Impact of net pen aquaculture on lake water quality

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Abstract A 3-year study was conducted by the U.S. Army Corps of Engineers assessing water quality related impacts of aquaculture of 250,000 channel catfish (*Ictalurus punctatus*) in floating net pens in the Rock Creek Arm of Lake Texoma, Oklahoma/Texas. Five large nylon nets suspended from a floating framework of galvanized metal anchored in open water 100 m offshore made up the net pens with fish stocking densities varying from 88 to 219 fish/m^3. Water quality sampling was conducted biweekly from April to September and monthly from October to March at three locations. On all sampling dates field measurements of water temperature, pH, dissolved oxygen, and conductivity were recorded at 1 m depth intervals and water samples were collected at a depth of 0.5 m and near the bottom of the water column at each site. Sample analyses included: total alkalinity, total hardness, turbidity, chloride, sulfate, orthophosphate, total phosphorus, nitrate-N, nitrite-N, total Kjeldahl nitrogen, total organic carbon, dissolved organic carbon, biochemical oxygen demand, and chlorophyll *a*. The results showed statistically significant decreases in water temperature and dissolved oxygen and significant increases in field conductivity in surface waters near the net pens relative to other sampling sites. The most dramatic water quality effect observed during the study was decrease in dissolved oxygen levels near the net pens following lake turnover in the second year.

Keywords Aquaculture; *Ictalurus punctatus*; lake water quality

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Introduction

Despite an increasing interest in aquaculture operations in the United States, few studies have adequately characterized the waste associated with these activities or assessed impacts of such operations on ambient water quality. A thorough understanding of these impacts is essential to protection and effective management of multi-use waters supporting aquaculture facilities. This paper presents results of a three-year study conducted by the Tulsa District, U.S. Army Corps of Engineers (COE) aimed at assessing water quality related impacts of aquaculture of channel catfish (*Ictalurus punctatus*) in floating net pens in Lake Texoma, Oklahoma/Texas.

The purpose of the project was to test the technical, operational, and economic feasibility of using Federal waters for commercial aquaculture. RedArk Development Authority (RedArk), a public trust and economic development organization serving a 21-county area of east-central and southeastern Oklahoma, was licensed to construct and operate a net pen facility in the Rock Creek Arm of Lake Texoma for annual production and commercial sale of approximately 250,000 channel catfish.

Description of study area

Lake Texoma is a 36,032 ha impoundment located at river kilometre 1,168.2 on the Red River that occupies portions of both south-central Oklahoma and north-central Texas (Figure 1). General water quality is characterized by moderate to high levels of mineralization with a predominance of sodium and calcium salts of sulfates and chlorides (Lelfeste *et al*., 1971).

Net pen facilities were located in the Rock Creek Arm of Lake Texoma adjacent to Platter Flats public use area (Figure 1). Rock Creek Arm covers a surface area of approximately 4 km^2, is 4.2 km in length, and has an average width of 0.8 km. Net pens were anchored in an open water location approximately 100 m offshore to allow maximum water exchange through the pens. At normal lake level, water depth beneath the pens was approximately 12 to 15 m.

Description of net pen facilities and operations

Culture facilities were patterned after net pens used for salmonid aquaculture in coastal regions throughout the world. Net pens consisted of five large nylon nets measuring 12.2 m by 6.1 m with a depth of approximately 6.1 m suspended from a floating framework of galvanized metal, wood decking, and styrofoam flotation. The entire structure was securely anchored offshore with cable length sufficient for changes in lake surface elevation. Fish stocking densities in each pen varied from 88 to 219 fish/m^3 over the 3-year study. Wide variations in lake surface elevation occurred at Lake Texoma over the study period.

Materials and methods

Water quality data were collected at three sampling sites within the Rock Creek Arm (Figure 1). Site 1 (Net Pen Site) was located immediately adjacent to the net pen facilities, Site 2 (Downstream Site) in the mouth of Rock Creek Arm, and Site 3 (Upstream Site) on the east side of Rock Creek Arm northeast of the pens. The Upstream Site was chosen as a "control" site due to its morphometric similarities to the net pen site and the anticipated movement of water toward the main body of the lake during hydropower generation and

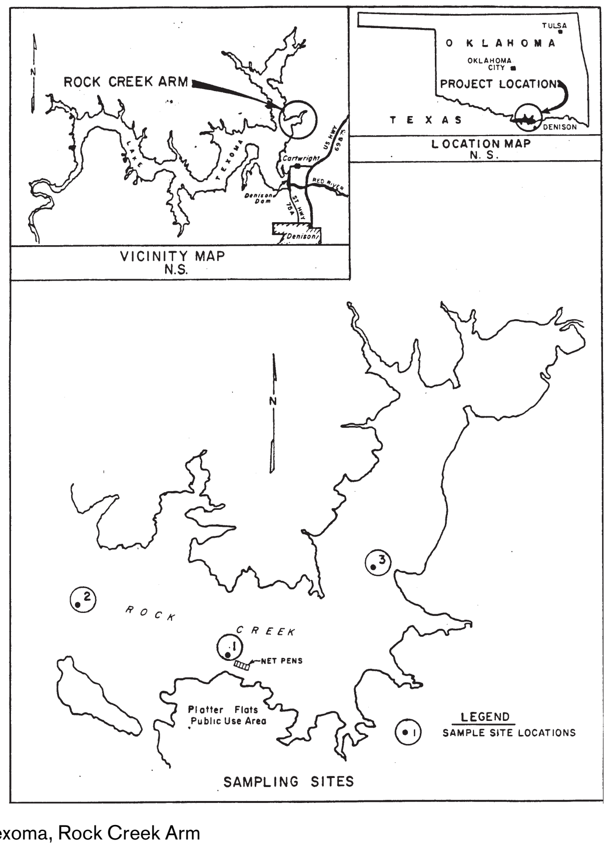

Figure 1 Lake Texoma, Rock Creek Arm

flood releases. Validity of this assumption was supported by initial flow measurements and results of solids traps experiments (Tulsa District USACE, 1989). Data collected at the Downstream Site were used in evaluating the possible movement of materials resulting from aquaculture activities from the pens toward the main body of the lake.

Sampling generally proceeded biweekly from April through September and monthly from October through March throughout the remainder of the study. In all, the study incorporated 38 sampling dates. Field measurements of water temperature, pH, DO, and conductivity were recorded at 1 m depth intervals and water samples were collected at a depth of 0.5 m and near the bottom of the water column (generally 10 to 12 m) at each site on all sampling dates. Secchi disc transparency was also measured at each site.

Water sample parameter analyses are listed in Table 1. Analyses were performed according to methods prescribed by the U.S. Environmental Protection Agency (EPA, 1983). Chlorophyll *a* concentrations (not corrected for phaeopigments) were determined fluorometrically (ASTM, 1979). Other sampling activities associated with the project included laboratory and *in-situ* measurements of sediment oxygen demand (SOD), sediment analyses, and solids traps experiments.

All data collected during the study (including winter data) were analyzed collectively. Despite this approach, growing season data were of increased importance in the analysis due to more frequent sampling during these months. Even though widely varying hydrologic conditions occurred during the study, analysis of data from the entire study was done for this evaluation.

Statistical analyses were conducted using Statistical Analysis Systems, Inc. (SAS) programs. Analysis of variance was performed using the General Linear Model (GLM) procedure and Duncan's multiple range tests used in means comparisons. A significance level of 0.05 was used throughout the study.

Study results

Field parameters

Water temperatures followed seasonal and spatial trends common to midwestern impoundments. Isothermal conditions were generally observed at all sites except the period from the early spring months until early or mid-September when thermal stratification occurred. Over the entire study, mean water temperature (including all depths) at the Net Pen Site was 0.6 to 0.8°C lower than means at the Downstream and Upstream sites. Tests for statistically significant differences in mean water temperature conducted on a depth-specific basis (1 m intervals) yielded unanticipated results. For all data, mean water temperatures among sites at the 0.5 and 1 m depths were not significantly different. However, mean water temperatures at all depths between 2 and 8 m at the Net Pen Site were significantly lower than those at the other two sites. At 9 and 10 m depths, mean temperatures were highest at the Upstream Site with those at the other two sites not significantly different. For each depth below 10 m, temperature means at all sites were significantly different.

Field pH readings over the entire study varied from 6.00 to 8.45 SU with the greatest range in values observed at the Net Pen Site. Individual readings on sampling dates were compared over the entire study. While differences among pH readings at sampling sites on each date were generally slight, differences that were observed were greatest in surface water strata. Field pH readings at 1 m were lowest at the Net Pen Site during 50% of the 38 sampling trips. Of these 19 trips, 16 occurred during the spring or summer seasons and 3 during the fall. Field pH readings at 1 m were highest at the Net Pen Site on only four of the 38 total sampling trips. Readings were lowest at the Upstream and Downstream sites five times each, over the entire study, with fairly even distribution of these dates among seasons.

Table 1 Mean and standard deviation (SD) for water quality parameters, Lake Texoma. Values include all sampling dates and water depths

Parameter	Net Pen, Site 1		Downstream, Site 2		Upstream, Site 3	
	Mean	SD	Mean	SD	Mean	SD
Water temperature (°C)	20.8	7.29	21.4	6.54	21.59	7.24
Dissolved oxygen (mg/L)	6.79	3.63	6.96	3.49	7.28	3.57
Conductivity (μS/cm)	1304	294	1310	279	1278	0.304
Total alkalinity (as $CaCO_3$)	127	13	128	13	127	12
Total hardness (as $CaCO_3$)	336	51	341	51	339	50
Turbidity (NTU)	6.9	3.6	7.9	24	7.1	3.9
Chloride (mg/L)	220	58	218	62	221	58
Sulfate (mg/L)	217	47.8	216.8	50.4	218	50.3
Orthophosphate (mg/L)	0.007	0.005	0.007	0.005	0.007	0.0004
Total phosphorus (as P) (mg/L)	0.036	0.014	0.032	0.021	0.034	0.012
Nitrate-N (mg/L)	0.138	0.199	0.156	0.229	0.153	0.226
Nitrite-N (mg/L)	0.014	0.018	0.011	0.008	0.01	0.006
Ammonia-N (mg/L)	0.061	0.051	0.059	0.053	0.053	0.041
Total Kjeldahl nitrogen (mg/L)	2.55	2.19	2.37	2.06	2.35	2.76
Total organic carbon (mg/L)	18	8	18	8	18	9
Dissolved organic carbon (mg/L)	17	8	16	8	17	8
Biochemical oxygen demand (5-day) (mg/L)	1.5	1	1.4	0.7	1.5	0.7
Secchi transparency (m)	1	0.3	1.2	0.3	1	0.2
Chlorophyll *a* (μg/L)	14.15	12.02	12.69	7.41	14.34	7.75

Conductivity readings were high, generally increasing with depth at all sampling sites. Mean conductivity readings (including all depths) were highest at Downstream Site (mean = 1,310 μS/cm) and lowest at Upstream Site (mean = 1,278 μS/cm).

Depth-specific tests (1 m intervals) for statistically significant differences in mean conductivity levels among sites were conducted using data from the entire study. While surface (0.5 and 1 m) means were not significantly different, means at all depths from 3 to 5 m at Net Pen Site were significantly higher than those at the other sites. At 6 m, means at all sites were significantly different. Means at the Net Pen and Downstream Sites at all depths from 9 to 12 m were not significantly different from each other but both significantly higher than those at Upstream Site.

Effects of net pen aquaculture activities on lake dissolved oxygen levels were important to this study. Therefore, DO data were subjected to a number of different analyses. Mean DO levels (average of readings from all depths) for the entire study period were lowest at Net Pen Site and highest at Upstream Site (means of 6.79 and 7.28 mg/L, respectively).

Clinograde oxygen profiles were recorded during summer stratification with drastic oxygen reductions occurring at approximately 8 to 10 m at all sites. In an attempt to define generalized aquaculture-related effects on DO levels in the water column as a whole and in epilimnetic and hypolimnetic layers, DO readings for each sampling date were segregated into surface (< 9 m) and bottom (> 9 m) compartments. Averages were then obtained over the entire water column and for surface and bottom layers (roughly corresponding to epilimnetic and hypolimnetic averages respectively for stratification periods) for all sampling dates (including nonstratification periods). Means of these values were then tested for significant differences among sites.

Using all data, the mean of entire water column averages at Net Pen Site (6.51 mg/L) was significantly lower than those for Upstream and Downstream Sites (6.97 and 7.23 mg/L respectively). Means of surface layer averages were significantly higher at Downstream Site than those at the other two sites (means = 7.33, 8.02, 7.59 mg/L for Net Pen, Downstream and Upstream Sites, respectively). Increased surface aeration due to the more open water location of Downstream Site relative to other sampling sites probably accounts for these differences. Means of bottom water layer averages were all significantly different using all data (means = 4.70, 5.09, 4.28 mg/L for Net Pen, Downstream and Upstream Sites, respectively).

As an alternative analysis method, tests for statistically significant differences in mean DO levels were conducted on a depth-specific (1 m intervals) basis (similar to analyses already presented for temperature and conductivity). Mean DO concentrations at all depths from 0.5 to 3 m at Downstream and Upstream Sites were not significantly different from one another but both significantly higher than those at Net Pen Site. At all depths from 5 to 9 m, mean values were significantly different at all sampling sites.

One anticipated effect of net pen aquaculture activities on lake water quality was a possible local reduction in DO near the net pens at lake turnover. While these conditions did not develop during Year 1, significant DO reductions were observed in the vicinity of the net pens following lake turnover near the end of August Year 2. While DO levels were depressed throughout the Rock Creek Arm at this time, DO concentrations at Net Pen Site were reduced to levels marginal for fish culture. On 7 September Year 2, surface DO concentrations were 7.64 and 6.29 mg/L at Downstream and Upstream Sites, respectively while a reading of 4.40 mg/L was recorded at the pens. During this time fish feeding activity was significantly reduced and an abundance of waste feed was observed floating in the pens. Relative contributions of overfeeding and lake turnover to oxygen depression near the pens were unknown. By 19 September Year 2, DO concentrations at the net pens were again similar to those measured at other sampling sites. Data collection ceased prior to lake turnover in Year 3.

Over the entire study, mean Secchi transparency was highest at Downstream Site (mean = 1.2 m) and identical at Net Pen and Upstream Sites (means = 1.0 m). Significant correlations were observed between Secchi transparency and Chlorophyll *a* at all sampling sites but were slightly closer at Downstream Site ($r = 0.68$, $p < 0.0001$, $n = 30$) than at Net Pen Site ($r = 0.53$), $p = 0.003$, $n = 29$) or Upstream Site ($r = 0.47$, $p = 0.009$, $n = 29$). Interestingly, significant correlations were observed between Secchi transparency and nephelometric turbidity at Net Pen Site ($r = 0.68$, $p < 0.0001$, $n = 33$) but correlations were not significant for these parameters at Downstream Site ($r = 0.24$, $p = 0.171$, $n = 33$) or Upstream Site ($r = 0.04$, $p = 0.848$, $n = 32$).

Laboratory analyses

Overall means and standard deviations for all water quality parameters at each sampling site are presented in Table 1. Little variation was observed among sites in total alkalinity, total hardness, chlorides or sulfates for any water depth or time period. Based on these analyses, waters in the vicinity of the Lake Texoma net pen site can be classified as very hard, highly mineralized, and well-buffered against drastic pH shifts.

Over the entire study, mean nephelometric turbidity was highest at Downstream Site (7.9 NTU) and lowest at Net Pen Site (6.9 NTU) (Table 1). Using all data, turbidity means in bottom water samples at Downstream Site were significantly lower than those at Net Pen and Upstream Sites. Significant differences were not identified in surface turbidity means over the entire study.

Due to the frequent role of phosphorus as the nutrient limiting growth of algal populations in lakes, effects of net pen aquaculture on phosphorus dynamics were of particular importance to this study. Orthophosphate concentrations were generally below analytical detection limits at all sites during spring and summer months and mean concentrations over the entire study varied little among sites (Table 1). Over the entire study, mean values from analysis of bottom water samples were slightly higher (by 0.001 to 0.003 mg/L) than those for surface samples. Using all data, means for orthophosphate concentrations in bottom samples at the Net Pen and Downstream Sites (mean = 0.009 mg/L at both sites) were significantly higher than the mean at Upstream Site (0.007 mg/L).

Total phosphorus concentrations ranged from 0.005 to 0.171 mg/L (as P) and averaged 0.034 mg/L over the entire study. Mean values for all samples (both depths) were highest at Net Pen Site (mean = 0.036 mg/L) and lowest at Downstream Site (mean = 0.032 mg/L) (Table 1). For surface samples only, total phosphorus means computed over the entire study were identical at Net Pen and Upstream Sites. In bottom water samples, Net Pen Site possessed the highest mean total phosphorus concentration for all data but significant differences among site means were identified.

Nitrogen parameters were of particular importance to this study due to the excretion of nitrogenous waste products by fish (Lagler *et al.*, 1962) and the ability of nitrogen to stimulate algal production in some aquatic systems (Wetzel, 1975). A nitrogen form of particular concern to aquaculturists is ammonia-N (NH_3-N). Ammonia concentrations for this study ranged from 0.008 to 0.320 mg/L with a grand mean of 0.058 mg/L. Site-specific overall means ranged from 0.053 mg/L at Upstream Site to 0.061 mg/L at Net Pen Site (Table 1). Over the entire study, mean ammonia concentration was highest in surface water samples at Downstream Site (0.065 mg/L) and highest in bottom samples at Net Pen Site (0.060 mg/L). Statistically significant differences in ammonia means did not exist among sites at any sampling depth.

Overall mean nitrite (NO_2-N) concentration was highest at Net Pen Site (0.014 mg/L) and lowest at Upstream Site (0.010 mg/L). Over the entire study, mean concentrations were considerably higher for bottom water samples than surface samples at Net Pen Site but similar at the two depths at Downstream and Upstream Sites. In surface samples, mean nitrite concentrations for all data were significantly different at Downstream and Upstream Sites but neither were significantly different from the surface mean at Net Pen Site. Over the same period, mean nitrite concentration in bottom water samples at Net Pen Site was significantly higher than those for Downstream and Upstream Sites.

Nitrate (NO_3-N) concentrations averaged 0.149 mg/L over all sites and sampling dates and ranged from <0.002 to 1.200 mg/L. The highest overall nitrate concentration existed at Downstream Site (0.156 mg/L) and the lowest at Net Pen Site (0.138 mg/L). Mean nitrate concentrations were generally slightly higher in surface samples than in samples collected near the bottom of the water column. Statistically significant differences in mean nitrate concentrations among sampling sites did not exist at any sampling depth.

Total Kjeldahl nitrogen (TKN) concentrations ranged from 0.10 mg/L at 10 m on 6 July Year 3 at Downstream Site to 20.25 mg/L at 0.5 m on 16 August Year 2 at Upstream Site. Overall mean TKN concentration over the entire study was highest at Net Pen Site (2.55 mg/L) and lowest at Upstream Site (2.35 mg/L). While statistically significant differences in mean TKN levels were not observed in surface or bottom samples, mean concentrations were highest at Net Pen Site in both surface and bottom samples.

Over the entire study period, very little variation was observed among sites or sampling depths in total organic carbon (TOC) or dissolved organic carbon (DOC) concentrations. For all data, overall means for TOC were identical (18 mg/L) at all three sampling sites. Biochemical oxygen demand (BOD) values varied from 0 to 5.6 mg/L over the entire study with a grand mean of 1.5 mg/L. Site-specific overall means were highest at Net Pen and Upstream Sites (means for both sites = 1.5 mg/L) and only slightly lower at Downstream Site (mean = 1.4 mg/L). Over the entire study, BOD values in surface samples were higher than those from bottom samples by an average of 0.7 mg/L. Statistically significant differences in BOD means were not observed between sampling sites in surface or bottom water samples.

An important objective of this study was to determine the effects of aquaculture activities on algal dynamics and overall productivity in the vicinity of the net pen facilities. While not a true measure of algal biomass, Chlorophyll *a* concentrations are frequently used as a relative measure of algal abundance. Over the entire study, Chlorophyll *a* values (0.5 m) ranged from 2.19 μg/L at Downstream Site on 2 May Year 3 to 69.85 μg/L on 15 June Year 1 at Net Pen Site. Overall site-specific means were 14.15, 12.69, and 14.34 μg/L at Net Pen, Downstream and Upstream Sites, respectively (Table 1). While net pen fouling by attached algae was a constant problem at the facility, floating algal mats or other evidence of nuisance algal "blooms" were never observed at any site.

Conclusions

In general, the most measurable effects of net pen aquaculture on lake water quality identified by this study were slight alterations in commonly measured limnological field parameters in surface waters near the aquaculture facilities. While statistically significant decreases in water temperature and dissolved oxygen and significant increases in field conductivity were observed in surface waters near the net pens relative to other sampling sites, the actual magnitude of these changes was slight and probable impacts on the biology and limnology of surrounding waters were negligible.

Probably the most dramatic water quality effect observed during the study was a decrease in dissolved oxygen levels near the pens following lake turnover in Year 2. These effects were not as pronounced during the high water year of Year 1. While localized, temporarily depressed DO levels are of major concern to fish culturists, these effects are less significant to overall lake biology due to the ability of native organisms to escape from and avoid stressful conditions. Nevertheless, these effects should be carefully considered and monitored in future net pen aquaculture activities.

Problems associated with nutrients and increased algal production resulting from net pen fish culture were not documented in this study. While aquaculture activities generate a considerable amount of nutrient wastes, water exchange through the net pens at the Lake Texoma site was apparently sufficient to reduce nutrient impacts through pollutant dispersion and natural assimilative processes.

Comparison of results of this study with other aquaculture-related water quality investigations illustrate the importance of sitting fish culture facilities in large, open waters with maximum water exchange and depth. Other investigators have reported numerous water quality effects from facilities located in small, shallow lakes or bays. Elay *et al.* (1972) reported significant increases in turbidity, alkalinity, total phosphorus, organic nitrogen, BOD and bacteria, and significant decreases in dissolved oxygen associated with cage catfish culture in White Oak Lake, Arkansas. Mean and maximum depths of this small lake were 2.4 m and 5.5 m, respectively. Trojanowski *et al.* (1987) documented significant increases in chlorophyll *a* near trout cages in two small, shallow (mean depths of 3.6 and 8.2 m) Polish lakes.

Results of this study were similar to those obtained at Bull Shoals Lake in north-central Arkansas (Hays, 1980). Net pen facilities similar to those used at Lake Texoma are located in a large, 81 surface ha cove in Bull Shoals Lake where water depths average 20 m. Approximately 200,000 rainbow trout and 250,000 channel catfish are grown to a catchable size each year in these net pens. Results of water quality sampling conducted monthly from 1 October 1978 to 31 January 1980 near the Bull Shoals facility indicated increased levels of ammonia, total phosphate and plankton abundance associated with fish culture activities. Significant changes in a number of other water quality parameters were not observed.

Considerable caution and common sense should be exercised in using results of this study to predict effects of net pen aquaculture on water quality in lakes possessing physical, chemical and hydrologic characteristics vastly different from those at Lake Texoma. High levels of mineralization, moderate productivity levels, and a high pH buffering capacity characterize Lake Texoma water quality. Effects of net pen aquaculture on water quality in poorly buffered, soft water lakes of varying trophic states might be more pronounced and considerably different than those measured by this study. Predictions of effects of aquaculture activities on lake water quality should therefore be conducted on a site-specific basis.

References

American Society for Testing and Materials (1979). *Annual book of ASTM Standards, Part 31 – Water*. ASTM, Philadelphia, Pa. pp. 1079–1083.

Eley, R.L., Carroll, J.H. and DeWoody, D. (1972). Effects of caged catfish culture on water quality and community metabolism of a lake. *Proc. Okla. Acad. Sci.*, **52**,10–15.

Environmental Protection Agency (1983). *Methods for Chemical Analysis of Water and Wastes*. Analytical Quality Control Laboratory, Cincinnati, Ohio.

Hays, T. (1980). Impact of net pen culture on water quality and fish populations on Bull Shoals Reservoir. National Marine Fisheries Service Project 2-338-R-1.

Lagler, K.F., Bardach, J.E. and Miller, R.R. (1962). *Ichthyology*. University of Michigan, Ann Arbor, Michigan.

Lelfeste, D.K., Blakey, J.F. and Hughes, L.S. (1971). *Reconnaissance of the chemical quality of surface waters of the Red River Basin, Texas*. Report No. 126, Texas Water Development Board. Austin, TX.

Trojanowski, J., Ratajczyk, H., Trojanowska, C. and Korzeniewski, K. (1987). Chlorophyll relationships in Letowo and Szczytno Male lakes with trout cage culture. *Pol. Arch. Hydrobiol.*, **34**(3), 279–308.

Tulsa District USACE (1989). *Water Quality Report: Effects of Net Pen Aquaculture on Lake Water Quality, Lake Texoma, Oklahoma & Texas, 1987–1989*. Tulsa Oklahoma.

Wetzel, R.G. (1975). *Limnology*. W.B. Saunders, Philadelphia, PA.