Spatial and temporal changes in nutrients and water quality parameters in four Puerto Rico reservoirs: Implications for reservoir productivity and sport fisheries restoration

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Water quality of reservoirs is the foundation of the ecological cascade that results in productive fisheries. The current study evaluated four tropical reservoirs (Dos Bocas, Cerrillos, Guajataca, and Lucchetti) in Puerto Rico for spatial and temporal dynamics in water quality parameters to better understand effects on bait fish and subsequently largemouth bass sport fisheries. Surface mapping, and depth profiles of *in situ* parameters of dissolved oxygen, pH, temperature and turbidity using an automated flow through Eureka Manta datason yielded distinct differences between reservoirs in space and time. Several limnological phenomenon were observed within this dataset including distinct influence of river inputs into reservoirs, the prevalence of irradiance avoidance, and substantial and significant oxyclines with depth at varying times of the year. These spatial variations in water quality variables result in direct implications for resource availability. Nutrient concentration ranges were significantly different between reservoirs ($F = 6.45$; $P < 0.05$) and were attributed to varying degrees of land use in the respective upland catchments (Dos Bocas $NO_{3-}N$: 0.8 mg/L; Guajataca NO_3-N: 0.04 mg/L). Nutrient concentrations were low in all reservoirs, with certain reservoirs (Cerrillos and Guajataca) being classified as oligotrophic. Although no direct correlations can be made to fish production, it is important to understand limits to resource production within these systems. Dissolved oxygen, pH, water temperature and nutrient concentrations all work in unison to provide a bottom-up controlled aquatic system that sustains phytoplankton production, baitfish and subsequently sports fisheries.

Key words: nutrients; productivity; fisheries; water quality

Introduction

Inter- and intra-system heterogeneity of water quality in reservoirs affects abundance, growth, and distribution of fishes. Reservoir productivity directly influences prey production, and is largely determined by availability and retention of nutrients and water chemistry parameters (Kimmel et al., 1990). This creates a bottom-up cascade to higher trophic levels, eventually resulting in increased biomass of sport fish (Carpenter and Kitchell, 1993). Likewise, within reservoir variability of physiochemical parameters can influence predator and prey distributions and interactions (Coutant, 1985; Neal et al., 2005), which can have considerable effects on biological function and management in these systems. In Puerto Rico, largemouth bass *Micropterus salmoides* are the primary sport fish, and much of the research and management activity is directed at this species. Management decisions for largemouth bass in Puerto Rico have been based on the assumption that primary productivity and prey availability are not limiting, yet conclusive data to this end are not available (Neal et al., 2009).

Spatial and temporal changes in concentrations of dissolved compounds (nutrients, sediments and agro-chemicals) will influence basic autotrophic dynamics with a cascading effect through the food web (Wetzel, 2001). Likewise, nutrient availability and contaminant concentrations are a product of land-use patterns within the watershed (Cech, 2010; Pennington and Cech, 2010), necessitating a watershed-scale approach to reservoir management. Good water quality is necessary for fisheries with increased non-point source pollution beyond an inflection point on a productivity scale, being in direct conflict for production (Thomas et al., 1992). In the tropics with conducive temperatures and conditions for production, oligotrophic systems would limit the production of higher trophic levels (Wetzel, 2001).

Studies to date have illustrated the relationships between water quality and freshwater biotic integrity (Miltner and Rankin, 1998; Rask et al., 2010; Weigel and Robertson, 2007; Weijters et al., 2009). Typically, most studies agree that there is a positive linear or curvilinear relationship between nutrients (total phosphorus) and chlorophyll *a* for most freshwater bodies (Miltner and Rankin, 1998; Weigel and Robertson, 2007). Weijters et al. (2009) highlighted, from a review of 240 studies, that land-use was the variable that explained the greatest variation in freshwater biodiversity. Miltner and Rankin (1998) described how increases in nutrient concentrations in Ohio freshwater systems, shifted carrying capacity away from smaller, sensitive fish species and subsequent effects on top piscivores, towards more tolerant omnivorous fish species. Similarly, in Finnish lakes, Rask et al. (2010) showed that high nutrient loadings resulted in eutrophic conditions and high algal biomass, which subsequently resulted in high biomasses of low value cyprinid fishes. This is not surprising as many cyprinid fish species take advantage of eutrophic conditions because of their effective planktivory and ability to consume plant material. Weigel and Robertson (2007) stressed, using a partial redundancy analysis that nutrients and water chemistry variables of dissolved oxygen, pH and water temperature accounted for the majority of variance on fish assemblage structure in Wisconsin non-wadeable rivers. These studies suggest that biotic integrity of freshwater systems, which includes sports fisheries production, is a product of nutrient delivery as influenced by upper catchment land-use, delivered system nutrient concentrations, and *in situ* water chemistry variables.

This study evaluated four sub-tropical reservoirs in Puerto Rico (Cerrillos, Dos Bocas, Guajataca and Lucchetti) for spatial and temporal variations of surface and profile water quality parameters (dissolved oxygen, pH, turbidity, temperature) and nutrient concentrations.

Materials and Methods

Water quality sampling of four reservoirs in Puerto Rico was undertaken in quarterly sampling periods. The sampling events occurred in February, June, August and December 2010. The temporal component of quarterly sampling allowed for monitoring changes through seasons and reservoir management cycles. The four reservoirs (Figure 1) monitored were selected for their popularity as sports fisheries (primarily largemouth bass and peacock bass *Cichla ocellaris*), and because each has a substantial research database available on these fisheries

Reservoir In-Situ Water Quality

All reservoirs were sampled for *in-situ* water quality parameters of dissolved oxygen (mg L^{-1}), pH, specific conductance (µS), temperature (°C), turbidity (NTU) and oxidation reduction potential (ORP; mV). Surface mapping of each reservoir took place to understand spatial patterns in parameters. An automated, flow through Eureka MANTA2 data-son was setup on the bow of a 4.3 m aluminum boat. Flow through setup consisted of a 12V bilge pump with a intake tube positioned 0.3 m below the water surface, connected with high density polyethylene tubing to the flow through chamber of the data-son. Flow through occurred from the bottom of the chamber to the top and discharge occurred over the side of the boat through high density polyethylene tubing. Water samples were analyzed every 10 seconds for the duration of the surface mapping exercise. Each water quality data point consisted of all the above mentioned water quality parameters as well as GPS coordinate of each sample recorded. The boat travelled at an average of 5 km $hour^{-1}$, with reservoir size determining time spent surface water mapping. Water quality parameters through depth were recorded with 25 depth profiles, evenly spaced within each reservoir. Depth profiles started at the surface, and were recorded at 1 m intervals until the oxycline was reached (<1 mg L^{-1}), whereby samples were taken every 2 m. The lowest recorded depth reading (cable restriction) was 28 m, which was well below the oxycline in all reservoirs. Recorded turbidity plumes at maximum depth in all reservoirs as a result of the data-son hitting the substrate bottom were removed from the respective data sets. The data-son was calibrated for respective water quality parameters prior to each quarterly sampling period, according to calibration instructions, to within quality assured, quality controlled specifications.

Within each reservoir a random number of surface water samples based on surface area of each reservoir were taken to analyze for select nutrients: nitrate-N, ammonia-N, soluble reactive phosphate and nitrite-N. Nitrite – N was initially analyzed for, but all water samples from February and June sampling events were non-detects for nitrite-N, and thus analysis was discontinued. Nutrients were collected in 250 ml polyethylene containers (Fisher Scientific), transported on ice and refrigerated. Samples were subsequently transported on ice to the Water Quality Analysis Laboratory, at the University of Puerto Rico, San Juan, Puerto Rico. Ammonia was analyzed using the QuickChem® Method 10-107-06-1-J, with minimum detection limits (MDL) of 0.01-2.0 NH_{3}-N mg L^{-1}. Nitrate + nitrite and Nitrate were analyzed using QuickChem® Method 10-107-04-1-B, by flow injection analysis, with MDL's between 0.002-0.10 NO_3, NO_2-N mg L^{-1}. Reactive P was analyzed using QuickChem® Method 10-115-01-1-A, by flow injection analysis colorimetry. Nutrient samples were incorporated in ARCMap to create spatial distributions of nutrient concentrations throughout each reservoir. Similarly spatial distributions of select water quality parameters including dissolved oxygen, turbidity, pH and temperature were created through ARCMap. Spatial mapping in ARCMap used inter-distance weighting to interpolate selected measures between sampling points. Inter-distance weighting was used over spatial kriging to avoid value manipulation and change from statistical interpolation through kriging. The low number of surface water samples was a limitation to the IDW, but the cost of additional sample processing was prohibitive. Two-dimensional maps of water parameters by depth were analyzed using Surfer™ Software. Latitudinal sites, with depth and selected water quality parameter were spatially arranged using inter-weighted distance to view changes in depth and latitude for each water quality parameter. Nutrient concentrations between reservoirs were compared using a one-way ANOVA, with an alpha of 0.05.

Results

In Situ Water Quality Parameters – Dissolved Oxygen, Temperature and pH

Dissolved oxygen, temperature and pH are all measures that are directly affected by phytoplankton productivity. Higher temperatures (general increase from February to June) correlated tightly with higher dissolved oxygen concentrations (February Range: 5.73 – 10.65 mg L^{-1}; August Range: 8.88 – 12.11 mg L^{-1}), and subsequently higher pH values (February Range: 7.89 – 8.80; August Range: 8.80 – 9.04) (Table 1). Using profile data three important limnological process were observed that occurred in all reservoirs: oxycline development, riverine influences with water quality and depth, and irradiance avoidance by photosynthesizing phytoplankton.

Distinctive oxycline development as result of temperature, density and oxygen concentration decreases with depth was observed in all four systems (Figure 2). The oxycline varies in depth and severity based on the season in all reservoirs, but the trends are similar. There was distinct oxycline development for June and August sampling events in deeper waters of Cerrillos Reservoir (Figure 2). Shallower waters (< 17 m) in August were oxic environments throughout the water column. A significant proportion of the water column was oxic in February (Figure 2), with similar results occurring for the December sampling event (not graphed). Figure 3 highlights the spatial distributions (latitude x depth) of dissolved oxygen concentrations in Lucchetti, Guajataca and Dos Bocas Reservoirs respectively for the month of June. Similar trends of strong oxycline development between 6 – 8 m in depth, with a significant proportion of the water column being anoxic were evident among all reservoirs.

The influence of river inflows were evident when water levels were high in Cerrillos Reservoir. The river influence was distinctly observed in a plot of specific conductance, temperature and dissolved oxygen with latitude for Cerrillos in February (Figure 4). When the water levels were drawdown (June, August and December ~ 12 m decrease) as a result of recreational activities, the river influence was negligible. Other reservoirs showed variable river influences with tributaries, but Cerrillos is the only reservoir with a distinct main river arm of the catchment that contributes the majority of water to the reservoir.

Irradiance avoidance was observed within all reservoirs (Figure 3 and 5). June and August sampling had the highest recorded surface water temperatures across the quarterly sampling periods. Often the highest dissolved oxygen recordings on depth profiles occurred at 2 – 4 m below the water surface. Oxygen concentrations were similar between the surface and 4 – 5 m with ranges of oxygen typically between 11 – 14 mg L^{-1} at 2 – 4 m below the surface. Irradiance avoidance by phytoplankton was common among all four reservoirs for June and August.

Turbidity was low in most reservoir surface waters (Lucchetti June Mean: 138 NTU; Range all other months and reservoirs: 3 – 79 NTU) (Figure 6). In Figure 6, there is a distinct trend of increasing surface turbidity from February to August in all reservoirs except Lucchetti. Lucchetti had the highest mean turbidity value in June of 138 ± 18 NTU. Most often, mean surface turbidity values were very low (<80 NTU). Higher values were encountered in shallow, tributary arms for each reservoir.

Surface Mapping of Nutrients: comparison between reservoirs

Comparing mean nutrient concentrations between sampling periods highlights certain temporal trends (Figure 7). Cerrillos had overall very low nutrient concentrations. Ammonia concentrations were less than 0.1 mg L^{-1} throughout the year. Nitrate, and soluble P concentrations were also low (> 0.3 mg L^{-1} and >0.04 mg L^{-1} respectively). Guajataca, similar to Cerrillos, has very low spatial and temporal concentrations of nitrate, ammonia and soluble P. Guajataca's catchment has some urban development in the upper reaches of the catchment (Figure 1), but for the majority, the Guajataca watershed is rural with low-density urban development pockets randomly dispersed throughout. Dos Bocas has the highest nutrient concentrations of any of the four reservoirs, including nitrate-N, ammonia-N and soluble phosphate. Lucchetti Reservoir is the highest located reservoir in its respective catchment (Figure 1). The upper reaches of the catchment are dominated with rural areas with high densities of abandoned and active coffee plantations. Lucchetti also has multiple tributaries that could influence water quality in terms of nutrients and sediments. Lucchetti had the second highest mean nitrate-N values for all the reservoirs when averaged over the three sampling periods. Ammonia and soluble P were low through time and had very low ranges (Ammonia: 0.02 – 0.08 mg L^{-1}; SRP: 0.01 – 0.2 mg L^{-1}).

Discussion

Nutrients, as resources, play an important role in bottom-up regulation of aquatic ecosystems, promoting primary productivity, increasing food availability and energy transfer through trophic levels to higher trophic states such as piscivores (e.g., largemouth bass). This is an important concept when exploring relationships that determine the productivity of sports fishery in freshwater systems such as reservoirs. Limnologists have been investigating reasons for and improvements to reservoir or lake productivity for the last 80 years. Schindler's (1978) classic examples of productivity limits as a result of N and P additions highlighted succinctly how systems are typically N and P limited. Water quality and reservoir productivity are synonymous with the growth of good fisheries. Management and regulation of reservoirs for water quality is prevalent in the temperate regions of US through the implementation of best management practices for the abatement of nutrients, and sediments, as well as several reservoir management strategies of drawdown, discharge and habitat management. Often, nutrients maybe added to oligotrophic systems to increase primary producer productivity and enhance the sports fishery. Very little is known and has been attempted for tropical sport fisheries management from a water quality perspective. Understanding spatial and temporal changes to in situ parameters such a dissolved oxygen, pH and temperature along the surface as well as with depth is vitally important to baitfish production and occurrence. Elucidating first order trophic level interactions between water quality parameters and baitfish will provide some insights in sport fisheries management in terms of species locations, food resource availability and habitat suitability within the entire reservoir. Changes in spatial and temporal nutrient concentrations will affect trophic level productivity within the reservoir, with extremes of excess and limitation affecting productivity. Manny et al. (1994) highlighted how phosphorus contributions from waterfowl were close to 70% of total P inputs into Wintergreen Lake, raising nutrient concentrations in the water column increasing primary productivity, chlorophyll-a and decreasing secchi disk transparency. Relative aquatic ecosystem productivity can be described using nutrient concentration data as well as *in situ* parameters of dissolved oxygen, pH and temperature.

Spatial and temporal surface water dissolved oxygen concentrations provide the basic ecological link to reservoir productivity. Dissolved oxygen is a response variable through bottom up controls such as phytoplankton productivity. Ideal conditions of DO, pH and temperature create conducive conditions for reservoir productivity – i.e., algal photosynthesis. Higher algal productivity in summer months (June / August) results in increasing dissolved oxygen production, increased carbon dioxide consumption, and an increase in the pH of the water column. Often though high irradiance at the surface resulted in photosensitivity of phytoplankton and photo irradiance avoidance was often prevalent in these reservoirs. Dissolved oxygen concentrations on the surface increase during daylight hours as a result of phytoplankton production suspended in the water column. Dissolved oxygen concentrations will also decrease with depth, as DO is removed through phytoplankton respiration and not replenished without mixing. Decreases in temperature of the water column results in density changes with depth and further hinders mixing to increase oxygen concentrations. From February through August, depth profiles of all four reservoirs showed similar patterns. There were strong stratifications of temperature and oxygen in June for all four reservoirs. Oxyclines typically fell between 4 – 8 m in June. Below 8 m oxygen concentrations fell sharply, often within 2 – 4 m oxygen concentrations were below 2 mg L^{-1}. Fish tolerances for oxygen concentrations are well published (refs). Warmwater fisheries have a lower limit threshold for oxygen concentrations of 3 – 4 mg L^{-1}. Weakly anoxic (< 2 mg L^{-1}), or anoxic conditions would limit the habitat selection of baitfish and sport fisheries species respectively.

Algal photosynthesis and reservoir production will be limited by nutrients. Nutrients are the basic elements required for algal growth. Nutrient concentrations in excess, will lead to a decrease in reservoir productivity, eutrophication and a decline in aquatic ecosystem health. A balance is required that enhances basic food web productivity through photosynthesis, but doesn't lead to an alteration of habitat suitability through changes to *in situ* water quality parameters. Total inorganic nitrogen concentrations were varied between reservoirs. Dos Bocas Reservoir displayed inter-reservoir heterogeneity in nutrient concentration between the two arms. Increased total inorganic N, including P, in the western arm of Dos Bocas is hypothesized as a result of runoff and delivery from high density urban developments in the upper reaches of the western arm catchment. The Grande de Arecibo watershed, within which Dos Bocas is situated, has a high amount of abandoned and active coffee plantations, but is also significantly larger than all other reservoir catchments. The eastern arms water quality is better than the western arm for two reasons: 1) no urban development in the upper reaches of the sub-catchment, 2) a reservoir in the upper reaches that has the opportunity to trap and transform sediments and nutrients prior to effluent reaching Dos Bocas. From observations the western arm also receives debris (garbage, refuse, organic materials) during rainfall events that accumulate on the dam wall, while over the same period there is very little debris in the eastern arm. Soluble reactive P concentrations were very low across all reservoirs < 0.2 mg L^{-1}. Median SRP concentrations between quarterly sampling events and across all reservoirs was 0.01 mg L^{-1}. This low concentration between reservoirs and the lack of phytoplankton turbidity associated with algal production might suggest that all these systems are phosphorus limited. Schindler (1978) revealed that both annual phytoplankton production and mean annual chlorophyll were tightly correlated with P loadings into freshwater systems. Schindler (1978) also highlighted that stratification whether by temperature or oxygen had no effect on the distribution of phosphorus and its effect on productivity. Low SRP concentrations in the current study across reservoirs and through time support this finding.

High surface turbidity (> 60 NTU) occurred in only three sampling events across all reservoirs (Lucchetti-June; Dos Bocas-June and August). Lucchetti Reservoir had very high surface measured turbidity in June as a result of strong winds causing significant turbulence, while high turbidity was encountered in Dos Bocas in June and August as a result of storm events bringing increased river inflows. Dos Bocas had significant differences in surface turbidity concentrations (60 NTU West/Urban arm vs. 30 NTU East/Reservoir arm) between the two river arms. Median surface turbidity levels across all reservoirs were typically very low 28 NTU, often with large Secchi depths (> 1.8 m). Low turbidity in all reservoirs coupled with high irradiance leads to photoinhibition. Light is required by all phytoplankton species for photosynthesis. Excess light, however, can inhibit photosynthesis through the photooxidative destruction of photosynthetic apparatus (Long et al., 1994). High irradiance and high levels of UV-A and B result in phytoplankton migrating through the water column for photosynthesis. Dissolved oxygen concentrations at the surface and are comparable to concentrations at 3 – 4 m. This is interesting as dissolved oxygen concentrations should be the highest at the surface and decrease with depth. In all reservoirs at all time intervals, except for the time where turbidity in the surface averaged over 60 NTU, dissolved oxygen concentrations increased from surface to 2 – 3 m and then returned to surface conditions at 4 – 5 m. Depending on the time of the year (December, February and August) dissolved oxygen concentrations slowly decreased with depth, whilst in June, strong oxyclines that had formed, below which oxygen concentration declined to less than 2 mg L^{-1} with 2 – 4 m. Typically these oxyclines were associated with thermoclines, stratifying the water column into areas of food resource availability and habitat suitability within the entire reservoir This strong thermo and oxy-cline that occurs in June could limit the diel migration of phytoplankton, and thus alter reservoir dynamics of resource availability for baitfish and sport fisheries respectively.

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Table 1. Variations in in situ surface water quality parameters for Luchetti, Cerrillos, Guajataca and Dos Bocas Reservoirs in Puerto Rico. Quarterly sampling occurred in February (1st), June (2nd), August/September (3rd) and November/December (4th).

Water Quality Parameter	**Lucchetti**				**Cerrillos**				**Guajataca**				**Dos Bocas**			
	1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th
Temperature Mean	25.08	29.5	30.47	26.1	25.80	29.4	31.05	26.4	27.14	29.7	30.9	26.3	26.80	30.3	30.69	26.4
S.E.	0.06	0.01	0.01	0.01	0.01	0.01	0.03	0.01	0.01	0.013	0.01	0.004	0.02	0.02	0.01	0.01
Median	25.1	29.7	30.42	26.1	25.8	29.3	31.11	26.5	27.1	29.5	30.93	26.3	26.7	30.3	30.63	26.4
Dissolved Oxygen Mean	8.31	13.7	10.27	9	5.73	10.1	8.88	9.73	9.28	10.03	10.56	7.2	10.6	13.1	12.11	13.1
S.E.	0.02	0.03	0.04	0.01	0.02	0.07	0.03	0.04	0.09	0.03	0.06	0.01	0.05	0.06	0.05	0.08
Median	8.19	14.0	10.22	8.99	5.6	9.5	8.75	9.3	9.29	9.7	9.97	7.14	10.3	13.2	12.05	13.9
Turbidity Mean	8.1	139.4	42.94	28.9	17.2	26.6	29.77	23.3	10.4	26.8	39.85	11	12.5	60.5	67.38	50.5
S.E.	0.16	15.9	0.79	0.27	3.1	0.47	1.03	0.2	0.88	1.1	0.51	0.09	0.15	2.1	11.63	0.3
Median	6.3	48.4	42.2	28.4	0.9	23.5	28.8	22	7.5	16.1	37.5	10.7	11.5	53.3	44.75	50.5
Specific Conductance Mean	284	210.1	233	234	217	197.5	185.9	191	289	221.0	202	253	193	156.9	168.9	150
S.E.	0.06	0.05	0.14	0.04	0.08	0.09	0.05	0.07	0.02	0.1	0.36	0.04	0.37	0.15	0.33	0.4
Median	284	210.2	232.7	234	218	198.4	185.9	191	289	221.5	205.8	253	193	158	170.3	146
pH Mean	8.33	9.04	8.80	8.57	7.89	8.70	8.91	8.65	8.51	8.51	8.82	8.1	8.80	9.06	9.04	9.1
S.E.	0.03	0.003	0.004	0.002	0.03	0.008	0.003	0.008	0.01	0.003	0.004	0.004	0.01	0.009	0.007	0.01
Median	8.32	9.08	8.82	8.58	7.88	8.66	8.9	8.61	8.53	8.5	8.78	8.13	8.80	9.1	9.08	9.3
Total N / reservoir	**549**	**741**	**159**	**947**	**884**	**697**	**309**	**611**	**1163**	**1116**	**484**	**1187**	**724**	**771**	**372**	**961**

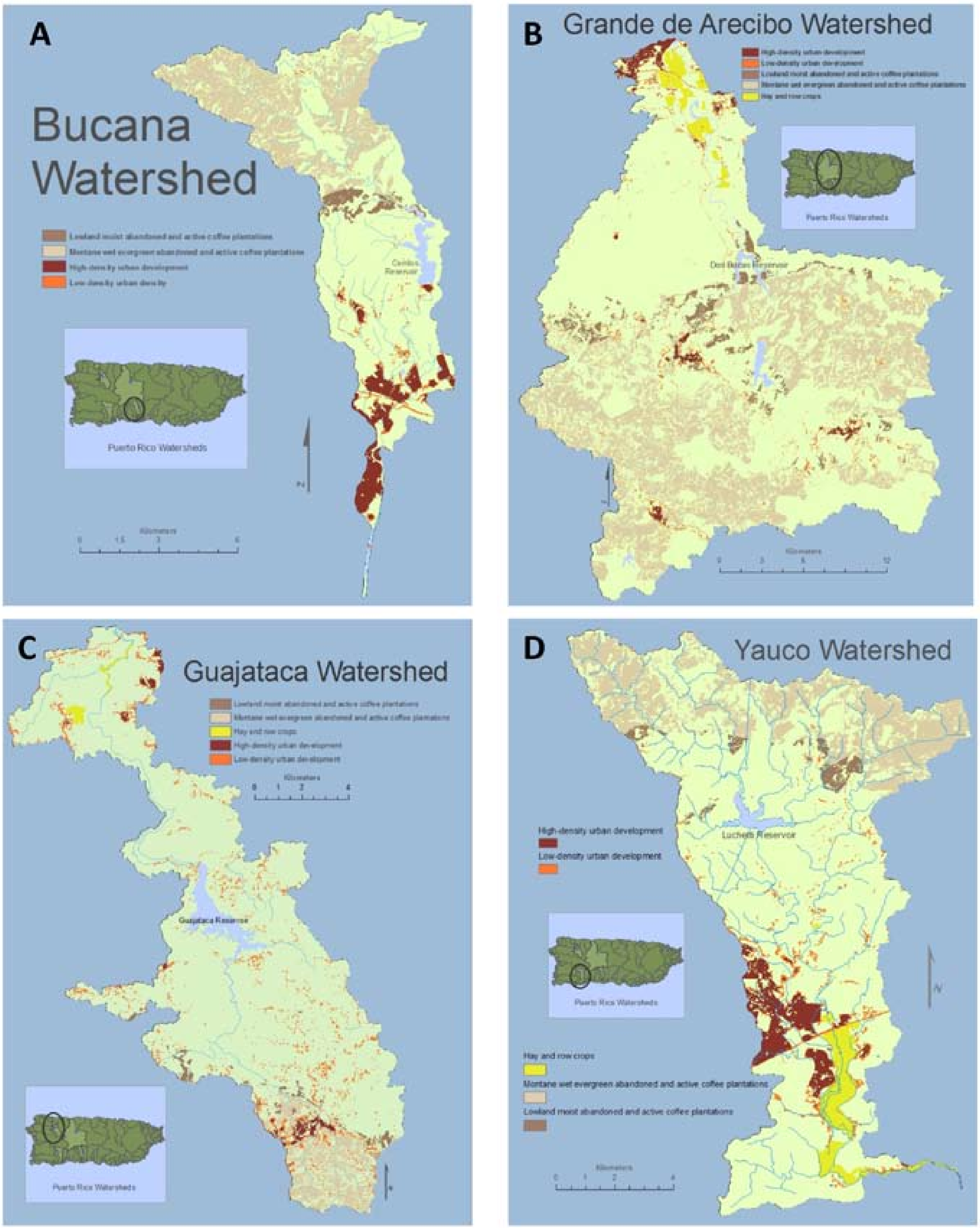

Figure 1. Watershed and reservoir locations of all four reservoirs, Cerrillos (A), Dos Bocas (B), Guajataca (C), and Lucchetti (D). Note the positioning of each reservoir in relation to one another and the variation in watershed size and upper catchment areas for each reservoir.

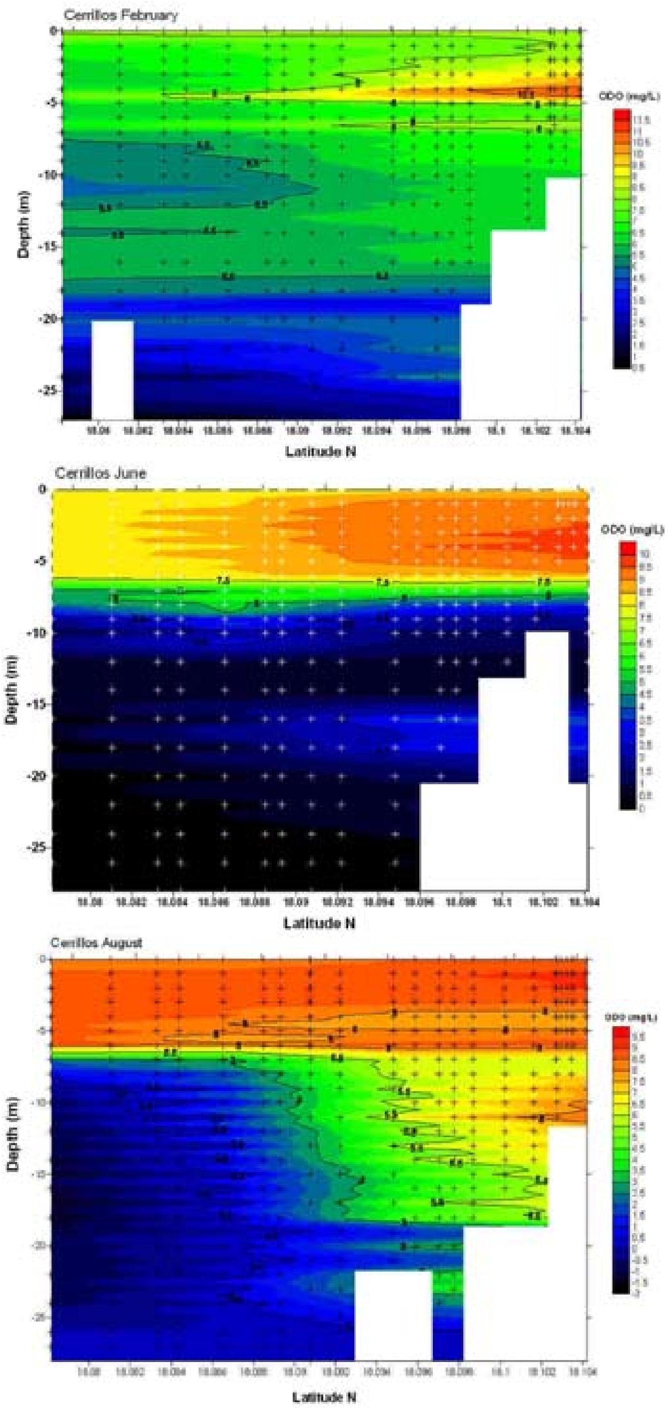

Figure 2. Surface and profile changes in dissolved oxygen concentrations (mg/L) for Cerrillos Reservoir for February, June and August. Note distinct oxy-cline development for summer (June), and August in deeper waters. Shallow waters (<17m) in August were oxic environments throughout the water column. Significant proportion of the water column was oxic in February, with similar results for December sampling event.

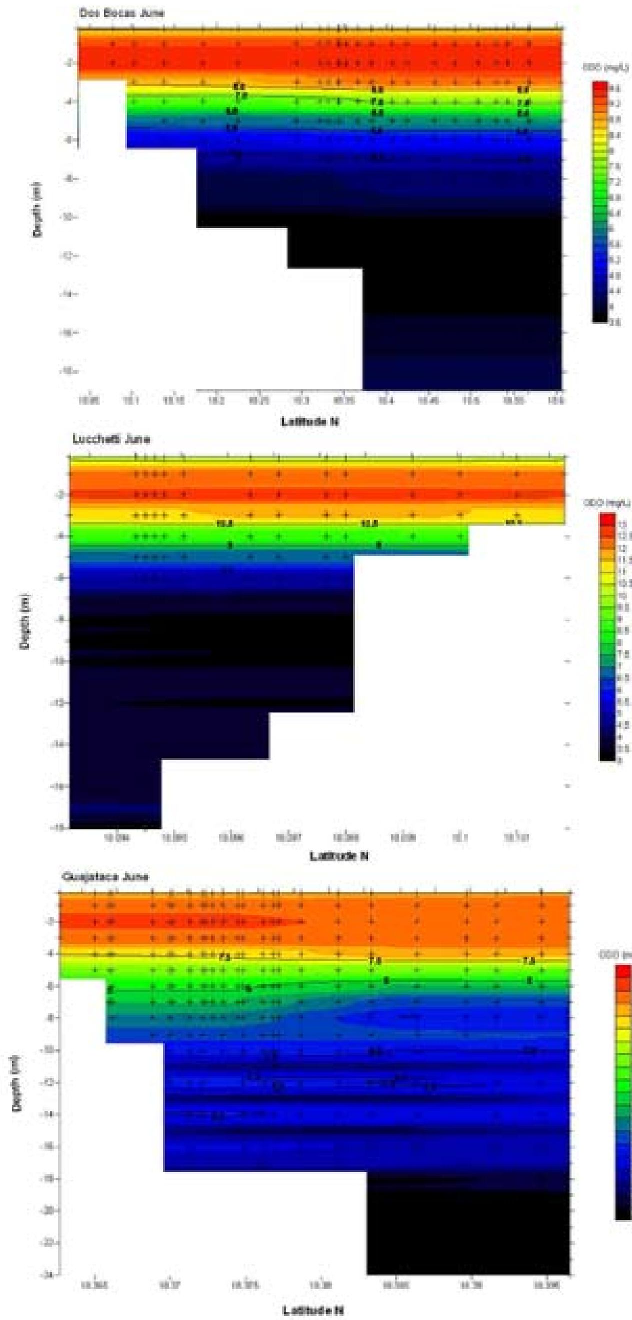

Figure 3. Spatial and depth distributions of dissolved oxygen concentrations (mg/L) for Dos Bocas, Luchetti and Guajataca Reservoirs.

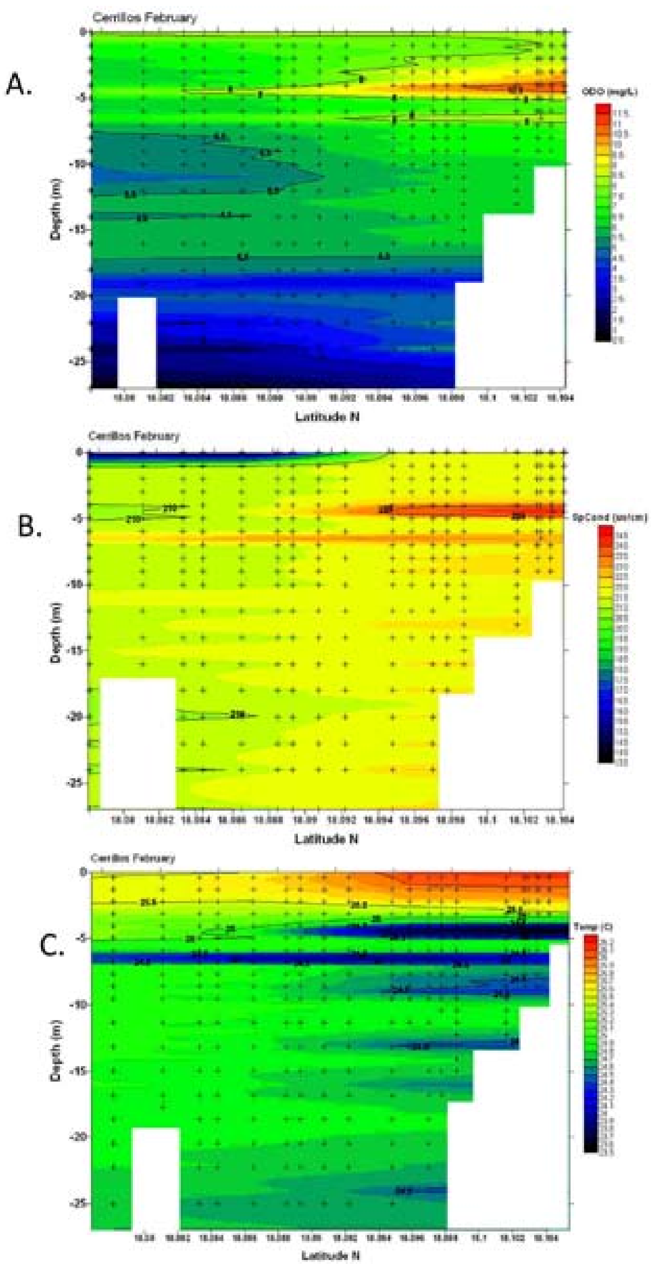

Figure 4. Dissolved oxygen (A), specific conductance (B) and temperature (C) spatial and depth distributions in Cerrillos Reservoir in February. Note distinct riverine signature in all three parameters as reservoir water levels were high.

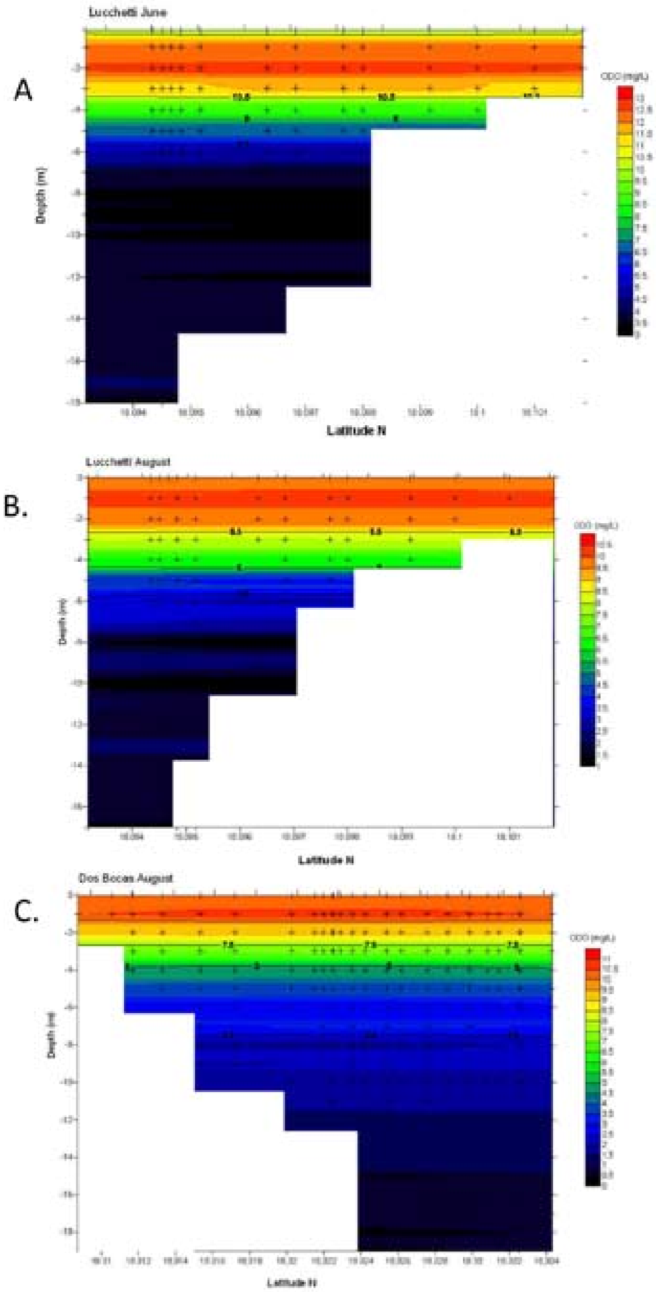

Figure 5. Dissolved oxygen profiles illustrating irradiance avoidance in Lucchetti in June (A), and August (B), and Dos Bocas in August (C).

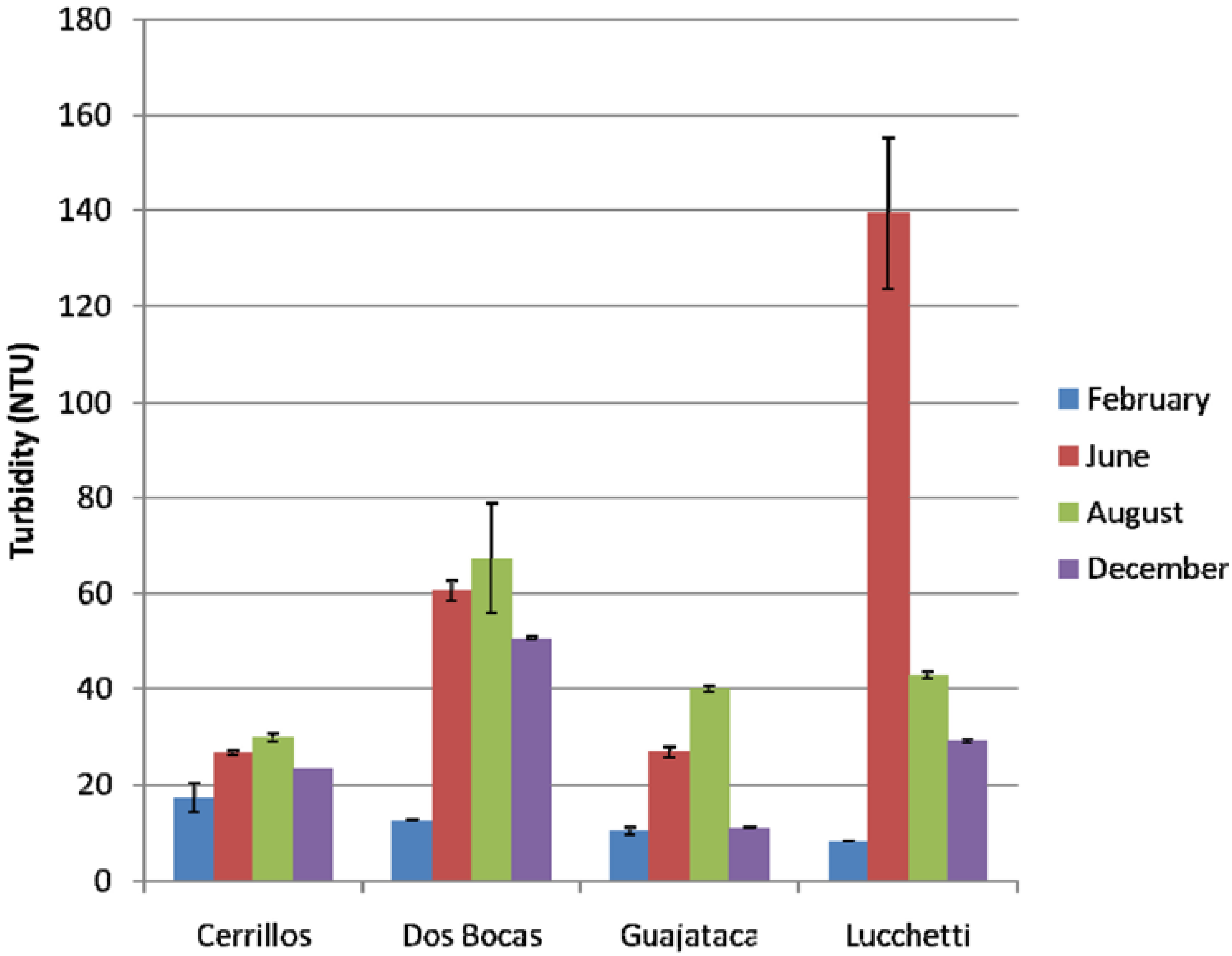

Figure 6. Mean turbidity (NTU± S.E.) for each reservoir by quarterly sampling period.

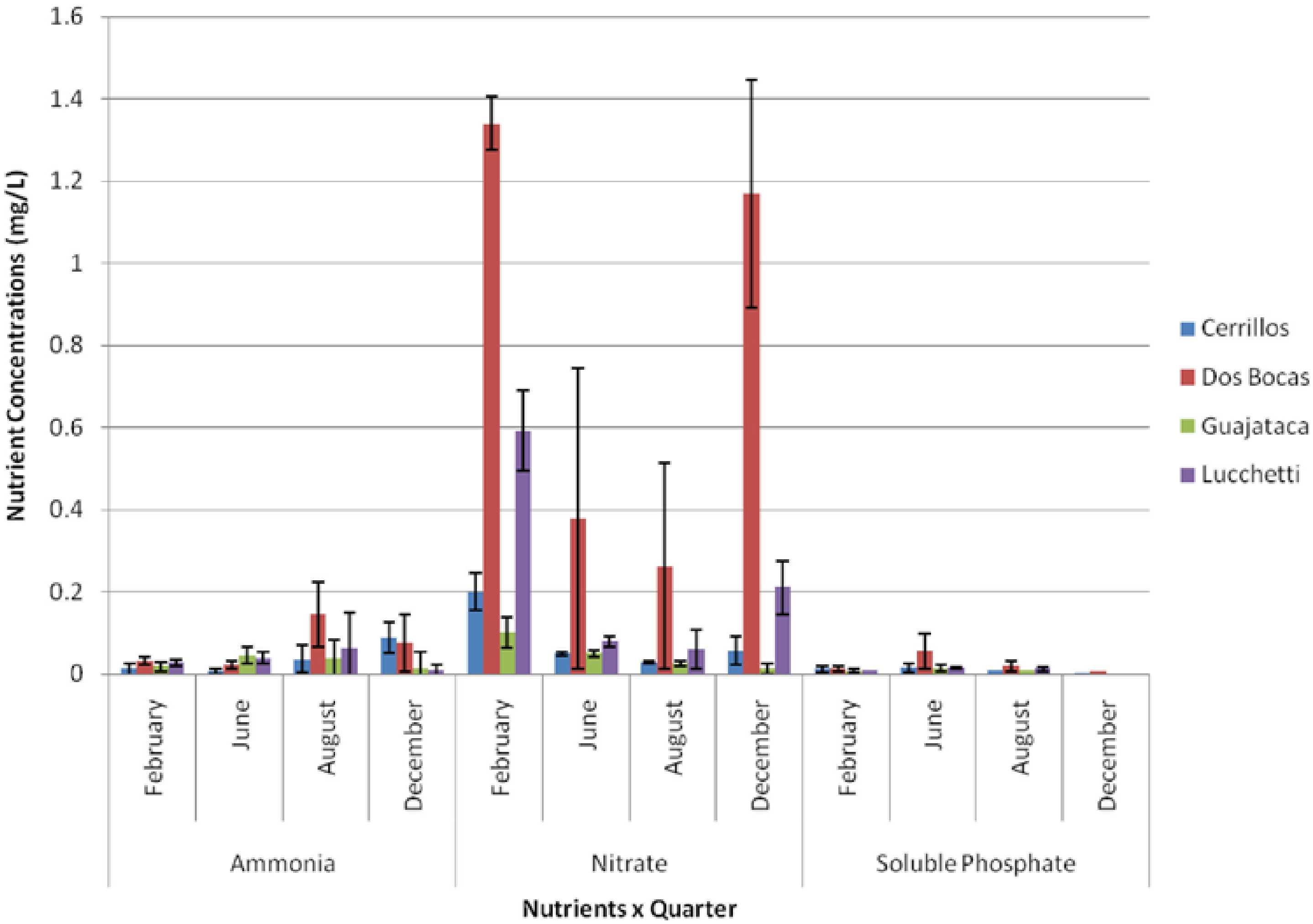

Figure 7. Mean surface nutrient concentrations for all four reservoirs (Dos Bocas, Cerrillos, Guajataca and Lucchetti) over the four quarterly sampling events in 2010.