PRESENT AND PAST NUTRIENT DYNAMICS
OF A SMALL POND IN SOUTHWEST FLORIDA

BY

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A DISSERTATION PRESENTED TO THE GRADUATE COUNCIL OF THE
UNIVERSITY OF FLORIDA
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

1979

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Abstract of Dissertation Presented to the Graduate Council
of the University of Florida in Partial
Fulfillment of the Requirements for the Degree of
Doctor of Philosophy

PRESENT AND PAST NUTRIENT DYNAMICS
OF A SMALL POND IN SOUTHWEST FLORIDA

By

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June, 1979

Chairman: Edward S. Deevey, Jr.
Major Department: Botany

Nutrient dynamics of a small pond in southwest Florida were modeled in space and time. The primary storage compartment of the system is the sediments, and the primary sources and sinks for nutrients are the atmosphere and ground water. Of the 93 g yr^{-1} of phosphorus entering the pond, primarily as bulk precipitation, approximately 69 percent is stored within the system and the remainder leaves through the ground water. About 2400 g of nitrogen enter the pond annually, and of this, 12 percent and 5 percent exit the system via the atmosphere and ground water, respectively.

The pond's age, determined by radiocarbon dating, is approximately 5000 years, and during this time the sediments have accumulated 124 kg of phosphorus and 3,140 kg of nitrogen. The atmosphere and ground water have made a net contribution (input minus output) of about 124 kg of phosphorus and 3600 kg of nitrogen during the past 5000 years, based on present-day rates and estimated changes in the sizes of the

receiving surfaces. The remainder, in the case of nitrogen, is assumed to be atmospheric loss.

The importance of the groundwater sink for phosphorus is demonstrated, and its potential role as a nutrient input source for surface-water discharge boundaries is discussed.

Comparison of the annual atmospheric phosphorus input rate to the results of other researchers seems to indicate that the present-day rate may be spatially constant for undisturbed regions. The 5000-year budget for the study pond indicates that the preindustrial atmospheric phosphorus input rate was about $27 \text{ mg m}^{-2} \text{ yr}^{-1}$, about 20 percent less than today's rate. This figure may be close to the preindustrial global rate.

Key words: Nutrient cycling; nutrient budgets; groundwater chemistry; bulk precipitation; sediment chemistry.

INTRODUCTION

One of the striking features of the pine flatwoods of southwest Florida is the number of rounded depressions or ponds which dot the landscape. For example, in Sarasota County, excluding the coastal strand, these ponds number an average of 15-20 per square mile. They range in size from a fraction of a hectare to many hectares. The ponds are shallow (one-half to a few meters deep, generally) and contain water much of the year. During the dry season (spring) only the deeper ponds retain water, but in the wet season (late summer) water may rise above the rims of the ponds and extend many meters into the pine flatwoods proper. Because of their relatively small size and closed basins, these ponds are promising subjects for nutrient budgeting considerations.

Urbanization in this part of southwest Florida has been extremely rapid with population growth rates approaching 6 percent per year in 1974 and 1975. It has been suggested that as the pine flatwoods are developed, the numerous ponds could be maintained in a somewhat natural condition and that urban runoff could be channeled into them and held until natural processes reduce nutrient concentration in the water column. In addition, the ponds would be connected by swales, and a natural buffer zone would be retained around them to provide a functional and aesthetically pleasing system.

Because of the interest in this concept, it is useful to gain a better understanding of the system dynamics of these ponds.

Of primary importance are the natural nutrient dynamics of the pond system including the relative sizes of the constituent components. In any future modeling of treatment capabilities, these baseline parameters are of critical importance. Secondly, assuming the ponds are natural nutrient accumulators, it is important to know if the pond system is tight, that is, do those nutrients which accumulate remain bound within the system "forever" or does the system release them? Thirdly, how has "flow through" changed over the life of the system and what are the implications of these changes with respect to system development?

This study is designed to answer these questions and is organized in the following manner. The present-day setting, environmental history and recent environmental trends are presented as background information. The next chapter discusses the primary input to the pond system, i.e., bulk precipitation. Ground water, which is the means by which a conservative nutrient, such as phosphorus, would leave the system, is discussed at this point. The following three chapters address the sizes and some interrelationships of the pond system storage compartments. The next chapter deals with the interaction between the major storage compartment, sediments, and groundwater output. In the next to last chapter the present-day nutrient budget, which is derived from elements of the previous chapters, is illustrated and discussed. Also in this chapter the derivation of the "lifetime" budget of the pond is presented and the "lifetime balance sheet" is discussed. The final chapter addresses some basic considerations about nutrient cycling, past and present, and ecosystem development of the pond system.

BACKGROUND

The Present Environment

Description, Location and Regional Physiography

The study pond is located in southern Sarasota County, Florida, between the Peace and Myakka Rivers. It is 2.9 km north of the Charlotte County line and 400 m east of Myakkahatchee Creek (Big Slough) (Figure 1). Its Mercator Projection coordinates are 27° 03' 33" north latitude and 82° 13' 31" west longitude. The region is in the coastal lowlands part of the Floridian section of the Coastal Plain province (Fenneman, 1938). According to White (1970), this physiographic region is the Gulf Coastal Lowlands of the Mid-Peninsular Zone. The province is extremely flat with a very gentle slope in a generally southwestern direction. In the immediate vicinity of the study pond, the slope is to the south-southwest at an approximate rate of one meter per thousand. The province is bordered on the north and east by the DeSoto Plain; on the south by the Immokalee Rise and Southwestern Slope; and on the west by the Gulf Coastal Lagoons, Gulf Barrier Chain, and the Gulf of Mexico. The Gulf Coastal Lowlands reach their maximum areal extent in this part of the state where, in the Caloosahatchee Valley, they follow the valley all the way to Lake Okeechobee. From the Caloosahatchee Valley, the Lowlands gradually narrow northward until near Bradenton, Florida, they are only about 15 km wide (White, 1970).

Figure 1. Location of the study pond.

Climate

The climate of the region is typified by warm, somewhat humid summers of long duration and short, mild winters with occasional invasions of cool northern air (Bradley, 1972). This climatic type was classified by Trewartha (1961) as humid mesothermal, humid subtropical subgroup and by Thornthwaite and Mather (1955) as moist, subhumid with a moisture surplus of 0 - 20 percent. The dominant factors controlling the climate are latitude and proximity to the Atlantic Ocean and Gulf of Mexico (Bradley, 1972).

Solar radiation for the region, according to Landsberg (1961), amounts to nearly $160 \text{ Kcal cm}^{-2}\text{yr}^{-1}$ at the surface and about half is stored as net radiation (Budyko et al., 1962). The mean annual temperature at Fort Myers, Florida, for the period 1937-1976 was 23.3°C ; the mean January temperature for that period was 18.1°C and mean July temperature, 27.9°C . Relative humidity year-round is usually 80-90 percent at night and decreases to 50-60 percent in the early afternoon. The mean summer wind speed is 11.6 km hr^{-1} , and mean dry season wind speed is 13.9 km hr^{-1} . From October through December, the direction of the prevailing wind is from the northeast; and for the remainder of the year from the east (NOAA, 1976). The mean annual precipitation at Fort Myers from 1937-1976 was 135.5 cm, 65 percent of which fell during the summer months (June through September). An average of 95 thunderstorm-days occurred each year with 78 percent of these in the summer months (NOAA, 1976).

The thunderstorm frequency during the summer months in peninsular Florida reaches a maximum for the United States and possibly for the entire earth (Trewartha, 1961). This phenomenon, according to Byers

and Rodebush (1948), results from strong low-level convergence caused by afternoon sea breezes moving into the peninsula from both east and west. This double sea breeze convergence stimulates the vertical growth of convective clouds. The convergence prevails up to an altitude of about 1,200 m with a maximum reached in the late afternoon when the two-sided sea breeze is usually strongest (Trewartha, 1961).

Tropical storms have, at times, contributed a significant amount of precipitation to the region. Court (1974) estimates that tropical storms from 1931-1960 accounted for 10-15 percent of the June to October rainfall in peninsular Florida. The chance of a storm of hurricane intensity striking the Fort Myers area in any given year has been estimated by Bradley (1972) to be 1 in 11.

Geology and Geomorphology

The sandy flatlands, as Parker and Cooke (1944) have called the region, are poorly drained and dotted with shallow ponds (Figure 2). These ponds are often nearly circular in shape, with diameters to a few hundred meters and are generally about one meter or so in depth. They occur in deep sands as well as in places where the sand mantle is thin. They may be related to solution of the underlying consolidated strata or to inequalities in the floor of a previously regressing sea (Parker and Cooke, 1944).

The surficial sands rest unconformably upon the Caloosahatchee Marl which in turn unconformably overlies the Tamiami Formation. The surficial sands are generally medium to fine grained, sometimes mottled, and with occasional fossiliferous members (Dubar, 1962; Brooks, 1966). The Caloosahatchee, a sandy, shell marl, indurated at the top

Figure 2. Generalized cross-sectional view of the study pond environs.

and containing abundant fossils, is generally less than one meter in thickness. Along the Myakkahatchee Creek, about 1 km NNE of the study pond, it is 60 cm thick (personal observation). The Tamiami is a fossiliferous, medium to coarse calcareous sand (Dubar, 1962; Brooks, 1966). The thickness of the Tamiami is undetermined here; however, it is most likely relatively thin since the underlying Hawthorne is known to outcrop a few kilometers to the north (personal observation; Vernon and Puri, 1964).

In recent years there has been considerable discussion about the ages and relationships of these strata. The following is a summary of Brooks' (1968) interpretation of the Plio-Pleistocene stratigraphy of the region. The Caloosahatchee Formation has two members. The Fort Denaud Member is late Pliocene age and corresponds to the Okeefenokee eustatic sea-level stand of +120-140 feet (36-43 m). The Bee Branch Member is Aftonian in age and corresponds to the Wicomico Sea which was at +90 to 100 feet (27-30 m). The surficial sands are divided into two formations. The Fort Thompson Formation (three members) is of Yarmouthian age and is related to the Penholoway (+70 feet, 21 m) and Talbot Terraces (+42 feet, 13 m). The Sangamonian age Pamlico Sea (+25 feet, 8 m) is represented by the Coffee Mill Hammock Formation. Apparently, the study pond has been above sea level since the Sangamonian interglacial period.

Soils

The dominant soil type in the sandy flatlands of the region is the Immokalee fine sand. This type is classified as a Ground-Water Podzol which is typified by a thin organic surface layer above a light grey,

leached layer that rests abruptly upon a black to dark greyish-brown B horizon (USDA, SCS, 1959). In the most recent soil classification system, this soil would be a sandy, siliceous, hyperthermic, arenic haplaquod (USDA, SCS, 1977).

The soil (sediment) of the study pond is classified as Delray fine sand in the center and Pompano fine sand in a concentric band between the center and the Immokalee fine sand of the sandy flatlands surrounding the pond. The Delray soil is a Humic Gley which is a poorly drained, hydromorphic group of soils with dark colored organic mineral horizons of moderate thickness underlain by mineral gley horizons. The Pompano soil belongs to the Low-Humic Gley group of soils. The group is characterized by poor drainage and a thin surface horizon moderately high in organic matter which overlies undifferentiated, mottled grey and brown, gley-like mineral horizons (USDA, SCS, 1959). In current soil taxonomy terminology, the Delray would be a loamy, mixed hyperthermic gross arenic argiaquoll, and the Pompano, an arenic or gross arenic ochraqualf (USDA, SCS, 1977).

In 1898, Dokuchaev first recognized the importance of several environmental factors in the formation of soils. Jenny (1941), elaborating on Dokuchaev's work, proposed the relationship that any soil property was a function of climate, organisms, relief, parent material, and time. The three soils of the study area dramatically illustrate this relationship. High rainfall and low relief dominate the soil forming processes for these soils. In combination, the two factors produce a groundwater table that is near the surface year-round. The three soils, however, represent a micro-environmental sequence of

relief which results in very different soil types. The surface of the Immokalee is about one meter above that of the Delray. The height of groundwater ranges from one to two meters below the surface of the Immokalee in the dry season to just above the surface during the rainy season. The same groundwater stand in the Delray is just above the surface to one-half meter below the surface in the dry season, and in the wet season a meter or more of surface water occupies the Delray depression. This phenomenon results in the leaching of the surface layers of the Immokalee soil as the dominant process and the accumulation of the leachates in the vicinity of the mean low water level. The acidity of the rainfall, as well as the acidity of the litter and leachate from the dominant plants, hastens the removal of organic matter and minerals from the surface layers of the Immokalee. In the Delray, however, the occurrence of standing surface water for much of the year minimizes oxidation and results in the accumulation of organic matter in the surface layers. However, in the dry years, especially with low winter rainfall, the water table drops below the surface and spodosolic processes may dominate in the Delray also. In the Pompano, neither process dominates and hence an intermediate soil type is formed.

None of the soils exhibit much pedogenic development. This is the result of the interaction of time and parent material. It is not known how long it takes for a well-defined soil profile to develop, and, perhaps, under the prevailing climatic and relief regimes of the study site, one could never develop. Other factors aside, the time required is directly related to the resistance to weathering of the parent material. The parent material of the study area soils is almost pure quartz sand (Dubar, 1962) which is a highly resistant substrate. These

materials have only been exposed to the agents of weathering since the regression of the Pamlico Sea (probably Sangamonian Age).

The Historical Environment

The pond system is four-dimensional, and the fourth dimension, time, may be the most critical for understanding the nature of the system. The agents of time are environmental conditions, which may be static or changing in the time frame of the pond's existence. Static conditions have a chronic effect upon the system, tending to drive it in one direction, and given sufficient time the end result will be the filling in or drying up of the pond with complete oxidation of sediments. Changing environmental conditions can have the same effect if the change is unidirectional, thereby intensifying the effects of static conditions. However, if the change is reversible, the effect will be preservation of the system as long as the period of any one direction does not exceed the system's capacity for resilience.

The pond system came into being about 5000 years ago (4565 ± 120 , University of Miami Radiocarbon Dating Laboratory--#UM1494). Since that time, it has been subject to the influences of sea level and climate as they affect groundwater height. Sea-level changes are the subject of much controversy today. Several authors (Shepard, 1963; Scholl and Stuiver, 1967; Milliman and Emery, 1968; Scholl et al., 1969) believe that sea level has risen continuously for at least the last 5000 years. The effect of a continuously rising sea level, and hence ground water, would be an increasing sedimentation rate. However, using the Scholl et al. (1969) curve, the increasing rate would be

decelerating for the past 5000 years and approaching stasis at the present.

A second group of investigators (Fairbridge, 1961; Mörner, 1969; Fairbridge, 1974) have indicated that sea level reached its present stand at about 6000 BP and has been fluctuating since then.

The effect of fluctuating sea level, and hence groundwater height, upon the pond would be to establish the sedimentary process as dominant during relatively high stands, but during low stands, an oxidizing environment would prevail and the pond would act more like a periodically flooded soil. The interaction of these two regimes would result in a pond system with a very slow net sedimentation rate. Several shallow Florida lakes and ponds are known to have very slow sediment accumulation rates, for example, Mud Lake's recent history, 0.39 mm yr^{-1} (Watts, 1971), Spanish Pond, 0.17 mm yr^{-1} (Deevey and Brenner, unpublished), and Site No. GDF-125, 0.2 mm yr^{-1} (Clausen et al., 1979).

Climatic fluctuations, instead of sea-level changes, may explain the peculiar sedimentary histories of these ponds. During periods of high precipitation and low evaporation, the sedimentary system would dominate in the pond and, the reverse being true, the oxidation process would dominate. It can be inferred from Denton and Karlen (1973) and LaMarche (1974), among others, that there have been alternating warm and cool periods during the late Holocene. The link between cooler temperatures and decreased precipitation is fairly well documented in late-glacial times (Damuth and Fairbridge, 1970; Bonatti and Gartner, 1973; Parmenter and Folger, 1974; Williams et al., 1974; Deuser et al., 1976; Gates, 1976), and Simpson and Hebert (1973) and Moran (1975) believe that in peninsular Florida this link may be due to the

inhibitory effect of decreased sea-surface temperatures on hurricane formation. From recent work in the Caribbean and equatorial Atlantic, several researchers have, in fact, reported differences in paleotemperatures ranging from 2 to 6°C, between glacial and nonglacial stages (Emiliani, 1966; Shackleton, 1967; Dansgaard and Tauber, 1969; Lynts and Judd, 1971). A decrease in hurricane activity would not only result in decreased precipitation but also a decrease in cloud cover during the high evaporation season of summer and early autumn.

Seasonal variation in precipitation and evaporation, apart from long-term climatic or sea-level changes, may be the dominant causal agent in the sedimentation pattern of the pond. A wet and dry cycle with the very short period of one year would have the same effect on total accumulation as long-term cycles.

It seems likely that some combination of seasonal and long-term climatic and sea-level changes have caused variations in groundwater heights which have resulted in an alternating accumulation-decomposition system in the pond. Following Scholl et al., (1969), sea-level rise would be a unidirectional environmental change in the experience of the pond. Long-term climate, on the other hand, is bidirectional and contains the nested bidirectional set, seasonal variation.

The influence of these patterns on the past nutrient dynamics of the pond has probably been considerable. It is evident that in the decomposition mode nitrogen and phosphorus would become available for exchange between components of the system. Perhaps less obvious is the fact that with changing groundwater heights, the sizes of the interfaces between components would also change and, hence, so would rates of exchange.

Recent Trends

We have seen that environmental conditions have been different in the past, and it is interesting to speculate on what may be in the future for this region. The pattern of glacial and interglacial cycles is well documented (Prell, 1974; Shackleton and Opdyke, 1973; Imbrie et al., 1973; Kukla, 1970; Hays et al., 1969) as is the pattern of cold and warm periods between major events, especially in recent times (LaMarche, 1974; Dansgaard et al., 1971; Lamb, 1969; 1966). According to Mitchell (1963; 1972), Reitan (1971), and Bryson (1974), we are headed toward another cool period. Whether it is just a cool fluctuation or a more pronounced cold period is unknown, as are the effects of man-made interferences.

The annual mean temperature change at Tampa, Florida, was compared to the average change for the Northern Hemisphere (Reitan, 1971; Mitchell, 1972) with relatively good agreement. The Tampa record extends sporadically into the 1820's, but no records exist from the late 1850's to the mid-1880's. From the available record, it can be seen that temperatures rose rather rapidly in the 1840's; there was a decline around the turn of the century and then another relatively rapid rise; a leveling-off occurred in the 20's and 30's and then a slight rise in the 1940's; and finally a post-1950 decline. Bryson (1974) has described the 1940's as a period of unprecedented warmth in the past millenium and both the Tampa and Northern Hemisphere curves seem to substantiate this claim for recent times.

With this in mind, the post-1950 temperature regimes for six peninsular Florida stations were compared to the 1940's thermal maximum (Table 1). The annual mean temperature for peninsular Florida

Table 1. Departure of post-1950 mean temperatures from pre-1950 means and some influencing factors at six stations in peninsular Florida.

Station	Years of Record	Departure of Annual $\bar{x}$ in $^{\circ}\text{C}$	Departure of Winter $\bar{x}$ in $^{\circ}\text{C}$ (Dec.-Feb.)	Departure of Summer $\bar{x}$ in $^{\circ}\text{C}$ (June-Aug.)	$\bar{x}$ Annual Long-wave Radiation Flux Ly day^{-1}	$\bar{x}$ Winter Long-wave Radiation Flux Ly day^{-1}	$\bar{x}$ Summer Long-wave Radiation Flux Ly day^{-1}
Tampa	39	-0.50	-1.28	-0.22	899	823	963
Orlando	39	+0.03	-0.28	+0.11	898	828	966
Ft. Myers	39	-0.28	-0.67	-0.06	911	846	966
W. Palm Beach	37	-0.28	-0.72	-0.11	917	860	963
Miami	36	+0.33	+0.11	+0.17	919	869	966
Key West	39	+0.01	-0.33	+0.06	935	889	979
$\bar{x}$		-0.12	-0.53	-0.01	913	853	967

DATA SOURCE: NOAA, 1976; Chang, 1971.

decreased by 0.12°C , but the winter temperature declined by 0.53°C and the summer by only 0.01°C .

One possible scenario for this pattern of temperature decline is the interaction between long-wave radiation flux and the CO_2 content of the atmosphere. Rasool and Schneider (1971) have shown that temperature increases as the logarithm of atmospheric CO_2 content, and Machta (1971) and Machta and Telegadas (1974) have shown a rapid rate of increase in CO_2 content in the last 40 years. Dansgaard et al. (1971) believe that, as indicated by the Camp Century ice core cycles, we should be in a cooling period, but Broecker (1975) says that the increase of CO_2 in the atmosphere has interfered with the natural cycle and modified the decline in temperature. This interference may be more significant in the summer when the long-wave radiation flux is 13 percent greater than in winter in peninsular Florida (Table 1). As a result, summer temperatures have changed little, but winter temperatures have declined at about the rate predicted by the Camp Century core. The net result is an annual change very close to that predicted by Broecker's (1975) combined effect of CO_2 and the Camp Century cycles.

Hydrologic evidence from peninsular Florida indicates that a dry period is approaching. Moran (1975) and Coleman (in preparation) have demonstrated that peninsular Florida has experienced unusually arid conditions in recent times and have attributed these to the decline in hurricane activity (Hope, 1975) in recent years due to a drop in low latitude sea-surface temperatures and persistently stronger upper-level westerlies over the Caribbean Sea (Simpson and Hebert, 1973). Supportive evidence of this hypothesis can be found in the

decline in river flow volumes in peninsular Florida. Coleman (in preparation) established that a sharp decrease in river flow in the Peace and Kissimmee Rivers had begun in the early 1960's. In addition, ten rivers, representing a combined drainage area of over 20,000 km² and a range in period of record from 27 to 46 years, were compared using post- and pre-1960 averages. The result was a 16-38 percent decrease in flow after 1960 (USGS, 1978). The implication is that peninsular Florida is experiencing drought conditions when compared to recent records.

A link between temperature and precipitation changes is evident at Tampa, Florida (Figure 3). A rapid warming occurred in the 1840's followed 40 years later by a substantial increase in precipitation. Temperature declined in the 1890's and precipitation 10 years later. This same pattern reappears later with temperature increasing rapidly from 1900-1920 and decreasing in the 1950's. Precipitation increase lags temperature again by 40 years and the decrease by only 10. Apparently, the response time for temperature-linked precipitation increase is about 4 times the response time for decreases.

With regard to the sea-surface temperature/hurricane activity hypothesis, it appears that the warming of the sea surface is a slower process than cooling. It is interesting to note that there has been little change in summer air temperatures in peninsular Florida in the last 40 years, but there has been a one-half degree centigrade drop in winter temperatures (Table 1). Since there has been little change in summer temperatures, it would seem that the evaporative and convective forces which control the growth of thunderstorms may not have changed.

Figure 3. Ten-year annual mean temperature (—) and precipitation (---) changes at Tampa, Florida (NOAA, 1976; U. S. Weather Bureau, 1933).

This indirectly tends to support the sea-surface temperature/hurricane hypothesis.

In summary, peninsular Florida appears to be cooling and drying with man-made factors interfering with the trend.

BULK PRECIPITATION

Introduction

The atmospheric input of nutrients to aquatic systems has been considered insignificant in relation to that contributed by terrestrial runoff. However, with increasing atmospheric pollution from various man-made sources, this may no longer be valid (Wetzel, 1975). Gambell and Fisher (1966) suggested that in areas where surface waters are low in dissolved materials, atmospheric inputs may be a major determinant of chemical composition. Likens and Bormann (1972) found that in some relatively oligotrophic, mountainous regions atmospheric fallout is a major contributory source of nutrients. At Lake Weir, Florida, the rainfall input of phosphorus and nitrogen was estimated to be about 15 percent of all surface runoff (Brezonik and Messer, 1977). In the sandy flatlands of Southwest Florida where topographic relief is almost totally absent, surface runoff is insignificant and groundwater movement is extremely slow. Atmospheric bulk precipitation (rainfall and dry fallout) is expected to be the major source of nutrient input to the small ponds of this region.

Methods

The sampling of bulk precipitation is subject to two major sources of error in the field: error due to poor sample preservation and that due to biological contamination. In order to have confidence in

nutrient analyses, EPA (1974) states that samples should not be held for more than 24 hours. Therefore, unless a daily sampling program is instituted, sample preservation can be a problem. Some researchers have attempted to circumvent this problem by employing refrigerated samplers (Gambell and Fisher, 1966; Pearson and Fisher, 1971; Mattraw and Sherwood, 1976). Refrigerated samplers are generally based on a modification of one described by Gambell and Fisher (1966) and consist of a glass funnel connected to a reservoir by tubing. The reservoir is contained in a commercial refrigeration unit or ice chest, and the temperature is artificially maintained at about 4°C. These collectors are expensive to install and maintain, and the samples, according to EPA (1974), should still not be held for more than 24 hours. In addition, the funnel is not the best receptacle for dry fallout. Dry particles falling on a dry surface are subject to removal by wind action.

In my study, due to economic constraints and the uncertainty of refrigerated preservation, I decided to use open polyethylene buckets with several centimeters (actual amount depended on the season) of acidic water in them. The pH (3.9) of this water was the same as the mean pH, i.e., $\bar{x}$ of $-\log [H^+]$, of the study pond. This pH was obtained by adding 0.01 N HCl to distilled, deionized water. The rationale behind this method is that, although the ponds and buckets differ considerably in physical, chemical and biological properties, by mimicking the acidity the receptacles could approach the functional regime of the pond. With respect to phosphorus, this method was considered to be adequate. Since phosphorus does not have a gaseous phase and since the particulate and soluble phases of total phosphorus

are used to determine the final number, the interchange between these two components was considered for this study to be unimportant. As for total nitrogen, the results should be viewed more critically. In the absence of clear knowledge of the interplay between gaseous and soluble phases of nitrogen, I cannot be sure that nitrogen exchange was not occurring at the air-water interface, and hence the nitrogen results should be interpreted as indicative of nitrogen inputs.

With regard to biological contamination due to bird feces, it was predetermined to discard those samples that were apparently contaminated. Samples with insects in them were analyzed to be compared with those without insects to see if there was a consistent and significant difference. Chlorophyll content was measured in several samples as a check for algal contamination.

Six bulk precipitation collectors were installed in duplicate on wooden platforms about 1.5 m above the ground surface at three sites in the study area. Two side-by-side collectors were installed in the study pond, two in the sandy flatlands about 20 m from the western edge of the pond and two in downtown Port Charlotte about 18 km southeast of the study pond.

Samples were collected biweekly from the beginning of June to the end of October, 1978. Samples were transported, on ice, to the laboratory where they were filtered immediately. The filter papers were oven dried and stored in jars to await sediment analysis. The filtrate was analyzed for nutrients by the following methods:

for TP: Persulfate digestion
Automated Colorimetric Ascorbic Acid
Reduction Method (EPA, 1974)

for TKN: Sulfuric acid digestion
Automated Selenium Method (EPA, 1974)

for $\text{NO}_3 + \text{NO}_2$: Automated Cadmium Reduction Method (EPA, 1974)

Filter papers and filter paper blanks were digested on a block digester in Fisher^R high temperature bath oil. The oil is used to allow uniform heating of the digestion tubes. The filters were digested by the sulfuric acid-hydrogen peroxide method (modified from EPA, 1974; see discussion in chapter on sediments). The digested sample was then analyzed by the same methods as the solution phase.

Concentration raw data were converted to $\text{mg m}^{-2} \text{yr}^{-1}$ by the following formula:

$$N (\text{mg m}^{-2} \text{yr}^{-1}) = \frac{C (\text{mg l}^{-1}) \times V (\text{l}) \times 10,000 \text{ cm}^2 \text{ m}^{-2} \times 365 \text{ days yr}^{-1}}{A (\text{cm}^2) \times D (\text{days})}$$

where:

N = amount of nutrient

C = concentration of nutrient

V = field volume for solution phase; digestion tube
volume for particulate phase

A = area of the plane defined by the top of the
receptacle ($374.11 \pm 1.72 \text{ cm}^2$)

D = number of days sample was exposed to the
atmosphere

Results

The nutrient data were averaged over the sampling period with the result that one number was obtained for each phase (solution, particulate and total) in each of the six collectors (raw data appear in Appendix, Tables A-1 - A-6). Several samples, however, were less than

detection limits, and these presented somewhat of a problem. The first impulse is to exclude them from the mean. However, this has the effect of establishing an unrealistically high mean since all the excluded values are at the low end of the range. A better estimate of the true mean can be achieved by including them. But what is the best way to deal with values that are less than detection limits? The best estimate of the true values for these samples can be obtained by narrowing the range as much as possible and then taking the midpoint. The range was narrowed, in the case of phosphorus, using the orthophosphate phosphorus value as the low end of the range when this value was above detection limits. As for nitrogen, the low end was established by the total value of ammonia and nitrate+nitrite when these were above detection limits. In some cases, the measured constituents of total phosphorus and total nitrogen were also less than detection and zero was used as the low end of the range.

The first priority of data analysis was to determine if statistical differences existed between duplicate collectors. The differences between the mean of duplicate collectors were compared using a t-test. At an α of 0.05 there is no difference between duplicate collectors at any of the three sites for either phosphorus or nitrogen (Tables 2-7). Based on this conclusion, duplicate collectors were lumped at each site, increasing the N (number of samples), and thereby allowing for more sensitive intersite comparisons.

The next question to consider is: Do the ponds receive different amounts of phosphorus and nitrogen than the sandy flatlands? To answer this question, the new means, achieved by averaging the results from intrasite collectors, were compared using the t-test of the

Table 2. Comparison of total phosphorus ($\text{mg m}^{-2} \text{yr}^{-1}$) in bulk precipitation collectors at Port Charlotte, Florida.

Phase	North Collector		South Collector		t	α
	$\bar{x} \pm s$	n	$\bar{x} \pm s$	n		
Solution	75.9 $\pm$ 43.6	8	52.3 $\pm$ 29.5	8	1.174	0.272
Particulate	46.8 $\pm$ 20.8	8	33.6 $\pm$ 19.9	8	1.297	0.220
TOTAL	122.7 $\pm$ 42.6	8	85.9 $\pm$ 33.7	8	1.916	0.080

Table 3. Comparison of total phosphorus ($\text{mg m}^{-2} \text{yr}^{-1}$) in bulk precipitation collectors in the study pond (North Port, Florida).

Phase	North Collector		South Collector		t	α
	$\bar{x} \pm s$	n	$\bar{x} \pm s$	n		
Solution	11.9 $\pm$ 6.0	9	9.8 $\pm$ 7.8	7	0.610	0.558
Particulate	20.6 $\pm$ 11.7	9	16.2 $\pm$ 6.8	7	0.882	0.394
TOTAL	32.5 $\pm$ 14.5	9	26.0 $\pm$ 10.3	7	1.002	0.344

Table 4. Comparison of total phosphorus ($\text{mg m}^{-2} \text{yr}^{-1}$) in bulk precipitation collectors in the sandy flatlands near the study pond (North Port, Florida).

Phase	East Collector		West Collector		t	α
	$\bar{x} \pm s$	n	$\bar{x} \pm s$	n		
Solution	21.3 $\pm$ 19.0	11	17.1 $\pm$ 11.2	11	0.632	0.539
Particulate	17.9 $\pm$ 14.5	11	14.2 $\pm$ 9.1	11	0.717	0.483
TOTAL	39.2 $\pm$ 26.0	11	31.6 $\pm$ 16.9	11	0.813	0.427

Table 5. Comparison of total nitrogen ($\text{mg m}^{-2} \text{yr}^{-1}$) in bulk precipitation collectors in Port Charlotte, Florida.

Phase	North Collector		South Collector		t	α
	$\bar{x} \pm s$	n	$\bar{x} \pm s$	n		
Solution	1,231 $\pm$ 269	8	1,470 $\pm$ 967	8	0.673	0.513
Particulate	238 $\pm$ 164	8	200 $\pm$ 166	8	0.461	0.664
TOTAL	1,470 $\pm$ 328	8	1,670 $\pm$ 989	8	0.543	0.606

Table 6. Comparison of total nitrogen ($\text{mg m}^{-2} \text{yr}^{-1}$) in bulk precipitation collectors in the study pond (North Port, Florida).

Phase	North Collector		South Collector		t	α
	$\bar{x} \pm s$	n	$\bar{x} \pm s$	n		
Solution	776 $\pm$ 300	9	571 $\pm$ 282	7	1.391	0.189
Particulate	77 $\pm$ 48	9	95 $\pm$ 71	7	0.606	0.561
TOTAL	853 $\pm$ 317	9	666 $\pm$ 298	7	1.201	0.260

Table 7. Comparison of total nitrogen ($\text{mg m}^{-2} \text{yr}^{-1}$) in bulk precipitation collectors in the sandy flatlands near the study pond (North Port, Florida).

Phase	East Collector		West Collector		t	α
	$\bar{x} \pm s$	n	$\bar{x} \pm s$	n		
Solution	752 $\pm$ 528	11	788 $\pm$ 559	11	0.155	0.880
Particulate	81 $\pm$ 92	11	76 $\pm$ 54	11	0.155	0.880
TOTAL	833 $\pm$ 546	11	864 $\pm$ 580	11	0.129	0.899

difference between two means. Once again, with an α of 0.05, no differences were observed in either phosphorus or nitrogen, and hence all four collectors at the two sites were combined to establish a new mean for a relatively undisturbed natural area in North Port, Florida (Tables 8 and 9). These means were $104.3 \pm 41.7 \text{ mg m}^{-2} \text{ yr}^{-1}$ and $33.0 \pm 18.5 \text{ mg m}^{-2} \text{ yr}^{-1}$ of total phosphorus at Port Charlotte and North Port, respectively. Total nitrogen was $1,569 \pm 717 \text{ mg m}^{-2} \text{ yr}^{-1}$ at Port Charlotte and $816 \pm 461 \text{ mg m}^{-2} \text{ yr}^{-1}$ at North Port (Tables 10 and 11).

These means were then compared to see if there is a difference between atmospheric nutrient input to a small but rapidly growing urban area, Port Charlotte, and a relatively undisturbed area, North Port. The results are illuminating indeed. The differences between both phosphorus and nitrogen are very highly significant and approximately three times as much phosphorus and twice as much nitrogen are falling on Port Charlotte as on North Port, near the study pond (Tables 10 and 11). The nitrogen to phosphorus ratio is also different between Port Charlotte and North Port. The N:P ratios in the soluble, particulate, and total components of bulk precipitation are: 21.1, 5.4 and 15.0 for Port Charlotte and 46.8, 4.7 and 24.7 for North Port (Tables 10 and 11).

Discussion

According to Brezonik and Messer (1977), studies on nutrient inputs in the subtropics are extremely scarce. However, there is one study in peninsular Florida which can be compared to these results. At Gainesville, Florida, 290 km north of this study, Brezonik et al. (1969) reported rainfall input values of $44 \text{ mg m}^{-2} \text{ yr}^{-1}$ of phosphorus

Table 8. Comparison of total phosphorus ($\text{mg m}^{-2} \text{yr}^{-1}$) between North Port, Florida, sites.

Phase	Pond Collectors		Flatlands Collectors		t	α
	$\bar{x} \pm s$	n	$\bar{x} \pm s$	n		
Solution	11.0 ± 6.7	16	19.2 ± 15.4	22	1.991	0.056
Particulate	18.7 ± 9.8	16	16.2 ± 11.8	22	0.691	0.495
TOTAL	29.7 ± 12.8	16	35.4 ± 21.8	22	0.933	0.364

Table 9. Comparison of total nitrogen ($\text{mg m}^{-2} \text{yr}^{-1}$) between North Port, Florida, sites.

Phase	Pond Collectors		Flatlands Collectors		t	α
	$\bar{x} \pm s$	n	$\bar{x} \pm s$	n		
Solution	686 ± 302	16	770 ± 531	22	0.568	0.582
Particulate	85 ± 58	16	79 ± 74	22	0.269	0.797
TOTAL	771 ± 313	16	849 ± 550	22	0.509	0.624

Table 10. Comparison of total phosphorus ($\text{mg m}^{-2} \text{yr}^{-1}$) between Port Charlotte and North Port, Florida.

Phase	Port Charlotte		North Port		t	α
	$\bar{x} \pm s$	n	$\bar{x} \pm s$	n		
Solution	64.1 $\pm$ 40.7	16	15.7 $\pm$ 13.0	38	6.641	<0.001
Particulate	40.2 $\pm$ 20.8	16	17.2 $\pm$ 11.0	38	5.314	<0.001
TOTAL	104.3 $\pm$ 41.7	16	33.0 $\pm$ 18.5	38	8.765	<0.001

Table 11. Comparison of total nitrogen ($\text{mg m}^{-2} \text{yr}^{-1}$) between Port Charlotte and North Port, Florida.

Phase	Port Charlotte		North Port		t	α
	$\bar{x} \pm s$	n	$\bar{x} \pm s$	n		
Solution	1,351 $\pm$ 696	16	735 $\pm$ 446	38	3.897	<0.001
Particulate	219 $\pm$ 161	16	81 $\pm$ 67	38	4.483	<0.001
TOTAL	1,569 $\pm$ 717	16	816 $\pm$ 461	38	4.617	<0.001

and $580 \text{ mg m}^{-2} \text{ yr}^{-1}$ of nitrogen. It is not known whether these values include dry fallout. Pearson and Fisher (1971) studied atmospheric nutrient inputs in New England, New York and Pennsylvania and found an annual input of 16 mg m^{-2} of phosphorus and 297 mg m^{-2} of nitrogen.

The nutrient input of phosphorus at North Port is greater than that of the New England study, but peninsular Florida is thought to be a high phosphorus area. The nitrogen input at North Port is greater than either of the above studies, but the variance around my mean is more than half of the mean, and the variance in the two comparative studies is unknown. In addition, my study only encompasses about half of a year, although it includes elements of both wet and dry seasons.

The Port Charlotte nutrient inputs are high when compared to the North Port results and the northern studies. The Port Charlotte values, however, are low by comparison to those obtained in a recent study of bulk precipitation (East Central Florida Regional Planning Council Report, unpublished). In an improved pasture, based on one sample, a rate of $200 \text{ mg-p m}^{-2} \text{ yr}^{-1}$ was calculated and at Tampa, Florida, based on two samples, $300 \text{ mg-p m}^{-2} \text{ yr}^{-1}$.

GROUND WATER

Introduction

In light of the almost total absence of relief and high soil permeabilities of this region, it was suspected that the surface of the water table is the major sink for nutrients, particularly phosphorus, which does not have a gaseous phase in its cycle. Data on the nutrient composition of the water-table aquifer of the region are not abundant, and data on Sarasota County are unknown to the author. However, the U. S. Geological Survey (1978) has monitored wells, tapping various aquifers in surrounding counties and found that phosphorus and nitrogen are highly variable, ranging from a few hundredths of a milligram per liter to several milligrams per liter. Sutcliffe (1973) has analyzed the chemical composition of several wells in Charlotte County and found nitrates in the water-table aquifer in the Cape Haze area to average 0.8 mg l^{-1} (two observations) but has no data on phosphorus in this aquifer. In the shallow artesian aquifer (sampling interval = 20-26 m), he reports values of 0.14 and 5.8 mg l^{-1} of phosphate and nitrate, respectively, based on a single observation. The need for more extensive nutrient composition studies on this important sink seems fairly obvious.

Methods

In 1976, four shallow groundwater wells (1.2 m below ground surface) were installed around pond 11 (about 850 m northeast of the study pond, Figure 4) at the major compass points. Water height was measured in these at varying intervals from July to November, 1976, and once in June, 1977. With these data, the direction and strength of the head can be calculated. For example, on July 2, 1976, the groundwater height in the south well was 7 cm above the water height in the east, 23 cm above the north and 30 cm above the west. In order to determine the groundwater equipotential contours for this date, it is necessary to find the point on the north-south transect at which groundwater height would be 7 cm below the water height in the south well (Figure 5). The same is done on the west-south transect, then a line is drawn through the two points and the east well, giving a 7 cm equipotential contour relative to the south (highest groundwater stand) well (Figure 5). Subsequent contours are represented by lines equidistant from the original contour at all points. Groundwater flow direction is perpendicular to the contours at any point.

Figure 6 shows the groundwater contours and flow direction for all 1976 sampling dates (variation in flow direction is discussed later). The direction of flow was generally east to west in 1976. Based on this analysis in April, 1978, ten wells were installed at the study pond in the following configuration: four replicate wells were placed two meters apart on a line perpendicular to the east-west transect on the eastern edge of the pond; four wells were placed on a line perpendicular to the same transect with the same spacing on the western edge of the pond; and one well each on the western end of the northeast-southwest transect

Figure 4. The study site environs.

Figure 5. Calculated groundwater (GW) equipotential contours on July 2, 1976.

Figure 6. Groundwater equipotential contours and flow directions during 1976 at Pond 11.

and the southeast-northwest transect (Figure 7). These last two served a double purpose: to provide more than two points so that the groundwater surface could be quantified in the manner described above; and to insure that the groundwater flow results obtained from the pond 11 wells, upon which the placement of the study pond wells is based, were not anomalous.

All ten wells were placed at a depth of about 1.5 m (Figure 8). This depth was approximately 0.5 m below the bottom of the center of the pond insuring that the wells would be receiving water that had passed through the pond sediments. All wells were screened for 0.5 m of their length, i.e., the region below the bottom of the center of the pond. The east group of wells, therefore, would monitor inputs of water and nutrients to the pond sediments and the west group the outputs from the sediments.

The wells were sampled monthly from April through November, 1978, by the following method. Water heights were measured by dropping a weighted tape in the wells and recording the difference between the top of the well and the surface of the water in it. The wells were then pumped dry and allowed to refill before taking a water sample to avoid sampling the possibly contaminated water standing in the pipe. Water samples were placed on ice and returned to the laboratory for nutrient analyses.

Nutrients were analyzed by the same methods described in the bulk precipitation chapter. Groundwater contours and flow direction were calculated by the method described for pond 11 wells.

Figure 7. Location of groundwater (GW) wells at the study pond.
X = groundwater well.

Figure 8. Cross-section of the pond showing input (east) and output (west) wells.

Results and Discussion

Analysis of the nutrient data from the groundwater wells indicates a substantial difference in the total phosphorus concentration but not in the total nitrogen concentration between the east and west well groups (Tables 12 and 13). Before the wells were grouped, they were tested for differences within the group, and when none was found for either parameter, the four east wells were combined and likewise the west. Mean total phosphorus concentration in the east wells was 0.16 mg l^{-1} and in the west, 0.338 mg l^{-1} . This difference was tested for statistical significance and was found to be so at an α of 0.0019. Mean total nitrogen concentration was 2.09 mg l^{-1} in the east and 2.04 mg l^{-1} in the west. These were rather obviously not significantly different from one another.

Figure 9 shows groundwater contours and direction of flow at the study pond for the 1978 sampling dates. (The August-October contours are missing because surface water was standing at the wells during this period.) The direction of flow is generally westward toward Myakkahatchee Creek discharge boundary; however, there is considerable variation in the direction of the flow. This was also seen at pond 11 in 1976. This variation is believed to be the result of manipulation of surface-water levels in Snover and Cocoplum Waterways (Figure 4). Both of these canals have numerous control structures, and if, for example, water is held in Snover and released from Cocoplum, the groundwater gradient would swing around toward the south. Conversely, if surface water is held in Cocoplum and released from Snover, the direction of maximum head loss would tend to be more northerly. The ancestral flow patterns are, therefore, apparently interrupted.

Table 12. Concentration (mg l^{-1}) of phosphorus and nitrogen in groundwater input wells in 1978.

Date	Well E-1	Well E-2	Well E-3	Well E-4
4 Apr	0.282	0.268	0.179	0.362
10 May	0.386	0.146	0.453	0.811 ^a
7 Jun	0.257	0.548	0.343	--
6 Jul	0.189	0.126	0.115	0.209
4 Aug	0.098	0.070	0.073	0.082
30 Aug	0.093	0.049	0.097	0.108
28 Sep	0.123	0.101	0.078	0.088
27 Oct	0.057	<0.046	<0.046	0.048
21 Nov	0.119	0.045	0.065	0.133
$\bar{x} \pm s$	0.179 ± 0.109	0.153 ± 0.165	0.158 ± 0.145	0.147 ± 0.107
Combined $\bar{x} \pm s$	0.160 ± 0.130			
4 Apr	1.60	2.42	2.72	10.33
10 May	1.63	1.72	5.59	7.16
7 Jun	1.63	4.98	2.68	--
6 Jul	1.06	0.97	1.48	2.20
4 Aug	1.12	1.28	1.55	1.49
30 Aug	1.14	1.28	1.55	1.36
28 Sep	0.88	0.74	1.44	1.59
27 Oct	0.85	0.81	0.94	1.41
21 Nov	1.59	1.12	1.11	1.83
$\bar{x} \pm s$	1.28 ± 0.33	1.70 ± 1.33	2.12 ± 1.44	3.42 ± 3.40
Combined $\bar{x} \pm s$	2.09 ± 1.99			

-- No sample; well was dry.

^aOutlier, statistically eliminated by Q test.

Table 13. Concentration (mg l^{-1}) of phosphorus and nitrogen in groundwater output wells in 1978.

Date	Well W-1	Well W-2	Well W-3	Well W-4	Well SW	Well NW
Phosphorus						
4 Apr	0.220	0.818	0.826	0.744	0.255	0.648
10 May	0.675	--	2.020 ^a	0.831	0.227	2.300 ^a
7 Jun	0.408	--	0.550	0.988	0.302	1.010 ^a
6 Jul	0.143	0.209	0.225	0.456	0.058	0.042
4 Aug	0.092	0.131	0.163	0.239	0.051	0.057
30 Aug	0.114	0.534	0.079	0.413	0.039	0.035
28 Sep	0.113	0.035	0.180	0.647	0.046	0.087
27 Oct	0.222	<0.046	0.146	0.286	<0.046	0.068
21 Nov	0.079	0.084	0.116	0.366	0.053	0.346
$\bar{x} \pm s$	0.229 $\pm$ 0.196	0.262 $\pm$ 0.301	0.286 $\pm$ 0.263	0.553 $\pm$ 0.261	0.117 $\pm$ 0.110	0.183 $\pm$ 0.232
Combined $\bar{x} \pm s$	0.338 $\pm$ 0.277					
Nitrogen						
4 Apr	4.29	2.31	1.92	1.43	2.24	3.12
10 May	2.92	--	2.16	+	2.15	11.60
7 Jun	7.67	--	2.55	3.08	4.25	10.99
6 Jul	1.38	1.40	1.25	1.23	1.18	1.07
4 Aug	1.29	1.94	1.44	1.33	1.35	1.46
30 Aug	1.20	1.66	1.46	1.25	1.43	1.67
28 Sep	1.43	1.85	2.31	1.48	1.83	2.19
27 Oct	0.91	1.66	2.29	2.24	1.74	2.72
21 Nov	1.67	1.56	2.56	2.14	2.04	3.06
$\bar{x} \pm s$	2.53 $\pm$ 2.20	1.77 $\pm$ 0.30	1.99 $\pm$ 0.50	1.77 $\pm$ 0.66	2.02 $\pm$ 0.91	4.21 $\pm$ 4.08
Combined $\bar{x} \pm s$	2.04 $\pm$ 1.22					

-- No sample; well was dry.

+ No sample; contaminated.

^a Outlier, statistically eliminated by Q test.

Figure 9. Groundwater equipotential contours and flow directions for 1978 sampling dates. x = groundwater well, • = pond center.

periodically, but these manipulations have only occurred since the waterways were constructed several years ago. Also, they have apparently not significantly affected the basic east to west flow of phosphorus, as is evidenced by the concentration differential between the east and west wells and is not evident between the east and southwest or northwest wells.

The results from Figure 9 were plotted (Figure 10), and the monthly areas under the curve calculated and used to obtain the monthly means (Table 14). Also plotted on Figure 10 is the curve for July to November, 1976, which was developed from data on pond 11.

The mean annual direction of flow in 1978 was 282° , between west and west-northwest. The mean dry season (April-June) direction was 220° or southwest and the mean for wet and intermediate seasons (July-March) was 302° , between west-northwest and northwest.

The generally westerly direction of groundwater flow supports the phosphorus concentration differential and indicates a net movement of phosphorus by groundwater through the pond, elevating concentrations down-gradient from the pond.

In order to quantify this effect in terms of amount of phosphorus moved, it is necessary to know the discharge ($\text{m}^3 \text{ year}^{-1}$) of water moving through the pond. Discharge (Q) can be calculated by Darcy's Law:

$$Q = PIA$$

where:

P = permeability of the water-table aquifer
($\text{m}^3 \text{ day}^{-1} \text{ m}^{-2}$)

I = head loss (m m^{-1})

Figure 10. Direction of groundwater flow during 1976 and 1978.

• 1976
○ 1978

Table 14. Groundwater movement through the study pond.^a

Date	$\bar{x}$ Direction (°)	$\bar{x}$ Head Loss (mm m ⁻¹)	$\bar{x}$ Pond Water Hght (cm)	$\bar{x}$ Area of Planar Section (m ²)	$\bar{x}$ Discharge (m ³ day ⁻¹)	$\bar{x}$ Discharge Per Month (m ³)
Jan	312	1.44	62	28.5	0.150	4.65
Feb	297	1.31	64	28.7	0.138	3.86
Mar	281	1.17	56	28.0	0.120	3.72
Apr	255	1.58	31	25.5	0.147	4.41
May	193	3.92	4	18.6	0.267	8.28
Jun	213	3.12	-7	15.8	0.180	5.40
Jul	271	1.58	45	27.6	0.160	4.96
Aug	287	1.04	80	30.1	0.115	3.57
Sep	301	0.62	86	30.4	0.069	2.07
Oct	316	1.05	86	30.4	0.117	3.63
Nov	329	1.48	71	29.4	0.159	4.77
Dec	328	1.58	66	29.0	0.168	5.21
$\bar{x}$ Annual	282 ±43	1.84 ±0.81	54 ±30	26.8 ±4.7	0.149 ±0.048	
TOTAL ANNUAL						54.53

^aFor derivation see text.

A = area (m^2) of the planar section passing through the center of the pond and sediments perpendicular to the line of flow.

The first term of the equation (P) was obtained from the Soil Interpretation Record for the Immokalee Soil Series (National Cooperative Soil Survey, 1977) and field inspection and personal communication with Warren Henderson, the regional soil scientist. Permeability was determined to be $3.66 \text{ m}^3 \text{ day}^{-1} \text{ m}^{-2}$.

The head loss at the study pond for each sampling date was obtained by calculating the difference in water height between groundwater contours along a line perpendicular to the groundwater contours (Figures 5 and 9). The values for each date are then plotted and the area under the curve gives monthly means (Figure 11). The average head loss at pond 11 was obtained in the same manner and plotted on Figure 11. Apparently during the wet season, high-water months, there is a decrease in gradient steepness that was not recorded in 1978 since water level was above the surface at all four sets of wells. This gradient change was incorporated into the 1978 data (Table 14) by using the area under the dashed line (Figure 11), an approximation of 1976, for these months. The mean annual head loss is 1.84 mm m^{-1} .

The third term of the equation (A) is somewhat more difficult to obtain. Area (A) is defined as that planar section which passes through the center of the pond perpendicular to the line of flow and limited on the bottom by the bottom of the sediments, and on the top by the surface of the sediments (Figure 12). The bottom of the sediments was located at several points along a transect perpendicular to mean flow direction. Water height varies throughout the year. Two years, 1977

Figure 11. Head loss during 1976 and 1978. (— — —) correction to 1978 data based on 1976 data.

Figure 12. Study pond water heights during 1977 and 1978.

and 1978, of water height data are plotted in Figure 12; 1977 was a relatively dry year and 1978 relatively wet. The areas under the curves were calculated per month, and the months averaged to give a representative year (Table 14). The mean water heights were then drawn on figures like Figure 13 and the enclosed area calculated (Table 14).

The mean daily discharges for each month were computed using the formula $Q = PIA$ (Table 14). These were then multiplied by the days in the month which gives mean monthly discharges which when summed give total annual discharge. The total discharge per year was 54.53 m^3 (Table 14).

An approximation of the net amount of phosphorus leaving the pond per year can be obtained by multiplying the concentration difference between east and west wells by the volume of water passing through the pond. This difference is 0.178 mg l^{-1} . The amount of phosphorus lost is 9.7 g.

Figure 13. Area of the planar section (hatched) passing through the pond center during high and low water-level periods (mean of 1977 and 1978). Note: dashed line equals water height.

SEDIMENTS

Introduction

In an earlier, preliminary study it was determined that the great majority of nutrients was contained in the sediments of these pond systems (unpublished). This is, of course, expected since the sediments are the oldest and most functionally conservative component of the pond. Most analyses of sediment deposition have been based on a single core from the deepest point of a basin (for example, Davis, 1969; Kerfoot, 1974; Likens and Davis, 1975). This approach was considered to be inadequate for this study. Several researchers have shown that sediment deposition is not uniform throughout a basin but rather that more sediment is deposited in the deeper portions than in the shallower (Wilson and Opdyke, 1941; Deevey, 1955; Lehman, 1975). This observation is compounded by varying decomposition rates which are expected to be greater in the shallower parts of a basin than in the deeper. Particularly, this should be true, given their intermittent nature, of the shallow ponds of southwest Florida.

A second criticism of the single core approach is that it does not address the problem of areal distribution in sediments. The homogeneity or lack thereof can be determined only by a multiple core approach.

Methods

Figure 14 is a representation of the sediment sampling scheme that was determined to define most adequately the sediment compartment, given the economic constraints imposed upon the study. The basic plan is three replicate center cores and four concentric rings, with four cores each, at 20 cm intervals of elevation. The center cores are within 1.5 m of the deepest point in the pond. The placement of cores on the concentric rings alternates between cardinal and minor points of the compass. Three additional center cores were obtained for radiocarbon dating, but only one was needed since it contained sufficient carbon for reliable dating.

The center and inner three rings of cores were collected in the spring of 1978 and the outermost on August 30, 1978. The cores were collected using a rig which consisted of a tripod with an adjustable chain fastened at the top. A piston, composed of two rubber stoppers and an eyebolt with washers and adjustable nuts, was connected to the end of the chain. The coring tubes were of U. S. Plastics Corp., 1/16" (0.16 cm) thick, clear Lexan polycarbonate tubing.

When the appropriate place for a core was located, the piston was inserted into a clean tube and the nuts tightened until a good seal was obtained. The chain was then adjusted until the piston rested on the top of the sediment. The tube was then pounded gently into the sediment down to and slightly beyond the point at which significant resistance was encountered. This occurs in nearly pure sand or clay, which was interpreted to be the bottom of the pond sediments. The remainder of the tube was then filled with water to equalize pressure,

Figure 14. Sediment sampling scheme.

NOTE: (•) = sediment core; (—) = 20 cm-interval surface elevation contours; and (---) = the edge of the pine-palmetto association.

pulled up by hand, and capped at the end. The tube was sawed off at the piston and this end also capped. The advantage of clear plastic tubes, although some strength must be sacrificed, is that the core can be immediately inspected to insure that the maximum amount of information with regard to stratigraphy, etc., has been preserved.

The cores were returned to the laboratory for extrusion and sectioning. The cores were extruded by pushing a rubber stopper through the tube with a wooden rod. All cores were inspected and the top 3 cm removed as it was determined that this was a well-defined root-mat zone. The three center cores were sectioned at 5 cm intervals below the top three. The three radiocarbon cores were also measured. The six center cores all displayed rather well-defined sediment/underlying material boundaries. The boundaries were defined by a rather abrupt lightening in color and increase in sand and particularly clay. The range in occurrence of this boundary was from 78-87 cm with a mean at 82 cm.

The outer cores exhibited less well-defined boundaries. The color gradient was more gradual, and there was little increase in clay. This was expected, however, since the clayey underlying material is essentially flat and the bottom of the sediments curve up away from the center (Figure 15). The approximation of the bottom of these outer sediments was made on the basis of color change, and the cores below the top 3 cm were sectioned into the same number of intervals (16) or multiple thereof as the center cores. This was done in order to equate all cores in depositional time as more sediment accumulates in the deeper parts of the basin (Lehman, 1975; etc.). The outer two concentric-ring cores contained so little pond sediment (in all but

Figure 15. Two cross-sectional views of the study pond basin.

one case 6 cm or less below the top 3 cm) that it was impractical to follow this scheme.

After sectioning, all segments were measured to determine volume, placed in labelled jars and oven-dried at 105°C for 20 hours. Some samples were dried for longer periods with no additional change in weight (Black et al., 1965, Methods of Soil Analysis, specifies an overnight drying time is sufficient for soil analyses). The dried sediment samples were weighed and their bulk densities (dry weight in gm/volume in cm³) recorded.

The organic matter content of the samples was determined by loss on ignition. This technique was deemed acceptable since previous ground and surface water analyses showed negligible amounts of inorganic carbon. The difference in sample weights before and after one hour in a muffle furnace at 550°C was determined to be the weight of organic matter in a sample. Several samples were tested with longer ignition times, but no additional weight loss was obtained and so one hour was found to be adequate.

Several digestion techniques for phosphorus were tried using a block digester. It had been predetermined that a precision error of 10 percent of the mean and a recovery of 90 percent would be acceptable and allow for a meaningful interpretation of the results. Three methods were tried on the block digester: perchloric acid (after Black et al., 1965), perchloric acid - nitric acid (modified from Jackson, 1958) and sulfuric acid - hydrogen peroxide - selenium dioxide (modified from EPA, 1974); but all three yielded poor reproducibility or recovery.

It was thought that the problem might lie in nonuniform heating capacity of the block digester. To overcome this problem, Fisher^R high-temperature bath oil was added to the block digester prior to inserting the digestion tubes. With this new technique, the simplest and safest digestion method, sulfuric acid - hydrogen peroxide, was attempted with favorable results. During the three months that the nutrient analyses were run, 24 samples of National Bureau of Standards (NBS) Standard Reference Material (SRM) green cement were analyzed. This standard was chosen because its phosphorus content was at the upper end of the range of phosphorus in the pond sediments. The results of the NBS cement analyses were as follows: recovery 99.6 percent; standard deviation, 7 percent of the mean. As a double-check on the method, a sample of Lake Michigan sediment, which closely approximated the texture of the pond sediments, was analyzed in duplicate, and 0.0080 and 0.0082 percent phosphorus were found. The Canadian Center for Inland Waters had analyzed the same sample and reported 0.0089 percent phosphorus.

One advantage of the method is that it can be used simultaneously for nitrogen determinations. The quality of the nitrogen data was periodically checked by analyzing samples of orchard leaves (NBS, SRM). Eight samples were analyzed during the three-month period with a mean recovery of 116 percent and a mean standard deviation of 3 percent of the mean. The concentration of nitrogen in the orchard leaves was at the high end of the range of nitrogen in the pond samples.

After digestion, the samples were analyzed using the Single Reagent Method (EPA, 1974) on a Technicon autoanalyzer. In this method the reaction of orthophosphate with ammonium molybdate followed

by reduction with ascorbic acid produces a blue color which can be colorimetrically measured. For nitrogen, the reaction of ammonia, sodium hydroxide, alkaline phenol and sodium hypochlorite develops a blue color designated as indophenol (EPA, 1974).

Results and Discussion

The basin appears to be hypersinusoidal in shape and basically symmetrical along the east-west transect (Figure 15). On the north-south transect the basin floor slopes more gradually toward the north than the south, and consequently there is more accumulated sediment on the north side of the center.

The raw data, converted to mg cc^{-1} by multiplying by the bulk densities, are tabulated in Appendix Tables B-1 - B-19. As to the reliability of the data, several samples were run in triplicate for organic matter, nitrogen and phosphorus. Table 15 shows the standard deviations about the means of these samples expressed as percent of the means. It had been predetermined that the percent standard deviation should be less than or equal to ten in order for the analyses to be of maximum use. This criterion was met; however, the median is probably a more useful measure of the precision of the chemical analyses since the mean tends to overweight outliers.

Table 15. Percent standard deviation

Parameter	Number of Triplicates	Range (%)	$\bar{x}$ (%)	Median (%)
Organic matter	27	0.8 - 23.3	4.9	3.9
Nitrogen	34	1.5 - 21.3	7.4	5.1
Phosphorus	37	0.4 - 18.5	6.2	5.6

In addition, two samples were run in triplicate for nitrogen and phosphorus on several different days to test for day-to-day sources of error. One sample was run on five different days, and the standard deviation as percent of the mean was 6.6 for phosphorus and 13.7 for nitrogen. The other sample, run on six days, was 7.1 percent for phosphorus and 8.7 percent for nitrogen. It appears from these analyses that the between-day error is greater than the within day error, and the nitrogen is more sensitive to between-day error than phosphorus.

As previously mentioned, the sediment/underlying-substrate boundary was well defined at the pond center, but away from the center the boundary is somewhat indistinct. I decided to use organic matter content to determine this boundary away from the center. The mean organic matter content immediately below the boundary in the center was 43 mg cc^{-1} (Appendix Tables B-1 - B-3). Therefore, it was decided that if organic matter content drops below this concentration for two successive segments, the boundary had been passed. The two successive segments rule was chosen to preclude the possibility that sand lenses in the sediment would be considered as the boundary.

In light of this definition of the bottom of the sediments, the reliability of the data from the sediments only was analyzed with somewhat better reproducibility for nitrogen and phosphorus than was found in all samples (Table 16).

The data in Appendix Tables B-1 - B-19 were averaged and totaled for each parameter. The means for the center cores and within concentric rings were compared for each parameter using a "t" test of the two most different means within a group. No significant ($\alpha = 0.05$)

Table 16. Percent standard deviation

Parameter	Number of Triplicates	Range (%)	$\bar{x}$ (%)	Median (%)
Organic matter	24	0.8 - 23.3	5.3	4.2
Nitrogen	28	1.5 - 13.1	5.3	4.1
Phosphorus	31	0.4 - 13.4	5.1	4.4

differences were found for any parameter between the center cores or within concentric rings. It was determined to combine the center cores and the cores within each ring, resulting in an average center core and an average core for each ring (Tables 17-21).

The mean totals for organic matter, nitrogen and phosphorus in the center and each ring (Tables 17-21) were plotted against distance from the center (Figures 16-18). Carbon was not plotted since its value was derived from organic matter and nitrogen. To calculate the total amount of each substance in the sediments, the formula for computing the volume of a solid of revolution was borrowed from solid geometry and modified as follows:

$$V = \frac{2\pi A r}{1000}$$

where:

V = Total amount (kg)

A = Area under the curve (g cm^{-1})

r = Distance from the axis of symmetry to the center of gravity (cm)

The axis of symmetry in this case is a line passing through the center of the sediments (Figures 16-18). The center of gravity for any plane

Table 17. Summary of data for center sediment cores.

Surface elevation: 3.42 m ms1
 $\bar{x}$ bottom elevation: 2.60 m ms1
 $\bar{x}$ distance from center: 0.0 m

Parameter	Core Designation (n) ^c			$\bar{x}$ center $\pm s^d$
	C1 (17)	C2 (17)	C3 (17)	n = 15
^a $\bar{x} \pm s$ (mg C L ⁻¹)				
Organic matter	74.2 $\pm$ 18.2	79.0 $\pm$ 16.7	78.3 $\pm$ 19.0	77.2 $\pm$ 17.8
Carbon	31.7 $\pm$ 7.6	33.8 $\pm$ 6.9	33.5 $\pm$ 7.9	33.0 $\pm$ 7.4
Nitrogen	2.77 $\pm$ 1.25	3.24 $\pm$ 2.02	2.83 $\pm$ 1.44	2.95 $\pm$ 1.58
Phosphorus	0.144 $\pm$ 0.038	0.164 $\pm$ 0.041	0.165 $\pm$ 0.051	0.157 $\pm$ 0.044
^b Total (mg)				
Organic matter	6,302	6,712	6,662	6,559 $\pm$ 224
Carbon	2,692	2,873	2,850	2,805 $\pm$ 99
Nitrogen	235.4	275.7	240.1	250.4 $\pm$ 22.0
Phosphorus	12.20	13.96	13.97	13.38 $\pm$ 1.02

^a $\bar{x}$ is the weighted mean concentration under 1 cm² of sediment.

^bTotal under 1 cm² of sediment.

^cn is the number of core segments.

^d $\bar{x}$ is for all cores in the group.

Table 18. Summary of data for the first concentric ring of sediment cores.

Surface elevation: 3.62 m msl
 $\bar{x}$ bottom elevation: 2.79 m msl
 $\bar{x}$ distance from center: 8.2 m

Parameter	Core Designation (n) ^c				$\bar{x}$ ring 1 $\pm$ s ^d	
	NW1 (17)	NE1 (16)	SE1 (17)	SW1 (16)		
$\bar{x} \pm s$ (mg CC ⁻¹) ^a	Organic matter	78.8 $\pm$ 12.7	82.5 $\pm$ 17.9	72.8 $\pm$ 16.0	77.6 $\pm$ 22.5	77.9 $\pm$ 17.5
	Carbon	33.9 $\pm$ 5.5	35.5 $\pm$ 7.6	31.3 $\pm$ 6.9	33.3 $\pm$ 9.6	33.4 $\pm$ 7.5
	Nitrogen	2.58 $\pm$ 0.74	2.69 $\pm$ 1.00	2.42 $\pm$ 0.62	2.66 $\pm$ 1.11	2.59 $\pm$ 0.90
	Phosphorus	0.136 $\pm$ 0.030	0.149 $\pm$ 0.031	0.132 $\pm$ 0.036	0.133 $\pm$ 0.031	0.138 $\pm$ 0.032
Total (mg) ^b	Organic matter	7,702	6,600	6,190	6,205	6,674 $\pm$ 711
	Carbon	3,311	2,836	2,658	2,662	2,867 $\pm$ 308
	Nitrogen	251.8	215.2	205.7	212.9	221.4 $\pm$ 20.7
	Phosphorus	13.29	11.90	11.26	10.68	11.78 $\pm$ 1.12

^a $\bar{x}$ is the weighted mean concentration under 1 cm² of sediment.

^b Total under 1 cm² of sediment.

^c n is the number of core segments.

^d $\bar{x}$ is for all cores in the group.

Table 19. Summary of data for the second concentric ring of sediment cores.

Surface elevation: 3.82 m msl
 $\bar{x}$ bottom elevation: 3.55 m msl
 $\bar{x}$ distance from center: 19.6 m

Parameter	Core Designation (n) ^c				$\bar{x}$ ring 2 $\pm$ s ^d
	N1 (9)	W1 (9)	E1 (9)	S1 (10)	
Organic matter	70.7 $\pm$ 24.1	83.5 $\pm$ 40.4	95.9 $\pm$ 48.6	98.3 $\pm$ 56.4	87.4 $\pm$ 44.0
Carbon	30.2 $\pm$ 10.2	35.5 $\pm$ 16.9	41.0 $\pm$ 20.5	42.1 $\pm$ 24.0	37.3 $\pm$ 18.6
Nitrogen	2.72 $\pm$ 1.44	3.45 $\pm$ 2.48	3.49 $\pm$ 2.49	3.58 $\pm$ 2.41	3.32 $\pm$ 2.18
Phosphorus	0.104 $\pm$ 0.030	0.098 $\pm$ 0.032	0.120 $\pm$ 0.039	0.113 $\pm$ 0.038	0.109 $\pm$ 0.035
Organic matter	2,863	1,878	2,157	2,457	2,339 $\pm$ 422
Carbon	1,221	799	923	1,052	999 $\pm$ 181
Nitrogen	110.4	77.6	78.5	89.4	89.0 $\pm$ 15.3
Phosphorus	4.23	2.21	2.70	2.82	2.99 $\pm$ 0.87

^a $\bar{x}$ is the weighted mean concentration under 1 cm² of sediment.

^bTotal under 1 cm² of sediment.

^cn is the number of core segments.

^d $\bar{x}$ is for all cores in the group.

Table 20. Summary of data for the third concentric ring of sediment cores.

Surface elevation: 4.02 m msl
 $\bar{x}$ bottom elevation: 3.93 m msl
 $\bar{x}$ distance from center: 28.7 m

Parameter	Core Designation (n) ^c				$\bar{x}$ ring 3 $\pm$ ^d	
	NW2 (1)	NE2 (5)	SE2 (3)	SW2 (3)		
^a Total (mg C) $\bar{x}$	Organic matter	76.4 ^e	78.1 $\pm$ 42.7	80.4 $\pm$ 32.3	73.4 $\pm$ 27.5	77.4 $\pm$ 31.6
	Carbon	30.7 ^e	33.1 $\pm$ 17.5	33.9 $\pm$ 13.0	31.1 $\pm$ 11.5	32.6 $\pm$ 12.9
	Nitrogen	7.19 ^e	3.53 $\pm$ 3.42	4.50 $\pm$ 2.61	3.36 $\pm$ 1.65	4.03 $\pm$ 2.68
	Phosphorus	0.156 ^e	0.117 $\pm$ 0.066	0.124 $\pm$ 0.045	0.102 $\pm$ 0.036	0.118 $\pm$ 0.049
^b Total (mg) $\bar{x}$	Organic matter	229	1,172	724	661	697 $\pm$ 386
	Carbon	92	497	305	280	294 $\pm$ 166
	Nitrogen	21.6	53.0	40.5	30.2	36.3 $\pm$ 13.5
	Phosphorus	0.47	1.76	1.11	0.92	1.07 $\pm$ 0.54

^a $\bar{x}$ is the weighted mean concentration under 1 cm² of sediment.

^bTotal under 1 cm² of sediment.

^cn is the number of core segments.

^d $\bar{x}$ is for all cores in the group.

^eSingle observation only (see Appendix Table A14).

Table 21. Summary of data for the fourth concentric ring of sediment cores.

Surface elevation: 4.21 m msl
 $\bar{x}$ bottom elevation: 4.16 m msl
 $\bar{x}$ distance from center: 50.8 m

Parameter	Core Designation (n) ^c				$\bar{x}$ ring 4 $\pm$ ^d n = 6
	N2 (2)	W2 (1)	E2 (2)	S2 (1)	
^a $\bar{x} \pm s$ (mg CC ⁻¹)					
Organic matter	89.0 ^e	86.8 ^e	77.0 ^e	99.0 ^e	86.3 $\pm$ 11.5
Carbon	37.9 ^e	35.7 ^e	32.9 ^e	41.3 ^e	36.6 $\pm$ 4.8
Nitrogen	3.70 ^e	4.23 ^e	2.92 ^e	5.95 ^e	3.90 $\pm$ 1.14
Phosphorus	0.080 ^e	0.098 ^e	0.070 ^e	0.119 ^e	0.086 $\pm$ 0.020
^b Total (mg)					
Organic matter	890	260	770	297	554 $\pm$ 323
Carbon	379	110	329	124	236 $\pm$ 138
Nitrogen	37.0	12.7	29.2	17.9	24.2 $\pm$ 11.0
Phosphorus	0.80	0.29	0.70	0.36	0.54 $\pm$ 0.25

^a $\bar{x}$ is the weighted mean concentration under 1 cm² of sediment.

^b Total under 1 cm² of sediment.

^c n is the number of core segments.

^d $\bar{x}$ is for all cores in the group.

^e One or two observations only (see Appendix Tables A16-A19).

Figure 16. Total organic matter (OM) in the sediments of the pond. S = axis of symmetry; G = line through the center of gravity; A = area under the curve; r = distance from S to G; and V = total amount.

Figure 17. Total nitrogen (N) in the sediments of the pond. S = axis of symmetry; G = line through the center of gravity; A = area under the curve; r = distance from S to G; and V = total amount.

Figure 18. Total phosphorus (P) in the sediments of the pond. S = axis of symmetry; G = line through the center of gravity; A = area under the curve; r = distance from S to G; V = total amount.

passing through the center of the sediments lies on a line parallel to the axis of symmetry and at a distance from that axis such that one-half of the area of the plane (A) lies on either side of the line (Figures 16-18).

By this method, it was determined that 85,800 kg of organic matter, 3,140 kg of nitrogen, and 124 kg of phosphorus were contained in the sediments. By the formula,

$$\text{carbon} = (\text{organic matter} - \text{nitrogen}) 0.444$$

where 0.444 is the percent carbon in the cellulose molecule and assuming the composition of organic matter to be primarily cellulose, the total carbon in the sediments was found to be 36,701 kg.

MACROPHYTES

Methods

Macrophyte above-ground biomass was harvested in June, 1976. One meter square plots were clipped, bagged and taken to the laboratory to be oven-dried (at 60°C) and weighed.

Plant samples from each of the subcompartments of the macrophytes in the ponds were collected in June and again in September of 1976. These samples were returned to the laboratory, separated into roots, shoots and leaves, oven-dried, ground in a Wiley mill and stored to await chemical analysis.

Phosphorus in the macrophytes was obtained by sulfuric acid digestion (APHA Standard Methods, 1976) followed by automated colorimetric analysis. Nitrogen and organic carbon percentages in the macrophytes were obtained by combustion and subsequent thermal conductivity measurement by the use of a Perkin-Elmer elemental analyzer.

Results and Discussion

The following vegetation pattern generally prevails in the pond. *Nuphar luteum* (L.) Sibthorp and Smith (yellow pond-lily) occupies the pond center. Also in the center but occurring over a larger area is the spike-rush (sedge) *Eleocharis baldwinii* (Torrey) Chapman. In a more or less concentric ring outside of the spike-rush grows *Panicum hemitomon* Schultes (maidencane). From the edge of the *Panicum* to the

pine-palmetto association a somewhat diverse community occurs. This community is dominated by *Hypericum fasciculatum* Lamarck (sand-cypress), *Eupatorium capillifolium* (Lamarck) Small (dog-fennel) and *Andropogon glomeratus* (Walter) BSP (beardgrass).

Above-ground biomass data, nutrient concentration data and total amounts of nutrients are presented in Tables 22, 23 and 24, respectively. Amounts of nutrients in the plant compartment of the system are relatively insignificant when compared to those found in the sediment compartment. The total amount of phosphorus in the plants was 1.1 percent of the total in the sediments; total nitrogen was 0.7 percent; and total carbon, 2.4 percent. This is not unexpected since the plants are a short-term storage compartment by comparison to the sediments.

A comparison of seasonal differences in nutrient concentrations in the macrophytes lead to some interesting conclusions. The concentration of phosphorus increased rather substantially in all macrophytes between June, the end of the dry season, and September, the end of the rainy season (Table 23). This "luxury" consumption is greatest in those species which occupy the center (deepest part) of the pond and appears to be related to the species niche. The greatest luxury consumption (September concentration equal to 3.9 times June) was found in *Eleocharis*, a submerged aquatic; followed by the floating-leaved *Nuphar* (3.3 times in the leaves); and the emergent *Panicum* (3.0 times in the leaves). The basically terrestrial *Eupatorium* doubled its concentration, and the woody *Hypericum* exhibited only a small increase (Table 23). This pattern suggests that submerged plant parts have the ability to absorb phosphorus and that the more of the plant that is submerged, the greater the absorptive capacity, i.e., increasing the

Table 22. Plant above-ground biomass data (June-July, 1976)

Plant spp.	Area Occupied (m ²)	Biomass (g m ⁻²)	Total Weight (kg)
<i>Nuphar</i>	221	15 ± 6	3.3
<i>Eleocharis</i>	548	a	a
<i>Panicum</i> (live)	1085	179 ± 70	194.2
<i>Panicum</i> (dead)	1085	732 ± 263	794.2
<i>Hypericum</i>	7222	0.75 ± 1.9	5.4
<i>Eupatorium</i>	7222	44 ± 27	317.8
<i>Andropogon</i> (live)	7222	46 ± 44	332.2
<i>Andropogon</i> (dead)	7222	27 ± 46	195.0
TOTAL	9076		1842.1

^aBiomass for *Eleocharis* was not obtained.

Table 23. Concentration (%) of phosphorus, nitrogen and carbon in the plant species of the pond during June and September, 1976.

Plant spp.	Phosphorus		Nitrogen		Carbon	
	Jun	Sep	Jun	Sep	Jun	Sep
<i>Nuphar</i>						
leaves	0.242	0.796	3.04	4.06	44.0	48.2
petioles	0.223	0.576	1.08	1.37	37.2	42.5
<i>Eleocharis</i>	0.220	0.864	1.75	1.75	46.6	45.7
<i>Panicum</i>						
leaves (live)	0.122	0.368	2.82	2.88	46.6	48.5
stems	0.109	0.250	0.67	0.33	43.7	46.9
leaves (dead)	0.064	a	0.84	a	46.0	a
<i>Hypericum</i>						
leaves	0.110	0.141	1.63	1.45	56.2	63.5
stems	0.033	0.051	1.64	0.59	50.3	50.6
roots	0.054	a	1.83	a	50.2	a
<i>Eupatorium</i>						
leaves	0.143	0.287	3.06	2.97	52.2	54.0
stems	0.085	0.192	1.22	1.55	46.8	47.1
roots	0.087	a	1.10	a	47.2	a
<i>Andropogon</i>						
shoots (live)	0.082	a	1.12	a	48.9	a
roots	0.032	a	1.07	a	46.9	a
shoots (dead)	0.014	a	0.30	a	46.9	a

^aData not collected.

Table 24. Total amount (kg) of phosphorus, nitrogen and carbon in the plant compartment of the pond during June, 1976.^a

Plant spp.	Phosphorus	Nitrogen	Carbon
<i>Nuphar</i>	0.008	0.07	1.3
<i>Eleocharis</i>	b	b	b
<i>Panicum</i>			
live	0.224	3.39	87.7
dead	0.508	6.67	365.3
<i>Hypericum</i>	0.004	0.09	2.9
<i>Eupatorium</i>	0.362	6.80	157.3
<i>Andropogon</i>			
live	0.272	3.72	162.4
dead	0.027	0.59	91.5
Total live	0.870	14.07	411.6
Total dead	0.535	7.26	456.8
TOTAL	1.405	22.83	868.4

^aBased on mean concentration in above-ground parts.

^bNo biomass data for *Eleocharis*.

surface to volume ratio with respect to phosphorus appears to be directly related to concentration of phosphorus in the plant.

There is substantial evidence to support this contention. For example, Twilley (1976) and Twilley et al. (1977) found that *Nuphar luteum* does, in fact, absorb phosphorus through its leaves, and other researchers (McRoy and Barsdate, 1970; Bristow and Whitcombe, 1971; DeMarte and Hartman, 1974) have reported this phenomenon for other submerged and emergent macrophytes.

Another interesting phenomenon is the apparent phosphorus conservation mechanism implied by the difference in concentration in living and dead plant parts (Table 23). *Panicum* apparently translocates 48 percent of the phosphorus from dead leaves to other living parts of the plant whereas *Andropogon* translocates 83 percent. This may be controlled by an evolutionary mechanism which is related to the species' ability to occupy aquatic habitats. The basically terrestrial *Andropogon* retains considerably more of its phosphorus than the emergent *Panicum* since the former must meet its phosphorus needs through root absorption only.

Seasonal differences in nitrogen concentrations are slight with the exception of *Hypericum* stems which lose about two-thirds of their nitrogen between June and September. Nitrogen is mobile in plants (Gauch, 1972), and this change may reflect transport of nitrogen from the stem to actively growing plant parts as the season progresses. This hypothesis is supported by the fact that both *Panicum* and *Andropogon* tend to conserve about two-thirds of the nitrogen in dead plant parts (Table 23).

Carbon concentrations are interesting in the fact that nearly all parts of all species increased in carbon content as the season progressed

(Table 23). This may be the result of an increasing amount of lignin production later in the growing season. The starch and cellulose molecules are 44 percent carbon, and most common sugars and organic acids are about 40 percent carbon. However, the three primary aromatic alcohols in all angiosperm lignins, coniferyl alcohol, sinapyl alcohol and p-coumaryl alcohol (Salisbury and Ross, 1969), contain 67 percent, 63 percent and 72 percent carbon, respectively (Freudenberg, 1965). The increased production of these "carbon heavy" compounds could account for the increase in carbon content observed in September (Table 23).

WATER

Methods

Nitrogen and phosphorus in the pond water were collected and analyzed according to the methods described in the bulk precipitation chapter. Total organic carbon in a sample was converted to carbon dioxide by catalytic combustion in an Oceanography International^R total carbon analyzer. The carbon dioxide formed is measured directly by an infrared detector. The measured carbon dioxide is directly proportional to the concentration of carbonaceous material in the sample (EPA, 1974).

Results and Discussion

Table 25 contains water height, surface area and volume data. Water height was measured directly. Surface area was determined by plotting the respective water heights on a predrawn figure of the basin shape and then calculating from the diameter. Volumes were calculated by addition of frustra for several water heights and then plotting a water height-volume curve from which the remaining volumes were obtained. Table 26 contains the nutrient data for the pond water during 1978.

Unlike static surface water features where changes in concentrations of nutrients usually reflect planktonic population "blooms" and "crashes," the study pond's biological dynamics are confounded by

Table 25. Surface hydrology of the pond (1978).

Date	Water Height (m)	Area (m ²)	Volume (m ³)
10 Jan	.47	1,512	220
24 Jan	.50	1,653	275
9 Feb	.59	2,073	475
23 Feb	.70	2,734	822
6 Mar	.74	3,043	950
21 Mar	.80	3,685	1253
3 Apr	.68	2,574	775
14 Apr	.55	1,934	365
26 Apr	.43	1,345	170
10 May	.27	452	45
24 May	.34	915	85
7 Jun	.21	244	18
21 Jun	.21	244	18
6 Jul	.61	2,124	525
19 Jul	.85	4,286	1525
4 Aug	1.20	9,076	4366
16 Aug	1.21	9,076	4484
30 Aug	1.10	9,076	3522
12 Sep	.93	5,558	2025
28 Sep	1.05	7,815	2800
10 Oct	.99	6,866	2490
27 Oct	.89	4,855	1775
9 Nov	1.00	6,977	2520
21 Nov	.91	5,153	1875
6 Dec	.85	4,286	1525
20 Dec	.76	3,217	1080

Table 26. Nutrient data for the pond (1978).

Date	Amount			Concentration (mg l ⁻¹)		
	TP (g)	TN (kg)	TOC (kg)	TP	TN	TOC
10 Jan	46.42	.47	5.61	.211	2.12	25.5
24 Jan	105.05	.42	7.38	.382	1.52	26.9
9 Feb	53.68	1.34	10.76	.113	2.83	22.7
23 Feb	<279.48	1.45	19.11	<.340	1.76	23.3
21 Mar	145.35	1.68	27.82	.116	1.34	22.2
3 Apr	<60.45	1.67	34.49	<.078	2.16	44.5
14 Apr	<40.15	.71	13.87	<.110	1.94	38.0
26 Apr	87.38	.67	7.46	.514	3.92	43.9
10 May	6.44	.17	2.37	.143	3.68	52.6
24 May	15.98	.22	3.77	.188	2.55	44.4
7 Jun	2.27	.08	1.28	.126	4.60	71.2
21 Jun	2.81	.09	1.24	.156	5.10	68.7
6 Jul	19.43	.99	17.59	.037	1.89	33.5
19 Jul	74.73	2.44	65.27	.049	1.60	42.8
4 Aug	183.37	5.02	152.37	.042	1.15	34.9
16 Aug	98.65	5.29	129.14	.022	1.18	28.8
30 Aug	186.67	6.52	138.77	.053	1.85	39.4
12 Sep	125.55	2.90	84.65	.062	1.43	41.8
28 Sep	89.60	4.54	88.48	.032	1.62	31.6
10 Oct	59.76	3.66	92.13	.024	1.47	37.0
27 Oct	<81.65	3.11	N.A.	<.046	1.75	N.A.
9 Nov	40.32	3.40	83.16	.016	1.35	33.0
21 Nov	155.63	3.00	94.69	.083	1.60	50.5
6 Dec	111.33	1.77	63.75	.073	1.16	41.8
20 Dec	19.44	1.74	41.26	.018	1.61	38.2

TP = Total Phosphorus

TN = Total Nitrogen

TOC= Total Organic Carbon

N.A.=contaminated

changes in water volume. To understand this relationship, assume that there is a constant amount of some substance in the water. When water volume increases, the concentration of the substance would decrease, and conversely a decrease in volume of water would show an increase in concentration. Therefore, changes in concentration do not necessarily reflect changes in productivity rates. These rate changes can be ascertained by comparing the magnitude of volume and concentration changes (Figure 19). For example, total organic carbon triples from March to June, but water volume decreases by two orders of magnitude and so an apparent bloom is, in fact, a crash.

When concentrations are converted to amounts, changes in productivity become readily apparent (Figure 20). There are three population blooms: one large summer increase and two smaller ones in early spring and late fall. The pattern very closely follows changes in water volume which appears to be a dominant population controlling mechanism. As volume increases so does productivity, to fill the new habitat; but as volume declines, the population crashes as many more individuals are removed from the water column than are added. The net effect of this pattern is to keep concentrations relatively constant. The ratio of maximum to minimum water volume is approximately 250 to 1; for amount total organic carbon, it is about half of this; and for nitrogen and phosphorus, about 82 to 1. By contrast, concentration maxima of carbon and nitrogen are only 3 to 4 times their respective minima and phosphorus 32 times.

Another interesting effect of fluctuating water height and its consequent changes in surface area is the change in the area available for receiving atmospheric inputs. Figure 20 shows the total amounts

Figure 19. Nutrient concentration and water volume changes during 1978.

Figure 20. Atmospheric (Atm) inputs and nutrients in the water column.

of nitrogen and phosphorus falling on the pond water surface during sampling intervals. The changing amounts reflect both changes in atmospheric input rates and changes in pond water surface area. It should be noted that changes in the amounts of nutrients in the water column are generally an order of magnitude greater than the atmospheric inputs for respective intervals. However, the mean amounts of nitrogen (2.1 kg) and phosphorus (80 g) in the water column for the year are not very different from the total yearly inputs of nitrogen (3.1 kg) and phosphorus (120 g). It appears that the pond water may achieve steady state with atmospheric inputs over relative long duration, but in the short term, regeneration from the sediments probably plays the dominant role in supplying nutrients for seasonal changes in productivity.

This is consistent with the work of other researchers who have found that both the decomposition of dead aquatic macrophytes and the active "pumping" by living specimens contribute substantial amounts of phosphorus to the water column. Reimold (1972) found that a *Spartina* marsh on the coast of Georgia released $601 \text{ mg-P m}^{-2}\text{day}^{-1}$; McRoy et al. (1972) reported that *Zostera* in an Alaskan lagoon added $62 \text{ mg-P m}^{-2}\text{day}^{-1}$ to the water column; and Twilley (1976) showed that *Nuphar* was capable of adding only $2 \text{ mg-P m}^{-2}\text{day}^{-1}$. The large differences observed are most likely related to biomass (Twilley, 1976) since the biomass of *Spartina*, a grass, is considerably greater than *Nuphar*.

If we take the amount of phosphorus added to the water column between 21 June and 4 August (approximately 180 g) (Figure 20) and divide by the number of days and by the average surface area (Table 16), we can calculate an addition rate of about $1 \text{ mg-P m}^{-2}\text{day}^{-1}$. By

subtracting that amount added as bulk precipitation (approximately $0.1 \text{ mg-P m}^{-2}\text{day}^{-1}$) (Figure 20), it is estimated that, for the period under consideration, $0.9 \text{ mg-P m}^{-2}\text{day}^{-1}$ were regenerated from the sediments by some combination of mechanisms. This is about one-half of Twilley's (1976) results and considerably less than Reimold (1972) and McRoy et al. (1972). These differences may in part be due to biomass differences. For example, when converted to a dry weight basis, *Nuphar* contributed $210 \text{ mg-P g}^{-1}\text{day}^{-1}$, whereas *Zostera* added only about $90 \text{ mg-P g}^{-1}\text{day}^{-1}$ (Twilley, 1976). As stated above, *Zostera* appeared to contribute 30 times more phosphorus than *Nuphar*. Differences may also be attributed to water chemistry, plant characteristics, etc. (Twilley, 1976).

NUTRIENT DYNAMICS OF THE POND SYSTEM

Introduction

In the chapter on bulk precipitation we found that the pond receives a substantial amount of nitrogen and phosphorus from atmospheric fallout. There is an additional smaller input from ground water. Nitrogen entering the system can leave through the groundwater sink and by nitrification or denitrification, also exit the system in the gaseous state via the atmosphere. Phosphorus, on the other hand, rarely exists in the gaseous state, and, therefore, phosphorus can only exit the system through the groundwater sink (see background chapter for discussion of surface-water runoff). This chapter will discuss the dynamics of these nutrients, particularly phosphorus, as they pass through the system.

Methods

Only one additional method needs to be presented here. Available or movable phosphorus (orthophosphate phosphorus and poly-phosphorus), that which can be removed by leaching of the sediments, was determined for several samples from the cores of concentric rings 1 and 2 and the center cores. Samples were analyzed according to the method of Black et al., 1965 (part 2, p. 1043). Solution pH was adjusted to 3.9 (the mean pH of the pond water and ground water).

Methods pertaining to all other parameters discussed here can be found in the preceding chapters.

Sediment Nutrient Dynamics

Although intuitively it might seem that the pathway of nutrients through the water column to the sediments ought to be perpendicular to the water surface, in reality there is directional transport of sediment and its constituents toward the deepest part of a basin (Deevey, 1955; Rigg, 1958; Pewé et al., 1965; Lehman, 1975), i.e., sediment focusing (Likens and Davis, 1975). These studies, however, have dealt with static lake basins, in general, and not seasonal ponds such as the study pond, and although the study pond exhibits an hypersinusoidal sediment deposition pattern (Figure 15), it is not known whether some nutrients are deposited during the dry season along the continuously receding pond edge. A comparison of the wet and dry season nutrient concentrations (see chapter on pond water) does indicate a concentrating effect during the dry season implying transport toward the center. However, the concentration and amount values are highly variable and are confounded by those amounts which are bound-up in macro-organisms. The problem of whether some phosphorus escapes the sediment focusing mechanism and is transported directly downward near the periphery of the pond probably cannot be addressed in this study. Suffice it to say that a substantial amount of sediment and its constituent nutrients is focused toward the pond center.

Not only is the sediment deeper toward the center of the pond and, therefore, total organic matter, nitrogen and phosphorus greater, but also mean phosphorus increases toward the center of the pond (Tables 17-21). Mean organic matter and nitrogen do not exhibit a regular areal trend and appear to be fairly constant.

Regression analysis illustrates the relationship between nitrogen and organic matter and phosphorus and organic matter. Nitrogen is positively related to organic matter throughout the sediments, and the amount of error in nitrogen explained by organic matter remains constant (Table 27). The phosphorus-organic matter relationship changes from the periphery to the center of the pond. Toward the periphery, phosphorus is highly correlated with organic matter, but approaching the center, the relationship breaks down and is practically nonexistent in the center. The breakdown in the phosphorus-organic matter relationship is evident as a "bulge" in phosphorus at approximately 20-40 cm in the center and near-center cores (Appendix B, Tables B-1 - B-19). For example, in Table B-1, phosphorus decreases from 0.267 mg cc^{-1} at the top to 0.087 mg cc^{-1} at about 10 cm and then increases to 0.232 mg cc^{-1} at about 30 cm after which it declines to the bottom of the sediments.

Table 27. Regression analysis of nitrogen (N) and phosphorus (P) on organic matter (OM)

Location	N on OM		P on OM	
	r^2	α	r^2	α
Center	0.81	<0.0001	0.30	<0.0001
Ring 1	0.77	<0.0001	0.56	<0.0001
Ring 2	0.84	<0.0001	0.69	<0.0001
Ring 3	0.83	0.0002	0.89	<0.0001
Ring 4	0.81	0.0122	0.76	0.0200

The implication of this pattern is that phosphorus, incorporated in organic matter is directed toward the pond center and becomes part of the sediments. With the oxidation of organic matter, both nitrogen

and phosphorus are freed. The nitrogen is eventually released to the water column, but the phosphorus remains in the sediments in the available state. Some of this available phosphorus may become incorporated into plant material again or "pumped" back into the water column by macrophytes (Twilley, 1976; etc., see earlier). However, when water levels drop below the top of the sediments, the unbound phosphorus and that which becomes available due to rapid oxidation of exposed organic matter is now free to move vertically in the sediments by the leaching process and should accumulate in the vicinity of the mean low water level. This would explain the phosphorus bulge in the sediments near the center of the pond.

Changes in the nitrogen-to-phosphorus ratio with depth appear to be indicative of this pattern (Appendix, Tables B-1 - B-19). In the center of the pond phosphorus increases rather rapidly relative to nitrogen in the top 20 cm. The ratio remains fairly constant from about 20-40 cm followed by a gradual increase to the bottom of the sediments where another sharp decline is observed. This pattern is believed to be the result of downward movement of phosphorus to the vicinity of the mean low water level for dry years (40-50 cm in 1977), as well as the release of nitrogen to the water column through decomposition. A similar pattern is seen in the first concentric ring of sediment cores except that the ratio increases slightly at about 40-50 cm and more dramatically at 60-80 cm. The top of the sediments here is 20 cm above the top of the pond center, and hence the mean low water level would be at 60-70 cm. The outer rings show the decline in the nitrogen-to-phosphorus ratio at the top of the sediments but not the rise near the bottom. This is due to the fact that the

mean low water level would be below the deepest samples in these three rings.

As further support for the downward movement of phosphorus, Figure 21 shows the depth distribution of available, or movable, phosphorus in the center and first and second rings of sediment cores. Unfortunately, for the sake of a clear demonstration of downward phosphorus movement in the sediments, the pond did not completely dry up during the year of the study due to unusually high winter precipitation. However, the outer ring has slightly more available phosphorus at lower depths than the center or first ring (Figure 21). During May and June of 1978, the surface-water level dropped below the top of the sediments of ring 2 thus exposing these to the leaching process (see pond water chapter). The lowest water levels occurred for a couple of weeks in June, at which time the level was 19 cm below the top of the second ring of sediments. Note that the available phosphorus curve for ring 2 differs from the other two only in the top 20 cm (Figure 21).

Additional evidence for downward transport of movable phosphorus during dry periods was observed at pond 11 (Figure 4) in 1977. In June of that year water level dropped to 40-50 cm below the top of the sediment in the center of pond 11. Two wells were installed at different depths in the center of pond 11. One well, placed 15 cm below the surface of the sediments, was dry on June 20, 1977; the other, 45 cm deep, contained an ortho phosphate phosphorus concentration of 1.26 mg l^{-1} . Two weeks later and after approximately 13 cm of rainfall, the surface well had a concentration of 0.19 mg l^{-1} , and the deeper well, 0.50 mg l^{-1} . The implication is that available phosphorus was removed from the upper sediments to the region of the deeper well.

Figure 21. Available phosphorus (P) distribution with depth (Z).

When the "new" rains came, they were relatively low in phosphorus content, and apparently there was little leachable phosphorus left at the top of the sediments, and hence the 15 cm well was substantially lower in phosphorus content than the previous reading in the 45 cm well. The deeper well also showed a reduction in phosphorus from the earlier sample, but this is thought to be an artifact of the mixing of upper and lower water since water can enter the well pipe from the sides as well as the bottom.

If, indeed, the total phosphorus bulge is the result of vertically translocated available phosphorus, then the phosphorus at the bulge should have been measured as available but was not (compare Figure 21 with Appendix B tables). One explanation for this discrepancy is that the phosphorus that has been moved is complexed with iron when it reaches the vicinity of the mean low water level. In soils subject to alternating oxidizing and reducing conditions, iron tends to accumulate (Hesse, 1971). Under these conditions a silica-iron-phosphate complex would be formed which would render the phosphorus inactive with respect to available phosphorus analysis.

Sediment/Groundwater Interaction

In the previous section we have seen that some of the phosphorus in the sediments is unbound and can potentially be removed from the sediments in the ground water. In the chapter on ground water, it was shown that phosphorus concentrations are higher on the down-gradient side of the pond. Apparently ground water does remove at least some of the unbound phosphorus from the sediments; however, to predict the expected areal concentration distribution of phosphorus on the output

side of the pond, it is necessary to understand the geometry of the pond sediments.

The sediments are hypersinusoidal in shape, and a front of water passing laterally through such a body would encounter considerably more volume at the center than at the periphery of the body. The volume of sediments decreases in all directions from the center and with reference to the front of water decreases in two dimensions, both parallel and perpendicular to the axis of flow. Figure 22 illustrates this point. If we imagine columns of water of arbitrary width on the water front, we can see that the column which passes directly through the center will encounter more sediment volume than those passing at some distance from the center.

The effect of this phenomenon on the areal distribution of phosphorus removal, and therefore on the expected concentration distribution of phosphorus in the ground water, can be quantified by double integration of phosphorus over distance. The first integration variables are total phosphorus, a function of depth, and distance parallel to the axis of flow. Total phosphorus values ($\text{mg under } 1 \text{ cm}^2$) are obtained for the center and four concentric rings from Tables 17 - 21, and these values are plotted against distance for each one-centimeter wide band in Figure 23. For example, the band that passes through the center of the pond contains nine phosphorus data points, two for each concentric ring and one for the center. The total phosphorus under each band was calculated and these totals are indicated in Figure 23.

At this point we have the total phosphorus encountered by seven one-centimeter wide columns of water passing through the pond sediments at discrete intervals. However, in order to determine the "phosphorus

Figure 22. Three-dimensional view of a quarter section of the pond sediments showing volume changes with distance from the center.

Figure 23. Areal view of the sediments showing bands of total phosphorus (---) parallel to mean groundwater flow. NOTE: numbers are total phosphorus (g) under the bands; and (x) = groundwater sampling wells.

picture as seen by the water front," it is necessary to perform a second integration, that is, change in total phosphorus over change in distance perpendicular to the axis of flow (Figure 24).

We would expect, based on the above consideration, that the greatest concentration of phosphorus down-gradient from the pond would occur in the direction of mean groundwater flow, that is, 282° (Table 14). From this point, the concentration should decrease in either direction similar to the curve in Figure 24. Although the groundwater sampling wells were not originally set up to monitor a distribution such as that predicted by the sediment geometry, it is fortunate that six of the ten wells were installed on the western side of the pond. These six wells are depicted on Figure 23, and from their relationship to the bands of total phosphorus, it seems as though they should show the pattern described above.

To test this idea, the concentrations of phosphorus in the west and northwest wells (Tables 12 and 13) were plotted against distance from the centerline, i.e., the line parallel to the axis of flow which passes through the center of the pond (Figure 25). The southwest well was excluded since its mean concentration was not significantly different from that in the east wells, that is, input concentration. A quadratic equation of the form $y = 0.693 + 0.019x - 0.001x^2$ was fitted to the five points ($r^2 = 0.77$, $\alpha = 0.16$), and although not significant (not unexpected with only five points), the fit is a fairly good one. The peak of the predicted concentration pattern is shifted off the centerline by about 7 meters. One possible explanation for this shift would be a change in the mean direction of groundwater flow. A change

Figure 24. Distribution of total phosphorus in the sediments encountered by the groundwater front as it passes through the sediments.

Figure 25. A. Distribution of total phosphorus in the sediments (from Figure 24);
 B. Predicted groundwater phosphorus concentration down-gradient from the
 pond. NOTE --- = x input concentration; (x) = groundwater data point,
 and (o) = sediment data point.

in direction of about 10° toward the north would account for the discrepancy.

It should be pointed out here that the mean groundwater flow direction measured today may not be the same as the mean flow direction for the last several years. This is an important consideration since, owing to the slowness of groundwater flow, the phosphorus recorded in the wells today left the center of the pond several years ago. Groundwater flow velocity will be discussed in detail in the next section.

If the peaks of the two curves in Figure 25 are aligned and compared in the region where they overlap by linear regression, the following results are obtained: $r^2 = 0.84$, $\alpha = 0.03$. This groundwater model is admittedly statistically weak, but the weakness is believed to be the result of high variation in groundwater phosphorus and the low number of sample wells. From a logical standpoint, based on the phosphorus distribution in the sediments through which the groundwater must pass, this model is by far more acceptable than to assume a uniform concentration differential across the pond.

The mean concentration difference between input and output wells estimated by the new model is obtained by computing the area defined by curve B and the dashed line (input concentration, Figure 25). This concentration difference is 0.426 mg l^{-1} , and the total amount of phosphorus loss per year is 23.2 g.

Available Phosphorus and Groundwater Concentrations

The phosphorus which moves in the ground water should be that which is in the available state in the sediments. If we assume that

all of the available phosphorus dissolves in the ground water and moves laterally, we can calculate the expected concentration in the output wells by the following formula:

$$C = \frac{P}{\theta}$$

where: C = concentration in the interstitial water (mg l^{-1})

P = available phosphorus in the sediment ($\mu\text{g cc}^{-1}$)

θ = porosity (% expressed as a decimal).

Porosity is determined in the following manner (Black et al., 1965):

$$\theta = \frac{[(OM)K_1 + (1-OM)K_2] - BD}{(OM)K_1 + (1-OM)K_2}$$

where: θ = porosity (% expressed as a decimal)

OM = organic matter (% expressed as a decimal)

K_1 = particle density of cellulose (1.61 g cc^{-1})

K_2 = particle density of quartz sand (2.65 g cc^{-1})

BD = measured bulk density (g cc^{-1})

The concentration in the interstitial water was calculated for each segment in the center and first ring for which available phosphorus had been measured. These were then plotted against depth to arrive at a mean concentration in the interstitial water of the sediments at the pond center. The mean concentration was 1.84 mg l^{-1} which is approximately 1 mg l^{-1} higher than the maximum predicted concentration at the output end of the system.

This result leads to one of three possible conclusions. All of the available phosphorus measured in the sediments may not become

soluble and therefore would not move out of the pond system in ground water. This may be dependent on, for instance, the $\text{Fe}^{2+}/\text{Fe}^{3+}$ balance which in turn is dependent on the redox potential of the sediment interstitial water matrix. Another possible explanation of the discrepancy involves the mechanism by which water level drops in the dry season. If the level drops by *in situ* evaporation, the effect would be to concentrate the interstitial available phosphorus resulting in relatively high concentrations in the groundwater wells. However, if water level drops due to negative artesian pressure caused by evaporation of distance recharge areas, there would not be a concentrating of interstitial available phosphorus resulting in lower concentration in the groundwater wells.

The third possible explanation lies in the fact that phosphorus sampled in the output wells reflects sediment nutrient dynamics and hence available phosphorus some time in the past, which may have been different than today. This is based on the fact that the velocity of groundwater flow is extremely slow. Velocity (V) can be calculated by a modification of Darcy's Law (see, for example, Domenico, 1972):

$$V = \frac{Q}{\theta A}$$

where: Q = discharge (m^3yr^{-1})

θ = porosity (%)

A = Area (m^2) of the planar section.

Discharge ($54.53 \text{ m}^3\text{yr}^{-1}$) divided by porosity (0.36, calculated from the material underlying the sediments) times annual mean area of the planar section (40.1 m^2) equals about 3.78 m yr^{-1} which means that the

concentrations sampled in the west wells consist of, at least in part, phosphorus molecules which left the planar section passing through the pond center about 13 years earlier.

THE POND SYSTEM: PRESENT AND PAST

Present Nutrient Budget

The inputs, outputs and storages of nitrogen and phosphorus computed in the previous chapters can be combined into a nutrient budget for the pond in its present state (Figure 26). For those components which are indirectly functions of water height, i.e., atmospheric input and groundwater input and output, the mean for 1977 and 1978 was used to calculate their multipliers. The rationale here is that 1978 was a relatively wet year and 1977 relatively dry. This pattern of alternating wet and dry years is the norm for this part of Florida (NOAA, 1976; USGS, 1978), and it was felt that by using the data from the two years, a better estimate of the present prevailing conditions could be obtained.

The mean area of the pond water surface in 1977 and 1978 was $2,812 \text{ m}^2$ (based on the mean area of surface water, calculated from mean water heights in Figure 13), and the yearly atmospheric input of nitrogen and phosphorus was 2,295 g and 93 g, respectively. Based on the discharge calculated in the groundwater chapter, a net gain of 23 g of phosphorus and a net loss of 3 g of nitrogen is observed across the pond (Figure 26). In the case of nitrogen, a condition of stasis apparently exists. Since the sediments were sampled in April through June, June, and April through June values were calculated for the plant and water components, respectively. Only those plants within the mean

Figure 26. Present-day nitrogen (N) and phosphorus (P) inputs and outputs in grams per year; storages in grams.

area of pond water surface (see above) are included in the budget, that is, the *Panicum*, *Eleocharis* and *Nuphar*. Plants and water were minimal storage compartments. Their combined nitrogen and phosphorus were less than 1 percent of the total in storage (Figure 26).

At the present rates of exchange, the system appears to be storing 69 percent of the phosphorus input. There is no net loss of nitrogen in ground water, but nitrogen can leave the system through the atmosphere. This rate was not measured but can be calculated after some additional groundwork is laid (see later).

Historical Nutrient Budget

Four radiocarbon dates were obtained from the study pond (Figure 27). Net accumulation of organic matter began about 5,250 earth years ago (based on C^{14} date correction after Fairbridge, 1974). At this time water height was lower and hence water surface area smaller (Figure 28). The inputs from the atmosphere would have consequently been smaller and groundwater output no different than input since there had been no net accumulation of nutrients in the sediments. As sea-level rose (Shepard, 1963; Scholl et al., 1969; Möerner, 1969; among others) groundwater level also rose tipping the accumulation-decomposition balance in favor of accumulation, and the sediment compartment began to grow. Figure 28 shows the morphogenesis of sediments in the pond basin. Points away from the pond center were obtained by assuming the same percent change throughout the basin (Lehman, 1975). The amount of phosphorus input is obtained by multiplying the area of the paleo-pond water surface by the measured input rate ($33 \text{ mg m}^{-2} \text{ yr}^{-1}$), assumed to be constant through time. The paleo-pond water

Figure 27. Sedimentation rate curve.

Figure 28. Morphogenesis of the study pond basin. NOTE: Past mean water depths were assumed to be similar to the 1977-78 average, i.e., 54 cm.

surfaces are shown in Figure 28 and are based on the assumption that the mean depths were similar to those measured in 1977-78, and that, therefore, the mean surface-water areas were related to those calculated for the present. The amounts of phosphorus are plotted against time (sidereal years), and a total phosphorus input of about 180 kg was calculated for the life of the pond (Figure 29).

The groundwater outputs also changed with time, increasing as phosphorus was stored in the sediments. Output increased as a function of two variables: 1) phosphorus input from the atmosphere and hence phosphorus available to be stored, and 2) the size of the sediment compartment. As the sediment compartment increases, so do the chances of a water molecule to remove phosphorus (see nutrient dynamics chapter on relationship between total phosphorus in the sediments and groundwater output concentrations). The curve in Figure 30 is the combined effect of these two functions on the net phosphorus loss across the pond. The dashed curve in Figure 30 is obtained by reducing the total phosphorus loss in 1978 (23.2 g; see nutrient dynamics chapter) by the percent change in phosphorus input through time (Figure 29). The solid curve in Figure 30 is obtained by reducing the dashed curve by the percent change in the amount of sediment (Figure 28). By computing the area under the curve in Figure 30, it was determined that about 24 kg of phosphorus were lost since the inception of the pond.

The phosphorus budget for the pond system for the last 5000 years is as follows: of the 180.2 kg input from the atmosphere, 123.5 kg remained in the sediments, 0.7 kg were found in water and plants, and 24.3 kg were lost in ground water. The total accounted for is 148.5 kg which is about 32 kg less than the total input (Figure 31).

Figure 29. Amount of phosphorus (P) that has fallen on the pond surface since the pond began functioning.

Figure 30. Amount of phosphorus (P) lost to ground water since the pond began to function.
(---) = reduction due to change in P input;
(—) = reduction due to change in amount of sediment.

Figure 31. Nitrogen (N) and phosphorus (P) inputs, outputs and storages in kilograms for the life of the pond.

The groundwater nitrogen input and output are roughly equal (Figure 26), and the atmospheric input can be calculated by using a curve like that in Figure 29. The only difference is the starting amount, 2,295 g in the case of nitrogen. The nitrogen budget for the life of the pond is as follows. The atmosphere contributed 4,460 kg of nitrogen, ground water is roughly in steady state and total storage equals 3,150 kg (Figure 31). The remainder (input minus storage) is 1,313 kg.

Both the phosphorus and nitrogen budgets show inputs that are unaccounted for in storage and output. The most reasonable explanation for these discrepancies is that the input rates were lower in the past. If it is assumed that the rates measured today represent the industrialized period of the last century, the preindustrial rate which balances the phosphorus budget is about $27 \text{ mg m}^{-2} \text{ yr}^{-1}$. Assuming a similar rate increase for nitrogen after industrialization, 3597 kg of nitrogen would be the total input for the 5000-year life of the pond. This figure is 447 kg greater than that accounted for in storage and output, and the difference is assumed to be atmospheric output. This output is 12 percent of the estimated input and hence, for the present-day budget, 285 g of nitrogen leave the pond by this pathway each year (Figure 26).

CONCLUSIONS

As is generally accepted, the pine-flatwoods ponds are indeed nutrient accumulators. However, what may not be generally known is that even without surface outlets the ponds do release phosphorus to ground water. As for nitrogen, it is unknown whether exchange between sediments and ground water occurs since input and output concentrations are about equal.

For the past 5000 years, the study pond has stored 85 percent of its nitrogen input and at present is storing about the same as the ancestral rate. The net loss is assumed to be atmospheric exchange. On the other hand, the historical rate of phosphorus storage has been 78 percent, but the storage rate today is only 69 percent. The implication here is that at its inception the pond was accumulating nearly all of its phosphorus input, but its retention capacity has declined with the passage of time. This phenomenon is most likely related to the geometry of the pond basin and the morphogenesis of the sediments. As the pond fills with sediment, the volume of sediment increases at a faster rate than the area of the input surface. (For example, the base of a cone increases as the square of increments in height, whereas its volume increases as the cube of increments in height.) When surface water drops below the top of the sediments, a greater volume, relative to the input surface, is exposed to oxidation, i.e., loss of phosphorus from organic binding sites. Hence, a greater percentage of the input

phosphorus is rendered available to be removed from the system through groundwater exchange.

One implication of the water-table phosphorus sink is that each pond has a "trail" of relatively high phosphorus from the pond to the discharge boundary. All along the boundary there should be points where these trails bleed into the surface waters. In the case of Myakkahatchee Creek (total phosphorus concentration of about 0.2 mg l^{-1}) a concentration of $0.5 - 0.6 \text{ mg l}^{-1}$ (based on the mean groundwater loss; see nutrient dynamics chapter) at the bleeding points probably does not make a significant contribution to the ambient concentration in the creek. However, in areas where surface-water concentrations of phosphorus are very low, this groundwater bleeding may be a significant natural input source for this nutrient.

At this point, I would like to turn attention to the atmospheric phosphorus input rate and ecosystem development. The input value of $33 \text{ mg m}^{-2}\text{yr}^{-1}$ for my study is in the low range of other values for Florida (see bulk precipitation chapter) but is very close to those found in forested areas on the Canadian shield. For example, Gomolka (1975) found $37 \text{ mg m}^{-2}\text{yr}^{-1}$; Schindler and Nighswander (1970) report $35 \text{ mg m}^{-2}\text{yr}^{-1}$; Schindler et al. (1976) found $24-53 \text{ mg m}^{-2}\text{yr}^{-1}$; and Scheider (1978) estimated $35 \text{ mg m}^{-2}\text{yr}^{-1}$. Other researchers, such as Dillon (1974), have found higher values, but these may be due to local effects.

The implication of the similarity between atmospheric phosphorus input in a relatively natural area of Florida and in the forested Canadian shield is that the natural atmospheric contribution may be constant and in the mid-30's. This conclusion is at odds with two

New England studies. At Hubbard Brook, N. H., Likens et al. (1977) found a rate of about $10 \text{ mg m}^{-2} \text{ yr}^{-1}$ and at nine stations throughout New York, Pearson and Fisher (1971) found an average of $16 \text{ mg m}^{-2} \text{ yr}^{-1}$. The Pearson and Fisher study may serve to shed some light on the discrepancy between the New England values and the numbers reported by myself and the Canadian researchers. Pearson and Fisher used a dry glass funnel receptor for the rainfall and dry fallout mixture. The problem with a dry receptor is that that which blows onto it can also be removed by the same agent, i.e., wind (compare with my methods). One cannot be sure that dry fallout is actually being measured. I found the dry fallout fraction (in my study, particulate fraction) to be an important constituent, comprising 52 percent of the total at the study pond. If, indeed, Pearson and Fisher methods precluded dry fallout, and this component is roughly half of the total, their value is nearly identical to mine.

The weight of evidence, therefore, seems to indicate a spatially constant atmospheric input rate for phosphorus in relatively undisturbed areas. Based on my budgeting considerations, this rate is about 20 percent greater than the estimated ancestral rate. The 20 percent increase is thought to be the postindustrialization global increase in phosphorus input rate.

It has been shown that the pond system was controlled in the past by the complex interaction of climate and sea level, resulting in relatively slow system development. Based on the recent sedimentation rate, approximately 30 cm per 1000 years (Figure 27), the future life expectancy of the pond is about 4000 years. At this point, the surface of the sediment will have reached the level of the surrounding

terrain at which time the pond should be essentially a terrestrial system. However, climatic and sea-level changes (see chapter on background) could either shorten or lengthen the life of the pond. If mean ground water drops below the bottom of the sediments because of climatic or sea-level changes, oxidation of the sediments would return the pond system to a terrestrial depression, and this process could be very rapid. On the other hand, if ground water fluctuates between its present level and the bottom of the sediments, the pond system would continue to function indefinitely.

If the input rates were to increase significantly due to changes in land use, either globally or locally, productivity, and hence sedimentation, rates might also increase. If, for example, the sedimentation rate increased by 10 percent, a reduction in the life expectancy of the pond from 4000 to 3600 years might be expected.

APPENDIX A
CHEMICAL COMPOSITION OF BULK PRECIPITATION

Table A-1. Amount of total phosphorus ($\text{mg m}^{-2} \text{ yr}^{-1}$) in bulk precipitation collectors at Port Charlotte, Florida, from June through October, 1978.

Date	North Collector			South Collector		
	Solution	Particulate	Total	Solution	Particulate	Total
7 June	11.0	69.6	80.6	9.5	25.2	34.7
21 June	100.9	18.5	119.4	61.2	0.0 - 6.6	6.12 - 6.78
6 July	43.2	48.8	92.0	58.5	33.2	91.7
19 July	55.7	40.2	95.9	83.9	52.1	136.0
4 August	-	-	-	-	-	-
16 August	126.9	72.8	199.7	26.1	59.3	85.4
30 August	-	-	-	98.3	27.4	125.7
12 September	145.7	26.2	171.9	-	-	-
28 September	27.6	65.8	93.4	36.1	53.5	89.6
10 October	96.1	32.7	128.8	44.4	14.8	59.2
27 October	-	-	-	-	-	-
$\bar{x} \pm s^1$	75.9 $\pm$ 48.6	46.8 $\pm$ 20.8	122.7 $\pm$ 42.6	52.3 $\pm$ 29.5	33.6 $\pm$ 19.9	85.9 $\pm$ 33.7

- contaminated

¹mean includes midpoints for values less than detection limits.

Table A-2. Amount of total phosphorus ($\text{mg m}^{-2} \text{yr}^{-1}$) in bulk precipitation collectors in the study pond (North Port, Florida) from June through October, 1978.

Date	North Collector			South Collector		
	Solution ¹	Particulate	Total	Solution ¹	Particulate	Total
7 June	13.9	30.7	44.6	5.7	16.3	22.0
21 June	10.3	30.1	40.4	-	-	-
6 July	-	-	-	-	-	-
19 July	15.2	19.0	34.2	15.8	12.3	28.1
4 August	0.0 - 9.5	19.0	19.0 - 28.5	23.9	15.3	39.2
16 August	0.0 - 21.9	16.6	16.6 - 38.5	0.0 - 18.6	17.1	17.1 - 35.7
30 August	17.7	38.4	56.1	-	-	-
12 September	20.3	0.0 - 6.9	20.3 - 27.2	1.4 - 4.1	25.7	27.1 - 29.8
28 September	8.5 - 17.0	23.3	31.8 - 40.3	3.3 - 16.6	21.9	25.2 - 38.5
10 October	0.7 - 1.5	0.0 - 9.1	0.7 - 10.6	1.2 - 1.6	0.0 - 9.1	1.2 - 10.7
27 October	-	-	-	-	-	-
$\bar{x} \pm s^2$	11.9 $\pm$ 6.0	20.6 $\pm$ 11.7	32.5 $\pm$ 14.5	9.8 $\pm$ 7.8	16.2 $\pm$ 6.8	26.0 $\pm$ 10.3

- contaminated

¹For values less than the detection limit, the low point of the range was established by the $\text{o-P-O}_4\text{-P}$ value when this value was above detection limits; high point of the range is the detection limit for TP .

²Mean includes midpoints for values less than detection limits.

Table A-3. Amount of total phosphorus ($\text{mg m}^{-2} \text{yr}^{-1}$) in bulk precipitation collectors in the sandy flatlands near the study pond (North Port, Florida) from June through October, 1978.

Date	East Collector			West Collector		
	Solution ¹	Particulate	Total	Solution ¹	Particulate	Total
7 June	10.3	14.5	24.8	2.1	0.0 - 6.5	2.1 - 8.6
21 June	45.6	23.0	68.6	15.1	20.0	35.1
6 July	13.1	51.8	64.9	13.0	21.7	34.7
19 July	63.2	18.4	81.6	28.0	25.2	53.2
4 August	28.9	32.8	61.7	16.3	21.9	38.2
16 August	0.0 - 20.7	12.0	12.0 - 32.7	0.0 - 17.7	8.1	8.1 - 25.8
30 August	20.1	0.0 - 6.5	20.1 - 26.6	18.1	0.0 - 6.5	18.1 - 24.6
12 September	0.0 - 3.8	0.0 - 6.9	0.0 - 10.7	0.0 - 5.7	9.4	9.4 - 15.1
28 September	1.7 - 16.9	21.8	23.5 - 38.7	26.2	26.8	53.0
10 October	2.9	0.0 - 9.1	2.9 - 12.0	40.1	12.3	52.4
27 October	28.5	11.3	39.8	17.5	7.1	24.6
$\bar{x} \pm s^2$	21.3 $\pm$ 19.0	17.9 $\pm$ 14.5	39.2 $\pm$ 26.0	17.1 $\pm$ 11.2	14.2 $\pm$ 9.1	31.6 $\pm$ 16.9

- contaminated

¹For values less than the detection limit, the low point of the range was established by the $\text{o-P-O}_4\text{-P}$ value when this value was above detection limits; high point of the range is the detection limit for TP.

²Mean includes midpoints for values less than detection limits.

Table A-4. Amount of total nitrogen ($\text{mg m}^{-2} \text{ yr}^{-1}$) in bulk precipitation collectors at Port Charlotte, Florida, from June through October, 1978.

Date	North Collector			South Collector		
	Solution	Particulate	Total	Solution	Particulate	Total
7 June	1,050	329	1,379	759	105	864
21 June	1,059	32	1,091	644	0 - 23	644 - 667
6 July	992	491	1,483	569	209	778
19 July	1,154	228	1,382	1,129	344	1,473
4 August	-	-	-	-	-	-
16 August	1,821	383	2,204	1,779	290	2,069
30 August	-	-	-	1,270	140	1,410
12 September	1,122	141	1,263	-	-	-
28 September	1,280	270	1,550	2,203	487	2,690
10 October	1,373	32	1,405	3,407	0 - 32	3407 - 3439
27 October	-	-	-	-	-	-
$\bar{x} \pm s^1$	1,231 $\pm$ 269	238 $\pm$ 164	1,470 $\pm$ 328	1,470 $\pm$ 967	200 $\pm$ 166	1,670 $\pm$ 989

- contaminated

¹Mean includes midpoints for values less than detection limits.

Table A-5. Amount of total nitrogen ($\text{mg m}^{-2} \text{yr}^{-1}$) in bulk precipitation collectors in the study pond (North Port, Florida) from June through October, 1978.

Date	North Collector			South Collector		
	Solution ¹	Particulate	Total	Solution ¹	Particulate	Total
7 June	605	169	774	274	166	440
21 June	505 - 724	103	608 - 827	-	-	-
6 July	-	-	-	-	-	-
19 July	1,122	95	1,217	1,034	70	1,104
4 August	998	79	1,077	481 - 759	109	590 - 868
16 August	976	70	1,046	675	210	885
30 August	859	99	958	-	-	-
12 September	285	0 - 24	285 - 309	307	29	336
28 September	1,084	50	1,134	757	68	825
10 October	439	0 - 31	439 - 470	330	0 - 31	330 - 361
27 October	-	-	-	-	-	-
$\bar{x} \pm s^2$	776 $\pm$ 300	77 $\pm$ 48	853 $\pm$ 317	571 $\pm$ 282	95 $\pm$ 71	666 $\pm$ 298

- contaminated

¹For values less than the detection limit, the low point of the range was established by the NH_3 and NO_3+NO_2 values when these values were above detection limits; high point of the range is the detection limit for TN.

²Mean includes midpoints for values less than detection limits.

Table A-6. Amount of total nitrogen ($\text{mg m}^{-2} \text{ yr}^{-1}$) in bulk precipitation collectors in the sandy flatlands near the study pond (North Port, Florida) from June through October, 1978.

Date	East Collector			West Collector		
	Solution ¹	Particulate	Total	Solution ¹	Particulate	Total
7 June	703	56	759	334	37	371
21 June	810	123	933	686	71	757
6 July	586 - 1,045	343	929 - 1,388	583 - 1,037	193	776 - 1,230
19 July	1,255	80	1,335	1,360	151	1,511
4 August	462 - 643	37	499 - 680	642 - 773	25	667 - 798
16 August	2,079	40	2,119	634	89	723
30 August	337	48	385	703	35	738
12 September	140 - 190	0 - 24	140 - 214	208 - 283	70	278 - 353
28 September	660	65	725	2,201	78	2,279
10 October	369	21	390	696	73	769
27 October	523	71	594	293	0 - 31	293 - 324
$\bar{x} \pm s^2$	752 $\pm$ 528	81 $\pm$ 92	833 $\pm$ 546	788 $\pm$ 559	76 $\pm$ 54	864 $\pm$ 580

- contaminated

¹For values less than the detection limit, the low point of the range was established by the NH_3 and NO_3+NO_2 values when these values were above detection limits; high point of the range is the detection limit for TN

²Mean includes midpoints for values less than detection limits.

APPENDIX B
CHEMICAL COMPOSITION OF THE POND SEDIMENTS

Table B-1. Chemical composition of the pond sediments.

Core designation: C1
Location: Center

Surface elevation: 3.42 m msl
Bottom elevation: 2.60 m msl

Depth (cm)	Organic matter (mg cc ⁻¹)	C (mg cc ⁻¹) ^a	N (mg cc ⁻¹)	P (mg cc ⁻¹)
0- 3	175.4	73.3	10.26	0.267
3- 8	111.4	47.4	4.72	0.143
8-13	71.7	30.9	2.15	0.087
13-18	98.9	42.0	4.24	0.189
18-23	60.1	25.7	2.18	0.191
23-28	78.6	34.0	2.03	0.154
28-33	61.6	26.0	2.99	0.232
33-38	82.5	35.5	2.51	0.169
38-43	57.6	24.8	1.72	0.139
43-48	61.5	26.5	1.83	0.103
48-53	79.9	34.5	2.24	0.160
53-58	71.7	30.8	2.25	0.140
58-63	60.0	25.5	1.84	0.127
63-68	86.1	37.0	2.57	0.107
68-73	59.7	25.4	3.04	0.120
73-78	68.9	29.4	3.41	0.114
78-83	45.7	19.7	1.21	0.105
83-88	24.1			
88-93	24.3			

$$^aC = (\text{organic matter} - \text{nitrogen}) 0.444.$$

— — — Bottom of the sediments (see text).

Table B-2. Chemical composition of the pond sediments.

Core designation: C2 Surface elevation: 3.42 m msl
 Location: Center Bottom elevation: 2.60 m msl

Depth (cm)	Organic matter (mg cc ⁻¹)	C (mg cc ⁻¹) ^a	N (mg cc ⁻¹)	P (mg cc ⁻¹)
0- 3	164.4	66.9	13.78	0.262
3- 8	120.4	50.8	8.47	0.211
8-13	79.0	33.7	3.20	0.141
13-18	79.0	33.9	3.27	0.137
18-23	97.5	41.6	3.95	0.186
23-28	91.2	39.4	2.90	0.237
28-33	87.9	38.0	2.68	0.235
33-38	82.7	35.7	2.73	0.220
38-43	62.4	26.8	1.92	0.176
43-48	60.6	26.2	1.78	0.154
48-53	79.4	34.2	2.37	0.174
53-58	62.8	27.1	1.75	0.103
58-63	58.3	25.1	1.78	0.107
63-68	79.9	34.5	2.34	0.133
68-73	67.5	29.0	2.76	0.138
73-78	74.1	31.9	2.57	0.144
78-83	61.1	26.3	2.40	0.139

83-88	59.4			
88-93	44.0			

^aC = (organic matter - nitrogen) 0.444.

--- Bottom of the sediments (see text).

Table B-3. Chemical composition of the pond sediments.

Core designation: C3
 Location: Center

Surface elevation: 3.42 m msl
 Bottom elevation: 2.60 m msl

Depth (cm)	Organic matter (mg cc ⁻¹)	C (mg cc ⁻¹) ^a	N (mg cc ⁻¹)	P (mg cc ⁻¹)
0- 3	---b	---b	---b	---b
3- 8	120.4	51.5	4.51	0.140
8-13	102.2	43.7	3.75	0.142
13-18	77.1	32.8	3.17	0.125
18-23	100.5	43.1	3.47	0.199
23-28	84.2	36.0	3.03	0.226
28-33	59.5	25.6	1.84	0.179
33-38	80.9	34.7	2.75	0.268
38-43	86.7	37.0	3.27	0.290
43-48	57.5	24.8	1.58	0.132
43-53	59.6	25.6	1.98	0.143
53-58	64.4	27.9	1.51	0.139
58-63	63.3	27.4	1.54	0.123
63-68	70.1	30.2	2.04	0.137
68-73	72.3	31.1	2.28	0.132
73-78	77.7	33.3	2.62	0.129
78-83	53.4	23.0	1.53	0.138

83-85	46.0	19.8	1.48	0.153

^aC = (organic matter - nitrogen) 0.444.

^bNo sample; contaminated.

--- Bottom of the sediments (see text).

Table B-4. Chemical composition of the pond sediments.

Core designation: NW1
 Location: 7.1 m northwest of center

Surface elevation: 3.62 m msl
 Bottom elevation: 2.67 m msl

Depth (cm)	Organic matter ₁ (mg cc ⁻¹)	C (mg cc ⁻¹) ^a	N (mg cc ⁻¹)	P (mg cc ⁻¹)
0 - 3.00	135.2	56.2	9.21	0.245
3.00- 8.75	60.8	26.1	2.08	0.113
8.75-14.50	88.4	38.0	2.92	0.132
14.50-20.25	106.6	45.8	3.43	0.159
20.25-26.00	89.7	38.3	2.97	0.152
26.00-31.75	90.1	38.9	2.84	0.191
31.75-37.50	78.3	33.6	2.53	0.174
37.50-43.25	82.4	35.7	2.09	0.163
43.25-49.00	93.6	40.4	2.67	0.183
49.00-54.75	91.0	39.2	2.78	0.139
54.75-60.50	68.3	29.2	2.46	0.115
60.50-66.25	69.9	30.6	2.07	0.101
66.25-72.00	75.4	32.4	2.34	0.103
72.00-77.75	73.2	31.5	2.19	0.102
77.75-83.50	68.8	29.6	2.07	0.104
83.50-89.25	70.0	30.2	1.93	0.115
89.25-95.00	62.4	27.0	1.61	0.138

95.00-99.60	38.3			

^aC = (organic matter - nitrogen) 0.444.

--- Bottom of the sediments (see text).

Table B-5. Chemical composition of the pond sediments.

Core designation: NE1 Surface elevation: 3.62 m msl
 Location: 8.35 m northeast Bottom elevation: 2.84 m msl
 of center

Depth (cm)	Organic matter (mg cc ⁻¹)	C (mg cc ⁻¹) ^a	N (mg cc ⁻¹)	P (mg cc ⁻¹)
0- 3	163.0	69.0	7.65	0.227
3- 8	119.5	50.7	5.27	0.207
8-13	83.3	35.8	2.71	0.151
13-18	61.9	26.8	1.59	0.112
18-23	63.6	27.0	2.91	0.151
23-28	103.8	44.7	3.15	0.181
28-33	101.1	43.7	2.68	0.181
33-38	107.0	46.4	2.53	0.181
38-43	76.3	32.6	2.94	0.174
43-48	79.4	34.2	2.44	0.147
48-53	75.7	32.7	2.08	0.161
53-58	71.2	30.7	2.04	0.139
58-63	64.3	27.7	1.92	0.122
63-68	62.7	27.2	1.47	0.093
68-73	73.9	31.9	2.14	0.106
73-78	78.5	33.7	2.57	0.137

78-83	39.4	17.1	0.94	0.147
83-88	39.5			
88-93	41.0			
93-98	41.1			

^aC = (organic matter - nitrogen) 0.444.

--- Bottom of the sediments (see text).

Table B-6. Chemical composition of the pond sediments.

Core designation: SE1
Location: 8.62 m southeast
of center

Surface elevation: 3.62 m msl
Bottom elevation: 2.79 m msl

Depth (cm)	Organic matter (mg cc ⁻¹)	C (mg cc ⁻¹) ^a	N (mg cc ⁻¹)	P (mg cc ⁻¹)
0- 3	160.1	68.3	6.38	0.191
3- 8	117.2	50.4	3.78	0.185
8-13	74.0	31.8	2.48	0.141
13-18	76.1	32.9	2.05	0.155
18-23	66.7	28.7	1.95	0.176
23-28	72.6	31.4	1.99	0.187
28-33	84.4	36.3	2.66	0.163
33-38	84.4	36.2	2.97	0.179
38-43	64.0	27.3	2.47	0.150
43-48	68.7	29.4	2.47	0.116
48-53	56.0	24.0	2.01	0.088
53-58	62.1	26.6	2.10	0.100
58-63	63.3	27.2	1.95	0.096
63-68	62.7	27.0	1.94	0.093
68-73	68.7	29.4	2.41	0.105
73-78	71.6	30.7	2.48	0.094
78-83	49.5	21.3	1.60	0.109
83-88	43.3			
88-93	35.8			

$$^aC = (\text{organic matter} - \text{nitrogen}) 0.444.$$

— — — Bottom of the sediments (see text).

Table B-7. Chemical composition of the pond sediments.

Core designation: SW1 Surface elevation: 3.62 m msl
 Location: 8.72 m southwest Bottom elevation: 2.84 m msl
 of center

Depth (cm)	Organic matter (mg cc ⁻¹)	C (mg cc ⁻¹) ^a	N (mg cc ⁻¹)	P (mg cc ⁻¹)
0- 3	120.4	50.2	7.40	0.213
3- 8	144.9	62.0	5.17	0.168
8-13	94.2	40.3	3.53	0.140
13-18	83.1	35.6	2.97	0.150
18-23	89.0	38.1	3.20	0.187
23-28	71.0	30.4	2.46	0.135
28-33	63.8	27.5	1.94	0.116
33-38	98.7	42.2	3.74	0.203
38-43	66.1	28.4	2.17	0.119
43-48	73.1	31.5	2.24	0.141
48-53	77.2	33.2	2.36	0.125
53-58	47.4	20.5	1.31	0.100
58-63	62.6	27.1	1.48	0.105
63-68	69.2	29.8	2.15	0.123
68-73	74.4	32.1	2.21	0.104
73-78	54.1	23.5	1.21	0.092

78-83	30.0	13.0	0.77	0.106

^aC = (organic matter - nitrogen) 0.444.

--- Bottom of the sediments (see text).

Table B-8. Chemical composition of the pond sediments.

Core designation: S1
 Location 16.7 m south of center

Surface elevation: 3.82 m msl
 Bottom elevation: 3.57 m msl

Depth (cm)	Organic matter (mg cc ⁻¹)	C (mg cc ⁻¹) ^a	N (mg cc ⁻¹)	P (mg cc ⁻¹)
0 - 3.0	158.4	68.0	5.23	0.129
3 - 5.5	190.0	80.9	7.81	0.187
5.5- 8.0	120.2	51.1	5.07	0.117
8.0-10.5	119.6	50.6	5.57	0.139
10.5-13.0	76.1	32.6	2.65	0.105
13.0-15.5	97.0	41.8	2.79	0.111
15.5-18.0	47.4	20.4	1.56	0.083
18.0-20.5	42.6	18.4	1.21	0.071
20.5-23.0	56.5	24.3	1.72	0.090
23.0-25.5	44.2	19.1	1.10	0.068

25.5-28.0	27.1	11.6	0.90	0.060
28.0-30.5	28.0	12.1	0.80	0.063
30.5-33.0	30.6	13.2	0.94	0.071
33.0-35.5	29.2	12.7	0.69	0.055
35.5-38.0	22.2	9.6	0.53	0.064
38.0-43.0	16.3	7.1	0.41	0.047
43.0-48.0	20.5	8.8	0.58	0.067
48.0-53.0	25.1			
53.0-58.0	18.8			
58.0-63.0	12.2			

^aC = (organic matter - nitrogen) 0.444.

— — — Bottom of the sediments (see text).

Table B-9. Chemical composition of the pond sediments.

Core designation: E1 Surface elevation: 3.82 m msl
 Location: 18.3 m east of Bottom elevation: 3.59 m msl
 center

Depth (cm)	Organic matter ¹ (mg cc ⁻¹)	C (mg cc ⁻¹) ^a	N (mg cc ⁻¹)	P (mg cc ⁻¹)
0 - 3.0	125.9	53.0	6.55	0.171
3.0- 5.5	143.3	60.8	6.28	0.156
5.5- 8.0	172.6	74.2	5.58	0.124
8.0-10.5	106.7	45.8	3.58	0.110
10.5-13.0	70.1	30.1	2.37	0.109
13.0-15.5	63.0	27.2	1.74	0.119
15.5-18.0	57.7	25.0	1.50	0.086
18.0-20.5	49.3	21.4	1.14	0.089
20.5-23.0	48.9	21.1	1.33	0.081

23.0-25.5	40.4	17.5	0.97	0.065
25.5-28.0	41.9	18.2	0.82	0.052
28.0-30.5	28.3	12.2	0.89	0.067
30.5-33.0	29.5	12.8	0.65	0.050
33.0-35.5	31.2	13.5	0.85	0.043
35.5-38.0	30.2	13.2	0.45	0.054
38.0-43.0	24.6	10.6	0.75	0.050
43.0-48.0	22.4	9.5	0.91	0.044
48.0-53.0	11.2			
53.0-58.0	10.7			
58.0-61.8	10.1			

^aC = (organic matter - nitrogen) 0.444.

--- Bottom of the sediments (see text).

Table B-11. Chemical composition of the pond sediments.

Core designation: N1
 Location: 21.4 m north of center

Surface elevation: 3.82 m msl
 Bottom elevation: 3.43 m msl

Depth (cm)	Organic matter (mg cc ⁻¹)	C (mg cc ⁻¹) ^a	N (mg cc ⁻¹)	P (mg cc ⁻¹)
0 - 3.0	86.1	36.3	4.25	0.099
3.0- 7.5	108.8	45.7	5.90	0.152
7.5-12.0	111.3	47.7	3.92	0.130
12.0-16.5	79.1	33.7	3.11	0.115
16.5-21.0	63.5	27.4	1.86	0.132
21.0-25.5	52.8	22.7	1.66	0.086
25.5-30.0	48.9	21.0	1.54	0.076
30.0-34.5	63.9	27.5	2.02	0.109
34.5-39.0	50.4	21.6	1.68	0.074

39.0-43.5	36.5	15.6	1.41	0.085
43.5-48.0	42.2	18.2	1.20	0.081
48.0-52.5	48.6	21.0	1.33	0.081
52.5-57.0	42.2	18.3	0.97	0.063
57.0-61.5	55.6	23.8	2.01	0.106
61.5-66.0	36.4	15.8	0.85	0.056
66.0-71.0	26.7	11.6	0.65	0.074
71.0-76.0	42.7	18.5	1.04	0.071

^aC = (organic matter - nitrogen) 0.444.

--- Bottom of the sediments (see text).

Table B-12. Chemical composition of the pond sediments.

Core designation: SW2 Surface elevation: 4.02 m msl
 Location: 27.9 m southwest Bottom elevation: 3.93 m msl
 of center

Depth (cm)	Organic matter (mg cc ⁻¹)	C (mg cc ⁻¹) ^a	N (mg cc ⁻¹)	P (mg cc ⁻¹)
0- 3	105.1	44.3	5.24	0.144
3- 6	59.6	25.3	2.65	0.078
6- 9	55.5	23.7	2.18	0.084

9-12	30.3	13.0	1.13	0.053
12-15	23.0	9.9	0.81	0.060
15-18	14.1	6.1	0.47	0.045
18-20	10.8	4.6	0.33	0.050

^aC = (organic matter - nitrogen) 0.444.

--- Bottom of the sediments (see text).

Table B-13. Chemical composition of the pond sediments.

Core designation: SE2 Surface elevation: 4.02 m msl
 Location: 24.8 m southeast Bottom elevation: 3.93 m msl
 of center

Depth (cm)	Organic matter (mg cc ⁻¹)	C (mg cc ⁻¹) ^a	N (mg cc ⁻¹)	P (mg cc ⁻¹)
0- 3	117.6	48.9	7.48	0.174
3- 6	60.3	25.3	3.35	0.108
6- 9	63.3	27.6	2.66	0.089

9-12	32.0	13.6	1.34	0.060
12-15	25.9	11.0	1.05	0.061
15-18	19.8	8.5	0.62	0.057
18-21	17.7	7.7	0.45	0.036
21-23	14.2	6.1	0.47	0.045

^aC = (organic matter - nitrogen) 0.444.

--- Bottom of the sediments (see text).

Table B-15. Chemical composition of the pond sediments.

Core designation: NE2 Surface elevation: 4.02 m msl
 Location: 27.4 m northeast Bottom elevation: 3.87 m msl
 of center

Depth (cm)	Organic matter (mg cc ⁻¹)	C (mg cc ⁻¹) ^a	N (mg cc ⁻¹)	P (mg cc ⁻¹)
0- 3	150.5	62.6	9.47	0.230
3- 6	75.0	31.9	3.23	0.111
6- 9	72.3	31.0	2.43	0.084
9-12	45.1	19.5	1.18	0.061
12-15	47.6	20.5	1.35	0.099

15-18	37.3	16.3	0.67	0.060
18-20	31.4	13.7	0.63	0.045

^aC = (organic matter - nitrogen) 0.444.

--- Bottom of the sediments (see text).

Table B-16. Chemical Composition of the pond sediments.

Core designation: S2
 Location: 43.3 m south of center

Surface elevation: 4.21 m msl
 Bottom elevation: 4.18 m msl

Depth (cm)	Organic matter (mg cc ⁻¹)	C (mg cc ⁻¹) ^a	N (mg cc ⁻¹)	P (mg cc ⁻¹)
0- 3	99.0	41.3	5.95	0.119
3- 8	37.7	16.2	1.21	0.044
8-13	18.7	8.2	0.26	0.043
13-18	11.5	4.9	0.49	0.040
18-23	7.1	3.1	0.22	0.035
23-28	8.1	3.5	0.26	0.053
28-30	4.9	2.0	0.30	0.037

^aC = (organic matter - nitrogen) 0.444.

--- Bottom of the sediments (see text).

Table B-17. Chemical composition of the pond sediments.

Core designation: N2
 Location: 53.0 m north of center
 Surface elevation: 4.21 m msl
 Bottom elevation: 4.13 m msl

Depth (cm)	Organic matter ₁ (mg cc ⁻¹)	C (mg cc ⁻¹) ^a	N (mg cc ⁻¹)	P (mg cc ⁻¹)
0- 3	127.9	53.8	6.63	0.149
3- 8	101.3	43.5	3.42	0.070

8-13	40.8	17.7	0.96	0.050
13-18	26.1	11.3	0.63	0.049
18-23	11.7	5.1	0.29	0.041
23-28.5	8.6	3.8	0.15	0.055

^aC = (organic matter - nitrogen) 0.444.

--- Bottom of the sediments (see text).

Table B-18. Chemical composition of the pond sediments.

Core designation: E2 Surface elevation: 4.21 m msl
 Location: 47.9 m east of Bottom elevation: 4.13 m msl
 center

Depth (cm)	Organic matter (mg cc ⁻¹)	C (mg cc ⁻¹) ^a	N (mg cc ⁻¹)	P (mg cc ⁻¹)
0- 3	130.7	55.8	5.12	0.126
3- 8	75.5	32.3	2.77	0.064

8-13	41.2	17.7	1.23	0.053
13-18	19.2	8.4	0.23	0.051
18-23	14.9	6.5	0.28	0.041
23-28	10.8	4.7	0.32	0.062

^aC = (organic matter - nitrogen) 0.444.

--- Bottom of the sediments (see text).

Table B-19. Chemical composition of the pond sediments.

Core designation: W2
 Location: 58.9 m west of center

Surface elevation: 4.21 m msl
 Bottom elevation: 4.18 m msl

Depth (cm)	Organic matter (mg cc ⁻¹)	C (mg cc ⁻¹) ^a	N (mg cc ⁻¹)	P (mg cc ⁻¹)
0- 3	86.8	36.7	4.23	0.098
3- 8	42.2	18.2	1.31	0.060
8-13	26.2	11.4	0.51	0.046
13-18	10.7	4.6	0.26	0.060
18-23	7.7	3.2	0.43	0.044
23-26.5	6.5	2.8	0.18	0.044

^aC = (organic matter - nitrogen) 0.444.

--- Bottom of the sediments (see text).

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BIOGRAPHICAL SKETCH

James Mark Coleman was born April 9, 1946, in Chicago, Illinois. He received his high school diploma from Gonzaga High School, Washington, D. C., in June, 1964. He enrolled at Loyola University, New Orleans, Louisiana, in September of 1964 and graduated from the same institution in 1969 with a Bachelor of Arts degree.

After attending the University of South Florida, Tampa, Florida, for one year, he entered the Graduate School of The University of Tennessee in March, 1973. He taught as a Graduate Teaching Assistant in Biology from June, 1973, to June, 1974, at which time he received a Graduate Fellowship from the U. S. Army Corps of Engineers to complete his research. He received a Master of Science degree in ecology from the University of Tennessee in August, 1975.

He entered the doctoral program at the University of Florida in September, 1975, and for one-and-a-half years held various teaching and research assistantships. After admission to candidacy early in 1977, he took a position as a research supervisor at Environmental Quality Laboratory, Inc., Port Charlotte, Florida, and is presently employed there. He is a member of the Ecological Society of America.

He is married to the former Lynda Lee Lundberg of Springfield, Virginia.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality; as a dissertation for the degree of Doctor of Philosophy.

Edward S. Deevey, Jr., Chairman
Graduate Research Professor of Botany
Florida State Museum

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

John J. Ewel
Associate Professor of Botany

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Frank G. Nordlie
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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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This dissertation was submitted to the Graduate Faculty of the College of Agriculture and to the Graduate Council, and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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