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POTENTIAL PHOSPHORUS LOAD REDUCTIONS UNDER THE LAKE OKEECHOBEE REGULATORY PROGRAM[1]

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ABSTRACT: Nutrient loading from beef pastures located within the northern Lake Okeechobee watershed in Florida, has been identified as a source of phosphorus contributing to the accelerated eutrophication of the lake. Since 1989 within the watershed, 557 agricultural drainage sites, mainly beef pasture, have been monitored for compliance under a regulatory program. Of those sites, 154 were actively monitored for phosphorus concentrations from October 1, 1998, to September 30, 1999. Of these 154 sites, 77 were considered to be out of compliance (OOC). An OOC site is defined as having runoff with a 12-month average phosphorus concentration exceeding the permitted discharge limit. The average annual phosphorous load from the 77 OOC sites for an eight-year study period from October 1, 1991, to September 30, 1999, was estimated using measured concentration values and simulated runoff obtained from an agricultural nonpoint source pollution model, CREAMS-WT. The 77 OOC sites produced an estimated average annual 46 metric tonnes of phosphorus load, of which an estimated 22 tonnes of phosphorus reached Lake Okeechobee on an average annual basis. The remaining estimated average annual 24 tonnes of phosphorus load was retained by streams and wetlands in the discharge transport system between the sites and the lake. The estimated average annual load reaching Lake Okeechobee from the OOC sites represented 11 percent of the phosphorus load above a five-year average annual target load for the lake. However, the OOC site drainage areas represented only 3 percent of the northern watershed that drains into the lake. Of the 77 OOC sites, 12 sites had an average annual phosphorus loading rate equal to or greater than 3.0 kg/ha and were placed on the priority list for the Critical Restoration Project in the Lake Okeechobee watershed. To estimate the possible phosphorus load reductions from the 77 sites, two scenarios were modeled. The first scenario reduced phosphorus concentrations in runoff to the permitted discharge limits under the Lake Okeechobee regulatory program. The second scenario changed current land uses to native rangeland with an estimated annual offsite total phosphorus areal loading rate of 0.114 kg/ha. These two scenarios are hypothetical with assumed concentration values and loading rate. Model results showed that the first management scenario reduced the average annual phosphorus load to the lake by an estimated 15 tonnes. The second scenario reduced the average annual phosphorus load to the lake by an estimated 21 tonnes.

(KEY TERMS: modeling; runoff; water quality; phosphorus transport; watershed management; nonpoint source pollution; monitoring.)

INTRODUCTION

Lake Okeechobee, the largest freshwater lake in the southeastern United States, is located in south central Florida. Over the past 30 years, the lake has experienced accelerated eutrophication due to excessive phosphorus loads. Cattle waste from the drainage basins north of the lake was determined to be a major source of the excessive loading (Boggess *et al.,* 1995). To control nonpoint source phosphorus runoff from all land uses (excluding dairies) in the Lake Okeechobee watershed, the South Florida Water Management District (SFWMD) developed the *Works of the District – Lake Okeechobee Basin Rule* (Chapter 40E-61, Florida Administrative Code) (SFWMD, 1989) (hereafter called the Rule). The Rule establishes total phosphorus concentration limits in the discharge flow from sites 0.2 ha in size or larger. The Rule requires that permitted sites that have drainage impacts on Lake Okeechobee and are located in the problematic basins be monitored bi-weekly for one year to determine if they meet the total phosphorus concentration limit. At the end of that year, if the average concentration exceeds the total phosphorus concentration limits, the sites are considered out of compliance (OOC) and continue to be monitored under the Rule. In accordance with the Rule, 557 discharge sites have been monitored under the Lake

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Okeechobee Works of the District (WOD) program. Due to resource constraints, the number of sites that are monitored is limited to 175 for each bi-weekly sampling event. Also, many sites permitted under the WOD program have no distinct drainage points and cannot be monitored. Other sites have discharge points that are not accessible. Total phosphorus concentrations were monitored at 154 sites during the period from October 1, 1998, to September 30, 1999. Of the 154 sites, 77 were OOC. After the first year of monitoring, a site is considered OOC if the 12-month rolling average phosphorus concentration in the site discharge is greater than the permitted discharge limit.

The estimated five-year average annual phosphorus load to Lake Okeechobee from the watershed for the period of 1995 to 1999 was 582 metric tonnes, which is 198 tonnes above the target of 384 tonnes (SFWMD, 2001). As part of ongoing efforts to reduce phosphorus to the lake, the Lake Okeechobee Water Retention/Phosphorus Removal Critical Restoration Project is being conducted in the Lake Okeechobee watershed. The Critical Restoration Project is designed to attenuate peak flows and reduce phosphorus loads through the restoration and/or creation of wetlands. Prior to on-site implementation, the Critical Restoration Project requires a priority list of high phosphorus load sites in the watershed. The most cost effective restoration projects can be implemented on sites selected from this priority list. This study used measured phosphorus concentration data to estimate the load contribution to Lake Okeechobee from the OOC sites and determined which sites to place on the priority list.

This study is an extension of the work done by Zhang and Essex (1997). The approach for determining the phosphorus loads from the OOC sites is similar in both studies. The main difference between the two efforts is the study period and the amount of available data. Zhang and Essex (1997) used a four-year study period, from October 1, 1991, to September 30, 1995. This study used an eight-year study period, from October 1, 1991, to September 30, 1999. In general, four more years of phosphorus concentration data were available for this study. With a bi-weekly sampling program, the maximum number of samples per year from a particular site is 26 if there is year-round discharge flow from the site. Additionally, the OOC sites did not stay the same between the two studies as more sites were permitted under the WOD program and as some OOC sites became compliance sites and vise versa.

The five objectives associated with the study reported here were: (1) identify the OOC sites in the northern Lake Okeechobee watershed for the 12-month period from October 1, 1998, to September 30, 1999; (2) estimate off-site phosphorus discharge loads using monitored phosphorus concentrations and model predicted runoff values; (3) estimate the phosphorus loads to Lake Okeechobee by taking into account the calculated phosphorus assimilation capacities of the transport system; (4) identify high phosphorus load discharge sites for the Critical Restoration Project; and (5) evaluate the potential phosphorus load reductions that might be achieved through better management of the OOC sites. For evaluating the potential load reductions, two hypothetical scenarios were considered. In the first scenario, phosphorus concentrations in runoff were reduced to the discharge limits established by the WOD program per the Rule. In the second scenario, the OOC sites were changed to native rangeland uses with an estimated annual off-site total phosphorus areal loading rate of 0.114 kg/ha (Harper, 1994).

SITE DESCRIPTION

Site Selection

Under the WOD program, personnel visited a maximum of 175 sites bi-weekly and took discharge phosphorus concentration grab samples from each site if there was runoff from the site. Many sites in the Lake Okeechobee watershed only have discharge during the wet season (April through September) or following a rain event. The timing of a site visit was not correlated to rain events and was random based primarily on personnel availability. The samples were analyzed, and the measured discharge phosphorus concentration values are stored in a database at the SFWMD. By searching this database, it was found that 154 sites had at least one measured discharge phosphorus concentration value from October 1, 1998, to September 30, 1999. For this 12-month period, the average number of samples per site was between eight and nine. Of these sites, 103 OOC sites were identified. In order for a site to be classified as an OOC site, the average discharge phosphorus concentration for the 12-month period from October 1, 1998, to September 30, 1999, must have been greater than the permitted discharge limit for the site as established by the WOD program per the Rule.

Of the 103 OOC sites, 20 were classified as internal or onflow sites that received high runoff concentrations from upstream sites; five sites had an average phosphorus concentration level within +0.05 of the limit (i.e., if the limit was 0.35 mg/L, the average value was less than or equal to 0.40 mg/L), and one site was a duplicate monitoring station. After eliminating these 26 sites, 77 discharge sites were then considered truly OOC sites for the period from October 1, 1998, to September 30, 1999 (Figure 1). This was the same process used for the site selection in the previous study (Zhang and Essex, 1997). Of the 77 sites used in this analysis, 30 were included in that previous study.

Site Drainage Boundary and Land Use

Once the OOC sites were selected, the drainage boundary for each site was determined based on elevation contours noted on U.S. Geologic Survey (USGS) 7.5-minute series topographic maps, the SFWMD hydrography coverage, and local knowledge of field drainage conditions. The drainage boundaries of the 77 OOC sites were delineated on the USGS maps for digitizing into a geographical information systems (GIS) database. Although the local topography is relatively flat, all OOC sites discharged runoff through well-defined locations (e.g., ditches). Each site's drainage boundary is shown in Figure 2.

The land use of each site during the 1998 to 1999 time period was determined by field observations. Of the 77 OOC sites, 63 were improved beef pasture, six were vegetable and other row crop farms, five were citrus groves, one site was used for raising ornamentals, one was operated as a sod farm, and one site was a high intensity cattle shipping station. Of the 30 sites in common with the Zhang and Essex (1997) study, the land use type changed for eight of those sites. Of these eight sites, two were converted to more intensive land uses, four were converted to similar land uses, and two were converted to less intensive land uses.

METHODS

Runoff Estimation

GIS Databases. The drainage boundaries, land ownership information, and land use types were entered into a GIS database. The total drainage area for the 77 OOC sites was 14,825 ha. The soil data in a GIS format were obtained from Negahban *et al.* (1995). The soil database contained the type and location of soil associations in the Lake Okeechobee watershed along with the percentage of land area. The two databases were "merged" into a third database containing unique combinations of land use and soil association for each OOC site. Then the area for each field (a unique combination of land use and soil association) was obtained. For the OOC sites, the predominant soil association was Smyrna-Immokalee (fine sand to sand; 68 percent), followed by Floridana-Riviera (sand; 19 percent), Basinger-Urbanland (fine sand; 6 percent), Felda-Chobee (fine sand to fine sandy loam; 2 percent), Wabasso-Felda (fine sand; 2 percent), Zolfo-Tavares (fine sand to sand; 2 percent), and Terra Ceia-Samsula (muck; 1 percent).

Runoff Modeling. Because measured flow was not available for the OOC sites, discharges were estimated using the Chemical, Runoff, and Erosion from Agricultural Management Systems – Water Table (CREAMS-WT) model (Knisel, 1980; Heatwole *et al.,* 1987, 1988). A field is defined as having a single land use, relatively homogeneous soils, spatially uniform rainfall, and single management practice (Knisel, 1980). Each site may contain one or more fields.

Weather input data required by CREAMS-WT included daily rainfall, monthly average temperature, and monthly average solar radiation. Among the five weather stations (Figure 1) used in this study, the Archbold Biological Station (ARCHBOLD) measures all weather data required, station S65C measures rainfall and temperature, and the remaining three stations measure rainfall only. Four of the rainfall stations were used in the previous study (Zhang and Essex, 1997). The fifth rainfall station is no longer active. Therefore, a nearby station (S133) approximately 500 m to the east of the discontinued station was used for this study.

The study period from October 1, 1991, to September 30, 1999, was selected based on the availability of phosphorus concentration data. The daily rainfall data for each of the five stations were retrieved from a SFWMD database. Any missing data were replaced by using data from a nearby rainfall station. Each station had less than 40 days (1.4 percent) of missing data for the eight-year study period. For the area of the 22 major drainage basins in the northern Lake Okeechobee watershed (Figure 1), a Thiessen weighted rainfall average was determined based on the method described in Wanielista *et al.* (1997). The Thiessen weights for the rainfall stations were 40.7 percent for ARCHBOLD, 19.8 percent for S65E, 17.6 percent for S65C, 11.0 percent for JUDSON, and 10.9 percent for S133 (Figure 1). The weights were used to determine daily rainfall amounts during the eight-year period.

The Thiessen weights for the temperature stations were 47.5 percent for the ARCHBOLD station and 52.5 percent for the S65C station. If a station was missing data, the other station provided the missing data. The average monthly temperature was determined by averaging the recorded daily high and low temperatures provided by the ARCHBOLD station or

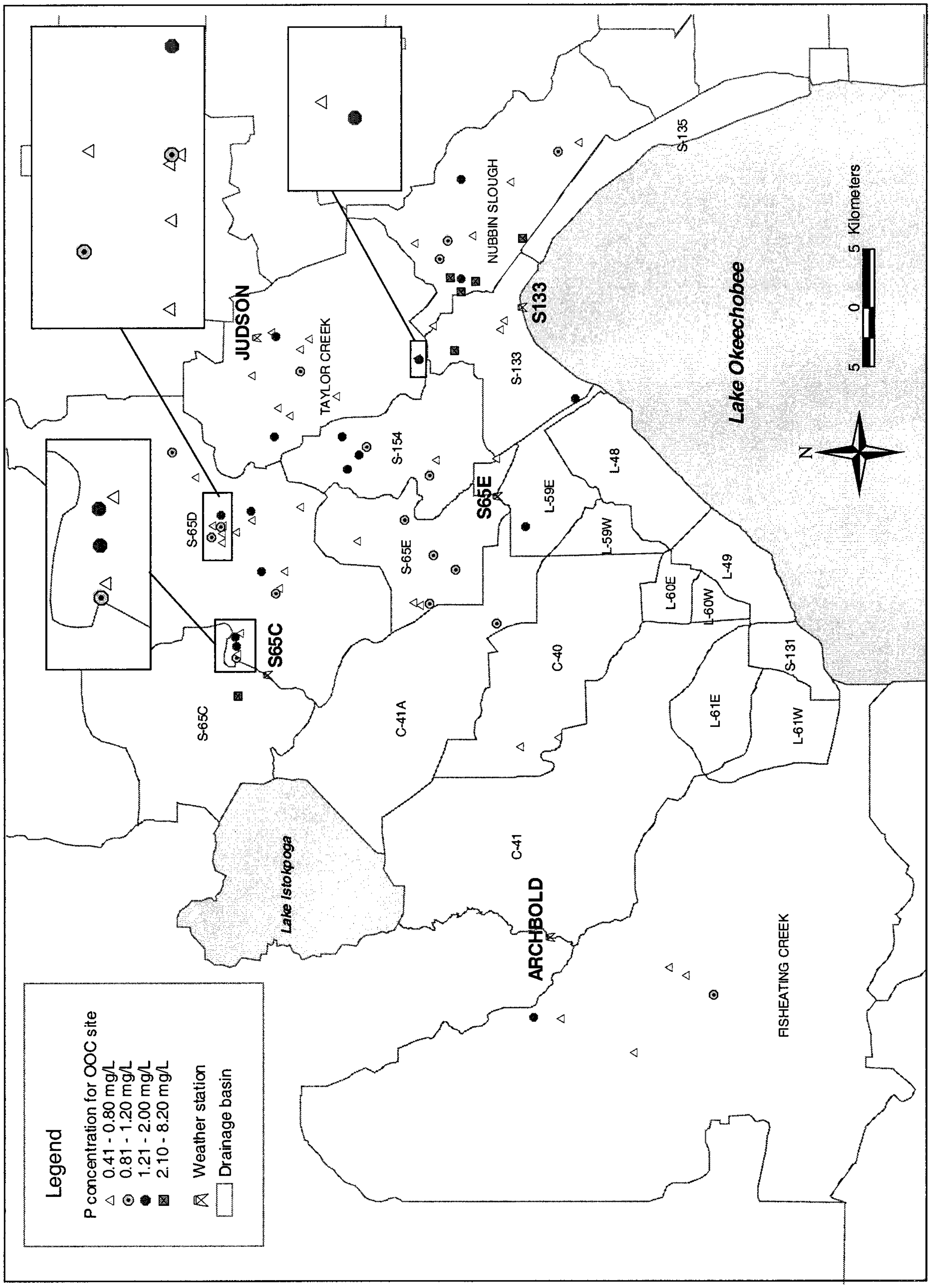

Figure 1. Phosphorus (P) Concentrations for Out-of-Compliance (OOC) Sites and Weather Stations in the Lake Okeechobee Watershed.

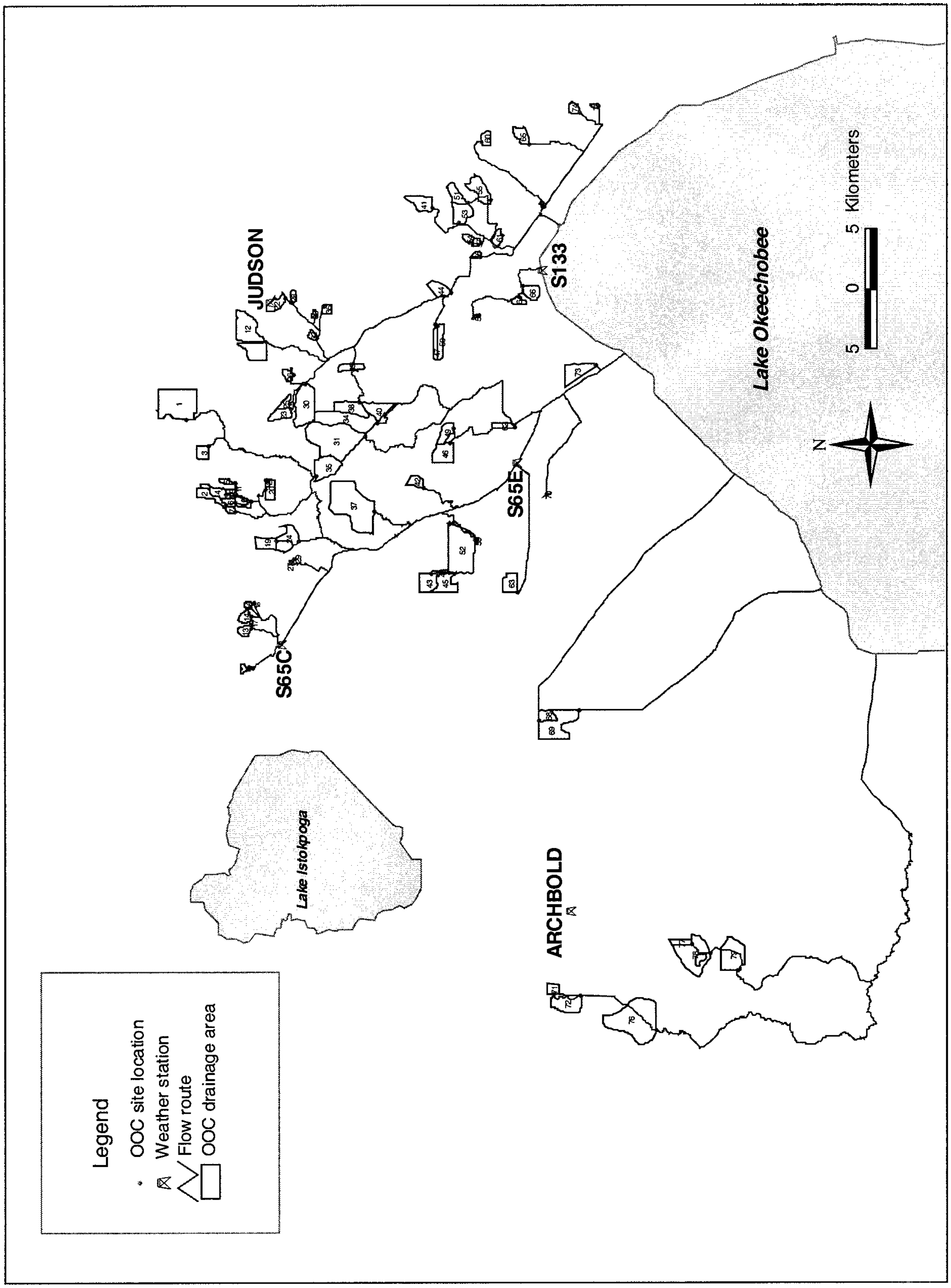

Figure 2. Drainage Boundaries and Flow Routes for Out-of-Compliance (OOC) Sites in the Lake Okeechobee Watershed.

by averaging the recorded daily temperature retrieved from the S65C station.

ARCHBOLD provided the solar radiation data except for 27 months during the eight-year study period when no data were recorded. Only one station in the SFWMD database had any significant data for those 27 months. Therefore, 14 months of data were provided from a station in Palm Beach County on the south side of the lake approximately 109 km from ARCHBOLD. The remaining 13 months of data were obtained from the previous study (Zhang and Essex, 1997) that used a weather generation program, WGEN, to estimate the solar radiation values (USDA, 1984). Other required input to CREAMS-WT included land use, soil, and model parameters. Land use and soil parameters were taken from the GIS database, and model parameters were taken from Kiker *et al.* (1992) and Zhang *et al.* (1995). Fifteen model runs were required to predict the runoff for the 77 OOC sites, which had 15 combinations of land uses and soil associations.

CREAMS-WT computed daily runoff volumes per unit area. Average annual unit runoff for each field was computed from the sum of all the daily unit runoff volumes during the eight-year study period divided by eight. The average annual runoff volume for a field was obtained from the average annual unit runoff and the field area. The field area was provided by the GIS database. If two or more fields comprised an OOC site, the total average annual runoff volume was computed as the sum of the average annual runoff from each field for the site.

Off-Site Phosphorus Load Estimation

Selection of Method for Determining Edge-of-Field Phosphorus Loads. Three methods were evaluated for estimation of edge-of-field phosphorus loads. Method 1 computed daily phosphorus loads by assigning a phosphorus concentration to each of the estimated daily runoff volume per unit area for the period the site was monitored under the regulatory program. If the available phosphorus data interval was two weeks or less, the daily phosphorus concentration assigned to the runoff was the concentration value measured the least number of days from the date with missing concentration data. When the available phosphorus data interval exceeded two weeks, the average of the two consecutive bounding sample values was used to estimate the phosphorus concentrations on the non-sampling dates. The daily phosphorus load was obtained by multiplying the assigned concentration by the estimated daily unit runoff volumes. Then all the daily loads were added together, divided by the number of years the site was monitored, and multiplied by the area of the field to obtain the average phosphorus loads per year for the field. If a site contained two or more fields, the average phosphorus loads per year for each field were added together to obtain the total average phosphorus loads per year for that particular site.

The advantage of Method 1 is that a phosphorus concentration is applied for every day a runoff volume is estimated for the site. The disadvantage is associated with assigning a specific measured phosphorus concentration with a specific estimated daily runoff. The average annual number of measured concentration data points was 10 for each OOC site, while the average annual number of daily runoff events was 39 for each OOC site. Based on this, on average at least 74 percent of the runoff events would not have corresponding measured concentration data. The assignment of concentration values to days with estimated daily runoff values resulted in periods with estimated runoff but no close corresponding phosphorus concentration measurement although multiple site visits would have occurred during the period of the estimated runoff. This assignment process also resulted in periods of no runoff estimates when phosphorus concentration data had been measured. Therefore, measured concentration data sampled during an actual runoff event were not being included in the off-site load estimations.

Method 2 computed the average annual unit runoff by summing all the daily runoff values for the years that the site was monitored during the study period and dividing by those number of years. This method addressed the fact that the 77 OOC sites have different periods of record (i.e., sites were monitored for different length of times during the eight-year study period). Of these sites, 21 have less than four years of monitoring, 15 have between four and six years of monitoring, and 41 have between six and eight years of monitoring. The average annual runoff volume was calculated by multiplying the average annual unit runoff by the field area. If a site contained two or more fields, the runoff volume for the entire site was obtained by summing the runoff volume for each field. The average phosphorus concentration was obtained by averaging all of the measured phosphorus concentration values for the time that the site was monitored during the eight-year study period. The average annual off-site phosphorus load for the site was obtained by multiplying the site's total average annual runoff volume by the average phosphorus concentration.

The advantage of Method 2 is the use of an average annual unit runoff instead of a daily unit runoff as used in Method 1. According to Heatwole *et al.* (1987), CREAMS-WT provides better predictions of average annual runoff volumes than it does daily volumes.

Unlike Method 1, which did not use all the measured concentration data, all the concentration data values were used for the load estimation since an average phosphorus concentration was used. Additionally, with the limited number of phosphorus concentration data points, using an average phosphorus concentration for the entire monitoring period for the site tends to lessen the dependence on individual data points, especially since there is not a corresponding measured flow for each concentration data point. Therefore, the result is an estimated average annual off-site phosphorus load with the understanding that the estimated load is an average value with a good potential for the actual loads to be higher or lower. The disadvantage is that the average annual unit runoff may not be a representative average value for the site if the monitoring period is relatively short and if the weather patterns during that period were indicative of wet or dry years.

Method 3 was the same as Method 2 except that the average annual unit runoff was calculated from the sum of all the daily runoff values during the eight-year study period instead of the runoff values for the period that the site was monitored during the eight-year study period. Therefore, the average annual unit runoff was determined by dividing the sum of the daily runoff values by eight instead of the number of years that the site was monitored. The advantage of this method is that it minimizes the effects of changes in the weather data from year to year. The result is an average total phosphorus loading value that is more representative of an OOC site in the northern Lake Okeechobee watershed during an average weather year for the region. The disadvantage is that the effect of higher or lower phosphorus concentration values may not be as significant in the final load results.

All three methods were applied to five different sites to test the differences among the methods. These five sites included three land uses (improved pasture, citrus, vegetables) and three soil associations. They have various sizes, different monitoring periods, and average phosphorus concentration values ranging from 0.68 mg/L to 1.49 mg/L. Of the five sites examined, the numerical comparison of the three methods did not clearly favor one method over another (data not shown). All three methods provided load results that were either the minimum, maximum, or average for at least one of the five sites examined.

Method 3 was selected because the basis of its calculations was the eight-year study period and it does not have the drawbacks of the other two methods. However, Method 3 estimates an average annual load. The actual annual load for each year of the study period was probably higher or lower than this estimated average annual load. But with the limited amount of phosphorus concentration data available and with no measured flow values, Method 3 was determined to be the appropriate estimation method. Method 1 was not selected because it relies on accurately matching a particular daily estimated runoff value with a certain measured phosphorus concentration. If measured or estimated runoff values were available on the same days as the measured concentration values, then Method 1 would probably have been selected. However, the uncertainty in the CREAMS-WT model to provide daily values (Heatwole *et al.,* 1987) made Method 1 undesirable. Method 2 has the drawback of being based on the number of years that the site has been monitored during the eight-year study period. Depending on which years were monitored, the phosphorus loading value would likely reflect whether the monitoring years were wet or dry years.

Off-Site Phosphorus Load Estimation. Phosphorus loads from OOC sites were estimated from the observed average annual phosphorus concentration and the simulated average annual runoff volume (Method 3). The average annual loads were computed based on the eight-year period from October 1, 1991, to September 30, 1999. For example, at Site 1, the average annual measured phosphorus concentration is 0.82 mg/L, and the average annual off-site runoff volume is 28,735.6 ha-cm. Then, the off-site phosphorus load would be 28,735.6 ha-cm x 0.82 mg/L x 0.1 kg-L/mg-ha-cm = 2,356.3 kg.

Phosphorus Assimilation

Phosphorus assimilation capacity is influenced by diverse physical, chemical, and biological factors. These factors include phosphorus sorption/desorption by sediments, water flow rate and travel length, and phosphorus uptake by vegetation. Currently, a simple first-order exponential decay function used to describe phosphorus assimilation with flow travel distance in channels and wetlands (SFWMD, 1989) is

$$C_o / C_i = e^{-a\,TL} \tag{1}$$

where C_o is the phosphorus concentration at the basin outlet (mg/L), C_i is the phosphorus concentration at the OOC site outlet (mg/L), "a" is the phosphorus assimilation coefficient (km^{-1}), and TL is the total length of the transport system (km). Values of "a" for each major drainage basin in the watershed were obtained from the University of Florida (1993) and were based on a regression analysis using basin phosphorus loading targets listed in Negahban *et al.* (1995). The total stream length (TL) was measured from the site drainage outlet to the drainage basin outlet. The TL values were computed from a hydrography coverage using the ArcView GIS 3.2 Network Analyst extension software. Values of "a" and TL are listed in Table 1 for each OOC site. The assimilation ratios, C_o/C_i, listed in Table 1 were computed from Equation (1). The drainage boundaries for the OOC sites and the flow routes to determine the TL values are shown on Figure 2.

TABLE 1. Estimated Assimilation Ratios, C_o/C_i, for Out of Compliance Sites.

Site Number	a (km^{-1})	TL (km)	C_o/C_i*	Site Number	a (km^{-1})	TL (km)	C_o/C_i*
1	0.068	28.2	0.15	40	0.025	17.5	0.65
2	0.068	21.0	0.24	41	0.056	13.5	0.47
3	0.068	24.6	0.19	42	0.099	10.8	0.34
4	0.068	20.9	0.24	43	0.099	15.2	0.22
5	0.068	21.2	0.24	44	0.056	11.6	0.52
6	0.068	20.2	0.25	45	0.099	14.8	0.23
7	0.068	19.9	0.26	46	0.025	7.4	0.83
8	0.068	20.1	0.25	47	0.056	2.7	0.86
9	0.068	20.1	0.25	48	0.099	13.9	0.25
10	0.068	18.8	0.28	49	0.025	7.5	0.83
11	0.068	20.1	0.25	50	0.056	3.0	0.85
12	0.056	17.6	0.37	51	0.056	12.3	0.50
13	0.068	17.6	0.30	52	0.099	9.7	0.38
14	0.068	19.4	0.27	53	0.056	9.2	0.60
15	0.155	3.5	0.58	54	0.056	8.0	0.64
16	0.068	19.8	0.26	55	0.056	10.3	0.56
17	0.068	17.9	0.30	56	0.106	9.5	0.37
18	0.068	19.8	0.26	57	0.099	12.0	0.30
19	0.068	11.5	0.46	58	0.056	9.8	0.58
20	0.068	19.8	0.26	59	0.056	5.3	0.74
21	0.068	20.6	0.25	60	0.025	0.5	0.99
22	0.056	18.5	0.35	61	0.099	9.9	0.38
23	0.056	17.4	0.38	62	0.106	4.2	0.64
24	0.068	9.4	0.53	63	0.056	11.5	0.53
25	0.056	16.8	0.39	64	0.106	3.3	0.70
26	0.056	16.5	0.40	65	0.056	1.4	0.92
27	0.068	11.2	0.47	66	0.068	21.4	0.23
28	0.056	17.8	0.37	67	0.025	20.2	0.60
29	0.068	11.5	0.46	68	0.180	9.8	0.17
30	0.056	14.6	0.44	69	0.017	75.2	0.28
31	0.025	20.0	0.61	70	0.017	72.4	0.29
32	0.056	13.9	0.46	71	0.180	0.0	1.00
33	0.056	15.9	0.41	72	0.056	11.6	0.52
34	0.025	18.9	0.62	73	0.056	11.2	0.53
35	0.068	13.7	0.39	74	0.017	64.8	0.33
36	0.056	16.5	0.40	75	0.017	55.9	0.39
37	0.099	15.0	0.23	76	0.017	54.0	0.40
38	0.056	14.7	0.44	77	0.017	49.7	0.43
39	0.056	10.8	0.55	Average	0.065	17.6	0.44

*$C_o/C_i = e^{-a\,TL}$.

Phosphorus Loads to Lake Okeechobee

The total average annual phosphorus load that reached Lake Okeechobee from the OOC sites was computed by multiplying the assimilation ratio and the off-site phosphorus load from each site and summing the results. This computation assumes that no runoff volume losses occur in the transport system (i.e., streams and wetlands) and that no phosphorus assimilation occurs from the drainage basin outlet to the lake. As a consequence, these loads are conservative estimates. These were the same assumptions made in the previous study (Zhang and Essex, 1997).

Phosphorus load reductions from each site were estimated under two scenarios. The first scenario assumed that the off-site phosphorus concentrations were equal to the established discharge limits (e.g., 0.35 mg/L for improved pastures). For example, at Site 1, the measured average annual phosphorus concentration is 0.82 mg/L. If the off-site phosphorus concentration in the runoff were reduced to 0.35 mg/L, the expected phosphorus load reduction to the lake would be 28,735.6 ha-cm x (0.82-0.35) mg/L x 0.15 x 0.1 kg-L/mg-ha-cm = 202.5 kg, which is a 57 percent reduction for the site. The value of 0.15 is the assimilation ratio as defined in Equation (1).

The second scenario assumed the land uses for all OOC sites were changed to unused native rangeland. According to Harper (1994), the land use category recreational/open space, which includes recreational lands such as parks, open space, undeveloped land that may be occupied by native vegetation, and rangeland, has an annual off-site total phosphorus areal loading rate of 0.114 kg/ha. For example, the area of Site 1 is 756.2 ha. The estimated phosphorus load to the lake from Site 1, without incorporating any reduction scenarios, is 353.4 kg. The expected phosphorus load reduction to the lake would then be 353.4 kg – (0.114 kg/ha x 756.2 ha x 0.15) = 340.5 kg, which is a 96 percent reduction for the site. The value of 0.15 is the assimilation ratio as defined in Equation (1). The total phosphorus load reduction to the lake is the summation of the phosphorus load reduction from each OOC site for each reduction scenario. Because of phosphorus accumulation in soils from past land use, the loading rate of 0.114 kg/ha in this proposed scenario may take a very long time to achieve as phosphorus leaches out of soil.

RESULTS AND DISCUSSION

The estimated total average annual runoff volume for the 77 OOC sites was 447,345 ha-cm (Table 2). The total off-site average annual phosphorus load from the 77 OOC sites was 46.3 tonnes (Table 2). After the runoff leaves the OOC sites, some phosphorus is retained by the transport system (i.e., streams and wetlands), and the remaining phosphorus enters Lake Okeechobee. The OOC sites resulted in an estimated 21.7 tonnes of phosphorus load reaching Lake Okeechobee on an average annual basis (Table 2). If the phosphorus concentrations leaving the OOC sites did not exceed the discharge concentration limits, the average annual phosphorus load to Lake Okeechobee is reduced by an estimated 14.7 tonnes (Table 2). If the land uses were changed to native rangeland for all OOC sites with an off-site annual total phosphorus areal loading rate of 0.114 kg/ha, the average annual phosphorous loads to Lake Okeechobee are reduced by an estimated 20.9 tonnes (Table 2). This land use change would result in an average annual phosphorus load to the lake of approximately 1 tonnes from all 77 OOC sites.

The estimated five-year average annual phosphorus load to Lake Okeechobee from the entire watershed from 1995 to 1999 was 198 tonnes above the lake target load of 384 tonnes (SFWMD, 2001). The estimated phosphorus load to the lake from the OOC sites accounts for 11 percent of the phosphorus load above the target. The drainage area for the OOC sites was approximately 3 percent of the total northern Lake Okeechobee watershed drainage area. If phosphorus concentrations leaving the OOC sites did not exceed the discharge concentration limits, the phosphorus load above the target load would be reduced by an estimated 7 percent. Similarly, if the land use of all OOC sites was changed to native rangeland with an off-site annual total phosphorus areal loading rate of 0.114 kg/ha, the phosphorus load above the target load to the lake would be reduced by an estimated 10 percent. The Florida Department of Environmental Protection (FDEP) recently proposed a more stringent target load for Lake Okeechobee. This target is 135 tonnes per year. Under this FDEP target, the five-year annual phosphorus load to Lake Okeechobee from 1995 to 1999 was 447 t above target. Therefore, the estimated phosphorus load to the lake from the OOC sites would account for approximately 5 percent of the phosphorus load above the target.

Although reduced phosphorus loads from the OOC sites represent a portion of the desired phosphorus load reduction to Lake Okeechobee, it is unlikely that the lake's total phosphorus concentrations will display any noticeable decrease, at least in the short term. In order to achieve the loading rates in the two proposed scenarios, a long time will be required as phosphorus leaches out of the soil. More importantly, the internal loading of phosphorus from the lake sediments is high – about equal to the external loading on an annual

TABLE 2. Summary Comparison of the Previous Study (Zhang and Essex, 1997) With This Study.

	Zhang and Essex (1997)	**This Study**
Study period	Oct. 1, 1991 to Sept. 30, 1995	Oct. 1, 1991 to Sept. 30, 1999
12-month period used to determine the out-of-compliance sites	Oct. 1, 1994 to Sept. 30, 1995	Oct. 1, 1998 to Sept. 30, 1999
Number of out-of-compliance sites	57	77
Area of out-of-compliance sites (ha)	14,769	14,825
Average annual rainfall (cm)	127	127
Average annual temperature (°C)	22.3	22.3
Average annual solar radiation (Langley)	356.3	331.9
Total average annual runoff volume (ha-cm)	362,071	447,345
Average phosphorus concentration (mg/L)	1.78	1.35
Total average annual off-site phosphorus load (t)	44.3	46.3
Average phosphorus assimilation coefficient, a	0.077	0.065
Average length of transport system, TL (km)	13.9	17.6
Average annual phosphorous load to the lake (t)	22.0	21.7
Average unit phosphorus load to the lake (kg/ha)	2.5	2.0
Percentage of phosphorus assimilated (percent)	50.3	53.2
Average annual load reduction to the lake if phosphorus concentration C_i = limit* (t)	15.5	14.7
Average annual load reduction to the lake if phosphorus concentration C_i = 0.1 mg/L (t)	20.1	
Average annual load reduction to the lake if annual off-site total phosphorus areal loading rate LR = 0.114 kg/ha (t)		20.9

*Permitted discharge limit.

basis (Olila and Reddy, 1993). The internal loading acts as a buffer mechanism, obviating any potential short-term decrease of phosphorus concentration in the lake caused by external load reductions. However, phosphorus load reductions from the entire watershed should have a positive impact on the lake's water quality in the long term (Steinman *et al.,* 1999).

Phosphorus loading rates for the OOC sites averaged 2.0 kg/ha, whereas the estimated phosphorus loading rates for individual sites ranged from 0.1 kg/ha to a maximum of 21.0 kg/ha. The next highest estimated loading rate, compared to the maximum rate, was 9.8 kg/ha. Of the 77 OOC sites, 12 sites had an estimated phosphorus loading rate equal to or greater than 3.0 kg/ha and were placed on the priority list for the Critical Restoration Project. The average edge-of-field phosphorus concentrations for these sites ranged from 1.49 mg/L to 8.52 mg/L. These 12 sites represent approximately 15 percent of the area of all OOC sites. However, the phosphorus loading to the lake from these sites represented approximately 44 percent of the load to the lake from the OOC sites. Of the 12 sites, six were buy-out dairies, four were heifer farms, one was a hog farm, and one was a high intensity cattle shipping station. Each of these land uses was intensive, and the residual accumulation of phosphorus in soils is evident. All 12 sites are described as nearly level and having poorly drained soils.

Six of these 12 sites were on the priority list of ten sites provided in Zhang and Essex (1997). Three of the six priority sites are currently enrolled in the Critical Restoration Project. The process of implementing phosphorus reduction strategies has begun on another site. The remaining eight sites should be examined to identify cost-effective phosphorus management strategies that reduce off-site phosphorus loads.

A summary comparing the results of the previous study (Zhang and Essex, 1997) with this study is presented in Table 2. The study period for the first study was from October 1, 1991, to September 30, 1995, while the period for this study was for four additional years through September 30, 1999. For the two studies, the total area of OOC sites, the average annual phosphorus loading to Lake Okeechobee, and the potential phosphorus load reductions are essentially unchanged. The total estimated off-site phosphorus loads were approximately 2 tonnes higher in this study than in the previous study. This study also had a higher total average annual runoff volume, which is significantly affected by the solar radiation input data to the CREAMS-WT model. Lower solar radiation values used in this study resulted in lower plant evapotranspiration and higher runoff volume. The average total stream length for this study is higher than the previous study due to the location of the OOC sites within the watershed. This resulted in a slightly higher phosphorus assimilation percentage for this study as compared to the previous study.

SUMMARY AND CONCLUSIONS

Cattle waste from the basins north of Lake Okeechobee has been identified as a source of phosphorus contributing to the accelerated eutrophication of the lake. Pasture sites with excess phosphorus discharge are potential targets for corrective management actions designed to reduce phosphorus loads. This study utilized the CREAMS-WT model and measured phosphorus concentration values to estimate the magnitude of the phosphorus load reduction resulting from two management scenarios.

Seventy-seven OOC sites with phosphorus concentrations in runoff exceeding regulatory limits were identified during the period from October 1, 1998, to September 30, 1999. The measured total phosphorus concentration values and the simulated average annual runoff volume were used to estimate phosphorus loads from these sites. The model simulation period was from October 1, 1991, to September 30, 1999, and was chosen based on the availability of phosphorus concentration data. The 77 OOC sites produced an estimated 46 tonnes of phosphorus load, and an estimated 22 tonnes reached Lake Okeechobee on an average annual basis. The streams and wetlands retained the remaining phosphorus load. An estimated 15 tonnes of phosphorus load reduction per year would be expected if phosphorus concentrations in runoff from these sites do not exceed the discharge limit established by the SFWMD *Works of the District - Lake Okeechobee Basin* Rule. If the land uses were changed to native rangeland with an off-site annual total phosphorus areal loading rate of 0.114 kg/ha, an estimated 21 tonnes of phosphorus load reduction would be expected on an average annual basis from these OOC sites.

Of the 77 OOC sites, 12 sites had a phosphorus loading rate equal to or greater than 3.0 kg/ha. These sites were placed on the priority list for the Lake Okeechobee Water Retention/Phosphorus Removal Critical Restoration Project. On-going research is being conducted by the SFWMD to identify remedies and associated costs for these sites and to evaluate the cost-effectiveness of strategies for reducing phosphorus loads. Furthermore, a GIS-based modeling package is being developed for analyzing phosphorus load reduction from all problematic sites, including dairy and nondairy land uses. This package will enable users to interactively examine these sites for any specified period, to prepare and store data for modeling, and to display all data and modeling results in a GIS Arc/Info environment.

The estimated average annual phosphorus load reaching Lake Okeechobee from the OOC sites represented 11 percent of the phosphorus load above a five-year average annual target load for the lake. Therefore, the target load for the lake cannot be achieved just through reducing the off-site phosphorus load from the OOC sites. Because the total OOC site drainage area represented only 3 percent of the northern watershed that drains into the lake, phosphorus loading from the other areas within the watershed, such as dairies and the lake sediments, need to be addressed. Several programs besides the Critical Restoration Project, such as the Phosphorus Source Control Grant Program, the Dairy Best Available Technology Program, the Isolated Wetland and Restoration and Creation Program, and the Lake Okeechobee Pilot Dredging Project, plan to address the other sources of phosphorus.

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LITERATURE CITED

Boggess, C. F., E. G. Flaig, and R. C. Fluck, 1995. Phosphorus Budget-Basin Relationships for Lake Okeechobee Tributary Basins. Ecological Engineering 5:143-162.

Harper, H. H., 1994. Stormwater Loading Rate Parameters for Central and South Florida. Environmental Research and Design, Inc., Orlando, Florida.

Heatwole, C. D., K. L. Campbell, and A. B. Bottcher, 1987. Modified CREAMS Hydrology Model for Coastal Plain Flatwoods. Transactions of the ASAE 30(4):1014-1022.

Heatwole, C. D., K. L. Campbell, and A. B. Bottcher, 1988. Modified CREAMS Nutrient Model for Coastal Plain Flatwoods. Transactions of the ASAE 31(1):154-160.

Kiker, G. A., K. L. Campbell, and J. Zhang, 1992. CREAMS-WT Linked With GIS to Simulate Phosphorus Loading. ASAE Paper No. 92-2016, St. Joseph, Michigan.

Knisel, W. G. (Editor), 1980. CREAMS: A Field-Scale Model for Chemicals, Runoff, and Erosion From Agricultural Management Systems. U.S. Department of Agriculture, Conservation Research Report No. 26, 640 pp.

Negahban, B., C. Fonyo, W. G. Boggess, J. W. Jones, K. L. Campbell, G. Kiker, E. Flaig, and H. Lal, 1995. LOADSS: A GIS-Based Decision Support System for Regional Environmental Planning. Ecological Engineering 5:391-404.

Olila, O. G. and K. R. Reddy, 1993. Phosphorus Sorption Characteristics of Sediments in Shallow Eutrophic Lakes of Florida. Arch. Hydrobiol. 129:45-65.

SFWMD, 1989. Interim Surface Water Improvement and Management (SWIM) Plan for Lake Okeechobee. South Florida Water Management District, West Palm Beach, Florida.

SFWMD, 2001. Surface Water Improvement and Management (SWIM) Plan Update for Lake Okeechobee. South Florida Water Management District, West Palm Beach, Florida.

Steinman, A. D., K. E. Havens, N. G. Aumen, R. T. James, K-R. Jin, J. Zhang, and B. Rosen, 1999. Phosphorus in Lake Okeechobee: Sources, Sinks, and Strategies. *In:* Phosphorus Biogeochemistry of Subtropical Ecosystems: Florida as a Case Example, K. R. Reddy, G. A. O'Conner, and C. L. Schelske (Editors). CRC/Lewis Publisher, New York, New York.

University of Florida, 1993. Lake Okeechobee Agricultural Decision Support System: Model Verification/Calibration/Sensitivity Analysis (Version 2.2). Report Submitted to the South Florida Water Management District, West Palm Beach, Florida, by the Institute of Food and Agricultural Sciences, Dept. of Agricultural Engineering and Dept. of Food and Resources Economics, University of Florida.

USDA, 1984. WGEN: A Model for Generating Daily Weather Variables. ARS-8, U.S. Department of Agriculture, Washington, D.C.

Wanielista, M., R. Kersten, and R. Eaglin, 1997. Hydrology: Water Quality and Quality Control. John Wiley and Sons, Inc., New York, New York.

Zhang, J., C. T. Haan, T. K. Tremwel, and G. A. Kiker, 1995. Evaluation of Phosphorus Loading Models for South Florida. Transactions of the ASAE 38(3):767-773.

Zhang, J. and E. Essex, 1997. Phosphorus Load Reductions From Out-Of-Compliance Sites in the Lake Okeechobee Watershed, Florida. Applied Engineering in Agriculture 13(2):193-198.