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QUANTITATIVE AND QUALITATIVE RESPONSES OF LAKE EOLA TO URBAN RUNOFF

BY

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B.S.C.E., University of Maryland, 1977

THESIS

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ABSTRACT

For temperate lakes which receive a variable nutrient loading with seasonal variance in their hydrology, it is necessary to consider the dynamic response of the lake to these variable nutrient loadings. An approach to evaluate Lake Eola water quality responses to dynamic discharge of nutrients is presented. The major source of nutrients for this lake is stormwater runoff containing nitrogen and phosphorus. A mass balance of nutrient sources and sinks for the period of one year (April 1980 - March 1981) was performed. To accomplish this, a field determination for various parameters of the hydrologic budget was performed on a monthly basis. A monthly water quality analysis of the lake was measured.

It was determined that Lake Eola was phosphorus limited and that 87% of the Total Phosphorus entering the lake via stormwater runoff was retained in the bottom sediments. Retention of various nutrients ranged from 77% to 93%.

In order to evaluate the dynamic response of this lake, it was necessary to consider the retention of the nutrients as a function of time. The inductive methodology for this analysis and an example for Total Phosphorus is presented.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to the following persons for their efforts in the completion of this work. First and foremost, I would like to thank Dr. Yousef A. Yousef for his invaluable guidance and direction throughout this study. I would also like to thank Prof. Harvey Harper for his supply of the lake column quality data.

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Last, but certainly not least, I would like to express my appreciation to Sharon Darling and Lee Yi for the typing of this Thesis.

BIOGRAPHICAL SKETCH

Timothy Brian Walsh was born in Washington, D.C. in 1955. He attended the University of Maryland where he received his B.S.C.E. in 1977. Thereafter, he worked for short periods of time for a private consulting firm and the U.S. Army Corps of Engineers. Since 1980, he has attended the University of Central Florida. The work performed for his thesis was conducted in Lake Eola Park, Orlando, Florida.

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CHAPTER I

INTRODUCTION

Many investigators have stressed hydrologic parameters from drainage basins, however, the impact of these parameters on quality of receiving water body has not been investigated. Not until recently, Federal, State and local agencies responsible for the integrity of our streams and lakes, have stressed investigating the environmental impact of stormwater runoff on adjacent water bodies. It is realized that pollutants carried by the stormwater runoff to streams undergo complex processes and detailed analyses of these processes are an extremely difficult task.

Attention has been focused on Lake Eola located at the downtown Orlando, Florida. This lake attracts tourists, and is the location for many social events, concerts etc. It is a small landlocked lake located in downtown Orlando, Florida. It has a surface area of 1,176,120 square feet (109,224 m^2) at 88.00 MSL., volume of 11,675,458 cubic feet (330,649 m^3) and an average depth of 10 ft (3.0 M). It's surrounding watershed is comprised of commercial and residential area.

There are no constant flowing streams either entering or exiting the lake. However a drainage well to one of the upper confined aquifers maintains the lake level between 88.5 and 87.0 feet above mean sea level. The surrounding watershed drains via 13 storm sewers to the lake and drainage wells to a confined aquifer. One of these wells has become clogged and is inoperative. Therefore, the surface drainage to the lake appears to be 230 acres.

Stormwater runoff contains various pollutants which severely degrade the quality of the lake. Among its problems is the excessive algal blooms which bring about a eutrophic state. This condition usually occurs during the summer months which also coincides with the rainy season.

Scope and Objectives

In order to effectively design remedial techniques, it is necessary to understand lake responses to this unsteady state hydrologic cycle. Therefore, for the period of one year, the water budget of the lake was fully analyzed. This was performed by field measurement of the various parameters of the water budget, including evaporation, drainage well discharge, stormwater runoff, direct precipitation and groundwater seepage.

The results of this analysis were combined with lake quality data gathered throughout this same year. An attempt was made to correlate the quality parameters: Chlorophyl "a", Total Phosphorus, Total Orthophosphorus, Nitrate Nitrogen and Total Kjeldahl Nitrogen concentrations to precipitation events on a month by month basis.

The hydrodynamic impacts of the hydrologic cycle were analyzed using the mass-balance floating average calculation. A model was developed to simulate this hydrodynamic impact and calibrated for

Lake Eola for this study year. This model was mass-balanced in nature and utilized estimates developed in the floating average calculations.

CHAPTER II

LITERATURE REVIEW AND BACKGROUND THEORY

In determining the water budget for a lake, it is a standard practice to use a mass balance approach. The mass balance approach utilizes the concept that changes in lake storage are the result of differences in the net inflows and net outflows. Some of these paths that water may take in either entering or leaving the lake are shown in Figure 1.

An example of a mass balance equation for a lake is given below:

$$\Delta V = P + SF_I - SF_O + G_I - G_O + OF - E \tag{1}$$

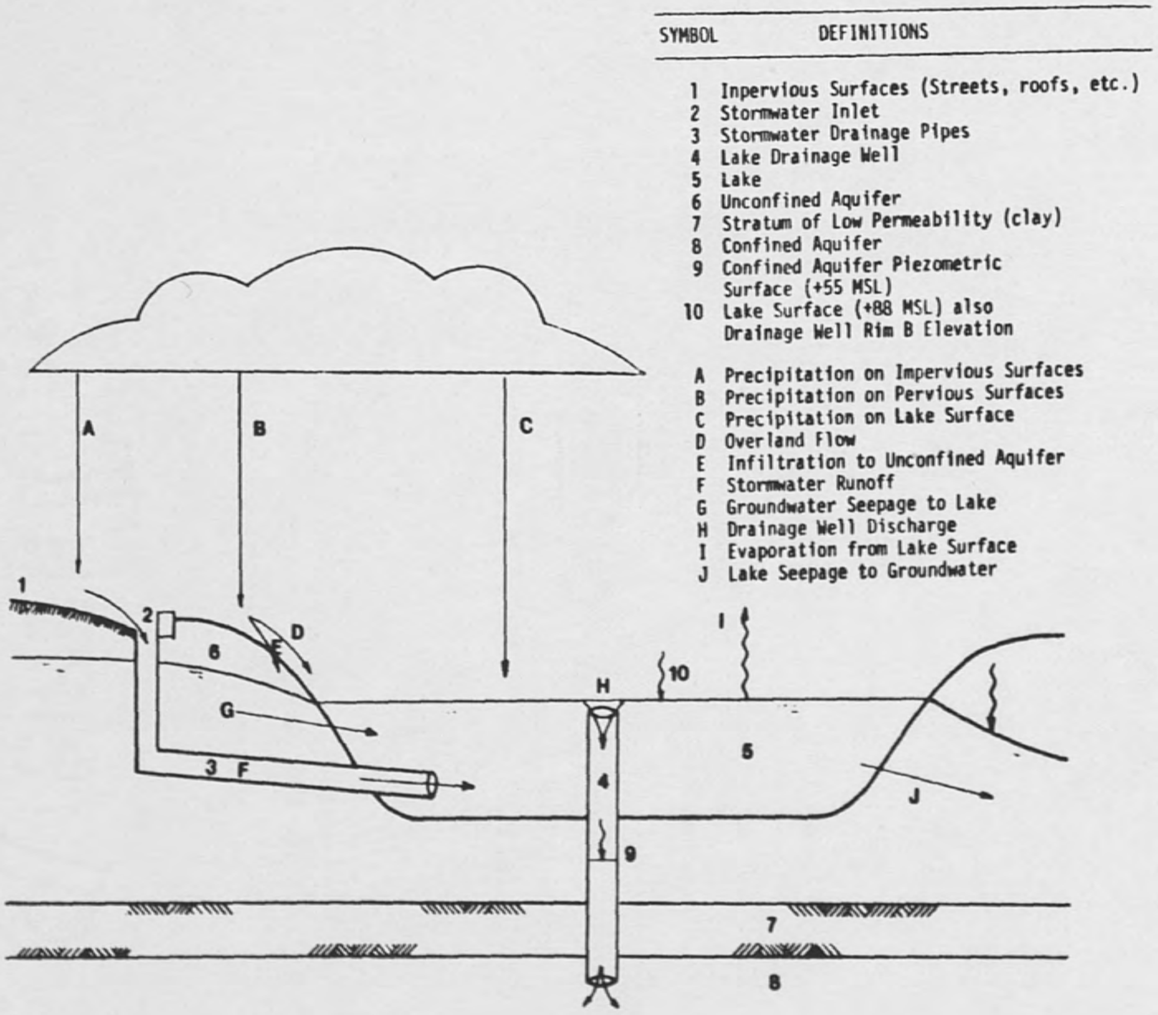
where:

ΔV = change in lake storage;
P = precipitation falling directly on the lake surface;
SF_I = stream inflow;
SF_O = stream outflow;
G_I = groundwater seepage flowing into the lake;
G_O = groundwater seepage flowing out of the lake;
OF = overland flow into the lake;
E = evaporation from the lake surface.

An evaluation of the methods for determining the various parameters of the above mass balance equation will be presented in the following pages.

Changes in Lake Storage

With proper topographic surveying techniques and a staff gage, changes in lake storage are easily measured by knowing the surface



SYMBOL	DEFINITIONS
1	Inpervious Surfaces (Streets, roofs, etc.)
2	Stormwater Inlet
3	Stormwater Drainage Pipes
4	Lake Drainage Well
5	Lake
6	Unconfined Aquifer
7	Stratum of Low Permeability (clay)
8	Confined Aquifer
9	Confined Aquifer Piezometric Surface (+55 MSL)
10	Lake Surface (+88 MSL) also Drainage Well Rim B Elevation
A	Precipitation on Impervious Surfaces
B	Precipitation on Pervious Surfaces
C	Precipitation on Lake Surface
D	Overland Flow
E	Infiltration to Unconfined Aquifer
F	Stormwater Runoff
G	Groundwater Seepage to Lake
H	Drainage Well Discharge
I	Evaporation from Lake Surface
J	Lake Seepage to Groundwater

Fig. 1. Schematic showing hydrologic parameters for Lake Eola watershed.

area of the lake and changes in lake stage.

Precipitation Measurements

Precipitation data has been collected from the time of the Ancient Greeks. Although no measurement of volume was recorded, the dates of rain and qualitative descriptions were. In approximately 400 B. C., Kautilya set out the first rain gage ever recorded. Several other ancient societies used rain gages for tax purposes on agricultural lands. Sir Christopher Wren (1632-1723) made the first self recording rain gage. However, there is no record of it ever being used for regular observations of rainfall. Perrault (circa 17th Century) measured annual rainfall in Paris and calculated that one-sixth of the volume of rainfall was sufficient for river flow volumes.

Many other rain gages have since been made; some self recording. There are also some rain gages with built-in radio transmitters for data collection in remote areas (Biswas 1967).

Rain gages come in various shapes and sizes also (Jones 1969). experimented with different orifice sized and shaped rain gages. He showed that both size and shape have effects on recordings. The larger gages, 12 inch diameter, recorded 2.5% more rainfall than the 8 inch diameter gages. Gages with sloping shoulders also collected 2-6% less rainfall than gages with the shape of a right cylinder.

Since Eichmeiser (1965) found a greater reduction in catch for the gage with the shortest stack extension above the shoulder, it may be assumed that the seriousness of the catch reduction will depend on the proximity of the sloping surface to the orifice as well as exposure to the wind.

Weiss (1963) stated that wind speed causes catch deficiencies on precipitation gages and that the effect is greater for snow than for rain. Weiss used momentum and energy equations to calculate the trajectory of a falling object with a wind force being exerted on it. He also stated that when a gage is raised above the ground and wind is present eddies are formed near the gage orifice resulting in deflection of the wind and rain by the gage.

Another problem with estimating precipitation by rain gages, and by far the most serious, is that a rain gage is a discrete sampling point and may or may not give an accurate average data over the watershed. It is advisable to set up a network of gages to try and minimize any local discontinuities, but unless every drop of precipitation is collected, it is impossible to be 100% confident of the estimates.

Several procedures have been proposed which provide an averaging technique for multi-gaged watersheds. The simplest and most straightforward is to take the arithmetic mean of all the gaged sites. This method is reasonably correct for area of flat topography with evenly spaced gages and for recorded values that do not appreciably differ from the mean.

These limitations can be partially overcome if topographic influences and areal representivity are considered in the selection of gage sites. Wilm, Nelson and Storey (1939) studied the rainfall distribution of two small mountainous watersheds of high topographic relief in the San Gabriel Mountains, California. Using 57 gages in one watershed and 47 gages in the other and 10 storms, they found deviations (standard error) between the arithmetic average and the weighted mean from isohyetal maps of -4.3 to 1.8% for one watershed and -1.3 to 6.8% for the other. The method employed was to draw parallel lines at 300 feet horizontal intervals perpendicular to the axis of the watershed. Where these lines crossed contours of 2100, 3100, 4100, and 5100 feet in elevations, gages were placed. In addition, they concluded that the requirements of accuracy of averages should be modified in inverse relation to the size and importance of the storms in these watersheds.

Sometimes the selection of gage sites is predetermined and a weighting technique is needed to accurately average the values recorded at the individual sites. Thiessen (1911) using a hypothetical watershed and storm with various intensities across the watershed determined the following method for calculating the weighted average:

1. Lines are drawn between adjacent gage sites.
2. A perpendicular bisector is drawn across these lines.
3. These bisectors then delineate a polygon about the gage site.
4. The area of each polygon is determined by planimetry and expressed as a percentage of the total area.
5. The weighted average rainfall is obtained by multiplying the precipitation values by its assigned percentage of area and totaling.

The major drawback of the Thiessen approach is the assumption that the rainfall varies linearly between the gage sites, which may or may not be valid.

The most accurate averaging technique is the construction of isohyetal lines or lines of equal precipitation. The area between the isohyetal lines is planimetered and multiplied by the average of the encompassing isohyets. Summation of the above values and division by the total area gives the most accurate weighted average of precipitation. The flexibility of the isohyetal method is both a help and a hinderance. Whereas, it allows the analyst to take into account surrounding features in its construction that might influence the weather, it also provides variability of isohyets drawn by separate analysts, and therefore, skill and judgement are required.

In addition to spatial variance of precipitation, sometimes one encounters the problem at a gage site where over time the catch of precipitation changes; for example, the construction of a large building, growth of trees, etc, adjacent to the gage site. To determine if the conditions surrounding a gage site have changed over time, Kohler (1949) proposed the double-mass analysis for testing the consistency of records at precipitation and stream gaging sites. The method employed is such that the values recorded at an individual site are plotted versus the mean average values for a network of sites in a cumulative manner over time. When the slope of the line changes, it becomes apparent that the consistency of the individual site with regard to the network of sites has changed. If the cause of this change in recording was from changes in meteorological conditions, the mean values would change in the same proportion and the slope of the line would not change. This concept has three implications. The first is that it provides a good check as to changes in the environment of a gage site. The second is that it allows for the correction of the values for this same site over time. The third is that, if necessary, to move a gage site, it is possible to determine if recording conditions are the same and if not, to allow for correction.

Singh (1968) presented a flow chart for a computer program that would facilitate the data handling of the Double-Mass Analysis method if a large network of gaging sites is to be frequently analyzed for consistency.

Stream Inflows and Outflows Measurements

Measurements of stream inflows and outflows can be made directly by the use of various available stream gages. However, in the case of Lake Eola where there are no constant running streams either into or out of the lake, stream gages are not appropriate. Instead, there are several urban stormwater sewer connections. For some time now, man has been studying methods for estimating the amount of water flowing in a stream generated by rainfall events. All of these methods include overland flow. Therefore, evaluation of the overland flow parameter in the mass balance equation will be covered in this section.

In the late 19th century, the Rational Method was developed. The Rational Method utilizes times of concentration, intensities of rainfall, watershed area and a runoff constant to determine the time and rate of flow in a stream. This method was developed for the peak flow design of urban storm sewers. Due to the small nature of the subwatersheds for each storm sewer, the Rational Method is reasonably accurate when considering the watershed in a micro sense. It is unreliable for estimating the time variant flow for the total watershed. It also requires accurate estimates of the runoff constant and the time of concentration.

Gregory and Arnold (1932) modified the Rational Method for the total watershed by taking into account the shape of the watershed, the slope of the watershed, the pattern of drainage and the elements of channel flow. Various other models have taken this approach. However, the major drawback of these types of models is the large number of input estimates which are subject to engineering judgement to be made. With field calibration, these estimates of the various drainage parameters can be optimized.

Hicks (1932) performed research measuring runoff from various covered lots with various slopes. This research supplied information on infiltration capacities of the soils in the Los Angeles area and overland flow rates for various slopes. In a sense, Hicks calibrated the Rational Method for the Los Angeles region and included conclusions that the infiltration capacity of a soil changes with the volume of precipitation.

Izzard (1947) developed a model to simulate overland flow for unsteady state flow conditions. Whereas, Izzard's research closely agreed with Hick's work, Izzard's method is limited by the equation $iL < 500$ where i is precipitation in inches per hour and L is length of travel in feet.

Sherman (1932) developed the unit hydrograph concept. This method is concerned not only with peak flow but also the time variance of the flows. The hyetograph or rainfall intensity vs. time plot is broken down into several storms of constant intensity and the individual hydrographs are summed to generate a composite hydrograph. This method requires an accurate unit hydrograph for the watershed in question. It does not take into account any changes in the unit hydrograph that would occur from changes in infiltration capacities of pervious areas for storms other than those used to generate the unit hydrograph. It also does not take into account any storage effects of the drainage system when summing the unit hydrographs.

More recently with the development of high speed digital computers, the linear reservoir concept has been utilized. In this method, a total rainfall excess for the entire watershed is generated overtime. This excess is placed in an imaginary reservoir and is released linearly based on the storage of water in the reservoir. A major problem with this method is selecting the linear constant thatdescribes the storage-discharge relationships of the reservoir. Also, the watershed in question may not act as a linear reservoir.

This latter problem may be taken into account by using not one but several reservoirs, with different storage-discharge relationships. In any event, this method is only as accurate as the input data supplied. Therefore, field calibration is required for each watershed.

An alternative to the Santa Barbara Urban Hydrograph Model was described by Diskin (1978). Basically, the rainfall excess is divided into two parts, the pervious and the impervious fractions. Each fraction is then routed through its own series of linear reservoirs. Diskin chose for the pervious fraction three reservoirs and for the impervious fraction two reservoirs. Then the size of the reservoirs (the storage-discharge relationship) was optimized by field calibration. The two parallel systems are then added together to obtain a composite hydrograph.

Hossain (1978) examined the accuracy of using a single unit hydrograph versus two unit hydrographs in a non-linear fashion. Certain storm events were used to develop the unit hydrographs. These unit hydrographs were then used to simulate other storms which were checked in the field for accuracy. Hossain concluded that no single unit hydrograph was valid for the watersheds he examined.

Hossain also examined using two unit hydrographs in a non-linear fashion to predict runoff-time relationships. Hossain concluded that the choice of the two hydrographs determined the accuracy of the predicted to the actual runoffs witnessed in the field.

Again, a major problem with using a unit hydrograph is that this hydrograph will generally change with intensity and volume of rainfall. Hossain did not discuss this in this paper. However, he did recognize this relationship in previous work on infiltration capacities of various permeable surfaces.

Evaporation Measurements

Many indirect methods are available for estimating the evaporation from lake surfaces. These methods vary in both amount and type of input estimates. In 1802, Dalton proposed the following equation for estimating evaporation (Lindsey, et al 1975):

$$E = (e_s - e_a)\ f(u) \tag{2}$$

where

E = evaporation in unit time
e_s = vapor pressure of the fluid at the surface
e_a = vapor pressure in the atmosphere above
$f(u)$= some function of the horizontal wind velocity

In 1931, Rohwer discovered a small variation in evaporation rates with changes in atmospheric pressures (Penman 1948). Reduced to sea level, Rohwer proposed the following equation:

$$E = 0.40\ (e_s - e_a)\ (1 + 0.17u_2)\ \text{mm/day} \tag{3}$$

where u_2 is the wind velocity measured two meters above the water surface.

Thornwaite (1939) proposed the theory that rates of evaporation were determined by a moisture concentration gradient in the turbulent lower atmosphere. From discussions with von Karman and Rossby, the following equation was derived:

$$E = K^2_o p(q_1 - q_2)/[\log(h_2/h_1)][\log(U_2/Z_o)] \qquad (4)$$

where:

E = evaporation from an open water body
p = density of the air
q_1 = moisture concentration at the lower level
q_2 = moisture concentration at the upper level
h_2 = height of the upper instruments
h_1 = height of the lower instruments
Z_o = roughness coefficient
K_o = Von Karman's coefficient
U_2 = wind velocity at the upper level

This formula takes into account the concepts of mixing length and shear stresses as developed by Prandtl and Von Karman (Thornwaite1939). It differs somewhat from the Dalton approach in that instead of the rate of evaporation being determined by moisture conditions at the boundary layer, the limiting factor is the rate of dissipation of the moisture in the atmosphere. Therefore, moisture measurements are required at two heights in the atmosphere.

Penman (1948) showed that the right order of magnitude of evaporation rates could be obtained by assuming that the main resistance to the evaporation "current" is provided by a thin layer of air next to the surface. In this layer, air movement is essentially non-turbulent and vapor movement across it is by a process of molecular diffusion.

Penman (1948) investigated evaporation from cylinders placed outside and exposed to various atmospheric conditions. Penman attempted to correlate evaporation with two theoretical evaporation mechanisms. The first, a sink strength concept followed Dalton's approach which states that evaporation is dependent on the difference of water vapor pressures between the atmosphere and the evaporating surface. The second, an energy balance approach, states that evaporation is dependent on the incoming short wave radiation from the sun and sky and the long wave radiation exchanges between the earth and sky. Penman concluded that although his data was scattered, but not very much worse than that obtained by other workers doing indoor experiments, it was significant and probably attributable to poor meteorological observations. Penman's work closely agreed with the sink strength work by Rohwer. For the energy balance, there was close agreement for one set of the surfaces which most closely satisfied the basic assumptions made in striking the balance. The other surfaces could not be correlated because the heat losses through the sides and bottom of the cylinders could not be measured.

Nordenson and Baker (1962) conducted experiments in an attempt to correlate pan to lake evaporation coefficients for various commonly used pans. Four U. S. Weather Bureau Class A pans (one shielded), two Bureau of Plant Industry Sunken Pans, one Sunken Colorado Pan, and one Sunken Young Screened Pan were tested against a sunken stock tank 15' in diameter and 2' deep. Using a ratio of free-water surface area to the area of the sides and bottom for the Bureau of Plant Industry pans, both insulated and sunken tests, the stock tank evaporation was adjusted to better simulate natural lake evaporation.

For the sunken pan tests, the pan to lake coefficients were greater than unity, but if corrected for heat losses through the sides and bottom yielded coefficients approximately 0.98 and 0.97. For the Class A pans, values of coefficients were 0.74 for the Silver Hill, Md. site and 0.69 for the Lake Hefner, Okla. site showing that pan to lake coefficients vary with climate.

When Christiansen (1968) was in Mediterranean countries, he found that every engineering firm's reports that he examined was using the Blaney-Criddle method for estimating water requirements. Christiansen devised a method that has the following form:

$$E = K\ R\ C \tag{5}$$

where:

E = monthly evaporation
K = dimensionless constant developed empirically
R = extraterrestial radiation with the same units as E
C = dimensionless coefficient based on climatic factors

The coefficient C is expressed as a product of subcoefficients C_x. These subcoefficients are parameters of temperature, wind speed, humidity, percentage of sunshine and elevation. Christiansen provides tables with various values for these subcoefficients. As opposed to the Blaney-Criddle method that only gives yearly estimates, Christiansen's method can be used to estimate monthly evaporation values.

Roberts and Stall (1966) conducted a detailed study of lake evaporation in Illinois utilizing a technique developed by the U. S. Weather Bureau. Monthly lake and pan evaporation rates were computed utilizing parameters of air temperature, dewpoint, solar radiation and wind speed. The results were checked for various periods over years at seven locations. They concluded that the process yields dependable results and can probably be used throughout the U. S.

Riley (1966) conducted experiments on the heat balance of a U. S. Weather Bureau Class A pan. Using two pans, one insulated and one not insulated, Riley discovered that in 10 out of 14 time periods, 29% of the total heat transferred to the uninsulated pan was from the sides and bottom. In the remaining periods, 6% of the heat leaving the pan was transferred through the sides and bottom. Elimination of this heat transfer resulted in a reduction of the daily evaporation rate by 28%.

Van Bavel (1966) conducted experiments correlating an equation, utilizing a combination of a surface energy balance equation and an approximate expression of water vapor and sensible heat transfer for potential evaporation, to net radiation, ambient air properties and surface roughness. The tests were performed in Pheonix, Ariz. using open water, bare soil and well-watered alfalfa and showed excellent agreement of calculated and measured values on an hourly and daily basis.

Kohler and Parmelle (1967) presented a technique for deriving free-water evaporation estimates from a network observations of air temperature, dew point, wind movement and incoming minus reflected radiation. The equations developed were tested with data collected at Lake Hefner, Okla., Lake Mead, Ariz.-Nev., Felt Lake, Calif., Silver Hill, Md., and Sterling, Va. Except for Felt Lake, which had a questionable water budget, all data was in close agreement with the equations used in the technique.

Burman (1976) examined three methods of estimating pan evaporation from climatic data and compared these estimates with measurements from nine locations around the world. The three methods examined were the Christiansen (multiple correlation), the Kohler, Nordenson and Fox (combination theory of sink strength and energy balance) and the Olivier method (theoretical, solar radiation and wet bulb depression). Burman concluded that no single method was satisfactory at all locations. However, the Kohler et al. method provided estimates within 10% at 5 locations and the estimates were only excessive at 2 locations. The Christiansen method, which required as much input data as the Kohler method, was satisfactory at some locations. Overall the Olivier method which required the least input data yielded the poorest results.

Evaporation rates can be computed from the various methods described above with varying degrees of confidence. The selection of the method will depend upon the availability of the input data. The amount of data required ranges from published climatic tables for the multiple correlation methods to data from sophisticated instrumentation for the energy balance and sink strength methods.

Seepage Measurements

In the past, a water budget analysis of a lake usually had a missing parameter. This was the seepage inflow or outflow. This volume of water was calculated by the difference of the lake storage volume from the measurable inflow rates and outflow rates integrated over time. This is readily seen by rearranging equation 1 to the following equation:

$$G_I - G_O = \Delta V - P - SF_I + SF_O - OF + E \qquad (6)$$

However, only the net volume of seepage can be estimated and the accuracy of this estimate depends upon the accuracy of the measurable components.

Groundwater flow into lakes is controlled by the difference between the phreatic surface of the groundwater table and the lake elevations. Seepage occurs in the direction from the higher elevation to the lower assuming there is a porous medium connecting them.

Besides the water budget difference method described above, another indirect method of determing seepage from the groundwater to the lake or vice versa is to place a network of observation wells around the lake and monitor the water table elevation and the lake stage. If an accurate permeability of the soil can be estimated and the depth to an impermeable stratum can be defined, a flow net consisting of equipotential lines and equiflow lines can be generated based on Darcy's Law and utilizing Dupuit's assumption.

Whereas, the depth to an impermeable stratum is easily defined, it is very difficult to estimate the permeability of in-situ subsurface materials over an extended area with any degree of accuracy.

Lee (1977) demonstrated a technique for direct measurement of groundwater seepage into Lake Sallie, Minn. The device used was a large cylindrical container open at one end (55 gallon drum), placed open end down and pressed into the lake bottom sediments. Through the top of the cylinder a collection device is connected. This collection device consists of a flexible plastic bag, which allows the water that has seeped into the bag to remain at the same pressure as the surrounding lake water. Over a period of time the seepage through the lake bottom displaces an equal volume of water in the drum which enters the flexible bag. This volume of water is measured. The velocity of the seepage is calculated by dividing the volume of water collected by the time of collection and the surface area of the lake bottom enclosed by the drum. Seepage velocities of -0.1 to 2.58 um s^{-1} were witnessed with this device. An additional benefit to this method is that it allows for samples of groundwater, which has just entered the lake but has not mixed with the lake water, to be analyzed chemically. Certain precautions have to be undertaken to do this, because there is some lake water in the drum at the beginning to the test.

Fellows and Brezonik (1980) performed similar tests on two large lakes in suburban Orlando. The two lakes tested were Lake Apopka and Lake Conway. The tests were performed as part of overall water budgets for the lakes. The barrels were placed along transects perpendicular to the shoreline located along the shoreline. Seepage contributed 17.5% and 2.0% of the total hydraulic inputs to Lakes Apopka and Conway, respectively. Seepage flows ranged from 0 to 112 $1/m^2$/day and most were from 4 to 30 $1/m^2$/day. Seepage occurred primarily within 30 m of the shoreline. A seepage hydrograph for a high intensity storm was developed for Lake Conway. The water entering the lake via seepage from this rain amounted to .6% of the direct input to the lake surface.

Eutrophication

Fresh water lakes are subject to various types of pollution which include siltation, pesticide, thermal and nutrient loadings among many others. The impact of nutrient loading will be discussed in this section. The pollution problem arises when nutrient loadings rise above levels which the lake can adequately assimilate and maintain the delicate balance of its former food chain. Excess nutrient is usually manifested in the form of excessive algal blooms, followed by algal death and decay causing oxygen depletion and sometimes anaerobic conditions. These anaerobic conditions are responsible for unpleasant odors and fish kills.

Two chemical species are generally considered growth limiting. They are phosphorus and nitrogen. Lee, Rast and Jones (1978) pointed out that "algae typically need 106 carbon atoms and 16 nitrogen atoms for each phosphorus atom for growth and reproduction. On a mass basis C: N: P is 100: 17.6: 2.4. However, many investigators indicated that most of the lakes and reservoirs were phosphorus limited. They also pointed out that generally freshwater impoundments are phosphorus limited while marine systems are generally nitrogen limited. However, in some instances, species such as iron or silicon or even Vitamin B_{12} may be the limiting factor.

Chiandani and Vighi (1974), in a detailed study of relative nutrient requirements found phosphorus to be limiting above N:P mass ratios of 10:1, nitrogen to be limiting below 5:1 and a proportional relationship between these values.

Fixation of atmospheric N_2 was found to allow phosphorus proportional development of Phytoplankton in lakes with ionic N:P rations in input as low as 5:1 (Schindler 1978a). Therefore, the eutrophic state of freshwater lakes has generally been classified with regard to phosphorus load.

Vollenweider (1969) presented a mass balance model for the phosphorus load. He developed a linear relationship bewteen the log of the area loading of phosphorus vs. the log of the mean depth divided by the hydraulic residence time. Certain "dangerous" and "permissible" loading limits were described to separate eutrophic, mesotrophic and oligotrophic lakes.

Dillon (1975) modified this approach by including a factor to account for sediment uptake of a fraction of this phosphorus load. The Larsen-Mercier and Malueg Model (1974) utilizes this sediment uptake approach to describe the steady state lake and the input phosphorus concentration relationships as a function of sediment uptake.

Thomann (1977) discussed the various loading plot diagrams by previous investigators with respect to their common mass balance derivation. He emphasized the fact that biomass does not follow a linear relationship with available nutrients. Schindler (1978b) responded by referring to work by Vollenweider (1976) and himself (1978a) showing relative phytoplankton response over a wide range of areal loading rates (0.03 to 0.58 $g\text{-}P \cdot m^{-2} \cdot y^{-1}$). He also cited that data from the recovery of Lake Washington, Seattle fits

Vollenweider's model very well. These models have the general form of:

$$(P) = \frac{L_c\ (1 - R)}{\rho Z} \tag{7}$$

Where

(P) is the lake Phosphorus concentration

L_c is the annual areal loading rate of phosphorus

R is the fraction of incoming phosphorus retained in lake sediments

ρ is the flushing rate of lake volume

Z is the mean depth

This approach is valid for steady-state or lakes receiving a more or less instantaneous load such as the spring turnover of northern lakes. However, R is a difficult parameter to estimate. Vollenweider (1976) calculated this perameter by writing an apparent settling rate $R = t_p/t_w$ where t_p is the phosphorus residence time, t_w is the hydraulic residence time.

By comparing R values for different lakes, $\bar{t}_p/t_w$ was thought to have the form

$\bar{t}_p/t_w = x\ .\ (t_w)^{-\alpha}$ for $o<x<1$, x and α are constants.

Calculated α was found for these lakes to be approximately 0.5.

Writing $\bar{t}_p$ strictly as a functionof t_w has led many to believe that reducing the annual loading rate L_c by 90% will reduce (P) by 90%.

This may be incorrect for two reasons. The first is the disregard for any concentration or geomorphology dependent removal mechanisms. The second is the exclusion of any possible baseline concentration.

The sediment uptake fraction of the Phosphorus load will determine the water column concentration and subsequently, the biomass concentration. To determine nutrient loading, King (1978) stressed the importance of the water budget for the lake and the geomorphology of the drainage basin. Various sediments washed into the lake play an important role in the lake's sediment uptake of nutrients. Jones and Bachmann (1978) sampled 50 lakes and reservoirs across the State of Iowa. Thirty-two of the water bodies were located on the Des Moines lobe of the Wisconsin Glacial drift sheet. Soils in this region are younger than soils in the rest of the State. They found significantly greater concentrations of conservative ions such as chlorides in the Des Moines lobe. Whereas, this did not directly address the sediment uptake of Phosphorus, it does support King's contention that the geomorphology of the drainage basin plays an important role in the chemical makeup of the lake.

Nutrients associated with bottom sediments are released under favorable environmental conditions. Fee (1979) artificially fertilized eight lakes in the experimental lakes area (ELA), northwestern Ontario. He found that "rates of primary production during the ice-free season were linearly related to the ratio of epilimnion sediment area to epilimnion volume." This suggests that sediment release of phosphorus is from sediments in the epilimnion region.

Yeasted and Morel (1978) used data of various limnological parameters from 128 phosphorus limited lakes to predict lake trophic state for given phosphorus loadings. It appeared that classification of the lakes followed the mass balance models developed by Vollenweider (1967) and Dillon (1975). They found that longer residence times increased the retention capacity of nutrients by lake. This implied that the uptake of phosphorus by the sediments was time dependent. Also, the mass balance models implied that higher flushing rates (shorter residence times) are positively correlated with lake quality. Whereas, this does not invalidate the mass balance models, it does show a need for increased complexities in these models.

Tapp (1978) compared the use of simple mass balance models with the Complex Reservoir Model developed by USEPA (EPAECO). This model includes not only hydrodynamic mass balance parameters but also water quality and biological responses. These include temperature, zooplankton, algae, alkalinity and pH among many others. It simulates various water quality responses such as dissolved oxygen, orthophosphorus, green and blue-green algae concentrations with respect to percent reduction of incoming phosphorus loading. The reservoir used in this study was Lake Harding, Georgia. Eutrophic conditions would still exist with 90% removal of point source phosphorus loadings. However, for 99% removal of point source phosphorus loadings, total areal loading rates approached the Dillon and Larcen-Mercier dangerous limits, implying some improvement could be expected over time.

Brown, Harris and Koonce (1978) performed batch experiments on the uptake kinetics of dissolved inorganic phosphorus by lake microorganisms. The kinetics were determined as a function of uptake rates of phosphorus for various added phosphorus levels. Radiophosphorus (P) was used as a tracer. The data did not follow a simple Michaellis-Menton equation. It was, however, consistent (although not exclusively) with two simultaneously operating simple Michaelis-Menton transport mechanisms.

This means that two Michaelis-Menton equations algebraically added can be as follows:

$$r = \frac{R\ max_1(S)}{Km_1 + (S)} + \frac{R\ max_2(S)}{Km_2 + (S)} \qquad (8)$$

where r is the enzyme reaction rate

$Rmax_x$ is the maximum enzyme reaction rate

(S) is the rate limiting specie substrate concentration

Km_x is the saturation constant and is equal to the substrate concentration when r = Rmax/2

Now the system has four unknowns, two Rmax's and two Km's and, therefore, an infinite number of solutions is available.

In a separate paper, Brown and Harris (1978) examined the validity of applying the cell quota concept (Droop 1968) to their previous work on uptake kinetics of phosphorus. This concept states that the microbial growth rate is partly regulated by the cell quota or nutrient content of the cell. This implies a storage of the phophorus by the cell for later use. Fundamentally, this concept separates or accounts for the differences between phosphorus uptake and cell growth rates. They found that as the cell quota increases the uptake rate decreases, for any substrate concentration and that increased substrate concentrations were necessary for changes in the cell quota to remain positive since growth is simultaneously occurring. Negative changes in the cell quota indicate requirements for growth rates are exceeding uptake rates.

In conclusion, much of the previous research on eutrophy of lakes has been devoted to classification of these lakes by nutrient loading and hydrologic parameters of the lake's watershed. Much of the data collected has been of the "average annual" type.

In Thomann's (1977) reply to Schindler, he included a quote by Vollenweider (1976) which addresses this point as follows:

"If further progress should be possible, then more complex models are needed. It seems to be particularly important to obtain a better hold on parameters which also exert an influence on loading tolerance, such as length of stratification, mixing cycles, depth to thermocline, hypolimnetic entrainment, water discharge and loading cycles, etc. Also the trophic-dynamic interrelationships in the sense of Lindeman (1942) requires much more sophisticated analyses."

"Attempts of this nature are underway in several places; however, there are a number of pitfalls to be avoided in order to avoid what Riley et al. (1949) have already prospected. In spite of the large amount of limnological literature on the subject, the trophic-dynamic interrelationships are still insufficiently understood. Careful mass balance studies, broken down into monthly, or even more timely closer episodes are scant. In addition, much of the data used for "verification" of limnological models have been drawn from nonreliable or at least inappropriate data banks and hence, this has hardly been to the advantage of model development."

It is realized that the bulk of trophic state studies have been performed on northern lakes. For the most part, these lakes are subject to receiving an almost instantaneous loading of nutrients during the spring turnover. For this reason, it is appropriate to analyze the data on steady-state or static conditions. The fact that the critical or maximum algal concentrations occur generally in the summer months and quality sampling generally is performed during this time lends support to the above contention.

Lake Eola is not subject to this instantaneous loading. It approaches a more continuous flow system. However, it is not a steady state flow system, due to the seasonally variant precipitation. Therefore, it must be analyzed hydrodynamically.

Hydrodynamic and quality responses of stormwater runoff are not known. Models to predict these impacts are scant or non-existent. Construction of a model to predict these impacts will require extensive quality and quantity data to precisely analyze the overlapping impacts of separate storm events.

CHAPTER III

FIELD TESTING AND METHODOLOGY

Introduction

The various hydrologic parameters for Lake Eola were measured from April 1, 1980 to March 31, 1981, thereby completing the water budget for one full year. These parameters can be classified as:

1. Inflows
    a. Direct precipitation on lake surface
    b. Stormwater Runoff
    c. Seepage from groundwater to lake
2. Outflows
    a. Discharge through drainage well
    b. Evaporation from lake surface
    c. Seepage from lake to groundwater

There are no surface streams entering or leaving the lake. Direct measurements of volumes of water were performed on (1) stormwater runoff and (2) discharge out via the drainage well.

Also, indirect measurements were performed on (1) seepage into and out of the lake (2) evaporation from lake surface and (3) direct precipitation onto the lake surface. Indirect measurement here refers to multiplying unit-area depth measurements by a corresponding area to obtain a total volume. A detailed discussion of these various measurement techniques, their problems and refinements made to them is contained in the following sections.

Direct Precipitation on Lake Surface

Measurements of direct precipitation onto the lake surface were performed by using a non-recording rain gage (Clear-Vu, Taylor Instrument Company). This gage has an orifice diameter of 4 inches (10.16 cm) or a surface area of 12.56 square inches (81.07 CM^2). Precipitation falling into the orifice enters via a funnel to a smaller diameter tube for a more sensitive reading. This tube is calibrated in 0.01 inches (0.254 MM). The maximum capacity of this inner tube is one inch of rain across the orifice area. Precipitation events, greater than one inch, overflow this inner tube and are collected in the larger tube that surrounds this inner tube. By subsequent emptying of the inner tube and pouring the overflow water back into the inner tube, precipitation events greater than one inch can be measured to an accuracy of 0.01 inch.

Lake Eola Park is a popular tourist attraction for the City of Orlando. The possibility of tampering or theft by curious passers by precluded establishing rain-gage location inside the park. The only possible safe place was behind the activities center located on the western shore of the lake. This center has a steeply pitched roof and a large scaffold on the order of 15 feet high would have been necessary to prevent shielding of the gage by precipitation events traveling from west to east. Therefore, the gage was placed approximately 2 miles southwest of the lake in an area unobstructed by overhanging trees or buildings. The orifice elevation was 3.5 feet (1.07 meters) above the ground. Whereas, this offsite location is recognized to compromise the data, it was hoped that freedom of tampering and that cumulative monthly depth would approach the cumultive monthly depth of an on-site location.

It should also be realized that spatial variation of precipitation is evident within the watershed itself. This was witnessed on May 10, 1980. High intensity precipitation was occurring on the southwestern corner of the lake, but none on the rest of the lake. Therefore, possibly, this off-site location problem is not that serious. Precipitation depths were recorded immediately following each event (within 12 hours) for one year from April 1, 1980 to March 31, 1980.

Discharge via the Drainage Well

A staff gage was placed on the back side of the activities center. It consisted of a 4 inch wide, one half inch thick and 5 foot long pine board painted with standard surveying stage markings with an accuracy of 0.1 foot. It was secured to the activities center by two bolts.

Due to the existence of wet and dry seasons in the Orlando area, the drainage well structure is equipped with a variable rim elevation. The variation is performed by either removing or replacing six inch high boards in a slide located on the front side of the drainage well. City employees perform this task. During the summer or wet season a board is removed to increase the drainage. During the winter or dry season, the board is replaced to maintain water levels. The board was removed in May 1980. However, it was never replaced in the fall. The lake perimeter is bounded by a retaining wall approximately 1 foot high. Except for January 1981, this wall kept the lake surface area a constant. During January 1981, the lake stage dropped to a point where a small portion of lake bottom area was exposed. Although no in-depth measurement of this area was made, it was field estimated at less than several hundred square feet and therefore ignored.

Therefore, lake stage changes indicated direct measurements of known volumes of inflows and outflows. Whereas, these changes included all of the various hydrologic parameters, Lake Eola's watershed has a very short time of concentration and as such the rate of lake stage change is predominantly due to runoff water and drainage well flows.

The time of concentration was measured to be less than 6 hours. This was possible by two storms in February 1981. Within 6 hours following the end of the precipitation event, the lake stage was recorded. It was again recorded 24 hours later. The cumulative rise in lake stage for this section was insufficient to allow water to discharge out via the drainage well. This precluded the possibility of an equal volume of stormwater being withdrawn by the drainage well and thereby causing no lake stage change. A more explicit explanation is discussed in the water budget analysis section.

Therefore, timely recordings of lake stage allow for direct calculation of volumes of water entering or leaving the lake since the surface area was constant. These lake stages were recorded on the order of 2 or 3 times weekly depending on the occurrence of precipitation events.

Two storms, one in July 1980 and one in October 1980 were selected to calibrate the temporal change in lake stage due to discharge via the drainage well. These storms were so selected for their long post event dry period. They allowed for a drop in stage of the lake to the drainage well rim. Precipitation depths of 0.48 and 0.85 were recorded for the two storm events, respectively.

Evaporation from Lake Surface

Evaporation estimates were made with a self recording evaporimeter (Model E801 Weather Measure Corporation). This machine measures unit-area depth evaporation in mm and is accurate to 0.5 mm. The manufacturer claimed that this machine was well correlated with the U. S. Weather Bureau Class A Pan. It consists of a wind-up clock that spins a graph papered drum. A pen arm traces an ink line recording changes in a float level. This float level is controlled by the water level in a reservoir. Water is drawn from this reservoir by evaporation through a Whatman #2 filter paper. The water is supplied to the filter paper by a cotton wick.

In accordance with manufacturer's recommendations, evaporation measurements were performed by shielding all but the filter paper from direct sunlight. This was accomplished by the use of a common brown paper grocery bag. A circular hole was cut with a single-edge razor blade. This hole was placed over the filter paper and attached to its retaining ring with scotch tape.

Due to the same problems of tampering plus the fact that this machine will not function if it is rained upon, it was unable to be left at the lake. Therefore, evaporation measurements were performed by placing the evaporimeter in a sunny place in Lake Eola Park at about 9:00 a.m. It would be set at zero and watched until about 5:00 p.m. Then, it would be brought back to the same site as the rain gage and reset to the level it was last at the lake. It was then allowed to run through the night until a full 24 hour test was completed.

As justification for this overnight off-site measurement, it should be realized that this site was within a couple hundred feet of another water body, namely, Clear Lake. Also, one has to realize that, with the abundance of waterbodies in the Central Florida Area, one can expect little or no spatial variations of humidity. Therefore, the windspeed variable in the evaporation equations presented in the literature review can be ignored. The windspeed variable was incorporated into these evaporation equations to allow for dispersion of the water vapor evaporated and supply a horizontal humidity gradient. With the numerous lakes in the area, most of which are larger than Lake Eola, this horizontal humidity gradient can be assumed to be negligible.

These evaporation estimates required a lot of man-time and could not be conducted every day of the year. Sometimes, the day selected for the test was rainy and then the test could not be run.

Except for the fall of 1980 (Sept - Dec), these tests were performed at least weekly. During the fall, the only time available to conduct these tests was on Saturday or Sunday and sometimes it rained. If it did, the test could not be run that week. However, at least two tests were performed each month.

An attempt was made to correlate an off-site sheltered evaporation estimate with on-site unsheltered estimates. The parameters of temperature and humidity were used as the basis. No meaningful correlation was found and the attempt was abandoned.

Seepage Into and Out of the Lake

Initially, an attempt to measure seepage was made by use of an apparatus similar to a falling head permeameter used in the geotechnic field. This apparatus had an advantage over the method by Lee (1977) in that it also measured the permeability of the bottom sediments. However it was found by field experimentation and sensitivity analysis that a seepage rate of 15 GPD/sq. ft. was required to gain meaningful results. When this was found not to occur for Lake Eola, the attempt was abandoned.

Another attempt started in May 1980. This attempt utilized a device described by Lee. A 55 gallon-drum with open end was pressed into the lake bottom. Water seeping into the drum from the groundwater displaced an equal volume of lake water through a hole in the top end of the drum. This displaced lake water traveled via a flexible tygon tube to a flexible storage plastic bag (alligator brand baggie) and allowed for direct measurement of a known volume of water in a specified period of time to calculate a seepage rate. By measuring the area of the open end of the drum, unit-area depth rates of seepage can be calculated.

To systematically quantify the seepage over the whole lake, a set of eight transects around the perimeter of the lake was established as shown in Figure 2. These transects ran perpendicular to the shoreline and contained one or more drums. The distance and depth of each drum from the shoreline along every transit were recorded to a maximum depth of 5.0 feet. This depth was so chosen because the pressing of the drum into the lake bottom requires a considerable amount of weight to ensure a good seal of the drum into the bottom. To do this, one simply stood on top of the drum. If the depth were greater than 5 feet one could not stand on top of the drum and breathe.

Four drums were obtained and cut cross-wise at different heights to obtain various sizes. The smaller ones were used for shallow depths and the larger ones were used for deeper depths.

To allow for gas build-up in the drum to escape between tests, the hole through which the tygon tube went was always arranged, such that it had the highest elevation. This way, no gas was trapped in the drum. See Figure 3.

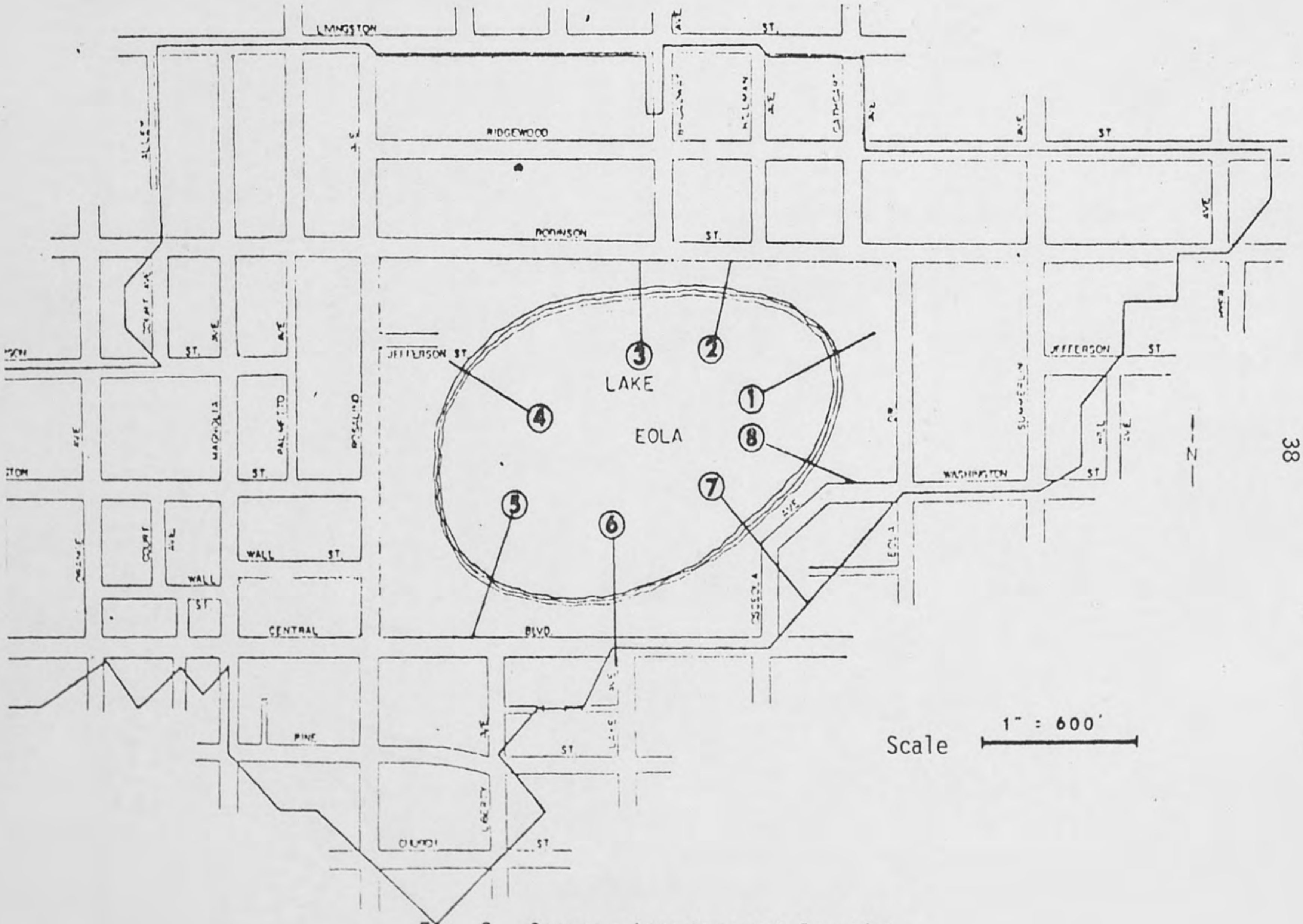
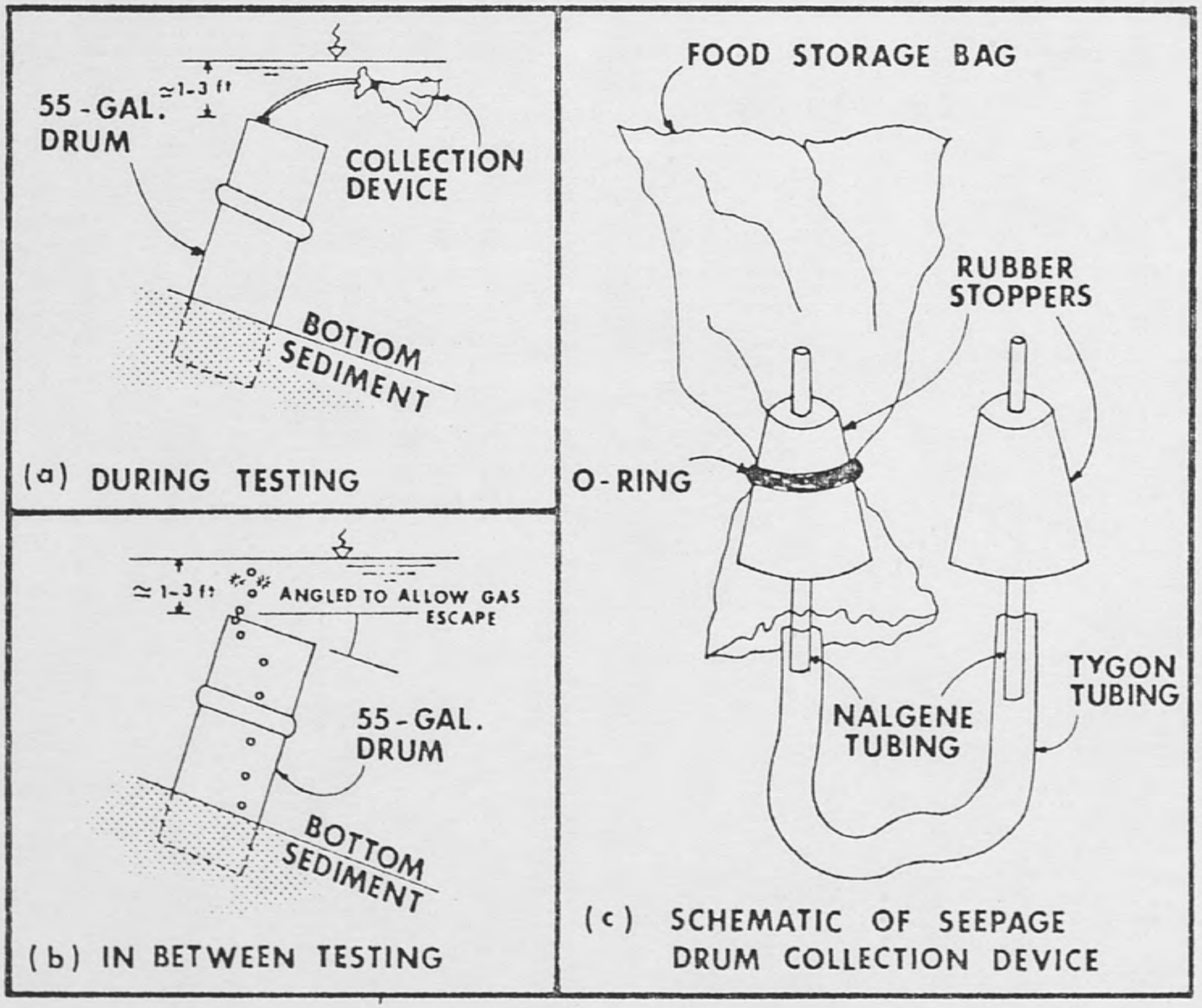


Fig. 2. Seepage drum transect location.



(a) DURING TESTING

(b) IN BETWEEN TESTING

(c) SCHEMATIC OF SEEPAGE DRUM COLLECTION DEVICE

Fig. 3. Schematic of drum placement for testing and gas escape and detail of collection device.

Initially, transects 1 and 2 were examined by placing four drums on each transect. The seepage rates per unit area were measured. Then, three of the barrels from each of these transects were relocated on transects 3 and 8, leaving one drum each on transects 1 and 2. The order of transect selection depended on the lake bottom slope. Flatter slopes would require more drums if spacing between drums was desired to be constant. Also, it was desired to leave a drum on each transect throughout the study year.

After transects 3 and 8 were examined, two drums from each transect were removed. Since the number of drums was now down to four, only one transect at a time could be examined. The order of remaining transects examined and their corresponding number of drums was transect 7, 4 drums; transect 4, 3 drums; transect 5, 2 drums; and transect 6, 1 drum. The drum always left on the transect was the one with the highest seepage rate in order to facilitate detection of small changes in seepage rates due to changes in the hydrologic cycles.

Transects 5 and 6 showed that water left the lake and seeped into the groundwater table. To measure these seepage rates, a known volume of water was placed in the collection bag (200 ml) prior to the start of the test and the volume remaining was measured at the finish of the test. At least two and most of the time three tests were run on each drum on every day of the test.

The duration of the test varied from a half-hour to over an hour depending on its position in the testing sequence and the rate of seepage expected at each location. This sequence was to walk around the lake to place the collection bags on the drums which took one half hour. Then, the water seeping into the first bag placed was measured and discarded. Then, the bag was replaced onto the flexible tube for the second round of tests. For the eight drums this required about one hour. Different starting points were randomly selected to try and scatter the duration of tests on each drum evenly with the others.

During January 1981, the drum remaining on transect 1 was above the lake surface and the seepage test could not be run.

Seepage tests were run approximately 3 times a week when weather permitted during the period of May to November, 1980.

Water Quality Sampling

Water quality samples were gathered from six locations in the lake throughout the study year. Two samples per month from each location were gathered from the warm weather months of April through October; one sample per month from each location was gathered from November through March.

Water samples collected from the lake were returned to the Environmental Engineering Laboratory at the University of Central Florida for water quality analysis. All samples were collected from the top 1 meter of the water column using a brass 2 liter Kemmerer Water sampler and stored in 1 gallon polyethelene containers which were completely filled to eliminate gas exchange. Samples were placed on ice in the dark for return to the laboratory.

The following determinations were performed on each sample collected: Chlorophyll "a", Total Phosphorus, Total and Dissolved Orthophosphorus, ammonia, nitrite nitrogen, nitrate nitrogen and Total Kjeldahl Nitrogen. All analyses were performed as described by Standard Methods For the Examination of Water and Wastewater (14th Edition).

CHAPTER IV

FIELD AND LABORATORY RESULTS

Introduction

Various parameters of the hydrologic system for Lake Eola watershed were collected for one year during April 1980 to March 1981 following techniques discussed in Chapter III. During the same period, various quality parameters for the lake, particularly phosphorus, nitrogen and chlorophyll "a" were measured periodically at two to four week intervals. The result of this investigation will be reported throughout this chapter.

Hydrologic Parameters

These parameters included: Changes in lake water, direct precipitation on the lake, drainage well discharge, stormwater runoff, evaporation and seepage.

Volume of Lake

The volume of water in Lake Eola at the drainage well rim elevation, 88 feet above mean sea level was determined in a previous study to be 11,675,458 cu ft (330,699 cu. m.) with a surface area of 27.0 acres (10.93 ha.). Therefore, the volume of the lake at any time can be calculated by multiplying the stage of the lake above or below the drainage well elevation by the surface area of the lake and adding to or subtracting from the volume of the lake at the drainage well elevation, as shown in Table 1.

TABLE 1

END OF MONTH STAGE AND LAKE VOLUME DATA FOR MONTHS MARCH 1980 THROUGH MARCH 1981

End of Month	Stage* Above/Below Drainage Well (ft)	Volume** Above/Below Drainage Well (ft^3)	Total*** Volume of Lake (ft^3)	% Volume Above/Below Drainage Well
March	+ 0.30	352,836	12,028,294	+ 3.0
April	+ 0.10	117,612	11,793,070	+ 1.0
May	+ 0.20	235,224	11,910,682	+ 2.0
June	+ 0.25	294,030	11,969,488	+ 2.5
July	+ 0.20	235,224	11,910,682	+ 2.0
August	+ 0.25	294,030	11,969,488	+ 2.5
September	+ 0.10	117,612	11,793,070	+ 1.0
October	+ 0.00	0	11,675,456	0.0
November	+ 0.50	588,060	12,635,518	+ 5.0
December	0.00	0	11,675,458	0.0
January	- 0.85	-999,702	10,675,756	- 8.5
February	0.00	0	11,675,458	0.0
March	+ 0.10	117,612	11,793,070	+ 1.0

* + denotes Above, - denotes Below

** a x 27 acres x 43560 ft^2/acre

*** b + 11,675,458 ft^3

It can be seen from Table 1 that the volume of water in the lake at the end of any month varied by less than +5.0% and -8.5% of the volume of the lake up to the drainage well elevation.

Direct Precipitation Volumes

The volume of direct precipitation onto the lake surface was calculated by multiplying the rainfall-depth collected in the precipitation gage each month by the surface area of the lake, as presented in Table 2.

TABLE 2

MONTHLY DIRECT PRECIPITATION VOLUMES

Month	Gage Reading (inches)	Volume	Average Monthly Precipitation (inches)
April	3.00	294,000	2.72
May	10.90	1,068,000	2.94
June	1.76	172,500	7.11
July	2.09	204,800	8.29
August	2.19	214,600	6.73
September	2.42	237,200	7.20
October	0.62	60,000	4.07
November	4.61	451,800	1.56
December	0.54	52,900	1.90
January	0.21	20,600	2.28
February	3.28	321,500	2.95
March	2.98	292,100	3.46

It should be noted that the year this study was performed was uncommonly dry as far as rainfall is concerned. Figure 4 depicts the average rainfall depths for the Orlando area superimposed on the April 1980 to March 1981 values collected during this study period.

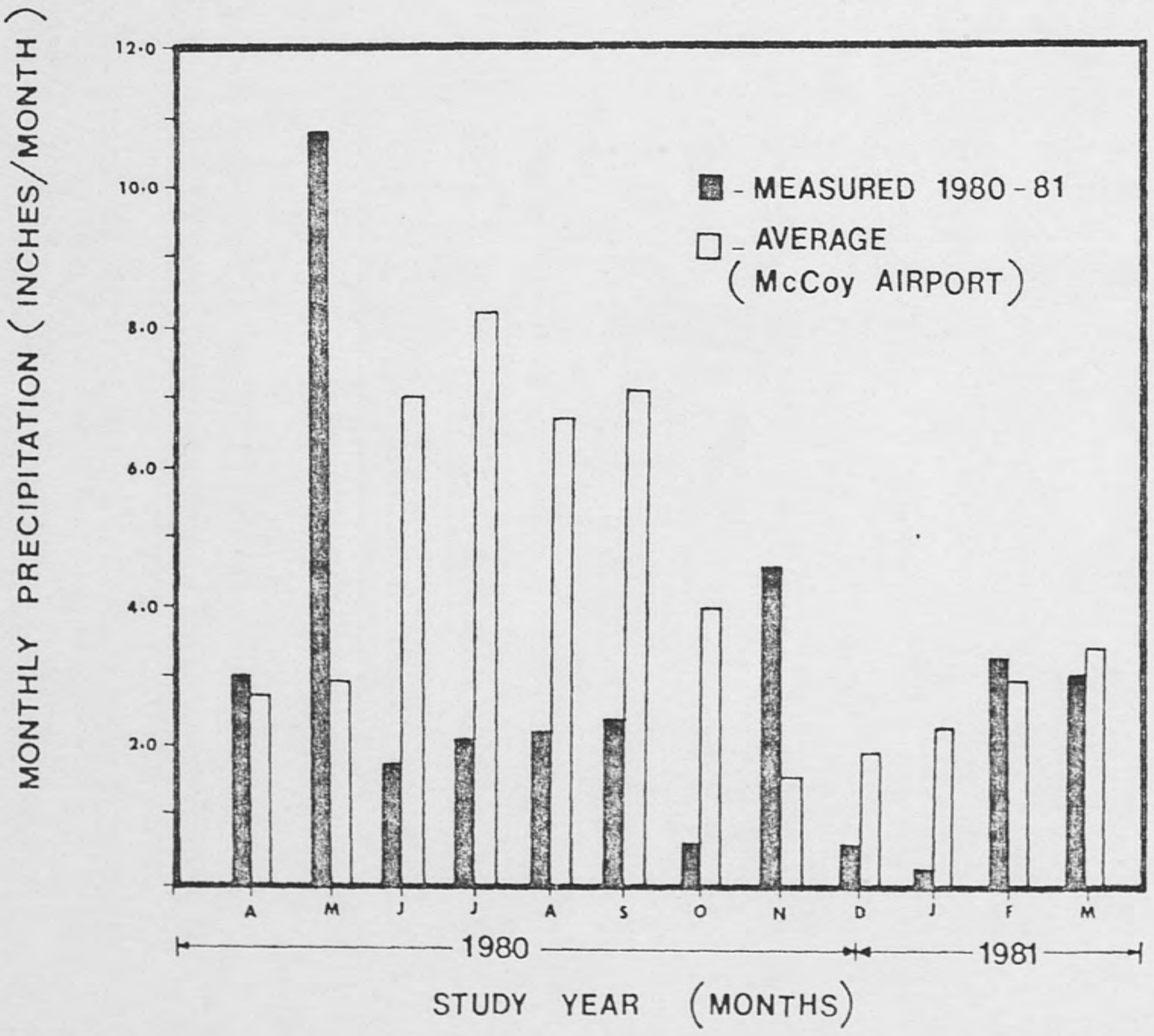


Fig. 4. 80-year average and measured monthly rainfall depths on Lake Eola watershed.

The rainfall deficit experienced during the study year was 16.6 inches below the average total of 51.2 inches or 32% below normal.

Volume Discharge Via Drainage Well

Observed discharge via drainage well may include direct water discharge to the aquifer through the rim of the well, evaporation during measured period and seepage through lake bottom and sides. However, all the rates of discharge from all sources other than the free flow through the rim appear to be insignificant over a short period of time. In order to calibrate an observed stage discharge relationship, two storms were selected for their long post event dry periods. This allowed for a maximum drop in stage without interference with the next precipitation event. The two events selected were the July 25, 1980 (0.48 inch) storm and the October 1, 1980 (0.85 inch) storm. The antecedent moisture condition of the July event was characterized by a very wet period. A total of 2.09 inches of precipitation were recorded including this storm for the five previous days. The October event was preceeded by 17 days of no rainfall. Therefore, it was hoped that this would represent various conditions of seepage effects. The duration of these storm events and the time of cessation was also accurately monitored. The lake stage and time of day was recorded for several days after each event. An evaporation estimate was also recorded and the corrected evaporation depth was subtracted from the stage drop. This stage drop over time for both storms was analyzed by regression analysis for several general equations, as shown in Figure 5.

The best fit equation had the exponential form:

$$S = ae^{(-bt)} \tag{9}$$

where:

S = lake stage above drainage well elevation, ft

t = elapsed time (hrs) after cessation of storm event

a = a constant = 13.6 cm or 0.446 ft

b = a constant = 0.00877 hr^{-1}

The rate of drawdown of the lake can be represented by:

$$\frac{dS}{dt} = abe^{-bt} = bS \tag{10}$$

If the discharge through the drainage well is:

Q_{dw} in ft^3/hr, then $Q_{dw} = AbS$

where:

A = surface area of the lake = 1,176,120 ft^2

S = stage of lake above drainage well rim elevation in ft.

Since the evaporation was subtracted from the lake stage drop and there was no interference with the next storm, the water budget parameters involved in this stage discharge relationship involve discharge via the drainage well, seepage into and seepage out of

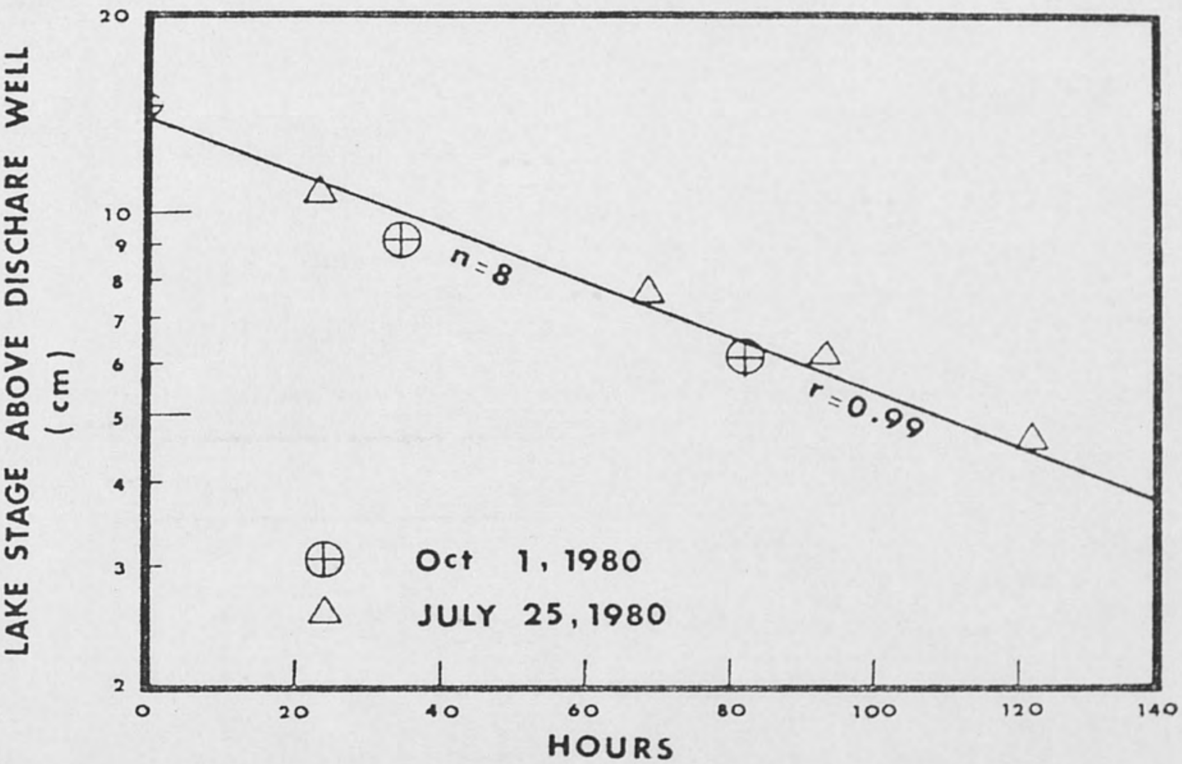


Fig. 5. Lake Eola drawdown through well over time.

the lake. However, seepage measurements appear to be very small and will have negligible effects on the data presented.

Observed drainage well discharge was approximated by recording the stage level several times a week. By utilizing the stage discharge relation of Figure 5 and the stage above the drainage well elevation, an estimate of each specific day's discharge can be made. Summing these daily discharges for a month results in the monthly discharge. An alternate method of calculating the monthly discharge is to utilize a "stage-day" concept. This concept is to add the individual day stages above the drainage well elevation and then incorporate this value in equation 10. This is possible only because of the linear form of this equation. This stage-day data and the monthly observed volume lost through the drainage well is depicted in Table 3.

It was necessary to approach the estimation of the lake discharge in this manner because of the nature of the hydrologic cycle of the Central Florida area. During the months of June through September, precipitation events are of the thermal shower type. It can be expected to rain on any given day; the only question being where. When the Lake Eola watershed is subjected to several of these events in a short period of time (1 week), the drainage well begins to take on continuous flow characteristics. Therefore, it would be invalid to consider the drop in stage times in the area of the lake as the total amount of water lost.

TABLE 3

MONTHLY ESTIMATES OF OBSERVED QUANTITY OUT OF LAKE EOLA VIA DRAINAGE WELL DISCHARGE

Month	Stage Day (ft)	Volume Lost (cu.ft x 10^6)	Precipitation Depth (in)
April	5.75	2.53	3.00
May	21.00	9.19	10.90
June	2.70	1.18	1.76
July	3.55	1.57	2.09
August	4.80	2.09	2.19
September	5.25	2.29	2.42
October	1.30	0.57	0.62
November	8.00	3.49	4.61
December	1.15	0.50	0.54
January	N/A	0.71*	0.21
February	0.10	0.02	3.28
March	5.20	2.27	2.98

* At no time was stage of lake above drainage well rim. Therefore, volume lost was due to seepage out and elevation. Subtracting estimated evaporation yields volume lost with the lake concentrations.

Stormwater Runoff Volumes

The volume of storm water runoff was estimated by measuring the stage of lake rise after a precipitation event. If the rise in Lake stage reached an elevation greater than the drainage well rim, an additional amount of water, namely that water leaving via the drainage well while this rise is taking place, must be attributed to the stormwater runoff volume. This total amount of lake input volume also contains the direct precipitation volume which must be considered as represented by the following equation.

$$V_{sw} = V_{sr} + V_{dw} - V_{dp} + V_e \tag{11}$$

Where

V_{sw} = the storm water runoff volume

V_e = the volume evaporated during the storm

V_{sr} = the increase in lake volume attributed to the stage rise

V_{dw} = the volume of water discharging out via the drainage during this stage rise

V_{dp} = the volume of water attributable to the direct precipitation on the lake surface

The stage rise volume was calculated by multiplying the rise in lake stage by the surface area of the lake. The volume of water discharging out during this stage rise was determined from drainage well stage-discharge relationship. The mid-point of the previous and post event stages was used as the stage variable in equation 10 This gives the average discharge for this time period. Using these mid-points the stage day concept can be used.

The volume of direct precipitation is simply the area of the lake times the recorded monthly precipitation depth. Due to the short time period for stage rise, evaporation was assumed neglible during a storm event. Monthly estimates of storm water runoff volumes to Lake Eola were calculated as shown in Table 4.

Lake Evaporation Volumes

The monthly lake evaporation volumes were calculated by averaging the 24-hr evaporimeter readings taken during the month.

TABLE 4

MONTHLY ESTIMATES OF STORM WATER RUNOFF VOLUME

Month	Precipitation (in)	Direct Precip. Volume (cu ft)	Stage Rise (ft)	Stage Rise Volume cu ft	Loss Through Drainage Well Volume (cu ft)	Total Stormwater Runoff Volume (cu ft) $\times 10^6$
April	3.00	294,000	0.80	940,900	1,143,100	1.79
May	10.90	1,068,000	3.45	4,057,600	3,500,400	6.49
June	1.76	172,500	0.60	706,000	267,000	0.80
July	2.09	204,800	0.75	882,100	412,700	1.09
August	2.19	214,600	1.10	1,293,800	428,200	1.50
September	2.42	237,200	1.15	1,353,500	489,700	1.60
October	0.62	60,800	0.30	352,800	58,000	0.35
November	4.61	451,800	2.00	2,321,700	1,256,100	3.12
December	0.54	52,900	0.225	264,900	98,000	0.30
January	0.21	20,600	0.125	150,600	0	0.13
February	3.28	321,500	1.10	1,293,700	25,000	1.00
March	2.98	292,100	0.85	999,700	710,300	1.71

This average depth was corrected with a pan to lake coefficient of 0.70. (Nordenson and Baker 1962). This value was selected since it was the average value of 22 values reported from various areas around the world with a standard deviation of 0.056 (Lindsey, Kohler, Paulus). It must also be recognized that most of the previous work on lake water budgets failed to recognize the influence of ground water seepage or at best estimated it by difference using an assumed pan-to-lake coefficient for evaporation.

This corrected depth was then multiplied by the surface area of the lake to give an average daily evaporation volume. Subsequent multiplication of the daily volume by the number of days in the month yields the monthly volume. This data is presented in Table 5.

TABLE 5

EVAPORATION DATA FOR STUDY YEAR

Month	Number of Measurements	Average Reading (mm)	Min. Readings (mm)	Max Reading (mm)	Monthly Volume (cu ft)
April	5	5.15	4.25	6.81	417,000
May	5	5.30	3.92	6.10	430,000
June	8	4.87	3.24	7.86	294,000
July	8	5.72	3.56	6.21	479,000
August	7	5.56	3.45	6.92	466,000
September	6	5.24	4.37	6.10	425,000
October	4	4.50	3.75	6.32	377,000
November	4	3.33	2.38	5.82	270,000
December	3	2.90	2.43	3.62	243,000
January	5	3.43	3.21	3.71	287,000
February	2	3.53	2.86	4.21	267,000
March	5	4.60	3.45	6.89	385,000

Seepage Volumes

Seepage volumes into a lake or stream are exceedingly difficult to quantify. This is due to the broad area of entry and the many morphological factors which influence the rate of seepage across this area. For this reason the seepage volume was calculated by two methods. The first was by difference of lake volumes, inflows and outflows over the time interval. These values are presented in Table 6. This table also contains residence times of water in the lake based upon the rate of outflow and an average lake volume of 330.65 million liters.

Seepage volumes were also estimated by the utilization of the seepage measurement drum method. This method measures seepage rates in units of volume . time $^{-1}$. area $^{-1}$. Therefore, in order to systematically quantify the total volume of seepage entering or leaving the lake, it was necessary to account for the spatial variation of seepage rates across the lake bottom.

During the calibration period for different transects, the average rate for each drum was plotted as a percent of the average of the maximum drum rate along each transect. It was noted that the seepage flux along transects would increase to a maximum value with increasing distance from the shoreline. However, the rate may decrease afterwards in drums located further away in the lake. The area beneath this curve yields the appropriate correction factor if only the maximum drum was left in place after the calibration period to collect additional data from one drum at each

TABLE 6

SEEPAGE VOLUME CALCULATIONS BY DIFFERENCE

Month	Change in Lake Volume		+ Outflows Per Month		- Inflows Per Month		Net Seepage	Residence Time
	V_{1t+1} (ML)	$-V_{1t}$ (ML)	$V_{dw} + V_{so}$ (ML)	V_{ev} (ML)	V_{dp} (ML)	$- V_{sw}$ (ML)	(ML) + in - out	(Days)
April	333.99	340.65	71.65	11.81	8.33	50.69	+ 17.69	119
May	337.32	333.99	260.27	12.18	30.25	183.80	+ 61.75	36
June	338.98	337.32	83.42	11.16	4.89	22.66	+ 18.69	222
July	337.32	338.98	44.46	13.57	5.80	30.87	+ 19.70	117
August	338.98	337.32	59.19	13.20	6.08	42.48	+ 25.49	142
Sept.	333.99	338.98	64.85	12.04	6.72	45.31	+ 19.87	129
October	330.66	333.99	16.14	10.68	1.72	9.91	+ 11.86	382
November	357.85	330.66	98.84	7.65	12.80	88.36	+ 32.52	93
December	330.66	357.85	14.16	6.85	1.50	8.78	- 16.46	488
January	302.34	330.66	20.11	8.13	0.58	3.68	- 4.34	363
February	322.33	302.34	0.71	7.56	9.10	-28.25	- 9.19	248
March	333.99	322.33	64.29	10.90	8.27	48.43	+ 30.15	136

* + means seepage to the lake
- \- means seepage out of the lake

transect. This correction factor has units of length as in Figure 6.

The length of shoreline attributed to each transect was taken to be the midpoint distance to the adjacent transects to the right and left of desired transect in question. These lengths are depicted in Table 7.

The values for these correction factors are depicted in Table 8. Multiplying these values by the average of the maximum drum on each transect yields units of volume · time^{-1} · length^{-1}, or seepage volumes per month per foot of shoreline.

TABLE 7

SHORELINE DISTANCE OF INFLUENCE FOR VARIOUS TRANSECTS (MIDPOINT DISTANCE OF ADJACENT TRANSECTS)

Transect #	Adjacent Transects #	Distance ft
1	2,8	302
2	1,3	343
3	2,4	422
4	3,5	640
5	4,6	692
6	5,7	595
7	6,8	442
8	7,1	280

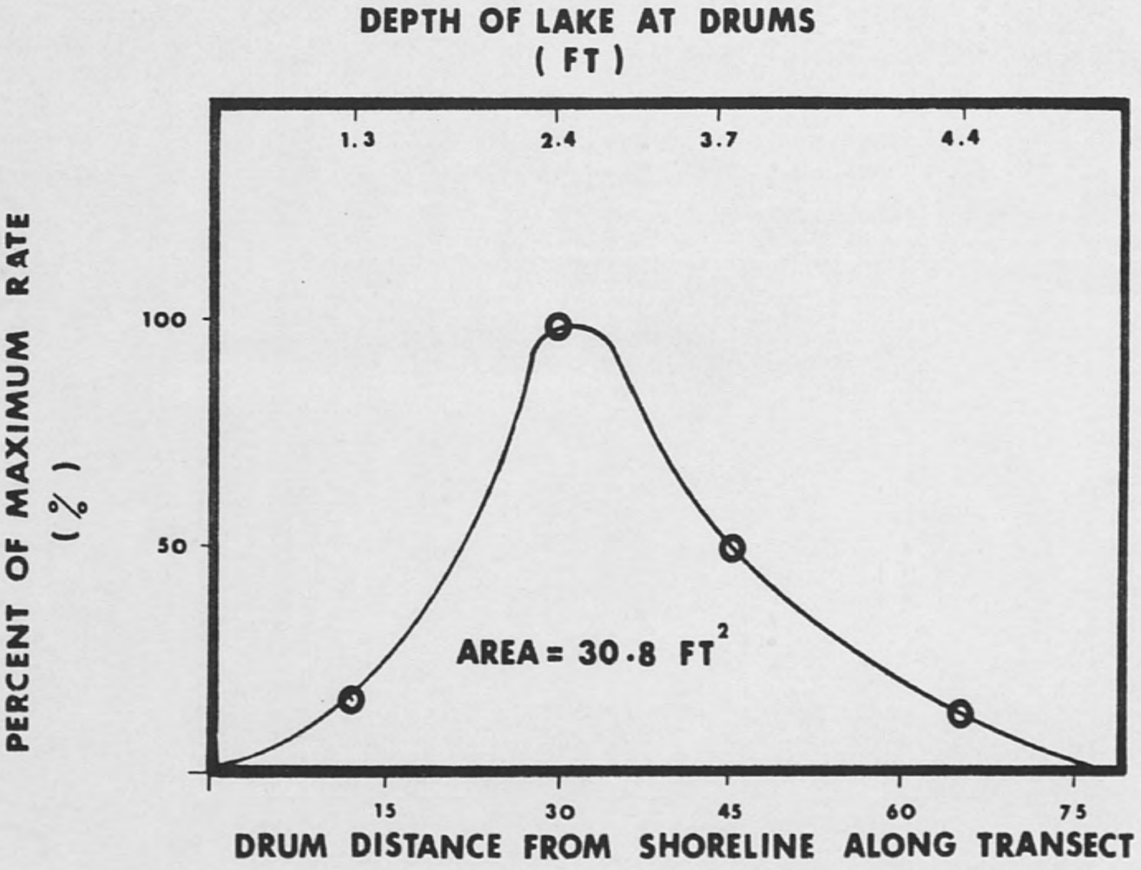


Fig. 6. Typical seepage rates as a percentage of maximum drum for transect 2.

TABLE 8

CORRECTION FACTORS FOR MAXIMUM DRUM SEEPAGE RATES

Transect #	Seepage Rate/Lineal Foot of Shore Line (ft)
1	20.57
2	30.80
3	12.18
4	18.00
5	11.64
6	9.21
7	22.81
8	18.67

Values for the monthly average of the maximum drum seepage rates for the different months and the different transects are depicted in Table 9. It is shown from Table 9 that infiltration and exfiltration can occur at the same time at different drum locations along the shoreline. A series of multiplication of values from Tables 7 through 9 yields the total volume of seepage per day for each transect. By accounting for the number of days in the individual months yields the total monthly volume of seepage per transect, as in Table 10.

Table 11 compares the two methods of seepage volume estimates namely by difference and seepage drums. It can easily be seen that substantial conflict occurs not only in magnitude of volume but also in net direction (in or out).

TABLE 9

THE MAXIMUM DRUM MONTHLY AVERAGE SEEPAGE RATES FOR TRANSECTS

Month	Average Maximum Drum Seepage Rate gpd/ft^2 **							
	1	2	3	4	5	6	7	8
April	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
May	N/A	N/A	N/A	+1.163	N/A	N/A	N/A	N/A
June	+0.016	N/A	+0.256	N/A	N/A	N/A	N/A	+0.129
July	+0.319	+0.286	+0.412	N/A	N/A	N/A	N/A	+0.136
August	+0.428	+0.263	+0.394	N/A	N/A	N/A	+0.186	+0.121
September	+0.594	+0.305	+0.778	+0.246	N/A	N/A	+0.219	+0.382
October	+0.281	+0.115	+0.256	+0.061	-0.631	-0.821	+0.164	+0.116
November	+0.617	+0.463	+1.194	+0.471	-0.493	-0.682	+0.321	+0.463
December	+0.146	+0.218	+0.189	+0.034	-1.153	-1.742	<0.001	+0.079
January	+0.061	<0.001	N/A*	<0.001	-1.591	-1.862	<0.001	<0.001
February	+0.264	+0.319	+1.041	+0.316	-0.786	-0.463	+0.220	+0.216
March	+0.236	+0.219	+0.742	+0.271	-0.741	-0.326	+0.116	+0.429

N/A not available
\+ denote ground water to lake
\- denote lake to ground water

* drum top out of water
** to convert to l/day·m^2, multiply by 40.74

TABLE 10

ESTIMATED VOLUMES OF SEEPAGE BY TRANSECT
THOUSAND GALLONS/MONTHS

Month	1	2	3	4	5	6	7	8
April	N/A							
May	N/A	N/A	N/A	N/A				
June	2.98	N/A	39.47	N/A	N/A	N/A	N/A	20.20
July	59.45	90.64	63.53	N/A	N/A	N/A	N/A	21.29
August	79.76	83.35	60.75	N/A	N/A	N/A	56.26	18.95
September	110.70	96.66	119.97	85.02	N/A	N/A	66.24	59.81
October	52.37	36.45	39.47	21.08	-152.48	-134.97	49.60	18.16
November	114.99	146.74	184.11	162.43	-119.13	-112.12	97.09	72.49
December	27.21	69.09	29.14	11.75	-278.62	-286.38	0	12.37
January	11.37	0	N/A	0	-384.46	-306.11	0	0
February	49.20	101.10	164.52	109.21	-189.93	- 76.12	66.54	33.82
March	43.99	69.40	114.42	93.45	-179.06	- 53.59	35.07	67.17

TABLE 11

COMPARISON OF SEEPAGE VOLUMES BY DRUM AND DIFFERENCE METHOD

Month	Drum Method			By Difference ML
	In ML	Out ML	Net ML	
April	N/A	N/A	N/A	17.69
May	N/A	N/A	N/A	61.73
June	N/A	N/A	N/A	18.69
July	N/A	N/A	N/A	19.70
August	N/A	N/A	N/A	25.49
September	N/A	N/A	N/A	19.87
October	0.84	-1.11	-0.27	11.86
November	3.01	-0.90	2.11	32.52
December	0.58	-2.19	-1.61	-16.46
January	0.04	-2.68	-2.63	- 4.34
February	2.02	-1.03	+0.99	- 9.19
March	1.60	-0.88	+0.72	+30.15

ML = million liters

Seepage was always measured as entering in the lake from the north and leaving out the south. Generally, seepage rates for the north and south transects peaked immediately after precipitation events; whereas, for the east and west transects, the peak occurred immediately prior to precipitation events. This is reasonable since, if the overall seepage gradient for this area is north to south, seepage from the east and west transects will be moving laterally against this overall gradient. Therefore a lateral gradient is being introduced to the system and the lake stage should be the control. At low lake levels this lateral gradient will be at its maximum and subsequently maximum seepage should be expected.

Immediately, to the south, there appears to exist a clay stratum over sand. This would inhibit changes in the groundwater table. Therefore, at high lake levels, the gradient will be greater and maximum seepage rates should exist.

If the gradient from the north is controlled by groundwater table storage then maximum seepage should exist when the storage is at a maximum or immediately after precipitation events.

It should be reemphasized that most of the water entered the lake via seepage prior to man's development of the area. Therefore, seepage did and probably still does play an important role in the water budget.

Water Quality Parameters

Average concentrations for stormwater runoff for Lake Eola were determined from a previous study (Wanielista, Taylor and Yousef 1981), as presented in Table 12.

TABLE 12

AVERAGE STORMWATER CONCENTRATIONS DURING 1979

Specie	mg/l
Total Phosphorus - P	0.48
Orthophosphorus - P	0.24
Nitrate - N	0.65
Total Kjeldahl Nitrogen - N	3.30

Also, the average concentration values for the water quality samples from the six stations is presented in Table 13. From this table it can be seen that the concentrations of various parameters measured throughout the study period ranged from BDL to 94.9 g-N/l for NH_3, 18-11.4 μg-N/l for NO_2, BDL-127 μg/N-l for NO_3, 205-963 μg N/l for TKN, 0-12 μg-P/l for dissolved orthophosphorus, 0-21 μg-P/l for orthophosphorus, 19-75 μg-P/l for total phosphorus and 8-37.5 μg/l chlorophyll *a*. High values of nitrogen and phosphorus were measured during the months of April and May.

TABLE 13

AVERAGE CONCENTRATIONS OF WATER QUALITY PARAMETERS FOR STUDY YEAR
APRIL 1980 - MARCH 1981

Date of Sample			Phosphorus µg P/l					Chy A µg/l
	NH_3	NO_2	NO_3	TKN	Dissolved Orthophos.	Ortho Phos.	Total Phosphorus	
3-11-80	15.8	1.8	9.2	347	4	9	N/A	14.6
4-7-80	BDL	6.8	113.0	597	0	5	60	20.3
5-14-80	21.5	4.4	127.0	N/A	N/A	14	58	14.2
5-28-80	7.0	5.2	93.2	676	9	14	75	25.5
6-10-80	BDL	5.4	58.0	N/A	0	12	49	35.3
6-24-80	18.5	5.6	56.4	490	1	21	72	37.5
7-8-80	18.0	5.5	42.4	587	6	21	48	15.1
7-29-80	73.0	5.0	85.7	963	0	11	50	12.7
8-12-80	BDL	5.0	25.2	578	0	1	41	11.6
8-26-80	41.1	6.3	26.4	502	0	5	46	21.1
9-10-80	94.9	5.5	BDL	N/A	0	0	32	16.6
9-24-80	54.9	5.7	31.5	N/A	0	0	42	11.5
10-9-80	56.7	6.2	BDL	205	0	2	19	8.0
10-30-80	22.2	6.3	24.7	517	0	0	35	9.3
11-20-80	BDL	7.5	42.4	302	0	9	51	19.2
12-11-80	39.6	11.4	57.4	N/A	0	9	47	15.7
1-13-81	29.1	4.9	34.2	303	0	0	40	14.5
2-18-81	BDL	3.6	62.3	338	0	11	54	12.3
3-30-81	52.5	3.2	56.3	596	12	16	61	19.2

N/A not available

CHAPTER V

ANALYSIS OF RESULTS AND DISCUSSIONS

The results collected throughout the course of this study have been presented in Chapter IV and are depicted in Figures 7 and 8. This chapter deals with analysis of results, interrelationships between various parameters of the hydrologic cycle, water quality analysis and relationships between quality and quantity aspects of Lake Eola.

Analysis of Quantitative Measurements

The various quantitative measurements taken to define the hydrologic budget were analyzed to determine if any correlation exists between two or more parameters. These correlations were determined using the best fit line by least squares method. Table 14 shows various relationships between various quantitative parameters of the hydrologic budget in Lake Eola. Good correlations were developed for relationships between precipitation and each of lake discharge through drainage well, stormwater runoff and hydraulic residence time. Correlation coefficients varied between 0.84 and 0.98. The functional forms were linear on arithmetic scales except for hydraulic residence time which showed an exponential function.

Figure 9 depicts the graphical representation of stormwater runoff volumes versus precipitation depths on a monthly basis.

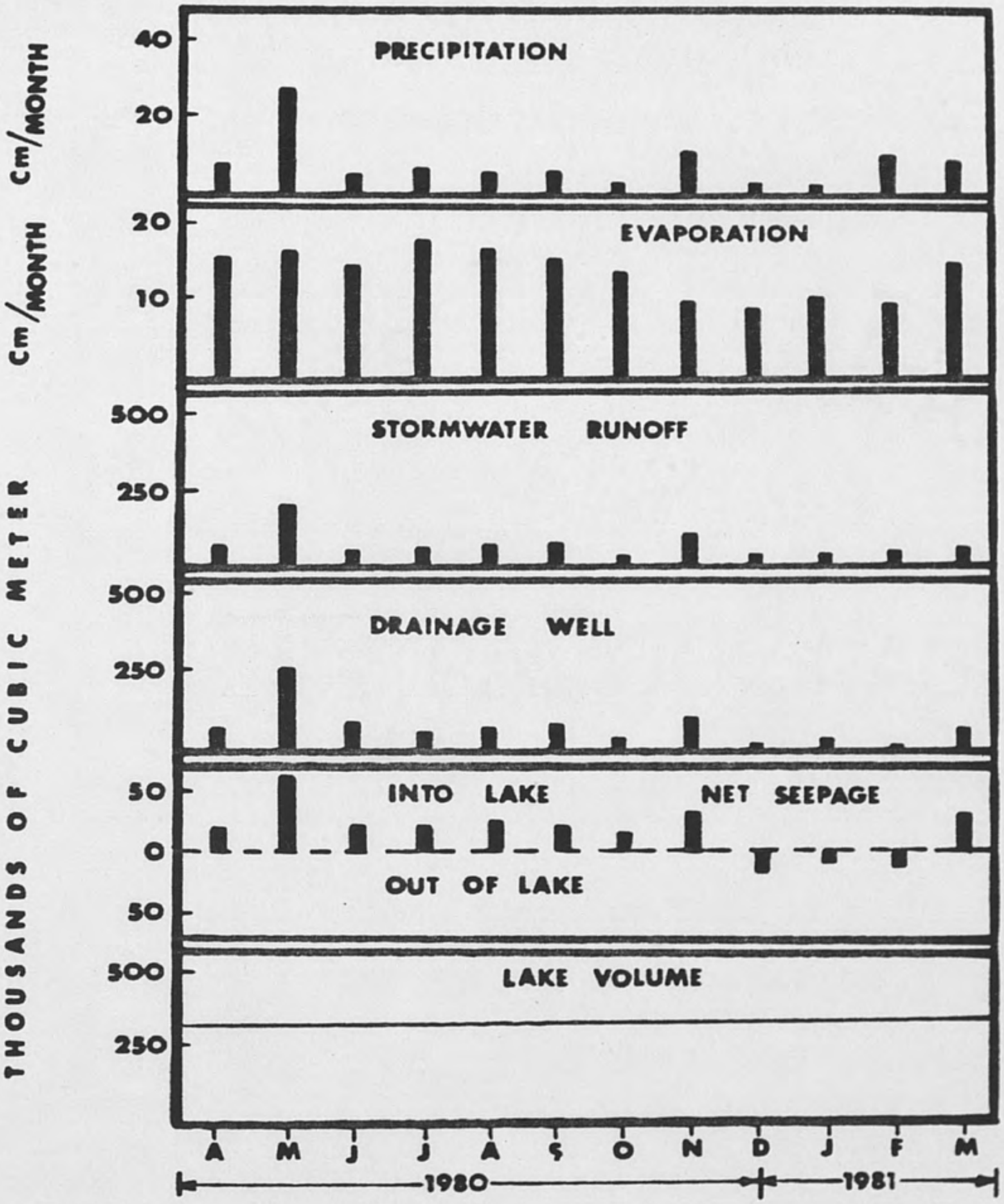


Fig. 7. Hydrologic parameters for Lake Eola drainage basin.

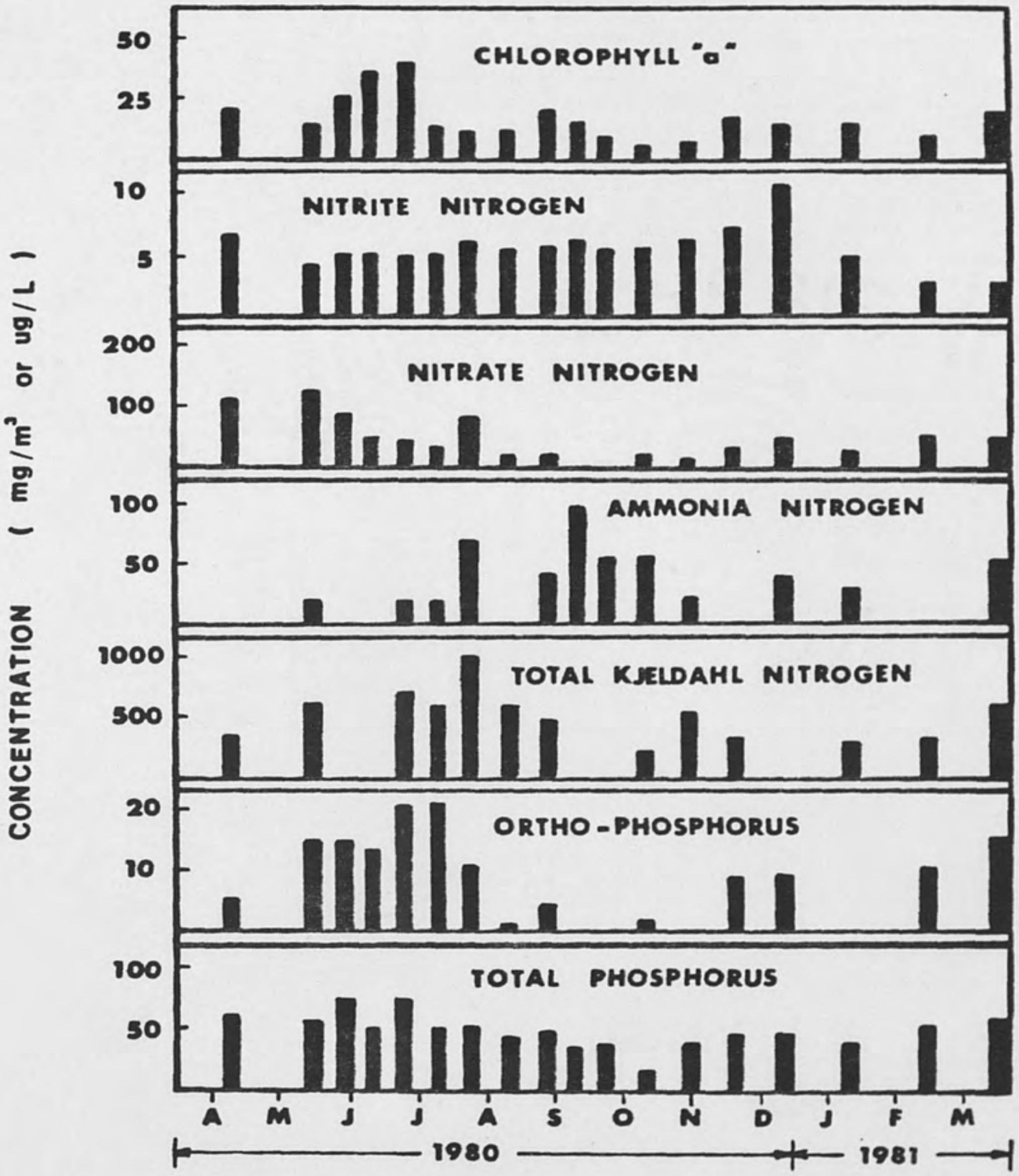


Fig. 8. Concentration of water quality parameters for Lake Eola, 1980/1981.

TABLE 14

FUNCTIONAL FORMS FOR CORRELATIONS BETWEEN VARIOUS PARAMETERS OF THE HYDROLOGIC BUDGET FOR LAKE EOLA

Independent Variable (X)	Dependent Variable (Y)	Functional Form	Correlation Coefficient r	Range		# of Observations
				X	Y	
Precipitation (inches)	Stormwater Runoff (million cubic feet)	$Y= -0.08+0.60X$	0.98	0.21-10.90	0.13-6.49	12
	Drainage Well Discharge (million cubic feet)	$Y= -0.12+0.81X$	0.94	0.21-10.90	0.02-9.19	12
	Hydraulic Residence Time (days)	$Y= 5.80e^{-0.226X}$	0.89	0.21-10.90	36-488	12

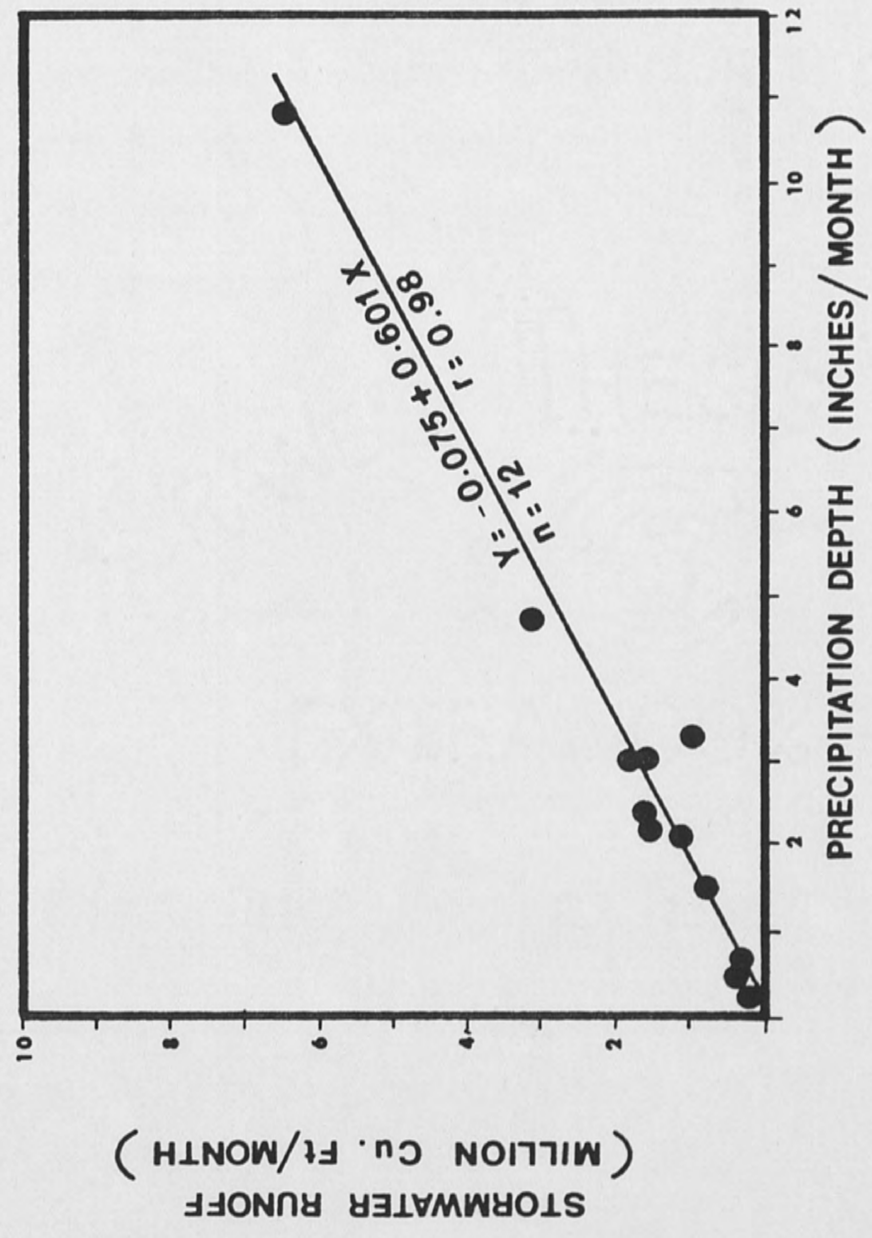


Fig. 9. Stormwater runoff volumes versus precipitation depths for Lake Eola from April 1980 to March 1981.

It has been observed that most of the inflows to the lake occured from stormwater runoff. It accounted for 66% of the total inflow. Seepage volumes accounted for 23% and direct precipitation for 11% of the total volume of inflow on a yearly basis.

Discharge via the drainage well was the predominant outflow volume. It accounted for 86% of the water lost throughout the year. Evaporation was estimated to account for 14% of the lake volume lost.

It should be noted that from April 1, 1980 to March 31, 1981 rainfall was 16.6 inches short of normal precipitation depths. This should be considered when extrapolating quantity data for this year in connection with more normally expected precipitation.

For a watershed of this size, one would expect a direct correlations of stormwater runoff and discharge via the drainage well with precipitation. It must be remembered that Lake Eola is a natural lake whose (before development took place) volume of water was generally supplied by groundwater seepage. In this area, evaporation matches direct precipitation.

The highly permeable sands in the original drainage area were not conducive to overland flow and subsequent natural stream formation. Originally, the residence time of any specie (water, phosphorus, etc.) was probably a function of the ground water seepage rate.

Again, since, originally this was a groundwater supplied lake it is not unreasonable to accept the net seepage calculations (23% of inflows) by the difference method as representing seepage ranges.

Whereas, the drum method used predicted net seepage volumes much lower than the difference method, it does provide valuable information as to the direction of flow. Perhaps with a more extensive transect layout (i.e. many more drums and deeper water drums) the two methods might approach closer values.

Normally, the yearly hydrologic cycle of the Central Florida Area is characterized by a summer rainy season of approximately 7 inches per month from June through September. Average rainfall for the rest of the year is approximately 3 inches per month. This did not occur during this study year. In fact, May experienced an actual rainfall of 10.90 inches which is more than normal expected value of 2.94 inches. June experienced a rainfall depth of 1.76 inches as opposed to its normal expectation of 7.11 inches.

Consequently, stormwater runoff and drainage well discharge volumes followed this abnormal precipitation cycle. The maximum stormwater runoff volume per month was 6.49 million cubic feet in May. The minimum was 0.13 million cubic feet occuring in January. Drainage well discharge peaked also in May with 10.90 million cubic feet and was lowest in February with 0.02 million cubic feet.

Analysis of Qualitative Measurements

Stormwater runoff from urban areas is usually contaminated with organic matter, sediments, nutrients, heavy metals, pesticides, bacteria and other toxins. These pollutants will eventually enter the adjacent environment in significant loadings depending on many factors, such as antecedent dry period, land use of the drainage basin, social and economic status, degree of urbanization, volume and type of traffic, industry and air pollution fallout. The magnitude of these loadings has led to a definite national need to study receiving water impacts.

Accurate estimates of pollutant loadings should reflect the dynamic nature of the system and require extensive and continuous recording of the water budget and pollutant concentrations. Pollutants are added at different rates during storm events and little, if any, is known about their fate in receiving water bodies. Therefore, simplified models were developed to assess pollutant loadings and effects on the quality of the receiving stream or lake. Kothandaraman and Evans (1979) tested Rand Lake in Illinois for quantity-quality correlations using a method developed by Simmons in 1976 for U.S.G.S. Nitrogen and phosphorus among other pollutants were estimated using this procedure and checked with a daily sampling scheme.

Estimates of pollutional loadings based on average concentration in runoff water for several storm events and calculated annual stormwater quantity from Lake Eola drainage basin were calculated by

Wanielista, Yousef and Taylor (1981). These estimates did not consider the fate and availability of pollutants to biological communities in lake. Quantities present in solution and fractions of those in suspension are readily available to plant and animal life. However, quantities retained by the bottom sediments may be locked into it and could become available when the source is depleted from the water body and the environmental conditions are favorable.

During the course of this study, responses of Lake Eola water to pollutional loadings, particularly phosphorus and nitrogen, have been assessed. Routine water samples from six different locations were collected, analyzed and the results were presented in Figure 8. This figure shows Total Phosphorus and orthophosphorus in μg-P/l, Total Kjeldahl Nitrogen, ammonia, nitrite and nitrate nitrogen in μg-N/l and chlorophyll *a* in μg/l for various analyses. The orthophosphorus concentrations were generally less than 20 μg-P/l and the Total Phosphorus concentrations were less than 60 μg-P/l.

Harper, Yousef and Wanielista (1979) concluded from bioassay studies that Lake Eola water is phosphorus limited when concentrations were less than 60 g-P/l. It appears that Lake Eola is phosphorus limited most of the time. Total Nitrogen to Total Phosphorus ratio varied between 5.7 and 17.3 and averaged 10.4, as shown in Table 15. Table 15 also shows the ratio of available nitrogen to available phosphorus. Available nitrogen was estimated by the 70 percent of total nitrogen and available phosphorus was estimated by the orthophosphorus concentration plus 30 percent of the difference between Total Phosphorus and orthophosphorus (Cowen and Lee, 1976). The values of available N:P varied between 10.6 and 52.1 and averaged 22.2. These data suggest that Lake Eola is phosphorus limited most of the time. Also, higher N:P ratios existed during wet weather months when compared with dry weather months. Nitrogen may have a higher mobility than phosphorus. Also, scour of bottom sediments by stormwater currents may resuspend the organic debris and increase the nitrogen content.

TABLE 15

AVERAGES OF TOTAL NITROGEN AND PHOSPHORUS CONCENTRATIONS IN LAKE EOLA WATER

Sampling Date	Average of Six Samples		Total N:P Ratio	Available N:P Ratio
	Total Nitrogen µg-N/l	Total Phosphorus µg-P/l		
4/07/80	716	65	11	23.3
5/28/80	774	89	8.7	16.8
6/24/80	552	93	5.9	10.6
7/08/80	634	69	9.2	15.3
7/29/80	1053	61	17.3	32.5
8/12/80	608	42	14.5	32.7
8/26/80	534	51	10.5	20.3
10/09/80	211	19	10.1	20.8
10/30/80	547	35	15.6	52.1
11/20/80	351	51	5.7	16.3
1/13/81	342	40	8.6	20.0
2/18/81	409	54	7.6	12.0
3/30/81	655	61	10.8	15.6

CHAPTER VI

QUANTITY-QUALITY ANALYSIS

Correlation between the water quality of Lake Eola to the stormwater runoff quantity, would be based on mass balance between sources of the nutrient species from stormwater runoff and sinks via the drainage well and seepage to the ground water table. In other words, seepage from the ground water to the lake was assumed to contribute no nutrients and evaporation was assumed to remove no nutrients. This can be represented by the following mass balance equation for each species where the change in lake mass is equal to the mass coming in minus both the mass leaving and that retained by the bottom sediments:

$$\begin{aligned} V_{\ell(t+1)} C_{\ell(t+1)} = {} & V_{\ell(t)} C_{\ell(t)} - V_{dw_{\Delta t}} C_{\ell(\Delta t)} + V_{sw_{\Delta t}} C_{sw_{\Delta t}} \\ & - V_{so_{\Delta t}} C_{\ell_{\Delta t}} + V_{sl_{\Delta t}} C_{sl_{\Delta t}} - V_{ev_{\Delta t}} C_{ev_{\Delta t}} \qquad (12) \\ & + V_{dp_{\Delta t}} C_{dp_{\Delta t}} \pm M_{sr_{\Delta t}} \end{aligned}$$

Where:

$V_{\ell_{t+1}}$ = Volume in Lake at time t + 1

$C_{\ell t+1}$ = Concentration in Lake at time t + 1

$V_{\ell t}$ = Volume in Lake at time t

C_{ℓ_t} = Concentration in Lake at time t

$V_{dw_{\Delta t}}$ = Volume of water leaving Lake via drainage well over time interval Δ

$C_{\ell_{\Delta t}}$ = Average of $C_{1(t + 1)}$ and C_{1t}

$V_{sw_{\Delta t}}$ = Volume of stormwater runoff over time interval Δt

$C_{sw_{\Delta t}}$ = Concentration of stormwater runoff

$V_{so_{\Delta t}}$ = Volume of seepage out of Lake over time interval Δt

$V_{sl_{\Delta t}}$ = Volume of seepage into Lake over time interval Δt

$C_{sl_{\Delta t}}$ = Concentration of seepage into Lake (assumed = 0)

$V_{ev_{\Delta t}}$ = Volume of evaporated water over time interval Δt

$C_{ev_{\Delta t}}$ = Concentration of evaporated water (assumed = 0)

$V_{dp_{\Delta t}}$ = Volume of direct precipitation over time interval Δt

$C_{dp_{\Delta t}}$ = Concentration of direct precipitation (assumed = 0)

$M_{sr_{\Delta t}}$ = Mass of species retained or released from bottom sediment

This equation can be reduced to

$$V_{\ell t + 1} C_{\ell t + 1} = V_{\ell t} C_{\ell t} - (V_{dw_{\Delta t}} + V_{so_{\Delta t}}) C_{1_{\Delta t}} + V_{sw_{\Delta t}} C_{sw_{\Delta t}} \pm M_{sr_{\Delta t}} \tag{13}$$

since $C_{ev_{\Delta t}}$, $C_{dp_{\Delta t}}$ and $C_{sl_{\Delta t}}$ were assumed to be zero.

The measurement data and results of the individual parameters of this equation for water quantity and water quality measurements have been presented.

All except one parameter of equation 13 are now defined or can be estimated. This undefined parameter, M_{sr}, which is the mass of nutrients retained by the sediments per month can now be calculated by difference. Tables 16 to 19 depict the various values of the parameters of equation 10 and the calculated M_{sr}, for the quality species: Total Phosphorus, Total Orthophosphorus, Nitrate Nitrogen and Total Kjeldahl Nitrogen. M_{sr} for all species tested was a negative value at every month throughout the study year. It is shown that M_{sr} is related to stormwater events since the lowest values were calculated for the dry weather months. M_{sr} values ranged between 0.7 - 70.1 kg per month for TP, 1.0 - 39 for OP, 2.4 - 100 for NO_3-N and 5.9 - 447 kg/month for TKN.

Cummulative M_{sr} values for the entire year of 1980/1981 were calculated as the percent retention (R) of various nutrients by bottom sediments and was estimated as shown in Table 20. R values were 86.8%, 93.3%, 85.8% and 77.6% for TP, OP, NO_3-N and TKN-N, respectively.

TABLE 16

MASS BALANCE CALCULATIONS FOR TOTAL PHOSPHORUS

Month 1980/81	$V_{1_{t+1}}$ ML	$C_{1_{t+1}}$ µg/1	V_{1_t} ML	C_{1_t} µg/1	$V_{DW_{\nabla t}}$ ML	$C_{1_{\nabla t}}$ µg/1	$V_{SW_{\nabla t}}$ ML	$C_{SW_{\nabla t}}$ µg/1	M_{SR} Kg
April	334	63	341	60	72	60	51	480	-19.4
May	337	66	334	63	260	66	184	480	-70.1
June	339	56	337	66	33	65	23	480	-12.0
July	337	43	339	56	45	46	31	480	-17.3
Aug.	339	35	337	43	59	39	43	480	-20.7
Sept.	334	37	339	35	65	30	45	480	-19.3
Oct.	331	47	334	37	16	43	10	480	- 0.7
Nov.	358	49	331	47	99	51	88	480	-35.4
Dec.	331	44	358	49	14	47	8.8	480	- 6.7
Jan.	302	47	331	44	20	40	36	480	- 1.1
Feb.	322	57	302	47	0.7	54	28	480	- 9.2
Mar.	334	61	322	57	64	59	48	480	-17.2

Σ 229.1
R = 84.8%

TABLE 17

MASS BALANCE CALCULATIONS FOR TOTAL ORTHO PHOSPHORUS

Month	$V_{1_{t+1}}$ ML	$C_{1_{t+1}}$ μg/1	V_{1_t} ML	C_{1_t} μg/1	$V_{DW} + V_{SO}$ ML	$C_{1_{Vt}}$ μg/1	V_{SW} ML	C_{SW} μg/1	M_{SR} Kg
April	334	9.5	341	7	74	5	51	240	-11.
May	337	15.2	334	9.5	260	14	184	240	-39.
June	339	16.3	337	15.2	33	16.5	23	240	- 4.
July	337	9.5	339	16.3	44	16	31	240	- 9.
Aug.	339	1.5	337	9.5	59	3	42	240	-13.
Sept.	334	0.5	339	1.5	65	0.0	45	240	-11.
Oct.	331	5.0	334	0.5	16	1	10	240	- 1.
Nov.	358	9.0	331	5	99	9	88	240	-19.
Dec.	331	4.5	358	9	14	9	88	240	- 4.
Jan.	302	5.5	331	4.5	20	0.0	3.6	240	- 1.
Feb.	322	13	302	12	0.7	11	28	240	- 6.
March	334	16	322	13	64	14	48	240	- 9.
									Σ-126
									R =93.3%

TABLE 18

MASS BALANCE CALCULATIONS FOR NITRATE NITROGEN

Month	$V_{1_{t+1}}$ ML	$C_{1_{t+1}}$ µg/1	V_{1_t} ML	C_{1_t} µg/1	$V_{DW} + V_{SO}$ ML	C_{Vt} µg/1	V_{SW} ML	C_{SW} µg/1	M_{SR} Kg
April	334	112	341	61	72	113	51	650	-8.2
May	337	84	334	112	260	110	184	650	-100
June	339	60	337	84	33	57	23	650	-21
July	337	45	339	60	44	14	31	650	-22
August	339	22	337	45	59	26	42	650	-34
Sept.	334	16	339	22	65	18	45	650	-30.4
Oct.	331	29	334	16	16	15	10	650	-1.9
Nov.	358	50	331	29	99	42	88	650	-45
Dec.	331	46	358	50	14	57	8.8	650	-7.6
Jan.	302	48	331	46	20	34	3.6	650	-2.4
Feb.	322	59	302	48	0.7	62	28	650	-13.7
March	334	56	322	59	64	57	48	650	-27.8
									Σ314
									R=85.8

TABLE 19

MASS BALANCE CALCULATIONS FOR TKN

Month	$V_{1_{t+1}}$ ML	$C_{1_{t+1}}$ µg/l	$V_{1_{t+1}}$ ML	C_{1_T} µg/l	$V_{DW} + V_{SO}$ ML	$C_{\nabla t}$ µg/l	V_{SW} ML	C_{SW} µg/l	M_{SR} Kg
April	334	637	341	472	72	597	51	3,300	- 72
May	337	583	334	637	260	676	184	3,300	-447
June	339	632	337	583	33	490	23	3,300	- 68
July	337	658	339	632	44	775	31	3,300	- 60
August	339	447	337	685	59	540	42	3,300	-179
Sept.	334	358	339	447	65	354	45.3	3,300	-158
Oct.	331	331	334	358	16	361	9.9	3,300	- 37
Nov.	358	302	331	331	99	302	88	3,300	-263
Dec.	331	302	358	302	14	302	8.8	3,300	- 33
Jan.	302	320	331	302	20	303	3.6	3,300	- 8.9
Feb.	322	411	302	320	0.7	338	28	3,300	- 56
March	334	595	322	411	64	503	48	3,300	- 5.9
									Σ1441
									R = 77.6

TABLE 20

SEDIMENT RETENTION OF STORMWATER NUTRIENTS IN LAKE EOLA

Nutrient Species	Water Column Loadings (kg)	Runoff Volume (1000 cubic meters)	Stormwater* Average Concentration (mg/l)	Estimated Runoff Mass Loadings (kg)	%R Retained by Sediments
Total Phosphorus P	41.1	563	0.48	270.2	86.8
Ortho Phosphorus P	9.1	563	0.24	135.1	93.3
NO_3^{-2}-N	52	563	0.65	3.66	85.8
TKN-N	417	563	3.30	18.58	77.6

* Wanielista, Yousef, Taylor 1981.

If the quantity of stormwater runoff/precipitation can be correlated to the quality parameters of the lake, the question concerning the length of time a storm event can impact the lake needs to be addressed. To do this, a floating average calculation was performed for the various quality parameters vs. precipitation depth. Monthly stormwater runoff correlates well with monthly precipitation depths (r=0.98), as is shown in Figure 10.

Floating averages are the arithmetic mean of the lake concentration and of the precipitation depths for the specified consecutive period of time . The intervals of 2 to 4 consecutive months periods were selected.

Figures 10 to 13 depict the floating, averages of the Total Phosphorus lake concentrations vs. the monthly precipitation depths for the various time intervals. Table 21 displays the floating average correlations for the species: Total Phosphorus, Ortho-Phosphorus, Nitrate Nitrogen, TKN and Chlorophyll "a".

From Table 21, it can be seen that in all cases if greater than a one month time interval was considered, the correlation coefficient increased. Therefore, it may be concluded that the effect of the stormwater runoff continues for several months. The correlation coefficient (r) increased from 0.65 to 0.89 for Total Phosphorus from 0.41 to 0.80 for ortho-phosphorus and from 0.17 to 0.65 for chlorophyll "a". For nitrate-nitrogen, the increase in correlation coefficient was from 0.61 to 0.90 and TKN's correlation

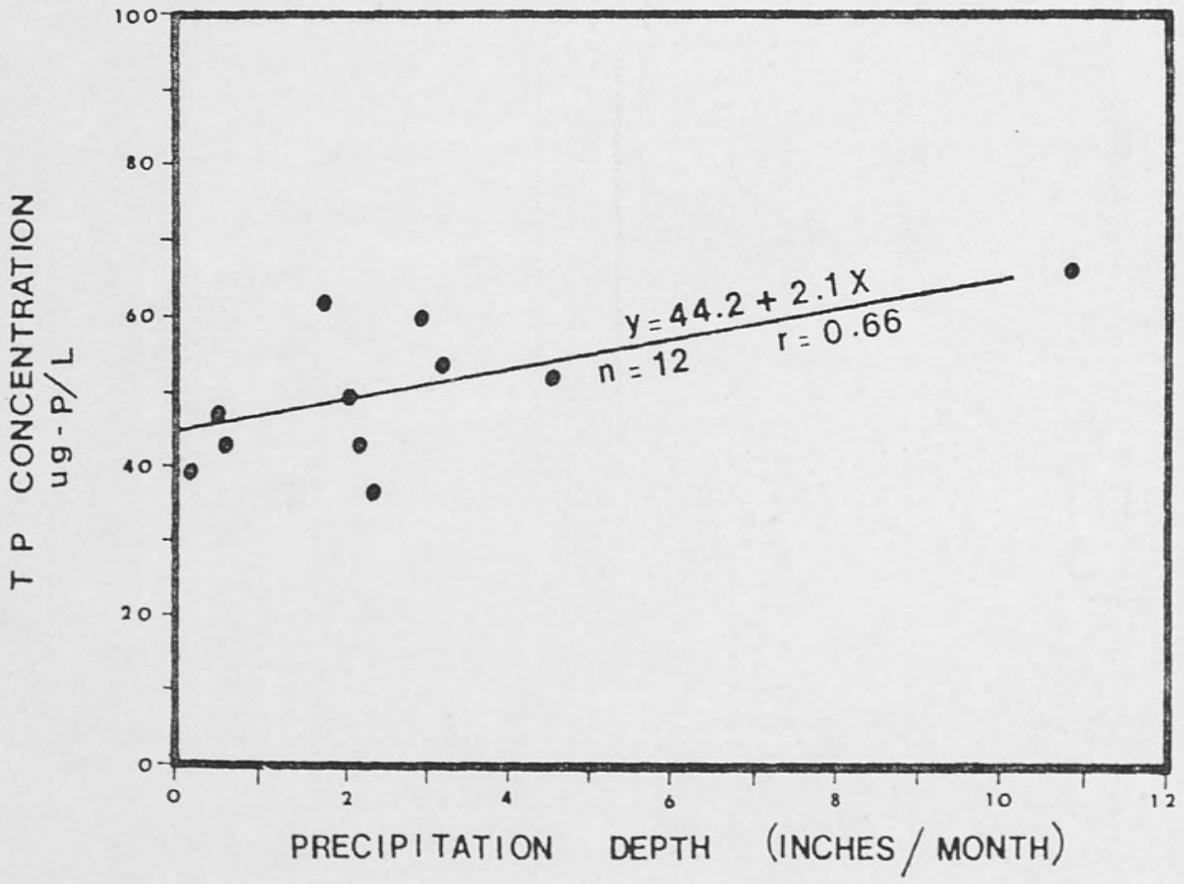


Fig. 10. Total phosphorus concentration versus precipitation depth for a one-month floating average interval.

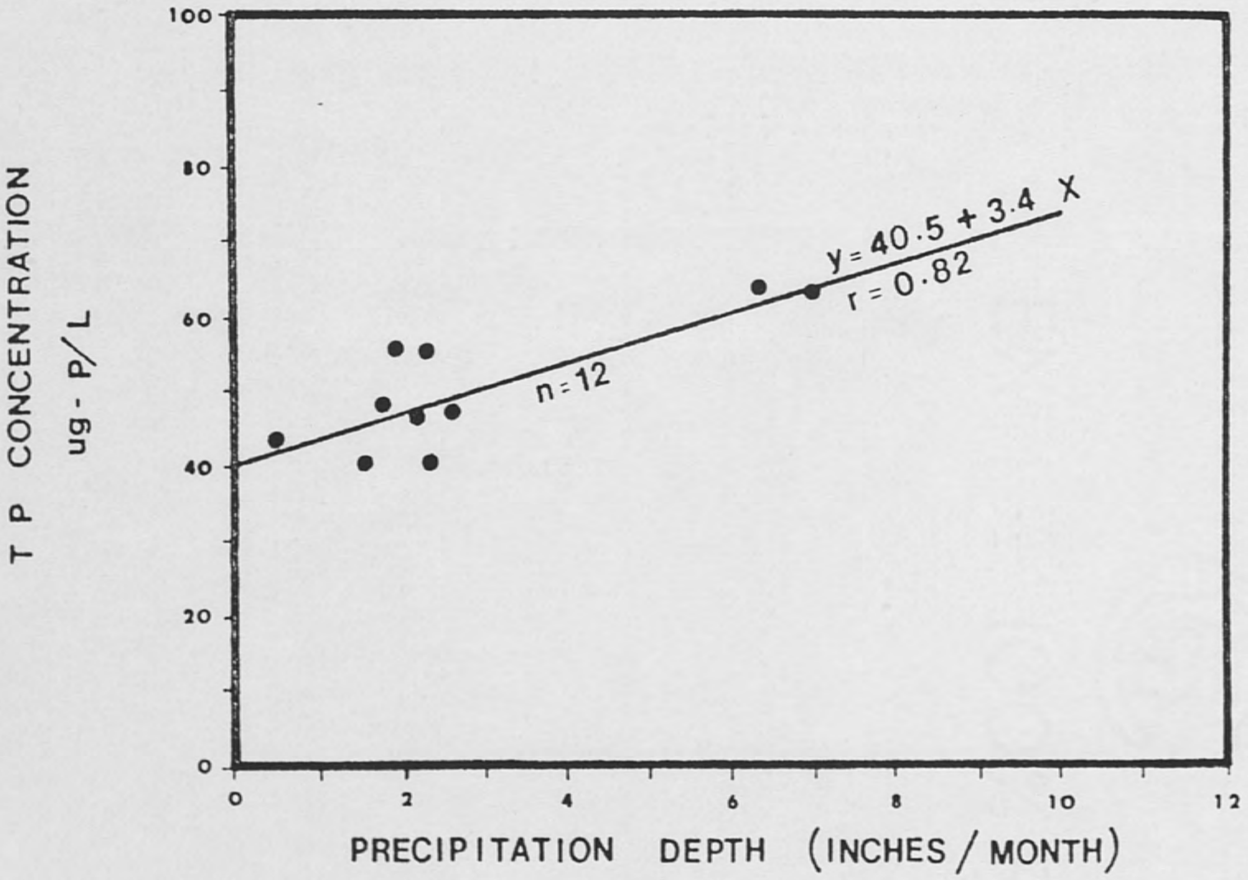


Fig. 11. Total phosphorus concentration versus precipitation depth for a two-month floating average interval.

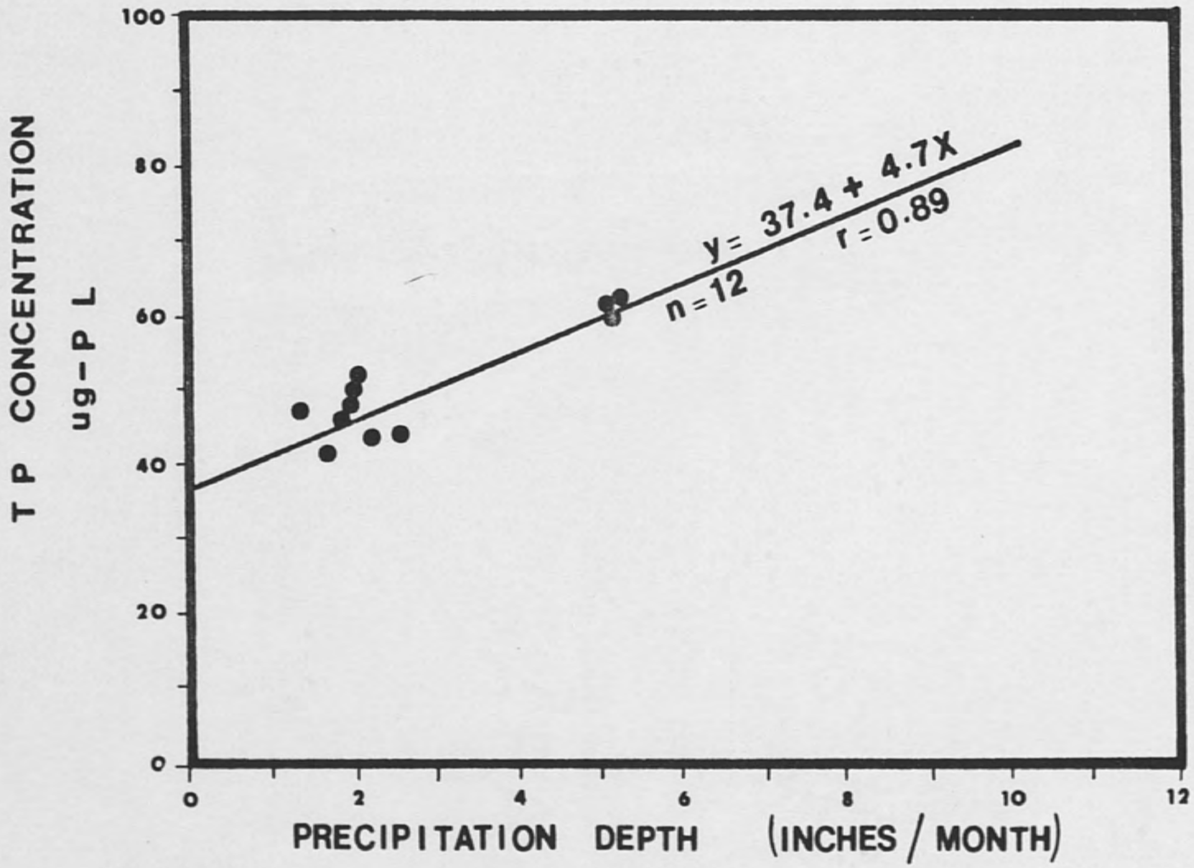


Fig. 12. Total phosphorus concentration versus precipitation depth for a three-month floating average interval.

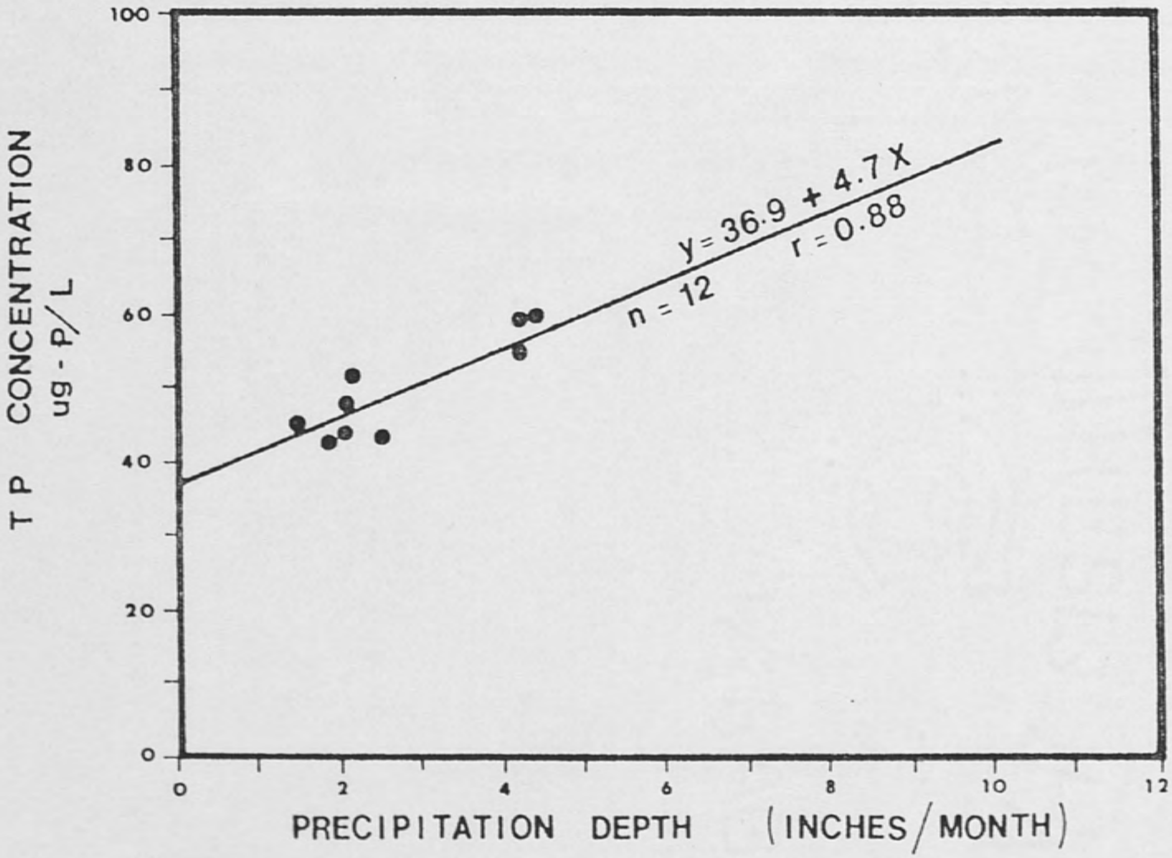


Fig. 13. Total phosphorus concentration vs. precipitation depth for a four-month floating average interval.

TABLE 21

RELATIONSHIPS BETWEEN FLOATING AVERAGE PRECIPITATION ON LAKE EOLA WATERSHED AND WATER QUALITY PARAMETERS IN THE LAKE

Independent Variable X	Dep. Var. Y for:		Functional Form	Correlation Coefficient r	Range		Number of Observations
	Parameter	Floating Average Period			X	Y	
Average Precipitation (inches/month)	Total Phosphorus (μg-P/l)	1 month	Y = 44.2+2.1X	0.65	0.21-10.90	37-66	12
		2 months	Y = 40.5+3.4X	0.82	0.38- 6.91	40-64	
		3 months	Y = 37.4+4.7X	0.89	1.30- 5.21	41-63	
		4 months	Y = 36.9+4.7X	0.88	1.51- 4.41	43-60	
	Ortho-phosphorus (μg-P/l)	1 month	Y = 5.17+.875X	0.41	0.21-10.90	0-16	12
		2 months	Y = 4.22+1.20X	0.48	0.38- 6.91	1-16	
		3 months	Y = 2.92+1.77X	0.65	1.30- 5.21	1-16	
		4 months	Y = 1.55+2.31X	0.80	1.51- 4.41	3-12	
	Chlorophyll "a" (mg/m^3)	1 month	Y = 16.2+0.41X	0.17	0.21-10.90	8.7-36.4	12
		2 months	Y = 13.2+1.55X	0.61	0.38- 6.91	11.4-28.1	
		3 months	Y = 12.6+1.92X	0.65	1.30- 5.21	13.0-25.5	
		4 months	Y = 12.2+2.3X	0.59	1.51- 4.41	13.2-26.7	
	Nitrate Nitrogen (μg/N-l)	1 month	Y = 34.8+6.82X	0.61	0.21-10.90	15-113	12
		2 months	Y = 21.7+10.9X	0.79	0.38- 6.91	17-112	
		3 months	Y = 15.7+12.7X	0.83	1.30- 5.21	20-93	
		4 months	Y = 6.72+15.2X	0.90	1.51- 4.41	25-86	
	TKN (μg-N/l)	1 month	Y = 398+24.0X	0.43	0.21-10.90	302-775	12
		2 months	Y = 345+40.3X	0.59	0.38- 6.91	302-636	
		3 months	Y = 308+56.4X	0.59	1.30- 5.21	302-647	
		4 months	Y = 289+62.4X	0.58	1.51- 4.41	311-634	

coefficient increased from 0.43 to 0.58. In all cases, as the time interval increased, the slope of the best fit line increased and the Y-intercept decreased.

Lake Tropho-Dynamic Model Approach

For lakes typical of Florida environment, receiving a continuous unsteady flow containing nutrients (i.e. not northern lakes with a large spring turnover) it is inadequate to describe Dillon's "R", or the percent of incoming load retained by lake sediments as a single number from 0 to 100%. It is a continuous function over time. Consider, for instance, a parcel of incoming water with some nutrient concentration. A certain mass of nutrients is associated with this parcel. Initially, when this mass has just entered the lake, all is contained in the water column. Therefore, R = 0, or (1 - R) = 100%. As time progresses more and more of the mass either leaves the lake via discharge or is retained by the sediments. Therefore, R increases or (1 - R) decreases. At some time all of this mass has either left the lake or is retained in the sediments and R reaches 100% or (1 - R) = 0%.

The following model is an attempt to predict lake nutrient specie concentration over time to allow for this changing R and also to allow for changes in the incoming nutrient flux (i.e. variations of runoff within the hydrologic cycle). It will also allow for the possibility of a baseline concentration that might exit with no runoff at all.

If Vollenweider's (1976) contentions that settling of the species is the primary mechanism for nutrient removal to the sediments, then an approach similar to Sherman's (1932) unit-hydrograph kernel can be used to describe (1-R(t)). It should be recognized that this approach does not consider changes in R with respect to concentration (C). Therefore, a more correct approach would be to write (1 - R(t,C)). However, if the range of C is small, (1-R(t)) may satisfy the lake's response to continuous inflows of nutrients.

Stormwater runoff into Lake Eola occurs from discrete storms of various sizes. As the size of the storm increases, the concentration of the stormwater runoff decreases. A descriptive model can be developed using Sherman's approach to streamflow simulation. Individual masses of incoming nutrients follow a kernel function as shown in Figure 14 with regard to their lifetime in the water column. Monthly precipitation depths generate monthly runoff volumes. Incorporating a first flush characteristic of concentration of this runoff yields monthly masses of nutrients for precipitation depths. This incoming mass is diluted and some is discharged via the drainage well. Therefore, an effective lake concentration rise related to monthly precipitation depths can be realized without rigorous consistency of units. By this, it is meant that since precipitation implies stormwater runoff, which in turn carries nutrient masses, which in turn is diluted by the lake water, monthly precipitation depths can be related to concentration increases or decreases

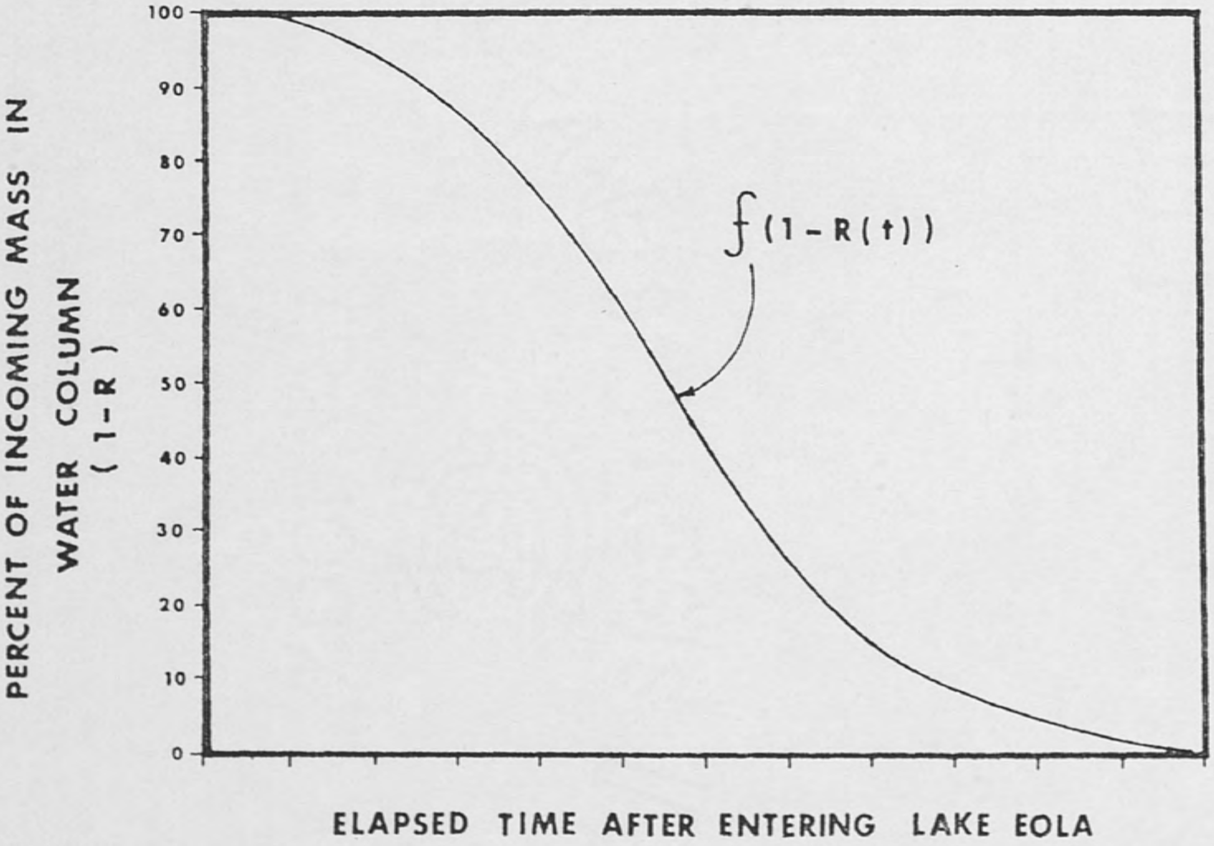


Fig. 14. A schematic of kernel function relating percent specie retention with elapsed time after entering the lake.

without considering the intermediate steps. The superposition of various time interval floating average calculation upon the same plot yields this estimate, as is shown in Figure 15. The slope of the line yields the effective concentration rise for precipitation depths. It has incorporated the first flush, dilution and nutrients flush out via the discharge well characteristics of the lake. The Y-intercept represents the baseline concentration.

The lake concentration at any time can be written mathematically as:

$$\sum_{n=0}^{t} (\Delta C_{p(t)} - [1 - R(t-n)]) + [C_{BL}] = [C_t] \qquad (14)$$

where:

$\Delta C_{p(t)}$ = lake concentration rise for monthly precipitation depth, as in Figure 15

$(1-R(t))$ = kernel function of Figure 14

C_{BL} = baseline concentration

C_t = lake concentration at time t

Graphically, this can be represented as is shown in Figure 16.

The lake can be assumed hydrodynamically open on both ends since a continuous source of runoff water is coming to the lake with no prolonged dry periods available to allow the lake concentration to reach baseline values. With the three unknowns (baseline concentration, effective lake concentration rise for corresponding precipitation depth and kernel function), and the absence of a known starting point, a trial and error solution is required and a family of

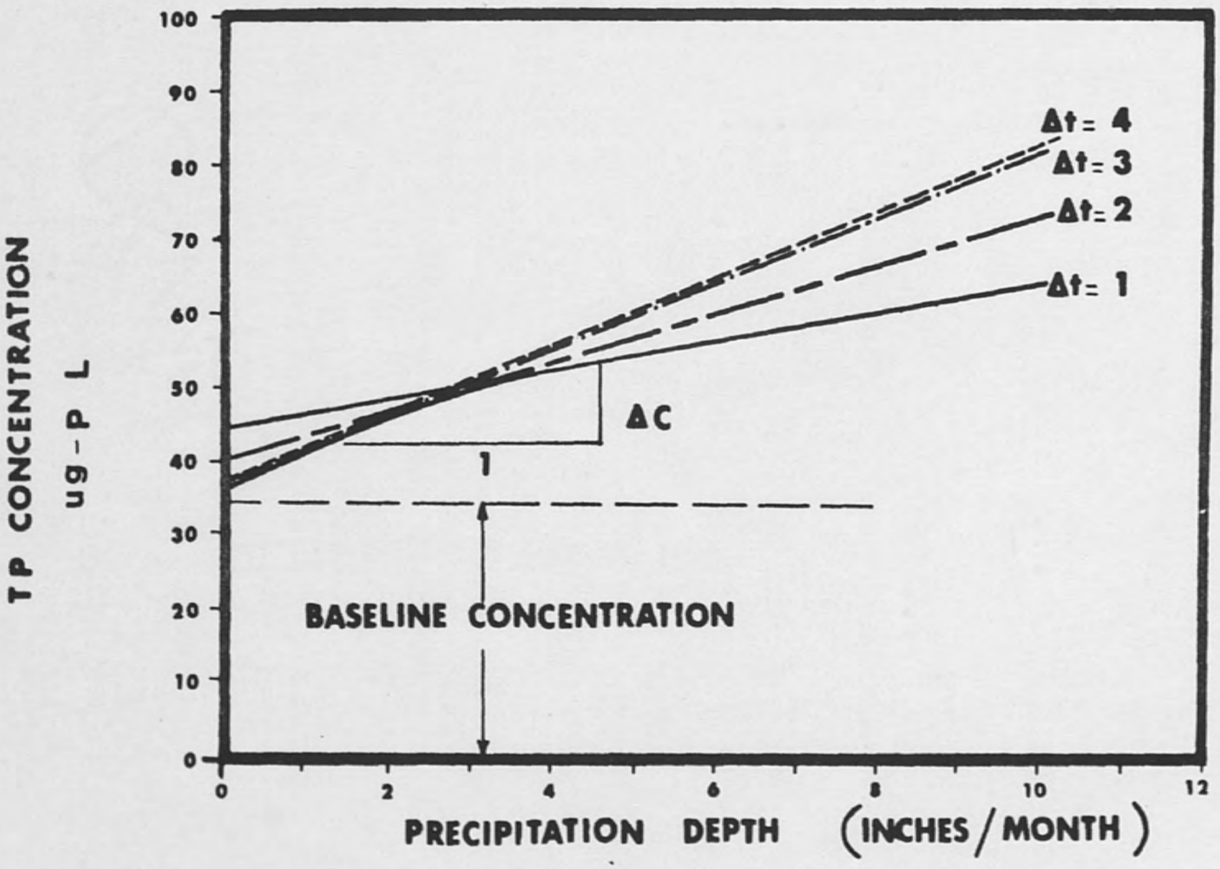


Fig. 15. Phosphorus concentration rise versus monthly precipitation for various floating average intervals.

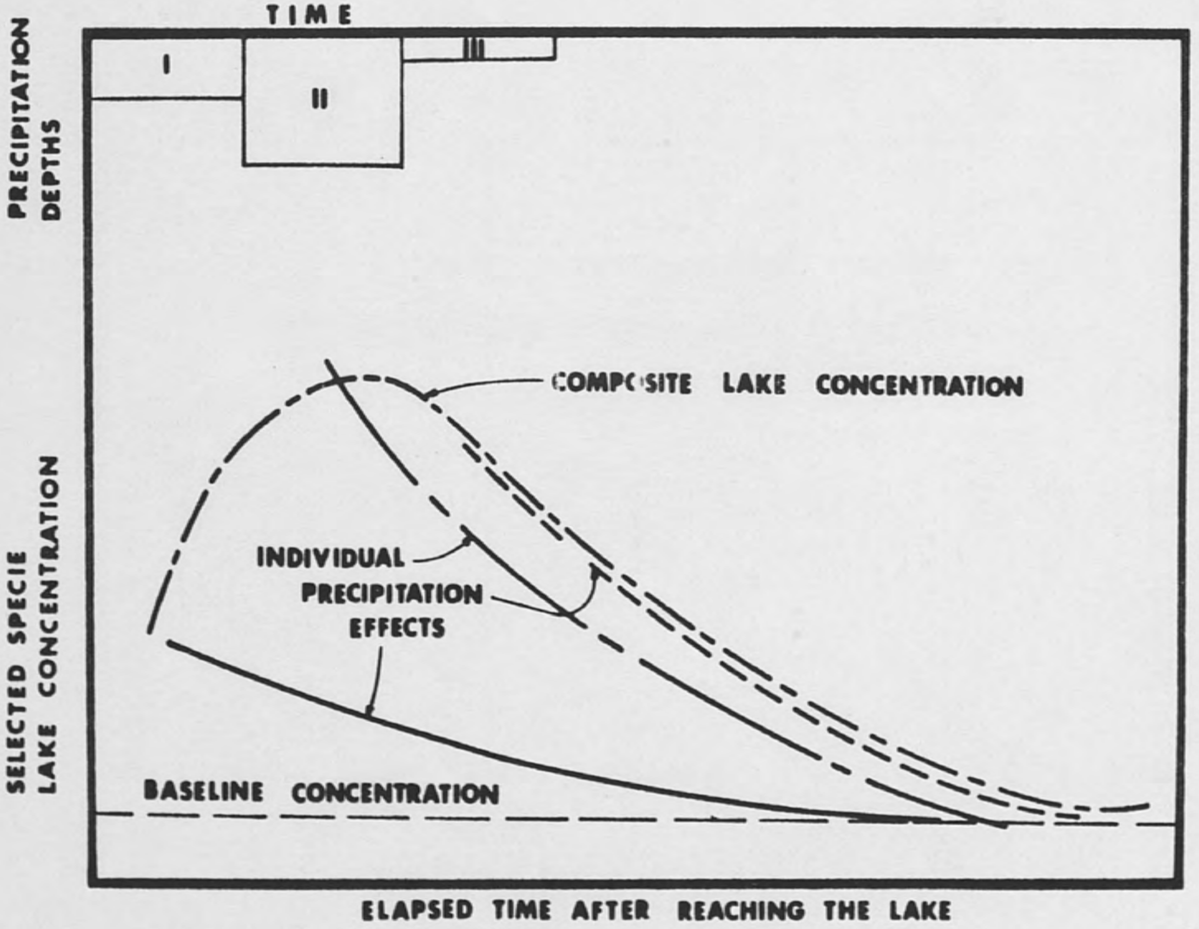


Fig. 16. Hypothetical curves showing an approach to calculating composite lake concentrations from varying rainfall events.

surfaces is evident in the solution. However, with a long period of lake concentration and precipitation data, the solution will collapse upon the true surface.

Monthly precipitation is a collection of discrete storms and not a continuous event. Therefore, errors in estimating dc/di may evolve from the temporal distribution of these discrete storms within each month and allowance for errors in the composite lake estimate must be made. Also, the time after a storm event when the quality samples were gathered may cause errors.

Since the hydrologic cycle witnessed during this study period was abnormally dry, the simplification of writing the kernel function of (1 - R(t,C)) as (1 - R(t)) can be validated by obtaining the same kernel for a more normally wet year. If the same kernel is not apparent, the removal mechanisms are substantially concentration dependent.

The same model might be used to model the algal growth response to stormwater runoff. In this case (1-R(t)) would have an initial rise in value to account for the time lag of growth after the stormwater nutrients enter. The shape of the kernel function might be expected to appear as in Figure 17. However, due to complexities of growth kinetics, direct superposition of monthly precipitation effects may be not valid.

A sensitivity analysis may be performed to determine the importance of accurately defining the three unknowns, namely first

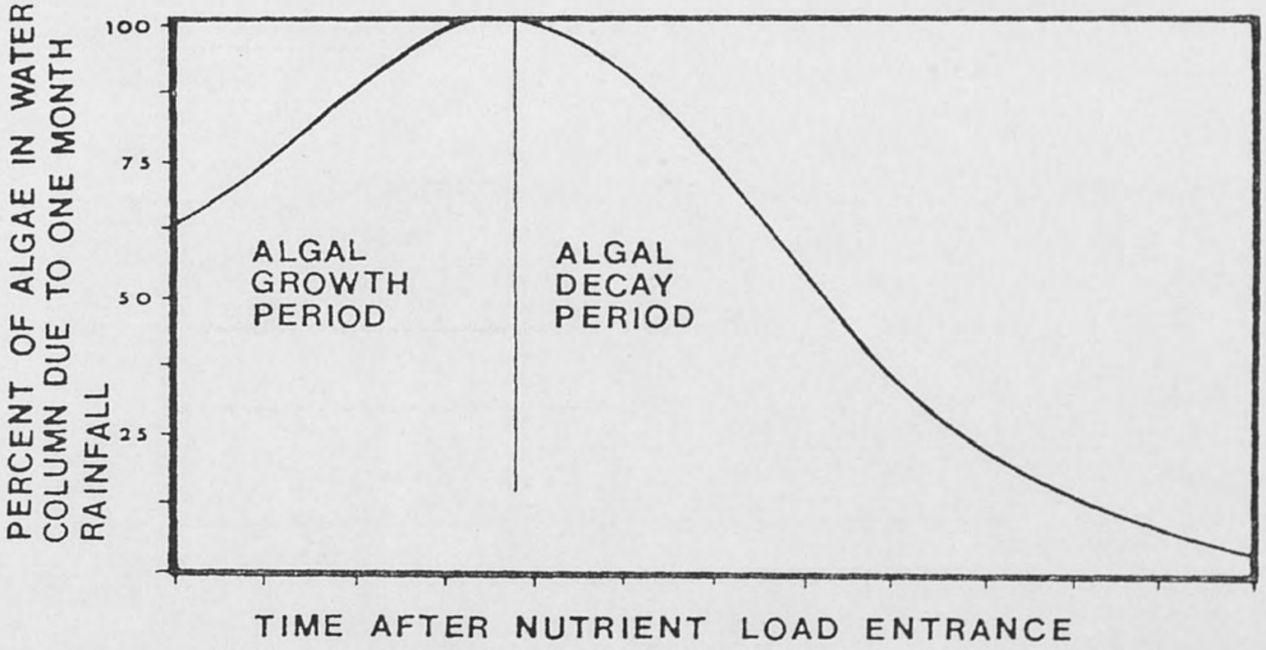


Fig. 17. A schematic of kernel function relating algal growth and decay with elapsed time after introduction of nutrients to the lake.

flush curve, kernel curve and baseline concentration. Each unknown is believed to be of equal importance in describing the variable concentration curve. An accurate estimate of the baseline is important for accurately defining the valley concentrations (I). The first flush or change in lake concentration curve is responsible for accurate peak definition (II). The kernel function defines the skewness of peak decline (III), as shown in Figure 18.

Computation Procedures

The computation procedure for predicting lake concentration over time with variations in monthly rainfall follows exactly the procedure of Sherman's (1932) Unit Hydrograph procedure.

The instantaneous monthly contribution is assigned a value from a first flush curve, as is shown in Figure 15. Its contribution with increasing time changes in the manner described by the kernel function of Figure 14. Every month follows the same procedure and the individual contributions are directly added. Then the baseline concentration is added to gain the composite lake concentration as in Figure 16. Algebraically, this can be expressed as:

$$[C_L] = [C_{BL}] + [C_{FF_t} \cdot (1-R(t)] + [C_{FF_{t-1}} - (1-R(t-1)]$$

$$+ [C_{FF_{t-2}} \cdot (1-R(t-2)] + \ldots + [C_{FF_{t-n}} \cdot (1-R(t-n)] \quad (15)$$

where:

C_{FF_t} = the instantaneous monthly contribution

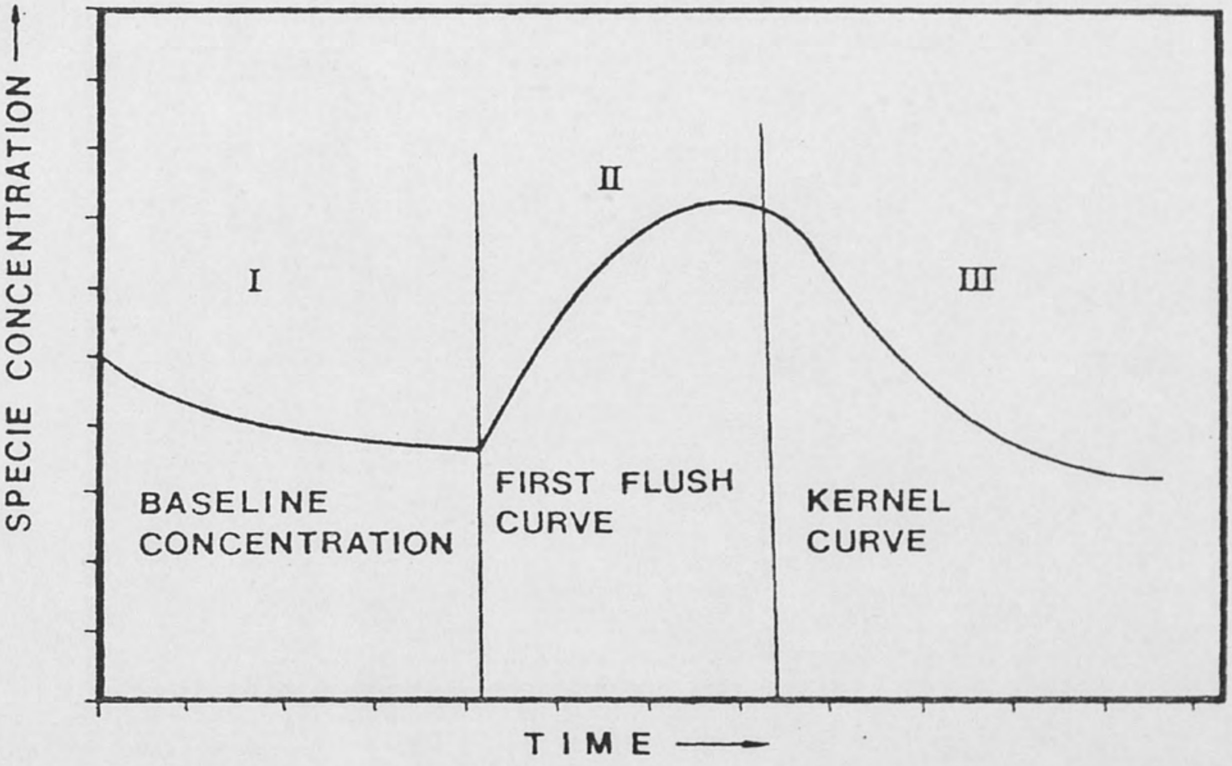


Fig. 18. Schematic representation of changes in specie concentration with storm event.

It should be re-emphasized that the calibration requires a trial and error solution on all three curves. If substantial deviation of predicted and actual concentration occurs, Figure 18 should be used for rational individual curve modification.

This model was calibrated for the specie, Total Phosphorus, for quantity and quality data for Lake Eola from April 1, 1980 to March 31, 1981, by trial and error. This calibration is depicted in Figures 19 and 20. Table 22 depicts the computation process.

Table 22 requires some explanation as to the selection of the various values or curves selected for use in the computation process. The precipitation values were those actually recorded by the rain gage. The expected rise in Total Phosphorus concentration was selected from Figure 15. The stormwater runoff was assumed to have first flush characteristics. Therefore, months with lower rainfall have a disproportionately higher expected rise in concentration per inch of rainfall than months with higher rainfalls. The value chosen for each month except May was assumed to be equal to the monthly precipitation times 5 μg-P/l (which is approximately equal to the slope of the four-month floating average calculation). The expected rise in concentration for May, which had an abnormally high rainfall, was assumed to be equal to its precipitation depth times 2.75 μg-P/l (which is approximately equal to the one-month floating average calculation).

It is recognized that these are somewhat arbitrary assumptions, however, they are conservative estimates of the stormwater runoff

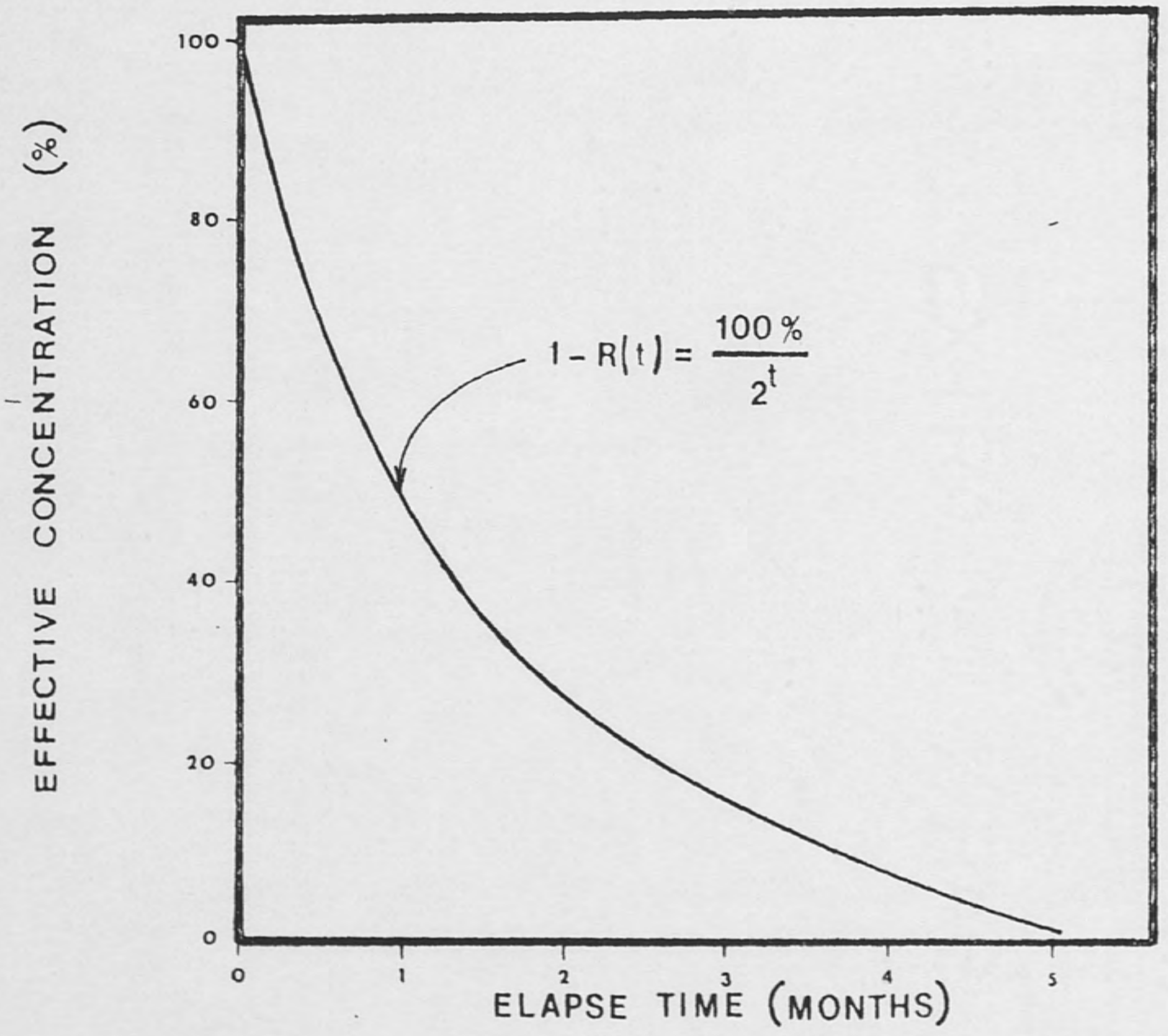


Fig. 19. Normalized phosphorus concentration after introduction to the lake showing its decay function.

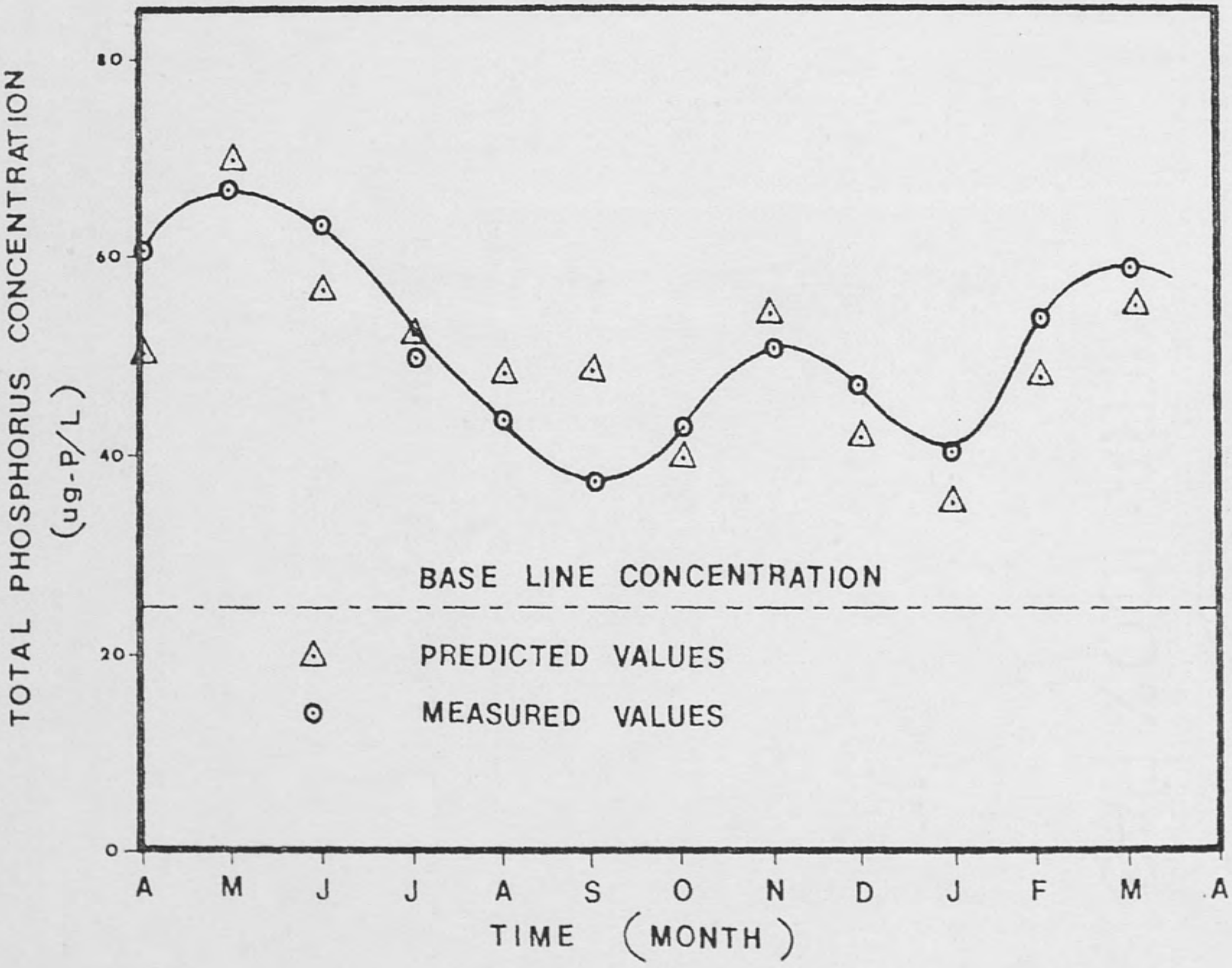


Fig. 20. Actual and predicted Lake Eola Total Phosphorus concentration. April 1980-March 1981, by trial and error.

TABLE 22

COMPUTATION SHEET FOR TOTAL PHOSPHORUS USING TROPHO-DYNAMIC MODEL

Month	Precip. Inch/Month	Expected rise in TP µg-L-P	(1-R) t for various *Time Intervals after reaching the lake														
			(1)	(2)	(3)	(4)	(5)										
JAN.	2.75	13.8	13.8	6.9	3.4	1.7	0.0	-	-	-	-	-	-	-	-	-	-
FEB.	1.64	8.2	-	8.2	4.1	2.0	1.0	0.0	-	-	-	-	-	-	-	-	-
MAR.	1.51	7.6	-	-	7.6	3.8	1.9	1.0	0.0	-	-	-	-	-	-	-	-
APR.	3.00	15.0	-	-	-	15.0	7.5	3.8	1.9	0.0	-	-	-	-	-	-	-
MAY	10.90	30.0	-	-	-	-	30.0	15.0	7.5	3.8	0.0	-	-	-	-	-	-
JUN.	1.76	8.8	-	-	-	-	-	8.8	4.4	2.2	1.1	0.0	-	-	-	-	-
JUL.	2.09	10.4	-	-	-	-	-	-	10.4	5.2	2.6	1.3	0.0	-	-	-	-
AUG.	2.19	10.9	-	-	-	-	-	-	-	10.9	5.4	2.7	1.4	0.0	-	-	-
SEP.	2.42	12.1	-	-	-	-	-	-	-	-	12.1	6.0	3.1	1.5	0.0	-	-
OCT.	0.62	3.1	-	-	-	-	-	-	-	-	-	3.1	1.5	0.8	0.4	0.0	-
NOV.	4.61	23.1	-	-	-	-	-	-	-	-	-	-	23.1	11.6	5.8	2.9	0.0
DEC.	0.54	2.7	-	-	-	-	-	-	-	-	-	-	-	2.7	1.4	0.7	0.3
JAN.	0.21	1.1	-	-	-	-	-	-	-	-	-	-	-	-	-	0.6	0.3
FEB.	3.28	16.4	-	-	-	-	-	-	-	-	-	-	-	-	-	16.4	8.2
MAR.	2.98	14.9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	14.9
*FROM Figure 15		Σ				22.6	40.4	28.5	24.2	22.1	21.3	13.2	29.1	46.5	18.6	20.5	23.7
		Baseline Concentration µg/L-P				27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4	27.4
		Composite Lake Concentration Predicted µg/L-P				50	67.8	55.9	51.6	49.5	48.7	40.6	56.5	43.9	36.0	47.9	54.1
		Month				A	M	J	J	A	S	O	N	D	J	F	M
		Actual Lake Concentration				60	66	65	46	39	37	43	51	47	40	54	59
		Δ = Predicted Concentration - Actual Concentration				-10	1.8	-9.1	+5.6	-10.5	+ 11.7	-2.4	+5.5	-3.1	4.0	-6.1	-4.9

$\sigma = 11.18$ µg

$\Delta\sigma = 8.53$

impacts on lake quality. Also, as has been previously stated, there is a family of solutions available in a model with three unknown parameters (i.e., baseline concentration, first flush characteristics and kernel curve) and with no known starting point. Therefore, it should be realized that this example provides one of an infinite set of surfaces. It is simply meant to provide an example of the proposed tropho-dynamic model and should not be construed as the only possible solution for calibration of Lake Eola to this model.

These expected monthly concentration rises are then placed in their appropriate row of the matrix of Table 22, each one being offset in time from the previous month. The function of (1-R(t)) is determined by trial and error until the peaks and valleys of the predicted curve are in approximately the same time position. The relative magnitudes of the peaks above the valleys are similar to the actual lake concentrations. The particular kernel function for this example with the assumed first flush characteristics is presented in Figure 19. This function appears to have the form of exponential decay, as in:

$$(1-R)(t) = \frac{100\%}{2^t} \qquad (16)$$

The average values for predicted and actual lake concentrations versus time curves are equal. Figure 20 depicts the predicted and actual lake concentrations for the study year.

The errors in predicting lake concentration from measured lake concentrations ranged from +32% in September to -17% in April. However, the standard deviation of these differences between actual and predicted values was 8.53 μg-P/l. The standard deviation of the actual lake concentrations was 11.18 μg-P/l.

Summary

For the lake quality parameters analyzed, it can be seen that Lake Eola removes most of the nutrients entering the lake. The percent of incoming mass retained by the sediments ranged from 77.6 for TKN to 93.3 for Total Ortho Phosphorus. This value is extremely dependent upon the value selected for incoming stormwater concentration since lowering this estimate to the magnitude of the individual lake specie concentration would yield percentages close to zero and raising them would yield percentages approaching units.

On a month-by-month basis, at times more mass is retained than comes into the lake. This is evident in any month whose lake specie concentration is less than the previous month.

This implies that the effect of one month's precipitation carries over into the subsequent month. This is borne out by the improving correlations for the different floating average calculations with corresponding increasing time intervals.

The tropho-dynamic lake model seems to have merit for predicting the unsteady state hydrologic effects on the concentration of Total

Phosphorus. However, besides any obvious errors in sampling scheme or laboratory testing, a basic logic flaw might possibly exist. The use of Vollenweider's assumption of an "apparent" settling velocity considers only concentration independent mechanisms for specie removal to the sediments. Concentration dependent removal mechanisms such as adsorption are ruled out. Perhaps the concentration independent mechanisms predominate, but one should not assume so.

Performing similar water budget-quality analyses for more normal hydrologic years would provide either support or conflict with ruling out the concentration dependent mechanisms. If the kernel function should significantly change, concentration dependent mechanisms are significant and the model must now be modified to contain this fourth unknown (changes of shape of kernel due to composite lake concentration).

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Lake Eola is 11 hectares in surface area and receives high level pollutants in stormwater runoff from commercial and residential areas. Algal assays and trophic analysis models from previous studies concluded that phosphorus is most likely to be the limiting nutrient.

Various parameters of the water budget including evaporation, seepage, lake stage and rainfall/runoff measurements were routinely documented. Also, changes in water quality parameters of the lake and runoff samples were measured. The dynamic change in nutrient content, especially phosphorus and the associated algal response during wet and dry seasons were evaluated. Phosphorus loadings from stormwater and from bottom sediments released under anaerobic conditions during rainy seasons were found to be significant. The rate and extent of phosphorus loading from various sources were quantified.

This study demonstrated the dynamic nature of the hydrologic and nutrient inputs into Lake Eola from stormwater runoff. Therefore, careful consideration should be given in applying steady state models for prediction of eutrophic state of the lake. The following specific conclusions were reached:

1. An approach to predicting the fate of nutrients released to Lake Eola in stormwater runoff is presented. This methodology is based on a trial and error solution since three unknowns, namely, first flush function, decay function and baseline concentration exist.

2. The decay function for a nutrient specie after introduction to the lake can be determined. For Total Phosphorus in the lake, it is found that this function will follow an exponential decay as shown by:

$$[1 - R(t)] = \frac{100\%}{2^t}$$

where R(t) is the fraction retained after time "t" from introduction of the specie.

3. Using the above developed decay function for Total Phosphorus, it was possible to predict variations in concentrations of TP in Lake Eola water with time of year. The range of percent error between predicted and measured values varied between +32% and -16%. The range of measured values was from 37 to 66 μg-P/l. The range of predicted value was from 36 to 68 μg-P/l. The yearly predicted average concentration is similar to the yearly measured average concentration.

4. The decay function R(t) was used as a constant parameter by previous investigators. However, it appears that this parameter must be recognized as a function of time and/or concentration of a selected specie.

5. A sizeable fraction of the incoming nutrients to Lake Eola associated with stormwater runoff was retained in the lake sediments. On a mass balance basis, the overall yearly fraction of TP, OP, NO_3-N and TKN-N retained by the bottom sediments amounted to 86.8, 93.3, 85.8 and 77.6 percent, respectively.

6. The temporal variation of the nutrient species was considerable throughout the study year, with peaks in lake specie concentration occurring after the months of heaviest rainfall.

7. As should be expected for a watershed of this small size, the relationship between stormwater runoff and the precipitation was linear and followed this relationship:

$$y = -0.075 + 0.60X$$

where: y = stormwater runoff volume (million cubic feet)

X = monthly precipitation (inches)

with: $r = 0.98$ and $n = 12$

8. With the occurrence of several precipitation events within a short interval, it is necessary to consider the discharge of lake water via the drainage well as a continuous flowing stream and the exponential relationship of:

$$Q_{dw} = 0.00877\ AS$$

where: Q_{dw} = discharge rate (cubic feet/hour)

A = lake surface area (square feet)

S = stage above drainage well elevation (feet)

with: $r = 0.99$ and $n = 8$

9. Of the two methods used to estimate the monthly volume of seepage through the lake/sediment interface, the estimation by difference appears to be more reliable. By this method, net seepage inputs accounted for 23% of the hydrologic budget. Since Lake Eola is a natural landlocked lake and yearly evaporation is more or less equal to yearly precipitation, seepage must have been the predominant factor in the early hydrologic budget. The seepage drum technique is very labor intensive. However, it does allow for determination at specific locations as to whether the water is leaving or entering the lake. This method showed seepage to the lake along the northern shoreline and seepage out of the lake along the southern shoreline.

Recommendations

Analysis of any specific lake should include the aspects of the specific hydrology and geomorphology of its drainage basin. However, for generalization of water quality responses due to nutrient input, it is recommended:

1. Similar studies of the tropho-dynamic nature should be performed on other nutrient species and on other lakes in order to provide insights as to the actual retention mechanisms involved in the transport of non-conservative species to the bottom sediments.

2. A more frequent and detailed speciation of the nutrients in both stormwater runoff and lake water must be performed in order

to accurately determine the fate of various fractions of the selected specie released to the lake in stormwater runoff.

3. Whether or not the retention function "R" is a simple function of time or actually a function of time and some other parameter still needs to be addressed more thoroughly. Specifically, will the phosphorus retention capabilities of Lake Eola's sediments continue to retain under similar hydrologic conditions 87% of the stormwater phosphorus load?

4. With the purchase of a self-recording rain gage and a self-recording stage gage and the construction of a protective housing for the evaporimeter, a meteorological station could be located on some unobstructed platform on Lake Eola to determine the hydrologic budget for a more normally wet year.

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