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# Watershed Development and Eutrophying Potable Source-Water Reservoirs in a Warming Temperate/Subtropical Region

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**Abstract:** Reservoirs are increasingly valuable worldwide as potable source waters, yet in many geographic regions, their limnology and trophic status are poorly known. We characterized 14 drinking water reservoirs and their watersheds across the warming temperate/subtropical southeastern USA. Selected reservoirs had at least three years of accessible summer water quality data during 2010–2020, including Secchi depth, nutrients, and algal biomass as chlorophyll *a*, and depth profiles for temperature and dissolved oxygen. Most watersheds, including lands within a 10-km radius of the reservoirs, had sustained substantial urbanization and/or intensive industrialized animal production, in some cases including the discharge of partially treated human sewage or livestock slaughterhouse wastes near or into the reservoirs. Five reservoirs were assessed as mesotrophic; the others were eutrophic. Most were stratified, but ephemeral near-surface thermoclines were common, and many were too shallow (median depth 5.0 m) to maintain uniform temperatures in the relatively warm hypolimnia. Bottom-water hypoxia/anoxia occurred throughout the summers but, surprisingly, in 8 of 14 reservoirs hypoxia commonly extended to surface waters. In the Southeast as in many regions, drinking water reservoirs are poorly protected and degrading as livestock production and/or urban development increasingly characterize their watersheds. The eutrophication trajectory of these valuable resources should be used as an indicator of ecosystem health and water quality in developing more protective management and policy actions.

**Keywords:** chlorophyll; climate warming; cultural eutrophication; hypoxia; livestock; production; nutrients; drinking water; reservoirs; urbanization; watershed



**Citation:** Burkholder, J.M.; Kinder, C.A.; Allen, E.H. Watershed Development and Eutrophying Potable Source-Water Reservoirs in a Warming Temperate/Subtropical Region. *Water* **2023**, *15*, 4007. https://doi.org/10.3390/w15224007

Academic Editor: Marina Marcella Manca

Received: 7 October 2023
Revised: 8 November 2023
Accepted: 8 November 2023
Published: 17 November 2023



## 1. Introduction

Many reservoirs (artificial lakes or impoundments) worldwide are under escalating demands as water supplies, yet their basic limnology and trophic status are poorly known in comparison to natural lakes [1–3]. As in many regions, reliance on reservoirs to meet water demands in the southeastern USA is increasing [4]. Human population growth has made water availability an increasing concern, especially during more frequent droughts; such conditions also increase stress on aquatic organisms from higher temperatures and depressed oxygen availability [4].

Topographic variation in the landscape dictates reservoir morphometry; in particular, mountainous areas in the Southeast give way to rolling hills in the Piedmont, then to flatlands in the Coastal Plain. The impoundments reflect these changes, ranging from flooded gorges to turbid systems with relatively shallow basins that enhance vulnerability to extremes in annual runoff [4]. Their higher watershed area-to-water surface area ratios and higher shoreline development indices, relative to many natural lakes, also render them more susceptible to changes in land use practices, water withdrawals, and hydrologic cycles [5]. Impacts related to high nutrient loads would be mitigated by a short water residence time (days to months) in comparison with natural lakes (years) [5]. Nevertheless, reservoirs in this region are sustaining nutrient-related degradation such as excessive phytoplankton biomass and bottom-water oxygen deficits [6–8].

Despite their high abundance [9–11], surprisingly little information is available in peer-reviewed science about reservoirs in the Southeast, in part due to agency funding limitations and state policy decisions [12,13]. Inventory of watershed, morphometric, and water quality features—the latter including dissolved oxygen, nutrients, chlorophyll *a* concentrations, and trophic status—is lacking for these increasingly valuable resources. A previous compilation [9] included reservoirs from a broader region that were mostly used for flood control, from the perspective of background environmental conditions for aquatic biota.

The goal of this research was to provide a synthesis of the watershed characteristics, basic limnology, trophic status, and eutrophication trajectory (inferred from statistical trend analysis of suspended algal biomass as chlorophyll *a*, considered a first response variable to nutrient enrichment [5]) of drinking source-water reservoirs across the southeastern USA region. Emphasized watershed features included land use/land cover, major point sources, potable source-water use, and human and livestock populations as well as their estimated nutrient (nitrogen, N and phosphorus, P) inputs. The central hypothesis was that sub-watersheds drained by these valuable water resources—at a minimum, the lands adjacent to them—are maintained so as to protect them from major livestock production and urban development, thereby minimizing water quality degradation to help safeguard public health. If so, we expected that the reservoir ecosystems would be moderately productive rather than eutrophic, absent increasing algal biomass or other signs of deterioration, and that dissolved oxygen would be plentiful for beneficial aquatic life. None of these expectations were realized.

This work synthesizes the present status of potable source-water reservoirs in a representative warm temperate/subtropical region, the southeastern USA, from a eutrophication perspective. It contributes a novel inventory of estimated N and P contributions from human versus livestock wastes in watersheds drained by potable source-water reservoirs in the southeastern USA. It additionally adds key findings about drinking-water reservoirs in warm temperate/subtropical climates, such as hypoxia affecting from half to all of the water column as a common summer condition and, where sufficient data were available, statistically significant positive trends in near-surface chlorophyll indicating increased algal production over the past decade. This study shows that, as in many geographic regions, the water quality of drinking water reservoirs in the southeastern USA is poorly protected and degrading as watershed development and both human and livestock populations continue to increase. We suggest several actions to improve protection of these valuable resources, and we additionally consider the value of the eutrophication trajectory in guiding management and policy actions toward that goal.

## 2. Materials and Methods

The Materials and Methods are organized as follows. In preface to major topics by section, we explain the study duration/season of focus and the general requirements for reservoir inclusion in the analysis. Section 2.1 then presents the study area and list of the reservoirs assessed, followed by a description in Section 2.2 of the reservoir water quality data foundation. Section 2.3 explains the approaches we used to define and characterize the reservoir sub-watersheds, including the assessment of livestock and human waste N and P contributions as well as an inventory of major point sources. Section 2.4 describes our attempts to estimate reservoir use for drinking water supplies. Section 2.5 then details our methods for characterizing pertinent physical/chemical features of the reservoir and the assessment of water quality conditions using classical eutrophication parameters. Finally, Section 2.6 describes the basic statistics and an advanced statistical trend analysis model used to assess water quality conditions in the reservoirs.

This analysis focused on summer conditions (here, June through September) and extended from 2010 through 2020. Reservoirs without artificial aeration and 10 yr post-fill or older as of 2010 (to avoid elevated nutrients and other aberrant conditions from decomposition of the drowned landscape [14]) were selected for study if data were available for at least three summers during 2010–2020. Required data included depth profiles for temperature and dissolved oxygen (DO) and data ($n \geq 70$ for key parameters chlorophyll, TP, and N species) from surface waters or the photic zone (PZ; depth generally 0.5 to $\leq$3 m but PZ sometimes deeper) for Secchi depth, total suspended solids (TSS), pH, nutrients (total phosphorus, TP; nitrate+ nitrite N, $NO_x$; total ammonia, $tNH_3$; total Kjeldahl nitrogen, TKN), algal biomass indicated by chlorophyll *a* (chl*a*), and total suspended solids (TSS). Total nitrogen (TN) was calculated from TKN + $NO_x$. For statistical trend analysis (below), consistency of sampling (e.g., no skipped years) was important as well. We also assessed the available information about phytoplankton assemblages and harmful algal blooms. Fecal bacterial data were insufficient for inclusion in the analysis. Some reservoirs had data for *Escherichia coli* and/or enterococci, but sampling frequencies were too low to enable the calculation of geometric means or statistical threshold values.

### *2.1. Study Area and Reservoirs*

The southeastern USA was considered here as extending from northeastern Texas to the Atlantic Coast, including part or all of the states of Mississippi (MS), Tennessee (TN), Alabama (AL), Georgia (GA), and North Carolina (NC) (Figure 1). Drinking-water reservoirs with sufficient accessible data for analysis (see below) were not found in Louisiana, South Carolina, or Florida (Table S1). It should be noted that Toledo Bend Reservoir, along the Sabine River on the southeastern Texas/southwestern Louisiana border, is partly within Louisiana. It was omitted as an outlier among southeastern reservoirs due to its extreme size (73,491 ha, the largest reservoir in the USA South and the fifth largest in the USA by surface area). It is also minimally used as a potable source water by both states (Table S1). For balance, our approach was to include reservoirs across the region, emphasizing the central area insofar as possible (i.e., depending on accessible data) but also representing the farthest west and farthest east areas. Texas is often considered within the south-central USA rather than partly in the Southeast. Some reservoirs in eastern Texas that met data requirements were excluded to avoid over-emphasizing that area. Also, if several reservoirs along the same river met data requirements, two were haphazardly selected for inclusion in the analysis to avoid placing emphasis on one river over others. Thus, Joe Pool, Cedar Creek Reservoir, and Lake Lavon Lake on the Trinity River in Texas met data requirements, and the first two of these were included. Along the Coosa River system, Carters Lake in Georgia and Neely Henry Reservoir and Lay Lake in Alabama met data requirements, and the latter two were included.

A total of 14 reservoirs within nine river systems were included in the analysis (Figure 1), among the 41 initially assessed (below). The United States Geological Survey (USGS) hydrologic unit codes (HUCs) of the assessed reservoirs are as follows: Eagle Mountain 12030101, Cedar Creek 12030107, Ross Barnett 03180002, Guntersville 06030001, Neely Henry 03150106, Lay 03150107, R.L. Harris and Martin 03150109, W.F. George 03130003, Allatoona 03150104, Lanier 03130001, Norman 03050101, Jordan 03030002, and Falls 03020101.

### *2.2. Water Quality and Climate Data*

Major publicly accessible data sources used in this study included the Water Quality Portal (sponsored by the US EPA, the USGS, and the National Water Quality Monitoring Council [NWQMC]), the GA Environmental Quality Monitoring and Assessment Program (GOMAS) of the Georgia Department of Natural Resources (GA DNR), the Surface Water Quality Monitoring Program (SWQMP) of the Texas Commission on Environmental Quality [15], and for Lake Norman, Duke Energy Environmental Center, Huntersville, NC. In addition, we supplied the data used for Falls Lake.

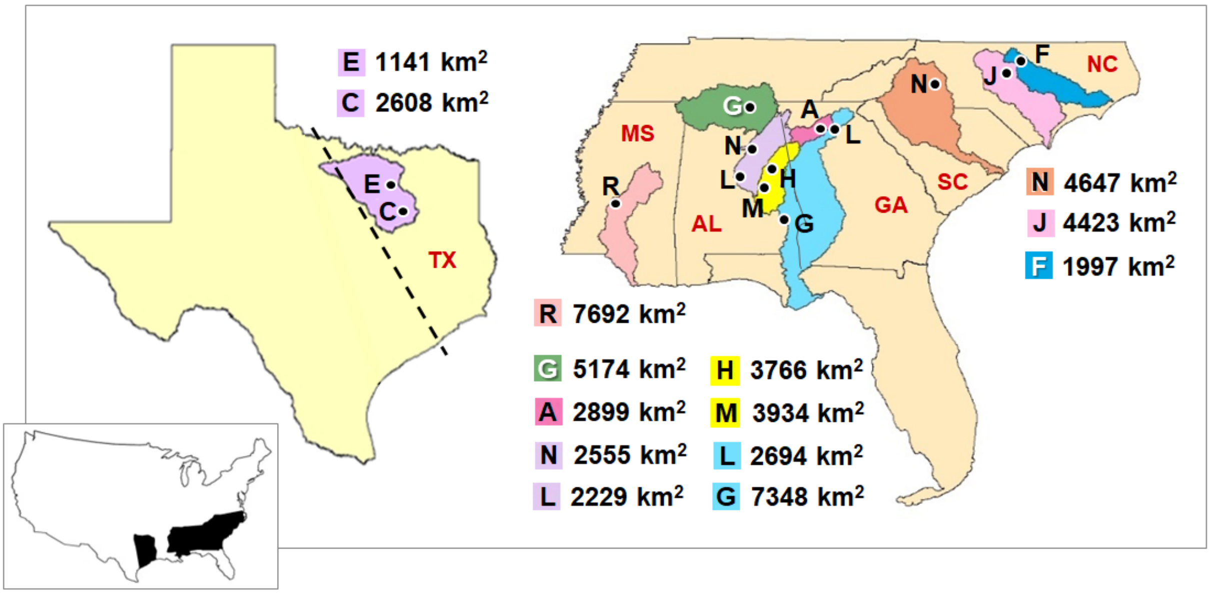


**Figure 1.** Insert map of the study area (black) and watersheds of river systems included in this study, from west to east in the southeastern USA: Upper Trinity River, eastern TX (Eagle Mountain and Cedar Creek reservoirs); Pearl River, MS (Ross Barnett Reservoir); Middle Tennessee-Elk River, AL-TN (Guntersville Reservoir); Etowah River, AL-GA (Allatoona Reservoir, GA); Coosa River, AL (Neely Henry and Lay reservoirs); Tallapoosa River, AL (Harris and Lake Martin reservoirs); Chattahoochee River, GA-AL (Lake Lanier, GA and W.F. George Reservoir, GA-AL); Santee River, NC-SC (Lake Norman, NC); Cape Fear River, NC (Jordan Lake); and Neuse River, NC (Falls Lake). Black dots indicate the locations of the potable source-water reservoirs. The sub-watershed (WS) area more specifically drained by each reservoir is also listed.

In most states (exception, east TX, above), there was a fundamental lack of basic limnological data in publicly accessible repositories (below), as indicated for 21 of the 41 reservoirs that were screened; 2 others with substantial data were artificially aerated; and 4 others were too young in age (i.e., filled < 10 yr prior to the beginning of the study period) (Table S1). For data on some reservoirs, state environmental agencies directed us to their interactive maps of active monitoring stations that, upon advanced search, proved to be obsolete, repeatedly inaccurate, or "dead ends" without data for the period of interest. Contacting the appropriate state agency personnel repeatedly was successful in some cases but not others. For example, we could not determine whether various SC reservoirs were data-rich. SCDHEC does not add data to the state's water quality data repository from private entities that had been bestowed ownership by the state of these valuable (normally considered public trust) USA surface waters because the data were not analyzed in a SC-certified laboratory. Seeking data from privately "owned" reservoirs was mostly unsuccessful, as there is no requirement for private entities to provide data upon request. Duke Energy responded regarding Lake Norman, NC, but other private entities did not. Similar policies impeded or barred data accessibility in the other states of this region (e.g., [16]).

Sampling varied across the region as follows: Two reservoirs (Jordan and Falls) were sampled biweekly to monthly and had the most robust nutrient datasets, whereas Norman and Falls had the most robust hydrologic datasets (Table S2). Five reservoirs (W.F. George, Allatoona, Lanier, Norman, and Falls) were sampled in all 11 yr. Jordan was sampled in 10 yr (excluding 2020) and was sampled only twice in summer 2018. Eagle Mountain, Cedar Creek, and Ross Barnett were sampled for 9 yr; Martin and R.L. Harris, sampled every 2–3 yr, had 5 yr of data; 4 yr of data were available for Lay and Neely Henry; and Guntersville had only 3 yr of data. Summer sampling frequency was generally monthly for 9 reservoirs, but only once per summer for Norman and twice per summer for Eagle Mountain and Cedar Creek.

Summer conditions in the region over the past ~two decades (2000–2020) were assessed as in [17], using air temperature and precipitation data from the National Centers for Environmental Information [18,19]. These data were obtained, where possible, from the county containing most of each reservoir or, alternatively, from the county closest to/drained by the lower reservoir.

### *2.3. Sub-Watersheds and Major Nutrient Sources*

Within the major river watersheds shown in Figure 1, the sub-watershed directly draining into each reservoir was characterized. The 14 sub-watershed areas were determined from Geographic Information Systems (GIS) analysis (Figure 2), using established drainage areas from the USGS National Hydrography Dataset [20]. The datasets for each main watershed (eight-digit hydrologic unit) were downloaded. Within each, the ten-digit sub-watersheds for each tributary of the reservoir of interest were selected and combined into a shapefile as the total sub-watershed area. For reservoirs in series along a river, the sub-watershed of the reservoir of interest included the area between the upper and lower dams. For a reservoir at the confluence of more than one river system, the sub-watershed included the area drained by both rivers above the reservoir dam. As examples, the sub-watershed for Jordan included the watersheds of the Haw River and New Hope Creek sidearms. The upper reaches of Norman included the Catawba River and several other tributaries, and the lands they drained were included in the Norman sub-watershed. Human population data for the sub-watersheds were obtained using GIS, estimated from 2020 US Census Bureau county data for percent change in population (2010–2020) [21], rounded to the nearest 100. Land cover data and impervious surface data were obtained from the most recent available National Land Cover Database [22].

Agricultural contributions to nutrient supplies in sub-watersheds were represented conservatively by livestock populations, omitting consideration of croplands. Although croplands historically have been important in the southeastern USA, they have increasingly been replaced by industrialized animal production, urbanization, and other land uses [23,24]. In these 14 sub-watersheds as of 2019, cultivated croplands comprised a median of only 1.9% of the total land cover (National Land Cover Dataset; mean, 2.0 $\pm$ 0.4%, maximum, 4.81% in the Guntersville sub-watershed). Populations of livestock in each sub-watershed were estimated from the most recently available (2017) total annual numbers per county using data provided by the US Department of Agriculture [25], for comparison with 2012 data [26] to assess change over the previous 5 yr. For each reservoir, GIS was used to determine the proportion of the sub-watershed that lay within each county. The total number of cattle, swine, poultry, and horses in the county was adjusted by the percentage of the county containing the sub-watershed, given the underlying assumption of homogeneity in livestock distribution across the county area. This necessary but flawed assumption likely resulted in conservative estimates of livestock populations in the sub-watersheds, since land cover maps (Figure 2) and other information (e.g., [27]) indicate that livestock are generally concentrated near surface waters.

Contributions to N and P in wastes from humans and animal groups in sub-watersheds were estimated as follows:

- Humans (1 average-sized)—5.7 kg N yr$^{-1}$ [28], 0.6 kg P yr$^{-1}$ [29];
- Cattle (1 average mature cow)—151.5 kg N yr$^{-1}$, 20.8 kg P yr$^{-1}$ [30];
- Swine (1 average-sized)—9.525 kg N yr$^{-1}$, 6.800 kg P yr$^{-1}$ [31];
- Poultry (1 average-sized bird produced)—broilers, 0.017 kg N and 0.0053 kg P excreted yr$^{-1}$ [32], likely conservative since broilers have increased in size (note that turkey production was minor (15 to 720 birds yr$^{-1}$ in the sub-watersheds), 10- to 10$^6$-fold lower than the abundance of chicken broilers);
- Horses (1 adult)—39.4 kg N yr$^{-1}$, 7.67 kg P yr$^{-1}$ [33].

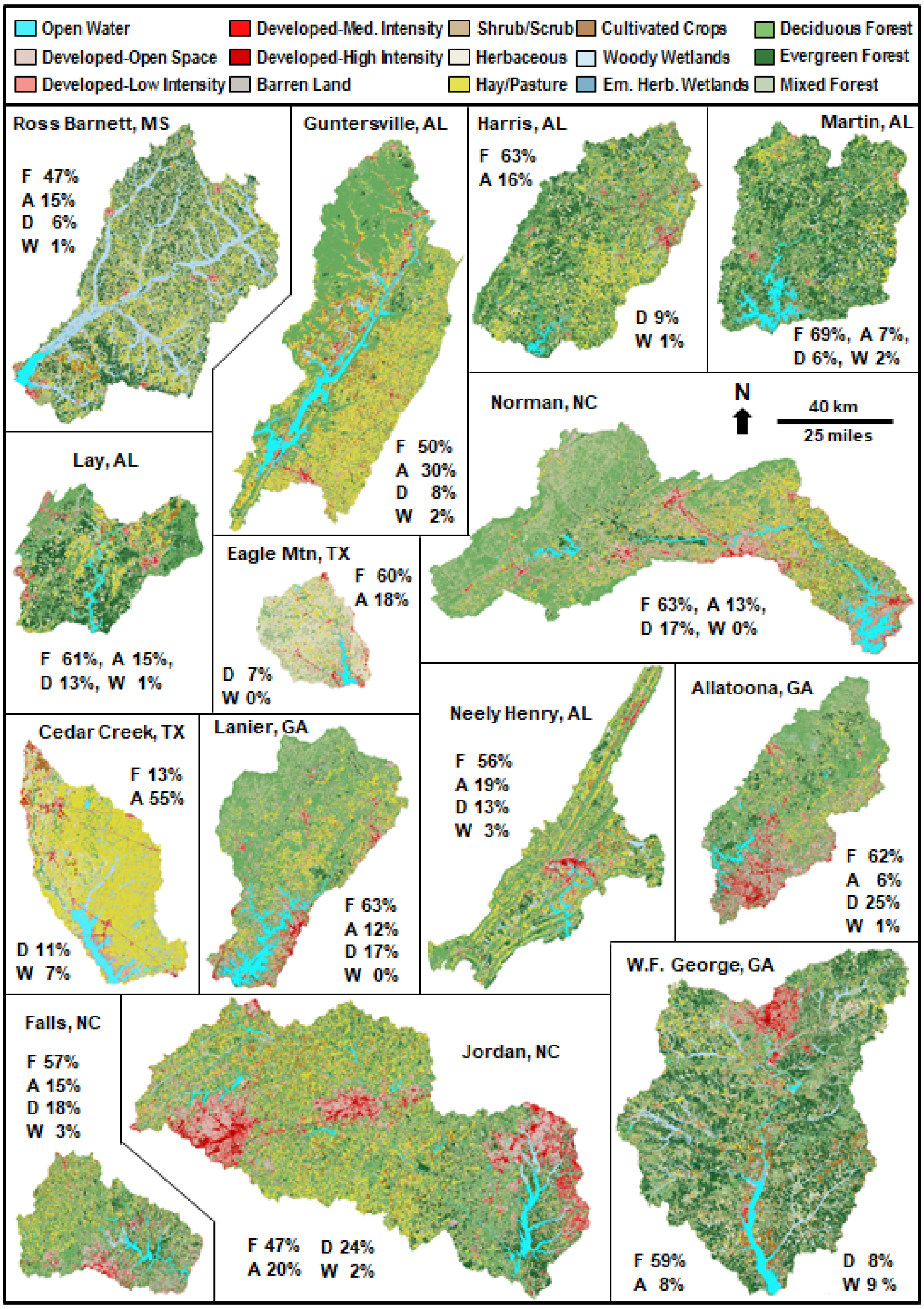


**Figure 2.** Watershed land cover (2019 National Land Cover Dataset), all to the scale indicated. Land cover abbreviations: F, Forest; A, Agriculture; D, Developed; W, Wetland; percentages rounded to the nearest integer. GIS maps of sub-watersheds—E. Allen.

Point source information for each sub-watershed emphasized major municipal wastewater treatment plants (WWTPs), mostly with secondary treatment as described by the US Environmental Protection Agency (EPA) [34], that discharge $\geq 3.79 \times 10^6$ L day$^{-1}$ ($\geq$ 1 million gallons per day, mgd), as well as livestock slaughterhouses and processing plants. This information was available in state environmental agency permitting records or on local governments' websites. Discharges from these sources include excessive concentrations of highly bioavailable N and P (e.g., [35,36]). Waste contributions from humans and livestock were assessed as major N and P sources potentially affecting the reservoirs.

The analysis of nutrient sources potentially affecting the reservoirs is conservative, as we did not attempt to estimate N and P contributions from cropland, as mentioned, septic effluent leachate, minor WWTPs ("package plants", known to be numerous in some sub-watersheds), or atmospheric inputs. Nutrients from urban stormwater sources were also not estimated, although land use categories were tracked to provide an indication of stormwater influences.

### *2.4. Water Supply Use*

Repeated searches did not identify a central database(s) at federal, state, or local levels for potable and other water withdrawals by source water during the study period. We attempted to emphasize potable water use that was estimated from piecemeal, sometimes-dated information identified from water treatment plants, the US EPA Safe Drinking Water Information System [37], various regional water districts and water supply plans, municipality and county websites, municipality annual drinking water quality reports, the US Army Corps of Engineers (USACE), and various consultants' reports.

### *2.5. Reservoir Physical Features*

#### 2.5.1. Morphometry and Stratification

The characteristics of the 14 reservoirs at the conservation pool were assessed using USACE data and numerous other identified sources as needed. Metrics included dam height; maximum length; mean and maximum depths; shoreline length, surface area, volume, and the ratio of watershed area-to-reservoir surface area at the conservation pool; and flushing rate $yr^{-1}$. Water withdrawal volumes per year, mainly for potable use, and the size of the population served were also assessed. Reported values for some fundamental characteristics were highly variable, exacerbated for maximum depth because high rates of sediment accrual (filling in) are common in reservoirs, including many in the Southeast region [38–40]. Maximum depths were determined using bathymetry maps and other identified sources; for some reservoirs, there was considerable variation in reports.

The shoreline development index ($D_L$) was estimated for each reservoir following the bias-corrected equation of Seekell et al. [41] to improve comparison among reservoirs with different surface areas at the conservation pool, using an average shoreline fractal dimension value of 1.43 estimated from the regression of the logarithm of shore length by the logarithm of area (14 reservoirs, d = slope $\times$ 2). This average d value was similar to the average d value for reservoirs elsewhere (e.g., 1.4) [42]. This $D_L$ index, basically the ratio of the shoreline length to the length of the circumference of a circle equal in area to that of the reservoir, was developed to indicate the potential for development of rooted macrophytes in the littoral zone and also more generally to indicate biological productivity [43]. The $D_L$ would be 1 for a perfectly circular waterbody; a large ratio >> 1, typical of run-of-river impoundments, indicates a more crenulated shoreline.

Stratification was inferred from temperature depth profiles taken in July during 2010–2020 as indicative of mid-summer conditions. The thermocline depth was considered here as the depth below which the greatest temperature gradient occurred, excluding the upper 1 m, and with at least a 1 °C change $m^{-1}$ [5,44].

#### 2.5.2. Environmental Data

With the exception of Falls Lake, which was sampled by the authors [8], available data were obtained from various identified sources as described. The data for all reservoirs were checked for spurious entries such as obvious outliers (e.g., an entry for Martin, 81 mg $NO_x$ $L^{-1}$; an entry for W.F. George, 53 mg TOC $L^{-1}$). Such information was omitted from the analysis, as well as other erroneous data (examples: temperature given in Fahrenheit units, DO concentration and percent saturation data switched, or repeated identical entries).

The dataset for background conditions and water quality of each reservoir is described in detail in Table S2 (specific years sampled, duration, stations, and *n* values). The number of summers sampled ranged from 3 (Guntersville) to 11 (Allatoona, W.F. George, Lanier, Norman, Falls); thus, *n* values for a given parameter sometimes varied by as much as tenfold). Furthermore, most sampling was conducted monthly, but frequency ranged from weekly to bimonthly (twice per summer, with an occasional skipped month) depending on the reservoir and year. Data for some parameters were not available for all 14 reservoirs: There were no Secchi depth data for Jordan Lake and only sidearm (rather than mainstem) data for Guntersville Lake. Six reservoirs (Guntersville, R.L. Harris, Lay, Neely Henry, Norman, and Martin) lacked data for TOC. Percent oxygen saturation data were not available for three reservoirs (Eagle Mountain, Cedar Creek, and Jordan). Turbidity data were not available for three of four highly turbid reservoirs (based on TSS and Secchi depth data), which would have skewed interpretations toward artificially higher water-column clarity, so turbidity was omitted from the analysis.

Water quality data in 11 of 14 reservoirs were analyzed from upper, middle, and lower reservoir areas (regions). Data for the others (Guntersville, W.F. George, and Martin) were available only from upper and lower region sites. Mainstem (channel) and side-channel data were combined for the overall characterization of water quality. Only side-channel stations were available for Guntersville, however, and only mainstem stations were available for Eagle Mountain and W.F. George. Where sufficient data for TN, TP, TSS, and chl*a* were available, additional separate analyses included a selected sidearm from Allatoona (Little River, site 4553, $n = 49$), Lanier (Flat Creek Cove, sites 4005 and 4007, $n = 69$–72), Jordan (Haw River, sites 55 C and 55 D, $n = 130$), and Falls (Lick Creek, site LC1, $n = 91$–92) to exemplify certain water quality conditions.

Sampling for water-column depth profiles of temperature and DO was conducted with hydrocasts. Measurements were mostly taken at 1-m intervals from the surface to ~0.5–1 m above the sediment. The deepest waters were not assessed in some reservoirs, however, so those depths were underrepresented, making the analysis of hypoxia conservative since bottom waters typically are most hypoxic [5]. The minimal depth affected by hypoxia in upper (headwater), middle, and lower (near dam) reservoir regions, and the percentage of the total water column affected, were also tracked. Continuous temperature/DO data were available in some or all years for two reservoirs (Norman and Falls, respectively). The high-frequency datasets enabled the construction of three-dimensional isopleth graphs for temperature and DO in Norman as a relatively deep system (mean depth 10.2 m, maximum depth 34.1 m) and relatively shallow falls (mean depth 5.0 m, maximum depth 11.9 m). Representative years were included to provide more detail about within-reservoir conditions. Hypoxia was defined here as <4 mg $L^{-1}$ following NC DEQ [45].

Protective numeric criteria for causative variables TN and TP are not available for most of the reservoirs [46], but water quality criteria for the response variable chl*a* were available from all states except MS (Ross Barnett Reservoir) and ranged from >5 µg $L^{-1}$ (some GA waters [47]) to >40 µg $L^{-1}$ (NC waters [45]) depending on the reservoir/within-reservoir location (Table S1). We assessed the data for violations of state chl*a* water quality standards. In addition, to gain insights about changes in TN, TP, the molar TN:TP ratio, and chl*a* over time, 2010–2020 data (throughout each year) were compared to the US EPA's [48–50] 25th percentile of all data for lakes and reservoirs in the three germane Level-III nutrient ecoregions (sub-ecoregions of V—South Central Cultivated Great Plains, IX—Southeastern Temperate Forested Plains and Hills, and XI—Central and Eastern Forested Uplands) that contain the 14 reservoirs. Reported 1990s chl*a* maxima from those documents were additionally compared to the 2010–2020 chl*a* maxima for the 14 reservoirs. The TP data (Allatoona, Lanier, and Norman), the $tNH_3$ data in general for reservoirs in AL and GA, and the $NO_x$ data for some reservoirs were especially problematic due to insufficient sensitivity in the analytic procedures used, which resulted in many data entries below detection.

Trophic state indices (TSIs) were calculated for June through August following [51], based on parameters TP and chl*a*. Secchi depth data were omitted from consideration as per [52] since these reservoirs commonly contained high abiotic turbidity. TSIs were interpreted as follows: Oligotrophic < 40, Mesotrophic 40–50, Eutrophic > 50 to <70, and Hypereutrophic $\geq$ 70. It should be noted that the substantial TP data for Allatoona, Lanier, and Norman that were listed as below detection (explained above) made this analysis more questionable for those reservoirs.

### 2.6. Statistics

Statistical analyses were conducted with log-transformed data using SAS version 9.4 software [53]. Analyses were performed at significance level $\alpha = 0.05$, and significance at $\alpha \leq 0.10$ was also reported. Regression models were developed using data means. Linear regression on climate summer air temperature and precipitation data from the National Centers for Environmental Information and the National Oceanic & Atmospheric Administration [18,19] were tested for significant change using the 21 summer values (averaged over 4 months) from 2000 through 2020.

Pearson correlation and regression analyses were performed on log-transformed data to assess potential relationships between chl*a* and TN, TP, the molar TN:TP ratio, and TSS. Correlation coefficients (r) and $p$ values were included to indicate goodness of fit. Correlations were evaluated as weak ($r \leq 0.20$ to 0.39), moderate (r = 0.40 to 0.59), strong (r = 0.60 to 0.79), or very strong ($r \geq 0.80$ to 1.00) following Evans [54]; also see [55]. Reported r values were 0.5 or higher.

The time-series model applied to nutrient and chlorophyll *a* data was an enhanced hybrid model that combined some non-parametric features with the parametric ARIMA model [8,56]. The model was created using PROC ARIMA, a parametric, autoregressive, integrated, moving-average modeling technique that assumes normality in distribution and allows strong statistical evaluation of seasonal (harmonic) and linear trends [53]. The parametric statistical modeling approach with some non-parametric features provided higher power with the parametric method than could have been achieved with a non-parametric test alone. If the model indicated a significant linear trend, the null hypothesis (zero slope over time) was rejected, and the trend parameter was used to calculate the beginning and end values of the trend and the percent change over the series.

At least 5 yr of data collected monthly or more frequently on a continuous basis (i.e., with minimal missing data) are considered the minimum needed for trend analysis [57–59]. This PROC ARIMA hybrid model requires at least 30 observations for reliable parameter estimates [53], which, with monthly summer data available in most of the reservoirs, meant that at least eight continuously sampled summers of data were needed. Only 5 of the 14 reservoirs (W.F. George, Allatoona, Lanier, Jordan, and Falls), and certain sidearms of Allatoona, Lanier, Falls, and Jordan met the data requirements for statistical trend analysis. Datasets for the other reservoirs skipped years (Table S1) or had too many missing summer months; among the latter were even Martin and Norman, with high $n$ values but many missing data.

## 3. Results

### 3.1. Climate

Summers in the southeastern USA showed evidence of warming over the past two decades (June–September 2000–2020). The mean minimum summer air temperature significantly increased ($p < 0.05$) by $0.5 \pm 0.1$ °C in 11 of the 14 sub-watersheds. Mean (+0.4 °C) and maximum (mean +0.3 °C, range +0.2 to +0.5 °C) summer air temperatures slightly increased. Summer precipitation was highly variable across the sub-watersheds. The western and eastern sub-watersheds became wetter (Eagle Mountain, Cedar Creek, and Ross Barnett +0.6 to +1.4 cm; Norman, Jordan, and Falls +0.5 to 3 cm per decade). Most central sub-watersheds decreased by −0.9 to −4.7 cm (mean −1.0 cm, median −0.9 cm).

### 3.2. Sub-Watershed Land Use/Land Cover and Human vs. Livestock Populations

The 14 sub-watersheds ranged in area from ~1140 (Eagle Mountain) to more than 7900 km$^2$ (Ross Barnett), with a median area of ~3300 km$^2$) (Table 1, Figures 1 and 2). The three most prominent general land cover categories (rounded to the nearest integer) were *forest* (deciduous +evergreen + mixed categories; median among sub-watersheds 58%), *agriculture* (hay/pasture + cultivated crops categories; median 14%), and *urban development* (developed open space + low, medium, and high intensity categories; median 12%). *Wetlands* (woody + emergent herbaceous categories), considered generally protective of surface waters [5,60], covered < 9% of all but 1 sub-watershed (Ross Barnett, 21%) and were ≤4% of the total land cover in 11 sub-watersheds. The highest remaining percentage of wetland coverage occurred in Cedar Creek (4%) and W.F. George (9%) (Figure 2). Forests and wetlands each showed small increases during 2008–2019 (overall median change about +1% for both; ranges −2 to 11% and −1 to 7%, respectively), whereas agricultural lands decreased by about the same amount (median change −3%, range −8 to ~0%).

**Table 1.** General features of the 14 reservoirs considered collectively (SE, standard error).

| Parameter | Mean ± 1 SE | Median | Range |
|---|---|---|---|
| **General** | | | |
| Reservoir age (yr) | 66 ± 6 | 60 | 40–109 |
| Watershed area (WS, $km^2$) | 3793 ± 516 | 3332 | 1141–7692 |
| Watershed land cover as of 2019 [a] | | | |
| Forest (%) | 52 ± 5 | 58 | 13–69 |
| Agriculture (%) | 17 ± 3 | 12 | 6–55 |
| Developed (%) | 13 ± 2 | 11 | 6–25 |
| Impervious Cover (IC, %) | 11 ± 1 | 11 | 5–21 |
| Wetlands (Herbaceous + Woody, %) | 4 ± 1 | 2 | ~0–21 |
| **Physical features** | | | |
| Dam height (m) | 36.7 ± 3.6 | 34.4 | 17.4–58.5 |
| Mean depth (m) | 7.7 ± 1.1 | 6.4 | 3.3–18.3 |
| Maximum depth (m) | 27.2 ± 3.3 | 24.7 | 12.8–48.2 |
| Mixed surface layer when present (depth, m) | 4.7 ± 0.5 | 4.5 | 1.5–7.9 |
| Summer thermocline when present (depth, m) | 6.6 ± 0.7 | 6.1 | 1.2–12.1 |
| Length at the conservation pool (km) | 60 ± 11 | 49 | 11–137 |
| Shoreline length at the conservation pool (SL, km) | 635 ± 110 | 490 | 150–1432 |
| Shoreline development index ($D_L$) | 6.54 ± 0.65 | 7.25 | 1.44–10.07 |
| Volume ($10^6$ $m^3$) | 798 ± 232 | 451 | 131–3150 |
| Flushing rate ($yr^{-1}$) | 11.8 ± 4.9 | 3.1 | 1.2–60.8 |
| Surface area at the conservation pool (SA, $km^2$) | 108 ± 20 | 93 | 35–282 |
| WS: SA ratio | 44 ± 6 | 40 | 17–87 |
| **Limnological data** (summer, June–Sept., reservoir-wide near-surface conditions) | | | |
| Temperature (°C); median *n* 848 (334–4541) | 28.8 ± 0.2 | 29.1 | 17.6–36.0 [b] |
| DO (surface, mg $L^{-1}$); median *n* 848 (328–4528) [c] | 7.5 ± 0.2 | 7.8 | 0–16.4 |
| DO (surface, % satn.); median *n* 825 (187–4524) [c] | 102.1 ± 2.3 | 102 | 2.7–221 |
| pH; median *n* 850 (334–4488) | 7.8 ± 0.1 | 7.9 | 5.3–9.9 |
| Secchi depth (m); median *n* 133 (82–394) [b] | 1.5 ± 0.2 | 1.3 | 0.08–6.0 |
| TSS (mg $L^{-1}$); median *n* 124 (85–794) [b] | 8.4 ± 1.6 | 6.5 | n.d.–223 |
| TP (µg $L^{-1}$); median *n* 126 (84–817) | 43 ± 8 | 27 | n.d.–470 |
| TN (µg $L^{-1}$); median *n* 126 (86–806) | 618 ± 61 | 622 | 55–2833 |
| TN:TP ratio; median *n* 126 (82–806) | 52 ± 5 | 55 | 2–506 |
| $tNH_3$ (µg $L^{-1}$); median *n* 127 (78–895) | 32 ± 8 | 22 | n.d.–726 |
| $NO_x$ (µg $L^{-1}$); median *n* 128 (86–806) | 65 ± 13 | 46 | n.d.–1600 |
| DIN (µg $L^{-1}$); median *n* 126 (78–793) | 96 ± 13 | 92 | n.d.–1760 |
| TKN (µg $L^{-1}$); median *n* 126 (86–806) | 552 ± 67 | 546 | n.d.–2820 |
| TON (µg $L^{-1}$, calculated); median *n* 124 (77–793) | 523 ± 64 | 520 | 0–2804 |
| TOC (mg $L^{-1}$); median *n* 109 (11–794) [c] | 5.4 ± 1.0 | 6.0 | 1.2–13.3 |
| Chl*a* (µg $L^{-1}$); median *n* 129 (82–823) | 20 ± 3 | 15 | n.d.–162 |
| Trophic State Index (TP and chl*a*) | 53.7 ± 1.0 | 51 | 17.4–109.9 |

Note(s): [a] Land cover percentages are rounded to the nearest integer. [b] Excluding outlier Lake Lanier, a flooded gorge in the Georgia mountains with a temperature range of 10.5 to 32.6 °C. [c] Means ± 1 SE are grand means for the individual reservoir means. The median was derived from the individual reservoir means, and ranges are from the original data (n.d., not detectable). Number of reservoirs = 14, except for percent DO saturation (11; data not available, n.a., for Eagle Mountain, Cedar Creek, and Jordan throughout the study; data available for W.F. George, Allatoona, and Lanier only from 2015 on); Secchi depth (13; data n.a. for Jordan); TOC (8; data n.a. for Guntersville, Harris, Martin, Lay, Neely Henry, and Norman); and TSS (13; data n.a. for Norman).

The greatest increase in land cover occurred for total development (median +4%, range +2 to +9%) (Figure 3). Total land coverage in development by 2019 (all categories: open space and low-, medium-, and high-intensity) averaged 13 ± 2% (median 12%, range 6–25%). Most of the increase in developed lands occurred in the categories of medium- and high-intensity development (median 63%, range 43 to 98%). Impervious cover (IC) increased by a median of 4% (range 2 to 9%) during 2008–2019, and was strongly related to the percent change in total developed land cover (all categories; Figure 4a).

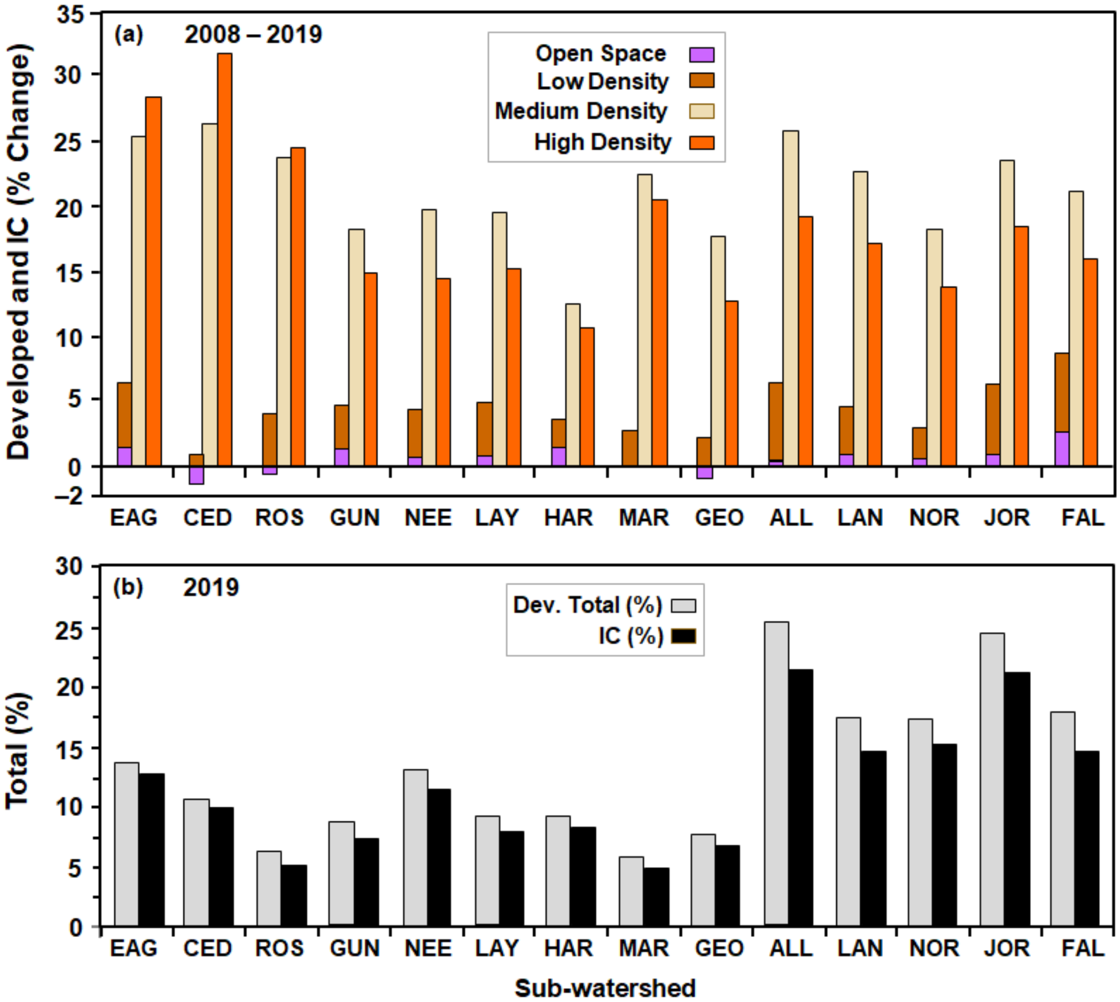


**Figure 3.** (**a**) Percent change (%) over the past ~decade (2008–2019) in developed land cover (all categories of density) within each total sub-watershed. (**b**) Percentage of developed land use (Dev., all categories) and impervious cover (IC) within each sub-watershed as of 2019. Land cover data from [22].

Land cover in the total sub-watersheds was compared to that within a 10-km radius adjacent to the reservoirs to assess total development, agriculture, and forest (Figure 4b). This comparison yielded insights as to whether the lands closest to the reservoirs had more forest vegetation that would offer buffer protection for reservoir water quality. The data provided little evidence of such protection. Land use percentages in development were significantly higher, and in forest, significantly lower, within the adjacent areas close to the reservoirs than in the total sub-watersheds (Figure 4b). Agricultural land use was generally less in the adjacent area but more variable ($p$ = 0.0913): It was less in the adjacent area for nine reservoirs (median 3.8%), similar for two (Lanier and Guntersville, 11.4% and 31.0%, respectively), and higher for three (by 15–36%). Adjacent land use in agriculture was <20% except in two reservoirs. Guntersville was similar in adjacent versus total sub-watershed land use (~30.5%), whereas agricultural land use adjacent to Cedar Creek was lower but maximal among the reservoirs (adjacent, 46.7%; total sub-watershed, 55.1%).

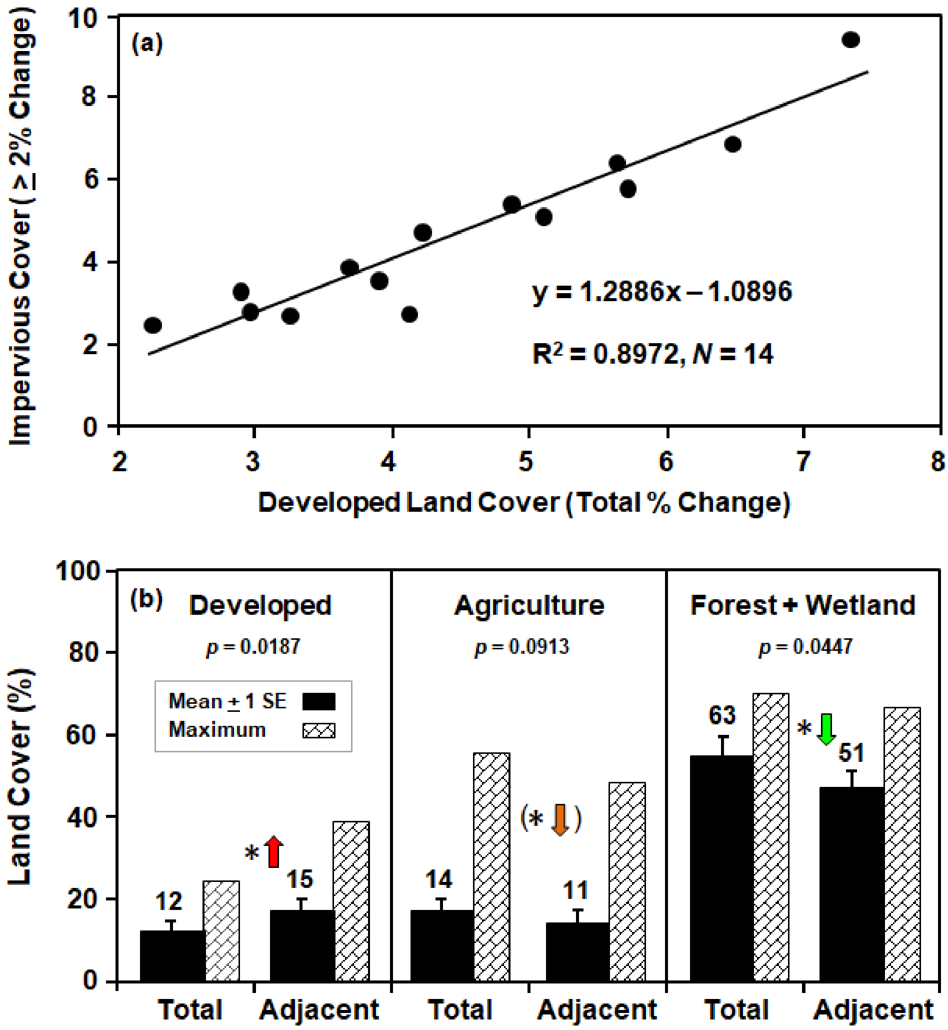


**Figure 4.** (**a**) Strong linear relationship between the percent change (≥2%, 2008–2019) in total developed land cover (all categories) and IC in the 14 sub-watersheds. (**b**) Land cover percentages (total developed, agricultural, and forest + wetland) as of 2019 in the *total* sub-watersheds versus within a 10-km radius *adjacent* to the reservoirs. Data are given as means ± 1 SE (black bars; median numbers above), and maxima are also shown. Arrows indicate whether the land use category is higher or lower in the adjacent area than in the total sub-watershed. Asterisks indicate statistical significance from two-tailed Student's paired *t* tests: (*) $p = 0.0913$; * $p < 0.05$. Land cover data from [22].

The human population as of 2020 ranged from ~70,900 (Martin) to 975,800 (Jordan) (mean 301,300 ± 62,300, median 177,900) (Figure 5a). Population density ranged from 9 to 242 people km$^{-2}$ (Martin and Allatoona sub-watersheds, respectively; mean 95 ± 21 and median 62 people km$^{-2}$). All sub-watersheds increased in population over the past decade except for those drained by Ross Barnett, W.F. George, and Martin, which decreased in population by −0.3 to −2% over the decade. The median change in population per sub-watershed was +5% (mean 7.0 ± 2.3%). Rapid urbanization characterized some sub-watersheds; those with the highest decadal increase in population included Cedar Creek (+24%), Allatoona (+18%), and Jordan and Falls (each +12%), coinciding with major shifts toward developed land uses (Table 1; Figures 2 and 3).

Agriculture assessment in this analysis emphasized industrialized livestock production as mentioned, specifically cattle, poultry, and swine (Figure 5b,c). Horse and swine populations were minor in most sub-watersheds (relative to cattle and poultry populations); they each contributed, on average, <1% of the total N and ≤2% of the total P in livestock wastes per sub-watershed. Only in the Falls sub-watershed was the contribution of horses to total livestock (N) (slightly) above 1% (1.2%). The highest contribution of horses to total livestock P (1–1.7% of the total) occurred in the Eagle Mountain, Allatoona, Lay, and Falls sub-watersheds. Swine wastes contained << 1% of the total livestock P except in the Jordan, Falls, Ross Barnett, Guntersville, and Neely Henry sub-watersheds (3.2–8.0%, highest in Neely Henry). The USDA livestock population census indicated that between 2012 and 2017, horse populations decreased in all sub-watersheds except Lay and Martin (+4 to +5%), and most substantially in W.F. George and Allatoona (−33 to −51%). Nine sub-watersheds each contained negligible swine populations (300–1700). The other five ranged in swine number from ~5600 (Falls) to 79,000 (Guntersville), and all sustained major decreases in swine populations (from −37 to −72%).

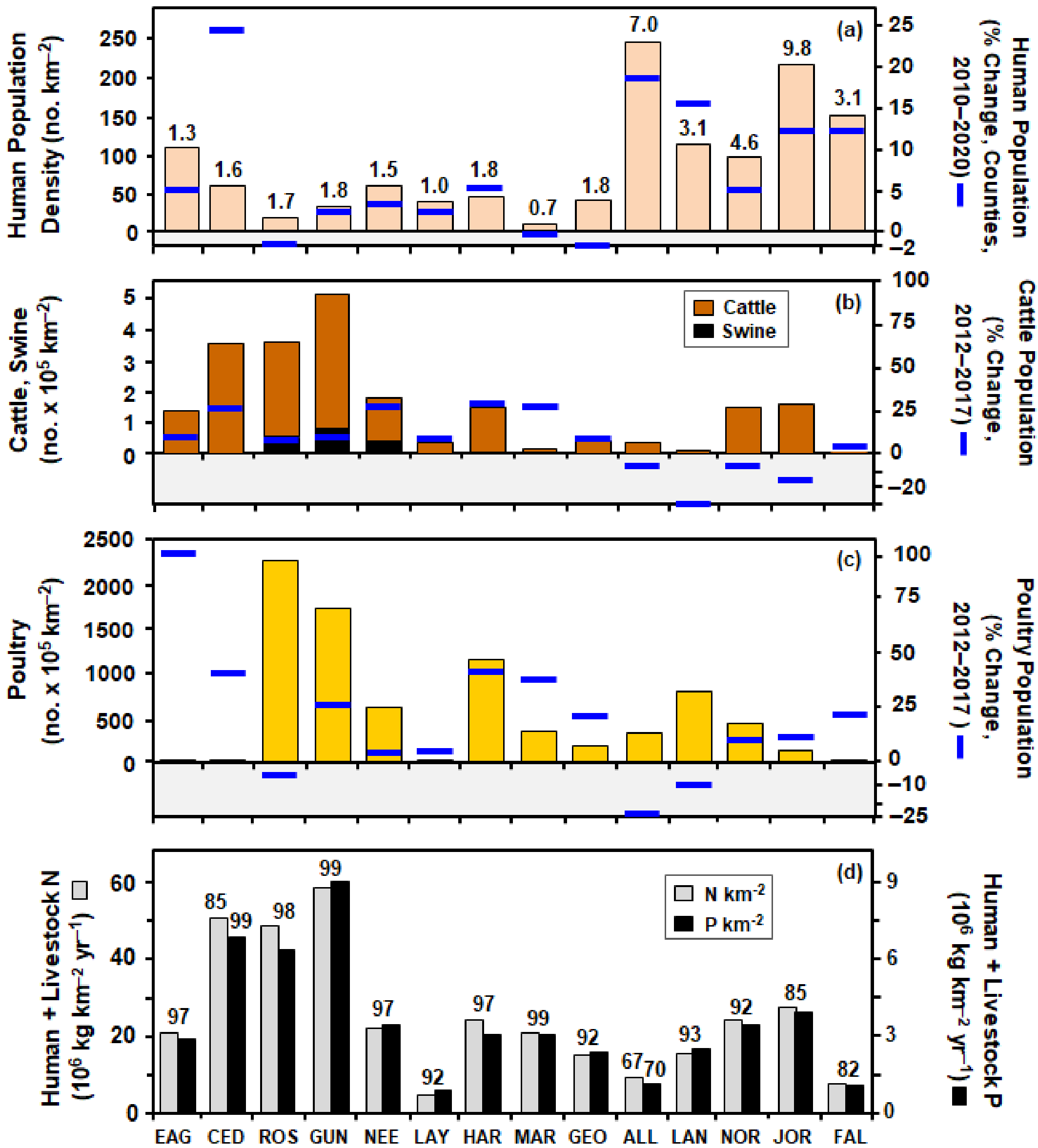


**Figure 5.** Human and major livestock populations in the sub-watersheds, and N and P contributions: (**a**) Human population (2020) and percent change over the past ~decade. Rounded numbers above bars indicate total population × $10^5$, estimated from 2021 county data [21] and GIS. (**b**,**c**) Cattle, swine, and poultry population densities as of 2017, and percent change in cattle and poultry over the most recent 5 yr (2012–2017). Note that % change is indicated for poultry > 1000 birds in 2012; swine were minor (see text)—their declines, in ROS, GUN, and NEE sub-watersheds, ranged from 37 to 58%. (**d**) Overall N and P are estimated as kg km$^{-2}$ yr$^{-1}$ in waste from humans + livestock. Numbers above bars indicate the percentage of the total N and P contributed by livestock wastes.

In contrast, over the 2012–2017 period, there was on average a 9.3% increase in both poultry (from 77.34 × $10^6$ to 831 × $10^6$ birds; increases in 11 sub-watersheds) and cattle (from 1.94 × $10^6$ to 2.09 × $10^6$ animals; increases in 10 sub-watersheds) (Figure 5b,c). Overall, the Ross Barnett and Guntersville sub-watersheds were highest in industrialized livestock production. The southeastern USA is known for industrialized poultry agriculture [24]. As expected, substantial poultry populations occurred in 8 sub-watersheds (Figure 5c), where broiler chickens outnumbered the other livestock groups by ~10- to 1000-fold. The highest poultry populations occurred in the Ross Barnett (MS, 234.4 billion $yr^{-1}$), Guntersville (GA, 174.8 billion $yr^{-1}$), and Harris (AL, 119.5 billion $yr^{-1}$) sub-watersheds, whereas poultry numbers were lowest in the two eastern TX sub-watersheds. Cattle were second in importance, followed by swine as a distant third. Cattle production was highest in the Guntersville, Cedar Creek, and Ross Barnett sub-watersheds (~2.83 to 3.57 × $10^5$ cattle $yr^{-1}$). The lowest total livestock numbers occurred in the two eastern TX sub-watersheds, dominated by cattle, and in the rapidly urbanizing Falls Lake sub-watershed (Figure 5b,c). Most swine were in the Ross Barnett, Guntersville, and Neely Henry sub-watersheds (3.6 to 7.9 × $10^4$ swine $yr^{-1}$).

Human and livestock wastes contributed a grand mean of 25.3 ± 4.4 × $10^6$ kg N $yr^{-1}$ sub-watershed$^{-1}$ (median 21.8 × $10^6$ kg N sub-watershed$^{-1}$ $yr^{-1}$; range 5.9 to 58.9 × $10^6$ kg N $yr^{-1}$) and 3.7 ± 0.7 × $10^6$ kg P $yr^{-1}$ (median 3.3 × $10^6$ kg P sub-watershed$^{-1}$ $yr^{-1}$; range 0.8 to 9.0 × $10^6$ kg P sub-watershed$^{-1}$ $yr^{-1}$) (Figure 5d). Lay's sub-watershed, with sparse livestock, contained the least livestock (N and P), whereas Guntersville—with the largest cattle population and second-largest poultry population among the sub-watersheds—contained the most. The grand mean TN:TP molar ratio from combined human + livestock wastes was 33 ± 4 (median 32), and the waste TN:TP ratio varied from 16 to 52 among the sub-watersheds. Human wastes were only 5 ± 2% of the total humans + livestock N and 8 ± 2% of the total humans + livestock P, on average, per sub-watershed (Figure 5d). In 11 sub-watersheds, human waste N and P contributions were <10% of the total human + livestock wastes. In the other sub-watersheds (Allatoona, Jordan, and Falls), human waste contributions of N and P were considerably higher (13–18% and 15–35% of the total humans + livestock wastes of N and P, respectively).

### *3.3. Reservoir Age and Physical Characteristics*

The 14 reservoirs ranged in age from 40 to 109 years post-fill (median ~60 yr) (Tables 1 and 2). They were mostly shallow (median depth 6.4 m), but the maximum depth of flooded gorges extended as deep as 48.2 m (maximum depth range 12.8 to 48.2 m). The reservoirs varied broadly in other features as well. The median volume was ~450 × $10^6$ $m^3$ (range 131 to 3150 × $10^6$ $m^3$); the median surface area at the conservation pool was 93 $km^2$ (range 35 to 282 $km^2$); and the median watershed-area-to-reservoir-surface-area ratio was 40 (range 17 to 87). The median flushing rate was 3.1 times $yr^{-1}$ but varied from 1.2 to 60.8 times $yr^{-1}$ (Table 1). The SL ranged from 150 to 1432 km (mean 635 ± 110 km, median 490 km), and the $D_L$ ranged from 1.44 for Ross Barnett with the simplest, most lake-like shoreline to 10.07 for river-like Neely Henry (mean 6.54 ± 0.65, median 7.26) (Table 1).

Mid-summer temperature depth profiles indicated that 9 of the 14 reservoirs were shallow (mean depth 5.0 ± 0.4 m, median 5.0 m, range 3.3 to 6.7 m; maximum depth averaged 19.3 ± 2.1 m). Most shallow reservoirs (8 of 9) commonly lacked a clear homothermal surface layer and a defined metalimnion; stratification was weak or absent on ~one-third of all sampling dates. Of the six that maintained stratification, only one had a shallow mean depth (Jordan, 4.3 m); the others had a mean depth of 12.5 ± 1.6 m (range 9.4 to 18.3 m; maximum depth averaged 41.2 ± 2.7 m) (Table 2).

**Table 2.** Profile of each reservoir considered, including river basin, age, dam height (DH), morphometric features (SL, $D_L$), and watershed-to-surface area ratio (WS:S.A.; see Figure 1 for WS data). For summer thermocline, descriptors weak and absent refer to stratification; data are given as mean ± 1 SE (median); and stratification as the percentage of dates sampled *.

| Reservoir (Basin, State, Year Filled—Age; DH in m) | Mean Depth, Max. Depth (m) | Summer Thermocline (m), ± Stratified | Flushing Rate $yr^{-1}$ | Volume at Conserv. Pool ($10^6$ $m^3$) | S.A. at Conserv. Pool ($km^2$) | WS: S.A. |
|---|---|---|---|---|---|---|
| Eagle Mountain—Trinity River, e. TX; 1934, 89 yr; DH 25.9 m, SL 150 km, $D_L$ 7.13 | 6.7, 14.0 | 6.8 ± 0.8 (6.5); absent/weak 89% | 1.2 | 221.9 | 35.2 | 32 |
| Cedar Creek—Trinity River, e. TX; 1966, 57 yr; DH 29.3 m, SL 515 km, $D_L$ 22.30 | 6.1, 19.5 | 5.0 ± 0.8 (5.5); absent/weak 63% | 4.1 | 795.2 | 133.0 | 20 |
| Ross Barnett—Pearl River, MS; 1965, 58 yr; DH 19.5 m, SL 169 km, $D_L$ 4.12 | 3.7, 12.8 | 9.2 ± 2.3 (11.1); absent 67% | 7.4 | 449.2 | 133.6 | 58 |
| Guntersville—Tennessee River, AL; 1939, 84 yr; DH 28.7 m, SL 1432 km, $D_L$ 24.05 | 4.6, 22.6 | 4.5 ± 0.5 (4.5); absent 67% | 28.1 | 200.0 | 282.1 | 18 |
| Neely Henry—Coosa River, AL; 1966, 57 yr; DH 17.4 m, SL 546 km, $D_L$ 22.84 | 3.3, 16.1 | -<br>absent 100% | 60.8 | 149.2 | 45.5 | 56 |
| Lay—Coosa River, AL; 1914, 109 yr; DH 39.5 m, SL 465 km, $D_L$ 18.82 | 6.7, 26.8 | 8.3 ± 4.9 (4.1); absent/weak | 40.6 | 324.1 | 48.6 | 46 |
| R.L. Harris (Lake Wedowee)—Tallapoosa River, AL, 1983, 40 yr; DH 45.7 m, SL 435 km, $D_L$ 18.69 | 12.2, 36.6 | 4.9 ± 0.4 (3.3); + all dates | 2.4 | 525.5 | 43.1 | 87 |
| Martin (Cherokee Bluffs Lake)—Tallapoosa River, AL; 1926, 98 yr; DH 51.2 m, SL 1196 km, $D_L$ 26.14 | 12.5, 45.7 | 6.3 ± 0.5 (6.0); + all dates | 2.1 | 2001 | 166.5 | 24 |
| W.F. George (Lake Eufaula); Chattahoochee River, GA; 1962, 61 yr; DH 47.2 m, SL 1030 km, $D_L$ 21.49 | 5.0, 30.5 | 3.3 ± 0.7 (3.2); absent/weak 45% | 1.3 | 1153 | 182.8 | 40 |
| Allatoona—Etowah River, GA; 1957—66 yr; DH 57.3 m, SL 435 km, $D_L$ 17.60 | 9.4, 41.5 | 5.1 ± 0.5 (4.7); + all dates | 3.2 | 453.3 | 48.6 | 59 |
| Lanier (Sydney Lanier)—Chattahoochee River, GA; 1957, 68 yr; DH 58.5 m; SL 1114 km, $D_L$ 25.16 | 18.3, 48.2 | 5.2 ± 0.6 (4.8); + all dates | 2.4 | 3150 | 156.0 | 17 |
| Norman—Catawba River, NC; 1965, 58 yr; DH 39.6 m, SL 837 km, $D_L$ 20.79 | 10.2, 34.1 | 8.3 ± 0.4 (9.3); + all dates | 1.8 | 1349 | 129.0 | 36 |

**Table 2.** *Cont.*

| Reservoir (Basin, State, Year Filled—Age; DH in m) | Mean Depth, Max. Depth (m) | Summer Thermocline (m), ± Stratified | Flushing Rate $yr^{-1}$ | Volume at Conserv. Pool ($10^6$ $m^3$) | S.A. at Conserv. Pool ($km^2$) | WS: S.A. |
|---|---|---|---|---|---|---|
| Jordan—<br>Cape Fear River, NC; 1983, 40 yr; DH 25.9 m, SL 290 km, $D_L$ 10.89 | 4.3, 19.5 | 4.3 ± 0.4 (4.1);<br>+ all dates | 6.1 | 265.4 | 56.4 | 78 |
| Falls—<br>Neuse River, NC; 1983, 40 yr;<br>DH 28.0 m, SL 280 km, $D_L$ 11.15 | 5.0, 11.9 | 4.1 ± 0.4 (4.1);<br>absent/weak 28% | 3.0 | 131.2 | 50.2 | 40 |

Note(s): * Maximum depths from bathymetry maps [61] unless otherwise noted. Other sources and notes: Eagle Mountain, Cedar Creek—[62]; flushing rate in [63]; other data [64,65]. Ross Barnett—Older source [66] listed maximum depth as 15.2 m, or maximum depth was listed as 7.0 m [61]. Guntersville—[67–69]. Other reports of maximum depth: 20.8 m [68], 18.2 m [70]. R.L. Harris—Surface area data [71,72]; other information [73–75]. Neely Henry, Lay—[76,77]. Examples of other reports of maximum depth: 16.2 m [78] or 13.7 m [79]. Bathymetry for Lay indicated a maximum depth of 31.1 m (vs. 26.8 m [68]). W.F. George—Flushing rate in [63]; other data from [67]. Allatoona—[67,80,81]. Lanier—mean depth [82]; watershed area [83]; water residence time [84]. Norman—Other reports of maximum depth given as 33.5 m [85] or 36.6 m [86]. Jordan—[67]; maximum depth is also reported as ~20.1 m [87]. Falls—[67,88].

### 3.4. Water Withdrawals, Human Populations Served, and Major Point Sources

The source waters varied substantially in estimated withdrawals for potable and other uses (Table 3). As explained, this basic information was not contained in an organized database; rather, it was tracked to a wide array of piecemeal sources. Moreover, data on human populations served were approximate for Cedar Creek and not available for auxiliary supply, according to R.L. Harris and W.F. George. The estimates of populations served and water withdrawn are thus provided only to indicate the general importance of the reservoirs as potable source waters.

**Table 3.** Water withdrawals for potable use, human populations served, and major point sources (defined as discharging > 3.79 × $10^6$ L $day^{-1}$ or 1 million gallons $day^{-1}$, mgd) in the sub-watersheds. [a] Point source data are from permits unless otherwise noted; discharge in L $day^{-1}$ is rounded to the nearest tenth (PP, processing plant; SH, slaughterhouse). Identified water quality concerns are also indicated [a].

| Reservoir | Potable/Other Withdrawals (Mean ×$10^6$ L $day^{-1}$, mgd) | Human Population Served (approx.) [b] | Discharge from Major Point Sources ($10^6$ L $day^{-1}$, mgd) [b] | Major Point Sources |
|---|---|---|---|---|
| Eagle Mountain | 46, 12 | 919,000 | 19.4, 5.1 | 4 municipal, including 1 that discharges directly to the reservoir |
| Cedar Creek | 710, 156 | <2,000,000 [c] | 25.8, 6.8 | 3 municipal |
| Ross Barnett | 228, 50 | 153,000 | > 36.3, > 12.3 | 5 municipal; 1 poultry PP (2016) avg. N load 536 kg $day^{-1}$ (195.6 tons $yr^{-1}$) |
| Guntersville | 18, 4 | >4200 | 103.3, 27.3 | 3 municipal + a 4th, Albertville (~23,000 people). Its WWTP, permitted at 11.5 mgd, presently averages ~7 mgd including ~3 mgd from 3 poultry PPs |
| Neely Henry | 109, 24 | 48,000 | 40.2, 10.6 | 4 municipal + 1 poultry SH (≥10 million chickens weighing ≥ 4535 tons processed $yr^{-1}$ as of 2017) [d] |
| Lay | 83, 22 | 35,900 | 34.1, 9.0 | 2 municipal |
| R.L. Harris | Tuscaloosa | ≤173,000 [c] | 5.7, 1.5 | 1 municipal |

**Table 3.** *Cont.*

| Reservoir | Potable/Other Withdrawals (Mean $\times 10^6$ L day$^{-1}$, mgd) | Human Population Served (approx.) [b] | Discharge from Major Point Sources ($10^6$ L day$^{-1}$, mgd) [b] | Major Point Sources |
|---|---|---|---|---|
| Martin | 91, 24 | 29,500 | 52.4, 11.5 | 1 municipal, 1 industrial with high discharge of carbonaceous biochemical oxygen demand ($CBOD_5$) (annual average 83 mg L$^{-1}$; range 53–117 mg L$^{-1}$) |
| W.F. George | 33, 7 | n.a. [c] | 226.8, 59.9 | 5 municipal |
| Allatoona | 129, 34 | 1,000,000 | 141.6, 37.4 | 7 municipal, including 1 that discharges directly to the reservoir ($15.1 \times 10^6$ L day$^{-1}$) and 1 with a pipe directly to the reservoir ($53 \times 10^6$ L day$^{-1}$) |
| Lanier | 1100, 242 | > 5,000,000 | 311.0, 68.4 | 6 municipal, 4 of which (representing 94% of the total effluent, $291 \times 10^6$ L day$^{-1}$) discharge into the reservoir. |
| Norman | 82, 18 | 97,970 | 143.9, 38.0 | 8 municipal |
| Jordan | 286, 63 | 700,000 | 533.7, 141.0 | 9 municipal |
| Falls | 186, 41 | 549,100 | 107.9, 28.5 | 3 municipal |

Note(s): [a] Sources: Eagle Mountain, Cedar Creek—[62,89–93]. The City of Fort Worth water treatment plant increased to treat $398 \times 10^6$ L day$^{-1}$ (105 mgd). Managed by the Tarrant Regional Water District (TRWD). Ross Barnett—largest potable source water in Mississippi; O.B. Curtis Water Treatment Plant (Jackson, MS, lost population in the past decade)—2011 average discharge given for >175,000 people and several industries [94]; the water treatment plant was recently upgraded to ~$189 \times 10^6$ L day$^{-1}$ (50 mgd) capacity [95]. Managed by the Pearl River Valley Water Supply District. Guntersville—Sunset Water Treatment Plant [96]. Managed by the Tennessee Valley Authority (TVA). Neely Henry—[37,78,97]. Managed by Alabama Power Company. Lay—[98,99]; population served [47]—Public Water Supply ID #AL0001671). Managed by the Alabama Power Company. R.L. Harris—1 of 2 reservoirs used by Tuscaloosa for drinking water [100,101]. Managed by the Alabama Power Company and the USACE. Martin—"Treasured Alabama Lake" designation [102]. Adams Water Treatment Plant [103]; also [37]. Managed by the Alabama Power Company. W.F. George—[104]. Managed by the USACE. Allatoona—Coosa tributary receives ~$87 \times 10^6$ L day$^{-1}$ (22.9 mgd) from the CCMWA + $42 \times 10^6$ L day$^{-1}$ (11.1 mgd) from Cartersville [105]. Managed by the USACE. Lanier—[83,106–108]; population served [109]. Managed by the USACE. Norman—Populations of Huntersville, Cornelius, and Davidson [110,111]. Managed by Duke Energy. Jordan—[87]; managed by the USACE. Falls—[112,113]; managed by the USACE. [b] Sources of permit data and other information: Texas Commission on Environmental Quality, TX CEQ, and Texas College of Osteopathic Medicine, TCOM; MS—Mississippi Department of Environmental Quality, MDEQ; AL—Alabama Department of Environmental Management, ADEM; GA—Georgia Environmental Protection Division, GA EPD; NC—North Carolina Department of Environmental Quality, NC DEQ; PPs and SHs from [114]. [c] Cedar Creek Reservoir is one of four source waters used as the collective water supply distributed by the TRWD. Data were not available about specific allocations from this reservoir. R.L. Harris—Estimated population served is based on the population of Tuscaloosa, which relies upon this reservoir as an auxiliary source water. W.F. George—The USACE controls water release to downstream locations; data are not available for municipal water supply in the area. Note that the Water Supply Act of 1958 authorizes the USACE to allocate water supply contracts from W.F. George, but at that time no water supply contracts had been issued for project storage [115]. [d] Refers to Koch Foods of Gadsden, LLC (ADEM permit AL0002119—effluent; permit AL00824—stormwater). The effluent permit is summarized as follows: No limits on discharge; presently $6.06 \times 10^6$ L day$^{-1}$ (1.6 mgd). Limits as monthly average (mg L$^{-1}$): TN 103; $BOD_5$ 16; $tNH_3$ 4.0; TKN 30; calculated $NO_x$ (nitrate + nitrite = TN—TKN) 69; TP (summer) 1.0; TP (rest of year, estimated from permitted P load) 22.9. Limits as daily maxima (mg L$^{-1}$): TN 147; $BOD_5$ 26; $tNH_3$ 8.0; TKN 45; calculated $NO_x$ 102; TP (summer) 1.5; TP (rest of year, estimated from permitted P load) 34.4. *Escherichia coli* (potentially harmful fecal bacteria, colonies 100 mL$^{-1}$): May through October—monthly average 126, daily maximum 298; Rest of year—monthly average 548, daily maximum 2507.

The reservoirs (except R.L. Harris, data n.a.) supplied an average of $18 \times 10^6$ to $1110 \times 10^6$ L day$^{-1}$ (Guntersville and Lanier, respectively; overall mean $226 \pm 89 \times 10^6$ L day$^{-1}$, median $96 \times 10^6$ L day$^{-1}$) for potable and other purposes. Data were not available for the number of people using W.F. George water; the other reservoirs were used by 4200 (Guntersville) to more than 5 million people (median 153,000). The reservoirs were about equally divided into categories serving large, moderate, and small human populations. Four reservoirs (Eagle Mountain, Cedar Creek, Allatoona, and Lanier) served nearly one million people or more, with maximum withdrawal from Lanier serving the Atlanta, GA, metropolitan area. Five were used for intermediate withdrawals (Ross Barnett—City of Jackson, MS; R.L. Harris—auxiliary source for the City of Tuscaloosa, AL; Norman—smaller population centers near the City of Charlotte, NC; Jordan and Falls—Triad/Piedmont population centers) and each served ~100,000 to 700,000 people. The remainder (Guntersville, Lay, Martin, and Neely Henry) sustained water withdrawals for ~4200 to 48,000 people.

During the past decade, these potable source waters all sustained inputs of partially treated effluents from at least one major point source (Table 3). The 14 sub-watersheds contained a median of 5 major point sources each (range 1–9) that potentially affected the reservoirs. Most discharged partially treated sewage with secondary treatment [116]. They were permitted to discharge an average of $127.6 \pm 39.0 \times 10^6$ L day$^{-1}$ (median $77.9 \times 10^6$ L day$^{-1}$) of effluent, not counting WWTP malfunctions, bypasses, etc. Three reservoirs, Eagle Mountain (1), Allatoona (2), and Lanier (4), received direct major discharges. Other major dischargers of nutrients and associated pollutants (suspended solids, chemicals, and pathogenic microorganisms known to cause disease in wildlife and humans [117]) included poultry processing plants and slaughterhouses in the Ross Barnett, Guntersville, and Neely Henry sub-watersheds. These sources were allowed to discharge effluents with no limits on extremely high concentrations of N and P and were permitted at extreme levels of other pollutants such as five-day BOD ($BOD_5$) as well (e.g., Table 3, footnote *d*), relative to background levels that were about 10- to 100-fold less [48,49].

### *3.5. Water Quality and Habitat Issues Identified by Resource Managers and the General Public*

In an extensive review of available information about the 14 reservoirs, from science publications to news media, we repeatedly noted identified concerns related to eutrophication (Table 4). Nutrient pollution issues—from algal blooms and/or increasing/high chl*a* to untreated sewage and poultry production wastes—were identified as concerns for all reservoirs except R.L. Harris (Table 4). Habitat degradation has been linked to noxious algal blooms, exotic/invasive species in Eagle Mountain, and low DO caused by dam operations for hydroelectric power in R.L. Harris (which would exacerbate eutrophication impacts). Exotic/invasive species, which can be promoted directly and indirectly by nutrient pollution [118], were an identified concern for all but four reservoirs (Harris, Martin, Allatoona, and Falls).

**Table 4.** Water quality and habitat-related concerns related to eutrophication, identified by resource managers, the general public, and scientists in peer-reviewed publications.

| Reservoir | Identified Concerns |
|---|---|
| The 2 TX reservoirs | ▪ Nutrient pollution, high chl*a*, noxious cyanobacteria blooms [89,119–122].<br>▪ Exotic/invasive species (e.g., zebra mussels, *Dreissena polymorpha*) [89,123]. |
| Eagle Mountain | ▪ Assessed as hypereutrophic [124].<br>▪ Declining water quality, habitat degradation for fish, and other exotic/invasive species (e.g., giant salvinia [89,125]). [a] |
| Cedar Creek | ▪ Toxic algal blooms exacerbated by climate change [126]. |
| Ross Barnett (MS) | ▪ Pathogenic bacteria from untreated sewage and other sources [127,128].<br>▪ Nutrient pollution, harmful algal blooms [7]; beneficial algal growth light-limited (high turbidity [129]).<br>▪ Exotic/invasive macrophytes (hydrilla, water hyacinth, alligatorweed, wild taro, and Cuban bulrush [130–132]).<br>▪ Vacuolar myelinopathy and causative neurotoxic cyanobacterium (*Aetokthonos hydrillicola*) [133]. |
| The 5 AL reservoirs | ▪ Site-specific chl*a* standards due to excessive algal growth [134]. |
| Guntersville | ▪ Contamination from raw sewage [135,136]. |
| | ▪ Exotic/invasive macrophytes (hydrilla, milfoil, water hyacinth, Cuban bulrush, and water spangles) cover about one-third of the reservoir surface [137,138]. |

**Table 4.** *Cont.*

| Reservoir | Identified Concerns |
|---|---|
| Neely Henry | ▪ Nutrient-impaired prior to this study [139]; nutrient pollution (especially P), high pH, organic enrichment, and low DO [140].<br>▪ Contamination from raw sewage and upstream poultry operations; low DO [141].<br>▪ Exotic/invasive macrophytes, hydrilla, and others [142,143]. |
| Lay | ▪ Nutrient-impaired prior to this study [139].<br>▪ Contamination from raw sewage [144].<br>▪ Industrialized poultry operation wastes [145].<br>▪ Long-term herbicide use to attempt to control major harmful benthic cyanobacteria [146,147] and exotic/invasive macrophytes [148,149]. |
| R.L. Harris | ▪ Damage to aquatic life from low DO caused by dam operations for hydroelectric power [150], which would exacerbate eutrophication impacts. |
| Martin | ▪ Increasing industrialized poultry operations in the watershed [151].<br>▪ High-biomass algal blooms [152], abundant cyanobacteria reservoir-wide [11,153]. |
| The 3 GA reservoirs | ▪ Excessive algal growth (site-specific chl*a* standards in [47]). |
| W.F. George | ▪ Exotic/invasive hydrilla; and vacuolar myelinopathy and causative neurotoxic cyanobacterium epiphytic on hydrilla [133]. |
| Allatoona | ▪ Sewage spills [154].<br>▪ High-biomass cyanobacteria blooms [155] were linked to dog death [156]. |
| Lanier | ▪ Localized cyanobacteria blooms, e.g., after a raw sewage spill into tributary Flat Creek [157].<br>▪ Over a 20-yr period, chl*a* was maximal in 2019, and algal blooms were linked to taste- and-odor problems in Lanier-sourced drinking water [158].<br>▪ Exotic/invasive macrophyte parrotfeather [159]. |
| The 3 NC reservoirs | ▪ Untreated sewage discharges (e.g., [160–162]).<br>▪ Vacuolar myelinopathy confirmed; causative neurotoxic cyanobacterial epiphyte also confirmed in Norman and Jordan [133]. |
| Norman | ▪ "Severe" cyanobacteria blooms near the dam [163,164].<br>▪ Hydrilla infestation [163]. |
| Jordan | ▪ Chl*a* strongly related to TN and TP [165].<br>▪ Much higher chl*a* in several sidearms than in the mainstem [166].<br>▪ Harmful cyanobacteria blooms [165]; cyanotoxins microcystin, cylindrospermopsin, and anatoxin are minimal (<0.05 µg $L^{-1}$) but β-N-methylamino-L-alanine (BMAA) is higher (<10 µg $L^{-1}$) [167].<br>▪ Headwaters are on NC's impaired waters list for nutrient and sediment pollution that has led to violations of chl*a*, turbidity, and pH water quality standards; occasional algal blooms and fish kills [168].<br>▪ Hydrilla infestation [169]. |
| Falls | ▪ Chl*a* was strongly related to TN and TP [169]; short-term experiments showed stronger phytoplankton stimulation by inorganic N + P co-enrichment than by either nutrient alone [170].<br>▪ Headwaters were on NC's impaired waters list for nutrient and sediment pollution that has led to violations of chl*a* and turbidity water quality standards; frequent algal blooms, occasional fish kills [168].<br>▪ In algal blooms (2011–2018), filamentous toxigenic cyanobacteria increased in both summer and winter seasons and were positively related to $tNH_3$ concentrations; toxigenic euglenophytes were more strongly related to P than to N [170].<br>▪ Chl*a* and TP significantly increasing in the middle/lower reservoir and sidearms as well [8]. |

Note(s): [a] Scientific name and growth habit(s) of exotic/invasive macrophyte species—submersed /floating hydrilla (*Hydrilla verticillata*) and parrotfeather (*Myriophyllum aquaticum*), other milfoil (*Myriophyllum* spp.); floating watermoss (*Salvinia* spp.; water spangles—*S. minima*; giant salvinia, *S. molesta*), water lettuce (*Pistia stratiotes*), and water hyacinth (*Eicchornia crassipes*); emergent alligatorweed (*Alternanthera philoxeroides*), wild taro (*Colocasia esculenta*), and Cuban bulrush (*Cyprus blepharoleptos*).

### *3.6. Reservoir Environment*

#### 3.6.1. Environmental Conditions

Summer water temperatures (June through September) ranged from 17.6 to 36.0 °C across the region; means among reservoirs were 27.1 to 29.9 °C, with a grand mean for all reservoirs of 28.8 ± 0.2 °C (mean ± 1 SE) and a median of 29.9 °C. Isopleth temperature profiles showed that the warmest temperatures (28–30°C) affected the upper 1 m of Falls Lake and the upper 8 m of Lake Norman over most of the season (Figure 6a,c). Deepest waters were 6–8 °C colder (22–24 °C) in Falls, whereas in Lake Norman, deepest waters were ~15 °C colder than surface temperatures during the warmest period from mid-July through late August.

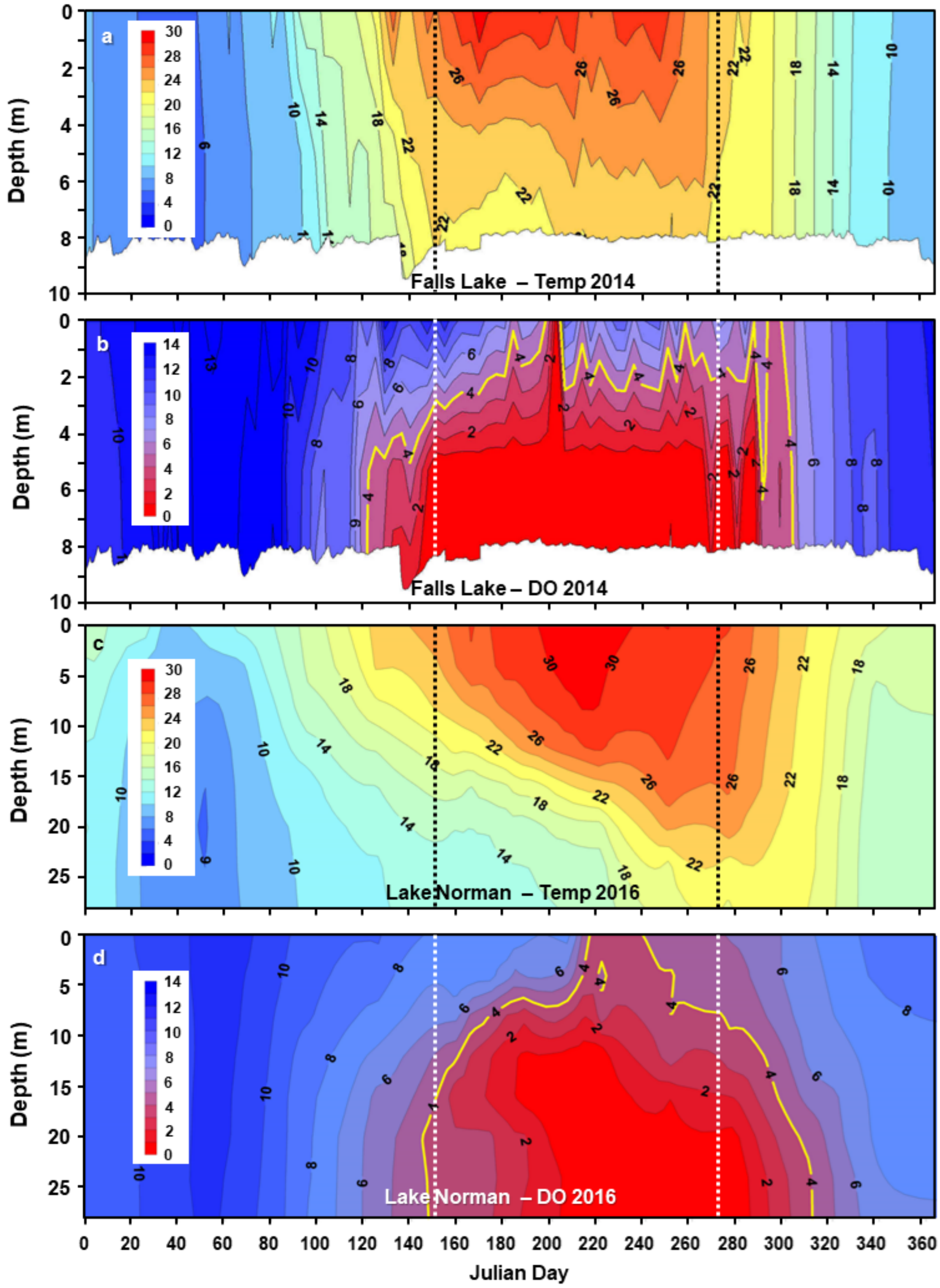


**Figure 6.** Isopleth graphs of summer temperature (scale, °C, June–September, Julian days 152–273) and DO (scale, mg $L^{-1}$) in representative years for (**a**,**b**) Falls Lake (lower station FLIN, 2014) and (**c**,**d**) Lake Norman (middle region station 13.0, 2016). Dashed lines delineate the summer season; yellow lines highlight the 4 mg $L^{-1}$ isopleth, the upper boundary for hypoxic conditions in NC water quality criteria [45].

The pH of reservoir surface waters ranged from 5.3 (Jordan) to 9.9 (Norman and Falls), with a grand mean of 7.8 + 0.1 (median 7.9), based on data taken in the morning/early afternoon hours (Table 1). All reservoirs had an average summer pH of 7.2 or higher. Ten reservoirs had pH minima of <7, indicating mildly acidic conditions and, in this region, poor buffering capacity [171]. The maximum pH in all 14 reservoirs was 9.0 or higher, indicating elevated algal/plant photosynthesis [5].

Data for summer water column clarity (light availability) indicated by Secchi depth were available from all reservoirs except Jordan, as mentioned. The grand mean Secchi depth among reservoirs was 1.5 ± 0.2 m (median 1.3 m, range 0.08 to 6.0 m) (Table 1). Five reservoirs were characterized by a mean Secchi depth < 1 m (Figure 7a); four had means > 2 m. All had minima ≤ 1 m; the most turbid areas indicated by minimal Secchi depth were Eagle Mountain (0.08 m), Falls Lake (0.1 m), and Cedar Creek (0.15 m). Most of the reservoirs have been described in reports and publications as noticeably turbid, but the grand TSS mean was relatively low, 8.4 ± 1.6 mg $L^{-1}$ (median 6.5 mg $L^{-1}$) (Table 1). The generally poor sampling frequency (twice per summer or once per month) would have missed various major stormwater/TSS events. TSS spikes indicative of maxima occurred in the four reservoirs with the lowest minimal Secchi depth readings (Ross, 223.0 mg $L^{-1}$; Eagle Mountain, 192.0 mg $L^{-1}$; Allatoona and Falls, 162.1 to 170.0 mg $L^{-1}$) (Figure 7b).

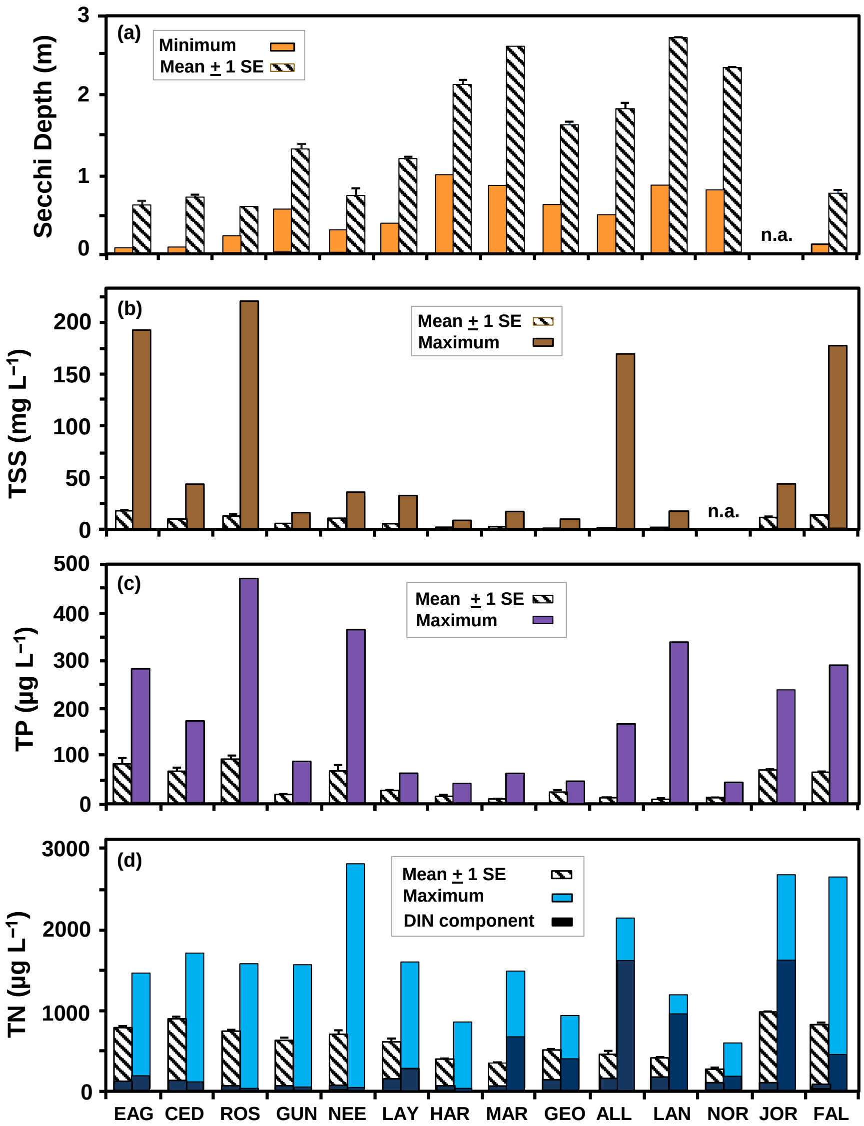


**Figure 7.** *Cont.*

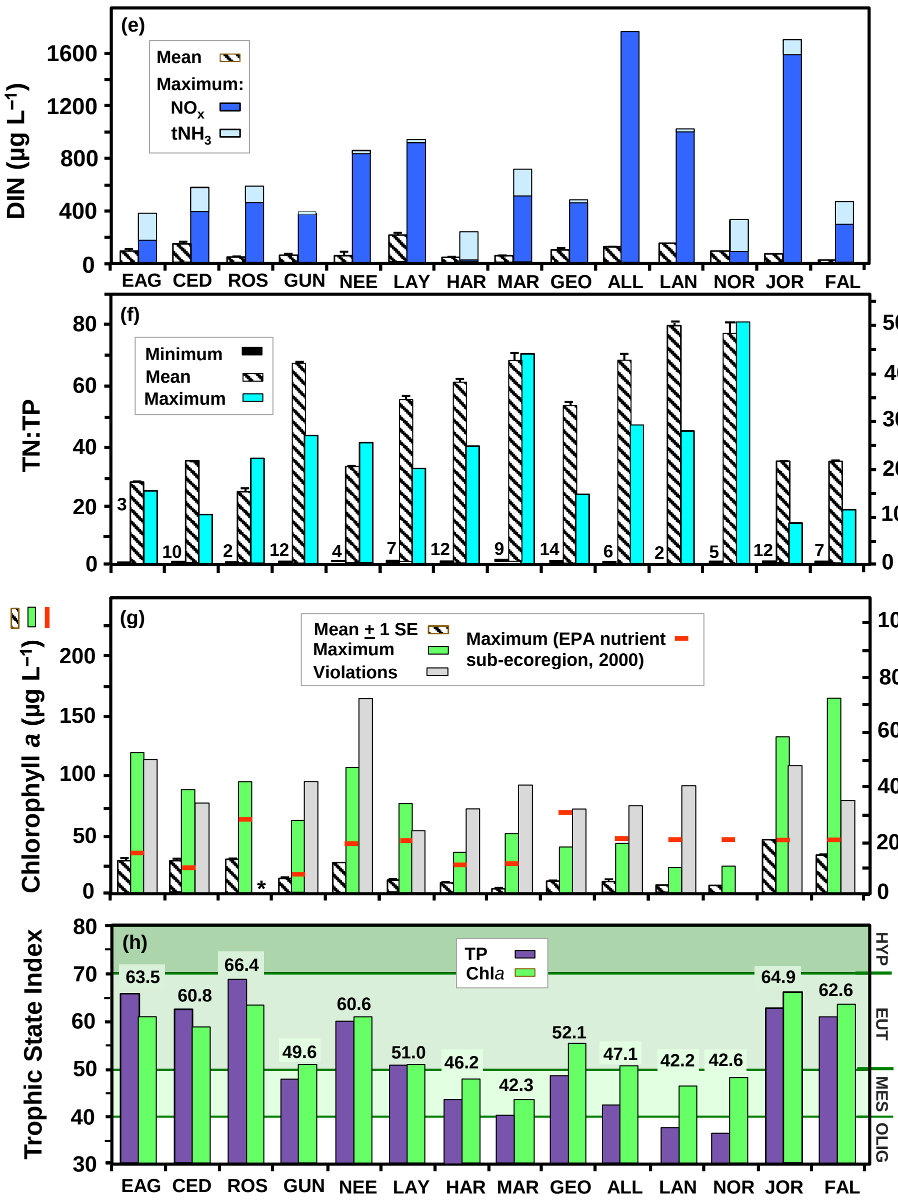


**Figure 7.** In each reservoir during summers as surface conditions: (**a**) Secchi depth (n.a., not available); (**b**) Total suspended solids (TSS); (**c**) Total phosphorus (TP); (**d**) Total nitrogen (TN), also showing dissolved inorganic N (DIN); (**e**) DIN; (**f**) Molar TN:TP ratio; (**g**) Chlorophyll *a* (chl*a*), also showing (orange bars) maxima suggested by the US EPA [46,48,49] in the germane nutrient sub-ecoregions during the 1990s, and the percentage of samples that exceeded the respective state standards (*—no MS chl*a* standard for Ross Barnett); and (**h**) Trophic state index (TSI; numbers are the combined TSI for chl*a* and TP). See Table S2 for *n* values and sampling information.

### 3.6.2. Water Quality and Trophic Status

Dissolved oxygen. All reservoirs had hypoxic bottom waters throughout the summers (Figure 6b,d, Figures 8 and 9). Unexpected, however, were hypoxic conditions affecting even surface waters in one or more areas (upper, middle, or lower regions) of 8 of the 14 reservoirs. Median DO conservatively indicated hypoxia throughout the water column of the upper (Ross Barnett, Guntersville), upper to middle (Jordan), upper and lower (Falls Lake), and lower (Eagle Mountain, Neely Henry, Lay, Allatoona) areas or regions (Figure 9). Among the reservoirs considered collectively, medians of 23%, 41%, and 58% of the water column in the upper, middle, and lower reservoir regions, respectively, were affected by DO < 4 mg L$^{-1}$ (Figure 8). Medians of 11%, 31%, and 41% of the water column in the upper, middle, and lower reservoir regions, respectively, were affected by DO < 2 mg $L^{-1}$ (Figure 8). Isopleth graphs showed that Norman and Falls sustained hypoxia that extended to surface and near-surface waters, especially during the warmest conditions (water temperatures of 28–30 °C).

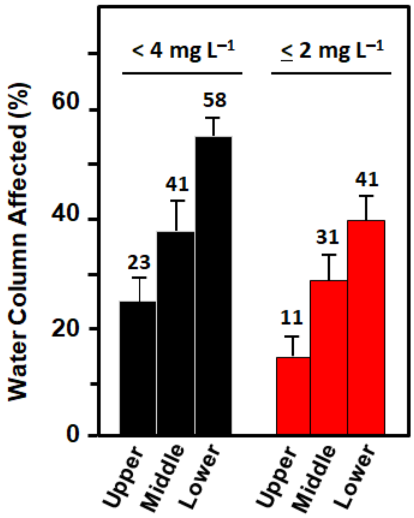


**Figure 8.** Percentage (%) of the total water column affected by hypoxia (black < 4 mg $L^{-1}$, orange $\leq$ 2 mg $L^{-1}$) in summer seasons (June through September, past ~decade) considering mainstem stations in all 14 reservoirs collectively. Data are given as means ± 1 SE; medians above each bar are rounded to the nearest integer.

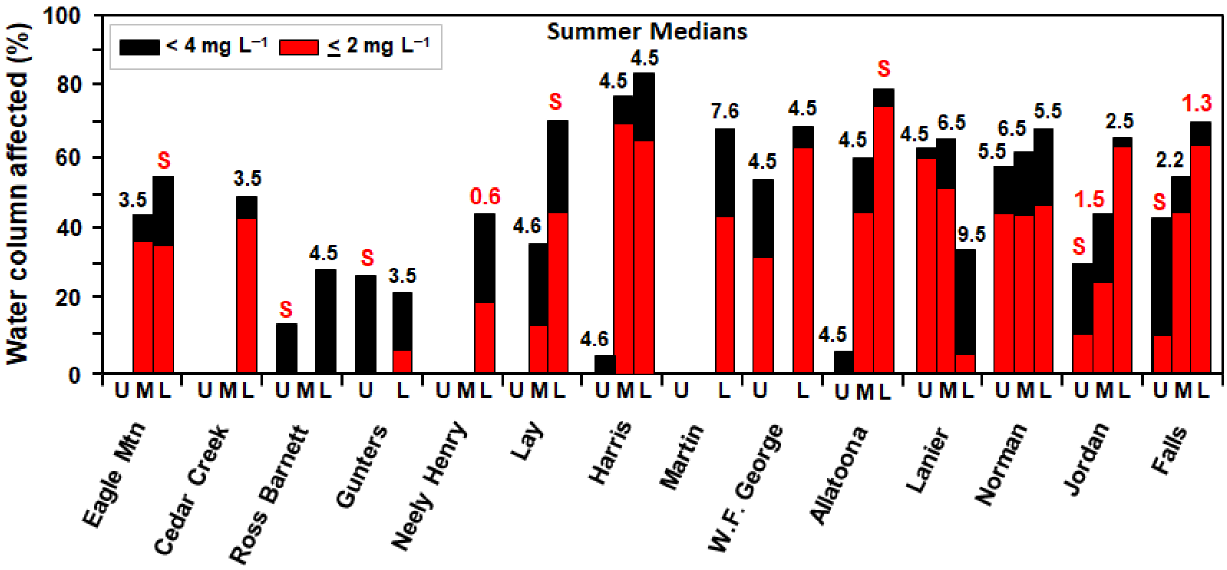


**Figure 9.** Median percentage (%) of the total water column affected by hypoxia/anoxia (<4 mg $L^{-1}$, black; $\leq$2 mg $L^{-1}$, orange) in summer seasons for mainstem stations in the upper (U), middle (M), and lower (L) regions of each reservoir. The uppermost depth (m) with hypoxic conditions is given above each bar; S = surface (0.5 m); here surface conditions are considered as depth $\leq$ 1.5 m. Spaces without bars indicate reservoir regions where summer median DO exceeded 4 mg $L^{-1}$ (i.e., no hypoxia as a median condition).

Surface DO was often undersaturated; among the 11 reservoirs with available data, nearly one-third of all surface measurements (32%) were below 95% saturation. Six reservoirs (Ross Barnett, Guntersville, Neely Henry, Lay, Norman, and Falls) were affected by severe undersaturation (<60%), known to be harmful to beneficial aquatic life [172] in their surface waters, with the worst in Falls (14% of sampling dates). Sampling was generally conducted in mid-morning to early afternoon, which would have underrepresented supersaturation from algal/plant photosynthesis [5]. Nevertheless, during the warm summers, supersaturation occurred in the surface waters of all 11 reservoirs (grand mean 9 ± 2% of sampling dates) at levels potentially harmful to aquatic biota (DO saturation > 125% [173]). Six reservoirs (Martin, Allatoona, Lay, Guntersville, Ross Barnett, and Neely Henry) were affected by supersaturation exceeding 150%, with the highest value (221%) in Allatoona.

Nutrients. Grand means for summer TP (43 ± 8 μg $L^{-1}$) and TN (618 ± 61 μg $L^{-1}$) suggested mesotrophic status following Dodds et al. ([174]: TP~25–70 μg $L^{-1}$, mean TN 500–1100 μg $L^{-1}$) (Table 1). Alternatively, the Organization for Economic Cooperation and Development (OECD) estimated trophic classification considering TP (but not TN) [175] and would assess the grand mean for summer TP in these reservoirs as suggestive of overall eutrophic status. Individual reservoir mean TP indicated eutrophic conditions (mean TP ≥ 70 μg $L^{-1}$ [175]) for 5 reservoirs (Eagle Mountain, Cedar Creek, Ross Barnett, Neely Henry, and Jordan) (Figure 7c). Maximal TP exceeded 150 μg $L^{-1}$ for 8 reservoirs; the highest values, suggestive of substantial spikes, were measured from Ross Barnett (470 μg $L^{-1}$), Neely Henry and Lanier (340–363 μg $L^{-1}$), and Eagle Mountain and Falls (280–289 μg $L^{-1}$). Mean TN in the five reservoirs with higher TP ranged from 703 to 1001 μg $L^{-1}$, whereas maxima ranged from 1458 to 2833 μg $L^{-1}$; a sixth reservoir, Falls, was third highest in maximal TN at 2679 μg $L^{-1}$ (Figure 7d).

Considering the 14 reservoirs collectively, a comparison of the US EPA's [43,44,46] subecoregional 25th percentile data for TP and TN in the 1990s versus the 2010–2020 ("2010s") 25th percentile data suggested that 25th percentile TP was similar (1990s, 23 ± 4 μg $L^{-1}$; 2010s, 26 ± 5 μg $L^{-1}$), with comparable ranges and maxima. In contrast, TN had increased from 346 ± 24 μg $L^{-1}$ (range 268–610 μg $L^{-1}$) in the 1990s to 474 ± 59 μg $L^{-1}$ (range 148 to 910) in the 2010s.

Molar TN:TP ratios generally suggested P limitation (grand mean 52 ± 5, median 55, overall range 2 to 506) (Table 1, Figure 7f) [176]. However, the minimum TN:TP ratio among the reservoirs (mean 8 ± 1, median 7, range 2 to 14) suggested substantial fluctuation, including, at times, the potential for N limitation. Furthermore, extremely low observed TN:TP ratios of 2 (Ross Barnett, Lanier), 3 (Eagle Mountain), and 4 (Neely Henry), as minimal values for these reservoirs, were indicative of a "sewage signature" (TN:TP ≤ 4–5 [177]). A comparison of the US EPA's [48–50] 25th percentile 1990s data to the 25th percentile 2010s data indicated comparable mean values for the reservoirs considered collectively (TN:TP 40 ± 13 vs. 49 ± 5), but a substantial decrease in the maximum TN:TP ratio (1990s, maximum 204.1; 2010s, maximum 100.2).

Organic N forms (TKN—t$NH_3$; grand mean 523 ± 64 μg $L^{-1}$) comprised ~85% of the mean TN considering the reservoirs collectively (Table 1). The remaining ~15% consisted of highly bioavailable DIN ($NO_x$ + t$NH_3$; grand mean 96 ± 13 μg $L^{-1}$, range n.d. to 1620 μg $L^{-1}$), although the percentage of mean TN as DIN varied widely (4–43%) (Table 1, Figure 7d). In contrast, during/following summer storms, as inferred from maximal values, about 30% of the maximal TN was DIN (range 1–79%) (Figure 7d). DIN as NOx (nitrate + nitrite) averaged 65 ± 13 μg $L^{-1}$ (range n.d. to 1600 μg $L^{-1}$), whereas t$NH_3$ un-ionized $NH_3$ + $NH_4^+$) averaged 32 ± 8 μg $L^{-1}$ (range n.d. to 726 μg $L^{-1}$) (Figure 7c). On average, 70% or more of the DIN was $NO_x$ in half of the reservoirs (Guntersville, Neely Henry, Lay, W.F. George, Allatoona, Lanier, and Jordan); $NO_x$ and t$NH_3$ were equally abundant in Ross Barnett, Harris, Martin, and Norman; the remaining three reservoirs (Eagle Mountain, Cedar Creek, and Falls) were characterized by a predominance of t$NH_3$ over $NO_x$.

TOC, measured from only 8 of the 14 reservoirs, averaged 5.4 ± 1.0 mg $L^{-1}$ (median 6.0 mg $L^{-1}$) (Table 1), exceeding the US EPA [178] recommendation of ≤4 mg $L^{-1}$ to avoid more costly potable water treatment. The three reservoirs with the highest TOC were Ross Barnett (median 9.0 mg $L^{-1}$, maximum 13.0 mg $L^{-1}$), Falls (median 7.2 mg $L^{-1}$, maximum 13.3 mg $L^{-1}$), and Jordan (median 7.2 mg $L^{-1}$, maximum 8.1 mg $L^{-1}$).

Statistical trend analysis of the mainstem W.F. George, Allatoona, Lanier, Jordan, and Falls suitable datasets for changes in N and P supplies indicated that over 2010–2020, TP increased by +25% in middle and lower regions of Falls ($p < 0.05$) (Table 5). There were also small but significant reservoir-wide trends for increasing TN (+13%, $p < 0.05$) in Jordan and for decreasing TN (–12%, $p < 0.086$) in Falls.

**Table 5.** Significant trend analyses (2010–2020, summer seasons) for the five reservoirs (W.F. George, Allatoona, Lanier, Jordan, Falls) and selected sidearms with sufficient consistently collected data for the trend analysis model ($\alpha < 0.10$). Mainstem data are reservoir-wide except that TP and chl*a* pertain to the mid-lower regions of Falls Lake.

| Reservoir | Parameter | *p* Value | Change (%) |
|---|---|---|---|
| Mainstem | | | |
| W.F. George | Chl*a* | 0.003 | +194% |
| Allatoona | Chl*a* | 0.038 | +121% |
| Lanier | Chl*a* | 0.009 | +195% |
| Jordan | TN | 0.05 | +13% |
| " | Chl*a* | 0.076 | +25% |
| Falls | TP | 0.05 | +25% |
| " | TN | 0.086 | −12% |
| " | Chl*a* | 0.026 | +73% |
| Sidearm | | | |
| Little River (Allatoona) | Chl*a* | 0.04 | +114% |
| Flat Cr. Cove (Lanier) | Chl*a* | 0.0006 | +365% |
| Haw River (Jordan) | TN | 0.07 | +15% |
| Lick Creek (Falls) | TP | 0.003 | +20% |
| " | TN | 0.02 | −12% |
| " | Chl*a* | 0.09 | +29% |

The sidearms of some reservoirs also had sufficient nutrient data for trend analysis: There were no significant trends in TN or TP for the Little River sidearm of Allatoona or the Flat Cove sidearm of Lanier. The Lick Creek sidearm of Falls Lake significantly increased in TP over the study period (+20%, $p = 0.003$) and also showed a small decrease in TN (−12%, $p < 0.02$) (Table 5). In contrast, the Haw River sidearm of Jordan sustained a small but significant increase in TN (+15%, $p = 0.07$).

Phytoplankton. The grand mean phytoplankton biomass as chl*a* (20 ± 3 μg $L^{-1}$) indicated overall eutrophic conditions (Table 1, Figure 7g) [5]. Five reservoirs were relatively low in algal biomass, with mean chl*a* ≤ 11 μg $L^{-1}$, and three were within 12 to 20 μg $L^{-1}$, which, together with consideration of maximal values, supported mesotrophic status. Six of these eight reservoirs, in addition, had maximal chl*a* values ≥ 30 μg $L^{-1}$. Chl*a* concentrations in the other six reservoirs (43%) indicated eutrophic status (Figure 7g). The highest mean and median chl*a* were measured in Falls (34–37 μg $L^{-1}$) and Jordan (40–46 μg $L^{-1}$). Maximal chl*a* captured major blooms (chl*a* ≥ 50 μg $L^{-1}$ [5]) in 10 of the 14 reservoirs, despite generally low sampling frequency (monthly to bimonthly; Table S2). Of the 10 reservoirs, 5 (Cedar Creek, Ross Barnett, Guntersville, Lay, and Martin) had maximal chl*a* ranging from 52 to 88 μg $L^{-1}$, and 4 (Eagle Mountain, Neely Henry, Jordan, and Falls) had maximal chl*a* ranging from 107 to 162 μg $L^{-1}$—highest in Falls and, secondly, in Jordan (Figure 7g).

Violations in chl*a* water quality standards (excluding Mississippi—no standard for Ross Barnett Reservoir) averaged 37 ± 5% (range, 0% for Norman to 72% for Neely Henry). Excluding Norman (with sparse data), the other 12 reservoirs exceeded the chl*a* standards in ~25% or more of samples (Figure 7g). If Ross Barnett was assessed using the highest criterion for the Coosa River basin in adjacent AL (>18 μg $L^{-1}$, a moderate standard), 86% of samples would have been in violation. Comparison of US EPA's [48–50] sub-ecoregional 25th percentile 1990s data (year-round, 5 ± 1 µg $L^{-1}$) to the 2010s mean 25th percentile data for the 14 reservoirs (9 ± 2 µg $L^{-1}$) suggested that the 25th percentile of data for chl*a* had increased overall, driven by substantial increases in 5 reservoirs. Maximal chl*a* reported by the US EPA [48–50] year-round in the 1990s vs. the 2010s (41 ± 4 µg $L^{-1}$ vs. 83 ± 14 µg $L^{-1}$, respectively) indicated that maximal chl*a* had doubled (highest in Falls, 202 µg $L^{-1}$).

An analysis of the log-transformed 2010–2020 summer TN, TP, TSS, and chl*a* data yielded significant moderate to very strong correlations for only five reservoirs, including W.F. George, Allatoona, Lanier, Jordan, and Falls (for each, $n \geq 200$). Of these, chl*a* was significantly correlated with TP in Jordan and Falls (coefficients: strong for Jordan, +0.61084; very strong for Falls, +0.84471), TN (coefficients: moderate for Jordan, +0.59645; very strong for Falls, +0.82466), and TSS (coefficients: moderate for Jordan, +0.58610; strong for Falls, +0.78205). In addition, there was a significant negative correlation between chl*a* and the TN:TP ratio (coefficients: moderate for Jordan, −0.50082; strong for Falls, −0.71989) ($p < 0.0001$).

Statistical trend analysis of the W.F. George, Allatoona, Lanier, Jordan, and Falls datasets indicated that during summers over the 2010–2020 period, suspended algal biomass (chl*a*) significantly increased in all five reservoirs, from +25% in Jordan to +194 to +195% in W.F. George and Lanier (Figure 10). Significant positive trends of increasing chl*a* were also found for the Little River sidearm of Allatoona (site 4553; +114%, $p = 0.04$), the Lanier middle-region sidearm Flat Creek Cove (+365%, $p = 0.0006$), and the Falls Lick Creek sidearm (site LC1; +29%, $p = 0.09$) during the 2010–2020 period, indicating that suspended algal biomass as chl*a* significantly increased in all five reservoirs (Figure 11a–c).

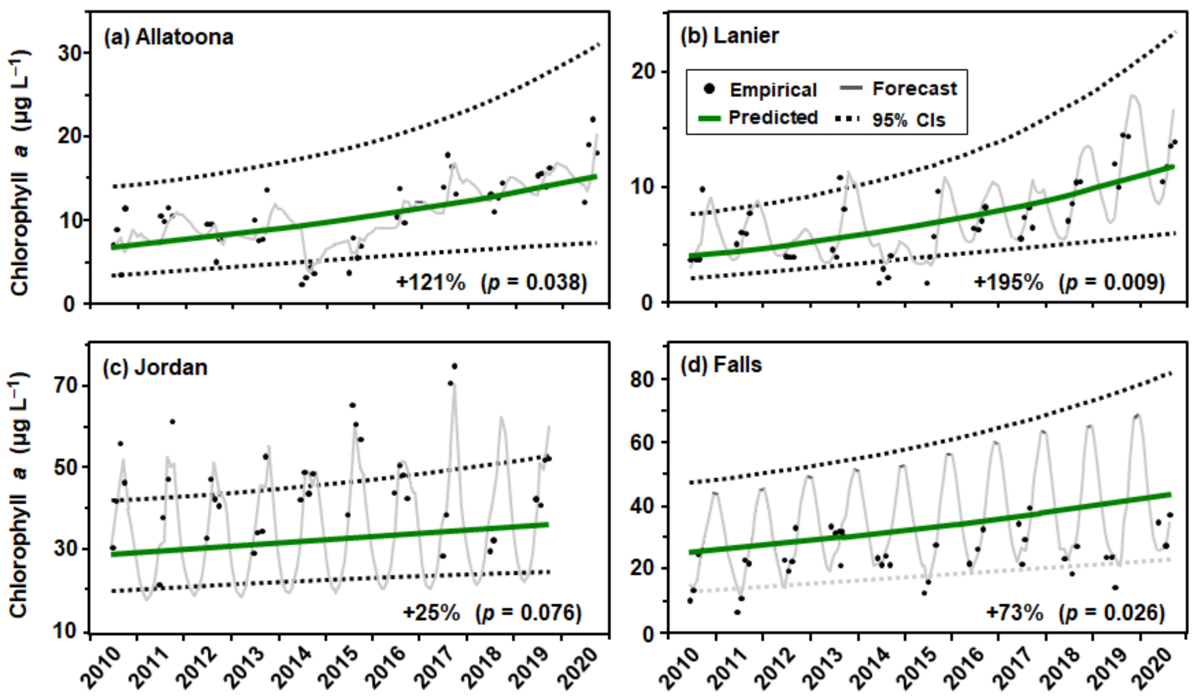


**Figure 10.** Mainstream channel chlorophyll *a*: Statistically significant positive trends over the past ~decade for near-surface summer chl*a* concentrations (June through September) reservoir-wide in (**a**) Allatoona Reservoir, (**b**) Lake Lanier, (**c**) Jordan Lake, and (**d**) middle and lower Falls Lake. Also (Table 4): Lake W.F. George (+194%, $p = 0.003$). Only those reservoirs had sufficient continuous data for testing with the statistical trend analysis model. Empirical data (single dots—monthly or as monthly means) are indicated along with trend lines (green) and 95% confidence intervals (CIs, dotted black lines) about the trend lines; solid light gray lines are the predicted (model-fitted) values, indicating seasonality.

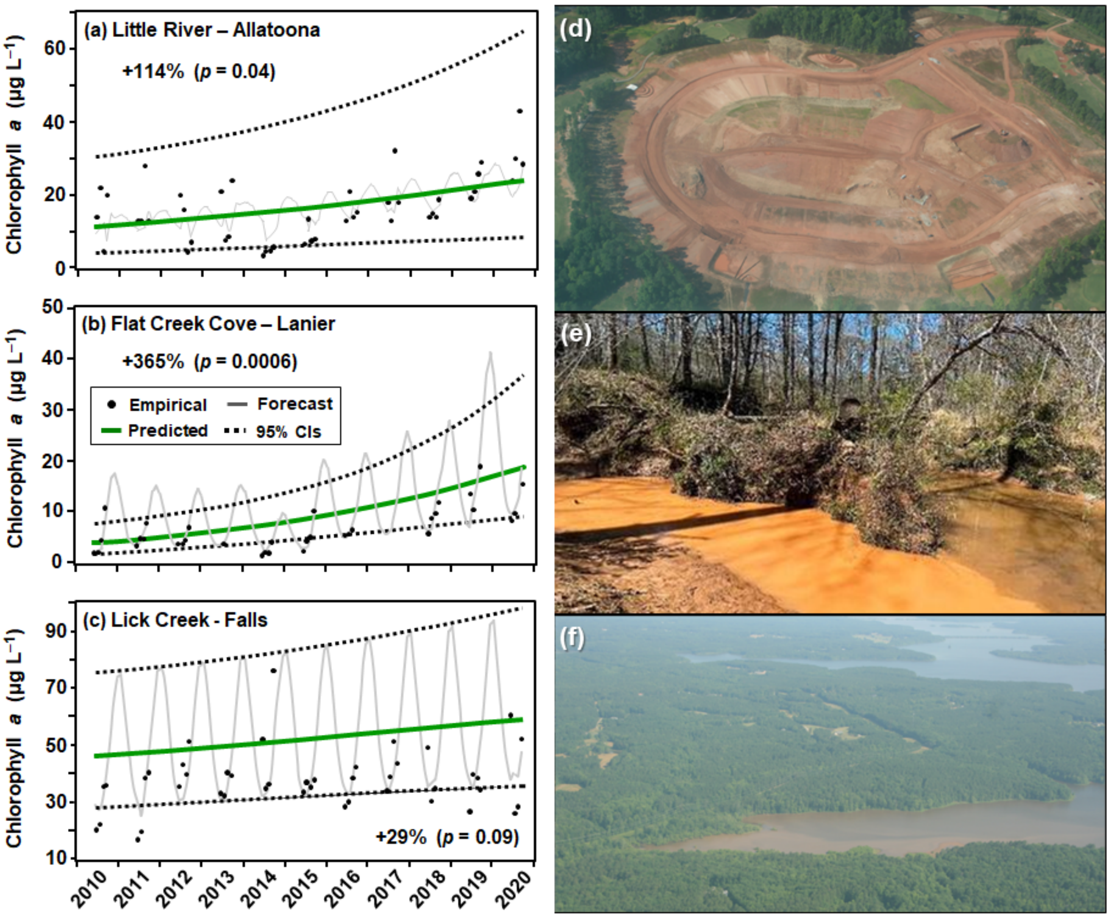


**Figure 11.** Sidearm conditions: (**a**–**c**) Statistically significant positive trends over the past ~decade for near-surface summer chlorophyll *a* concentrations (June through September) from (**a**) the Little River sidearm of Allatoona (site 4553), (**b**) the Flat Creek Cove sidearm of Lanier, and (**c**) the Lick Creek sidearm of Falls (site LC1). Data, trend lines, CIs, and predicted values as in Figure 10. (**d**–**f**) The Lick Creek sidearm and its sub-watershed are highly affected by watershed land disturbance: (**d**) dynamited clearing for a housing development, a recently common practice; (**e**) sediment- laden stream; and (**f**) an aerial photo of the highly turbid Lick Creek sidearm (foreground), also showing another, much cleaner sidearm and a portion of mainstem Falls Lake (background). Photos: Sound Rivers Neuse Riverkeeper Samantha Krop, with permission.

Sparse peer-reviewed information is available from 2010–2020 about phytoplankton assemblages in these potable source-water reservoirs, mostly including one study each of Ross Barnett, Allatoona, Lanier, and Jordan and two studies of Falls; and a recent publication [11] documenting widespread cyanobacteria abundance, estimated from satellite imagery, in nearly all 64 reservoirs assessed in the Southeast, including Cedar Creek, Eagle Mountain, and Martin. Nevertheless, photos from various sources (Figure 12), accounts of dogs dying after exposure to toxic cyanobacteria blooms, reports and websites of concerned citizen groups, and scattered news articles provide ample evidence that noxious algal blooms are known (Table 4), although poorly described in agency reports/datasets or science publications, from at least 10 of the 14 reservoirs. The photographic documentation includes high-biomass algal blooms in waters described here (below) or previously as oligotrophic to mesotrophic, such as Guntersville, Martin, Allatoona, and Lanier (Figure 12, and see [155]). The few published works thus far on cyanotoxins in these and other southeastern US reservoirs indicate that cyanotoxins (e.g., microcystins, cylindrospermopsins, and anatoxins) are ubiquitous but fortunately in low concentrations (<1 µg $L^{-1}$, usually much less [7,165,167]) except β -N-methylamino-L-alanine (BMAA) at <10 µg $L^{-1}$ [167].

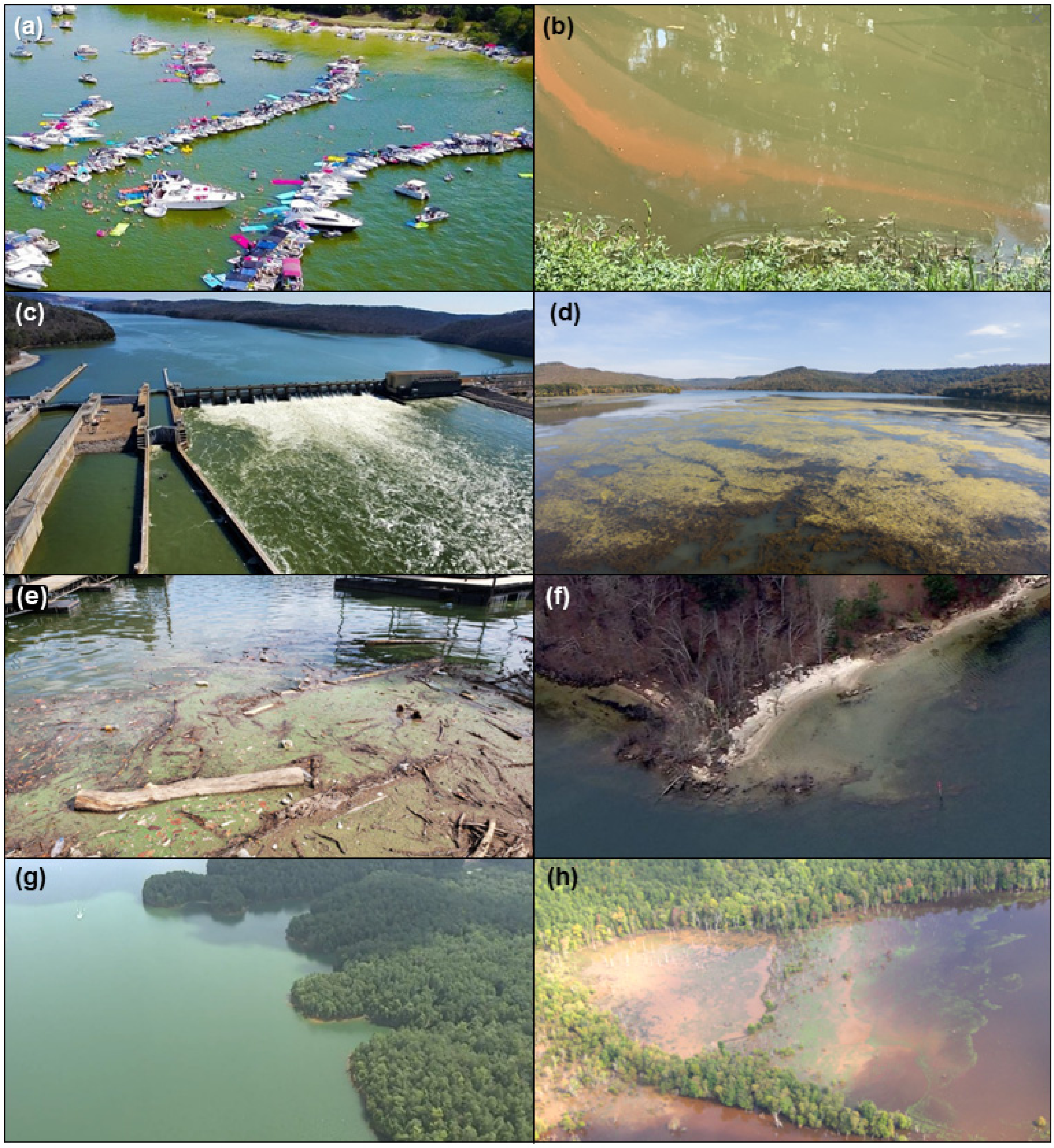


**Figure 12.** Examples of photo-documented algal blooms: (**a**) Eagle Mountain Lake—high-biomass bloom discoloring the water in Party Cove, with numerous swimmers and other recreationists. (**b**) Coosa River system (Neely Henry Lake)—mixed cyanobacteria/euglenophytes. (**c**,**d**) Guntersville Reservoir—(**c**) cyanobacteria bloom, (**d**) filamentous chlorophyte bloom, partially decayed. (**e**,**f**) Lake Lanier—(**e**) cyanobacteria bloom in 2020, downstream from a raw sewage spill; (**f**) cyanobacteria bloom in 2021. (**g**) Allatoona Lake—cyanobacteria bloom in 2019. (**h**) 2010 Falls Lake cyanobacteria bloom in the turbid upper reservoir. Photos, with permission: (**a**) Save Eagle Mountain Lake, https://www.seml.org (accessed on 8 October 2023); (**b**) Coosa Riverkeeper Justinn Overton; (**c**) Tennessee Valley Authority; (**d**) Jody White/Major League Fishing; (**e**) Lake Lanier Association, October 2020; (**f**) WSB-TV; (**g**) C. Buchanan, 11 Alive News; (**h**) Tina Motley.

Although Ross Barnett and Lay were reported to have abundant native macrophytes [131,132], the sudden major water depth fluctuations commonly imposed in the management of these reservoirs for flood control, together with often-high turbidity, prevent most native aquatic vegetation from flourishing [5]. Instead, exotic invasive species appear to be much more common in these reservoirs and/or their tributaries (Table 4), especially submersed/floating hydrilla, which is widespread throughout the Southeast [133]. Other exotic/invasive macrophytes reported to be abundant in one or more of these reservoirs include floating watermoss, water hyacinth, emergent alligatorweed, wild taro, and Cuban bulrush (Table 4).

Trophic State Indices. The grand mean TSI among the 14 reservoirs based on TP and chl*a* was 53.7 ± 1.8, within the Eutrophic range (50 to 70). The grand means for TP and chl*a* considered separately were also within the Eutrophic range (52.3 ± 3.0 and 55.1 ± 1.9, respectively). TSIs for TP alone spanned from Oligotrophic ($n$ = 2, Norman, 36.8; Lanier, 38.1) to Mesotrophic ($n$ = 5: Martin, Allatoona, Harris, Guntersville, and George, TSI 40.3 to 48.7) and Eutrophic ($n$ = 7, TSI range from 50.7 for Lay to 69.1 for Ross Barnett) (Figure 7h). In contrast, TSIs for chl*a* alone, considered a better predictor than TSI−TP for noxious algae such as cyanobacteria [179], assessed the reservoirs as either Mesotrophic ($n$ = 4: Harris, Martin, Lanier, and Norman, TSI 44.3 to 48.4) or Eutrophic ($n$ = 10, TSI range from 51.1 for Guntersville and Allatoona to 66.2 for Jordan). TSIs for TP and chl*a* considered together agreed most closely with TSIs for chl*a* alone: five reservoirs were Mesotrophic (Harris, Martin, Allatoona, Lanier, and Norman), and the rest were Eutrophic.

## 4. Discussion

Reservoirs, rather than natural lakes, characterize the landscape of the southeastern USA [9,60]. Although they are vitally important as water supplies, their limnology and water quality status are poorly known. This work contributes a novel characterization of the sub-watersheds, water withdrawals, morphometry, and water quality of 14 potable source-water reservoirs across the southeastern USA region, with a water quality focus on DO profiles, nutrients, and eutrophication status. Through the initial assessment of 41 drinking water reservoirs, we encountered a surprising lack of available/accessible information from the past ~decade on the water quality conditions of many of them. Basic information about their limnology (morphometry, thermoclines, stratification, water column oxygen availability) was often unavailable, conflicting, or fragmented in grey literature reports and/or city/county/local association websites. Current information on water use from these systems, populations served, and even major point and nonpoint sources in their sub-watersheds was found, or not, in scattered piecemeal sources.

### *4.1. General Features of the Reservoirs, Climate, and Sub-Watersheds*

The 14 potable source-water reservoirs with at least three recent summers (past ~decade) of DO depth profiles, N and P concentrations, and suspended algal biomass as chl*a* spanned from the northeastern Texas plains to flooded gorges in the Georgia highlands to the Piedmont of North Carolina. Although they vary substantially in age, depth, surface area, volume, water residence time, and other basic features, most share several traits in common. Nine are shallow (median depth 5.0 m, median volume 265.4 × $10^6$ $m^3$), and in mid-summers, eight of the nine commonly have weak or absent stratification with a poorly defined mixed surface layer and metalimnion, ephemeral near-surface thermoclines, and a relatively warm hypolimnion that does not maintain uniform temperatures. The other five are deeper and mostly larger in volume (median depth 12.2 m, median volume 1348.9 × $10^6$ $m^3$) and maintain stratification with well-defined thermoclines. Most of the sub-watersheds were characterized by high human and/or livestock populations contributing, especially the latter, massive amounts of N and P supplies. Five sub-watersheds are rapidly urbanizing, and their impervious cover well exceeds conditions known to be detrimental to the water quality and biota of receiving surface waters.

The Southeast is a warming region [180], as evidenced in this study. More generally, across the globe, the 2010–2019 decade was the warmest on record in more than 100 yr [10]. This region is also sustaining a higher percentage of intensifying heat waves than elsewhere in the USA [181]. The Southeast is already decreasing in stream flow and groundwater storage as the climate shifts [182,183]. Temperature is expected to continue to increase, resulting in more frequent, more intense heat waves, potentially strengthened stratification, more severe droughts, and more extreme rainfall events [10,180,184].

Like many other regions worldwide [1,3,185], the Southeast is also increasingly characterized by urbanization. Much of this region historically was heavily forested, but substantial sustained net forest loss had occurred by 2000 [181], and by 2019, median forest coverage in the 14 sub-watersheds was 58% (range 13–69%). Although the Southeast was once rich in wetlands as well [186], by 2019, wetlands comprised an overall median of only 2% of the 14 sub-watershed areas, and 10 sub-watersheds were at < 3% (as low as 0.2%) in wetland cover.

The major land uses that have replaced forests and wetlands are, of course, agriculture and urban development, with development now fast-outpacing agricultural land cover. By 2019, the overall median agricultural land use/land cover across the 14 watersheds was only 14%, much of it due to industrialized livestock production, which contributes major nutrient supplies to the watersheds (below). Total urban development (all categories, median 12%) was a few percent less in land coverage than agriculture and increased by a median of +4% (overall range +2 to 9%), mostly as medium- and high-density development characterized by high IC with severe adverse impacts on surface water quality [187].

The IC in these sub-watersheds is already excessive considering the potential for adverse impacts on surface waters, with an overall median of 11% IC and a range of 5–21% as of 2019. It was once thought that adverse aquatic impacts on beneficial aquatic life began to occur when IC exceeded 10% [188]. It is now accepted that IC within the range of $\geq$2 to 4% is detrimental to water quality and aquatic biota [189,190]. Urbanization more generally has caused changes in watershed hydrology in the Southeast that, in turn, have altered watershed sediment and solute export, such as higher concentrations of nutrients and other pollutants and overall net increases in pollutant loads transported downstream [191].

Sub-watershed human populations in this study varied by more than 10-fold. While human populations increased in all sub-watersheds, 9 of 14 sustained low to moderate growth, as indicated by a population change of $\leq$5% over the past decade ($\leq$0.5% yr$^{-1}$). In contrast, the other five sub-watersheds (Cedar Creek, Allatoona, Lanier, Jordan, and Falls) increased by +12% to +24% (1.2 to 2.4% yr$^{-1}$). Growth above 1% yr$^{-1}$ is considered rapid ([192] and references therein). Four of the five sub-watersheds with rapid growth also had the highest population densities (people per km$^{-2}$): Lanier 115, Falls 154.7, Jordan 220.6, and Allatoona 243.8. Diverse secondary impacts associated with rapid population growth [193] are exacerbated in small sub-watersheds with less absorptive soil area. It is not surprising, for example, that the water quality of Falls Lake is continuing to degrade, considering that it drains the smallest of these sub-watersheds and has among the highest human population growth rates and IC [8].

The reservoirs are depended upon by thousands (Guntersville, Lay, Neely Henry, Martin, and Norman), hundreds of thousands (Eagle Mountain, Ross Barnett, R.L. Harris, Falls, and Jordan), or millions (Allatoona, Cedar Creek, and Lanier) of people for safe potable water. Their sub-watersheds are not capped for urban development, which increased in all 14 sub-watersheds and, in some cases, rapidly escalated. The sub-watersheds include major municipal sewage point sources that discharge near (Falls, Jordan) or into (Eagle Mountain, Allatoona, Lanier) the reservoirs. In some watersheds, such as Falls, major sewage treatment plants have advanced beyond secondary treatment in a concerted effort to reduce the N and P discharges [194]. Nevertheless, the Southeast, as with most of the nation [116], remains characterized by mostly secondary treatment in major municipal WWTPs and no, or inadequate, N or P effluent limits. Secondary treatment (or restricted "tertiary" treatment designed to oxidize ammonia to nitrate and reduce TSS) yields final effluent with 10–40 mg TN L$^{-1}$ and 5–30 mg TP L$^{-1}$, including inorganic N ($N_i$) mostly as ammonia at ~10 mg L$^{-1}$ and about 90% of the TP as highly bioavailable phosphate [195]. Excessive ammonia is toxic to sensitive aquatic life [196], but WWTP permits usually require effluent toxicity tests only once or twice per year with adult stages of highly ammonia-tolerant species. Such N and P concentrations, sometimes set as "limits", are also extreme when compared to known stimulation of noxious algal blooms by ~0.3 mg $N_i$ $L^{-1}$ and ~0.08 mg TP $L^{-1}$ or less [5,197,198].

Livestock wastes contributed, on average, among the watersheds, more than 90% of the total N and P in human + livestock wastes. Even in the Allatoona, Jordan, and Falls sub-watersheds with rapid human population growth and declining agriculture, livestock contributed > 80% of the N and ~65–80% of the P in human + livestock wastes. The Southeast is renowned for industrialized livestock production [24,199], and 9 of the 14 sub-watersheds have substantial populations of cattle and/or poultry in particular. The Guntersville and Cedar Creek sub-watersheds were highest in livestock waste. For comparison, Iowa ranked second nationally in livestock sales during 2017 [200]. The livestock waste contributions to the Guntersville sub-watershed were comparable (~10% less) in total N tons to the median for 68 Iowa sub-watersheds based on an excellent though dated N and P budget for that state [201], and substantially higher in total P tons (Table 6). When normalized for sub-watershed area, manure N in the Guntersville and Cedar Creek sub-watersheds was 42–72% of the median kg N $km^{-2}$ $yr^{-1}$ for the Iowa sub-watersheds. Manure P on an areal basis was ~1.5× higher for Cedar Creek, or comparable to (~8% higher—Guntersville, than the median for Iowa sub-watersheds.

**Table 6.** Comparison of annual N and P contributed by livestock manures in Iowa sub-watersheds [201] versus the two sub-watersheds with the highest livestock manure N and P in this study. Data are given as totals and as totals per unit area.

| **Manure (kg km$^{-2}$ yr$^{-1}$)** | | | |
|---|---|---|---|
| **Unit** | **Area (km$^{2}$)** | **N** | **P** |
| Sub-watersheds * (IA), median | 2432 | 26,564 | 1592 |
| Guntersville sub-watersheds | 5174 | 11,222 | 1727 |
| Cedar Creek sub-watersheds | 2608 | 19,176 | 2641 |

Note(s): * All 68 Iowa sub-watersheds: range 16,028 to 38,894 kg N $km^{-2}$ $yr^{-1}$ and 684 to 4114 kg P $km^{-2}$ $yr^{-1}$ [201].

Contamination by sewage and animal wastes, including fecal bacteria, has been a common concern about the water quality of potable source-water reservoirs in the Southeast, as indicated in Table 4. Although sparse data were available during 2010–2020 for fecal bacteria in most reservoirs, maximal densities of 11,000 most probable number (MPN) of *Escherichia coli* 100 $mL^{-1}$ and 17,000 MPN 100 $mL^{-1}$ of fecal coliforms were reported in Lake Allatoona (April 2015). Maximal densities in data archives for eastern Texas reservoirs (Table S1) have included, as examples, 19,000 MPN 100 $mL^{-1}$ of *E. coli* (February 2012) and 20,000 MPN 100 $mL^{-1}$ of enterococci (January 2013) in Lake Houston, and 37,000 MPN 100 $mL^{-1}$ of *E. coli* in Joe Pool Lake (April 2020). In addition to the major water and air pollution that has been documented due to nonpoint runoff from livestock operations [202,203], the Guntersville, Ross Barnett, and Neely Henry sub-watersheds also contain major agricultural point sources that discharge poultry waste effluents containing extreme levels of contaminants such as $N_i$ ($\geq$100 mg $L^{-1}$), TP s ($\geq$20 mg TP mg $L^{-1}$), oxygen-demanding materials (BOD often $\geq$25 mg $L^{-1}$; see [204]), and harmful microbial pathogens (e.g., daily maximal *Escherichia coli* > 2500 colonies 100 $mL^{-1}$) [117].

Overall, the estimated N and P added to these sub-watersheds by human and livestock populations on an annual basis represent massive nutrient supplies for the nine sub-watersheds with substantial cattle and/or poultry. Watersheds with concentrated livestock populations have been reported to discharge 5- to 10-fold or more nutrients than watersheds in cropland or forestry [205]. The proportion actually reaching the reservoirs is outside the scope of this study, but would be higher for human population centers and livestock operations in close upstream proximity to the surface waters. In a major study of the Mississippi/Atchafalaya river basin, for example, agriculture was the dominant nutrient source, including ~18% from manures, followed by urban sources, including 13% from WWTPs and 8% from developing areas [206]. The proportion of N and P reaching surface waters from these sources increased from negligible to ~100% depending on proximity as well as other factors such as nutrient form and soil characteristics.

The southeastern USA region was previously evaluated as poor in use efficiency of agricultural P (ratio of outputs to inputs in sub-watersheds)—including northeastern TX, portions of MS, and much of AL, GA, and NC [207]. Northeastern TX and AL/GA areas drained by Guntersville and Lanier were assessed as poor in agricultural N use efficiency as well. Major human-related surplus N and P locations were often in areas of intensive livestock production. Such high-surplus N and P areas were described [207] as having a disproportionately degrading influence on downstream water quality, such as the drinking source-water reservoirs in this study. Kellogg et al. [208] similarly identified major areas of the Southeast as having exceeded the land's assimilative capacity for N and P due to excessive waste from livestock production.

As mentioned, abundant other sources of N and P, such as thousands of septic tanks, package sewage treatment plants, and atmospheric deposition, were not included in this analysis. For example, in Texas, ~20% of new homes rely on septic tanks, and nearly 70% of new wastewater is processed at package plants [209]. Even so, the sources of nutrients and associated pollutants considered here clearly threaten the water quality of the potable source-water reservoirs and increasingly challenge water treatment plant operators, especially in funding-limited facilities—which is, more broadly, a general problem in many geographic regions [3,210,211].

### 4.2. Reservoir Water Quality

Based on trophic state indices, five reservoirs were mesotrophic, all of which were relatively deep (median depth 12.2 m); the other nine shallow turbid systems (median depth 5.0 m) ranged from eutrophic (middle/lower regions) to hypereutrophic (upper regions). As expected, all reservoirs were characterized by bottom-water hypoxia/anoxia throughout the summer. Unexpected, however, was the extent: In all 14 reservoirs, more than half of the water column was hypoxic; moreover, hypoxia extended to surface waters in 8 reservoirs as a common occurrence (also see [8,212]). This finding from cast data supports an earlier published study with diel continuous data showing that all regions of Falls Lake commonly had hypoxic surface and near-surface waters [8]. The warm summer temperatures and widespread hypoxia/anoxia would be expected to limit available fish habitat in these reservoirs and to compress or "squeeze" the fish communities into warmer waters well above their thermal optima (sensu [213]).

Hypoxia is well known to stress and kill aquatic life [214,215]. Hypoxia affecting the entire water column has been described occasionally for reservoirs in other regions (e.g., [216,217]). Jones et al. [44] reported that in a representative year, 15 Missouri reservoirs averaged only a little higher than 4 mg DO $L^{-1}$ at the surface in late August. The reservoirs assessed here, in a warmer climate, apparently sustain more extreme conditions, which are expected to be exacerbated as climate warming progresses [4]. Surface/near-surface hypoxia has been described from limited depth profile data for other reservoirs in this region as well, such as Lake Houston, TX; Lake Mitchell, AL; and Lakes Marion, Moultrie, Murray, and Bushy Park Reservoir in SC (Table S1). For example, Bushy Park Reservoir, a major potable source water for the City of Charleston, SC, was sampled from September 2013 through April 2015 [218]. Surface hypoxia was documented at one or more stations in late July, early Nov., and late March based on morning measurements. In addition, on a late April date when both morning and afternoon measurements were taken, ~2 mg DO $L^{-1}$ was reported just below the water surface at one station throughout the day. Depth profiles available for 2019–2020 for Lake Wylie (Wateree), South Carolina (SC), documented < 2.5 mg DO $L^{-1}$ within 1.1 m from the water surface for two weeks in late September–October at a site near the dam where the depth was ~17 m [219].

The five reservoirs with sufficient continuous summer nutrient data for statistical trend analysis—W.F. George, Allatoona, Lanier, Jordan, and Falls—all significantly increased in algal biomass as chl*a* during the study, indicating that these potable source waters are continuing to become more productive. Of the two shallow eutrophic reservoirs, the chl*a* increase in Jordan coincided with a discernable but small increase in TN, whereas the chl*a* increase in Falls coincided with a significant increase in TP but a small decrease in TN. These data suggest that Jordan and Falls thus far are continuing to degrade, despite some recent positive management actions in Falls to decrease external nutrient inputs [194].

Shallow waters are usually more susceptible to eutrophication because of stronger sediment-water column interactions [220]. There is evidence, for example, of substantial internal N and P loading in Falls Lake from sediment accumulations over time [8,221]. Sidearms, shallower, often more protected from wind and wave action, and more poorly flushed than mainstem channel stations, can be especially prone to algal blooms fueled by incoming watershed nutrients and sediment legacy nutrient accumulations or extremely poor water quality from other incoming pollutants such as high suspended sediments from watershed development. The Lick Creek sidearm of Falls Lake exemplifies this phenomenon. In the watershed of this potable source water depended upon by ~600,000 people, lands draining into that sidearm have been dynamited to clear areas for new development [222,223] (Figure 12).

For most of these valuable potable source waters, the status of the primary producers is poorly described in peer-reviewed science publications or in reports for the general public.

Available evidence for aquatic macrophytes suggests that species richness and abundance are highest for exotic/invasive taxa known to thrive in turbid habitats affected by nutrient pollution and other stressors [176,224]. Algal blooms have mostly been poorly documented as well, although relatively sparse evidence suggests that they are common.

The Natural Resources Defense Council [225] developed a scorecard system to assess the quality of states' information on harmful algal blooms based on four categories: 1-accessibility of information; 2-response protocol and coordination; 3-data collection and use; and 4-public outreach. Qualitative scoring included excellent, good, satisfactory, poor, and fail. As of 2020, none of the states included in this study were scored as excellent in any category. Alabama "failed" in all categories; Georgia and Mississippi received a "good" for category 1 (accessibility of information) but otherwise "failed" (MS) or as assessed as "poor" (GA); and Texas "failed" in category 3 and was "poor" in the other categories. North Carolina received a moderate evaluation, with categories 1 and 3 "good", 2 (response) "poor", and 4 "satisfactory". Some states, such as North Carolina and Georgia, maintain databases on algal abundance and/or species composition for bloom events and have developed informational websites with general facts about blooms. According to the US EPA [226], summary reports by the states considered here to inform the general public about fresh-water harmful algal blooms as they occur and shortly after were not provided (TX, MS, AL, and GA) or were provided near the end of this study [227]. Other states in the region do not include potable source-water reservoirs (Louisiana, Florida), or their reservoirs did not meet the data requirements for this study (SC). Nevertheless, the potable source-water reservoir Lake Wylie (Lake Wateree), in SC, within the Catawba River watershed, is considered here as a special case.

Lake Wylie, assessed as eutrophic by the SCDHEC [228], is exemplary because it has a robust dataset on both planktonic and benthic harmful algae, building from a partnership among the SCDHEC's Harmful Algal Bloom Network, university specialists, the Catawba Riverkeeper, WaterWatch citizen scientists, Duke Energy employees, and various other entities. Excessive water-column N and P enrichment in Wylie has coincided with decreased DO and water clarity, elevated pH, and increasing cyanobacteria blooms both spatially and temporally, including toxigenic *Microcystis* [229]. In 20 experiments testing nutrient response, 12 (60%) indicated phytoplankton N + P co-limitation, and most of the rest indicated N limitation [229]. Wylie is also adversely affected by a benthic toxigenic filamentous mat-forming cyanobacterium, *Microseira* (*Lyngbya*) *wollei*. Its thick mats were first detected there in 2012. By 2019, more than 200 distinct benthic mats of *M. wollei* covered up to 60% of the total shoreline with ~$5 \times 10^6$ kg of biomass that exceeded 10 kg $m^{-2}$ in some areas [230,231]. Mats that drift into the shore and dry along the shorelines can release potent toxins into the adjacent water column [232]. For this harmful alga, legacy sediment P is much more important than water-column nutrient supplies; in fact, legacy sediment P was the only factor that realistically predicted its observed massive growth [231]. Lake Wylie is additionally infested with hydrilla and its (benthic) neurotoxic cyanobacterial epiphyte, *Aetokthonos hydrillicola* [133], a common condition for various reservoirs of all ages across the Southeast ([133] and references therein). The excellent work on Lake Wylie illustrates the importance of considering benthic as well as planktonic cyanobacteria in potable source-water reservoirs. Benthic toxigenic cyanobacteria are common in surface waters throughout the Southeast (e.g., Table 4—Lay Lake, and [147]). They appear to be increasing in distribution and abundance in other regions as well, and they are thought to be symptoms of freshwater ecosystem degradation [233,234].

The present study emphasized causal eutrophication variables N and P together with the response variable chl*a*, but also attempted to consider TOC. While N and P data were sparse for some reservoirs, TOC data were entirely lacking for six reservoirs. TOC is considered important because it helps guide potable water treatment. The US EPA [178] recommended TOC $\leq$ 4 mg $L^{-1}$ to avoid costly steps to remove appreciable carcinogenic trihalomethanes, formed by the reaction of higher TOC concentrations with disinfectant chlorine. Median TOC for the 8 reservoirs, 6.0 mg $L^{-1}$, was substantially higher than the EPA's recommendation; TOC was less than the EPA recommendation in only 3 reservoirs (W.F. George, Allatoona, and Lanier; medians 1.8–3.1 mg TOC $L^{-1}$).

### *4.3. Recommendations to Improve the Protection of Drinking-Water Reservoirs*

While human population growth, livestock growth, and related water demands increase across the Southeast [4], available evidence from this and other work (e.g., [8,231]) indicates that the region's vitally important potable source-water reservoirs are degrading. In general, these waters are poorly protected from contamination by nutrients and other pollutants from watershed urban and/or industrialized agricultural development. Most states in the region lack well-developed, comprehensive water policy and management plans for water budgets, organized central databases for monitoring and permitting water withdrawals, and other basic information [235]. Their human and livestock populations are mostly increasing, with escalating water demands projected as well as water shortages [180,209]. Unless major steps are taken to decrease the vulnerability of potable source-water reservoirs to watershed development, they should be expected to continue to degrade. The following recommendations are suggested to improve their protection.

Water quality protection in potable source-water reservoirs should be strengthened through more effective local, state, and federal regulation and enforcement. Presently, at the federal level, the US Clean Water Act addresses some issues about point sources and leaves others, as well as most issues about nonpoint pollution, largely unaddressed or approached through voluntary rather than required measures [236]. Protective measures are also needed at state and local levels, at a minimum, including land areas adjacent to the reservoirs. For example, land development ordinances commonly allow up to 70% IC in general and up to 50% IC in critical areas (e.g., [237]), much higher than is known to cause adverse impacts on adjacent surface waters (as mentioned, 2 to 4%) [194,195]. Massive pollution from industrialized livestock production is poorly regulated as well and requires major improvements in control of both point and nonpoint pollution [24,199,238]. States designate waters in protective-sounding categories such as "nutrient-sensitive", but after a waterbody develops noxious algal blooms, oxygen deficits, and fish kills, and watershed development is allowed to continue with minimal restrictions (e.g., [239]). Reporting requirements and regulations have been imposed on confined animal feed operations with a defined, large number of animals. Most operations produce livestock in numbers below that designated number, and those facilities as well as their pollutant contributions remain unknown or very poorly tracked by state and federal authorities [240,241]. Enforcement of environmental laws in the Southeast is also a serious problem [242]. For example, the major suspended sediments moving offsite from major land clearing and the resulting highly turbid Lick Creek sidearm of Falls Lake (Figure 12) show a common condition for many surface waters in the region: poorly enforced sediment erosion control regulations [243].

*Among the regulations needed for potable source-water reservoirs are protective numeric N and P nutrient criteria.* Development of such criteria was left to the states ~25 yr ago and remains mostly lacking [46], despite having been identified as critically needed to protect designated uses from further impairment due to nutrient pollution ([244], p. 8–2). Of the 14 reservoirs considered here, Eagle Mountain and Cedar Creek have TN and TP thresholds, but still for *narrative* criteria (0.08 mg TN $L^{-1}$, 0.07 mg TP $L^{-1}$) [245]. The three reservoirs in Georgia have excessive, non-protective site-specific standards for TN (W.F. George $\leq$ 3 mg $L^{-1}$; Allatoona and Lanier $\leq$ 4 mg $L^{-1}$) [47] relative to the US EPA's [48] recommendations (~0.3 to 0.35 mg $L^{-1}$). They also have "total lake loading per unit volume" standards for TP that are difficult to measure accurately or enforce.

All reservoirs except Ross Barnett have chl*a* standards that states have used as "surrogates" for excessive N and P, but such criteria are reactive and non-protective. There is commonly a lag period between TP and TN loads and supplies versus maximum phytoplankton response (e.g., [246]). Increased nutrient loads may not translate into increased algal biomass and related symptoms of nutrient pollution during the same season or year, depending on weather, water residence time, light, and other factors. Under conditions conducive to algal blooms, higher nutrient supplies—from external sources and/or accumulated legacy sediment N and P—then fuel noxious algal growth [247].

Potable source-water reservoirs should receive enhanced protection to improve public health safety through more concerted inventory, sampling, and realistic modeling. A central, comprehensive, well-organized repository accessible to the general citizenry should be established in each state for all of that information [209]. These reservoirs should be valued as sufficiently important to public health—not only by environmental and health agencies but also by the legislatures that control their dramatically reduced budgets—that their water quality is characterized by the states through consistent sampling, monthly or more frequently [248], continuously year after year. The data should be used to track reservoir eutrophication trajectories more accurately and to refine models (e.g., [249]) that can be applied to more reliably predict and alleviate climate change x pollution impacts.

Finally, strengthened protection of potable source-water reservoirs will require major improvements of both potable water and wastewater infrastructure, guided by plans to mitigate climate change impacts. Point sources such as municipal wastewater treatment plants are important to control due to their highly potent bioavailable N and P [35,36,250]. Yet, the southeastern USA is generally characterized by antiquated sewage treatment plants that have leaking infrastructure and discharge high concentrations of bioavailable N and P [5,116,195,209]. Similarly, much of the drinking water infrastructure throughout the Southeast is decades to more than a century old, losing 20–50% of treated water to leaks and breaks [209], needlessly wasting potable water while the source-water reservoirs sustain increasing demands [4]. The present infrastructure status is also contributing to their water quality degradation. Over the past 5 yr, more than 2700 notices of violation were issued for WWTPs in Mississippi, for example, and increasing wet weather, insufficient funds for maintenance, and a lack of rehabilitation pose what were described as "extreme threats" to wastewater infrastructure [209]. Most of the populations of these southeastern states, with the exception of GA, live in communities without any dedicated source of funding to improve stormwater quality [209]. The general neglect in state budgets for water-related infrastructure is reflected in the lists of impaired waters As of 2016, more than 3000 miles of AL rivers and streams and more than 60% of its lakes, reservoirs, bays, and estuaries were too polluted to support designated uses such as fish and wildlife habitat, recreation, fish consumption, and drinking water supply. About 60% of 14,415 miles of streams and rivers in GA, and about 80% of its lake and reservoir areas, are impaired and not supporting designated uses due to violations of one or more water quality standards [209]. Funding for significant improvements in water-related infrastructure in this region has been needed for decades and is now estimated by the US EPA to be in the multi-billion USA dollar range.

The American Society of Civil Engineers (ASCE) [209] assessed infrastructure status in the Southeast based on traits germane to this study, including wastewater infrastructure (D/D+), drinking water infrastructure (B- for Georgia to D for Mississippi; overall, C), condition of dams (D), and, for some states, stormwater controls (D+). The overall grade was "D", defined as "POOR: AT RISK–the infrastructure is in poor to fair condition and mostly below standard, with many elements approaching the end of their life service. A large portion of the system exhibits significant deterioration. Condition and capacity are of significant concern with strong risk of failure".

The ASCE report noted, as well (e.g., [209], p. 25), that "a degree of wishful thinking" seems to underlie states' stances on climate change. Thus, in addition to major funding, a second critical need in water-related infrastructure to protect potable source-water reservoirs in the Southeast is realistic planning for climate change that is already seriously affecting the region. As examples of present conditions, the Texas state government continues to deny human-related climate change [251,252]. Texas is now second only to Louisiana among USA states in funds paid for flood claims due to hurricanes and other major storms [253]. Texas sustained 11 presidentially declared disasters associated with flooding from 2015 to 2019, and from 2016 to 2019, the number of sanitary sewer overflows more than doubled, from 2500 to almost 6000 [209]. Such events add massive pollution to surface waters and therefore threaten potable source waters like Eagle Mountain and Cedar Creek. The high runoff also overwhelms water treatment systems and causes wastewater pump stations to fail. Wastewater and stormwater infrastructure is generally lacking or outdated by decades and failing in other states as well. Much of it has been assessed as not designed or sited to withstand increasing flooding and related damage from major storms as climate change progresses [180,209].

### 4.4. Classic Eutrophication Parameters and the Eutrophication Trajectory

Little improvement has been achieved in the protection of drinking-water reservoirs or their watersheds in most of the USA over the past few decades [211,254]. Watershed development continues generally unrestricted, whether point sources are industrial or municipal, because development is prioritized over drinking-water reservoir protection (e.g., [211,254]). These present realities exemplify what Berke et al. ([254], p. 450) described as "…continual resource degradation is a predicable outcome of failure by local government to account for entire ecological units when designing and implementing environmental policy".

Chlorophyll, nutrient concentrations, DO, and—where sufficient data are available—the eutrophication trajectory continue to be valuable for assessing reservoir ecosystem health and for guiding management actions to strengthen water quality protection. Nutrient pollution co-occurs with many chemical and microbial pollutants harmful to human health in both agricultural and urban settings [255,256]. Contaminants that directly affect human health are commonly elevated, as are nutrients, in waters that drain urbanizing areas [211,255]. Dissolved oxygen is critically important for aquatic life; nutrients fuel algal blooms and strongly affect DO; the buildup of toxic substances such as hydrogen sulfide in bottom waters and sediments; sediment retention vs. release of metals and other toxic materials; and summer chlorophyll from high-biomass cyanobacteria blooms exacerbate system hypoxia and, if toxic, also directly harm wildlife, pets, and humans [176]. Eutrophication, specifically N + P co-enrichment, was also experimentally related to an increase in a common taste-and-odor substance, supporting the authors' suggestion that decreasing nutrient pollution "at the watershed scale" could minimize off-flavor substance production while also improving reservoir ecosystem health and aesthetics [257]. Drinking source-water quality is strongly influenced, directly and indirectly, by eutrophication. The eutrophication trajectory remains a strong overall indicator of pollution and overall system health as watersheds draining into drinking-water reservoirs are allowed to continue to develop, with major point sources in close proximity and minimal restrictions on nonpoint source pollution.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15224007/s1, Table S1: Reservoirs assessed as unsuitable for inclusion in this study; Table S2: Sampling years and frequency, sites, and parameter *n* values by reservoir. References [258–260] are cited in the Supplementary Materials.

**Author Contributions:** Conceptualization, methodology, validation, formal analysis, investigation, visualization, and writing—review and editing, J.M.B., C.A.K. and E.H.A.; resources, project administration, and funding acquisition, J.M.B.; data curation, C.A.K. and E.H.A. All authors have read and agreed to the visualization and writing—review and editing, J.M.B., C.A.K. and E.H.A.; resources, project administration, and funding acquisition, J.M.B.; data curation, C.A.K. and E.H.A. All authors have read and agreed to the published version of the manuscript.

**Funding:** Funding support was provided by the City of Raleigh Public Utilities (Projects 528598-555915, 557545-558573, and 582470), the National Institute of Food and Agriculture (Projects 02601 and 02855), and the USGS/NC Water Resources Research Institute (Project 18-03-W).

**Data Availability Statement:** The data presented in this study are available upon request from the corresponding author, except for chlorophyll data from Falls Lake (in the process of being published as part of a graduate student's Ph.D. research), and Lake Norman data (used with permission from the Duke Energy Environmental Center).

**Acknowledgments:** We are grateful to our colleagues in the Center for Applied Aquatic Ecology for assistance on the Falls Lake component of the project, especially to Jenny James, Linda Mackenzie, Robert Reed, Josh Mathis, Joy-Lynn Rhoton, Nicole Lindor, Gail Blake, Susan Gauthier, and Dena Haugley. The manuscript was improved by helpful comments from Mike Mallin (UNC Wilmington), and by provision of data for Lake Norman from Julie E. Stahl and Maverick Raber (Duke Energy Environmental Center).

**Conflicts of Interest:** The authors declare no conflict of interest.

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