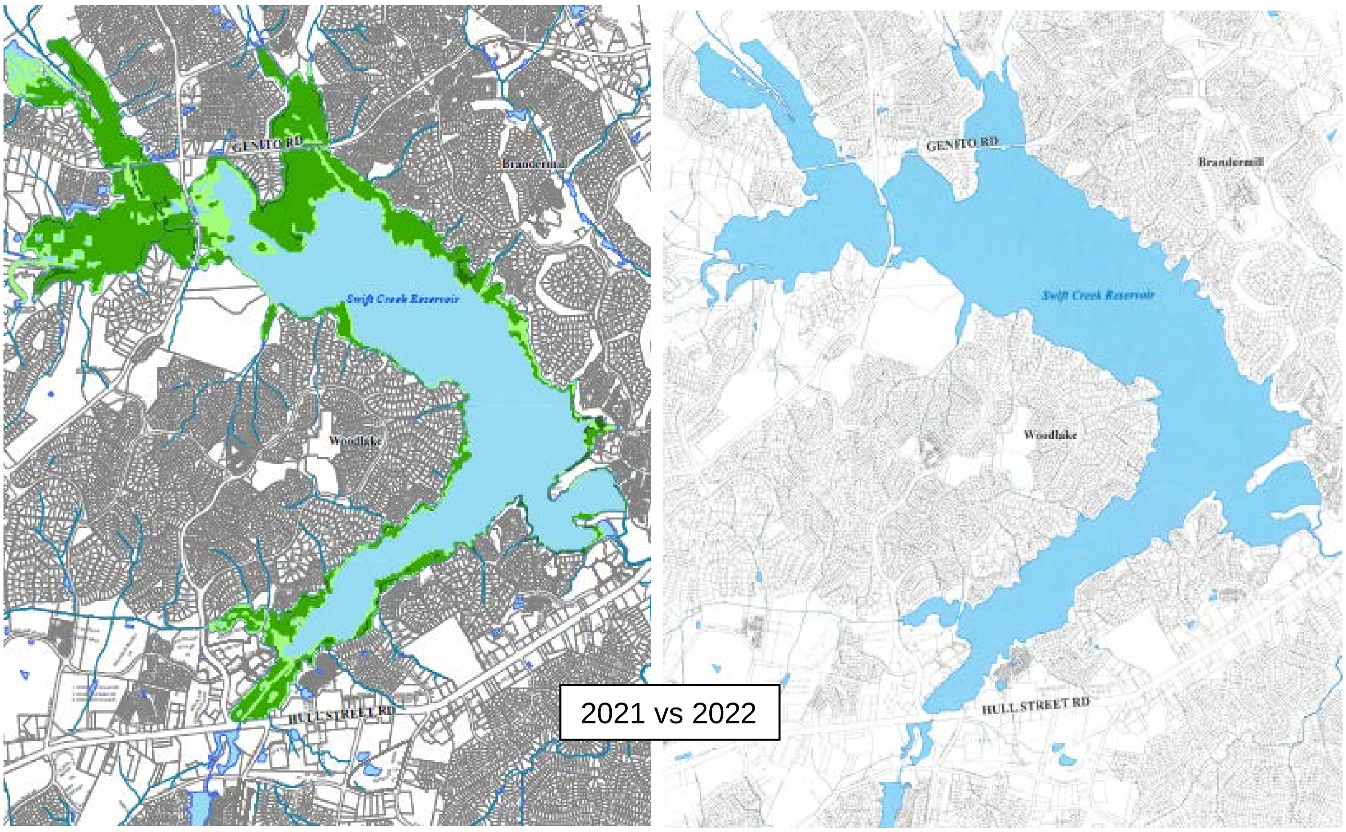
Swift Creek Reservoir Hydrilla Management Progress Update



Final Report

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Water Resource Services

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Project Background

Swift Creek Reservoir is a 1,700-acre (680 hectare) water supply impoundment serving Chesterfield County. It is located approximately 20 miles southwest of Richmond, Virginia. The watershed for Swift Creek Reservoir covers 61.9 square miles (roughly 40,000 acres or 16,000 ha). The reservoir was constructed in 1965, holds approximately 5.2 billion gallons (16,000 acre-feet) of water, and provides approximately 7.5 million gallons (23 ac-ft) of water to residents of Chesterfield County each day. It is relatively shallow (Figure 1) with a mean depth of 9.4 ft (2.9 m) and a maximum depth of just over 20 feet (6 m). The reservoir provides a variety of recreational opportunities, including electric and non-powered boating and fishing for what can be trophy sized fish, and is very popular for those uses. Contact recreation such as swimming is not permitted in this reservoir, which was constructed with its primary purpose as potable water supply.

Hydrilla verticillata (hydrilla) was first identified in the Swift Creek Reservoir in the summer of 2009. An estimated 842 acres, or approximately 50 percent of the reservoir, was covered with hydrilla by October of 2010, with dense mats of hydrilla in virtually all areas <8 feet (2.4 m) deep in the northern arm of the reservoir. Little hydrilla was found in the southern arm as of 2010, but this invasive plant continued to expand along the shallow margin of the reservoir. Low light restricts growth in Swift Creek Reservoir, such that only about 900 of the 1,700 acres would be considered susceptible at current light penetration levels. Yet this elevated level of peripheral submerged aquatic vegetation coverage can limit non-water supply uses of the reservoir and numerous complaints from the public were received. From a water treatment perspective, the Utilities Department had concerns for organic loading should a sudden massive die back of hydrilla occur, but dense vegetation near inlets tends to minimize suspended solids in the reservoir and is beneficial for water supply. Additional concern over the possibility of a toxic cyanobacterium growing on hydrilla has been expressed but limited testing found none of that cyanobacterium. The combination of hydrilla limitation on some public uses of the reservoir combined with Utilities Department acknowledgment of hydrilla as an invasive species with a variety of possible negative impacts led Chesterfield County to seek appropriate control strategies.

The full range of options was considered in a process sponsored by Chesterfield County but involving considerable public input. It was determined that the most appropriate option was stocking sterile grass carp, a biological approach with a successful track record for plant control in the southern USA. It was expected that most or even all plants in the reservoir would be eaten, but the loss of recreational utility without controls was considered severe enough to warrant action. It was also expected that some increase in algae might be experienced, but the treatment facility was expected to be able to handle this aspect of incoming water quality if the increase was not too severe. Copper sulfate treatments in parts of the reservoir for algae control were already common over the preceding decade, and the treatment system was considered up to the task of purifying the drinking water supply. Given the variability in results from almost any biological control of rooted plants and the ability of hydrilla to grow quickly and expand rapidly, additional local controls were expected to be needed, potentially including benthic barriers and/or mechanical harvesting.

A total of 10,500 grass carp were stocked in the reservoir in April of 2010. The average size for the stocked grass carp was roughly 12 inches (305 mm) in total length and the average weight was about 1.3 pounds (591 grams). The stocking rate was 6 fish per acre of reservoir, or 15 fish per vegetated acre (nearly all hydrilla), which is near the high end of the recommended stocking rate

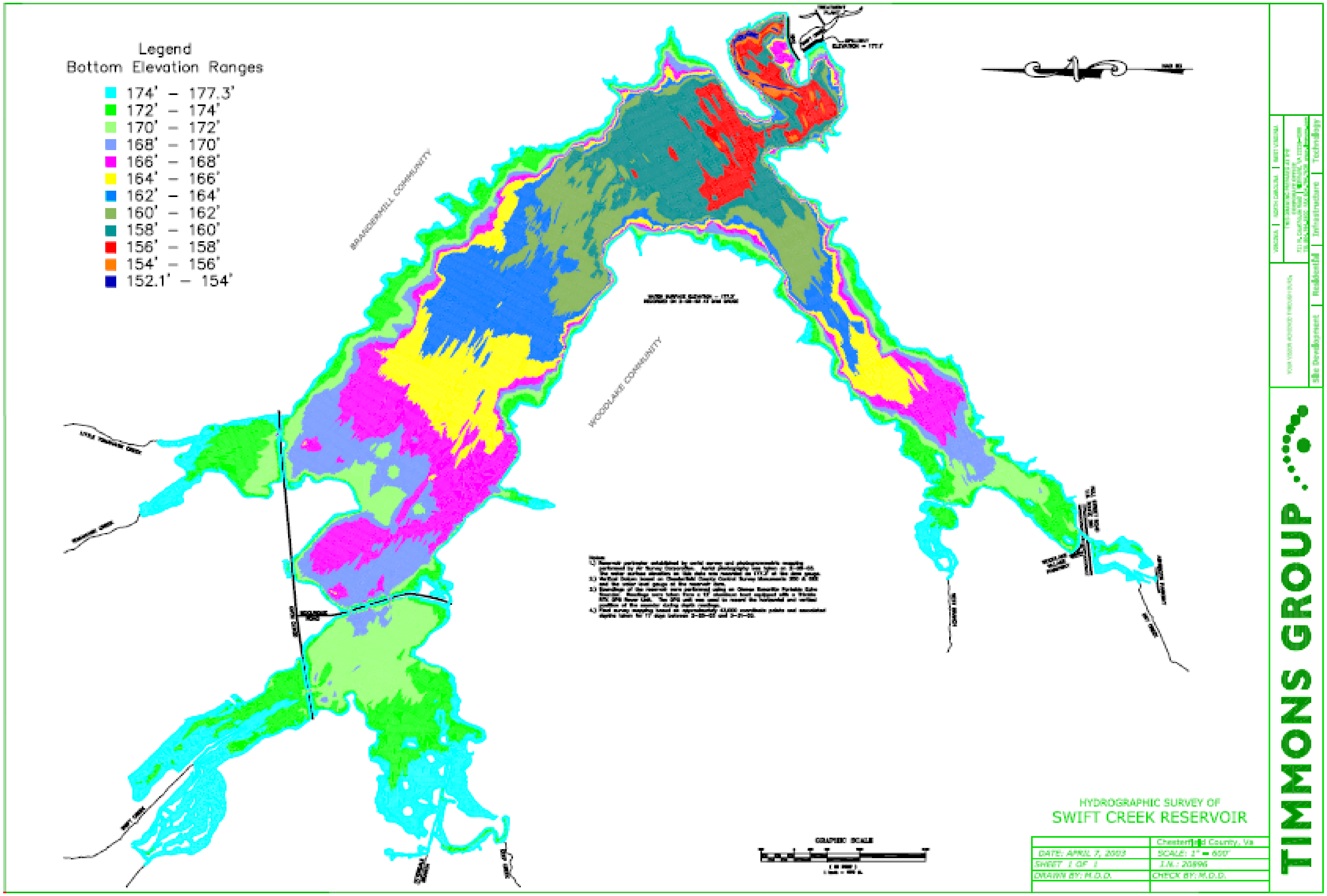


Figure 1. Bathymetry of Swift Creek Reservoir (2003)

range and was expected to allow for faster control of hydrilla growth. Plants, fish, and water quality have been monitored since the stocking of grass carp, and this report summarizes the results of those assessments.

Plant growth in the reservoir was negligible in 2011-2013; while it took a full year after stocking, grass carp at the initially stocked density collapsed the plant community. No further stocking was conducted in 2011-2014. Resurgence of hydrilla was observed in 2014, although coverage and biomass were not extensive. A total of 1,000 grass carp were added in spring 2015 to bolster the population of this sterile fish, a quantity estimated to suppress hydrilla growth without causing a complete collapse of the plant community. However, hydrilla resurgence continued and coverage reached 776 acres by August of 2015, some of it very dense.

An additional 3,000 grass carp were stocked in spring of 2016. The actual number of fish stocked represented just under 4 fish per vegetated acre from the maximum 2015 hydrilla coverage. Added to an unknown number of surviving grass carp from past stockings, it was hoped that adequate control might be achieved in 2017 after a year of grass carp growth. The problem is that the grass carp population is difficult to survey and when vegetation crashes, mortality and/or emigration are expected to increase but are largely unpredictable. The plant community was severely depressed in 2016, the same year that 3,000 grass carp were stocked and one year after 1,000 grass carp were stocked. This seems unusual as it normally takes at least a year for stocked fish to grow and have a pronounced impact. Other uncertain factors may have been at least partly responsible for the plant decline in 2016, and low light from high turbidity was a likely influence.

A thorough review of all collected data was conducted in 2017 to determine if a more scientific approach was possible. An index of hydrilla abundance was set up whereby low, medium and high-density growths were accorded different weighting factors, incorporating plant density into the coverage assessment to better reflect hydrilla abundance and the need for control. Hydrilla is very difficult to eradicate and limited coverage at the range of possible density may be the best situation that can be achieved. A model was set up to track plant community features and relate it to estimated grass carp population numbers and biomass, but with the grass carp population uncertain except for any recent stocking, there is high uncertainty in such relationships. The best data-based approach is to stock more grass carp if hydrilla coverage rises and fewer if it declines, but there may be at least a one-year delay in any measurable response. The model helps to refine how many grass carp to stock, but its accuracy is limited by uncertainty associated with grass carp mortality and emigration.

Because grass carp potentially live for many years, stocking too many can cause the plant assemblage to crash and stocking over at least a five-year period appears desirable, building a more stable population of multiple year classes of sterile fish. Chesterfield County, with the aid of WRS Inc., has been working toward a more balanced approach using grass carp since 2016, using models and actual data to assess the target level of grass carp biomass to achieve realistic goals for plant control. While there is inherent variation in biological control efforts that makes precise predictions very difficult, a logical scientific approach is being applied to maximize results. No grass carp were stocked in 2017 since plant coverage was minimal at the end of summer 2016 and the model indicated no fish addition was needed, but 500 fish of 12 to 15 inches were stocked in April 2018, 600 grass carp of 12 to 18 inches were stocked in April 2019, and 600 more at 12 to

18 inches were added in April 2020. This built a multi-age population that might be expected to provide greater stability in the control effort. Annual review of the accumulated data from ongoing monitoring has been conducted to inform management decisions each year.

Hydrilla coverage was higher than desired but fairly stable and not extreme on a reservoir-wide basis in 2018-2020. 2010 remains the worst year on record for the 14 years of the program, with 842 acres of hydrilla coverage. 2018-2020 were the 8th, 7th, and 6th worst years on record with hydrilla coverage between 474 and 585 acres. It is understandable how some residents would perceive conditions as being as bad or worse than ever because of the localized growths near their respective properties, but lakewide data are necessary to a fair assessment.

Some efforts at localized control have been attempted, mainly be installation of benthic barriers but the effort has been nominal overall. Any perception that all plant issues can be addressed solely by grass carp stocking should be discarded; the variability from biological controls is higher than any physical or chemical approach and complete control translates into overstocking on a regular basis. Such overstocking leads to a near absence of plants in the reservoir, an undesirable situation for both habitat and water quality. Secondary control measures by residents or homeowner associations will be needed to supplement grass carp as the primary hydrilla control mechanism.

Floods in 2018 and 2020 were large enough to allow grass carp to escape downstream and added considerable uncertainty to population estimates based on average expected mortality of 20% per year. Loss estimates were increased when the plant community collapsed or floods occurred, but the losses may have been even greater than estimated. Despite stocking 1,250 grass carp in 2021, more than double the rate of the previous three years, hydrilla expanded in 2021 and while still less than at the start of the program in 2010, coverage was the highest observed since 2015 and clearly not conducive to some non-supply uses of the reservoir. Chesterfield County has invested in a barrier to enhance fish retainment during floods and continues the grass carp stocking program, but the object remains to maintain some level of vegetation in the reservoir and overstocking should be avoided. Any collapse of the plant community may translate into a loss of grass carp by emigration or starvation, inducing additional uncertainty to any abundance predictions and necessitating a restart of the process to build a more stable, multi-year population of grass carp.

A residents' group, dissatisfied with conditions and the program as applied by Chesterfield County, sought input from scientists at the North Carolina State University, where considerable effort has been put into grass carp program research. A model developed for North Carolina lakes suggested a range of possible stocking rates, mostly higher than what has been done at Swift Creek Reservoir in recent years, but the overall approach is different. The NC Stocking Model recommendation is to stock enough grass carp to severely depress hydrilla but then to plant vegetation resistant to grass carp or create exclosures where other vegetation can grow without being consumed by grass carp. The NC model approach uses grass carp as one tool in an overall effort to shift the plant community from hydrilla to other species and is based on the premise that hydrilla should be eradicated or at least suppressed to the greatest extent possible as an invasive species. This is different from simply stocking grass carp to depress hydrilla abundance and requires considerably more effort and funding. It is also not an approach that has yielded widespread success to date, the ecology of hydrilla making it very hard to eliminate.

Considering the available data and models, the recommendation for grass carp stocking in 2022 from WRS was up to 3,000 fish. The decision-making process for carp addition has been subject to public pressure each year. A new local group had even suggested abandoning the model in favor of following a North Carolina State University group's suggestion of attempting to eliminate all hydrilla. The group's report detailed adding between 3,400 and 9,500 carp in 2022. Chesterfield County Utilities (CCU) rejected the conclusions of this report and proceeded with the current SCR model. CCU did go above the model's projection of adding 3,000 grass carp and added 3,500 grass carp, but at the time this was not predicted to crash the hydrilla population. The unknown variables complicating carp addition was carp loss due to the 2018 and 2020 floods and holdover grass carp stocked as far back as 2018.

In 2022 there was very little hydrilla present in May or June and none for the remainder of the year. Other plants were restricted to yellow water lily and pickerelweed, two species not preferred by grass carp. While mortality of grass carp under food-limiting conditions may allow more plant growth in 2023, increased size by those carp remaining may still exert enough pressure to minimize plants in the reservoir, especially with a starting point of no vegetation. Uncertainty is now too high to make reliable predictions for 2023.

As hydrilla has not proven to be a problem for the water supply function of Swift Creek Reservoir, and may in fact provide some water quality benefits, there are practical reasons to ensure the plant community does not collapse. Most interested parties would prefer that hydrilla not be present, but a substantial plant community is important to water quality and to fishing, whereby those wishing to have unfettered boat access may prefer to minimize all plants in the reservoir. Increased grass carp stocking appeared justified in 2022 but exceeding the carrying capacity of the reservoir for grass carp and minimizing the plant community is not consistent with multiple use goals. It takes time to develop a track record for plant management and typically more than one tool is required to achieve optimal conditions. Modelling helps support management decisions but is unlikely to provide accurate results and the use of data, in this case plant community features, is the most reliable support for decisions. Time lags in response dictate that conditions in some years will be better than in others and the use of localized control methods is strongly advised for ensuring adequate conditions for non-supply uses. This report updates the record and recommends actions for the next few years.

Plant Community Results

Plant data have been generated by the staff of the treatment facility for CCU. The plant community changed little in the first 6 to 12 months after grass carp were first stocked, consistent with experience elsewhere, as the smaller fish find it difficult to feed on dense hydrilla and avoid shallow water due to the threat of predation. The fish were eating and growing but did not have the total biomass to exert enough feeding pressure to make major changes in plant density. A year later, in spring of 2011, they reached a population size distribution that limited fear of predation and facilitated consumption of all hydrilla stands in the reservoir. The high stocking rate translated into rapid consumption of plants. As a result, hydrilla density plummeted, as did the density of most other plants (Figures 2-4). Yellow water lily (*Nuphar variegata*) was little affected by grass carp, and yellow floating heart (*Nymphoides peltata*) appears to have invaded the reservoir more

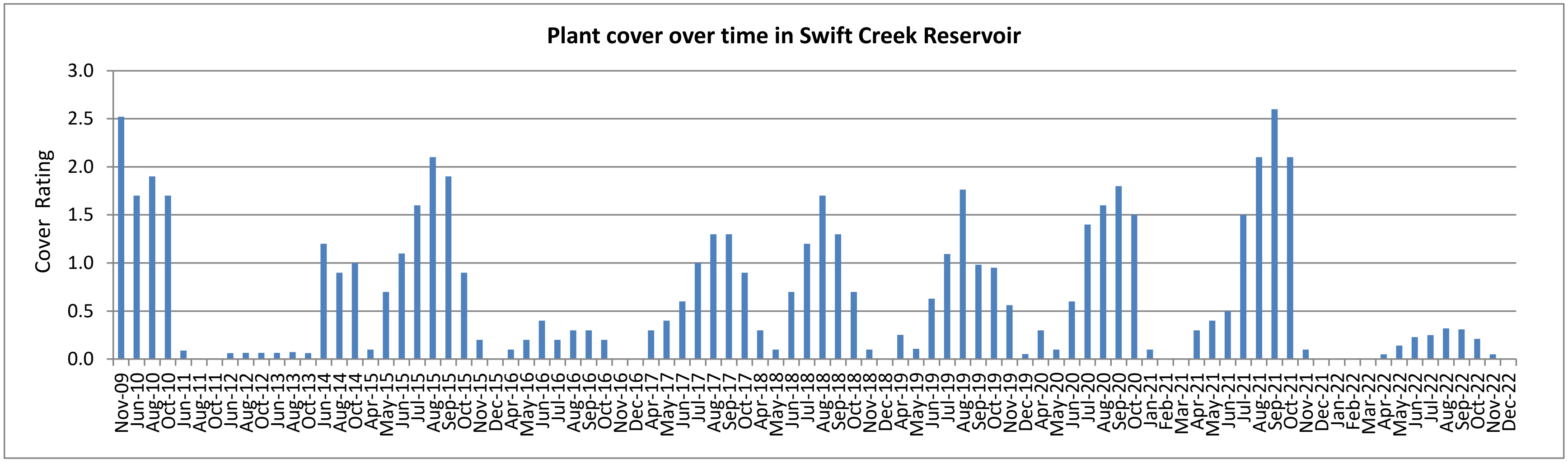


Figure 2. Total plant cover in Swift Creek Reservoir, 2009-2022.

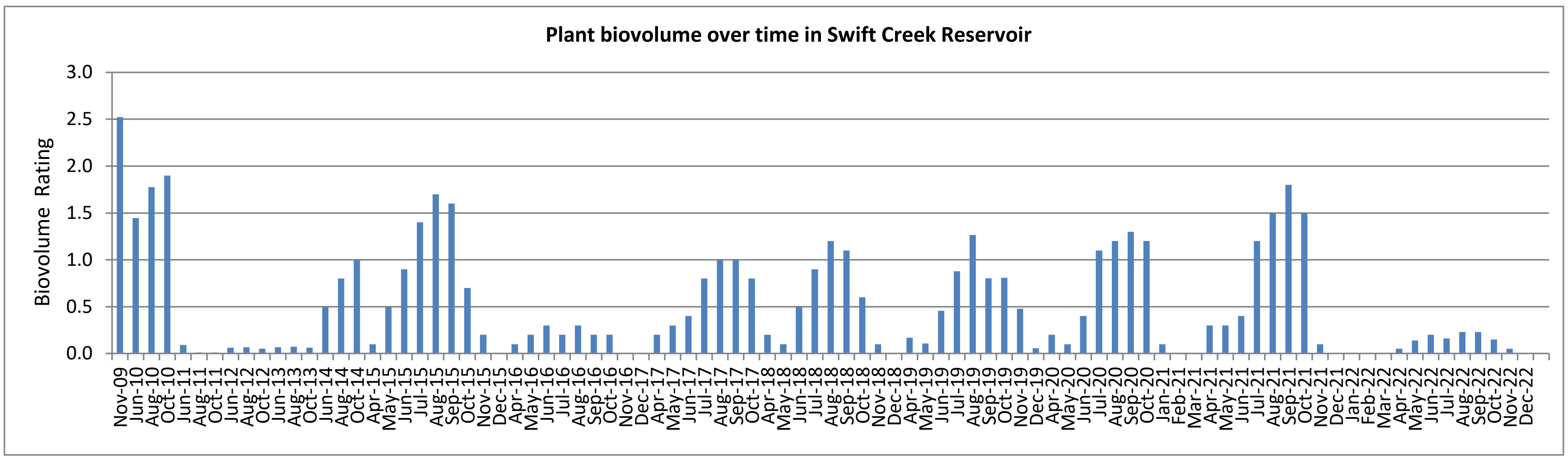


Figure 3. Total plant biovolume in Swift Creek Reservoir, 2009-2022.

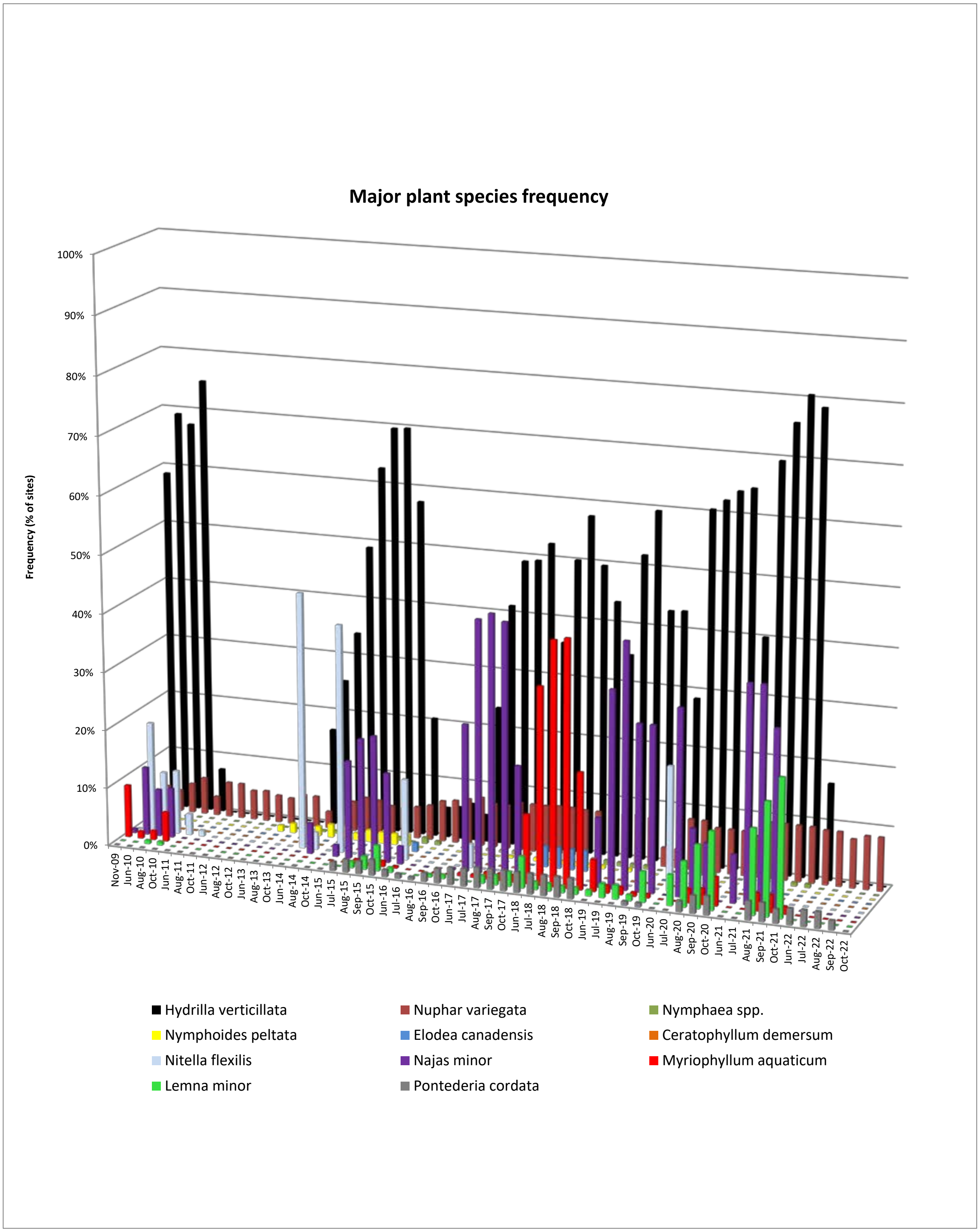


Figure 4. Frequency of plant species occurrence in SCR, 2009-2022.

recently, but all other species were virtually absent by late 2011 and remained absent through 2013 (Figure 4). Yellow water lily and yellow floating heart were found at only low abundance, so the plant community of Swift Creek Reservoir was minimal at the end of 2013. This was consistent with experience elsewhere with high grass carp stocking rates.

Grass carp have been observed feeding all over the reservoir, including in very shallow water once they have attained substantial size. They effectively minimized plant density until lowered grass carp population density decreased grazing pressure to the point where plants could grow. The rating categories in Figures 1 and 2 represent quartiles, with 1 = 1-25% (either cover or biovolume), 2 = 26-50%, 3 = 51-75%, and 4 = 76-100%. Fractional values <1 indicate a substantial number of 0 values (no plants), and all values for cover or biovolume were <0.1 between June 2011 and October 2013. Only a few plant species are not susceptible to grass carp herbivory, and those tend to be shallow water plants with floating or emergent leaves, not likely to take over large expanses of this reservoir. Plant biomass control through biological means was clearly demonstrated and was accomplished in just over one year after stocking. Approximately 16 months after initial stocking the reservoir had no detectable hydrilla plants present and was largely devoid of other vegetation.

While eradication of hydrilla is desirable, loss of all plants is not, and the lack of food for grass carp (as well as other plant eaters) can be expected to reduce stability in the reservoir. This can have negative impacts on water quality and the gamefish community. Maintaining some plant cover for multiple purposes is therefore desired. Many fish species depend on rooted plants for cover, invertebrates that represent valuable food for small fish associate with rooted plants, and dense plant assemblages can filter particulates from the water, a benefit to the water supply function of Swift Creek Reservoir. The absence of any significant vegetation in the reservoir caused a delay in any restocking of grass carp and considerable debate over how many grass carp to stock. Hydrilla demonstrated some resurgence in 2014 (Figure 4), as did a few other plant species, indicating that the number and/or biomass of grass carp had declined to a point at which plant control was no longer complete.

In June of 2014, approximately 9% of the reservoir had low growth of hydrilla, 1% had medium growth, and 0% had heavy growth. By October of 2014, 15% of the reservoir had dense hydrilla growth and another 5% had medium or low growth. A specified desirable level of plant growth, independent of the type of plants, is difficult to set, but between 10 and 25% cover or biovolume is believed to be acceptable from a multi-use perspective of Swift Creek Reservoir. Ideally, the total acreage of reservoir with hydrilla growth would be <25% or 425 acres while the acreage exhibiting medium to dense growth would be no more than 10% or 170 acres. Those criteria were met in 2014 through August. Total hydrilla coverage was below 25% at its peak in October but the coverage by medium to dense growths was higher than desired at about 18%. Growth accelerated in late summer, showing how fast hydrilla can regain dominance in the absence of adequate control. While hydrilla density was higher than desired at the end of 2014, the range of conditions in 2014 was within an acceptable range a majority of the growth season. Hydrilla died back over the winter of 2014-2015, as it does in most years at that latitude, but resurgence in 2015 was expected.

There are considerations for hydrilla distribution, with more plants preferred near the inlets for water quality management and less desired in the nearshore zone in the main body of the reservoir for recreational and aesthetic reasons. Managing for less dense hydrilla growth remained a need, and knowing that continued increase of hydrilla was likely, grass carp were again stocked in April 2015. Concern over excessive stocking and complete plant loss, with an inadequate track record to make an accurate prediction, lead to only 1,000 juvenile grass carp being stocked. However, as newly stocked grass carp tend to exert very limited pressure on plant biomass, hydrilla continued to resurge and covered almost as much of the reservoir by late summer 2015 than it had before any grass carp were stocked (Figures 2-4). Hydrilla died back again at the end of 2015, possibly aided by some grass carp feeding, but winter die back appears to be the norm north of the Carolinas.

With hydrilla continuing to resurge, a total of 3,000 additional grass carp at 12-15 inches were stocked in April of 2016. Added to the biomass of grass carp stocked in 2015 and any holdovers from 2010, this was speculatively anticipated to reverse the increasing trend in hydrilla abundance. Hydrilla abundance dropped off sharply (Figures 2-4), although it is not clear that grass carp were completely responsible for the hydrilla decline in 2016. Water clarity was lower in 2016 than in previous years of monitoring and may have reduced submergent plant growth. There were patches of hydrilla at all abundance levels, but 80% or more of survey sites had no hydrilla. This was not as complete a crash as in 2011, but hydrilla abundance was greatly suppressed. Hydrilla cover peaked in June at 150 acres (9%) and moderate to dense growths reached a maximum of 22 acres (1%) in August. Again, variability with biological control of a rapidly growing invasive plant species will be high and stability is likely to be low, but the 2016 plant community was close to being eliminated. Elimination would mean starvation and likely escape attempts for grass carp and inadequate habitat for many aquatic species.

Grass carp were not stocked in 2017, given that the 4,000 grass carp stocked in 2015 and 2016 were expected to grow and exert additional grazing pressure on the plant community. Given low plant abundance in 2016, it seemed likely that similar or less dense conditions would be observed in 2017. However, hydrilla was resurgent in 2017, reaching total cover of 588 acres, which is 35% of the reservoir area and 65% of the expected maximum coverage of about 900 acres, some areas being too deep to support plant growth. Moderate to dense patches occurred over 245 acres (14% of reservoir area, 27% of expected maximum coverage area). Common naiad (*Najas flexilis*) was also frequently encountered (Figure 4), and the frequency of a few other native species increased slightly. Naiad is a preferred food for grass carp, so these data suggest that grazing pressure was not extreme and that either the lower hydrilla abundance in 2016 may not have been due to grass carp alone or that a significant number of carp died or emigrated. Hydrilla cover and density in 2017 was above the desired range, but not to an extreme. The overall condition of the reservoir with regard to aquatic plants appeared favorable for fish and other water-dependent species. Density along shore in many areas where people would prefer open access was higher than desired, suggesting that additional control techniques may be necessary on a localized basis.

Considerable effort was devoted to data analysis and projections for results with different carp stocking schedules at the end of 2017. While many programs stock enough grass carp to greatly depress target vegetation and wait until the grazing pressure is virtually gone before restocking, the potential exists to establish a multi-aged grass carp population through smaller annual stocking rates that should be able to achieve a desired level of control without wiping out all vegetation. Only a few programs are working towards this goal, and none have yet maintained stable conditions for more than a few years. Yet creating and sustaining a more stable grass carp population is viewed as a valid approach to managing Swift Creek Reservoir.

Based on a model developed to bracket likely consequences of varied grass carp stocking rates, an annual stocking rate of 500 to 600 fish was proposed with occasional increases to as much as 2,000 grass carp as warranted by expected carp loss from advanced age, possible starvation, or escape. The latter two influences should be minimized by not allowing the plant community to collapse under excessive grazing pressure but aging out of fish from higher stocking levels in past years remains an issue. Floods that enhance escapement also represent a problem for stable plant management by biological means. The floods of 2018 and 2020 appear to have allowed a significant number of grass carp to pass downstream but there was no way to determine how many, adding uncertainty to any grass carp population estimate.

In developing the model, the range of both hydrilla coverage and density was considered. Having low density cover is perceived as acceptable for all uses, while medium and high-density cover may represent problems, although areas of low, medium and high-density cover are likely to be present when hydrilla growths are significant. To incorporate the range of cover and density in a single model variable, an effective cover rating system was devised. The ratio of biomass among low, medium and high-density areas was established based on the values obtained in the monitoring program over 10 years. Low density areas are normalized to a value of 1.0, while medium density growths are represented by a value of 1.77 and high-density growths are assigned a value of 2.33. In this system, an acre of medium density cover is worth 1.77 acres of low-density cover while a high-density acre is worth 2.33 acres of low-density cover. Therefore, cover of 100 acres by only low density growth would be listed as effective coverage of 100 acres, but 100 acres of medium density cover would be listed as 177 acres of effective coverage and 100 acres of high density cover would be listed as 233 acres of effective cover.

Based on the observed distribution of hydrilla over a decade and its effect on various lake uses, a goal of 10 to 25% effective cover was established. This goal can be revisited with adequate data but was chosen because it represented a range of coverage and density that should be achievable without wiping out the plant community in any year. This translates into more acres of low-density cover being allowable than for medium density cover than for high density cover. The highest effective cover values observed were prior to the start of grass carp stocking and in the first year (2010), with values slightly higher than 1,400 acres as effective cover. In reality, <850 acres of the reservoir actually supported hydrilla growth, but many of those acres had medium to dense growths, boosting the effective cover rating. Using this system, an effective cover rating of 650 is about as high as can be tolerated without widespread impairment of reservoir uses, while a rating less than about 260 suggests too few plants in the reservoir to support a healthy ecological system. If plants other than hydrilla can become established, the target for hydrilla coverage can be reduced, but plants are needed in this system to best support its full range of uses.

From a decade of experience with Swift Creek Reservoir it was believed that an effective biomass of grass carp between about 14,000 and 16,000 kg will keep the effective hydrilla cover in the target range. Depending on the size distribution, this will equate to about 4,000-5,000 actively feeding grass carp and provides a moderate to high number of carp per vegetated acre if control is achieved. However, both grass carp and hydrilla are biological organisms with ecological attributes that introduce variability over time and space, so maintaining stable conditions is not realistic. We are managing for a range of hydrilla cover and density that is intended to satisfy a range of reservoir uses on an extended timeframe. Other programs have often focused on just the number of grass carp believed to be in the system; the NC model follows this pattern and adjusts cohort classes due to mortality and emigration. Some models also assign consumption factors to fish at different ages to represent variable, age-based, feeding levels. The model developed for the Swift Creek Reservoir by CCU and WRS staff uses biomass as a surrogate for age and consumption rate, but ages fish out at 8 years, considering their contribution to grazing to be minimal after that time. CCU performed an alternative analysis with the same mortality assumptions as the existing model with age and consumption, and the results were similar to those of the existing model.

Based on the developed model, 500 grass carp of 12-15 inches were stocked in April of 2018 and 600 grass carp of 12-18 inches were stocked in each of April 2019 and 2020. Grass carp from previous years were estimated based on 20% mortality per year with increased but undocumented loss assigned if the plant community was eliminated or a flood occurred. The intent was to monitor the plant community and adjust the stocking rate as needed, but to focus on building a grass carp population with multiple year classes through smaller annual stocking rates.

Plant cover and biovolume (Figures 2 and 3) in 2018 through 2020 were similar to values in 2017 and the target for effective hydrilla cover and was slightly exceeded (Figure 5). Overall cover by hydrilla was lower in 2018 and 2019 than in 2017 but the coverage by moderate to dense patches was slightly higher, leading to similar effective cover ratings. Overall cover in 2020 was higher than in recent years but the coverage by high density growths was lower, again leading to a similar effective cover rating. Localized problem areas existed around the periphery as expected where dense patches sometimes interfered with human use of the reservoir and overall coverage was higher than desired, but stocking was not increased in an effort to avoid collapsing the plant community.

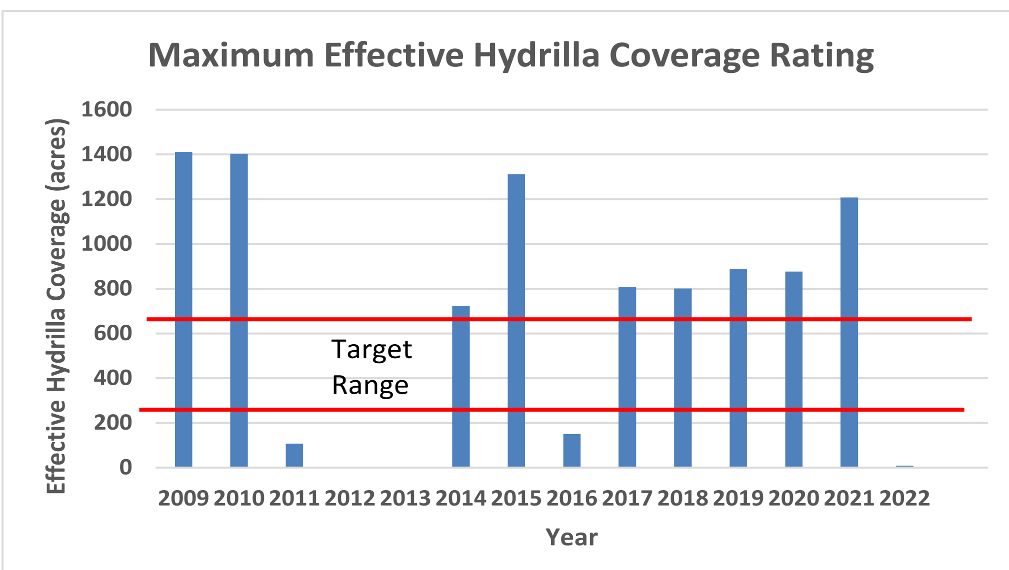


Figure 5. Effective hydrilla cover over time in Swift Creek Reservoir

Aging out of fish stocked in 2015 and 2016 was expected to reduce pressure on hydrilla over the next few years and the flooding of August 2020 caused the loss of an unknown number of fish that needed to be replaced, necessitating more stocking than usual in 2021. Adjustment of the model based on assumptions of higher loss rates for grass carp also suggested that slightly higher stocking might be sustained on a regular basis, but it was considered essential to avoid overstocking. Not knowing how many grass carp left the reservoir during 2018 and 2020 flooding limited the predictive capacity of the model, and even though the number of stocked grass carp was more than doubled in 2021 to 1250 fish, hydrilla expanded and covered more area with more medium and dense patches than in recent years, raising the maximum 2021 effective cover rating to 1208, the highest since 2015 and an increase of 36-51% over the 2018-2020 maximum values.

The loss rates for grass carp were apparently higher than estimated, probably as a result of floods in 2018 and 2020, and the hydrilla population increased substantially in 2021. More grass carp were believed to be needed in 2022 to regain control, even though the fish stocked in 2021 would be moving into prime grazing size. Application of two different models with varied assumptions about existing carp biomass and age/size distribution suggested that up to 3,000 additional grass carp could be stocked without collapsing the plant community. The NC model, intended to yield a stocking estimate that will minimize hydrilla, and by extension other edible plants, provided recommendations between 3,400 and 9,500 grass carp. A total of 3,500 grass carp were stocked and the vegetation community was almost entirely eliminated in 2022.

With regard to other plants observed in recent years, *Najas minor* was common in 2017 but *Myriophyllum aquaticum* was more abundant in 2018 (Figure 4). In 2019 no *Myriophyllum* was found and *Najas* was again the most abundant plant species after hydrilla. *Nitella* surged in spring of 2020 but was largely replaced by *Najas minor* in summer with *Myriophyllum aquaticum* less abundant. Both *Najas minor* and *Myriophyllum aquaticum* are invasive species, but the key point is that grazing pressure was not so high as to restrict all edible plant species from growing. Further, grass carp have dietary preferences such that some plants may survive and even increase somewhat if grass carp have adequate food resources. *Lemna minor* (duckweed) was more abundant later in 2020 than in previous years, possibly related to the August flooding. *Lemna* is a floating plant that needs elevated nitrate concentrations to thrive; its movement from inlet areas where it is most common to the rest of the reservoir and increased nitrate are both plausible flood effects. *Najas minor* was again the most abundant plant after hydrilla in 2021 until October when *Lemna* was more abundant, but five other species were also present in 2021, attesting to much reduced grazing control. Only *Nuphar variegata* and *Pontederia cordata*, neither a preferred food of grass carp, were present besides a little hydrilla in 2022.

Over the course of more than a decade since initial grass carp stocking, few plants other than hydrilla have been observed with any regularity (Figure 4). *Nymphaea* (white water lily), *Nuphar* (yellow water lily) and *Nymphoides* (floating heart, an invasive species) were encountered at low levels but are unlikely to get overly abundant in Swift Creek Reservoir as a function of depth and substrate limitations; these plants are least susceptible to grass carp. Small amounts of floating *Lemna* (duckweed) and the invasive *Myriophyllum aquaticum* (parrotfeather, which grows submerged or emerged or even on damp soil) were also found in 2015 after being absent since 2011 and parrotfeather was the most abundant plant after hydrilla in 2018. *Nitella* (stonewort, actually a form of algae) and *Naja*s (naiad, from the pondweed family) are highly edible by grass carp and were most abundant after hydrilla between 2014 and 2021 except for 2018. Those species will be outcompeted by hydrilla over time without control and consumed by grass carp with too much control. *Nitella, Najas*, and *Elodea* (all preferred grass carp food) may be useful indicators of how the program is doing. Their presence at low to moderate abundance should signify that grass carp grazing pressure is not too severe and their elimination may signal excessive grazing.

Fish Community Results

Fish data have been generated by AEC, a consulting and lake management firm contracted for this purpose in 2011 by Chesterfield County, and the Virginia Division of Game and Inland Fisheries, which took an interest in the project and has provided valuable support since 2012. Surveys occurred annually through 2017 although no grass carp were captured in 2015 through 2017 and no survey was conducted in 2018 or 2019. A more intensive survey done cooperatively between the state fish agency (now named Virginia Department of Wildlife Resources) and SOLitude, another consulting and lake management firm in 2020 added to our fish knowledge base. A one-boat, one-day fish survey was conducted by VDWR in 2021 but no grass carp were captured. No survey was conducted in 2022. The current policy is to perform a more detailed fish survey once every three to five years rather than a more limited effort every year.

Two fishery concerns have been voiced regarding the stocking of grass carp: 1) the grass carp population will crash when plant food is greatly reduced, and 2) other fish populations may suffer from the stocking, mainly from indirect impacts attributable to loss of vegetation. Certainly, the successful reduction of plant biomass would lead to food limitation of the grass carp, and the sterile grass carp population will not last indefinitely in this reservoir. Getting the right number of grass carp to exert adequate spring-summer control over plants but not to risk plant community crash and/or substantial die off or emigration over winter is a challenge, and some trial and error was expected from the start.

Impacts on other fish species are complicated; there is no food resource overlap, but it is possible that the reduction in plant biomass will shift the habitat value enough to favor some species and harm others that depend on plants for cover and related food sources (i.e., insects and small fish that congregate in dense plant stands). Superimposed on these natural interactions is angling pressure. Fisherman may remove substantial numbers of gamefish or even panfish and impact populations, but equally important may be the perception that gamefish are less abundant because there is a necessary change in fishing strategy when plant stands are minimal. Fishery surveys that generate reliable data for fish populations are therefore necessary to assess the fish community; the impressions of anglers cannot be relied upon in a situation like this, and even the results of any one fishery survey are not extremely reliable.

Grass carp were stocked in April of 2010 and a fish survey was conducted each year from 2011 through 2017. Surveys always sought to capture grass carp, but at different levels of effort, and considered other fish species in some cases, but not all species and not at the same level of effort. Electrofishing for several hours resulted in substantial numbers of grass carp being observed, but many fewer specimens were captured. Catch per unit effort for grass carp was 2.20 in 2011 and

2.25 in 2012, very similar values, but declined to 0.83 in 2013, 1.2 in 2014, and 0.82 in 2015 (Table 1, Figure 6). No grass carp were captured in 2016 or 2017, despite stocking in both 2015 and 2016 (Table 2). Carp captured in 2015 were larger, older specimens, not the recently stocked fish. No survey was attempted in 2018 or 2019. After 4 years with no grass carp data, 10 fish were captured in 2020 with a catch per unit effort of 0.9, similar to values in 2013-2015, and many more grass carp were viewed in inaccessible areas or running from the electric field. No grass carp were captured in 2021 although a few were observed.

It is not clear that the decline in grass carp being captured during surveys is entirely related to fewer grass carp being present, but it seems likely. The carp are known for having an acute avoidance behavior, making capture by the electroshocking process difficult. The decline is not just an artifact of the difficulty in catching these elusive fish, however, and the counts indicate a substantial decline of the population after 2012. Rather than a gradual decline, such as the hypothesized 20% loss per year, the data suggest a big reduction after 2012 and less variation thereafter. This is concurrent with collapse of the plant community.

Grass carp size change was documented from the fish that were captured (Figures 7 and 8). While the number captured was not large in any year, the fish were of similar size, being from the same year class, and the values appear reliable. Fish were about 1 foot long and 1.3 pounds (305 mm and 591 g) when stocked and grew rapidly in the first year. Growth in length leveled off after 2011. Increase in weight was substantial in 2011, followed by only modest increases in each of 2012 and 2013, concurrent with a lack of plants for those fish to eat. There was a distinct jump in average weight in 2014 and similar weight in 2015 after resurgence of hydrilla. The 2020 data suggest desirable weights and growth, with a length to weight relationship that pretty closely follows the standard curve for this species, based on data from other lakes. Viewed collectively (Figure 9), grass carp length vs. weight generally follows the standard curve, with some weights well above that expected from length when hydrilla was abundant and carp biomass was low. No weights fall far below the curve, suggesting that fish not finding food either die or escape; there are no skinny grass carp in the reservoir from fish surveys to date.

Variability among individual fish was high in 2014 and 2015, providing the greatest deviation from the curve in Figure 9. No grass carp were stocked in 2014 and no grass carp stocked in 2015 were recaptured that year, so the variation is a function of differential success by the fish stocked in 2010. With increased food availability, more growth can occur, but with the collapse of the plant community, some grass carp were much smaller than those that were more successful in foraging. Location of fish within the reservoir likely matters, with inlet areas and the shallowest peripheral locations harboring the most vegetation.

Predation mortality may be significant in the year of stocking (eagles were observed to catch small grass carp in 2010) but would decline over time. The NC model applies a first-year loss of 30% with mortality set at 20% after the first year. With a multi-year population structure established over time, the risk of any real impact to the overall population from predation is minimal. Some mortality within any population is expected each year, gradually lowering the number of grass carp, but likely balanced by increasing mean size, such that the overall biomass remains sufficient to keep plant growth in check. Yet there does appear to be substantial mortality or emigration of

Table 1. Grass carp data, 2010-2022.

	Grass Carp	CPUE	Avg Length	Avg Weight
Year	# caught	fish/hr	mm	g
2010	Stocked		305	591
2011	20	2.20	701	4,240
2012	9	2.25	738	5,116
2013	5	0.83	754	5,521
2014	2		873	10,120
2015	3		790	10,397
2016	0			
2017	0			
2018	No survey			
2019	No survey			
2020	10	0.9	864	10,796
2021	0			

Table 2. Grass Carp Stocking History 2010-2022.

Grass Carp Stocking History		
Year	# Grass Carp	Size (in)
2010	10,500	12
2011	0	0
2012	0	0
2013	0	0
2014	0	0
2015	1,000	12-15
2016	3,000	12-15
2017	0	0
2018	500	12-15
2019	600	12-18
2020	600	12-18
2021	1,250	12-18
2022	3,500	12-18

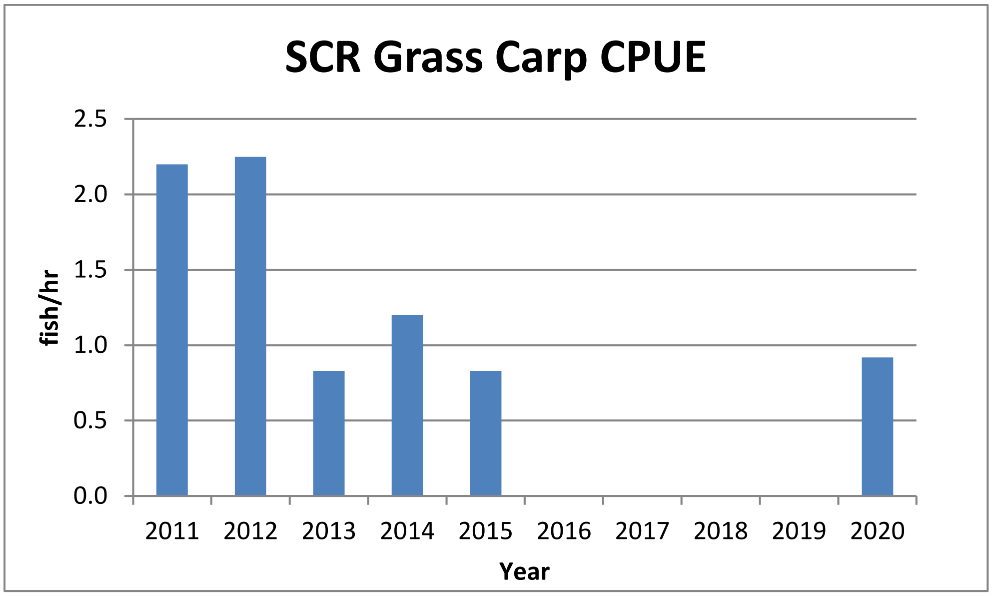


Figure 6. Catch per unit effort for grass carp in SCR, 2010-2020.

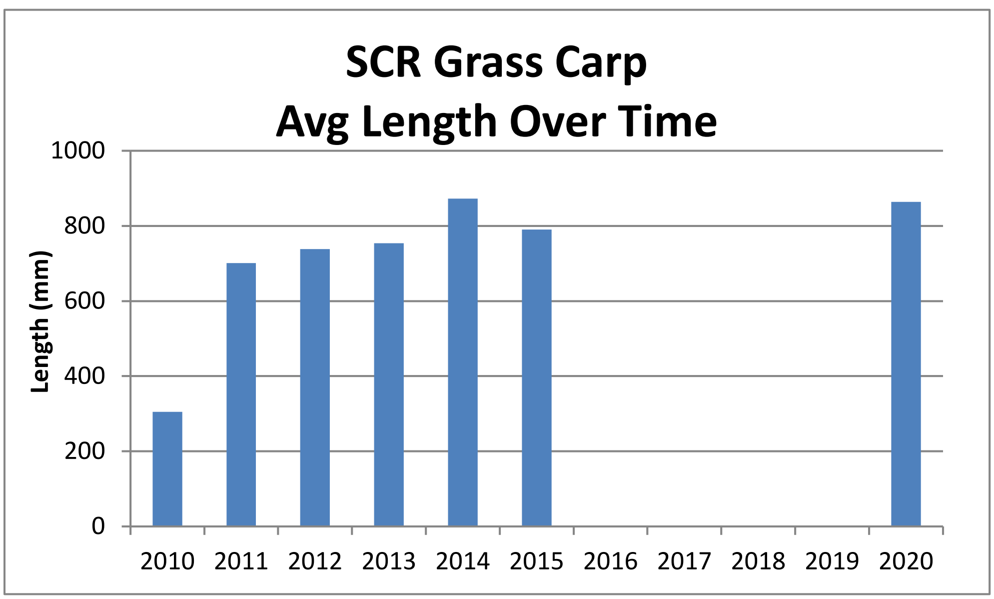


Figure 7. Average length of grass carp in SCR, 2010-2020.

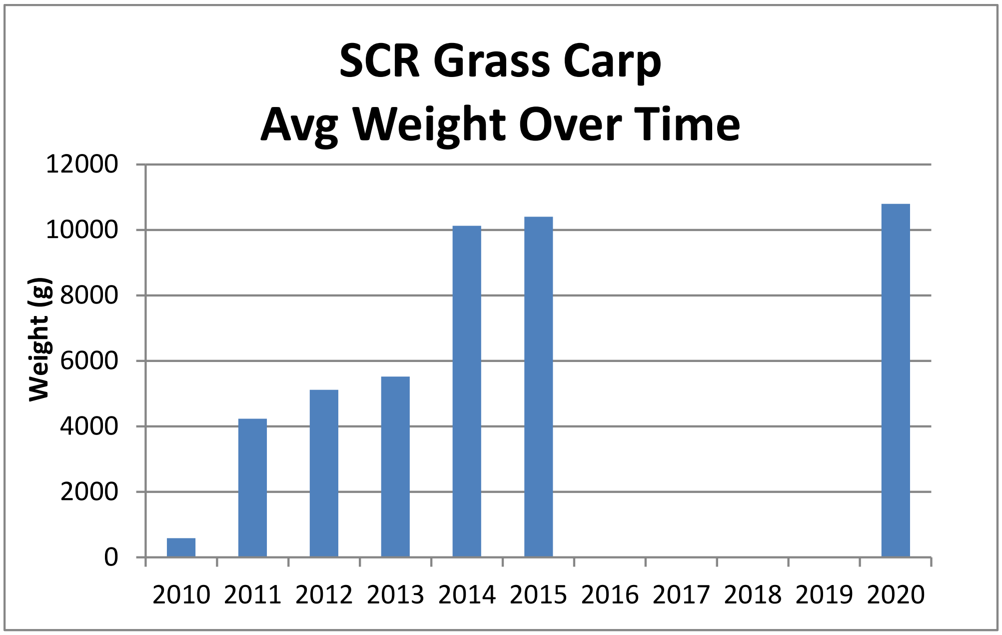


Figure 8. Average weight of grass carp in SCR, 2010-2020.

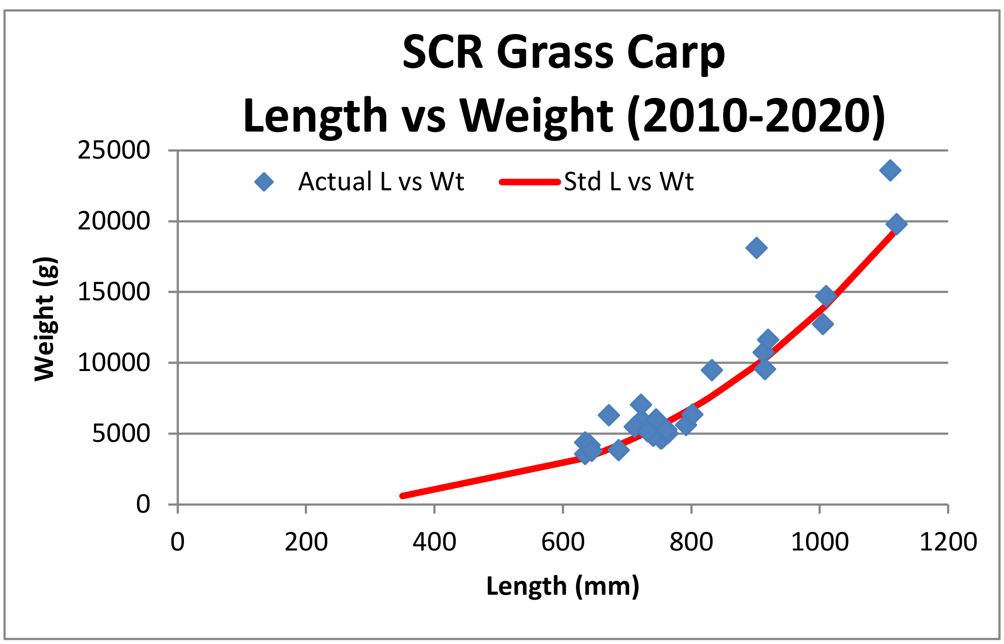


Figure 9. Average length vs weight for grass carp in SCR, 2010-2020.

grass carp between the 2012 and 2014 surveys, based on limited data for catch rate and size features. Food limitation restricted growth until summer of 2014, but by then there were apparently too few grass carp left to exert enough grazing pressure to control hydrilla (and other plant) growths. Older, larger grass carp are also not expected to feed as intensely as younger, smaller grass carp, and become less of a factor in plant control after 6-8 years.

The survey data are insufficient to allow reliable population estimates, but if we assume that the catch per unit effort data are representative, and there was a 20% decline each year after stocking, the population would have declined from 10,500 in 2010 to 8,400 in 2011 and then to between 3,000 and 4,000 over the 2012-2015 period. The 2012-2015 population would equate to 3 to 5 grass carp per vegetated acre of reservoir, with 750 to 900 acres possibly vegetated. This density of grass carp is well below the generally acknowledged vegetation elimination density of >10/vegetated acre. Stocking of grass carp in 2016 through 2021 was intended to rebuild the population although the floods in 2018 and 2020 introduced uncertainty through additional fish loss that could not be accurately estimated. It appears that about 11,000 kg of grass carp biomass is about the minimum to maintain any control over hydrilla while values >18,000 kg will surely cause a collapse of the plant community. While the model can still be improved with more data, it appears that a grass carp biomass between 14,000 and 16,000 kg as a multi-age population will keep hydrilla biomass in the target range for effective coverage. The impact of biomass between 11,000 and 14,000 kg or 16,000 and 18,000 kg will depend on other conditions, notably the starting point for vegetation density in the spring and carp size distribution.

The NC model maintains a focus on number of grass carp, although it incorporates a plant consumption factor that increases after the first year for several years, so there is acknowledgment that age and size matter as well as number of fish. The NC model also incorporates stocking some minimum number of grass carp based on the area of the target waterbody with hydrilla tubers that could germinate at any time, so for Swift Creek Reservoir the stocking rate would never be less than about 1,250 grass carp per year even if there was no hydrilla found unless tuber surveys revealed fewer acres where resurgence was possible. Stocking rates for areas of active hydrilla growth are based on enough fish to eliminate hydrilla, typically 15 per vegetated acre. Running a rendition of the NC model set up by CCU staff, stocking rates would have been mostly between 2,000 and 3,000 grass carp per year after the initial stocking, with a standing population of 8,000-9,000 grass carp. However, this would minimize hydrilla and other edible plants as well and is not consistent with a goal of maintaining a healthy plant community unless carp were excluded from some areas of the reservoir or planting of resistant species was conducted.

Potential impact on other fish species through habitat alteration is a rational concern, and fish surveys were conducted in the early years of grass carp stocking, but the later level of assessment effort and lack of data in some years limit conclusions. An appendix to the report on 2020 reservoir conditions provides available data and summarizes what is known as of 2020. Fish health metrics are generally favorable throughout the last decade and reproductive success is evident for nearly all species. Variation in fish abundance may relate to grass carp impacts on vegetation, but no impacts have been clearly attributed to hydrilla control at this point.

Lack of demonstrable fish impacts from grass carp introduction may in part be due to having enough vegetation to support a variety of species except in 2011-2013. Vegetation was very limited in 2014, 2016, and 2022, but only in summers of 2011-2013 was vegetation eliminated entirely and there are limited fish data after 2015. Production of trophy pickerel may have suffered, but largemouth bass are fairly tolerant of a wide range of vegetation features. Data for other species has not been adequate to detect any negative impacts of grass carp introduction. It is acknowledged, however, that some cover by a range of aquatic vegetation is desirable to support many fish species and the goal of CCU has never been to minimize plants in Swift Creek Reservoir, just to limit hydrilla.

Water Quality Results

Water quality in Swift Creek Reservoir is influenced by runoff from residential neighborhoods surrounding the reservoir, such that flows and related loads can vary substantially among years. The link between rainfall and phosphorus load is evident (Figure 10) and floods in 2018 and 2020 had substantial impact on the reservoir, but the relationship between precipitation and total phosphorus concentration in the reservoir is not strong (Figure 11). Processes in the reservoir are therefore important to converting phosphorus load into concentration and the use of phosphorus by algae. Dense plant assemblages can remove incoming solids and associated phosphorus. Most often the solids and phosphorus are products of non-point source runoff or tributary stormflow. The plant assemblages can condition water quality in Swift Creek Reservoir by helping to filter or settle out solids and a variety of associated contaminants, particularly phosphorus.

Grass carp convert plant biomass to fish biomass, but with an estimated 50% release of phosphorus and other nutrients in the process, possibly increasing algal production. The potential exists for grass carp to increase turbidity by removing plants that act as filters at inlets or by physically stirring up sediment during feeding. A rational concern prior to stocking grass carp was whether water quality would suffer appreciably. As treatment processes at the CCU facility were considered sufficient to address potential increases in algae and turbidity, the stocking was conducted, and water quality monitoring has continued with more sampling for more water quality features.

Phosphorus data from 1992 to 2022 suggest moderate to high levels of this important plant nutrient on average, with high peaks in some years (Figure 12). Until 2017 phosphorus values had not been significantly higher since grass carp stocking (mainly as a result of substantial interannual variability) and median values remained below the targeted upper threshold level of 0.040 mg/L in all but one year (2011). The phosphorus concentrations in 2017 and 2018 (Figure 12) were considerably higher than in past years, but most features of phosphorus concentration distribution returned to the 2011-2016 range in 2019-2022, except for higher maximum values in 2020 and 2021.

Overall, there is an apparent increase in total phosphorus with higher variability since grass carp were stocked. There has also been some additional development in the watershed and some change in climate, but the increase in overall rainfall over the last 30 years has been nominal (Figure 13). Note that concentrations in these graphs represent surface water samples in the main body of the reservoir and that concentrations from the bottom of the reservoir are higher during late summer.

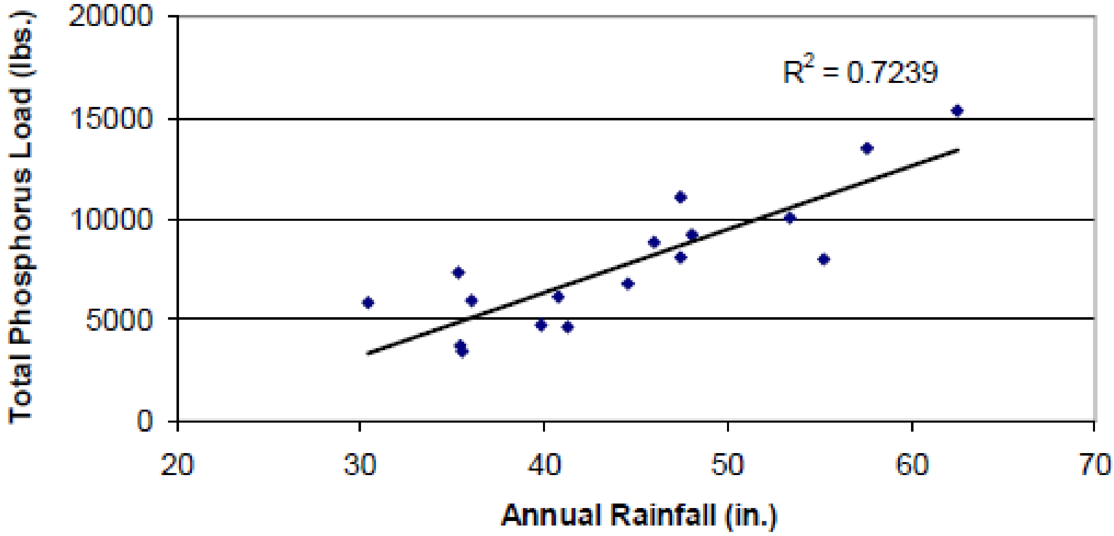


Figure 10. Correlation of phosphorus load to rainfall for Swift Creek Reservoir.

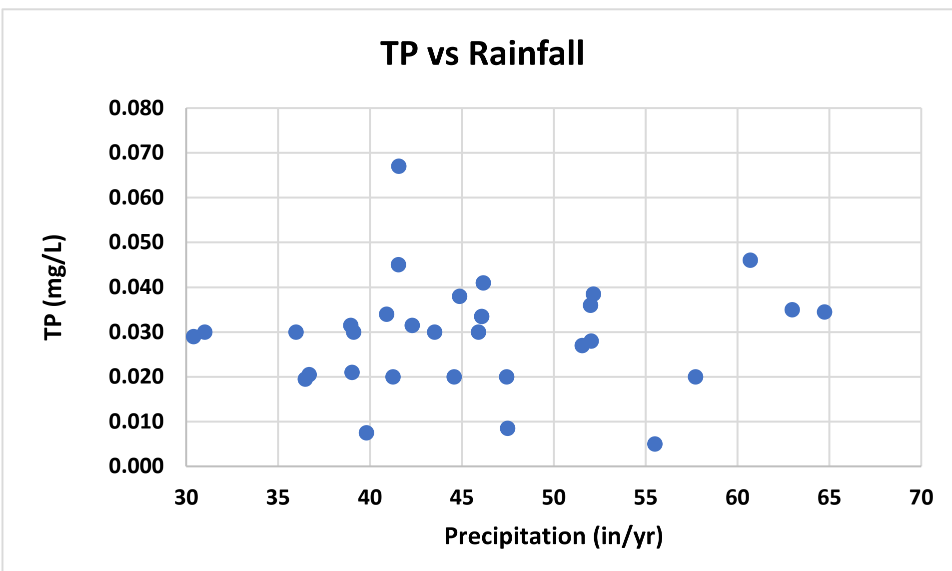


Figure 11. Relationship between total phosphorus and rainfall at Swift Creek Reservoir.

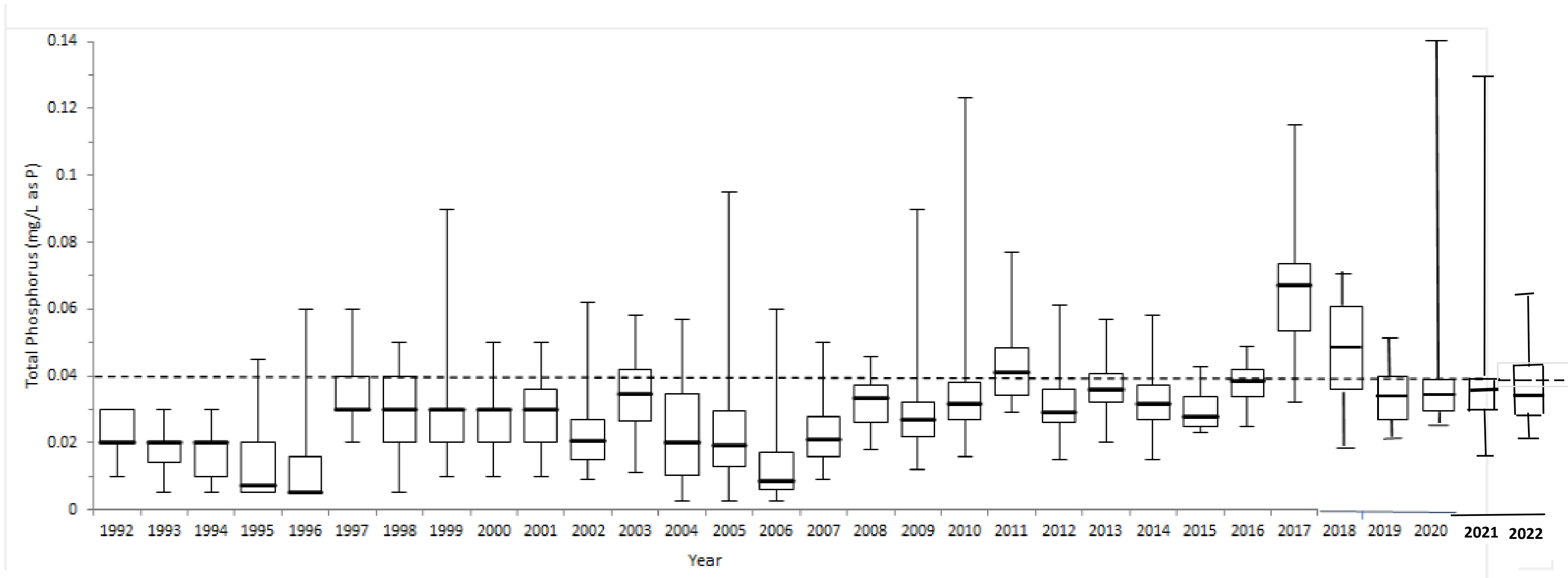


Figure 12. Annual phosphorus concentration statistics for SCR, 1992-2022.

(Box and whiskers plots include maximum and minimum values, 25th, 50th and 75th percentiles. Dashed line indicates 0.04 mg/L upper threshold for acceptable water quality in Virginia lakes.)

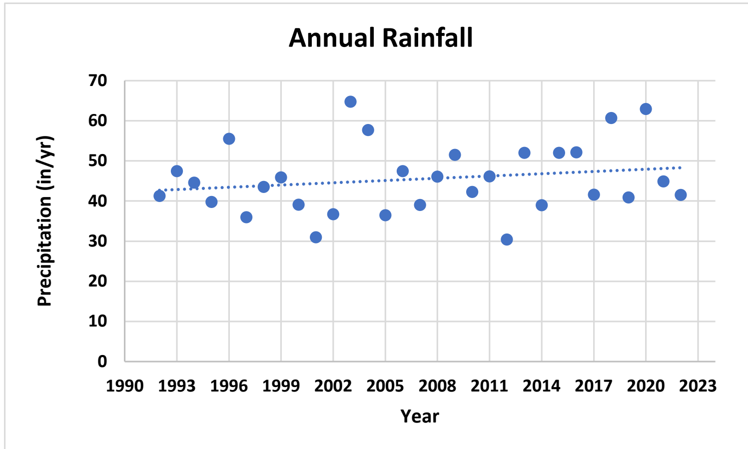


Figure 13. Precipitation near Swift Creek Reservoir over time.

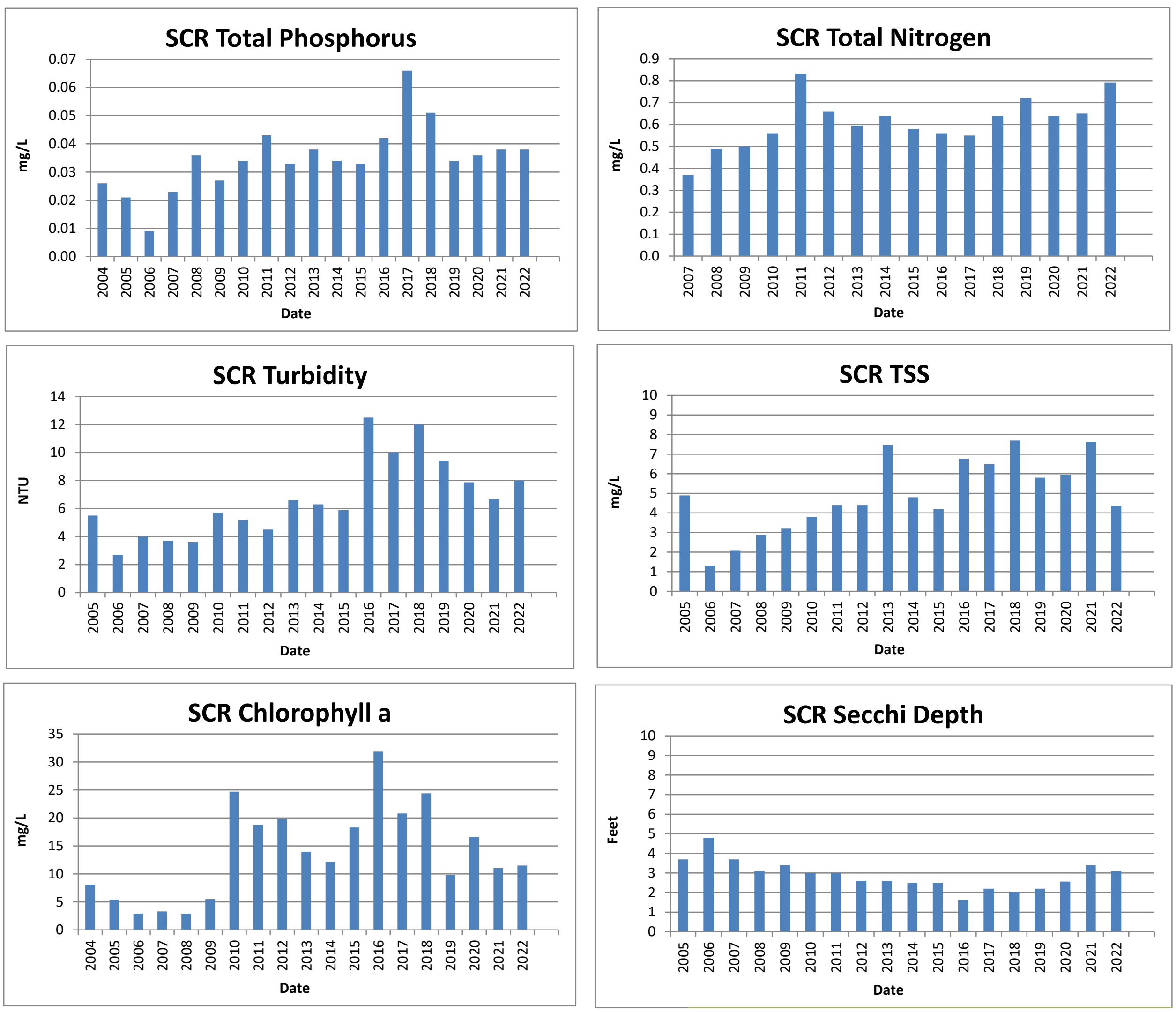


Figure 14. Annual mean surface values for key water quality variables in SCR.

This likely reflects release of phosphorus from sediment exposed to anoxic (no oxygen) conditions. Those conditions appear to be more severe in recent years, but the relationship to grass carp is unknown.

Comparison of annual median total phosphorus concentrations (Figure 12) from 1992-2009 vs 2010-2021 reveals a significant increase in total phosphorus ($P<0.01$) since grass carp were introduced to Swift Creek Reservoir. Comparison of the average annual total phosphorus concentrations (Figure 14) from 2004-2009 vs those from 2010-2022 also reveals a significant increase in total phosphorus since grass carp were stocked ($P<0.01$). Significant increases in total nitrogen, total suspended solids, turbidity, and chlorophyll-a ($P<0.01$ except for nitrogen at $P=0.022$) were also observed after grass carp were introduced (Figure 14), and water clarity measured as Secchi transparency significantly declined ($P<0.01$).

However, water clarity has never been high in Swift Creek Reservoir, owing to its large watershed, erodible soils, substantial development, and precipitation pattern. The relationship between water clarity measured as Secchi disk transparency and chlorophyll is weak for Swift Creek Reservoir, suggesting that non-algal turbidity is a major determinant of light penetration in this waterbody. What could be important about an increase in chlorophyll-a is the potential for increased algae to affect treatment needs.

Although algae that make up the phytoplankton may not be the biggest factor in water clarity in Swift Creek Reservoir, they are still of great concern for water supply and the algal community is tracked by CCU staff. Annual average cell counts for algae in the reservoir (Figure 15) have increased noticeably since grass carp were stocked, although there was a decrease after 2013 that coincides with hydrilla regrowth and apparent reduction in grass carp abundance. The average annual composition of the phytoplankton community (Figure 16) is moderately stable with a typical mix of green algae (Chlorophyta), golden algae (Chrysophyta, including multiple subgroups such as Bacillariophyta and Xanthophyta that are sometimes split off in various taxonomic schemes), and blue-green algae (Cyanophyta, more properly known as cyanobacteria). Yet the water treatment process must address day to day variation, and the annual composition is less important than monthly to seasonal patterns in algal community composition.

The monthly pattern for chlorophyll-a, detailed in the 2018 annual report, exhibits a very wide range, with minor algal blooms (loosely defined as chl-a >20 µg/L) possible in any month. The average monthly chlorophyll-a concentration exhibits a sinusoidal pattern with highest values in the summer months, a function of light and temperature, but average monthly values in excess of 20 µg/L in all but March, April and May. This means that the treatment system has to be ready to address algae issues at all times and staff must be especially vigilant during summer.

Composition of the phytoplankton matters on a monthly basis as well, with different types of algae representing different problems to be addressed through treatment. Many golden algae and cyanobacteria produce taste and odor, and some cyanobacteria can produce toxins. Many green algae are gelatinous and can more rapidly clog filters. The other algae in Swift Creek Reservoir, including small flagellated cryptomonads (Cryptophyta), dinoflagellates (Pyrrhophyta), and euglenoids (Euglenophyta), are not typically abundant enough to substantively impact water

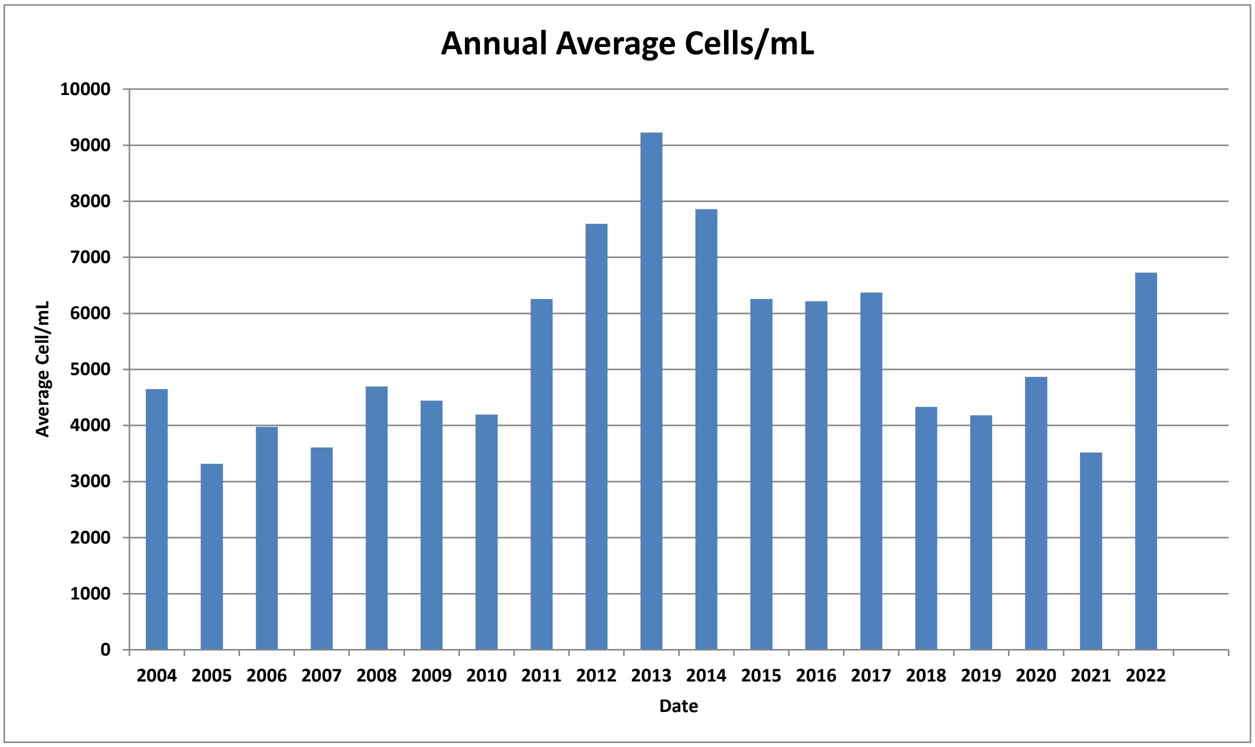


Figure 15. Annual average algae cell count in Swift Creek Reservoir, 2004-2022.

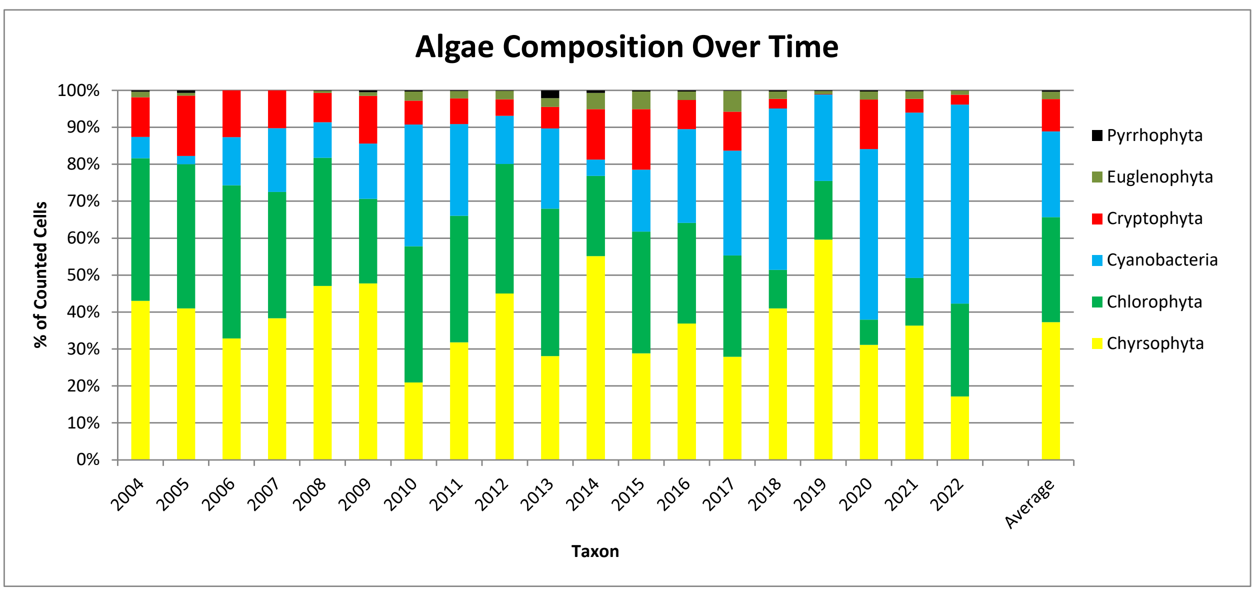


Figure 16. Algal community composition in Swift Creek Reservoir, 2004-2022.

quality and the treatment process, but the mix of greens, goldens and cyanobacteria represents enough of a challenge.

Based on algal community composition there has been no major shift in the algal assemblage as a result of grass carp stocking, although the three largest portions represented by cyanobacteria are from 2020-2022, a potentially disturbing trend. There are more algae in the water on average in most years post-stocking, but not different algae, and the impact on turbidity, solids content and water clarity is not extreme. However, the most abundant groups of algae in Swift Creek Reservoir do present issues for water supply and require adjustments in the treatment process to maximize finished water quality. Keeping algae abundance low in the reservoir reduces treatment costs and effort is devoted to minimizing algae in at least the outlet embayment where the water supply intake is located.

The relationship of hydrilla to overall algal abundance can be examined by comparing effective hydrilla coverage with chlorophyll-a (Figure 17) and algal cell counts (Figure 18). While the relationships are not strong, more hydrilla does appear to correspond to reduced chlorophyll-a and lower algal cell counts. This is consistent with expectations based on the filtering effect of hydrilla (and some other plants) on sediment- and nutrient-laden storm water inputs to the reservoir. It may also reflect alteration of other water quality features such that algae production is limited. Further, when hydrilla is suppressed, it is the result of consumption by grass carp which then excrete nutrients that can fuel algal blooms. The treatment system has so far been adequate to handle increased algae when hydrilla has been suppressed by grass carp, but having few plants in the reservoir is not ideal for water quality management. If hydrilla is to be minimized, other plant growths should be encouraged to limit algae treatment needs.

Algae control efforts in Swift Creek Reservoir have focused on application of low dose copper-based algaecides for many years (Figure 19). More recently a peroxide-based algaecide has been applied and sonic devices have been installed in the intake embayment. These recent efforts do not have enough of a track record to properly evaluate at this point, but both peroxides and sonication have been known to be successful in other waterbodies, especially for the control of cyanobacteria. Peroxides were applied in spring of 2017 and 2018 at 400 lbs total in each year, with two applications of 200 lbs each to the intake embayment. Cyanobacteria were not abundant at the time of treatment, but odor was present in the raw reservoir water. The treatment was successful in counteracting the odor, likely by oxidation of organics, and there was no recurrence of the odor. Algal counts were low in 2018 and 2019, no copper was applied in either year, but a small amount of peroxide was applied in 2018.

Cyanobacterial abundance was slightly higher than usual in 2020 and in late May there was concern over taste and odor generation from cyanobacteria. Treatment with both copper and peroxide was conducted in both the intake bay and main body of the lake in early June. Copper was applied on two days at a total of 800 lbs while peroxide was applied on three days at 1050 lbs total. No taste and odor event occurred and the average cell count for 2020 was only slightly higher than 2018 and 2019. Cyanobacteria represented a higher percentage of the total algal cell count in 2021 but the cell count was the lowest since grass carp were stocked and no copper or peroxide treatments were needed. Cyanobacteria were again more abundant than usual in late summer 2022 and the cell counts were elevated, but the water management team held off on any copper or

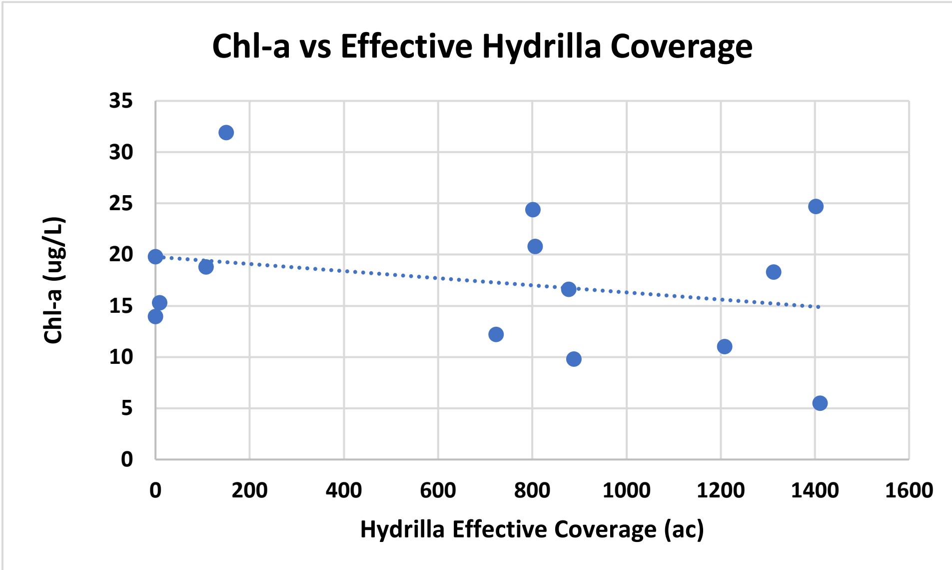


Figure 17. Chlorophyll-a concentration vs effective hydrilla coverage.

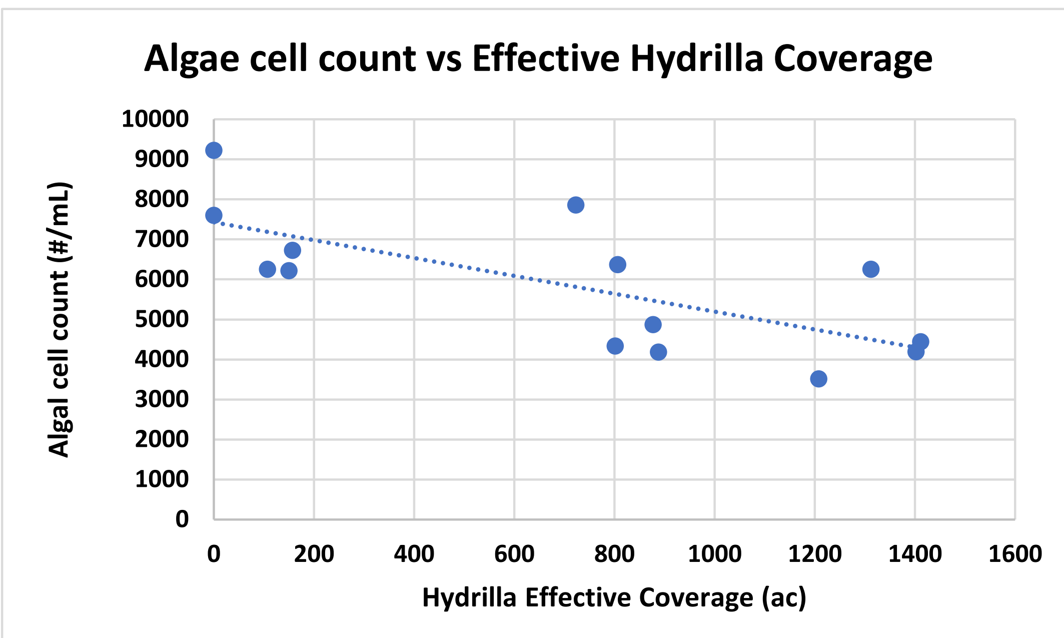


Figure 18. Algae cell concentration vs effective hydrilla coverage.

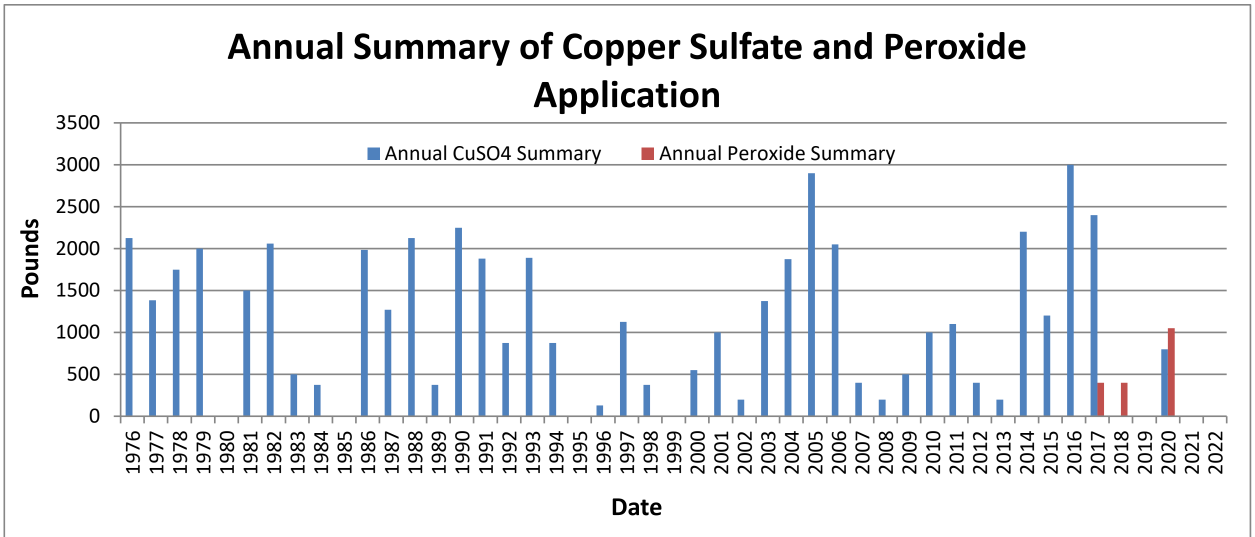


Figure 19. Annual total algaecide application to Swift Creek Reservoir, 1976-2022.

peroxide treatments and cell counts declined with a change in the weather. There were limited nutrient inputs from the watershed during the relatively dry summer of 2022; somewhat wetter conditions might have fueled much more severe algal blooms with the nearly complete absence of vascular plants in the reservoir.

The variability in hydrilla abundance experienced over the last decade therefore translates into uncertainty with regard to algal bloom frequency and a need for the county treatment staff to monitor frequently and react quickly to potential water quality problems affecting treatment needs. Raw water quality management has become more sophisticated over the last few decades and CCU has put considerable funding and staff time into monitoring and pro-active water quality management. Those focused on hydrilla control should not lose sight of the effort necessary to provide safe drinking water to consumers from Swift Creek Reservoir, created with water supply as its top priority.

There is one additional aspect of hydrilla control that bears mention in relation to water quality and ecological health. Work by Susan Wilde on Avian Vacuolar Myelinopathy (AVM), a fatal disease of birds, particularly eagles, has determined that it is caused by a toxic cyanobacterium *Aetokthonos hydrillicola* that is associated with *Hydrilla verticillata* growths in many southern reservoirs. Testing by Dr. Wilde of hydrilla samples from Swift Creek Reservoir found a single colony of *Aetokthonos hydrillicola* in 2009 and none in 2015, so the potential risk to resident eagles appears to be low, although periodic retesting is warranted. Along with a desire to maintain a plant community for fishery and water quality benefits, this revelation suggests that stocking grass carp at a lower density than necessary to completely eliminate hydrilla (and other plants) from the reservoir does not represent a major risk to sensitive wildlife.

Management Assessment and Recommendations

Overall Program Review

The grass carp stocking in 2010 was extremely effective in reducing hydrilla in Swift Creek Reservoir. It took about a year for the grass carp to grow to a size where they could forage effectively and freely throughout the reservoir, after which they quickly reduced hydrilla to an undetectable level in the reservoir. Given a major infestation of over 800 acres of reservoir with hydrilla prior to stocking, both the rate of change and shift in conditions were extreme. Vegetation of any kind was minimal between 2011 and 2013, and then increased to moderate levels over the summer of 2014. Plant growths, primarily hydrilla, were substantial in 2015, but did not exceed the levels measured in 2010 before any grass carp were stocked. Grass carp stocking in 2015 (1,000 fish at 12-15 inches) and 2016 (3,000 fish at 12-15 inches) contributed to low abundance of hydrilla in 2016, but other factors such as low light may also have been influential.

Pursuant to a review of the stocking program and projections for the degree of plant control from future stockings, no grass carp were stocked in 2017, 500 fish of 12-15 inches in length were stocked in 2018, and 600 fish of 12-18 inches were stocked in 2019 and 2020. The intention was to build a multi-age population of grass carp that might be more stable and provide more consistent control of hydrilla at some low level of abundance. Managing with biological controls is challenging as a function of inherent variability. Results through 2020 suggested that conditions were more stable but that overall grass carp biomass was still slightly low and hydrilla coverage and density were still higher than desired. Flooding in 2018 and 2020 allowed some grass carp to escape downstream, and review of average size of grass carp in each age class based on additional fish data from 2020 resulted in lower estimates of biomass in the applied model. Stocking was increased to 1,250 grass carp in 2021, remaining cautious to avoid overshooting the carrying capacity of the reservoir and collapsing the plant community again, but hydrilla increased substantially in 2021. The inability to know how many grass carp are in the reservoir at any point in time, a function of unknown mortality and emigration and difficulty in capturing grass carp in fish surveys, means that management has to be based on plant community features.

The species and abundance shifts observed in the plant community over the last decade reflect a mix of plant colonization and/or resurgence, continued grazing by grass carp, and abiotic influences such as low light from elevated suspended solids concentrations. Stocking grass carp to a level that guarantees reservoir-wide control at low plant density will not result in even conditions over time or space. There will be occasional plant patches that are denser than some reservoir users may like and may require alternative means of control such as benthic barriers or harvesting. An alternative approach, embraced by North Carolina and embodied in a model developed and applied by NCSU researchers, involves stocking in response to acreage of hydrilla and former acreage where tubers are expected to allow rapid recolonization if grazing pressure is reduced. While numerical factors are applied in acknowledgment of differential feeding over grass carp age, the NC model focuses on number of grass carp and is geared toward minimizing hydrilla growth. Unless an active planting program is adopted and/or exclosures (i.e., fencing or other barriers) are installed to keep grass carp from feeding on native vegetation, this will result in minimal plant biomass in the reservoir and is not consistent with water quality goals for water supply or overall fishery management goals.

Increased grass carp stocking in response to excessive hydrilla appeared necessary in 2022, but as stocked grass carp will be in the reservoir for many years barring plant community collapse and floods, stocking too many at once is known to create instability that will compromise management in future years. Building a multi-age population is considered the best approach to stable control, providing more consistent grazing pressure and being less susceptible to die off or reduced grazing by older fish. Achieving that multi-age population takes at least 5 years of relatively consistent stocking but can be disrupted by events like floods, and if the biomass that the plant community can sustain is exceeded by excessive stocking, mortality or emigration may increase to a point that requires a restart of the stocking sequence.

It is apparent that the initial stocking of 10,500 fish was more than the reservoir plant community could support. Many people may have appreciated the low plant density from 2011 into 2014, but it is not sustainable by biological means; stocked grass carp have to have food to survive. The addition of 1,000 grass carp in 2015 was a seemingly appropriate start to building a multi-age population but provided too little control to satisfy many users of Swift Creek Reservoir. The addition of 3,000 grass carp in 2016 may have provided better plant control but threatened possible plant community collapse in 2017 based on 2016 results and created a pulse of same aged fish moving through time that will cease to become effective grazers at roughly the same time and create instability in plant control. After no stocking in 2017, the lower stocking rates of 2018 through 2020 advanced the effort to create a multi-age population at an appropriate biomass but the floods of 2018 and 2020 are believed to have substantially increased grass carp losses from the reservoir. Hydrilla increased to unacceptable levels but not to the extent observed before grass carp were introduced.

Public concern over expanding hydrilla in 2021 put pressure on county government to increase the stocking rate. CCU did go above the model’s projection of adding 3,000 grass carp and added 3,500 grass carp, but at the time this was not predicted to crash the hydrilla population. Stocking projections were complicated by uncertain carp loss due to the 2018 and 2020 floods. The stocking of 3,500 grass carp in April 2022 and spring growths of hydrilla and other plants were nominal. All but two species of plants, neither preferred by grass carp, were eliminated by the start of summer. While the models are not expected to be highly accurate, the result of stocking 3,500 fish was near the predicted limit for eliminating vegetation and now the program is faced with having excessive biomass of grass carp for several years or increased mortality that will make compensatory stocking hard to estimate.

Adjustment of the model based on data accumulated to date can guide future stocking rate recommendations, but ongoing data collection should be used to make further adjustments on a year to year basis. Plant management is a mix of science, economics, and sociopolitics, that last category covering everything from regulatory constraints through public desires for a change in plan. All three “legs” of the management “stool” must be solid and of roughly equal length to make the stool useable. Therefore, public pressure must be balanced with the best available science and economics to avoid failure.

From the perspective of hydrilla control, the stocking of grass carp has been a major but not constant or complete success. Impacts on other fish and water quality are not positive, but the data do not indicate strong negative impacts from grass carp at this time. CCU has committed to working with all stakeholders to maximize the value of Swift Creek Reservoir to all users, but the range and priority of uses must be recognized. Immediate relief from hydrilla through increased stocking should not be expected when nuisances occur. Building a multi-age grass carp population remains a valid approach to gaining some reasonable level of control over hydrilla. Overstocking whenever hydrilla abundance is greater than desired is likely to produce results within a year but compromises other goals of reservoir management. Having additional methods of control is likely to be essential to consistently maintain desired conditions while not sacrificing water quality or fishery interests.

Maintaining an Appropriate Grass Carp Population in Coming Years

Critical to the modeling of carp-hydrilla dynamics under the Chesterfield model is estimation of the effective biomass of grass carp, which is not easily obtained by monitoring, as these fish are very skittish and difficult to capture. Instead, the data for average weight at different sizes as determined from what grass carp could be captured were applied to estimates of grass carp remaining in the reservoir as a function of stocking rate and expected natural die off, adjusted when the plant community collapses or other events like floods cause greater loss of stocked grass carp. Additional refinement was supported by the fish survey of 2020, which provided enough grass carp measurements to support the contention that growth and size distribution will conform roughly to the standard curve for this species, which provides a length vs weight relationship based on other studies (see grass carp section of this report for more details). This allowed an adjustment to the average weight of grass carp at different ages as applied in the model.

Also critical to the Chesterfield model and indeed to other models like the NC model is the estimation of loss rates for grass carp. The models are not overly sensitive to slight increases or decreases in mortality or emigration, but the effect builds over time and neither mortality nor emigration are constants in any waterbody. Model runs with different numbers of stocked grass carp in future years provide guidance on how many to stock and what plant community conditions can be expected. The Chesterfield model has employed a base mortality rate of 20% per year, raising it if the plant community collapses and adding as much as 30% loss in the event of a flood that allows emigration. The NC model uses a mortality rate of 30% for the first year and 20% thereafter, but lower emigration rates. In early 2022 the Chesterfield model was applied with a range of loss values to assess sensitivity and long-term impacts of whatever assumptions were made. An important caveat, however, is that adjustment after overstocking is problematic and a grass carp population that causes the collapse of the plant community may necessitate either no stocking for a year or more or higher recovery stocking, In either case, greater instability for the next 5+ years would be expected. Despite less than desirable hydrilla control with lower stocking rates, building to an appropriate grass carp number or biomass incrementally without exceeding the carrying capacity of the reservoir is viewed as essential to that approach to plant control.

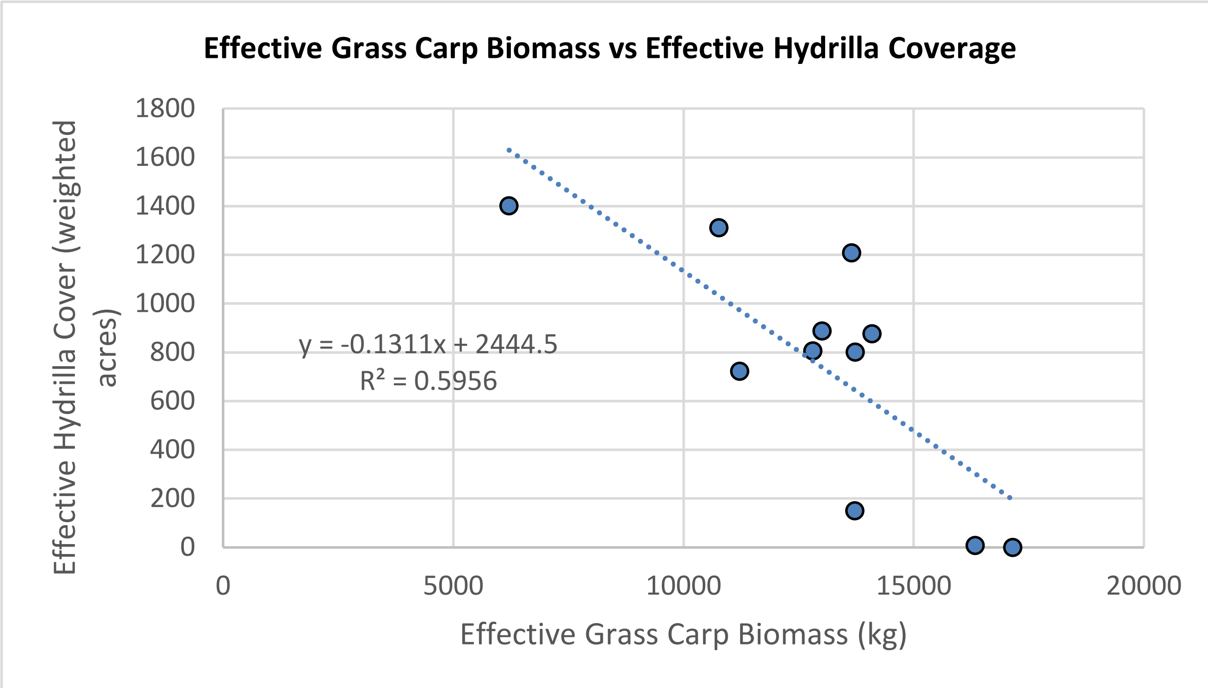
When considering plant abundance and distribution and the impact of grass carp stocking, it is important to keep in mind the inherent variability of biological populations and the many factors that affect population stability. Managing plants with biological controls is more difficult than doing so with physical or chemical controls, and more variation in results is to be expected. Yet grass carp offer an economical alternative, and other localized techniques can be applied where plant growth is too dense as a function of uncontrollable variation through biological control. The grass carp program seeks to determine the best stocking regime to maintain an acceptable level of control, and this is not reliably predictable from experience elsewhere. It is expected that management goals can be achieved over time, but the first decade of use has to be considered at least partly experimental, with adaptive management applied to reach reasonable goals within the constraints of biological variation, regulatory limits, and budgets.

Use of actual data to assess stocking needs focuses on the response of hydrilla to grass carp abundance. For Swift Creek Reservoir, an index of effective hydrilla coverage has been developed which weights denser growths more heavily that medium density growths which in turn are weighted more heavily than low density growths. The value is listed as acres, but it is acres at each density multiplied by 1,0, 1.77, or 2.33 in order of density, based on density comparisons from a decade of plant monitoring. Grass carp are expressed as biomass, which is an extrapolation from estimated number of grass carp in each age class and the average biomass of carp in each age class. The result as of the start of 2023, considered as a linear or polynomial regression (Figure 20), suggests that a grass carp biomass of about 14,000 kg is needed in Swift Creek Reservoir to sufficiently suppress hydrilla but that a biomass of about 17,000 kg will collapse the plant community.

There is variation in these relationships depending on the assumptions for grass carp loss each year, and the curve is fairly steep in the 14,000 to 17,000 kg range, leading to likely variation of results in any one year and limited accuracy of predictions. Additionally, the best fit regression does not explain more than two thirds of the variation in effective cover observed as a function of estimated grass carp biomass. That means that a full third of the variation in hydrilla cover is due to factors not accounted for in the model, such as turbidity or water temperature. Translating the existing relationship into an annual stocking recommendation is challenging and involves running the model with different assumptions to bracket a range of likely scenarios for the next few years.

With the addition of 1250 grass carp in 2021 and another 3,500 in 2022, the model now suggests that with no stocking at all, the biomass will exceed the current estimate of 17,000 kg to collapse the plant community for the next four years (through 2026). With just 500 fish stocked in 2023, the threshold for minimizing the plant community will be exceeded for five years (through 2027). Yet this assumes 20% mortality per year, and mortality is likely to rise with few plants available. The NC model suggests that at least 1250 fish must be stocked each year to compensate for mortality and to cover areas where hydrilla tubers are likely abundant and could germinate in any year. But stocking 1250 fish each year will keep the biomass above the plant community collapse threshold indefinitely and grass carp mortality can be expected to rise. If no fish are stocked, year class and size class gaps will exist, leading to later instability. Exceeding the carrying capacity of the reservoir has serious consequences, and the 2022 stocking has once again put the program into a situation of higher uncertainty.

If it is assumed that the loss of vegetation in 2022 will increase the loss rate of grass carp from 20% to 30% and that 30% loss rate holds for the next few years until grass carp biomass declines to <14,000 kg, the vegetative community should be minimal and no stocking would be needed until 2026. If we assume the most extreme loss rate applied to date of 50%, grass carp biomass



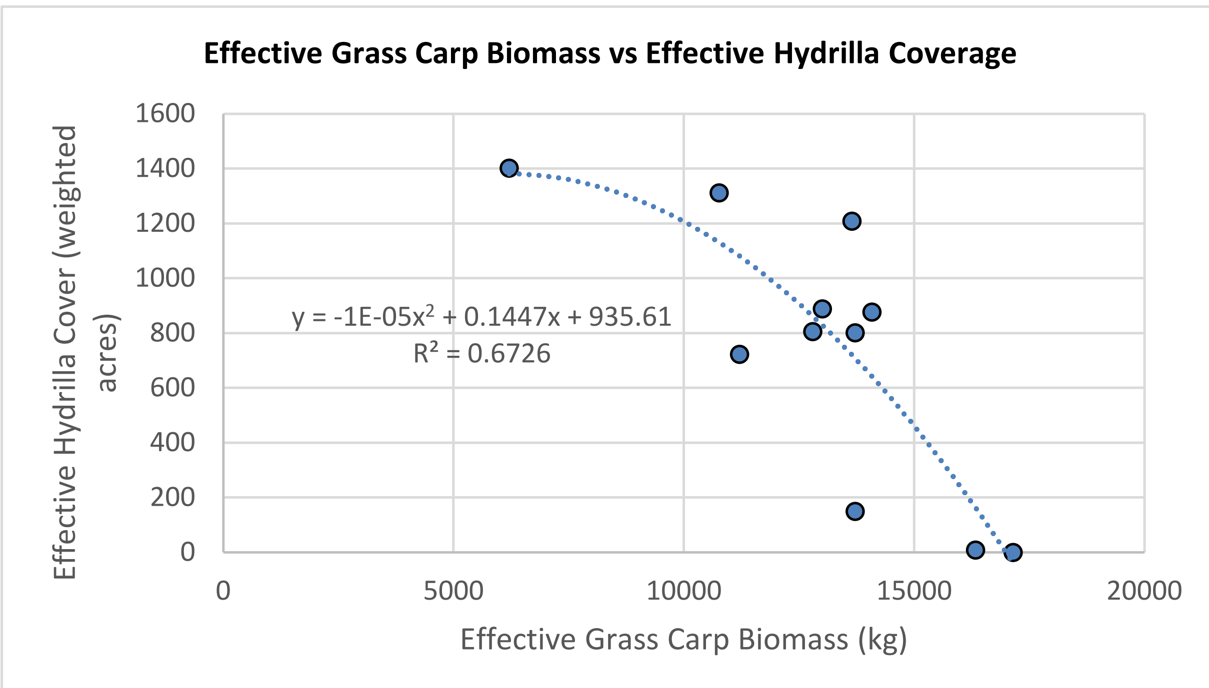


Figure 20. Relationship between grass carp biomass and hydrilla abundance

will decline to slightly less than 14,000 kg in 2023 and hydrilla will resurge. Consequently, any choice of stocking rate for 2023 depends on what loss rate is chosen and there is no way to know that before a stocking decision has to be made. Plant data in 2023 will be the best indicator.

Working from experience, we know that the initial stocking eliminated vegetation for about three years. Application of a 50% loss rate for grass carp when plants are absent would have limited control to two years, while application of a 30% loss rate matches predicted resurgence of hydrilla with what was observed. The severe depression of vegetation in 2016 after stocking 1,000 grass carp in 2015 and 3,000 in 2016, followed by hydrilla resurgence in 2017 with no stocking of grass carp that year, tracks fairly well with a 30% loss rate for grass carp with minimal plants as a food resource. Assuming a 50% loss rate, especially now with a very expensive barrier to loss over the dam in place, is not justified, while the 30% loss rate appears correct when plants are minimized.

Further, the situation in 2017 when hydrilla resurged involved stocking in two previous years with no stocking in the four years before that. The grass carp from the initial stocking in 2010 were expected to have "aged out" by 2017, providing minimal grazing pressure on plants. The situation in 2023 is that there has been stocking since 2018, with at least 500 fish per year and a total of 6450 grass carp added over the last 5 years. This provides a range of ages and sizes, and all of the fish that remain are expected to contribute to plant consumption in 2023. Adding even a few hundred more grass carp can be expected to minimize the plant community for multiple years.

The reservoir management group will need to decide if it wants to retain the goal of some intermediate hydrilla presence at the expense of some nuisance conditions or abandon that goal for another approach. As it is, the stocking in 2021 and 2022 has increased carp biomass to the point of near elimination of vegetation in the reservoir, and the best available modeling suggests that this will continue for several more years. Decision-makers could opt for complete plant control through annual stocking at a rate that maintains high biomass, accepting poor habitat for at least some fish species and declining quality of the raw water used to produce potable water by CCU. Areas like inlets where denser plant growths enhance water quality could be sequestered to keep grass carp out to the extent feasible, but this would require more structures like that built near the dam at great expense and limited access for boats.

Stocking to eliminate most vegetation from the reservoir is not consistent with all use goals, but certain stakeholders have pushed to make hydrilla elimination a goal of reservoir management The 2022 stocking decision results may be popular with these stakeholders, but this has set back the long-term goal of adding annual classes of carp to produce more consistent and intermediate levels of control. Monitoring will be necessary over the next few years to determine when the building of annual year classes of sterile grass carp can be resumed to lead to a more stable and diverse population of grass carp in terms of age and size within the reservoir.

It is expected that the current excess biomass of grass carp will decline over the next few years, at which time stocking can resume, possibly according to the plan developed back in 2017 and perhaps with slightly more fish each year (e.g., 750 instead of 500 or 600) to rebuild a multi-year population of grass carp at a biomass that will suppress hydrilla to an intermediate extent. This will not satisfy some users of the reservoir but is consistent with water supply and fish and wildlife habitat uses.

Summary and Recommendations

The initial stocking of 10,500 grass carp in 2010 eliminated nearly all plants from the reservoir in 2011 through 2013. Mortality and/or escape of grass carp, exacerbated by the lack of food resources in the reservoir, resulted in a smaller population of larger individuals that was unable to maintain control of the plant community in general and hydrilla in particular by late 2014. The growth pattern for plants in 2014 was generally favorable for all uses of the reservoir, with the possible exception of localized interference with boat access. Complete loss of control appears to have occurred in 2015, with hydrilla expanding to coverage and density levels approaching those observed prior to control with grass carp.

Restocking of grass carp in 2015 and 2016 regained vegetation control but may have been aided by elevated turbidity and lower light penetration. No stocking occurred in 2017, after which a policy of annual stocking at a lower level was adopted; 500 grass carp were added in 2018, 600 were added in 2019 and 2020, and 1,250 were stocked in 2021, all in response to fairly stable but higher hydrilla coverage than desired. Hydrilla abundance increased in 2021, again approaching pre-grass carp levels. Grass carp losses between 2016 and 2021, related to floods in 2018 and 2020 as well as aging out of old grass carp stocked in 2010, reduced grass carp abundance beyond what was needed to maintain control over hydrilla. Stocking of 3,500 grass carp in 2022, the most since the original stocking and slightly more than in 2016, caused another collapse of the plant community. Added to still actively grazing fish from 2018-2021, even with projected increased loss rates due to floods, the 2022 stocking exceeded the capacity of the plant community to withstand grass carp grazing.

Stocking no grass carp in 2023 is recommended. While this will create a year class gap, it allows a period of monitoring that may shed light on how much control the 2022 stocking can exercise after collapse of the plant community and potentially increased mortality of grass carp thereafter. Some level of stocking should resume in 2024, commensurate with indications from 2023 plant monitoring and any change in management goals. If the building of a more stable, multi-year grass carp population is still favored, the 2024 stocking should probably be no more than 500 fish, but a review of the 2024 plant data should inform that decision. At some point the stocking rate might be increased to about 750 grass carp to build a slightly larger population than was achieved by 2018-2020 stocking, but the addition of 3,000+ grass carp has now twice proven to be too much for the vegetative community to survive.

Available data for the plant community is extensive and allows useful tracking of conditions. Plant surveys are the most reliable way to assess program progress and status. County personnel have become proficient at plant surveys and the quantity of data collected provides reliable estimates of plant abundance and distribution. These plant surveys should continue.

Data for the fish community is less extensive but still quite useful. Additional fish surveys help in evaluating progress and model assumptions, but the difficulty in capturing enough grass carp to support a population estimate suggests that adjustments to stocking should be based on plant community features. Fish surveys are still recommended, but it may be best to do them less frequently (every 3-5 years) and expend more effort to collect more and better data. Model adjustment based on fish survey data has improved our predictive capability and periodic review to assess impacts on the game fishery of Swift Creek Reservoir is needed. Impacts on the fish community by grass carp stocking are not direct, but loss of vegetation as observed and high variability among years cannot be a positive influence. No negative impacts from grass carp stocking have been clearly documented, but several impacts are likely and better documentation is needed.

Consideration of plant growth patterns over each year suggests that selecting a single target value for percent cover or frequency of occurrence is not realistic, given just seasonal variation, and conditions will vary around the reservoir such that some areas may have no plants while others have what might be perceived as excessive growths. Variation will have to be tolerated if grass carp are to be the primary plant control, and a range of 10-25% frequency for hydrilla is about as narrow as can be expected. That projection is entirely consistent with experience elsewhere, including discussion in the NCSU white paper prepared for a residents' group at Swift Creek Reservoir. Minimization of high-density growths may be possible, but elimination of plants, even just hydrilla, is not a rational goal in this system. Residents who are dissatisfied with plant density at their preferred access points are encouraged to apply benthic barriers or harvesting techniques within the framework of an approved plan to achieve acceptable local conditions.