EFFECTS OF INTRODUCED GROUNDWATER ON WATER CHEMISTRY AND FISH ASSEMBLAGES IN CENTRAL FLORIDA LAKES

By

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To my dad, Michael Leo Cooney, you are missed, and I will never stop loving and thinking about you.

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Abstract of Thesis Presented to the Graduate School
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EFFECTS OF INTRODUCED GROUNDWATER ON WATER CHEMISTRY
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Water levels in central Florida lakes have declined since the 1960s as a result of numerous factors. To maintain water levels in these lakes, the Southwest Florida Water Management District (SWFWMD) issued permits to pump water from limestone aquifers into lakes. I assessed effects of groundwater augmentation on limnological variables and fish assemblages in seven Central Florida lakes.

Pumping history information indicated that lake level fluctuations were reduced, and pumping volumes could replace the volume of water in a lake multiple times in a single year. Well water samples, when compared with current lake water samples, indicated that well water had higher mean total alkalinity and total phosphorus concentrations, and lower concentrations of total nitrogen and chlorides. The replacement of original lake water with aquifer water indicated similar patterns when comparing current lake water samples to historical samples prior to initial introduction of groundwater. Current lake water samples had higher mean pH, Secchi depth, total

alkalinity, total phosphorus, and chloride concentrations, and lower mean color, nitrogen and chlorophyll concentrations than historical means.

Historical fish population studies did not exist on these lakes therefore data from the augmented lakes were compared to 36 nonaugmented lakes in Florida. The mean values for catch per unit effort (CPUE), species richness and biomass of harvestable fishes were lower in augmented lakes than those in nonaugmented lakes. However, significant multiple linear regressions indicated that fish population responses of augmented lakes to environmental variables were similar to nonaugmented lakes with similar limnological characteristics.

Canonical correspondence analysis (CCA) was used to examine the relationship between the abundance of individual fish species and measured limnological characteristics. Most fish species and nonaugmented lakes were correlated with axis one of the CCA, whereas augmented lakes were more related to axis two, indicating that augmented lakes were characteristic of high total alkalinity and Secchi depth, and low chloride and phosphorus concentrations. Cluster analysis with these four variables further demonstrated the similarities in limnological characteristics among augmented lakes. Joint plots of the CCA indicated a high probability of a low abundance of individual species in augmented lakes compared to a majority of nonaugmented lakes.

One of the augmented lakes had much lower pumping rates than the others, and exhibited less of a shift in limnological variables from historical values, as well as had fish population characteristics more closely resembling those of nonaugmented lakes in the joint plot of the CCA. Therefore, reduced volumes of groundwater introduction could reduce the alteration of limnological and fish population characteristics.

INTRODUCTION

Lake water levels in central Florida have drastically decreased since the 1960s due to multiple influences. As a consequence of low precipitation (Stewart and Hughes 1974), groundwater levels were depressed and discharges of inlet streams were significantly reduced, causing lakes to receive little water input (Dooris and Martin 1979). Further, urban development changed Florida's drainage systems and diverted storm runoff away from lakes (Stewart and Hughes 1974), and agriculture endeavors withdrew water from lakes for citrus irrigation and freeze protection (Dooris and Moresi 1975). Population expansion also increased water demand, resulting in increased pumping of aquifer water at wellfields, subsequently lowering groundwater and lake levels (Stewart 1968; Stewart and Hughes 1974; Allen 1999).

Groundwater is utilized for public, industrial and agricultural purposes (Southwest Florida Water Management District [SWFWMD] 1998; Brenner et al. 2000). In the northern Tampa area, groundwater pumping at wellfields began in 1963 to meet the increased demands for water (Stewart and Hughes 1974). Wells ranged from 120 to 180 meters in depth and produced thousands of cubic meters of water a day from the Tampa and Suwannee Limestone Formations, the two uppermost layers of the Floridan Aquifer (Stewart and Hughes 1974; Sinclair 1977). The Floridan Aquifer is comprised of sand and clay in the upper regions, with dolomite comprising the lower regions (Stewart and Hughes 1974; Belanger and Kirkner 1994).

Lakes in the vicinity of the wellfields were hydraulically connected to the water table aquifer, meaning that water moved naturally between the lakes and the water table aquifer, a surficial aquifer located two to five meters below land surface (Stewart and Hughes 1974). As groundwater was pumped at wellfields, a localized cone of depression formed in the Floridan Aquifer, inducing an increase in leakage from the water table aquifer to the Floridan Aquifer. As a result, flow increased from the lakes to the water table aquifer, causing a decline in water levels in lakes near wellfields considerably greater than those that would naturally occur in lakes away from wellfields (Stewart 1968; Stewart and Hughes 1974; BRA 1996).

Landowners expressed concern with the declining lake water levels, and in order to address the issue, the SWFWMD permitted landowners to construct wells of similar depths to those in the wellfields for pumping water from the Floridan Aquifer into lakes (BRA 1982; Dooris et al. 1982; Belanger and Kirkner 1994; BRA 1996; Allen 1999). Water levels in these lakes are now constantly maintained slightly above original mean lake levels and are not pumped to a degree that will allow spill over (Stewart and Hughes 1974). However, maintaining lake levels at higher than normal levels accelerates evaporation rates, and also increases leakage of lake water, further increasing the permeability of lake-bottom sediments (Stewart and Hughes 1974; Belanger and Kirkner 1994). As lake water leakage increases, even more groundwater is necessary to maintain water levels year round (Stewart and Hughes 1974).

Previous investigations evaluated the altered water chemistry of augmented lakes and the consequent change in macrophyte growth and phytoplankton diversity. For example, Martin et al. (1976b) found that the elevated hardness of pumped groundwater increased the ability of augmented lakes to support hydrilla, Hydrilla verticillata, growth, and Dooris et al. (1982) found that phytoplankton diversity was enhanced in augmented lakes due to increased concentrations of inorganic carbon via groundwater input.

Little work has assessed effects of groundwater augmentation on fish communities (Bartos 1998; Allen 1999). I evaluated the influence of lake augmentation on limnological charateristics and fish populations in seven augmented lakes in central Florida in the summer of 2002. My objectives were to 1) determine limnological characteristics and pumping history of seven augmented lakes and their corresponding groundwater wells and compare the limnological characteristics between lakes, wells and historical data, 2) estimate fish population parameters in the lakes, and 3) compare augmented lake limnological characteristics and fish populations with those from a data base of 36 nonaugmented Florida Lakes.

METHODS

Study Sites

The seven augmented lakes are located in Pasco, Hillsborough, and Polk counties in central Florida (Figure 1). The lake surface areas (SA) were obtained from the *Gazetteer of Florida Lakes* (Shafer et al. 1986) and unpublished SWFWMD reports, and the locations of the lakes were obtained using global positioning system (GPS) coordinates from a Garmin GPSMAP 76 (Table 1). These lakes are not spring-fed from the Floridan Aquifer but do exchange water with surficial aquifers. Each lake exhibited significant declines in water levels due to reduced rainfall and wellfield pumping, where hundreds of thousands of cubic meters of water were removed from the Floridan Aquifer each day (Table 2), creating the necessity to pump Floridan Aquifer water into each lake to maintain lake levels. Goose Lake was the first of the study lakes to be augmented, (1954), and Loyce Lake the most recent (1996) (Table 1).

Limnological Characteristics

I assessed some important limnological characteristics of my study lakes in August, 2003. The percent lake area covered by aquatic macrophytes (PAC) was recorded using a boat-mounted Raytheon DE-719 Precision Survey Fathometer (Maceina and Shireman 1980). Seven transects were made across each lake at a constant speed while the fathometer recorded the presence or absence of plants on a paper roll. The total length of paper recorded on for each lake was divided into 100 equally spaced instantaneous samples, and the presence or absence of plants at these locations was recorded. The number of locations with aquatic vegetation present was expressed as a percentage (Canfield and Hoyer 1992).

For water chemistry, three 1-liter samples of water were collected at arm depth (~0.5m) in acid-cleaned Nalgene bottles at three mid-lake sampling stations established in each lake in August of 2003. The samples were immediately placed on ice and returned to the laboratory for analysis. Secchi depth (m) was measured at each station and averaged to determine mean Secchi depth. Dissolved oxygen concentration (mg/L) and temperature (^{o}C) were also measured with a Model 85 Yellow Springs Instrument (YSI) meter at about 40% of the depth at each mid-lake station and at the location of pumped water discharge.

Upon arriving at the laboratory (University of Florida, Gainesville, Florida), pH was measured immediately using an Orion Model 601A pH meter calibrated against buffers at pH 4.0, 7.0, and 10.0. Total alkalinity (mg/L as $CaCO_3$) was determined by titration with 0.02 molar H_2SO_4 (APHA 1989). Chlorophyll concentrations (µg/L) were determined spectrophotometrically (method 10200 H (2c), APHA 1989) following pigment extraction with ethanol (Sartory and Grobbelaar 1984). Total phosphorus concentrations (µg/L) were determined using procedures of Murphy and Riley (1962) with a persulfate digestion (Menzel and Corwin 1965). Total nitrogen concentrations (µg/L) were determined by oxidizing water samples with alkaline persulfate and determining nitrate-nitrogen with second derivative spectroscopy (D'Elia et al. 1977; Simal et al. 1985; Wollin 1987; Crumpton 1992). Chloride concentrations (mg/L) were determined by titration of the water samples with 0.0141 mole mercuric nitrate and using diphenylcarbazone for determining endpoints (Hach Chemical Company 1975). To analyze for color (platinum-cobalt units), water samples were first filtered through a Gelman type A-E glass fiber filter. Color was then determined by using the platinum-cobalt method and a spectrophotometer (APHA 1989).

Three 1-liter water samples were also collected from each of the wells supplying water to the lakes in August of 2003. The volume of the well delivery pipe was measured, and the pump was run to flush the pipe with at least twice the calculated volume before water samples were taken. These samples were placed on ice and returned to the laboratory and analyzed at the same time as the lake samples for pH, total alkalinity, total phosphorus, total nitrogen, and chloride concentrations. Chlorophyll concentrations and color were not determined for the well samples because natural filtration and lack of sunlight exposure that is characteristic of the Floridan Aquifer makes the levels of these variables negligible. Secchi depth was not measured within the well pipe.

The pumping history of each study lake was determined from unpublished SWFWMD reports. The daily, monthly and yearly averages from these reports were used to determine the average amount of groundwater pumped on a yearly basis. The volume of each lake was determined by multiplying the surface area of the lake by the average depth determined from the fathometer transects. The average volume of water pumped per year was then divided by the volume of the lake to determine the amount of times per year the water pumped would replace the current volume of water in each lake. Mountain Lake and Sunset Lake each share pumps with other lakes, and the amount of pumped water for individual lakes was not separately recorded. Therefore, I calculated the volume of all lakes receiving water from a shared pump, and determined the percentage of the total volume attributed to Mountain and Sunset lakes.

Finally, I compared the ranges and means of limnological characteristics of the augmented lakes to the well water, and to the limited amount of historical water chemistry data for the augmented lakes that existed prior to initial pumping of aquifer water.

Electrofishing

Fish populations in the seven augmented lakes were sampled during the warm season in July or August of 2002 using electrofishing. Electrofishing transects of continuous DC current were conducted for ten minutes to collect fish in the littoral area of each lake with a 4.3 m aluminum jon boat powered by a 15 horsepower outboard motor. Six transects were conducted at Clear, Dan and Sunset lakes, seven transects at Goose, Loyce and Saddleback lakes, and eight at Mountain Lake. The number of 10-minute transects indicate how many transects were necessary to circumnavigate the entire lake. Electrofishing equipment consisted of a generator (5000 Watt AC), pulsator (Coffelt model VVP 15) and a bow-mounted cathode probe supplying an electrical output of approximately seven amps. All collected fish from each transect were counted, measured to the nearest millimeter total length (TL), weighed to the nearest gram, and identified to species. Fish with total lengths less than 20 mm TL were not included in analyses due to selectivity of the gear (Reynolds 1996).

Due to the lack of fish population studies on these augmented lakes prior to the initial pumping of water, I compared the data collected from augmented lakes to a data set of 60 nonaugmented Florida lakes (Canfield and Hoyer 1992; Bachmann et al. 1996). Two lakes, Mountain and Gate, were removed from the 60 lake data set because they were augmented lakes. Three lakes, Apopka, Lochloosa and Harris, were also removed due to their surface areas being orders of magnitude larger than all other study lakes, because lake size influences species richness (Bachmann et al. 1996).

To assess the likelihood that more electrofishing transects would add additional species, I constructed curves, using Bachmann et al.'s method, for augmented and nonaugmented lakes demonstrating the cumulative number of fish species captured as more transects were conducted (Bachmann et al. 1996). To ensure that the right-hand portion of the curves flattened, the number of species captured in the next to last electrofishing transect was divided by the number of species captured in the last transect, and expressed as a percentage, which was termed the exhaustion index (Bachmann et al. 1996). All seven augmented lakes had exhaustion indexes of 100%, meaning that all captured species from each lake had already been captured by the next to last transect. In 19 of the 55 nonaugmented lakes, the exhaustion indexes were less than 90%, possibly indicating that these lakes were inadequately sampled. Therefore, these 19 lakes were not used in the analyses. The remaining 36 nonaugmented lakes had exhaustion indexes that equaled or exceeded 90%, indicating that the right-hand portion of the curves had flattened. These 36 nonaugmented lakes were used for comparison with the seven augmented lakes.

Fish Population Measures

For the seven augmented lakes and the remaining 36 nonaugmented lakes, I estimated catch per unit effort (CPUE) and species richness. Catch per unit effort (CPUE) was calculated by dividing the total number of individual fish captured in each transect by 10 minutes (duration of one transect), and then averaging across the total number of transects conducted in the particular lake (number of fish/minute). Species richness was calculated as the total number of fish species collected in each lake.

Evenness was calculated for both the number of individuals and the total weight of each species using Simpson's measure of evenness (Krebs 1999). Evenness attempts to measure how evenly the number of individuals or weight is distributed among all species in a community. The Simpson's measure of evenness (E) is defined as:

$$E = \frac{1/\sum (p_i / P)^2}{s} \qquad \text{(eq. 1)}$$

where p_i is the number of individuals or total weight of the ith species, P is the total number of individuals or total weight of all species, and s is the total number of species in each lake. This index is relatively unaffected by the rare species in the sample and ranges from 0 to 1 (Krebs 1999).

In addition, I also calculated a Shannon-Wiener index of diversity for both the number of individuals and the total weight of each species collected in each lake (Krebs 1999). Diversity attempts to account for evenness and richness by looking at both the number of species and how evenly distributed the number of individuals or weight is amongst the total number of species in each lake. The Shannon-Weiner index of species diversity (H') is defined as:

$$H' = \sum_{i=1}^{s} \frac{-p_i}{P}\left(\log_2 \frac{p_i}{P}\right) \qquad \text{(eq. 2)}$$

where p_i is the number of individuals or total weight of the ith species, P is the total number of individuals or total weight of all species, and s is the total number of species in each lake. For biological communities, H' ranges from zero to five (Krebs 1999), and is expressed in bits per individual (bits/individual).

I also calculated the total biomass of harvestable fish caught per minute in each of the lakes (Canfield and Hoyer 1990). These fish exceeded lengths at which anglers generally harvest the given species (Appendix A).

Fish Population Analysis

The relationships between fish population variables (CPUE, evenness, diversity, richness and harvestable biomass) and limnological variables (total alkalinity, chlorides, total phosphorus, total nitrogen, lake surface area, Secchi depth, chlorophyll, color and percent composition of submersed aquatic vegetation) were examined for the augmented and nonaugmented lakes using multiple linear regression. Prior to model selection, a Wilk-Shapiro test was performed on all dependent fish variables, except diversity, to test for normality (Procedure UNIVARIATE NORMAL, SAS 1996). The evenness index for both fish weight and number of fish, as well as CPUE and harvestable biomass, were $\log_{10}(x+1)$ transformed to increase normality. Stepwise model selection procedure was used to create multiple regression models (STEPWISE option, SAS 1996) with a significance level of 0.05 for independent variables to remain in the model.

Multiple regression models with only one significant independent variable predicting a fish population variable were graphed. Confidence limits of 95% were placed above and below the predicted regression line for each model, and the points corresponding to augmented lakes were examined for influence or diverging patterns.

Models with multiple significant habitat variables predicting a fish population variable were examined for possible influence by augmented lakes. This was done using influence diagnostics, including DFFITS, COVRATIO and studentized-residuals (SAS 1996). The DFFITS value represents the number of estimated standard errors that the fitted value changes if the point is removed from the data set (Myers 1990). A value close to zero indicates a low influence of the given point. The COVRATIO values display the reduction in the estimated generalized variance of the coefficient over what would be produced without the data point. A value close to one indicates little influence on the estimated generalized variance. Finally, studentized-residuals were used to detect outliers. A value close to zero indicates a minimal residual for the given point, indicating a non-outlier (Myers 1990). I concluded that if augmented lakes did not have extreme values for DFFITS, COVRATIO, and studentized residuals, then the observation would be within the overall pattern for nonaugmented lakes.

Canonical correspondence analyses (CCA) (PC-ORD 1999) is a multivariate analysis technique that utilizes data from two matrices to relate community composition to known variation in the environment (Ter Braak 1986). The CCA was used to arrange lakes and species of fish along environmental gradients. Catch per unit effort (fish/min.) was calculated as a measure of relative abundance for each species in each lake and placed in the primary matrix for comparison of community patterns across lake samples (Hinch and Collins 1993). Species observed in less than three of the 43 lakes (seven augmented and 36 nonaugmented) were removed from the analysis to reduce the effects of rare taxa. No rare taxa were found in the augmented lakes. The same limnological variables as in the multiple regressions were placed in the secondary matrix across lakes. Percent data (percent lake area covered by aquatic macrophytes) were arcsine(x/100) transformed (Zarr 1999) and all other directly measured environmental variables were $\log_{10}(x+1)$ transformed to reduce kurtosis (Palmer 1993).

Canonical correspondence analysis is not hampered by high multicollinearity between species, or between environmental variables (Palmer 1993). Therefore, preprocessing or elimination of multicollinear data is unnecessary. Similarly, CCA estimates the modal locations of highly skewed species distributions quite well, and is robust to violations of assumptions (Palmer 1993).

In CCA, lakes were assigned scores determined from weighted-averages of species abundances (Palmer 1993). A multiple linear least-squares regression was then performed with environmental variables as independent variables, and lake scores as the dependent variables. New lake scores were then assigned as the value predicted from the resulting regression equation. The algorithm continued re-standardizing lakes and species scores until they remained constant with progressing iterations. The product was the first ordination axis, which was a linear combination of environmental variables that maximized the correlation between lake and species scores. Second and higher ordination axes also maximized correlations with scores, uncorrelated with the previous axes (Ter Braak 1986).

Intraset correlations are the correlation coefficients between the environmental variables and the ordination axes (Ter Braak 1986). The signs and magnitudes of the intraset correlations were examined to assess the relative importance of each environmental variable in structuring the fish community. Intraset values less than -0.350 and greater than 0.350 were considered more highly correlated than those between -0.350 and 0.350. This criterion was arbitrary and was not intended to reflect statistical significance, and all intraset values are presented.

The canonical correspondence analysis was graphed on a joint plot, with the first three ordination axes (PC-ORD 1999). The lakes and species were examined for the dominant patterns in community composition as explained by the environmental variables, and the augmented lakes were further examined for diverging patterns. The intraset values of the CCA were also examined to determine which environmental variables were most strongly correlated with augmented lake scores. Those intraset values less than -0.350 and greater than 0.350 were considered more highly correlated, and were used to construct a cluster diagram (PC-ORD 1999).

RESULTS

Comparison of Limnological Variables

Augmented lakes had a smaller average surface area than nonaugmented lakes. The seven augmented lakes in this study had surface areas ranging from 13 ha to 39 ha (Table 1) with an average of 21 ha, whereas the nonaugmented lakes ranged from 1.8 ha to 271 ha, with an average of 83 ha. The range of percent lake area covered by aquatic macrophytes (PAC) displayed large variation for both augmented (10% to 58%) and nonaugmented lakes (0% to 100%) (Table 3). Four of the augmented lakes had Secchi depths greater than the average of the nonaugmented lakes (2.04 m), whereas all of the augmented lakes had pH levels higher than the average for the nonaugmented lakes (7.56) (Table 3). Three of the seven augmented lakes exceeded the range of the total alkalinity for the nonaugmented lakes (0.28 to 106 mg/L as $CaCO_3$), and all augmented lakes had values greater than the nonaugmented average (31.1 mg/L as $CaCO_3$). All augmented lakes but Saddleback had lower chlorophyll concentrations than the average for nonaugmented lakes (26.5 µg/L), and all had lower phosphorus and nitrogen concentrations than the average nonaugmented values (30.5 µg/L, and 939 µg/L respectively). Sunset Lake was the only augmented lake to exceed the average chloride concentration for the nonaugmented lakes (18.5 mg/L). Finally, the color values of the augmented lakes were within the range (1.25 to 57.5 Pt-Co units) and near the average (20.6 Pt-Co units) of the nonaugmented lakes (Table 3).

Groundwater Pumping History

Clear Lake had the smallest volume of the augmented lakes (1.20×10^5 m^3), and Mountain Lake had the largest volume (1.13×10^6 m^3) (Table 4). Similarly, Mountain Lake had the largest average volume of groundwater pumped into the lake (2.67×10^6 m^3/year), whereas, Sunset Lake had a dramatically smaller average than the rest of the lakes (9.97×10^4 m^3/year). The number of times that the volume of pumped groundwater replaced the volume of water in the lakes ranged from 0.238 to 3.28 times/year, with Sunset Lake having the lowest rate and Clear Lake having the highest (Table 4).

After investigating the water chemistry of the groundwater pumped from the wells at each lake and the historical data from several of the lakes prior to initial pumping (Table 5), numerous patterns were found. Loyce Lake was the only lake with historical Secchi depths prior to augmentation, and upon the addition of groundwater, the Secchi depth increased from 0.8 to 3.05 meters. In all of the lakes, the total alkalinity and total phosphorus concentrations in the well samples were higher than the current lake water samples, and in every case, the lakes increased in pH, alkalinity and total phosphorus since their historical measurements. Conversely, all but one well water sample, Saddleback lake, had lower total nitrogen concentrations than the current lake samples, coinciding with a decrease in nitrogen when compared to historical water samples (Table 5). The well water samples also had lower chloride concentrations than the current samples from the lakes; however, the two lakes with historical chloride data increased in chloride concentrations since the initiation of augmentation. Loyce, Saddleback, and Sunset lakes experienced a decrease in color, and Loyce Lake exhibited a decrease in chlorophyll when compared with from historical data, coinciding with groundwater pumping.

In each of the augmented lakes, groundwater was pumped at a location about 100 meters from the lake, and either formed a small stream or was run down a pipe where the water was released in an upward fashion, like a fountain. The mean oxygen and temperature levels measured at mid-lake stations were nearly identical to those measured at the end of these streams and pipes, where groundwater is introduced into the lakes.

Fish Population Comparisons

Catch per unit effort (CPUE) of all fish varied among the augmented lakes, with Goose Lake having the lowest (1.16 fish/minute) and Sunset Lake having the highest (10.7 fish/minute) (Table 6). Goose Lake also had the lowest species richness (5 species), and Clear Lake had the highest (11 species). However, Goose Lake had the highest index of evenness (*E*) by number of fish per species (0.70), and Sunset Lake had the lowest (0.21). Similarly, Goose Lake had the highest index of evenness by weight of fish per species (0.61), and Mountain Lake had the lowest (0.32). Species diversity (H') by number ranged from 1.37 to 2.41 at Sunset Lake and Clear Lake, respectively, and species diversity by weight ranged from 1.67 to 2.38 at lakes Dan and Sunset, respectively. Biomass of harvestable length fish ranged from 15.1 grams per minute at Clear Lake to 173 grams per minute at Mountain Lake.

The averages of mean CPUE and species richness of the nonaugmented lakes exceeded values at six of the seven augmented lakes (Table 6). The ranges and averages of the evenness and diversity variables of both the augmented and nonaugmented lakes were similar. However, the average of the mean harvestable fish biomass for the nonaugmented lakes exceeded the values of all seven augmented lakes (Table 6).

Multiple Regression Analysis

The multiple linear regressions with stepwise model selection for the augmented and nonaugmented lakes combined were all significant ($P < 0.05$) (Table 7). Limnological variables explained 13% to 63% of the variability in fish population variables in the nonaugmented lakes. Secchi depth was negatively related to diversity by number, and positively related to logarithm evenness (*E*) by number. Species diversity (*H'*) by weight was positively related to color and surface area. Log CPUE was positively related to chlorides and negatively related to Secchi depth and PAC. The log (*E*) by weight was positively related to total nitrogen as well as Secchi depth. Species richness was negatively related to total nitrogen and Secchi depth and positively related to chlorides and lake surface area. Log (harvestable biomass) was positively related to lake surface area and negatively related to Secchi and PAC. Diversity by weight was the only fish variable that was not related to Secchi depth.

The simple linear regressions of Secchi depth versus the logarithm transformation of evenness by number (Figure 2a) and Secchi depth versus diversity by number (Figure 2b) show that the data points for the augmented lakes are not outside of the 95% confidence intervals. However, the Secchi depth values of a majority of the augmented lakes are higher than the majority of the nonaugmented lakes.

The remaining four fish population parameters were all determined by multiple habitat variables. Therefore, I examined the influence diagnostics to determine the influence of augmented lakes on the multiple regressions. In each case, the absolute values of the studentized residuals were minimal, the COVRATIO values were close to one, and the absolute values of the DFFITS values were minimal, indicating that the augmented lakes had little influence on the multiple regressions, similar to the results of the simple linear regressions.

Canonical Correspondence Analysis

Canonical correspondence analysis (CCA) was used to explore the relationship between the abundance, as determined by catch per unit effort, of fish species, the lakes where they were found, and the tested limnological variables. The first three axes in the CCA, which are linear combinations of limnological variables that maximize the correlation between site and species scores, explained 26% of the variation (Table 8). The first canonical axis, which explained 12% of the variation, was positively correlated (>0.350) with chlorophyll, total phosphorus, total nitrogen, total alkalinity, color, surface area and chlorides, and negatively correlated (<-0.350) with Secchi depth and percent area covered by aquatic macrophytes (Table 9). The second canonical axis, which explained 7.7% of the variation, was positively correlated (>0.350) with chlorides and total phosphorus, and negatively correlated (<-0.350) with total alkalinity and Secchi depth. The third canonical axis, which explained 5.6% of the variation, was negatively correlated (<-0.350) with chlorides and color.

By definition, the majority of the variation was explained by the first axis. However, all of the augmented lakes, except for Sunset, were most highly correlated with axis two, in a negative fashion. There were only four other nonaugmented lakes that were most highly correlated with axis two in a negative fashion, demonstrating the similarities of the augmented lakes to each other in relation to environmental gradients. The six augmented lakes correlated with axis two were more characteristic of lower chlorides and total phosphorus, and higher Secchi depths and total alkalinity. In contrast, Sunset Lake, more negatively correlated to axis three, was characterized by higher chlorides and color (Table 9).

The joint plot of axis one versus axis two displayed the general pattern of the nonaugmented lakes along axis one (Figure 3). The six augmented lakes Clear, Dan, Goose, Loyce, Mountain and Saddle, were more negatively correlated to axis two than they were correlated to axis one, and were all located in the same general location of the joint plot (Figure 3). Similarly, in the joint plot of axis two versus axis three (Figure 4), these same augmented lakes were more highly correlated with axis two in a negative fashion than they were with axis three, and again were all located in the same general area of the joint plot, whereas Sunset Lake was more related to axis three, with only a slight negative correlation with axis two.

In joint plots, the lake points are found at the centroid of the species points that occur at that lake, allowing inferences to which species are likely to be present at a particular lake (Ter Braak 1986). Also, the species points are approximately the optima of where they are found in highest abundance, hence the abundance or probability of occurrence of a species decreases with distance from its location in the diagram. For example, the lined topminnow, Fundules lineolatus, was highly negatively related to axis one, as were two lakes, Turkey Pond and Keys Pond, that the topminnow was found in close proximity to in the joint plot (Figure 3). This species was found in only six of the 43 lakes, and in highest abundance in these two lakes, explaining its closeness to these two lakes (Figure 3). The lined topminnow's low abundance or absence in the other lakes demonstrates its distance from those lakes. Bluegill, Lepomis macrochirus, was found in all but two lakes, demonstrating this species ability to survive across varying environmental gradients. Accordingly, bluegill were located near the intersection of all three axes, where there is little correlation to high or low values of environmental variables (Figure 3 and 4). Consequently, those lakes within close proximity to the intersection of the axes, with little correlation to any of the three axes, have a higher probability of having higher abundances of bluegill and other fish species that are found near the intersection than those on the perimeter.

Six of the seven augmented lakes were found on the perimeter of the joint plots. Accordingly, all but one species of fish was at relatively large distances in the diagram from the six augmented lakes that were more correlated to axis two (Figure 3 and 4). The one fish species, taillight shiner, Notropis maculatus, which was found in close proximity to these six lakes, was only found in one of the augmented lakes, Clear Lake. This fish represented the second highest abundant fish species in Clear Lake, and was only found in four other lakes, at low abundances, explaining the close proximity to Clear Lake. Therefore, the lack of other species in close proximity to these six augmented lakes demonstrates that there is a higher probability that abundance of individual fish species in these six augmented lakes is lower than other lakes more close in proximity to species points. Sunset Lake is closer in proximity to several fish species points indicating a higher probability of a higher abundance of individual fish species in this lake as compared to the other augmented lakes.

Cluster Analysis

The intraset correlations of axis two of the CCA demonstrate that six of the augmented lakes were correlated with higher total alkalinity and Secchi depth, and lower chlorides and total phosphorus. These four environmental variables were used to create a cluster diagram (Figure 5). The cluster diagram displayed five of the augmented lakes

Clear, Goose, Loyce, Mountain and Dan, in a small cluster. Saddleback Lake, the other augmented lake correlated with axis two of the CCA, is grouped in the next closest small cluster. This further demonstrates the similar limnological characteristics of the augmented lakes with large volumes of groundwater introduction. Sunset Lake is not closely clustered with any of the other augmented lakes, but rather with two other nonaugmented lakes that, like Sunset Lake, were also most correlated with axis three in a negative fashion.

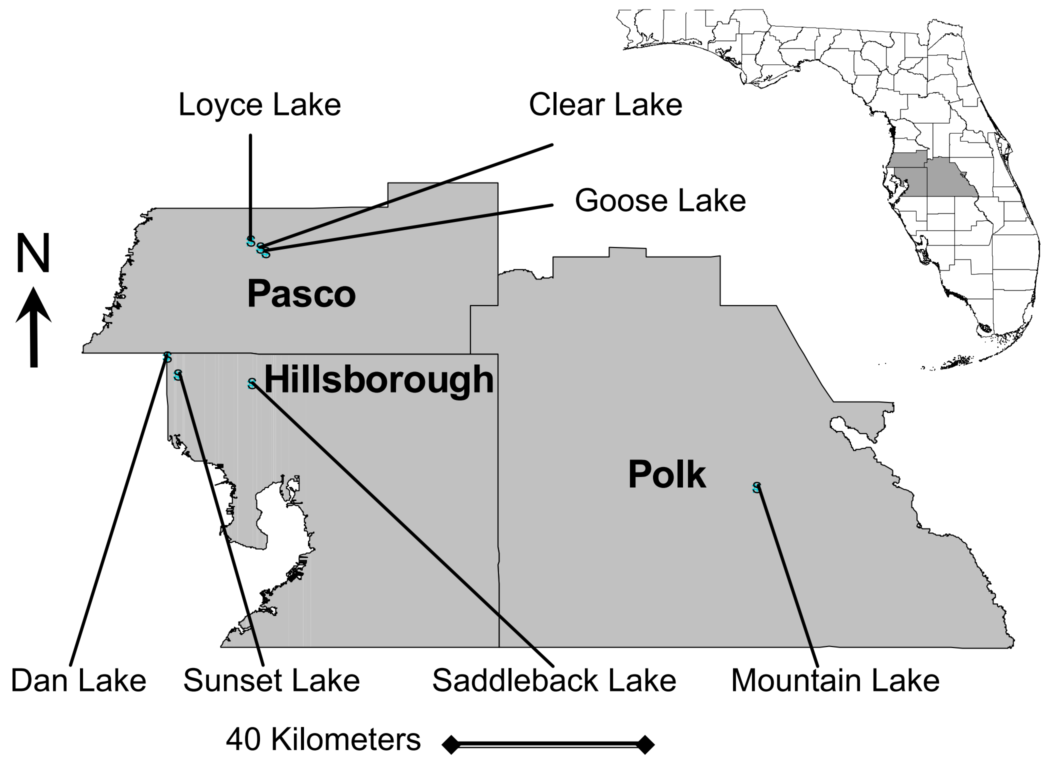

Figure 1. Augmented lakes sampled in three Florida counties.

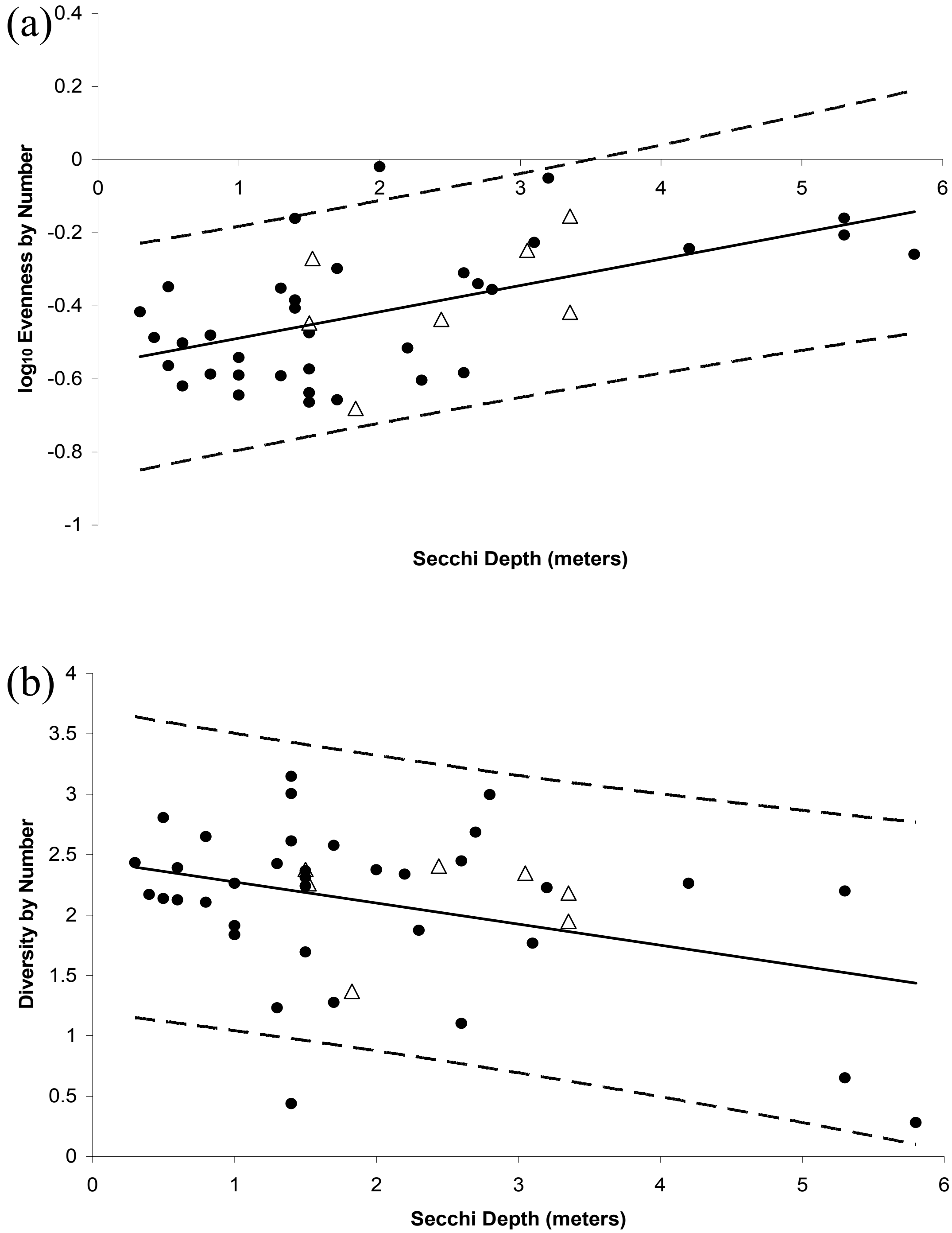

Figure 2. Simple linear regressions of (a) Log_{10} transformation of species evenness by number of fish versus Secchi depth (r^2=0.298, df=42, p-value<0.001), and (b) diversity by number of fish versus Secchi depth (r^2=0.134, df=42, p-value=0.016), with regression lines (—) and 95% confidence intervals for an observation around the lines (- -) for nonaugmented (•) and augmented lakes (△).

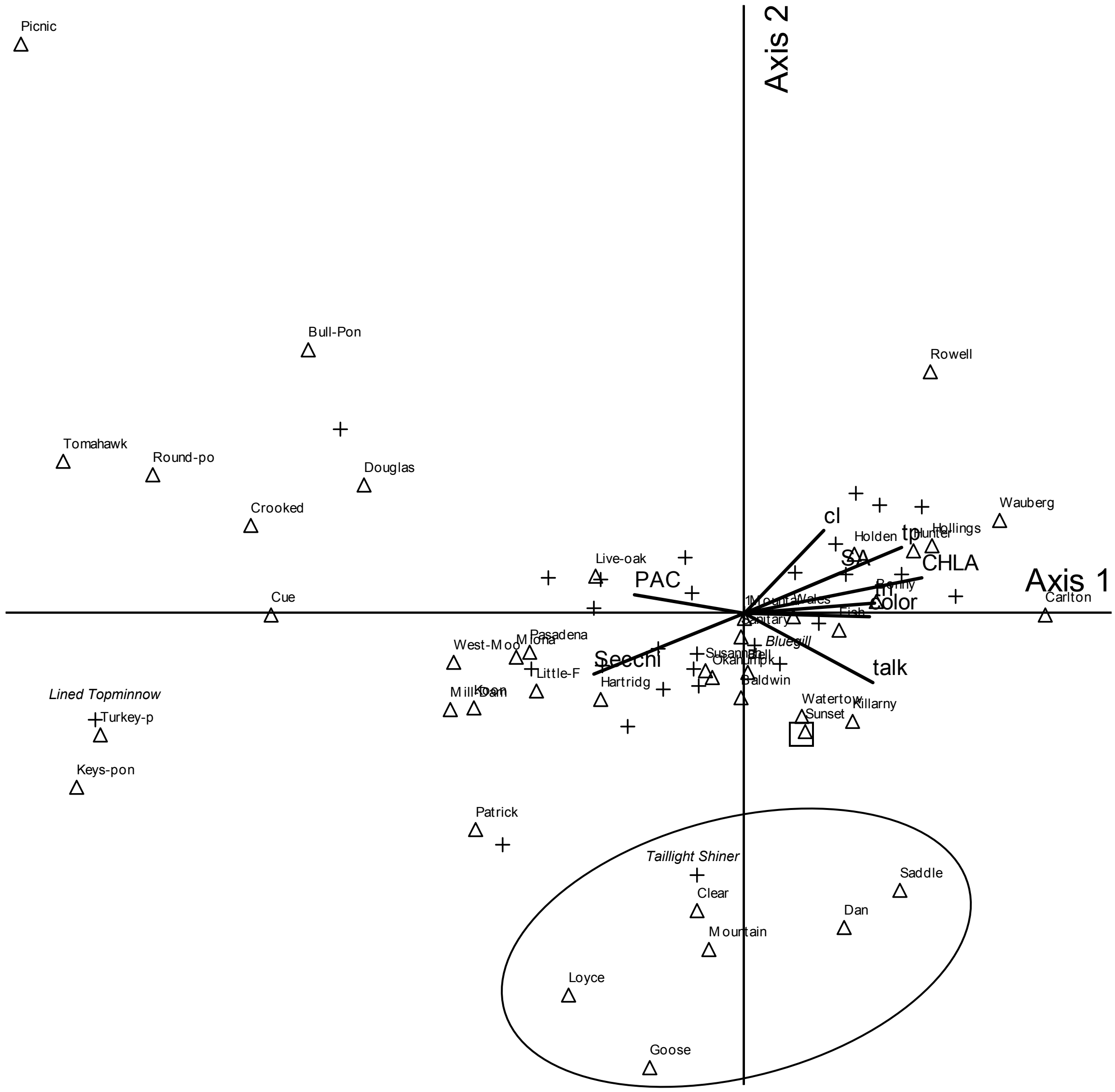

Figure 3. Joint Plot of axis 1 versus axis 2 of the canonical correspondence analysis with lakes (△) and species (+) plotted along environmental gradients. Limnological characteristics include: percent area covered by aquatic macrophytes (PAC), Secchi depth (Secchi), total alkalinity (talk), color, total nitrogen (tn), chlorophyll (CHL), total phosphorus (tp), Surface Area (SA) and chloride (cl). Augmented lakes include: Clear, Dan, Goose, Loyce, Mountain, Saddleback (Saddle) and Sunset. The oval contains six augmented lakes that are most related to axis 2. The box contains Sunset Lake.

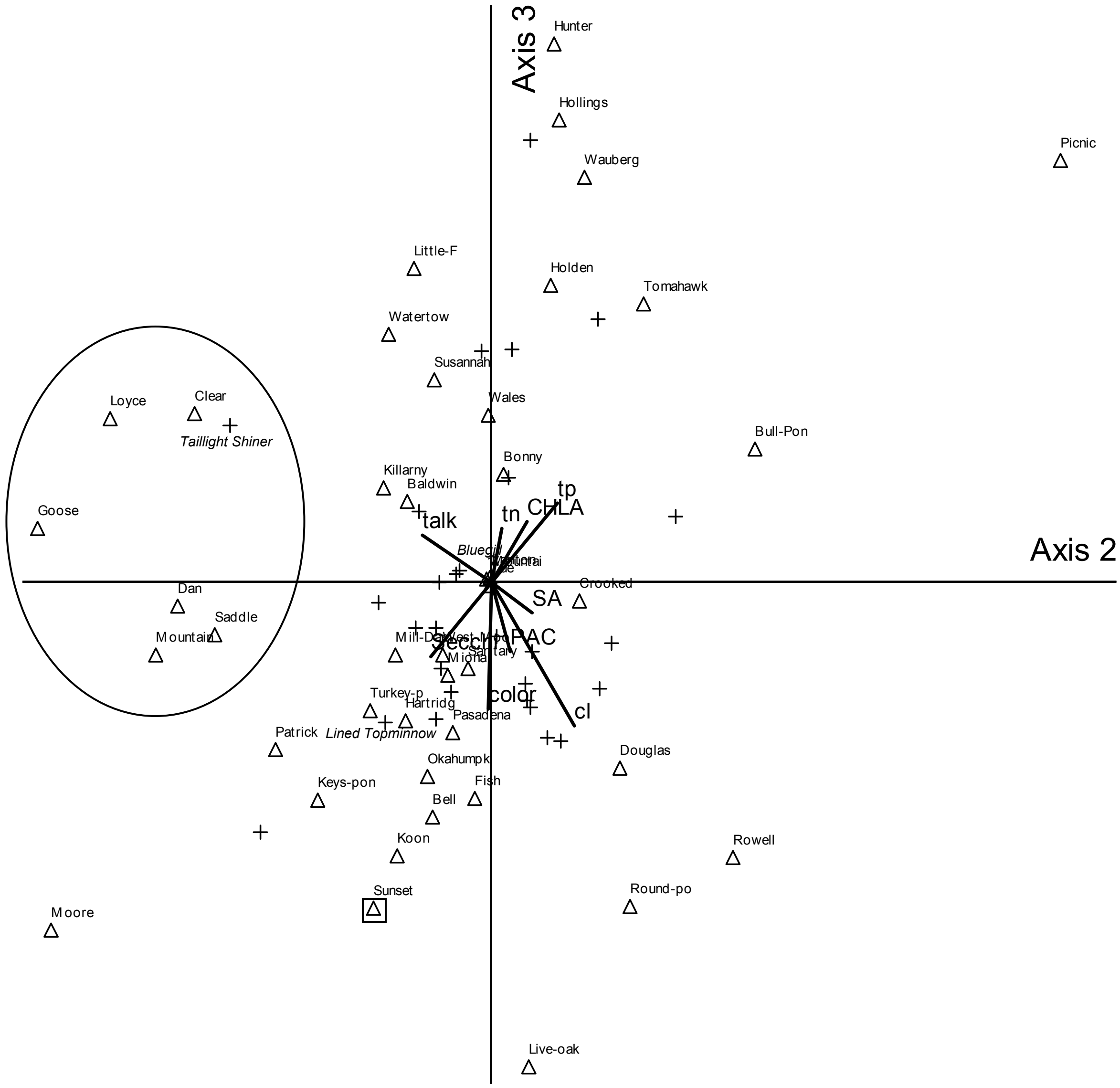

Figure 4. Joint Plot of axis 2 versus axis 3 of the canonical correspondence analysis with lakes (△) and species (+) plotted along environmental gradients. Limnological variables include: percent area covered by aquatic macrophytes (PAC), Secchi depth (Secchi), total alkalinity (talk), color, total nitrogen (tn), chlorophyll (CHL), total phosphorus (tp), surface area (SA) and chloride (cl). Augmented lakes include: Clear, Dan, Goose, Loyce, Mountain, Saddleback (Saddle) and Sunset. The oval contains six augmented lakes that are most related to axis 2. The box contains Sunset Lake.

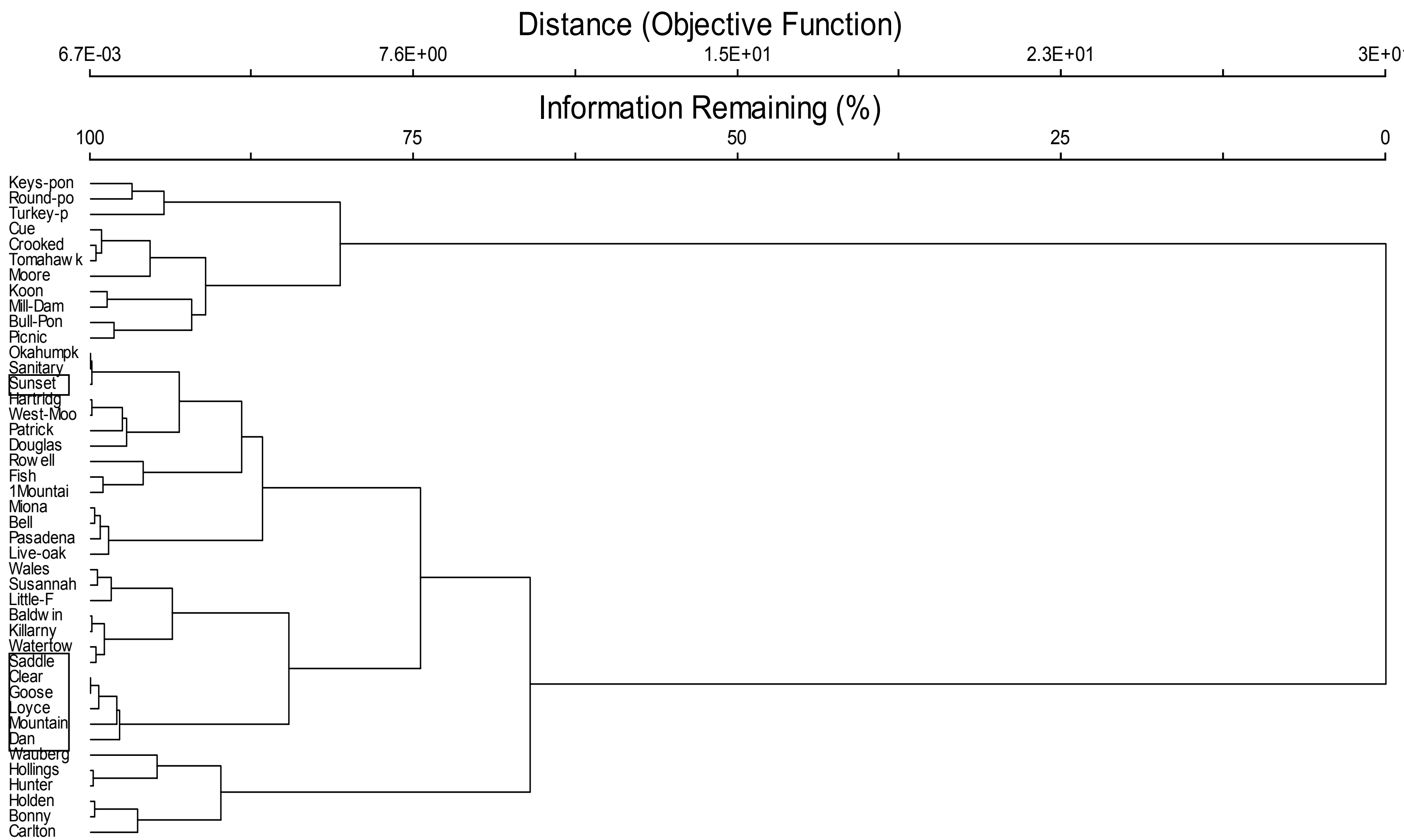

Figure 5. Cluster analysis of lakes using total alkalinity, chloride, total phosphorus, and Secchi depth. Augmented lakes (boxed) include Clear, Dan, Goose, Loyce, Mountain, Saddleback (Saddle) and Sunset.

Table 1. The county, wellfield in closest proximity, location, surface area, average depth determined with fathometer and year of first groundwater augmentation for the seven study lakes. Mountain Lake is not within the vicinity of a wellfield, but rather, requires augmentation due to its proximity to the highest elevation in peninsular Florida, on the Lake Wales Ridge, increasing its elevation above the surficial aquifer.

Lake	**County**	**Wellfield**	**Latitude**	**Longitude**	**Surface Area** (ha)	**Average Depth** (m)	**Year of First Augmentation**
Clear	Pasco	Eldridge-Wilde	28.3625ºN	82.4789ºW	16	1.50	1978
Dan	Hillsborough	Cross Bar Ranch	28.1667ºN	82.6464ºW	14	3.18	Early 1970's
Goose	Pasco	Eldridge-Wilde	28.3559ºN	82.4702ºW	15	1.49	1954
Loyce	Pasco	Eldridge-Wilde	28.3758ºN	82.4958ºW	18	1.73	1996
Mountain	Polk	Elevation	27.9348ºN	81.5898ºW	39	2.92	1975
Saddleback	Hillsborough	Section 21	28.1194ºN	82.4942ºW	13	2.56	1968
Sunset	Hillsborough	Cross Bar Ranch	28.1345ºN	82.6267ºW	15	2.83	1976

Table 2. The number of wells, the average volume of water pumped each day from all wells combined, and the year of initial service for the wellfields in close proximity to the augmented lakes.

Wellfield	**Number of Wells**	**Average Volume Pumped** (m^3/day)	**Initial Year**
Cross Bar Ranch	17	1.00×10^5	1981
Eldridge-Wilde	58	8.52×10^4	1956
Section 21	8	3.79×10^4	1963

Table 3. Mean limnological characteristics in 2003. These include percent lake area covered by aquatic macrophytes (PAC), Secchi depth, ph, total alkalinity, total chlorophyll, total phosphorus, total nitrogen, chloride, and color. Water chemistry means were based on three samples per lake, and PAC was measured using transects with a recording fathometer. Nonaugmented lake means are from 36 Florida lakes.

Lake	**PAC** (%)	**Secchi** (m)	**pH**	**Total Alkalinity** (mg/L as $CaCO_3$)	**Total Chlorophyll** (µg/L)	**Total Phosphorus** (µg/L)	**Total Nitrogen** (µg/L)	**Chloride** (mg/L)	**Color** (Pt-Co units)
Augmented									
Clear	58	2.44	7.80	115	5.60	13.3	427	6.00	23.3
Dan	14	1.52	8.00	120	15.6	16.7	890	9.92	53.0
Goose	52	3.35	7.90	107	3.20	12.3	670	6.92	31.7
Loyce	28	3.05	7.80	103	1.60	8.00	463	7.17	16.0
Mountain	44	3.35	9.03	64.7	8.40	14.3	487	9.67	15.0
Saddleback	12	1.52	8.27	76.3	34.4	19.3	737	7.67	42.0
Sunset	10	1.83	7.77	56.0	20.2	18.0	810	27.1	44.0
Mean	31.1	2.44	8.08	91.7	12.7	14.6	641	10.6	32.1
Nonaugmented									
Mean	44.2	2.04	7.56	31.1	26.5	30.5	939	18.5	20.6
Range	0-100	0.30-5.80	4.30-9.18	0.28-106	0.82-159	0.83-159	99.0-1750	2.50-51.7	1.25-57.5

Table 4. Groundwater pumping history in augmented lakes. Variables include lake volume, the average volume of groundwater pumped per year, the years of historical pumping data averaged, and the number of times the volume of pumped water would replace the volume of water in the lake in one year.

Lake Name	**Lake Volume** (m^3)	**Average Volume Pumped** (m^3/year)	**Years**	**Fill Rate** (times/year)
Clear	1.20×10^5	3.94×10^5	1990-98	3.28
Dan	4.77×10^5	7.61×10^5	1994-98	1.60
Goose	2.23×10^5	3.19×10^5	1990-98	1.43
Loyce	3.13×10^5	3.50×10^5	1995-98	1.12
Mountain	1.13×10^6	2.67×10^6	1989-94	2.36
Saddleback	3.33×10^5	4.43×10^5	1968-71	1.33
Sunset	4.19×10^5	9.97×10^4	1977-01	0.24

Table 5. Water chemistry of groundwater from well samples and historical lake water samples prior to initial augmentation. Variables include date of collection (month/year), Secchi depth, pH, total alkalinity, total chlorophyll, total phosphorus, total nitrogen, chloride, and color. Secchi depth, total chlorophyll and color were not determined for groundwater. Blanks for historical lake samples indicate missing data.

Lake Name	**Date** (month/year)	**Secchi** (m)	**pH**	**Total Alkalinity** (mg/L as $CaCO_3$)	**Total Chlorophyll** (µg/L)	**Total Phosphorus** (µg/L)	**Total Nitrogen** (µg/L)	**Chloride** (mg/L)	**Color** (Pt-Co units)
Well Samples									
Clear	8/2003		7.7	177		25.0	310	5.95	
Dan	8/2003		7.8	210		77.0	440	7.50	
Goose	8/2003		7.6	184		40.0	330	5.00	
Loyce	8/2003		7.6	178		28.0	420	5.50	
Mountain	8/2003		7.7	152		60.0	450	3.00	
Saddleback	8/2003		7.2	232		40.0	910	4.50	
Sunset	8/2003		7.8	189		68.0	660	8.60	
Mean			7.6	189		48.3	503	5.73	
Historical Lake Samples									
Loyce	7/1995	0.80	6.9	36.0	28.0	5.00	2670	5.00	50.0
Loyce	7/1984		6.1	6.00				3.00	78.0
Sunset	5/1976		5.6	20.0				16.5	90.0
Saddleback	3/1968		5.5	14.0					40.0
Saddleback	2/1968		6.1	14.0					60.0

Table 6. Fish population measures of augmented and nonaugmented lakes. These include number of electrofishing transects (N), mean catch per unit effort (CPUE), standard deviation of the catch per unit effort (CPUE SD), species richness, species evenness by number, species evenness by weight, species diversity by number, species diversity by weight and mean harvestable fish biomass. Nonaugmented lake averages are from 36 Florida lakes.

Lake	**N** (transects)	**Mean CPUE** (fish/ minute)	**CPUE SD**	**Richness** (species)	**Evenness by Number**	**Evenness by Weight**	**Diversity by Number**	**Diversity by Weight**	**Mean Harvestable Fish Biomass** (grams/ minute)
Augmented									
Clear	6	7.05	5.96	11	0.37	0.40	2.41	2.30	74.7
Dan	6	1.65	0.68	7	0.54	0.33	2.26	1.67	15.1
Goose	7	1.16	0.89	5	0.70	0.66	1.95	1.86	51.9
Loyce	7	1.31	0.51	8	0.57	0.44	2.35	2.13	32.6
Mountain	8	3.38	0.92	9	0.38	0.32	2.18	1.77	173
Saddleback	7	1.71	0.45	10	0.36	0.35	2.38	2.12	38.4
Sunset	6	10.7	3.76	10	0.21	0.47	1.37	2.38	26.5
Mean	6.71	3.85		8.57	0.45	0.42	2.13	2.03	58.9
Nonaugmented									
Mean	5.26	7.45		10.4	0.44	0.37	2.22	1.98	208
Range	3-6	0.58-36.1		2-18	0.28-0.96	0.17-0.66	0.28-3.15	0.31-2.82	3.87-1150

Table 7. Significant linear regression models predicting dependent fish variables at nonaugmented and augmented lakes combined. Dependent fish variables include $\log_{10}$ of catch per unit effort (lcpue), $\log_{10}$ species evenness by number (levennum) and weight (levenwt), species diversity by number (divnum) and weight (divwt), species richness (rich), and $\log_{10}$ harvestable fish biomass. Independent variables include surface area of lake (ha, sa), percent area coverage of aquatic macrophytes (%, pac), Secchi depth (m, Secchi), total alkalinity (mg/L, talk), total chlorophyll (µg/L, chl), total phosphorus (µg/L, tp), total nitrogen (µg/L, tn), chloride (mg/L, cl), and color (color).

Model	**R-square**	**df**	**P-value**
lcpue = 0.724 + 0.016(cl) - 0.134(Secchi) - 0.004(PAC)	0.509	42	<0.001
levennum = -0.561 + 0.072(Secchi)	0.298	42	<0.001
levenwt = -0.669 + 0.00008(tn) + 0.069(Secchi)	0.246	42	0.004
divnum = 2.448 - 0.017(Secchi)	0.134	42	0.016
divwt = 1.215 + 0.004(sa) +0.017(color)	0.495	42	<0.001
rich = 10.803 + 0.113(cl) - 0.002(tn) + 0.019(sa) - 1.407(Secchi)	0.626	42	<0.001
lharvest = 2.302 + 0.002(SA) - 0.133(Secchi) - 0.005(PAC)	0.402	42	<0.001

Table 8. Results of canonical correspondence analysis (CCA) for 34 fish species abundances, as measured by catch per unit effort, from 43 lakes in Florida. Proportional limnological variables were arcsine(x/100) transformed; all other limnological variables were $\log_{10}(x+1)$ transformed. Species - environmental correlations were conducted using Pearson tests.

Statistic	Axis 1	Axis 2	Axis 3
Eigenvalue	0.335	0.214	0.153
Species-Environmental Correlations	0.875	0.866	0.822
% Variance in species data explained by the axis	12.2	7.7	5.6
Cumulative % of variance in species explained	12.2	19.9	25.5

Table 9. Intraset correlation between the limnological variables examined and the three axes in the canonical correspondence analysis (CCA) using 34 fish species abundances, as measured by catch per unit effort, from 43 lakes in Florida. Percent area covered by aquatic macrophytes (PAC) was arcsine(x/100) transformed. All other environmental parameters were $\log_{10}(x+1)$ transformed. Intraset correlation may help indicate which environmental variables structure the community, as well as help determine which environmental variables are most influential in a site. The higher the absolute value of the intraset correlation, the more the parameter explains the variation. Values below -0.350 and above 0.350 were considered more highly correlated than those between -0.350 and above 0.350, and are followed by a * for emphasis.

Variable	Axis 1	Axis 2	Axis 3
Total Alkalinity	0.643*	-0.450*	0.185
Chloride	0.400*	0.526*	-0.574*
Total Phosphorus	0.793*	0.420*	0.317
Total Nitrogen	0.649*	0.064	0.211
Surface Area of Lake	0.479*	0.262	-0.124
Secchi Depth	-0.753*	-0.399*	-0.296
Chlorophyll	0.888*	0.299	0.239
Color	0.629*	-0.027	-0.506*
PAC	-0.553*	0.117	-0.279

DISCUSSION

Historically, the water chemistry of lakes in central Florida differs significantly from the chemistry of aquifer water in the same vicinity (Dooris and Martin 1979; BRA 1996; Hassell et al. 1997). The historical data from the augmented lakes prior to initial groundwater introduction demonstrated lower levels of pH, alkalinity, and water clarity prior to augmentation, similar to typical small lakes in central Florida that contain acidic, soft, tannin-colored water, with low levels of bicarbonate, inorganic carbon, alkalinity, conductivity, and calcium (Canfield 1981; Canfield and Hoyer 1988; BRA 1996; Hassell et al. 1997).

The water chemistry of the augmented lakes in this study shifted to levels resembling the water chemistry of aquifer water upon the introduction of large volumes of groundwater, by which an entire lakes volume can be replaced several times a year. As groundwater is introduced, the replacement of original lake water is generally characterized by increases in clarity, pH, hardness, bicarbonate, inorganic carbon, alkalinity, conductivity, calcium, magnesium, dissolved solids, nitrogen and sodium concentrations, all of which are chemical characteristics of water contained in the Floridan Aquifer (Stewart and Hughes 1974; Martin et al. 1976a; BRA 1982; Dooris et al. 1982; BRA 1996; Hassell et al. 1997). Dooris and Martin (1979) noted that increased pumping of aquifer water caused a shift in the water chemistry of augmented lakes to closely resemble the chemical characteristics of aquifer water. It is apparent that the patterns of increasing pH, alkalinity and clarity in my study lakes are analogous to those of previously studied augmented lakes.

Another noted effect of groundwater pumping, as reported by Canfield and Hoyer (1990) in Gate Lake and Mountain Lake, Florida, is the addition of nutrients. The well water samples in the seven augmented lakes had higher mean concentrations of phosphorus than both historical and current lake water sample levels. Conversely, in all sampled augmented lakes but Saddleback Lake, nitrogen concentrations were lower than sampled well water and historical values. However, the nitrogen to phosphorus ratios are much greater than 17, suggesting that phosphorus is the limiting nutrient in each of the seven augmented lakes (Florida Lakewatch 2000). The addition of groundwater demonstrates an increase in the limiting nutrient in the augmented lakes.

Despite the overall increase in phosphorus by groundwater introduction, these augmented lakes are still characterized by low total phosphorus (< 20 μg/L). Trophic states, according to concentrations of phosphorus, indicate that all of the studied augmented lakes were either oligotrophic or mesotrophic (Forsberg and Ryding 1980). Therefore, there is little expected change in fish population parameters due to increased nutrient introduction in the studied augmented lakes.

The cluster analysis (Figure 6) of total alkalinity, chlorides, total phosphorus and Secchi depth versus all 43 lakes demonstrated the similarity in water chemistry of six of the augmented lakes to each other, and of one of the augmented lakes to a group of nonaugmented lakes. Despite being in three different counties, six of the augmented lakes were similarly characterized by higher alkalinity, lower chlorides, lower phosphorus and higher Secchi depths, whereas Sunset Lake was more characterized by lower total alkalinity and higher chloride concentrations. This was likely a result of the lower average volume of groundwater pumped into Sunset Lake each year (9.97×10^4 m^3/year) compared to the range of yearly averages of the other augmented lakes (3.19×10^5 to 2.67×10^6 m^3/year). Therefore, reduced groundwater introduction could decrease the effects of shifted water chemistry, resulting in a lake more characteristic of natural limnological characteristics.

Another change that augmented lakes endure is reduced water level fluctuation. For example, Mountain Lake experienced lake level fluctuations of approximately 3 m during the 1940s and 1950s, whereas the recent stage fluctuation indicates a much narrower overall range of variation of about 1 m during the past decade (BRA 2001). Similarly, Saddleback Lake experienced less than 0.5 m of fluctuation in the ten years following augmentation, and showed very little response to heavy rainfall, as caused by the artificial head placed on the lake above the already lowered potentiometric head (Jones 1978). The other augmented lakes were also characterized by comparable lake level fluctuation reduction.

The combination of increased water clarity, increased nutrients, increased hardness, and reduced water level fluctuation could change the characteristics of aquatic plant communities in augmented lakes. Increased water clarity increases light penetration, often allowing plants to grow faster and at greater depths (Canfield et al. 1985). Likewise, increased nutrients also increase plant growth. Also, Martin et al. (1976b) found that the elevated hardness of pumped groundwater increased the ability of augmented lakes to support hydrilla, Hydrilla verticillata, growth. Consequently, many of the augmented lakes have had a history of aquatic plant problems. For example, Mountain and Saddleback lakes have been stocked with grass carp, Ctenopharyngodon idella, treated with aquatic herbicides and had harvest programs to decrease the amount of plants (Canfield and Hoyer 1990; personal communication with lake residents). Conversely, Goose Lake and Clear Lake are in the middle of a wellfield, and do not have public access or people living on them. Therefore, there is no concern for aquatic vegetation control. These two lakes yielded the highest PAC of the augmented lakes.

Little work has assessed effects of groundwater augmentation, and the ensuing alterations to lake characteristics, on fish communities (Allen 1999). Cowx (2000) found that the discharge of groundwater lowered dissolved oxygen concentrations and reduced water temperatures in the River Ouse, Yorkshire, UK, and suggested that the low dissolved oxygen concentrations could cause asphyxiation of fish with possible loss of sensitive species if chronic, and the low water temperatures could reduce fish growth, leading to a decline in stock (Cowx 2000). In Florida, groundwater generally has lower temperatures and dissolved oxygen concentrations than surface water (McKinset and Chapman 1998). However, well introduced groundwater is not pumped directly into the lakes in Florida as is the case in the River Ouse. The streams and the pipes that deliver the groundwater to the lakes in Florida allow the water to warm up and aerate before entering the water body, as demonstrated by the similarity of mid-lake and discharge measurements. Further, the difference in temperature between groundwater and lake water in Florida is less than that of the study in Yorkshire, decreasing this concern in Florida lakes.

The effects of the nutrient introduction by means of groundwater pumping in the previously mentioned Canfield and Hoyer (1990) study were not detrimental to the fish populations, and instead, were possibly beneficial with respect to species diversity, total fish biomass, and sport-fish-abundance. Allen (1999) found similar results with respect to increased fish species diversity in one augmented lake in Florida (Round Lake). However, in contrast to Canfield and Hoyer (1990), Allen (1999) found that Round Lake had significantly lower total fish biomass and density as compared to two nonaugmented lakes.

The augmented lakes in my study had little influence on the regressions of fish population parameters versus limnological variables, suggesting that the fish populations in the augmented lakes were similar to fish populations in nonaugmented lakes with similar limnological characteristics. However, there is evidence that the limnological variables shifted from their original levels to those more indicative of aquifer water. Therefore, one must consider that as the limnological variables shifted with groundwater introduction, the fish populations in the augmented lakes responded by shifting correspondingly along the gradient of the regression.

The data from the nonaugmented lakes in this study were collected from 1986 to 1990. Therefore, the limnological and fish population parameters could have changed in these lakes over time in a similar fashion to the augmented lakes, making it difficult to compare the two samples. However, upon inspection of numerous limnological variables, including pH, total phosphorus, total nitrogen and total alkalinity, from several of the nonaugmented lakes, the changes were either small or obsolete. For example, both Lake Susannah had the same pH (7.8) in 1988 and 1999, and similar alkalinities over the same time period (30.8 and 30.7 respectively). Also, the magnitudes of change from the few limnological parameters measured historically from the augmented lakes were much greater than the magnitudes of change for the nonaugmented lakes. Although extensive limnological parameter studies were not performed on the augmented lakes prior to groundwater introduction, several patterns emerged from the limited data available.

As groundwater was pumped, the augmented lakes were characterized by increased Secchi depths, total alkalinity, phosphorus and chloride. They were also characterized by decreases in total nitrogen and color, and would most likely all increase in percent area covered by aquatic macrophytes if people did not control their levels. Augmentation also increases surface area.

Upon placing these characteristics in the multiple regressions for all lakes, several fish population responses can be predicted for augmented lakes. However, it is difficult to predict exact changes on a temporal scale due to the lack of previous limnological studies on these lakes. For example, there were no previous estimates of PAC on the augmented lakes, and only one lake had a historical secchi depth measurement. Therefore, the following are projected patterns for fish population parameters based on general observed patterns for the limnological parameters. The pattern of increase or decrease for catch per unit effort over time with groundwater introduction is difficult to determine since chloride concentrations, Secchi levels and PAC increase with groundwater pumping, acting as opposing terms in the regression. However, the average catch per unit effort for the augmented lakes (3.85 fish/minute) was much lower than average catch per unit effort of the nonaugmented lakes (7.45 fish/minute), suggesting that catch per unit effort decreased. Evenness by number would increase because Secchi depth increases with groundwater pumping. Evenness by weight would have opposing terms since total nitrogen decreases and Secchi increases, making it difficult to determine the pattern. Diversity by number would decrease with groundwater pumping due to increasing Secchi depth, opposing the results reported by Canfield and Hoyer (1990) and Allen (1999). Conversely, diversity by weight would increase due to increasing surface area and color. Both richness and harvestable biomass have opposing values as groundwater increases, making their change with groundwater augmentation difficult to determine. However, similar to catch per unit effort, mean species richness and mean harvestable fish biomass were lower for the seven augmented lakes (8.57 species and 58.9 g/minute respectively) than for the 36 nonaugmented lakes (10.4 species and 208 g/minute respectively), indicating a lower average number of species, individuals and weight of fish of harvestable size than those lakes without groundwater being pumped.

The multiple regression analyses were useful for indicating that fish populations of augmented lakes did not deviate from the patterns of nonaugmented lakes. However, multiple regressions are unable to indicate the patterns for numerous individual fish species across multiple limnological variables in multiple lakes. The joint plots of the CCA suggested that the abundance, expressed as catch per unit effort, of individual species in six of the augmented lakes had a high probability of being low compared to a majority of nonaugmented lakes, agreeing with the Round Lake study by Allen (1999). This also corresponded with the finding that catch per unit effort of all species and species richness were low in these lakes compared to nonaugmented lakes. Further, a majority of all fish species abundances were more correlated to the first axis of the CCA, whereas the majority of augmented lakes were highly correlated to the second axis, explaining that the gradient of environmental patterns determining the fish community in these augmented lakes was different than the gradient determining fish communities in a majority of nonaugmented lakes.

A study in Max Lake, Wisconsin, examined the effects of groundwater pumping on fish population dynamics for largemouth bass and yellow perch populations (Engel et al. 2000). The groundwater pumping failed to alter growth, abundance, biomass, or mortality of yellow perch and largemouth bass 3 to 7 years old. However, very little water was pumped into the lake as compared to the amount of water pumped into the studied augmented lakes in Florida. Only 5% of the water in Max Lake was replaced each year by augmentation, as compared to the range of about 24% to 328% in the seven augmented lakes. However, similar to the comparison of Sunset Lake to the other studied augmented lakes, low volumes of introduced groundwater could have reduced effects on water chemistry and fish population responses compared to lakes with high volumes of groundwater introduction.

Numerous studies discuss fish growth and biomass responses to alterations in water chemistry. Many have focused on the relationship between trophic states (as described by Forsberg and Ryding 1980) and fish communities in lakes. Both fish growth (Larkin and Northcote 1969; Bayne et al. 1994) and fish production (Downing et al. 1990; Ney 1996) are closely correlated with total phosphorous concentrations in lakes. Similarly, total phosphorous concentrations (Kautz 1980; Hanson and Leggett 1982; Yurk and Ney 1989; Hoyer and Canfield 1991; Lee et al. 1991; Bayne et al. 1994; Bachmann et al. 1996), total nitrogen concentrations (Bachmann et al. 1996), and chlorophyll concentrations (McConnell et al. 1977; Ogelsby 1977; Jones and Hoyer 1982; Bachmann et al. 1996), are all positively related to total fish biomass in lakes. Conversely, oligotrophication, the reversal of the eutrophication process, is accompanied by declines in growth, standing stock, and harvest in fish (Ney 1996). Each of these studies displays a positive correlation between fish productivity, fish biomass, and fish abundance as eutrophication proceeds. The Forsberg and Ryding (1980) guidelines for trophic state indicate that the augmented lakes range from oligotrophic to mesotrophic, possibly explaining for the low CPUE and low harvestable biomass found in these lakes. However, the slight increase in nutrients caused by groundwater introduction may have slightly increased these fish population variables from their original levels.

Several investigations have also reported decreases in the relative abundance of piscivorous fish, with possible losses of sensitive species, as a consequence of eutrophication (Larkin and Northcote 1969; Persson et al. 1988; Bachmann et al. 1996; Ney 1996). Opportunistic, eurytolerant, non-piscivorous species are likely to replace stenotolerant, piscivorous fishes with increasing fertility of lakes (Ney 1996), causing higher standing crops of such fish species as gizzard shad, Dorsoma cepadianum, threadfin shad, Dorosoma petenense, and common carp, Cyprinus carpio, in eutrophic and hypereutrophic lakes (Hasler 1947; Larkin and Northcote 1969; Bachmann et al. 1996).

No evidence was found in this group of augmented lakes to suggest that piscivorous fish were being replaced by eurytolerant, non-piscivorous fish. For example, bluegill was the most abundant fish species present in six of the seven augmented lakes. Also, threadfin shad were found in only one of the augmented lakes, Sunset Lake, where limnological variables are more closely related to nonaugmented lakes. Further, in Sunset Lake there were healthy populations of reproducing largemouth bass, bluegill, black crappie, warmouth and redear sunfish of multiple size ranges, while only one school of shad was encountered. Therefore, these lakes are far from being in the hypereutrophic range where these problems occur in fish populations, and there is no evidence that the increase in nutrients from groundwater introduction into the studied augmented lakes caused losses of species.

Numerous studies have found that lake size is the dominant factor determining fish species richness in Florida lakes, in which the number of fish species increases with increasing lake surface area (Barbour and Brown 1974; Matuszek and Beggs 1988; Keller and Crisman 1990; Bachmann et al. 1996). In this study, species richness was positively correlated to the surface area of augmented and nonaugmented lakes combined in the multiple regression. Florida lakes are generally shallow, with flat slopes, and a small decrease or increase in lake level stage creates a dramatic alteration in surface area (Dooris 1982), possibly having a major effect on fish communities. For example, Mountain Lake is listed as having a surface area of 55 hectares prior to lake level declines (BRA 2001). Corresponding with the drop in water level was a decrease in the lake surface area, upon which augmentation returned the surface area to 39 hectares. This was a decline from the original surface area, but larger than the surface area without augmentation. Therefore, the lake could display a decrease in species richness from historical fish population data prior to water level declines, but an increase from periods immediately prior to augmentation.

Allen (1999) suggested that fish population responses to augmentation may be variable and depend on the original water chemistry of the natural lake relative to the water chemistry of the pumped groundwater. Therefore, prior to initial groundwater introduction for augmentation of lake levels, a comparison of water chemistry characteristics from lake water and well water from within close proximity, and estimating the volume of pumped water that will be necessary to maintain lake levels, may be useful in determining expected shifts in water chemistry and fish populations. If surface area is also a dominant factor in determining fish population parameters, it may be important to not only monitor water chemistry, but also surface area prior to initial declines and initial pumping.

MANAGEMENT IMPLICATIONS

Hassel (1994) suggested that augmentation is not a good long-term solution to restore lake levels to reasonable levels because of altered environmental factors. He further states that lake augmentation is a short-term remedy for a long-term problem. It is apparent that Hassel is correct in stating that environmental factors have been altered in augmented lakes. However, without augmentation, many of the lakes would go dry, as was the case of Loyce Lake prior to groundwater introduction.

Augmentation allows for lakes to be utilized for boating, swimming and other recreational activities. It also allows for lake and wetland hydrology to be maintained and fish and wildlife habitat to be provided. Further, fish, bird, reptilian, mammalian, insect and aquatic plant populations were all seen in the augmented lakes in this study. Without augmentation, it is likely fish would die, and the use of the lakes for recreational purposes would be compromised.

The human population in the Tampa area is constantly increasing, along with the demand for water. As the population further expands from Tampa into the suburbs, more wellfields will be created, and more lakes will be affected. Similarly, as the existing wellfields increase the amount of water they withdraw the cones of depression will increase, affecting more lakes in the future. Granting more permits for lake level augmentation with groundwater pumping will further alter limnological characteristics until the demand for groundwater is decreased. However, lakes will still be able to be utilized and fish populations will still be able to exist and reproduce, despite possible shifts with altered environmental patterns. It has also been suggested that these shifts were minimized with reduced levels of groundwater pumping.

Another change that could improve fish population parameters, and reduce changes in plant community characteristics, is an increase in water level fluctuation (Bonvechio and Allen in press). A more natural water level regime could be created by augmenting during rainy seasons, and allowing the lakes to decrease in level during the dry season.

APPENDIX
COMMONLY HARVESTED FISH SPECIES

Table A-1. Commonly harvested fish species, and the total length (mm) at which they are generally first harvested.

Species Name	**Scientific Name**	**Size** (mm)
Chain pickerel	Esox niger	400
Yellow bullhead	Amerius natalis	280
Brown bullhead	Ameirus nebulosus	280
White catfish	Ameirus catus	280
Channel catfish	Ictalurus punctatus	280
Largemouth bass	Micropterus salmoides	280
Sunshine bass	Morone chrysops x M. saxatilis	280
Black crappie	Pomoxis nigromaculatus	240
Redbreast sunfish	Lepomis auritus	200
Warmouth	Lepomis gulosus	200
Bluegill	Lepomis macrochirus	200
Redear sunfish	Lepomis microlophus	200
Flier	Centrarchus macropterus	200

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BIOGRAPHICAL SKETCH

Patrick Cooney was born and raised in El Dorado Hills, a small and fast growing town in the Sierra-Nevada Mountain Range in northeastern California. Upon graduating from high school, he moved to Miami, Florida, to pursue a degree in both biology and marine science from the University of Miami. During this time, he enjoyed studying abroad and conducting research on marine life and marine ecosystems in Townsville, Australia, while attending James Cook University, near the Great Barrier Reef. After graduating from the University of Miami, he promptly moved to Bahia de Kino, Mexico (located on the Sea of Cortez), to study an obligate mutualism between the Senita moth and the Senita cactus, and fish for Dorado, Coryphaena hippurus. Once this research was completed, he returned to Florida to spend time with friends and conduct research on freshwater fish and water chemistry at the University of Florida in Gainesville. He will continue to feed his hunger for knowledge, and teach others the knowledge he has attained.