIZE-EFFICIENCY
Comments: Cited in Wetzel.

93. Hallam T. G., Lassiter R. R., Li J., and Suarez L. A. (1990) "Modelling individuals employing an integrated energy response: Application to Daphnia." *Ecology* 7(13), 938-954.
Keywords: COPY, DAPHNIA, ENERGY, HATHAWAY, LIPIDS, MODEL, REPRODUCTION
Comments: Sets up a population model based on the energetics of a single Daphnia.

94. Haney J. F. Zooplankton grazing as a control mechanism in algal blooms; A method for the study of the effect of algal toxins on zooplankton vertical migration. (Research report 31, Water Resource Research Center, University of New Hampshire. Available from the National Technical Information Service, Springfield, VA 22161 as PB81-143364.)

95. Haney J. F. (1985) "Regulation of cladoceran filtering rates in nature by body size, food concentration, and diel feeding patterns." *Limnol. Oceanogr.* **30**(2), 397-411.
Keywords: BODY LENGTH, COPY, DAPHNIA, FILTERING RATE, HOLOPEDIUM, IN SITU, LAGOONS, PHOSPHORUS-32, SWAIN, ZOOPLANKTON
Comments: Used radioactive yeast to measure filtering rate in situ with clear acrylic containers. 5-10 minute incubation. At night filtering rates were higher and more consistent.

96. Haney J. F., and Buchanan C. L. (1980) *The role of zooplankton vertical migration in structuring the phytoplankton community.* Water Resource Research Center, University of New Hampshire, Durham, NH, available from the National Technical Information Service, VA 22161 as PB81-112633.
Keywords: ALGAE, DAPHNIA, ECOLOGY, GRAZING, HATHAWAY, LAGOONS, LIGHT, MIGRATION, MODEL, NEED, ZOOPLANKTON
Comments: modelling of a pond population with particular attention to the role of vertical migration of zooplankton.

97. Hawkins P. R., and Griffiths D. J. (1987) "Copper as an algacide in a tropical reservoir." *Water Res.* **21**(4), 475-480.
Keywords: ALGAE, BLUEGREENS, COPPER, COPPER SULFATE, COPY, HATHAWAY, TOXICITY, ZOOPLANKTON
Comments: Discusses the effects of copper on flora and fauna of a reservoir. Also describes the fate of copper after its application to the system. Cladoceran populations took longest to recover from the application; it looks as though it took about one month for the cladocerans to come back.

98. Heifetz P. B., and Quinlan A. V. (1987) Evaluation of the effect of light intensity on the rate of photo biomass production by the blue-green alga Spirulina platenis in semi-continuous suspension

culture. In *Bioprocess Engineering Colloquium*, pp. 57-61. ASME, New York, NY, proceedings of the Bioprocess Engineering Colloquium held in Boston, MA, Dec. 13-18, 1987. Conf. #11032.
Keywords: INCOMPLETE, ALGAE, BLUEGREENS, GROWTH, HATHAWAY, LIGHT, MODEL, NEED, PRODUCTION
Comments: Actually this is a model for commercial algae production machinery, but may be useful in analyzing nutrient needs.

99. Helgen J. C. (1987) "Feeding rate inhibition in crowded Daphnia pulex." *Hydrobiologia* **154**, 113-119.
Keywords: ALLELOPATH, CHLAMYDOMONAS, DAPHNIA, DENSITY DEPENDENT, #LAGOONS, SWAIN

100. Helgen J. C., Larson N. J., and Anderson R. L. (1988) "Responses of zooplankton and Chaoborus to Temephos in a natural pond and in the laboratory." *Arch. Env. Cont. Tox.* **17**, 459-471.
Keywords: COPY, DAPHNIA, EPHIPPIA, HATHAWAY, PESTICIDES, TOXICITY
Comments: Shows that even very low pesticide concentrations can have drastic effects on pond biota.

101. Herzig A. (1985) "Resting eggs - a significant stage in the life cycle of crustaceans Liptodora kindti and Bythotrephes longimanus." *Verh. Internat. Verein. Limnol.* **22**, 3088-3098.
Keywords: BENTHOS, CLADOCERA, COPY, DAPHNIA, DIAPAUSE, EPHIPPIA, HELGEN, LIGHT, PHOTOPERIOD, TEMPERATURE
Comments: Examines the production, fate, and hatching of ephippia in microcrustaceans.

102. Hill D. T., and Mullens W. K. (1986) "Computer design of anaerobic lagoons using the rational design standard." *AEA* **2**(2), 190-192.
Keywords: ANAEROBIC, HATHAWAY, LAGOONS, MODEL, NEED, TREATMENT, WASTEWATER
Comments: Computer model for pond design using the Rational Design Standard - not for facultative ponds, but may be useful.

103. Holm H. W., and Vennes J. W. (1970) "Occurrence of purple sulfur bacteria in a sewage treatment lagoon." *Appl. Microbiol.* **19**(6), 988-996.
Keywords: ALKALINITY, BACTERIA, BOD, CHROMATIUM, CITATION TYPO, COPY, LAGOONS, PH, PHOSPHATE, PURPLE SULFUR, SULFATE, SULFIDES, SWAIN, THIOCAPSA
Comments: cited in 504.

104. Horn W. (1981) "Phytoplankton losses due to zooplankton grazing in a drinking water reservoir." *Int. Rev. ges. Hydrobiol.* **66**(6), 787-810.
Keywords: ALGAE, COPY, DAPHNIA, FILTERING, GRAZING, #LAGOONS, LIGHT, METHOD, SWAIN, TEMPERATURE, ZOOPLANKTON
Comments: cited in 533.

105. Horn W., and Benndorf J. (1980) "Field investigations and model simulation of the dynamics of zooplankton populations in fresh waters." *Int. Rev. Gesamtens Hydro.* **65**(2), 209-222.
Keywords: COPY, DAPHNIA, GROWTH RATE, HATHAWAY, MODEL, MORTALITY, PRODUCTION, ZOOPLANKTON
Comments: Ecological model used to simulate Daphnia population dynamics in a German reservoir. Net growth rate of Daphnia (hyalina) said to be 0.1-0.2/d at the beginning and -0.02

to -0.1 when the population was in decline. Birth rate (gross growth rate) fluctuated between 0.03 and 0.1/day. High mortality rates of about 0.1/d were found in the summer. Discusses the "ill effects of spatial heterogeneity in zooplankton distribution" on field data acquired through sampling. We also experienced this problem.

106. Houng H., and Gloyna E. F. (1983) *Center for Research in Water Resources Technical Reports*, No. CRWR-203, *Phosphorus utilization and recycle in waste stabilization ponds.* Center for Research in Water Resources, Austin, TX.
Keywords: HATHAWAY, LAGOONS, MODEL, NEED, PHOSPHORUS, SEDIMENT, TREATMENT, WASTEWATER
Comments: Mainly a phosphorus model for treatment ponds; allegedly accurate

107. Howsley R., and Pearson H. W. (1979) "pH dependent sulphide toxicity to oxygenic photosynthesis in cyanobacteria." *FEMS Microbiol. Letts.* **6**, 287-292.
Keywords: ALGAE, ANABAENA, BLUEGREENS, COPY, LAGOONS, OSCILLATORIA, PH, PHOTOSYNTHESIS, SULFIDES, SWAIN, TOXICITY
Comments: Cited by Skoglund; half-inhibitory concentrations between 36 and 100 uM total sulphide at pH 8.00.

108. Jorgensen S. E., and Gromiec M. J., eds. (1985) *Developments in Environmental Modeling*, 7, *Mathematical models in biological wastewater treatment.* Elsevier, Amsterdam.
Keywords: ALGAE, CARBONATES, FRITZ, HATHAWAY, LAGOONS, LIGHT, MODEL, NITROGEN, PHOSPHORUS
Comments: The Fritz model is detailed herein. In Walter library: TD755.M385 1985

109. Kankaala P. (1983) "Resting eggs, seasonal dynamics, and production of Bosmina longispina maritima (P.E. Muller) (Cladocera) in the northern Baltic proper." *J. Plankton Res.* **5**(1), 53-69.
Keywords: BOSMINA, CLADOCERA, COPY, DIAPAUSE, EPHIPPIA, GROWTH, HELGEN, LIGHT, REPRODUCTION
Comments: Studied Bosmina in the Baltic sea. Says "the fact that resting egg numbers decreased 50% in the sediment from 19 April to 17 May is in accordance with Stross's (1966) observation that prolonged storage in low temperatures permitted synchronous activation of Daphnia resting eggs." Sediment was re-supplied in August-October. Suggests that unpredictability of water conditions may well account for large annual variations in population numbers.

110. Kimerle R. A., and Enns W. R. (1968) "Aquatic insects associated with midwestern waste stabilization lagoons." *J. Water Pollut. Control Fed.* **40**(2), R31-R41.
Keywords: CHIRONOMID, COPY, INSECT, LAGOONS, SWAIN

111. King D. L. (1970) "The role of carbon in eutrophication." *J. Water Pollut. Control Fed.* **42**, 2035-2051.
Keywords: ALGAE, ALKALINITY, BLUEGREENS, CARBON, COPY, EUTROPHICATION, LAGOONS, SUCCESSION, SWAIN

112. Klomp R., Los F. J., van Pagee J. A., and de Rooy N. M. (1991) "Modelling the eutrophication process of lake IJssel." *WST* **16**(4), 687-698.
Keywords: ALGAE, BLUEGREENS, EUTROPHICATION, GREENS, HATHAWAY, MODEL, NEED, NETHERLANDS, NUTRIENTS, PH, ZOOPLANKTON
Comments: Describes modeling efforts for the Rhine outflow into Lake IJessel. Uses a eutrophication model BLOOM II in conjunction with CHARON, a water chemistry model. Notes

uncertainties wrt zooplankton modeling and phytoplankton behavior. CHARON could be helpful to Mark Deutschmann.

113. Konig A., Pearson H. W., and Silva S. A. (1987) "Ammonia toxicity to algal growth in waste stabilization ponds." *WST* **19**(12), 115-122.
Keywords: ALGAE, AMMONIA, BOD, CHLORELLA, EUGLENA, HATHAWAY, LAGOONS, NEED, NITROGEN, PH, TEMPERATURE, TOXICITY, WASTEWATER
Comments: Discusses pond performance as related to algal growth, and the factors affecting that growth - especially ammonia

114. Koopman B. L., Benemann J. R., and Oswald W. J. (1979) Pond isolation and phase isolation for control of suspended solids concentration in sewage oxidation pond effluents. In *Performance and Upgrading of Wastewater Stabilization Ponds*, (eds. Middlebrooks E. J., Falkenborg D. H., and Lewis R. F.), pp. 104-123. U.S. EPA, EPA-600/9-79-011, Cincinnati, Ohio.
Keywords: ALGAE, CHLOROPHYLL, COPY, DAPHNIA, LAGOONS, OSCILLATORIA, SWAIN, ZOOPLANKTON

115. Korpelainen H. (1986) "The effects of temperature and photoperiod on life history parameters of Daphnia magna (Crustacea: Cladocera)." *Fresh. Bio.* **16**(5), 615-620.
Keywords: COPY, DAPHNIA, DIAPAUSE, HATHAWAY, LIFE TABLES, MORTALITY, PHOTOPERIOD, REPRODUCTION, TEMPERATURE
Comments: Life tables presented linking Daphnia growth and death rates to temperature. Nice set of references - see esp. articles by Porter . . .

116. Krenkel P. A., and French R. H. (1982) "State-of-the-art of modeling surface water impoundments." *WST* **14**(1/2), 241-261.
Keywords: ALGAE, AMMONIA, COPY, D.O., HATHAWAY, HYDRODYNAMICS, MIXING, MODEL, NITRATES, NITROGEN, OXYGEN, PHOSPHORUS, ZOOPLANKTON
Comments: An overview, but discusses the importance of relating biological processes to hydrodynamic effects in water bodies. Looks worthwhile.

117. Kroes J. (1987) "Sludge sampler for waste lagoons." *AEA* **3**(2), 258-260.
Keywords: BENTHOS, HATHAWAY, HELGEN, LAGOONS, NEED, SAMPLING, TREATMENT
Comments: This sludge sampler might be useful, as sludge sampling is generally a pain.

118. Kuentzel L. E. (1969) "Bacteria, carbon dioxide, and algal blooms." *J. Water Pollut. Control Fed.* **41**(10), 1737-1747.
Keywords: ALGAE, BACTERIA, BLUEGREENS, CO2, COPY, LAGOONS, ORGANICS, SWAIN

119. Lampert W. (1988) "Cascading effects in lake ecosystems: The role of diel vertical migrations of zooplankton." *Wiadomosci Ekologiczne WEKLAF* **34**(2), 123-141.
Keywords: DAPHNIA, GRAZING, HATHAWAY, LIMNOLOGY, MIGRATION, MODEL, MORTALITY, NEED, PREDATION, ZOOPLANKTON
Comments: Mentions the concept of "edible" algae. Affirms the notion that DVM is an adaptive response to the avoidance of predation. Nighttime grazing is said to enhance primary production.

120. Lampert W., and Schober U. (1980) The importance of "threshold" food concentrations. In *Evolution and Ecology of Zooplankton Communities*, (ed. Kerfoot W. C.), pp. 264-267. University Press, Hanover, NH.

Keywords: CARBON, COPY, DAPHNIA, FEEDING, FOOD, GROWTH, HATHAWAY, REPRODUCTION, STARVATION
Comments: Discusses "carbon limitation" on the growth rates of Daphnia populations - that growth rates tail off when all food is scarce. She talks about daphnia feeding on detritus. Probably detritus is never lacking in treatment ponds. But the concept of starvation is introduced here.

121. Lee C. M., Turner C. A., and Huntington E. (1986) Factors affecting the culture of Daphnia magna. In *ASTM Special Publication 921* Vol. 9, pp. 357-368. ASTM, Philadelphia, from conference: Aquatic Toxicology and Environmental Fate, sponsored by Unilever Research Lab, Bebington, England.
Keywords: DAPHNIA, FOOD, HATHAWAY, LIGHT INTENSITY, NEED, PHOTOPERIOD, TEMPERATURE
Comments: Found that there is a strong light vs. temp vs. food interaction that can influence juvenile production, though the individual effects of increasing temperature or photoperiod were trivial.

122. Lewis R. F. (1979) Historical review of oxidation ponds as they impact secondary treatment and water quality. In *Performance and Upgrading of Wastewater Stabilization Ponds*, (eds. Middlebrooks E. J., Falkenborg D. H., and Lewis R. F.), pp. 4-14. U.S. EPA, EPA-600/9-79-011, Cincinnati, Ohio.
Keywords: COPY, LAGOONS, ODOR, REVIEW, SWAIN, TASTE, WATERWAY IMPACT

123. Lijklema L., Coin L., Harremows P., Imhoff K. R., Ives K. J., Ludwig R. G., Toerien D. F., Milburn A., and Izod E. J. (1987) "Water pollution research and control: Part 1, Proceedings of the thirteenth biennial conference of the International Association on Water Pollution Research and Control." *WST* **19**(4), 322p.
Keywords: HATHAWAY, LAGOONS, MICROORGANISMS, NEED, TREATMENT, WASTEWATER
Comments: Actually a whole bunch of articles . . .

124. Losordo T. M., Piedrahita R. H., and Ebeling J. M. (1988) "Automated water quality data acquisition system for use in aquaculture ponds." *Aq. Eng.* **7**(4), 265-278.
Keywords: D.O., HATHAWAY, LIGHT, NEED, PH, SAMPLING, TEMPERATURE, WEATHER, WIND
Comments: Claims to have developed an automated system to record weather data, and water quality data: pH, DO, PAR, temp at up to 8 depths and 1.75 m. Would be useful for further studies on the ponds.

125. Luck F. N., and Stefan H. G. (1990) *Physical Limnology of the Harris Wastewater Stabilization Ponds: July 1989 to October 1990.* St. Anthony Falls Hydraulic Laboratory, Minneapolis, St. Anthony Falls Hydraulic Laboratory Project Report No. 309.
Keywords: COPY, D.O., HATHAWAY, LAGOONS, LIGHT, LIMNOLOGY, PH, SECCHI, TEMPERATURE, WEATHER
Comments: Excellent and extensive physical data set for stabilization pond in central Minnesota.

126. Lung W., and Paerl H. W. (1988) "Modeling blue-green algal blooms in the lower Neuse River." *Water Res.* **22**(7), 895-905.
Keywords: ALGAE, BLUEGREENS, D.O., DIATOMS, FLOW, HATHAWAY, HYDRODYNAMICS, MODEL, NEED, NITROGEN, PHOSPHORUS

Comments: Algal model developed for riverine systems. Models green, blue-green, and diatom groups; as well as nitrogen and phosphorus and DO. Suggests mixing conditions play a large role in supporting blue-green blooms.

127. MacArthur J. H., and Baillie W. H. T. (1929) "Metabolic activity and duration of life: I. Influence of temperature on longevity in Daphnia magna." *J. Exp. Zool.* **53**, 221-242.
Keywords: DAPHNIA, GROWTH, HATHAWAY, LIFE TABLES, MAGNA, METABOLISM, NEED, PETERS, REPRODUCTION, TEMPERATURE
Comments: Referenced in Peters, p234. Relates temp to lifespan. Part one of a two-part series.

128. MacKay M. A., Carpenter S. R., and Soranno P. A. (1990) "The impact of two Chaoborus species on a zooplankton community." *Can. J. Zool.* **68**, 981-985.
Keywords: CHAOBORUS, CHLOROPHYLL, COPY, DAPHNIA, GRAZING, HATHAWAY, POPULATION, PREDATION, PULEX, ZOOPLANKTON
Comments: Showed that Chaoborus CAN have a significant effect on the Daphnia population. Used bag experiments. Interesting.

129. Mackenthun K. M., and McNabb C. D. (1961) "Stabilization pond studies in Wisconsin." *J. Water Pollut. Control Fed.* **33**(12), 1234-1251.
Keywords: BOD, COLIFORMS, COPY, H2S, ICE COVER, LAGOONS, LIGHT, OXYGEN, SWAIN, TEMPERATURE, TN, TP, WISCONSIN

130. Mara D. (1987) "Waste stabilization ponds: problems and controversies." *WQI* **1987**(1), 20-22.
Keywords: DESIGN, HATHAWAY, LAGOONS, LOADING, NEED, OVERVIEW, TREATMENT, WASTEWATER
Comments: Overview of the pond situation. Tells about operation, maintenance and performance in general terms

131. Mara D. D., and Marecos do Monte M. H., eds. (1988) *Waste Stabilization Ponds.* Pergamon Press, Elmsford, NY.
Keywords: LAGOONS, NEED, SWAIN

132. Mara D. D., Pearson H. W., and Mills S. W. (1989) "Big is not best with waste stabilization ponds." *WQI* **1**, 28-29.
Keywords: ALGAE, COPY, DAPHNIA, DESIGN, DESIGN - DEPTH, GRAZING, HATHAWAY, LAGOONS, TREATMENT, WASTEWATER, WIND, ZOOPLANKTON
Comments: discusses design and its influence on pond performance. Might be interesting wrt St. Peter's large ponds. Worth looking at. Suggests various ways of decreasing algae, including reducing detention time!

133. Marais G. V. R. (1970) Dynamic behavior of oxidation ponds. In *2nd International Symposium for Waste Treatment Lagoons*, (ed. McKinney R. E.), pp. 15-46. Missouri Basin Engineering Health Council & Federal Water Quality Administration, Lawrence, Kansas.
Keywords: ALGAE, ALGAL TAXONOMY, BOD, COPY, ENERGY, LAGOONS, MODEL, OXYGEN, STRATIFICATION, SWAIN, TEMPERATURE, WIND

134. Martin N. J., and Fallowfield H. J. (1989) "Computer modelling of algal waste treatment systems." *WST* **21**(12), 1657-1660.
Keywords: ALGAE, AUSTRALIA, CLIMATE, HATHAWAY, LAGOONS, MODEL, NEED, PHOTOSYNTHESIS, PRODUCTION, TEMPERATURE, WEATHER

Comments: Modelled the top 40 cm in a high-rate algal pond. Useful for design? Pond area said to be inversely proportional to O2 production per sq. m. Melbourne used as a test site. Predicates growth on only light intensity and temperature; assumes no other limiting factors.

135. Mathur R. P., and Sinha A. K. (1985) Diurnal studies of a Micro-aquatic engineered ecosystem. In *Proceedings of the First International Symposium on Environmental Technology for Developing Countries*, pp. 235-245. Plenum Press, New York, NY, From conference held in Istanbul, Turkey, July 7-14, 1982; sponsored by Bogazici University, Istanbul.
Keywords: ALGAE, ALKALINITY, BACTERIA, D.O., DIEL, DIURNAL VARIATIONS, HATHAWAY, LAGOONS, NEED, PH, SOLAR RADIATION, TEMPERATURE, TREATMENT, WASTEWATER
Comments: Results of studies of diurnal fluctuations of pond parameters are given

136. May R. M., ed. (1976) *Theoretical ecology - principles and applications*. Blackwell Scientific, London.
Keywords: COMPETITION, HATHAWAY, HERBIVORES, POPULATION, PREDATION
Comments: In Ent/Fish library: 574.50184 T343

137. McCauley E., and Murdoch W. W. (1987) "Cyclic and stable populations: plankton as paradigm." *Am. Nat.* **129**(1), 97-121.
Keywords: ALGAE, COPY, CYCLE, DAPHNIA, #LAGOONS, PULEX, REVIEW, STEADY-STATE, SWAIN, ZOOPLANKTON
Comments: The idea of edible algae is used here. Analyzes 20 years of Daphnia and algae data. Temperature does not seem to play a factor in the population cycles.

138. McKinney R. E. (1962) *Microbiology for Sanitary Engineers*. McGraw-Hill, New York.
Keywords: ALGAE, BACTERIA, COPY, LAGOONS, SWAIN
Comments: Requested mpcal 89.3.23. Cited in #446 as documenting algal role.

139. McKinney R. E., ed. (1970) *2nd International Symposium for Waste Treatment Lagoons*. Missouri Basin Engineering Health Council & Federal Water Quality Administration, Lawrence, Kansas.
Keywords: COPY, LAGOONS, SWAIN
Comments: About 40 contributed chapters.

140. McNaught D. C. (1989) "Functional bioassays utilizing zooplankton: a comparison." *Hydrobiologia* **188/189**, 117-121.
Keywords: BIOASSAY, COPY, CRUSTACEANS, DAPHNIA, FEEDING, FUNCTIONAL, HATHAWAY, LINDANE, PESTICIDES, REPRODUCTION, RESPIRATION, TOXICITY, ZOOPLANKTON
Comments: Has information on the response of Daphnia to lindane.

141. McNaught D. C., and Hasler A. D. (1964) "Rate of movement of populations of Daphnia in relation to changes in light intensity." *J. Fish. Res. Bd. Can.* **21**, 291-318.
Keywords: DAPHNIA, HATHAWAY, LIGHT, MIGRATION, NEED
Comments: Cited in Wetzel.

142. McNaught D. C., and Scavia D. (1976) Application of a model of zooplankton composition to problems of fish introductions to the Great Lakes. In *Modeling Biochemical Processes in Aquatic Ecosystems*, (ed. Canale R.), pp. 281-304. Ann Arbor Press, Ann Arbor, MI.

Keywords: ALGAE, COPY, DAPHNIA, GRAZING, GROWTH, HATHAWAY, MODEL, PREDATION, ZOOPLANKTON
Comments: Develops a zooplankton model for phytoplankton in the great lakes. Model includes portions for predation, growth, respiration, mortality. Predation weighed heavy in his situation.

143. Meador J. P. (1991) "The interaction of pH, dissolved organic carbon, and total copper in the determination of ionic copper and toxicity." *Aq. Tox.* **19**(1), 13-32.
Keywords: COPPER, DAPHNIA, DOC, HATHAWAY, LC50, MAGNA, NEED, PH, TOXICITY
Comments: Toxicity of copper held to be due to its ionic speciation. Bioavailability is the key. 48 hr LC50 said to be about 0.5 ng IONIC copper; the ionic form said to be highly correlated with toxicity. Sounds similar to the ammonia situation described by Erickson.

144. Messer J., Ho J., and Grenney W. J. (1984) "Ionic strength correction for extent of ammonia ionization in freshwater." *Can. J. Fish. Aquat. Sci.* **41**(811-815), 811-815.
Keywords: AMMONIA, CONDUCTIVITY, COPY, DEUTSCHMAN, HATHAWAY, IONIC STRENGTH, IONIZATION, TOXICITY
Comments: Allows further ionization fraction calculations for ammonia based on solution ionic strength. Maybe should be included in pond simulations since conductivity is so high in those waters.

145. Metcalf & Eddy, ed. (1972) *McGraw Hill Series in Water Resources and Environmental Engineering, Wastewater Engineering: Treatment, disposal, re-use*, 2nd ed. McGraw-Hill, Inc., Boston.
Keywords: AMMONIA, COPY, HATHAWAY, WASTEWATER
Comments: Gives typical wastewater characteristics.

146. Middlebrooks E. J. (1987) "Design equations for BOD removal in facultative ponds." *WST* **19**(12), 187-193.
Keywords: BOD, DESIGN, LAGOONS, LUCK, MODEL, NEED, TREATMENT, WASTEWATER
Comments: Testing of design equations against actual pond field data showed that none gave a great fit; the plug flow equation worked best.

147. Middlebrooks E. J., Jones N. B., Reynolds J. H., Torpy M. F., and Bishop R. P. (1978) *Lagoon information source book.* Ann Arbor Science, Ann Arbor, MI.
Keywords: ALGAE, HATHAWAY, LAGOONS, MODEL, ZOOPLANKTON
Comments: Actually a big bibliography with a nice introduction explaining pond systems. In Walter library: 016.6283 L137

148. Middlebrooks E. J., Middlebrooks C. H., Reynolds J. H., Watters G. Z., Reed S. C., and George D. B. (1982) *Wastewater Stabilization Lagoon Design, Performance and Upgrading.* Macmillan, New York.
Keywords: COPY, DESIGN, HYDROLOGY, LAGOONS, SEALING, SLUDGE, SWAIN, WATER HYACINTH
Comments: UNIV MN ENGINEERING LIBE: TD 746.5 .W363 1982.

149. Middlebrooks E. J., Reynolds J. H., Middlebrooks C., Schneiter R. W., Stenquist R. J., and Johnson B. A. (1983) *Design Manual, Municipal Wastewater Stabilization Ponds.* U.S. Environmental Protection Agency, EPA-625/1-83-015, Washington, D.C.
Keywords: ALGAE, BOD, COPY, DESIGN, FACULTATIVE, LAGOONS, ODOR, SWAIN

150. Mitchell B. D., and Williams W. D. (1982a) "Factors influencing the seasonal occurrence and abundance of the zooplankton in two waste stabilization ponds." *Australian J. Mar. Fresh. Res.* **33**, 989-997.
Keywords: AUSTRALIA, COPEPOD, COPY, DAPHNIA, LAGOONS, MESOCYCLOPS, OXYGEN, SIMOCEPHALUS, SWAIN, TEMPERATURE, ZOOPLANKTON

151. Mitchell B. D., and Williams W. D. (1982b) "Population dynamics and production of Daphnia carinata (King) and Simocephalus expinosus (Koch) in waste stabilization ponds." *Australian J. Mar. Fresh. Res.* **33**, 837-864.
Keywords: AUSTRALIA, COPY, DAPHNIA, GROWTH RATE, LAGOONS, LENGTH-WEIGHT, SIMOCEPHALUS, SWAIN

152. Mitchell S. A. (1990) "Factors affecting the hatching of Streptocephalus macrourus Daday (Crustacea; Eubranchiopoda) eggs." *Hydrobiologia* **194**, 13-22.
Keywords: ANOSTRACAN, COPY, D.O., DIAPAUSE, EPHIPPIA, HATCHING, HELGEN, LIGHT, TEMPERATURE
Comments: Found that light was the only factor of those investigated that was obligatory for hatching. Temperature of incubation was important.

153. Moore M. V., and Winner R. W. (1989) "Relative sensitivity of Cerodaphnia dubia laboratory tests and pond communities of zooplankton and benthos to chronic copper stress." *Aq. Tox.* **15**, 311-330.
Keywords: BENTHOS, COPEPODS, COPPER, COPY, DAPHNIA, HELGEN, POPULATION, ROTIFERS, TOXICITY, ZOOPLANKTON
Comments: Compared lab tests and in situ tests. Surprisingly, found that Daphnia populations increased with the addition of copper! Attributed this to the elimination of a algae-excreted toxic compound by the algacidal Cu.

154. Moreno M. D., Soler A., Saez A., and Moreno J. (1984) "Thermal simulation of deep stabilization ponds." *Tribune du Cebedeau* **3?**, 415-428.
Keywords: LAGOONS, MODEL, NEED, SWAIN
Comments: Cited in 536.

155. Moreno M. D., Medina M. A., Moreno J., Soler A., and Saez J. (1988) "Modeling the performance of deep waste stabilization ponds." *W. Res. Bull.* **24**(2), 377-387.
Keywords: ALGAE, COPY, HATHAWAY, LAGOONS, MODEL, NITROGEN, PHOSPHORUS, TEMPERATURE
Comments: From Swain's collection. OK model, but a bit weak on the ecological aspects of the ponds.

156. Murray B. G. (1979) *Population dynamics - alternative models.* Academic Press, New York.
Keywords: HATHAWAY, LOTKA, MODEL, POPULATION, PREDATION
Comments: In Ent/Fish library: 574.524 M961

157. Myklebust R. J., and Harmston F. C. (1962) "Mosquito production in stabilization ponds." *J. Water Pollut. Control Fed.* **34**(3), 302-306.
Keywords: COPY, LAGOONS, MACROPHYTES, MOSQUITO, SWAIN, WASHINGTON STATE

158. Neill W. E. (1981) "Impact of Chaoborus predation upon the structure and dynamics of a crustacean zooplankton community." *Oecologia (Berl.)* **48**, 164-177.

Keywords: BOSMINA, CHAOBORUS, CLADOCERA, COPY, DAPHNIA, DIAPHANOSOMA, LAGOONS, PREDATION, SWAIN, ZOOPLANKTON
Comments: Cited in 533. Says that Chaoborus will have short-term effects on a population. BUT: food limitation seemed to have a much stronger impact on the prey population than predator concentration.

159. Nemerow N. L., and Bryson J. C. (1963) "How efficient are oxidation ponds?" *Wastes Eng.* **34**(3), 133-5,159.
Keywords: COPY, EVAPORATION, LAGOONS, NEW YORK, SLUDGE, SWAIN
Comments: March issue. Loadings averaging 130 pounds BOD per day were satisfactorily treated." No correlation between loading and efficiency. Two ponds at Air Force Base.

160. New G. R. (1987) "Predicting Waste Stabilization Pond Performance Using An Ecological Simulation Model," [Dissertation], Utah State University.
Keywords: ALGAE, AMMONIA, BOD, COPY, D.O., HATHAWAY, LAGOONS, LOADING, MODEL, NITROGEN, OXYGEN, PHOSPHORUS, ZOOPLANKTON
Comments: Contains excellent review of literature. Adapts a fast-flushing reservoir model to use with Corrine, Utah ponds.

161. Oleszkiewicz J. A., and Sparling A. B. (1987) "Wastewater lagoons in a cold climate." *WST* **19**(12), 47-53.
Keywords: AERATION, BOD, DESIGN, H2S, LAGOONS, LOADING, LUCK, NEED, PH, SULFUR, TEMPERATURE
Comments: Especially concerned with effects of overloading and odor control.

162. Orcutt J. D., and Porter K. G. (1984) "The synergistic effects of temperature and food concentration on life history parameters of Daphnia." *Oecologia (Berl.)* **63**, 300-306.
Keywords: COPY, DAPHNIA, FEEDING, FOOD, GROWTH, HATHAWAY, LIFE TABLES, MORTALITY, POPULATION, PREDATION, TEMPERATURE
Comments: Good info on food limitations to growth. Referenced in Porter & Orcutt

163. Oswald W. J. (1963a) "Fundamental factors in stabilization pond design." *Adv. Biological Waste Treatment* **3**, 357-393.
Keywords: COPY, DESIGN, LAGOONS, SWAIN
Comments: Requested MPCAL 89.3.17

164. Oswald W. J. (1963b) "Light conversion efficiency of algae grown in sewage." *Transactions ASCE* **128**, 47-83.
Keywords: ALGAE, COPY, LAGOONS, SWAIN
Comments: Cited by Roesler (443).

165. Oswald W. J. (1988) The role of microalgae in liquid waste treatment and reclamation. In *Algae and Human Affairs*, (eds. Lembi C. A. and Waaland J. R.), pp. 255-281. Cambridge University Press, New York.
Keywords: ALGAE, COPY, HARVEST, LAGOONS, METHANE, NUTRIENTS, SWAIN

166. Oswald W. J., Gotaas H. B., Ludwig H. F., and Lynch V. (1953a) "Algae symbiosis in oxidation ponds II. Growth Characteristics of Chlorella pyrenoidosa Cultured in sewage." *Sewage Ind. Wastes* **25**(1), 26-37.
Keywords: ALGAE, BOD, CHLORELLA, CHLOROPHYLL, INTERESTING, LAGOONS, OXYGEN, SENESCENCE, SWAIN

Comments: Chlorella may inhibit the saprophytic bacteria necessary to decomposition of algae. In batch culture Chlorella eventually senesces, producing yellow color.

167. Oswald W. J., Gotaas H. B., Ludwig H. F., and Lynch V. (1953b) "Algae symbiosis in oxidation ponds III. Photosynthetic oxygenation." *Sewage Ind. Wastes* **25**(6), 692-705.
Keywords: ALGAE, EXPERIMENT, INTERESTING, LABORATORY, LAGOONS, OXYGEN, SWAIN, SYMBIOCON
Comments: Laboratory study in a "balanced aquarium" sealed from the atmosphere.

168. Oswald W. J., Gotaas H. B., Golueke C. G., and Kellen W. R. (1957) "Algae in waste treatment." *Sewage Ind. Wastes* **29**(4), 437-457.
Keywords: AEROBIC, ALGAE, BACTERIA, BOD, CALIFORNIA, COPY, DESIGN, EFFICIENCY, LAGOONS, OXYGEN, OXYGENATION FACTOR, SWAIN, WINTER
Comments: Oxygenation factors above about 1.8 that occur in shallow ponds as a result of excess algal growth lead to a high pH, which is shown to inhibit bacterial oxidation of influent sewage.

169. Oswald W. J., Golueke C. G., Cooper R. C., Gee H. K., and Bronson J. C. (1964) "Water reclamation, algal production and methane fermentation in waste ponds." *Adv. Water Poll. Res.* **2**, 119-140.
Keywords: ALGAE, BOD, COPY, DESIGN, DETENTION PERIOD, LAGOONS, METHANE, NITROGEN, SWAIN
Comments: California: 3-5 day detention. Trying to maximize algal production to oxidize waste BOD and sell algae.

170. Pano A., and Middlebrooks E. J. (1982) "Ammonia nitrogen removal in facultative wastewater stabilization ponds." *J. Water Pollut. Control Fed.* **54**, 344-351.
Keywords: AMMONIA, COPY, LAGOONS, NITROGEN, SWAIN

171. Parker C. D. (1962) "Microbiological aspects of lagoon treatment." *J. Water Pollut. Control Fed.* **34**, 149-161.
Keywords: BACTERIA, COPY, LAGOONS, SWAIN
Comments: Concerned with the quantity of bacteria available to break down BOD - says more important than the quantity of algae. Doesn't seem to contain hard conclusions.

172. Parker C. D., Jones H. L., and Taylor W. S. (1950) "Purification of sewage in lagoons." *Sewage Ind. Wastes* **22**(6), 760-775.
Keywords: ALGAE, AUSTRALIA, COPY, FLOW-THROUGH, LAGOONS, OXYGEN, SWAIN
Comments: Cited in 446 as documenting role of algae. But, does not do that too well.

173. Parkhurst B. R., Bradshaw A. S., Forte J. L., and Wright G. P. (1979) "An evaluation of the acute toxicity to aquatic biota of a coal conversion effluent and its major components." *Bull. Environm. Contam. Toxicol.* **23**, 349-356.
Keywords: AMMONIA, BIOASSAY, COPY, DAPHNIA, HATHAWAY, LC50, PH, TOXICITY
Comments: Studied the effects of an organics-rich effluent water. Found that ammonia was the main toxicant in the treated water. Gives a scheme for evaluating constituents' contributions to toxicity on the basis of LC50's.

174. Patil H. S., Dodakundi G. B., and Rodgi S. S. (1975) "Succession in zoo- and phytoplankton in a sewage stabilization pond." *Hydrobiologia* **47**(2), 253-264.
Keywords: ALGAE, CHLAMYDOMONAS, CHLORELLA, COPY, EUGLENA, INDIA, LAGOONS, PHACUS, PROTOZOA, SUCCESSION, SWAIN, THIOCYSTIS, ZOOPLANKTON

Comments: Dominated by greens and euglenoids.

175. Pearson H. W., Mara D. D., Mills S. W., and Smallman D. J. (1987) "Factors determining algal populations in waste stabilization ponds and the influence of algae on pond performance." *WST* **19**(12), 131-140.
Keywords: ALGAE, AMMONIA, HATHAWAY, LAGOONS, LIGHT, NEED, SULFIDES, WASTEWATER
Comments: Considers algal growth in wastewater and inhibitory effects of ammonia and sulfides.

176. Peters R. H., and De Bernardi R., eds. (1987) *Memorie dell'Istituto Italiano di Idrobiologia Dott. de Marchi, Daphnia*, Vol. 45. Consiglio Nazionale delle Ricerche, Istituto Italiano di Idrobiologia, Verania Pallanza.
Keywords: COPY, DAPHNIA, FOOD, HATHAWAY, LIFE HISTORY
Comments: General reference on Daphnia. Contains many summaries of current research on Daphnia, by top Daphnia scientists.

177. Peters R. H., and Downing J. A. (1984) "Empirical analysis of zooplankton filtering and feeding rates." *Limnol. Oceanogr.* **29**(4), 763-784.
Keywords: COPY, DAPHNIA, FILTERING, GRAZING, #LAGOONS, LENGTH-WEIGHT, SWAIN, ZOOPLANKTON

178. Pfeffer J. T. (1970) Anaerobic lagoons--Theoretical considerations. In *2nd International Symposium for Waste Treatment Lagoons*, (ed. McKinney R. E.), pp. 310-319. Missouri Basin Engineering Health Council & Federal Water Quality Administration, Lawrence, Kansas.
Keywords: ANAEROBIC, LAGOONS, NEED, SWAIN, THEORY
Comments: cited by Lennander

179. Pipes W. O. Jr. (1961) "Basic biology of stabilization ponds." *Water Sewage Works* **108**(4), 131-136.
Keywords: COPY, LAGOONS, SWAIN
Comments: April issue. Lots of undocumented advice; thought processes not too bad.

180. Porter K. G. (1981) Limits to the control of algal populations by grazing zooplankton: The environmental theater and the ecological play. In *Proceedings of Workshop on Algal Management and Control, March 9-12, 1980, Pacific Grove, CA. Technical Report E-81-7. May 1981. Final Report*, pp. 121-130. Army Waterways Experiment Station, Vicksburg, MS.
Keywords: ALGAE, BIOMANIPULATION, BLUEGREENS, ECOLOGY, EUTROPHICATION, FOOD, GRAZING, GREENS, HATHAWAY, NEED, NITROGEN, NUTRIENTS, PHOSPHORUS, POPULATION, PROTOZOANS, ROTIFERS, ZOOPLANKTON
Comments: Talks about how zooplankton grazing has its limitations - size, palatability. Says that zp can affect species composition. Shapiro's work is similar.

181. Porter K. G., and Orcutt J. D. J. (1980) Nutritional adequacy, manageability and toxicity as factors that determine the food quality of green and blue-green algae for Daphnia. In *Evolution and Ecology of Zooplankton Communities*, (ed. Kerfoot W. C.), pp. 268-281. University Press, Hanover, NH.
Keywords: ALGAE, BLUEGREENS, COPY, DAPHNIA, EDIBLE ALGAE, FEEDING, FOOD, GREENS, HATHAWAY
Comments: Discusses size limitations on algae as a food source for Daphnia.

182. Preul H. C., and Wagner R. A. (1987) "Waste stabilization pond prediction model," [Dissertation], Cincinnati University. (cited in WST, 19:12)
Keywords: BOD, CLIMATE, COPY, HATHAWAY, HYDRAULIC ROUTING, LAGOONS, MODEL, PHYSICAL MODEL
Comments: Stresses hydraulic routing, with BOD modelled using a first order equation. Does not include ecological components.

183. Raschke R. L. (1970) "Algal periodicity and reclamation in a stabilization pond ecosystem." *J. Water Pollut. Control Fed.* **42**(4), 518-51?
Keywords: ALGAE, LAGOONS, SWAIN
Comments: cited in 528.

184. Reynolds E. C. Jr., and Ahlstrom S. B. (1979) Design and construction of wastewater stabilization ponds. In *Performance and Upgrading of Wastewater Stabilization Ponds*, (eds. Middlebrooks E. J., Falkenborg D. H., and Lewis R. F.), pp. 51-62. U.S. EPA, EPA-600/9-79-011, Cincinnati, Ohio.
Keywords: COPY, DESIGN, LAGOONS, SWAIN
Comments: Detailed information on pond construction.

185. Reynolds J. H., Swiss R. H., Macko C. A., and Middlebrooks E. J. (1979) "Facultative lagoon performance." *Prog. Wat. Tech.* **11**(4/5), 361-376.
Keywords: ALGAE, BOD, COLIFORMS, COPY, DESIGN, LAGOONS, LOADING, MODEL, SS, SWAIN, UTAH
Comments: Corinne Utah intensive study. Hydraulic residence time 88.3 days. Seven ponds in series.

186. Rich L. G. (1989) "Troubleshooting aerated lagoon systems." *Pub. Works* **120**(11), 50-52.
Keywords: AERATION, COPY, DESIGN, HATHAWAY, LAGOONS, WASTEWATER
Comments: The article deals specifically with aerated systems, but may be useful for analysis of Minnesota's facultative systems.

187. Riley M. J., and Stefan H. G. (1987) *Dynamic Lake Water Quality Simulation Model "MINLAKE"*. St. Anthony Falls Hydraulic Laboratory, Minneapolis, Project Report No. 263.
Keywords: ALGAE, AMMONIA, COPY, D.O., HATHAWAY, MODEL, NITROGEN, PHOSPHORUS, ZOOPLANKTON
Comments: Introduction to and explanation of the water quality model MINLAKE. Pond model based on this lake model.

188. Riley M. J., and Stefan H. G. (1988) "MINLAKE: A dynamic lake water quality simulation model." *Ecol. Modelling* **43**, 155-182.
Keywords: ADVECTION, ALGAE, CHLOROPHYLL, COPY, DETRITUS, LAGOONS, LAKE, MODEL, NITROGEN, OXYGEN, PHOSPHORUS, SWAIN, TEMPERATURE, ZOOPLANKTON
Comments: Condensed form of previous reference.

189. Rivera F., Sanchez M., Lugo A., Ramirez P., Ortiz R., and Calderon A. (1987) "Ciliates in a waste stabilization pond system in Mexico." *WASP* **34**(3), 245-262.
Keywords: ALKALINITY, CILIATES, HATHAWAY, LAGOONS, NEED, NITRATES, SURVEY, TEMPERATURE, TREATMENT, WASTEWATER, ZOOPLANKTON
Comments: Survey of ciliated zooplankton in wastewater treatment ponds; attempt made to correlate physicochemical parameters with species present.

190. Rivera F., Vilaclara G., Lugo A., Ramirez P., Robles E., and LaBastida A. (1988) "Comparison between the spatial distribution patterns of flagellates and some physicochemical parameters in a waste stabilization pond." *WASP* **37**(1-2), 1-12.
Keywords: ALGAE, DISTRIBUTION, FLAGELLATES, HATHAWAY, LAGOONS, MEXICO, MICROORGANISMS, NEED, PROTOZOA, WASTEWATER, ZOOPLANKTON
Comments: Survey of spatial distribution of flagellates in pond in Mexico, with correlations with physicochemical parameters.

191. Roesler J. F., and Preul H. C. (1970) Mathematical simulation of waste stabilization ponds. In *2nd International Symposium for Waste Treatment Lagoons*, (ed. McKinney R. E.), pp. 180-186. Missouri Basin Engineering Health Council & Federal Water Quality Administration, Lawrence, Kansas.
Keywords: ALGAE, BOD, COPY, LAGOONS, MODEL, OXYGEN, SWAIN, TEMPERATURE

192. Russell C. S., ed. (1975) *Ecological modeling in a resource management framework.* Resources for the Future, Washington, D.C., Proceedings of a symposium sponsored by the National Oceanic and Atmospheric Administration, and Resources for the Future.
Keywords: ALGAE, BLUEGREENS, CLEANER, EUTROPHICATION, HATHAWAY
Comments: "CLEANER" does model blue-green algae. In Ent/Fish library: 574.50184 Ec73

193. Sackellares R. W., Barkley W. A., and Hill R. D. (1987) "Development of a dynamic aerated lagoon model." *J. Water Pollut. Control Fed.* **59**(10), 877-883.
Keywords: DYLAMO, HATHAWAY, LAGOONS, MODEL, NEED, WASTEWATER
Comments: Tells about DYLAMO - a computer model for aerated lagoons. Discusses calibration and verification, strengths and weaknesses.

194. Sand-Jensen K. (1989) "Environmental variables and their effect on photosynthesis of aquatic plant communities." *Aquat. Bot.* **34**, 5-25.
Keywords: CO2, DIC, #LAGOONS, LIGHT, MACROPHYTES, OXYGEN, PHOTOSYNTHESIS, REVIEW, TEMPERATURE
Comments: Potentially useful in understanding growth of macrophytes.

195. Santos M. C., and Oliveira J. F. S. (1987) "Nitrogen transformations and removal in waste stabilization ponds in Portugal: Seasonal variations." *WST* **19**(12), 123-130.
Keywords: HATHAWAY, LAGOONS, MODEL, NEED, NITROGEN, WASTEWATER
Comments: Discusses seasonal changes . . .

196. Scanferlato V. S., and Cairns J. J. (1990) "Effect of sediment-associated copper on ecological structure and function of aquatic microcosms." *Aq. Tox.* **18**, 23-34.
Keywords: ALGAE, BACTERIA, BENTHOS, COPPER, COPY, HATHAWAY, SEDIMENT, TOXICITY, ZOOPLANKTON
Comments: Devised small aquaria to simulate in vivo microcosms. Added copper to the sediments and studied solid/liquid partitioning, and effects on biota above. Found that respiration was depressed, also chl-a production, depending on the concentrations added.

197. Scavia D. (1981) Use and interpretation of detailed, mechanistic models of phytoplankton dynamics. In *National Oceanic and Atmospheric Administration Technical Report*, pp. 196-222. National Oceanic and Atmospheric Administration; Great Lakes Environmental Research Lab, Ann Arbor, MI, Report E-81-13. (from papers presented at workshop, April 10-12, 1979)

Keywords: INCOMPLETE, ALGAE, CARBONATES, GRAZING, HATHAWAY, LIGHT, MODEL, NEED, NITROGEN, NUTRIENTS, OXYGEN, PHOSPHORUS, SILICON, STRATIFICATION, ZOOPLANKTON
Comments: Phytoplankton dynamics model applied to Lake Ontario. Apparently has nutrient, zooplankton, and O2 components.

198. Scavia D., and Robertson A., eds. (1979) *Perspectives on lake ecosystem modeling.* Great Lakes Environmental Research Laboratory; National Oceanic and Atmospheric Administration, Ann Arbor.
Keywords: INCOMPLETE, ALGAE, CLEANER, GRAZING, HATHAWAY, PHOSPHORUS, ZOOPLANKTON
Comments: in ENT/Fish library: 574.52632 P432

199. Scheithauer E., and Bick H. (1964) Oocologische untersuchungen an Daphnia magna und Daphnia pulex im frieland und im laboratorium. In *Scientific Papers from Institute of Chemical Technology*, pp. 439-., Prague (Czechoslovakia).
Keywords: INCOMPLETE, AMMONIA, BACTERIA, DAPHNIA, H2S, HATHAWAY, MAGNA, MORTALITY, NEED, OXYGEN, PH, PULEX, TEMPERATURE, TOXICITY
Comments: Reference from which Dinges drew his ammonia vs. pH toxicity curves. Also presents table of "Extreme tolerances and positive population increase ranges for D. pulex". Practically the only reference that attempts to identify the conditions under which Daphnia can exist in treatment ponds.

200. Schluter M., Groeneweg J., and Soeder C. J. (1987) "Impact of rotifer grazing on population dynamics of green microalgae in high-rate ponds." *Water Res.* **21**(10), 1293-1297.
Keywords: ALGAE, BLUEGREENS, COPY, DOMINANCE, EDIBLE ALGAE, GRAZING, GREENS, HELGEN, HROP, LAGOONS, MICRACTINIUM, ROTIFERS, SCENEDESMUS, SUCCESSION
Comments: "... a collapse of dominant Scenedesmus populations, coinciding with the appearance of rotifers, has been observed by several authors and in different geographical regions..." Micractinium (inedible bl-gr) then came in. Did experiments to confirm the idea.

201. Sexauer W. N., and Karn R. V. (1979) *Stabilization pond operation and maintenance manual*, 2nd ed. Minnesota Pollution Control Agency, St. Paul, prepared by the Operations and Training Unit of the Minnesota Pollution Control Agency.
Keywords: ALGAE, BOD, COLIFORMS, COPY, D.O., HATHAWAY, LAGOONS, LEMNA, MACROPHYTES, PH, PHOSPHORUS, SS
Comments: Manual used for training of pond operators in Minnesota. Much information about practical aspects of pond operation and maintenance.

202. Shapiro J. (1980) "The importance of trophic level interactions to the abundance and species composition of algae in lakes." *Dev. Hyd.* **2**, 105-116.
Keywords: ALGAE, APHANIZOMENON, BLUEGREENS, COPY, DAPHNIA, EUTROPHICATION, HATHAWAY, PESTICIDES, TOXICITY, ZOOPLANKTON
Comments: Suggests that algal levels and algal species in lakes are controlled by zooplankton populations.

203. Shapiro J. (1990) "Current beliefs regarding dominance by blue-greens: The case for the importance of CO2 and pH." *Verh. Internat. Verein. Limnol.* **24**, 38-54.

Keywords: ALGAE, BLUEGREENS, BUOYANCY, CO2, COPY, DOMINANCE, GRAZING, GREENS, HATHAWAY, LIGHT, NITROGEN, PH, PHOSPHORUS, TEMPERATURE, ZOOPLANKTON
Comments: Shapiro sums up his arguments for the idea that blue-greens become dominant under conditions of elevated pH. Discounts the: elevated temperature idea, the N/P ratio idea, the low light idea, the buoyancy hypothesis, and the zooplankton grazing idea. Presents the results of his bag experiments wherein he produced green dominance by lowering the pH. Follows the ideas of D. King.

204. Shei P., Iwakuma T., and Fuji K. (1988) "Population dynamics of Daphnia rosea in a small eutrophic pond." *Ec. Res.* **3**(3), 291-304.
Keywords: ALGAE, CERATIUM, DAPHNIA, EUTROPHICATION, FOOD, HATHAWAY, NEED, POPULATION
Comments: Studied population trends in the pond. Suggested that food limitations controlled the population of D. rosea.

205. Shelef G. (1979) "Improving stabilization ponds efficiency and performance." *Prog. Wat. Tech.* **11**(4/5), 389-404.
Keywords: BOD, DESIGN, HROP, LAGOONS, LOADING, LUCK, NEED, TREATMENT, WASTEWATER
Comments: Israeli systems for improving performance of pond operations and allowing increased loading. Discusses HROP systems and re-circulation as means of handling higher loads.

206. Sheng Y., Liu Y., and Peene S. (1988) Hydrodynamic modeling of shallow lagoons and lakes. In *Hydraulic Engineering Proceedings, 1988 National Conference on Hydraulic Engineering*, pp. 582-587. ASCE, New York, NY, Conf. #12114.
Keywords: FLOW, HATHAWAY, HYDRODYNAMICS, LAGOONS, LIMNOLOGY, MODEL, NEED, WIND
Comments: Discusses flow and circulation patterns in several shallow Florida water bodies.

207. Shin H. K., and Polprasert C. (1988) "Ammonia nitrogen removal in attached-growth ponds." *J. Env. Eng.* **114**(4), 846-863.
Keywords: ALGAE, AMMONIA, ATTACHED-GROWTH, HATHAWAY, LAGOONS, MACROPHYTES, NEED, NITROGEN, NITROGEN REMOVAL, VOLATILIZATION, WASTEWATER
Comments: equations for the ammonia-nitrogen removal were developed; volatilization and nitrification found to have little effect. The main remover is uptake by biomass.

208. Singh V. P., and Saxena P. N. (1969) "Preliminary studies on algal succession in raw and stabilized sewage." *Hydrobiologia* **34**, 503-512.
Keywords: ALGAE, LAGOONS, SUCCESSION, SWAIN
Comments: cited in 742.

209. Sless J. B. (1974) "Biological and chemical aspects of stabilization pond design." *Rev. Environ. Health* **1**(4), 327-354.
Keywords: ALGAE, BOD, CHLORELLA, COPY, DESIGN, DIURNAL, EUGLENA, LAGOONS, LIGHT, OXYGEN, PH, SWAIN, TEMPERATURE
Comments: Good diurnal data, 0-50 cm. Short retention times, of less than 20 days.

210. Smith V. H. (1983) "Low nitrogen to phosphorus rations favor dominance by blue-green algae in lake phytoplankton." *Science* **221**, 669-671.

Keywords: ALGAE, BLUEGREENS, COPY, DOMINANCE, EUTROPHICATION, GREENS, HATHAWAY, NITROGEN, PHOSPHORUS, SUCCESSION
Comments: Advances the hypothesis that a nitrogen/phosphorus ratio (TN/TP) less than 29:1 will favor bluegreens. The effect is attributed to blue-greens' better ability to assimilate nitrogen under conditions where it is scarce.

211. Smith V. H. (1987) *Report - Water Resources Research Institute of the University of North Carolina*, Number 233, *Prediction of nuisance blue-green algal growth in North Carolina waters.* University of North Carolina, Chapel Hill, NC, Report Number 233.
Keywords: ALGAE, BLUEGREENS, HATHAWAY, MODEL, NEED, NUTRIENTS, PRODUCTION, RESERVOIRS, TREATMENT
Comments: The author evaluated models to see which could successfully predict blue-green percentages in the NC reservoirs. She found none performed adequately! She suggests some reasons for this.

212. Spencer C. N., and King D. L. (1984) "Role of fish in regulation of plant and animal communities in eutrophic ponds." *Can. J. Fish. Aquat. Sci.* **41**, 1851-1855.
Keywords: ALGAE, BASS, CLADOCERA, COPEPOD, COPY, DAPHNIA, FISH, LAGOONS, LIGHT, MACROPHYTES, MINNOW, ROTIFER, SECCHI, STICKLEBACK, SWAIN

213. Spencer C. N., and King D. L. (1987) "Regulation of blue-green algal buoyancy and bloom formation by light, inorganic nitrogen, CO2, and trophic interaction." *Hydrobiologia* **144**, 183-192.
Keywords: ANABAENA, BIOMANIPULATION, BLUEGREENS, BUOYANCY, CLADOCERA, CO2, COPY, DOMINANCE, FISH, GREENS, HATHAWAY, LIGHT, NITROGEN, SUCCESSION, ZOOPLANKTON
Comments: Very interesting. Suggests that in order for bluegreens to appear, reduced light intensity must be created by blooms of greens or diatoms. If grazing zooplankton keep the water clear, blue-greens may never appear.

214. Srivastava A., Mathur R., Bhargava R., and Singh J. (1986) "Limiting factors in animal waste fed stabilization ponds." *J. Inst. Eng. (Ind.)* **66**(3), 101-185. (part EN 3)
Keywords: ALGAE, BACTERIA, BORON, GROWTH, HATHAWAY, LAGOONS, MAGNESIUM, NEED, NITROGEN, PHOSPHORUS, WASTEWATER
Comments: optimization of algal growth is studied to determine the best combination of nutrients

215. Sterner R. W. (1990) "The ration of nitrogen to phosphorus resupplied by herbivores: Zooplankton and the competitive arena." *Am. Nat.* **136**(2), 209-229.
Keywords: ALGAE, COPY, FEEDING, HATHAWAY, MORTALITY, NITROGEN, PHOSPHORUS, ZOOPLANKTON
Comments: Discusses the recycling of nutrients as a result of zooplankton digestion and excretion; and the effects of that on phytoplankton competition for nutrients.

216. Stross R. G., Nobbs P. A., and Chisholm S. W. (1979) "SUNDAY, a simulation model of an arctic Daphnia population." *Oikos* **32**, 349-362.
Keywords: COPY, DAPHNIA, FOOD, GROWTH, HATHAWAY, MODEL, PARAMETERS, POPULATION, REPRODUCTION, TEMPERATURE
Comments: A complicated model based on Daphnia metabolism patterns, size and instar characteristics. Uses many estimated and "guessed" parameters. Focuses on metabolism as the basis for population changes.

217. Stutz-McDonald S. E., and Williamson K. J. (1979) "Settling rates of algae from wastewater lagoons." *Jour. Env. Eng. Div.* **105**, 273-282.
Keywords: ALGAE, COPY, LAGOONS, METHOD, SETTLING, STOKES LAW, SWAIN

218. Swartzman G., and Rose K. A. (1983/1984) "Simulating the biological effects of toxicants in aquatic microcosm systems." *EM* **22**(104), 123-134.
Keywords: ALGAE, HATHAWAY, MODEL, NEED, NITROGEN, NUTRIENTS, PHOSPHORUS, TOXICANTS, TOXICITY, ZOOPLANKTON
Comments: Model allows for 8 groups of phytoplankton, 5 groups of zooplankton, and nitrogen and phosphorus. Somehow coordinated by a simulator called AEGIS.

219. Tabata K. (1962) "Toxicity of ammonia to aquatic animals with reference to the effect of pH and carbon dioxide." *Bull. Tokai Reg. Fish. Res. Lab.* **34**, 67-73.
Keywords: AMMONIA, COPY, DAPHNIA, HATHAWAY, LC50, NITROGEN, PH, TOXICITY
Comments: Cited by EPA and Erickson as a source of data for ammonia toxicity for Daphnia. One of the few references that give any data for toxicity for a time period of less than 48 hours.

220. Thirumurthi D. (1974) "Design criteria for waste stabilization ponds." *J. Water Pollut. Control Fed.* **46**(9), 2094-2106.
Keywords: BOD, COPY, DESIGN, DESIGN COEFFICIENT, LAGOONS, LIGHT, SWAIN, TEMPERATURE, TOXICITY
Comments: cited in 536.

221. Thomann R. V. (1982) "Verification of water quality models." , 923-940.
Keywords: INCOMPLETE, COPY, EUTROPHICATION, HATHAWAY, MODEL, OXYGEN, VERIFICATION
Comments: From CME 8550 class references. Discusses the theoretical aspects of the process of model verification, including statistical analysis.

222. Thomann R. V., and Mueller J. A. (1987) *Principles of Surface Water Quality Modeling and Control.* Harper & Row, New York.
Keywords: ALGAE, COPY, FOOD, HATHAWAY, HYDRODYNAMICS, LIGHT, MODEL, NITROGEN, PHOSPHORUS, ZOOPLANKTON
Comments: Good text on various water quality modeling considerations. Describes several approaches to zooplankton and algae modeling.

223. Thomas P. R., and Phelps H. O. (1987) "Study of upgrading waste stabilization ponds." *WST* **19**(1-2), 77-83.
Keywords: ALGAE, BOD, COLIFORMS, D.O., HATHAWAY, HYACINTHS, LAGOONS, NEED, PH, SS
Comments: Use of water hyacinths to upgrade ponds.

224. Thurston R. V, Russo R. C., and Emerson K. (1977) *Aqueous Ammonia Equilibrium Calculations.* Fisheries Bioassay Laboratory, Montana State University. Technical Report No. 74-1, Bozeman, Montana.
Keywords: AMMONIA, LAGOONS, PH, SWAIN, TEMPERATURE, TOXFILE
Comments: NH3 is the toxic species. NH4+ is nontoxic. pH 7=.4%. pH 8=3.8%. pH 9=28.4% pH 9.5= 55.7% pH 10=79.9%.

225. Thurston R. V, Russo R. C., Fetterolf C. M. Jr., Edsall T. A., and Barber Y. M. Jr., eds. (1979) *A Review of the EPA Red Book: Quality Criteria for Water.* American Fisheries Society, Bethesda, Maryland.
Keywords: AMMONIA, H2S, #LAGOONS, MERCURY, MPCA LIBRARY, REVIEW, SELENIUM, SWAIN
Comments: pca library 58.01.

226. Todd J. (1988) "Design ecology solar aquatic wastewater treatment." *BioCycle* **29**(2), 38-40.
Keywords: ALGAE, HATHAWAY, INNOVATIONS, LAGOONS, MARTHA'S VINEYARD, NARRANGANSETT BAY, NEED, POND DESIGN, SOLAR RADIATION, SUGARBUSH, WASTEWATER, ZOOPLANKTON
Comments: looks like a non-technical overview of pond function, but discusses interesting applications and refinements made in resort areas.

227. Towne W. W., Bartsch A. F., and Davis W. H. (1957) "Raw sewage stabilization ponds in the Dakotas." *Sewage Ind. Wastes* **29**(4), 377-396.
Keywords: COPY, DIURNAL, LAGOONS, LIGHT, NORTH DAKOTA, OXYGEN, SOUTH DAKOTA, STRATIFICATION, SWAIN, TEMPERATURE
Comments: Cited in 528. Surprisingly good paper. Diurnal data for 3 days. Oxygen and chlorophyll data 0 to 50 inches, 6 samples, morning to evening.

228. Trussell R. P. (1972) "The percent un-ionized ammonia in aqueous ammonia solutions at different pH levels and temperatures." *J. Fish. Res. Bd. Can.* **29**, 1505-1507.
Keywords: AMMONIA, COPY, HATHAWAY, IONIZATION, PH, TEMPERATURE, TOXICITY
Comments: Gives a method for calculating un-ionized ammonia depending on temperature and pH. Was adapted for use in pond modeling.

229. Tseng I., and Wang S. C. (1986) "Effective control of algae problems with copper sulfate in a reservoir." *WS* **4**(1), 131-139. (proceedings of the 5th Water Supply Conference of the Asian Pacific Region of IWSA; Seoul, South Korea)
Keywords: INCOMPLETE, ALGACIDE, ALGAE, BLOOMS, CHINA, COPPER, COPPER SULFATE, HATHAWAY, NEED, RESERVOIRS, SUCCESSION, TREATMENT
Comments: Treatment of a large reservoir in China with CuSO4 is discussed, along with results and effects on the water ecology. Claims that copper levels in the reservoir diminished by 50% after only 2 days.

230. Uhlmann D. (1967) "Beitrag zur Limnologie saprotropher Flachgewasser." *Arch. Hydrobiol.* **63**(1), 1-85.
Keywords: COPY, DAPHNIA, HATHAWAY, MORTALITY, OXYGEN, TOXICITY
Comments: This is the paper that Dinges based his oxygen requirement ideas upon; Dinges' oxygen chart is essentially a duplication of one that appears in this article. The article is in German. Referenced in Dinges.

231. Uhlmann D. (1979) "BOD removal rates of waste stabilization ponds as a function of loading, retention time, temperature and hydraulic flow pattern." *Water Res.* **105**, 193-200.
Keywords: BOD, COPY, LAGOONS, LOADING, RETENTION TIME, SWAIN, TEMPERATURE

232. Uhlmann D., and Wegelin R. (1966) *Oxydationsteiche, theorie, betriebserfahrungen, hinweise fur bau und betrieb.* WTZ - Mitteilungen Wiss. Techn. Zentrum Liepzig VVB, Leipzig (East Germany).
Keywords: ALGAE, DAPHNIA, FEEDING, HATHAWAY, LAGOONS, NEED, OXYGEN, SS, TOXICITY
Comments: The oxygen toxicity reference; the other Uhlmann being the "klarwasserstadium" paper.

233. U. S. E.P.A (1976) *Quality Criteria for Water.* U.S. Environmental Protection Agency, Washington, D.C.
Keywords: AMMONIA, DINDORF, H2S, #LAGOONS, MERCURY, REVIEW, SELENIUM, SWAIN, TOXICITY

234. U.S. EPA, ed. (1983) *Design manual: Municipal wastewater stabilization ponds.* U.S. Environmental Protection Agency, Washington, DC, EPA-625/1-83-015.
Keywords: ALGAE, ALKALINITY, AMMONIA, BACTERIA, BOD, COPY, D.O., DESIGN, LAGOONS, LIGHT, LUCK, NITROGEN, NUTRIENTS, PH, PHOSPHORUS, SULFUR, TEMPERATURE, TREATMENT, WASTEWATER
Comments: Nice general summary of pond processes. Good section on definitions and nomenclature of pond operation regimes.

235. U.S. EPA (1984) *Ambient water quality criteria for ammonia - 1984.* United States Environmental Protection Agency, Washington D.C., prepared by the Office of Water Regulations and Standards).
Keywords: AMMONIA, COPY, D.O., DAPHNIA, HATHAWAY, PH, TOXICITY
Comments: Actually, Judy Helgen has the copy; I have only a few pages copied. Gives information on ammonia toxicity to daphnia under controlled laboratory situations. Chronic, acute, magna, pulex.

236. U.S. E.P.A (1985) *Ambient Water Quality Criteria for Ammonia--1984.* U. S. Environmental Protection Agency EPA 440/5-85-001, Duluth, MN.
Keywords: AMMONIA, DAPHNIA, LAGOONS, PH, REVIEW, SWAIN, TEMPERATURE, TOXFILE, TOXICITY, ZOOPLANKTON
Comments: The concentration of NH3 increases with increasing pH and with increasing temperature. LC50's for Daphnia magna (similar to Daphnia pulex) ranged from 2.4 to 2.8 mg/L in water of pH 8 to 8.2 (chronic test).

237. U. S. E.P.A (1986) *Quality Criteria for Water 1986.* U.S. Environmental Protection Agency 440/5-86-001, Washington, D.C.
Keywords: AMMONIA, DINDORF, H2S, #LAGOONS, MERCURY, REVIEW, SELENIUM, SWAIN, TOXICITY

238. Vanni M. J. (1984) Biological control of nuisance algae by Daphnia pulex: experimental studies. In *Lake and Reservoir Management. Proceedings of the Third Annual Conference*, pp. 151-156. U. S. Environmental Protection Agency, Washington, D.C.
Keywords: INCOMPLETE, ALGAE, CHLOROPHYLL, COPY, DAPHNIA, EQUILIRACTIONATION, EXPERIMENT, GRAZING, LAGOONS, PULEX, SWAIN, TP, ZOOPLANKTON
Comments: Daphnia pulex had a dramatic effect on phytoplankton abundance in Larimore Pond. Apparently an equilibrium was reached between D. pulex grazing and phytoplankton abundance--D. pulex never approached extinction.

239. Vanni M. J. (1988) "Freshwater zooplankton community structure: introduction of large invertebrate predators and large herbivores to a small-species community." *Can. J. Fish. Aquat. Sci.* **45**, 1758-1770.
Keywords: BOSMINA, CHAOBORUS, COPY, DAPHNIA, DIAPHANOSOMA, ELA, EXPERIMENT, #LAGOONS, SWAIN, ZOOPLANKTON
Comments: This experiment supports previous hypotheses that invertebrate predation may be a very important determinant of freshwater zooplankton community structure.

240. Vennes J. W. (1970) State of the art--oxidation ponds. In *2nd International Symposium for Waste Treatment Lagoons*, (ed. McKinney R. E.), pp. 366-376. Missouri Basin Engineering Health Council & Federal Water Quality Administration, Lawrence, Kansas.
Keywords: COPY, LAGOONS, RESEARCH NEEDS, SWAIN, THEORY

241. Verma A. M., Dudani V. K., Kumari B., and Kargupta A. N. (1988) "Algal population in paper mill waste water." *Ind. J. Env. Health* **30**(4), 388-390.
Keywords: ALGAE, HATHAWAY, LAGOONS, NEED, PH, WASTEWATER
Comments: Identifies 26 algal species in an industrial effluent with high pH, toxic materials including phenols.

242. Vincent W. F., and Silvester W. B. (1979a) "Growth of blue-green algae in the Manukau (New Zealand) oxidation ponds. I. Growth potential of oxidation pond water and comparative optima for blue-green and green algal growth." *Water Res.* **13**, 711-716.
Keywords: ALGAE, ANABAENA, BLUEGREENS, CHLORELLA, COPY, GREENS, LAGOONS, PH, SWAIN, TEMPERATURE

243. Vincent W. F., and Silvester W. B. (1979b) "Growth of blue-green algae in the Manukau (New Zealand) oxidation ponds. II. Experimental studies on algal interaction." *Water Res.* **13**, 717-723.
Keywords: ALGAE, ALLELOPATH, ANABAENA, BLUEGREENS, CHLORELLA, COPY, LAGOONS, MICROCYSTIS, SWAIN

244. Vonshak A., and Richmond A. (1988) "Mass production of the blue-green alga Spirulina: an overview." *Biomass* **15**(4), 233-247.
Keywords: ALGAE, BLUEGREENS, HATHAWAY, LAGOONS, NEED, NUTRIENTS, PRODUCTION
Comments: Discusses factors important to the commercial production of algae.

245. Waddington J. I. (1963) "Munich fish ponds." *J. Inst. Sew. Purif.* 7, 214-215.
Keywords: CARP, COPY, FISH, GERMANY, LAGOONS, MUNICH, SWAIN
Comments: Human consumption (circa 1963).

246. Walters C. J., Krause E., Neill W. E., and Northcote T. G. (1987) "Equilibrium models for seasonal dynamics of plankton biomass in four oligotrophic lakes." *Can. J. Fish. Aquat. Sci.* **44**, 1002-1017.
Keywords: ALGAE, COPY, DAPHNIA, FILTERING, FISH, HATHAWAY, MODEL, PREDATION, PRODUCTION, ZOOPLANKTON
Comments: Observed cyclical patterns in zooplankton populations, tried to model them. Discusses the lack of predatory effects on zooplankton biomass. Suggests using zooplankton biomass as a measure of primary productivity, rather than chla data.

247. Wetzel R. G. (1983) *Limnology*, 2nd ed. Saunders College Publishing, Philadelphia.

Keywords: AMMONIA, BACTERIA, COPY, DAPHNIA, HATHAWAY, LIMNOLOGY, MIGRATION, NITROGEN, OXYGEN, PHOSPHORUS, SULFUR
Comments: Definitive text on limnology.

248. Whittaker R. H. (1975) *Communities and Ecosystems*, 2nd ed. Macmillan, New York.
Keywords: HATHAWAY, LOTKA, NUTRIENTS, PHOSPHORUS, POPULATION, PREDATION, PRODUCTION
Comments: In St.Paul library: 574.55 W617 1975

249. Wrigley T. J., and Toerien D. F. (1990) "Limnological aspects of small sewage ponds." *Water Res.* **24**(1), 83-90.
Keywords: ALGAE, AMMONIA, CHLOROPHYLL, COPY, HATHAWAY, LAGOONS, LIMNOLOGY, NITROGEN, PHOSPHORUS, TREATMENT, ZOOPLANKTON
Comments: Seems to discuss mainly changes in pond chemistry with time; I don't see the limnology part from the abstract. Focuses on the algal growth and its needs. Links euglenoid blooms with Daphnia population surges - a phenomenon also seen at Harris, MN ponds.

250. Youngberg B. (1977) *Center for Ecological Modeling Reports, Application of the aquatic model CLEANER to a stratified reservoir system*.,, Report No. 1. (EPA R 8050-47010, 6803-2142, NSF DEB 75-14168 A01)
Keywords: INCOMPLETE, ALGAE, BLUEGREENS, BOD, CLEANER, D.O., FISH, HATHAWAY, HYDRODYNAMICS, MODEL, NEED, NITROGEN, NUTRIENTS, PHOSPHORUS, ZOOPLANKTON
Comments: Discusses the model CLEANER in terms of its application to a reservoir in Czechoslovakia. Says the model falls short in its hydrodynamic representations, but is good biologically.

251. Zaret T. M. (1978) "A predation model of zooplankton community structure." *IVTAL* **20**(4), 2496-2500. (Proceedings of Congress in Denmark, 1977)
Keywords: ALGAE, CRUSTACEANS, ECOLOGY, FISH, FOOD, GRAZING, HATHAWAY, MODEL, NEED, NUTRIENTS, PREDATION, ZOOPLANKTON
Comments: This is a predation model, listing predators according to type and size of prey selected. Predicts zooplankton and fish composition according to predation chain. Could be useful in identifying predation parameters.

252. Zison S. W., Mills W. B., Deimer D., and Chen C. W. (1978) *Rates, constants, and kinetics formulations in surface water quality modeling*. US EPA, Athens GA, EPA Report number 600/3-78-105, December 1978.
Keywords: ALGAE, COPY, FOOD, GRAZING, GROWTH, HATHAWAY, MODEL, POPULATION, TEMPERATURE, ZOOPLANKTON
Comments: A compendium of rates and coefficients used in aquatic modeling.