Swift Creek Reservoir Hydrilla Management Progress Update

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Project Background

Swift Creek Reservoir is a 1700 acre (680 hectare) water supply impoundment serving Chesterfield County. It is located approximately 20 miles southeast 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 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 (trophy bass and pickerel), and is very popular for those uses.

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 it was expected that this invasive plant would continue to expand along the shallow margin of the reservoir. Low light restricts growth in Swift Creek Reservoir, such that only about 900 of the 1700 acres would be considered susceptible. Yet this elevated level of peripheral submerged aquatic vegetation coverage severely limits most uses of the reservoir and numerous complaints from the public were received. From a water treatment perspective, the Utilities Department had concerns of organic loading should a sudden massive die back of hydrilla occur. The combination of limited capability of public use of the reservoir combined with Utilities Department concern for organic loading from die back lead to Chesterfield County seeking 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 plants would be eaten, but the loss of recreational utility without controls was considered severe enough to warrant such 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. Copper 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.

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 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. Resurgence of hydrilla was observed in 2014, although coverage and biomass were not extensive. A total of 1000 grass carp were added in spring 2015 to bolster the population of this sterile fish, but hydrilla resurgence continued and coverage reached 776 acres by August of 2015, some of it very dense. An additional 3000 grass carp were stocked in spring of 2016. No grass carp were stocked in 2017, but 500 fish of 12 to 15 inches were stocked in April 2018. This report is intended as an update on management progress and to support reasoned management planning.

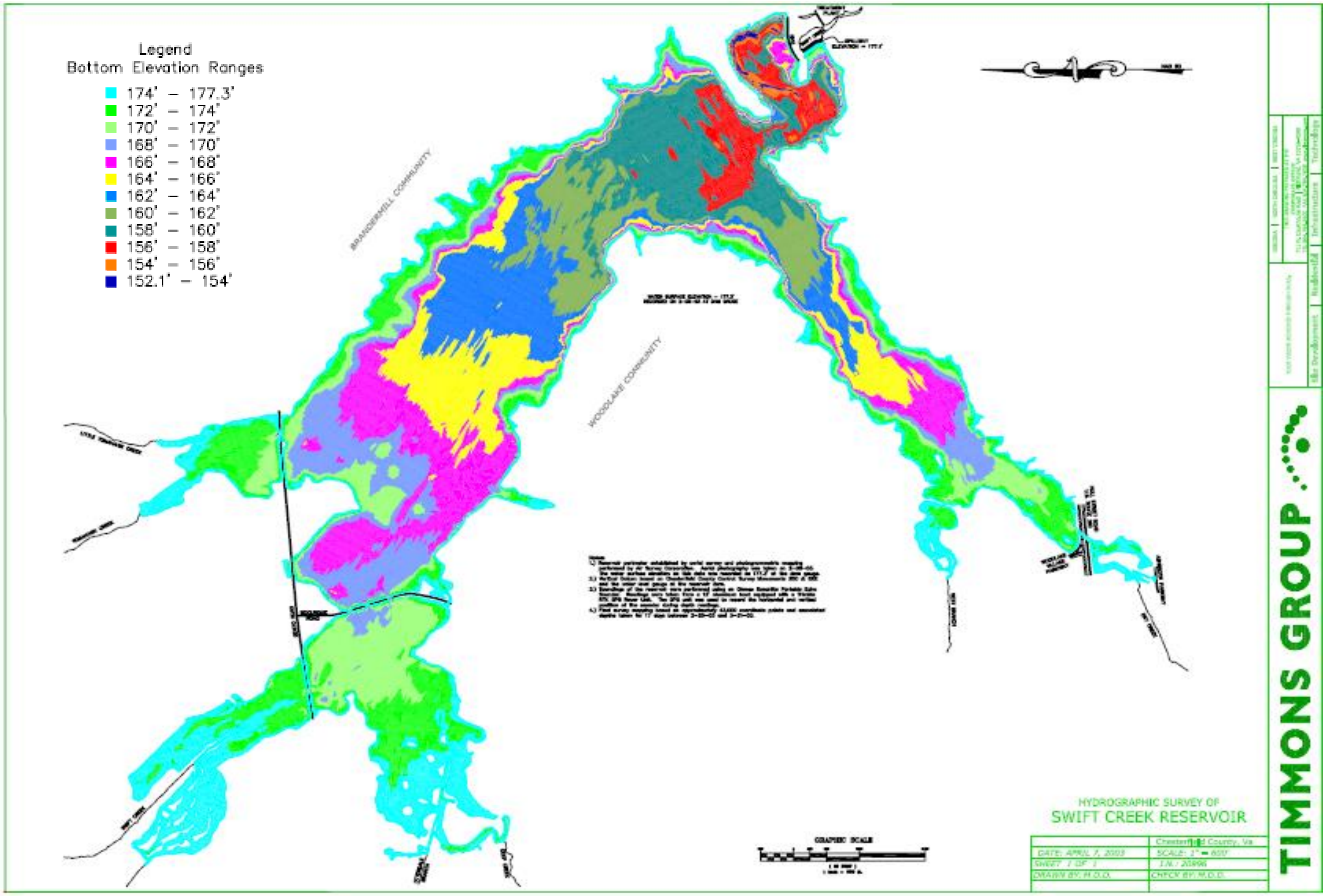

Figure 1. Bathymetry of Swift Creek Reservoir (2003)

Plant Community Results

Plant data have been generated by the staff of the treatment facility for Chesterfield County. The plant community changed little in the first 6 to 12 months after grass carp were first stocked (Figure 2). This is 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 recently, but all other species were virtually absent by late 2011 and remained absent through 2013 (Figure 5). 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.

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 3 and 4 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 leaves, not likely to take over large expanses of this reservoir. The goal of reducing plant biomass through biological control was clearly achieved and was accomplished in just over one year after stocking. Approximately 16 months after initial stocking the reservoir had no hydrilla present and was largely devoid of other vegetation.

However, maintaining some plant cover for multiple purposes was 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 (Figures 2-5), 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 light growth of hydrilla, 1% had medium growth, and 0% had heavy growth. By October of 2014, 15% of the reservoir had heavy hydrilla growth and another 5% had medium or light growth. A specified desirable level of plant growth, independent of the type of plants, has not been set, but between 10 and 25% cover or biovolume is believed to be acceptable from a multi-use perspective of Swift Creek Reservoir. Hydrilla levels were below that range in June 2014 and slightly exceeded it by October. Growth accelerated in late summer, showing how fast hydrilla can regain dominance in the absence of adequate control.

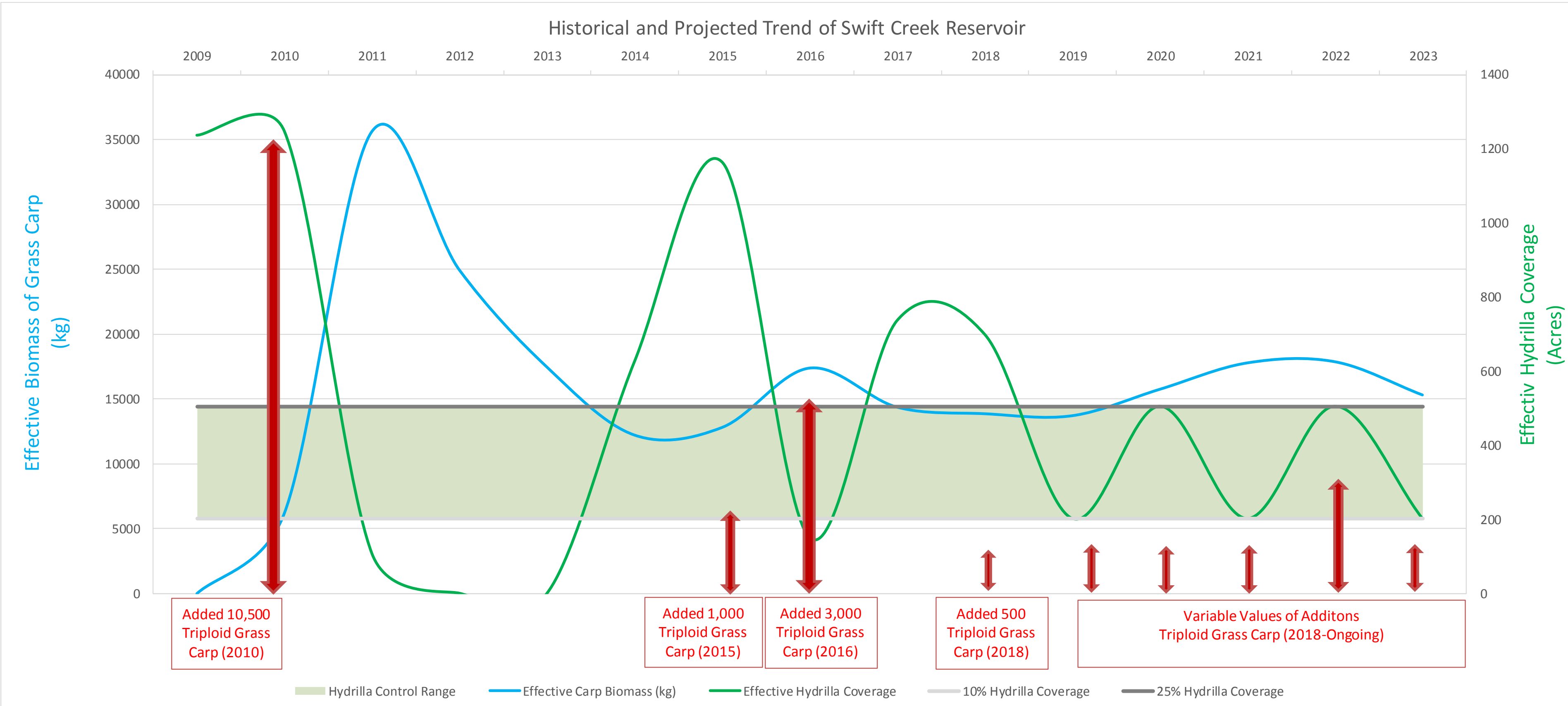

Figure 2. Modeled hydrilla and grass carp biomass in Swift Creek Reservoir, 2009-2023.

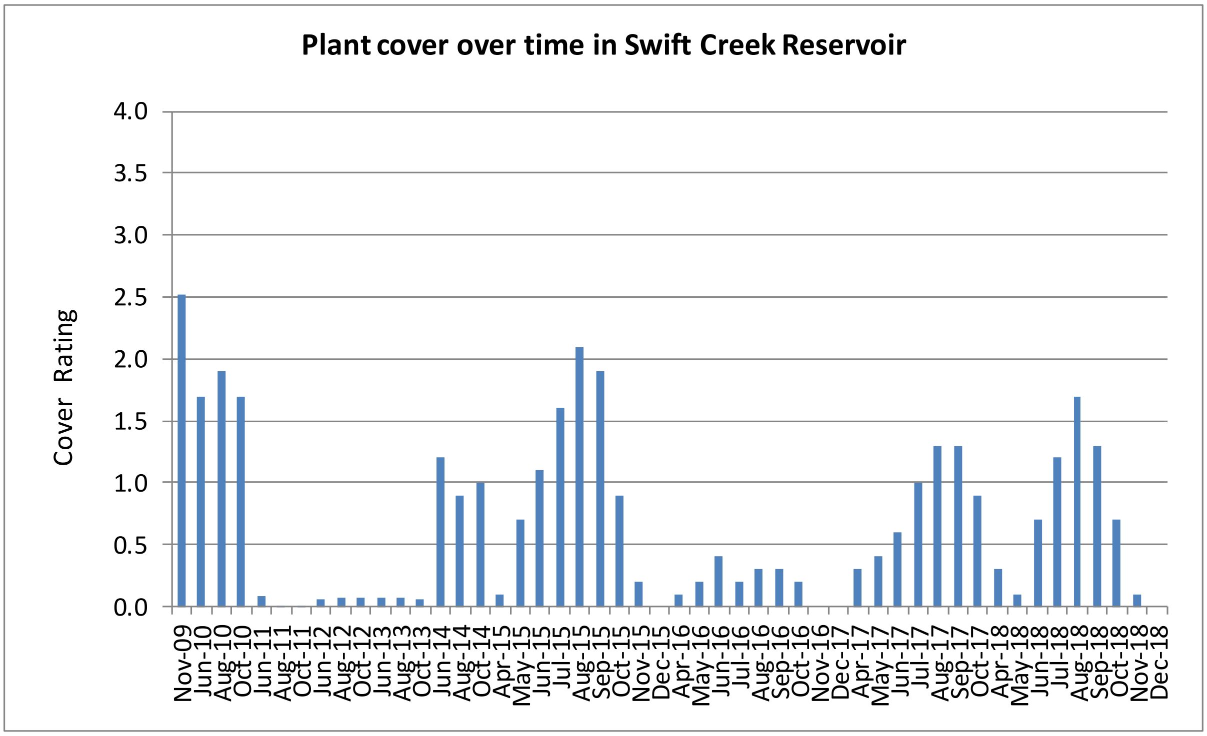

Figure 3. Total plant cover in Swift Creek Reservoir, 2009-2018.

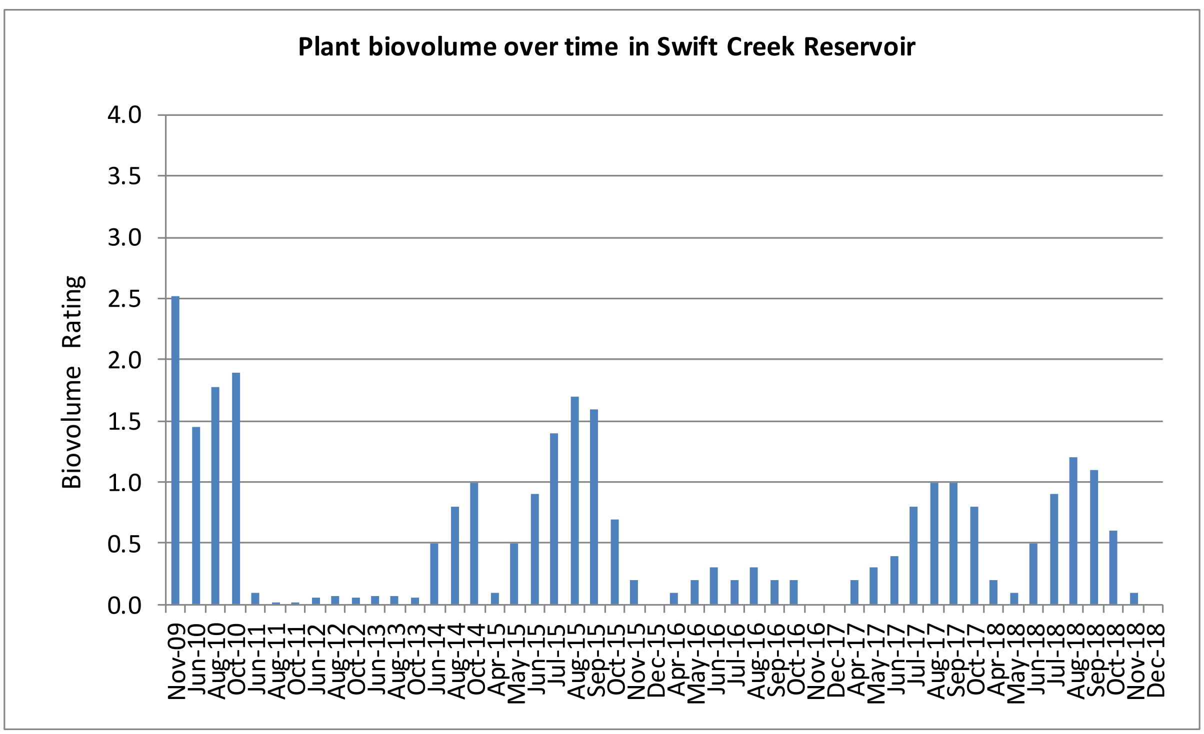

Figure 4. Total plant biovolume in Swift Creek Reservoir, 2009-2018.

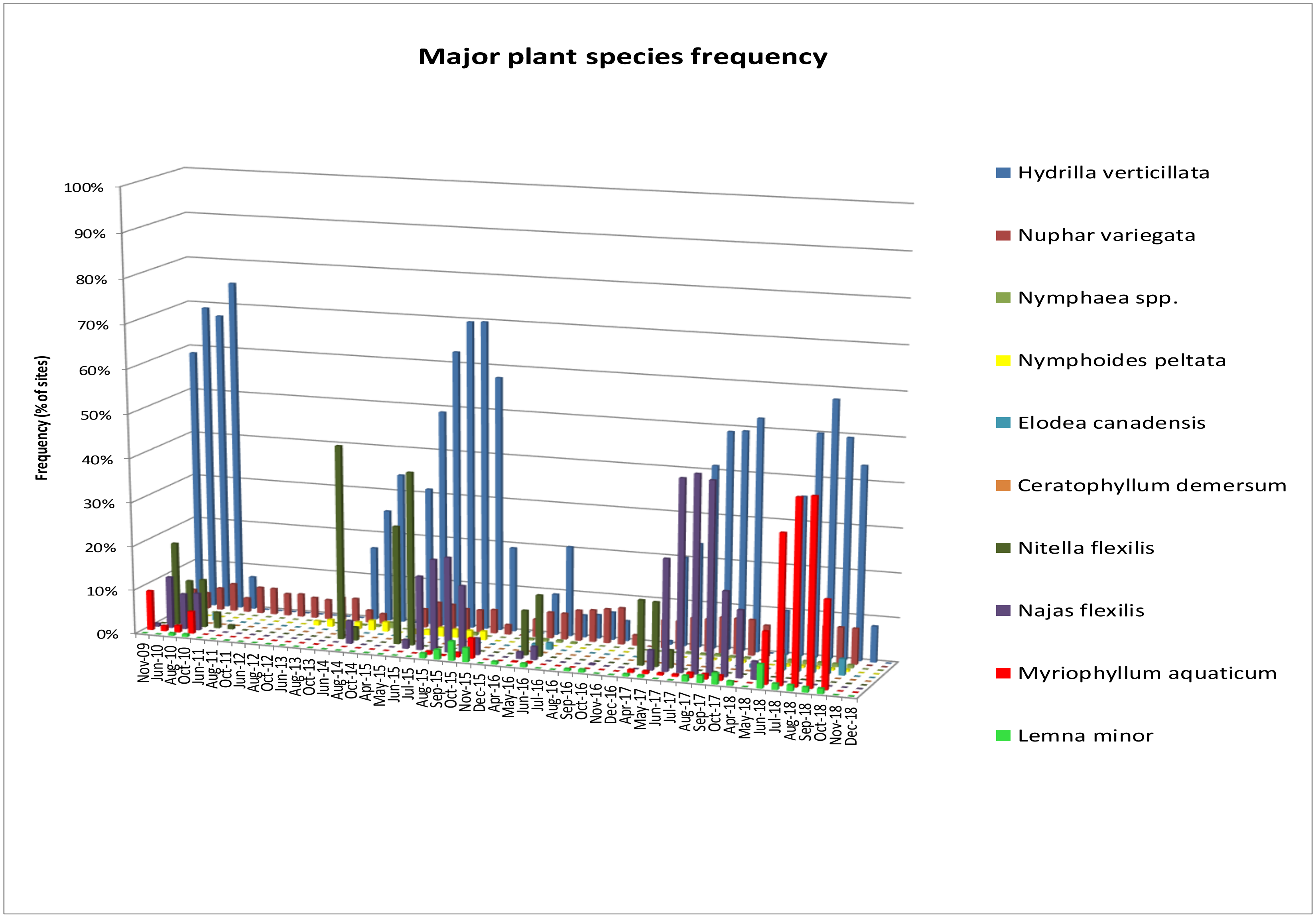

Figure 5. Frequency of plant species occurrence in SCR, 2009-2018.

Hydrilla died back over the winter of 2014-2015. While hydrilla density was a bit higher than desired at the end of 2014, the range of conditions over the summer of 2014 was within the desired control band of 10-25 percent of vegetative cover for a majority of the growth season. There are issues of 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. Knowing that continued increase of hydrilla was likely, grass carp were again stocked in April 2015, but concern over excessive stocking and complete plant loss lead to only 1000 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 as much of the reservoir by late summer 2015 than it had before any grass carp were stocked at a similar density level (Figures 2-5). Hydrilla died back again at the end of 2015, possibly aided by some grass carp feeding, but winter die back appears to be a frequent occurrence north of the Carolinas.

A total of 3000 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 apparently enough to minimize hydrilla abundance (Figures 2-5), 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.

Grass carp were not stocked in 2017, but the 4000 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 (Figure 2), reaching high frequency and achieving high biomass at a few sites. Common naiad (*Najas flexilis*) was also frequently encountered (Figure 5), 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 is not yet extreme and that the lower hydrilla abundance in 2016 may not have been due to grass carp alone. Hydrilla frequency in 2017 was above the desired range of 10 to 25%, peaking at about 35%, but most sites had only trace or sparse growth. The overall condition of the reservoir with regard to aquatic plants appeared favorable for fish and other water-dependent species.

Considerable effort was devoted to data analysis and projections for results with different carp stocking schedules at the end of 2017. While most 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 average annual stocking rate of 500 fish was proposed and 500 grass carp of 12-15 inches were stocked in April of 2018. 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 3 and 4) in 2018 were similar to values in 2017. While some peripheral areas had more plants than other areas, the frequency, coverage and biomass were mostly within the desired range. Overall plant conditions in the reservoir were acceptable by established standards but localized problem areas existed as expected. Hydrilla frequency and abundance was similar in 2018 to 2017, but whereas *Najas flexilis* was common in 2017, *Myriophyllum aquaticum* was more abundant in 2018 than in any previous year. *Najas flexilis* is a native species and a preferred food of grass carp while *Myriophyllum aquaticum* is an invasive species not preferred by grass carp. This would seem to suggest that grass carp predation pressure was substantial in 2018 but that it is having the negative consequence of promoting at least one undesirable species. At the same time, turbidity was again high in 2018, suggesting that light may be restricting plant growth as much as grazing pressure.

Over the course of the 8-year period since initial grass carp stocking, few plants other than hydrilla have been observed with any regularity (Figure 5). *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) or *Naja*s (common naiad, from the pondweed family) were most abundant in 2014 and 2015 after hydrilla and are desirable plants in almost any reservoir. They 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) are 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. The increased frequency of common naiad in 2017 was therefore encouraging, while its decline in 2018 with a rise in parrotfeather represents a concern.

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. As more is learned, it is expected that management goals can be achieved, 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.

It is apparent that the number of grass carp initially stocked (10,500) was more than necessary to control hydrilla and collapse the plant community. It took over a year (2010-2011) for the grass carp to grow and feed such that plants declined to negligible levels, after which plant cover or biomass was minimal for two more years, through 2013. However, loss of grass carp over that period (with increased mortality likely when food resources became scarce) resulted in limited control in 2014 and seemingly no control in 2015, creating a strong oscillation in plant abundance.

The stocking of 1000 grass carp in April 2015 was not expected to have any measurable impact until 2016 and was probably not nearly enough to augment whatever remnant grass carp population was present, so control of hydrilla in 2016 seemed unlikely without more grass carp. The stocking of 3000 grass carp in the spring 2016 may have added enough grazing pressure to depress plant abundance to low levels without eradication, but the increase in hydrilla in 2017 suggests that other factors kept hydrilla abundance low in 2016 and that the necessary biomass of grass carp was still not achieved through 2017. The trick is balancing grass carp stocking and growth with normal mortality and avoiding starvation induced losses.

Turbidity was higher in 2016 than in previous years, was slightly lower in 2017 but still elevated relative to pre-2016 values and was again high in 2018. Algae abundance assessed as chlorophyll-a has risen since grass carp were stocked and was higher in 2016-2018 than all but one previous year of monitoring. Average water clarity was the lowest it has been over the 2016-2018 period. This could have reduced plant growth or may have reduced predation risk enough for young grass carp to allow expanded feeding in shallower areas. This remains speculative but is consistent with observations. Assuming continued containment, survival and growth of the grass carp stocked in 2015-2018, plus supplemental stocking in 2019, plants would not be expected to be more abundant in 2019 than they were in 2017-2018. Yet there is uncertainty that is compounded by factors beyond our control.

Consideration of how many grass carp to stock is complicated by the lag time for any effect and the importance of both numbers of grass carp and size of grass carp, both of which change over time. From a plant community perspective, the conditions observed in 2014 and in the early summer of 2017 and 2018 appear to be along the lines of what is desirable for management of a multi-use reservoir. We do not know how many grass carp were present or what the total grass carp biomass was in 2014. The plant community was not as diverse as would be preferred and some nuisance conditions were observed by October 2014, but the overall level of cover and biovolume appeared appropriate. The plant community in 2017 and 2018 contained limited species and hydrilla was dominant, but overall cover and biovolume were generally desirable on a reservoir-wide basis in the early summer. At the peak of the growth season the overall cover was slightly above the target range of 10 to 25 percent and the rise of *Myriophyllum aquaticum* in 2018 is a concern.

Annual winter die back of many species of plants is another complication. Virginia is certainly not tropical or subtropical but is at the mild end of the temperate range, and cold winter temperatures tend to cause many plant species to die back. What returns the following spring at what density is a complex function of overwintering of some vegetative parts, seed reserves (or other propagules, like winter buds), and ongoing grazing by grass carp. Winter die back creates a food shortage, one that may prompt grass carp to die, become more dormant, or seek to emigrate in search of more plants to eat.

Measures have been taken by Chesterfield County to minimize the risk of escape from Swift Creek Reservoir. A two-phase fence is in place that limits passage through the outlet cove to the actual spillway. The fencing arrangement is inspected annually and meets VDGIF approval as an appropriate control. Escape should therefore have minimal impact on the grass carp population. However, flooding in 2018 from very large storms compromised the barrier twice and some grass carp may have escaped during these brief periods. In the absence of any fish survey in 2018 and a failure to capture grass carp in 2016 or 2017, we have minimal data that will help assess the population.

Mortality from lack of food is a threat when there are no plants present during the growing season and fish are unhealthy going into winter. However, where fish have fed adequately during the growing season, limited metabolism over winter allows a high percentage of fish to survive. Avoiding complete loss of plants will therefore aid grass carp survival. Plant die back was observed in both 2017 and 2018, but grass carp did not eliminate plants to the extent observed in 2012-2013, so grass carp should have entered the winter in a healthy condition. The extent to which dormancy and escape will play a role going into 2019 is unknown.

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 have been captured since 2015 and no survey was conducted in 2018. More effort may be necessary to properly assess the fish community and support management decisions, but the available data are assessed here.

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 combination of number and size of grass carp to exert adequate spring-summer control over plants but not to risk 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 source 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 in each of 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 being 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.

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. Yet the very small number of grass carp actually caught increases uncertainty and limits conclusions.

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, a distinct jump in average weight in 2014 and similar weight in 2015. With only 2 grass carp collected in 2014 and 3 carp captured in 2015, measured changes are not highly reliable. Grass carp appeared food limited by the end of 2011 into 2014 but were not in poor condition in any year based on the fishery surveys.

Variability among individual fish also increased in 2014 and 2015, and no grass carp stocked in 2015 were recaptured, so the variation is a function of differential success by the fish stocked in 2010. With increased food availability, more growth can occur, but those fish that were starving in 2012-2013 were much smaller than those that were more successful in foraging. Location within the reservoir likely matters and failure to collect any grass carp stocked in 2015 may be related to them remaining in the dense hydrilla beds near the inlets which were inaccessible to the electrofishing boat. The length vs. weight curve for grass carp stocked in 2010 (Figure 9) looks fairly normal for that species but with only 6 data points, reliability is limited.

Predation mortality may have been significant in the year of stocking (eagles were observed to catch small grass carp in 2010) but would have declined over time and been minimal by 2012. 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 remained sufficient to keep plant growth in check. Yet there does appear to be substantial mortality or emigration of 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

Table 1. Grass carp data, 2010-2017.

	Grass Carp	CPUE	Avg Length	Avg Weight
Year	# caught	fish/hr	mm	g
2010	Stocked		305	591
2011	20	2.20	701	4240
2012	9	2.25	738	5116
2013	5	0.83	754	5521
2014	2	1.20	873	10120
2015	3	0.83	790	10397
2016	0	0	-	-
2017	0	0	-	-

Table 2. Grass Carp Stocking History 2010-2018.

Grass Carp Stocking History		
Year	# Grass Carp	Size (in)
2010	10500	12
2011	0	0
2012	0	0
2013	0	0
2014	0	0
2015	1000	12-15
2016	3000	12-15
2017	0	0
2018	500	12-15

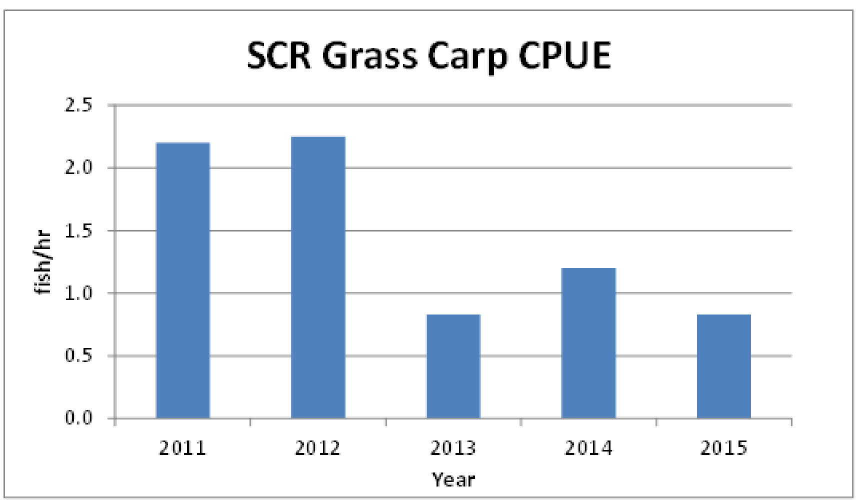

Figure 6. Catch per unit effort for grass carp in SCR, 2010-2015.

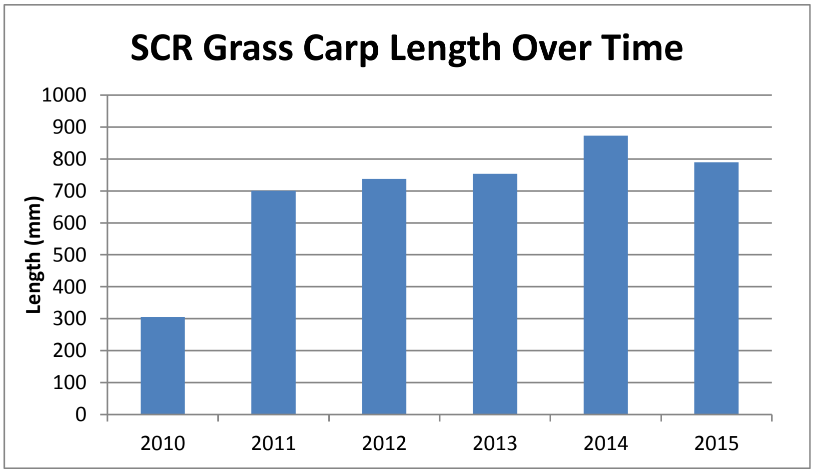

Figure 7. Length of grass carp in SCR, 2010-2015.

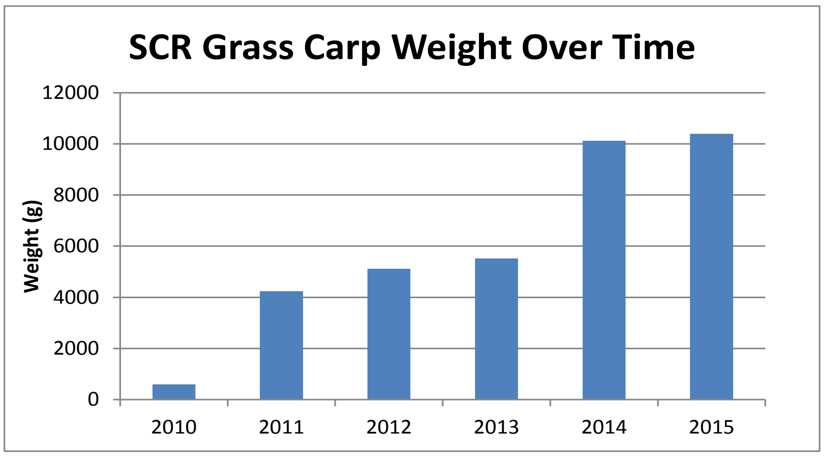

Figure 8. Weight of grass carp in SCR, 2010-2015.

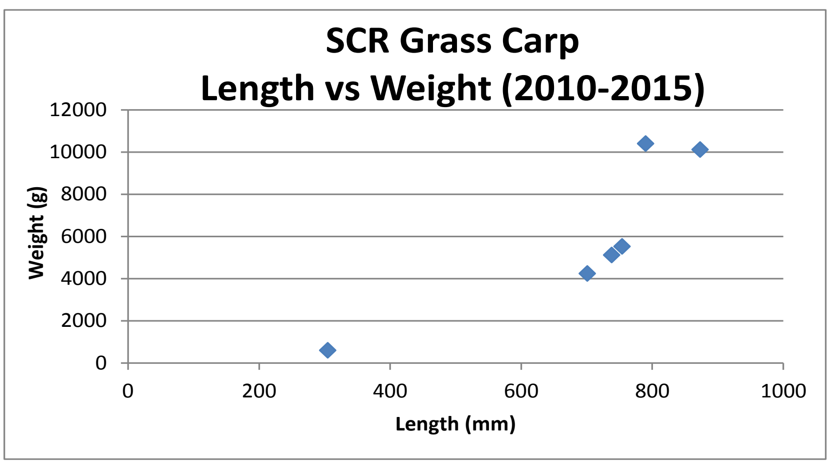

Figure 9. Average length vs weight for grass carp in SCR, 2010-2015.

plant) growths. Older, larger grass carp are also not expected to feed as intensely as younger, smaller grass carp, and may become less of a factor in plant control after about 5 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 in the first year after stocking, the population would have declined from 10,500 in 2010 to 8400 in 2011 and then to between 3000 and 4000 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 and near the low end of the scale used anywhere (1-20 grass carp/ac, usually 3-12/ac).

Potential impact on other fish species through habitat alteration is a rational concern, and the same fish surveys that captured grass carp provided some data on other fish as well. Not all surveys were as focused on other species as necessary to get data that would provide clear insights, but surveys in 2012 and 2014-2017 provide some insights. Additionally, reports of trophy bass and pickerel extend back about 40 years and provide context.

There is no indication of serious and sustained negative impact on the largemouth bass population between 2012 and 2017, but there is variation and reduced abundance in some size categories that may be related to hydrilla control efforts (Figure 10). Bass remained plentiful and many large specimens were present through the 2015 survey. There was a decline in larger bass in 2014, but bass seemed to rebound in 2015. Likewise, there a decline in small bass in 2016 with a rebound in 2017. The catch per unit effort was substantial and condition factor and proportional stock densities indicated a thriving population through 2015, despite fluctuations in plant abundance. Smaller bass were not retained for counting in 2013, limiting comparability of 2013 data to those of other years, but overall population statistics were still very favorable. Yet catch per unit effort, proportional stock density and relative stock density all declined markedly in 2016. As this was after a year of limited hydrilla growth, declines might relate to plant community fluctuations, but there is no consistent pattern. Catch per unit effort remained low in 2017 despite increased plant abundance, yet the proportional stock density in 2017 was the highest recorded since grass carp were stocked. Not too much emphasis should be placed on any single survey and continued annual fish surveys are strongly advised, preferably with greater effort to provide a better assessment of key species. It appears that the fishery is not especially stable but is fairly resilient.

Chain pickerel would be expected to fare poorly in the absence of vegetation, as plants are important to both reproduction and foraging for that species. Only three surveys (2014, 2015 and 2017, Figure 11) provided adequate data to assess the pickerel population, and some vegetation was present in those years. Greater abundance of small pickerel and the more continuous size distribution in 2015 suggests that the increase in vegetation over 2014 was beneficial, but the pattern did not hold up with even more vegetation in 2017.

The fall surveys of 2012 and 2014-2017 have shown considerable variability in catch rate for chain pickerel, with respective catch per unit effort values of 3.3, 22.8, 41.2, 2.0 and 28.5 fish/hr. The 2017 survey collected 114 chain pickerel for a CPUE of 28.5 fish/hr. Catch rates do appear to correspond to the abundance of vegetation, but this may be as much a function of collection method

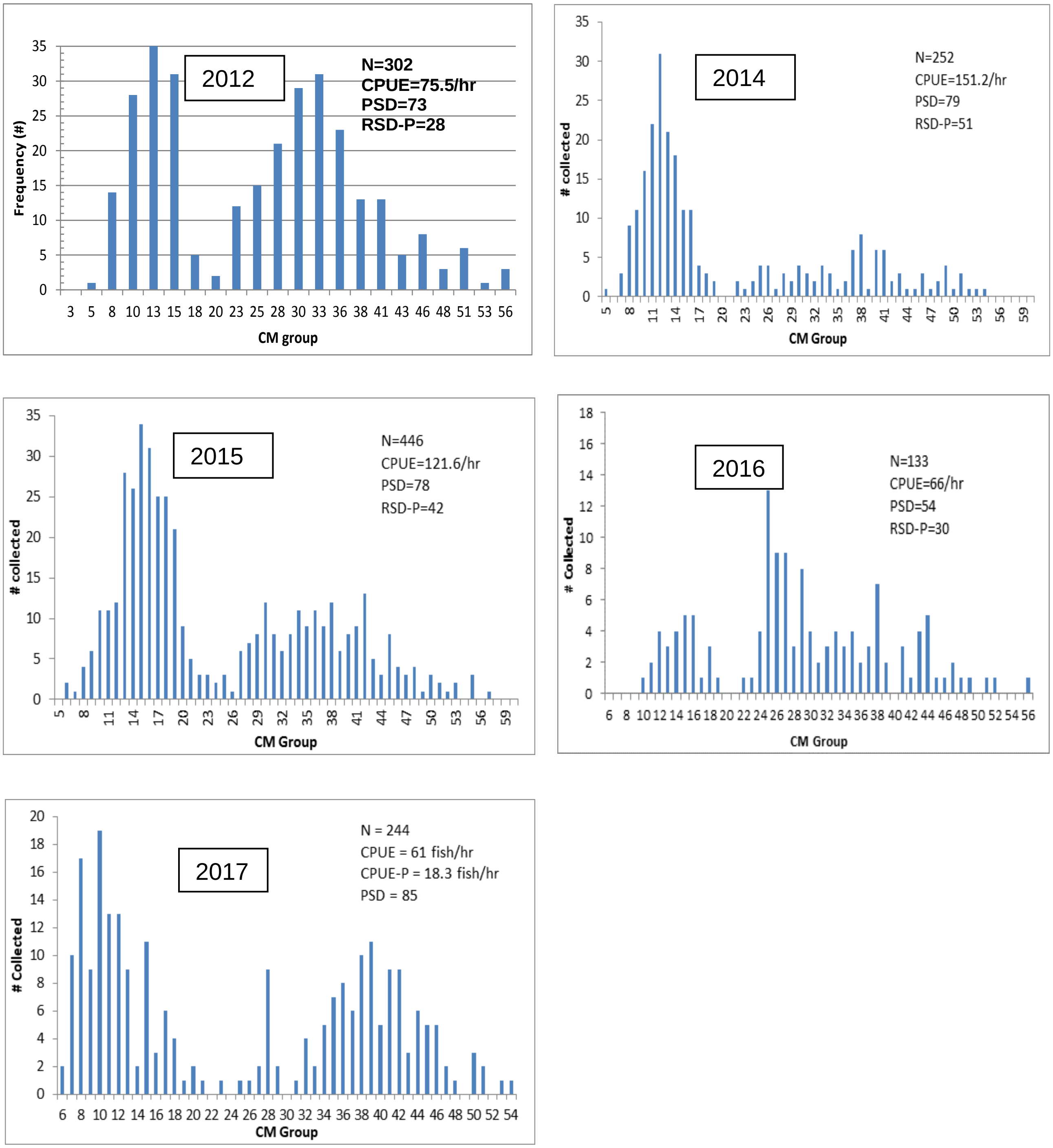

Figure 10. Largemouth bass length distribution in SCR over time.

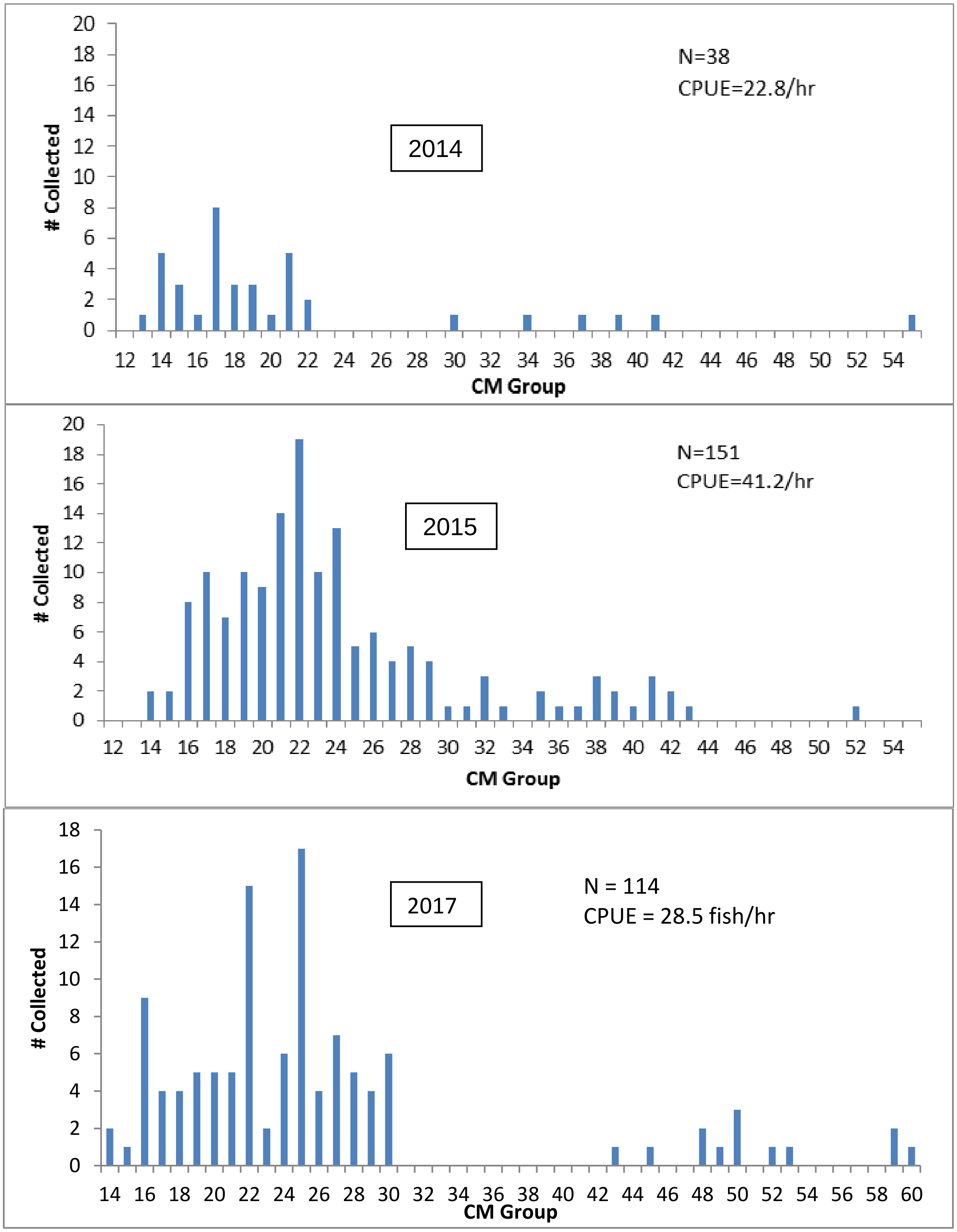

Figure 11. Chain pickerel length distribution in SCR over time.

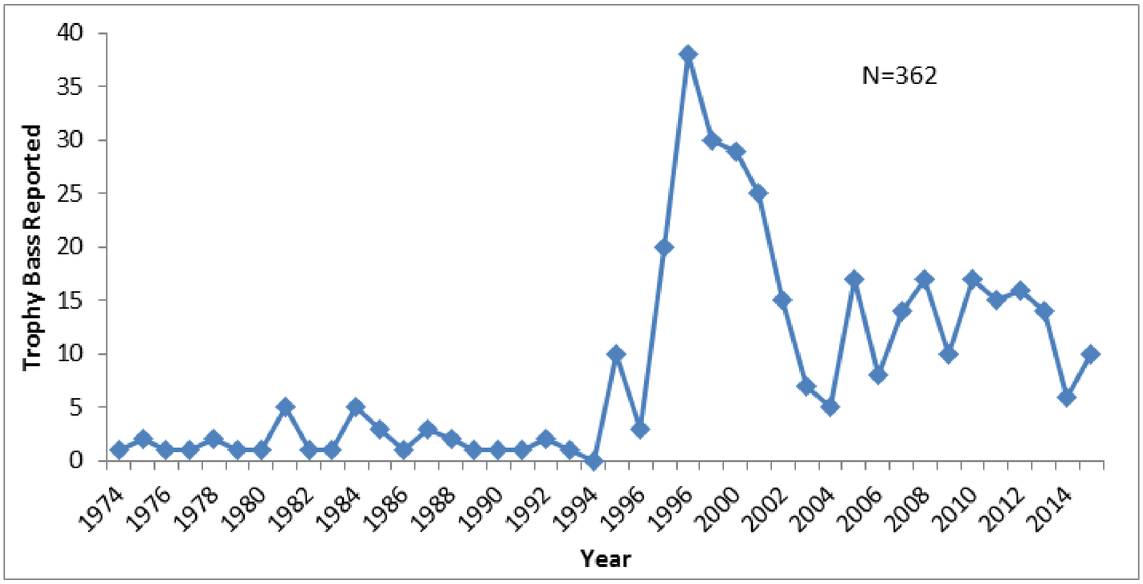

Figure 12. Trophy largemouth bass citations from Swift Creek Reservoir.

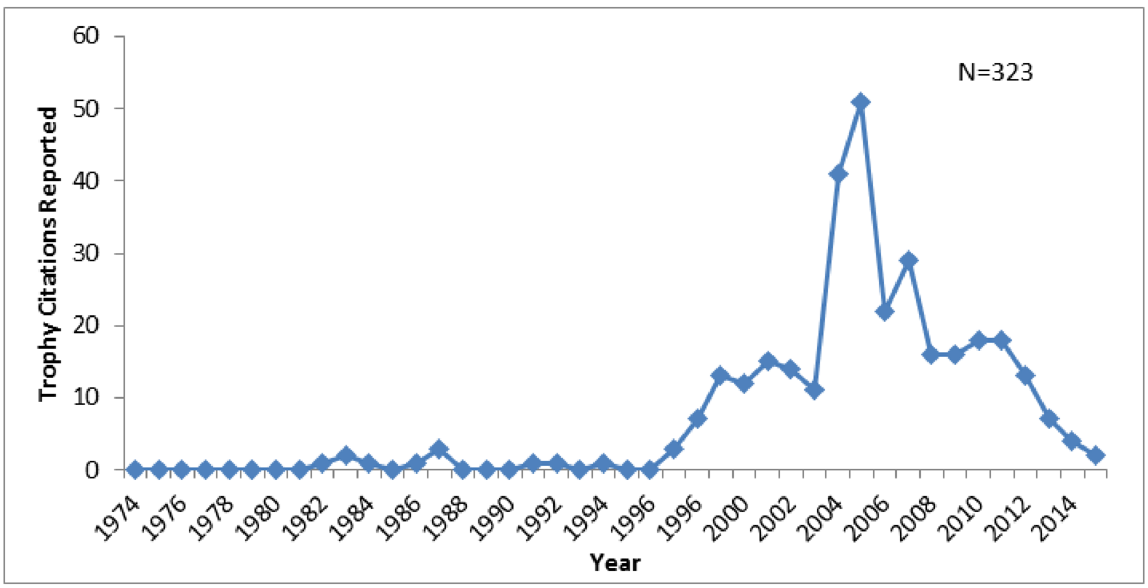

Figure 13. Trophy chain pickerel citations from Swift Creek Reservoir.

as actual abundance. An additional complication noted by the Virginia DGIF is the great expansion of the population of cormorants on the reservoir in recent years, which increases predation on smaller fish, including pickerel, especially in the absence of dense vegetative cover.

Records of trophy largemouth bass (Figure 12) and pickerel (Figure 13) indicate that conditions were not very favorable until the mid-1990s, after which the number of large gamefish increased. This is probably related to the development of a forage base but may also relate to the plant community. It is not related to the presence of hydrilla, which was not significant in the Swift Creek reservoir until 2009. The capture of trophy largemouth bass peaked in 1996 and declined through 2004, then rose slightly and has fluctuated at a moderate level for the last decade. Reports of trophy bass from Swift Creek Reservoir make it the 4^{th} best bass fishery in the region. While not too much should be read into minor fluctuations, there was a declining pattern from 2010 into 2014 with an increase in 2015 that could be related to grass carp and vegetation elimination. It could also be that anglers had to learn to change tactics with less vegetation, and such changes tend to come slowly. Trophy catch data have not been provided since 2015.

The trophy pickerel record indicates an increase from 1997 to a peak in 2005, followed by a strong decline through 2015. Since hydrilla was not a major component of the plant community until 2010, neither the increase nor decrease is strongly linked to hydrilla, but improved chain pickerel populations have been noted by the VDGIF in reservoirs where hydrilla has invaded. It is also apparent that the decline has been steady and precipitous since 2011 when vegetation was depressed by grass carp. Chain pickerel are usually associated with weedy conditions for spawning, juvenile cover, and feeding. Hydrilla provided high pickerel habitat value and the loss of plants after grass carp were stocked would be expected to decrease habitat value for this species.

From 2004 through 2012, the chain pickerel population in Swift Creek Reservoir yielded more trophy specimens than any other Virginia Lake. Swift Creek Reservoir was still the second largest provider of trophy pickerel among Virginia lakes in 2013 despite apparent population decline. No small pickerel were captured in the 2013 fish survey, but there were increases in 2014 and 2015 with the return of vegetation. Data available from 2016 were inadequate to draw any conclusions but did not suggest improved conditions with regard to pickerel. Yet a major portion of the decline in reported trophy chain pickerel in Swift Creek Reservoir occurred before grass carp were stocked, so other factors appear involved and should be investigated.

VDGIF fishery surveys have indicated continued large schools of gizzard shad that act as forage for many gamefish species in Swift Creek Reservoir, and may act as a buffer against cover loss, at least in terms of forage base for fish. Chain pickerel require vegetation at multiple points in their life cycle, but many other species do not. White catfish and a bowfin were also caught during the surveys, but too few specimens were obtained to draw meaningful conclusions. The black crappie population is large, and bluegill sunfish, redear sunfish, and yellow perch are common. Grass carp have altered the landscape within Swift Creek Reservoir, and after 8 years with grass carp it can be said that gamefish populations have not benefitted, but it is not certain that negative attributes of fish populations are a clear result of vegetation loss through grass carp grazing. It would be helpful to increase effort in future fish surveys to ensure adequate assessment of grass carp, bass and pickerel; while this may not be easy, it is necessary if reliable conclusions are to be drawn.

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 runoff volume and phosphorus load is evident (Figure 14). It is therefore difficult to draw conclusions about grass carp impacts on water quality based on any one or a few years of data. Grass carp convert plant biomass to fish biomass, but with an estimated 50% release of phosphorus and other nutrients in the process, and the potential to increase turbidity by physical means exists as well. A rational concern prior to stocking grass carp was whether water quality would suffer appreciably. As treatment processes at the Chesterfield County facility were considered sufficient to address potential increases in turbidity, the stocking was conducted, and water quality monitoring has continued as it has in the past.

Phosphorus data from 1992 to 2016 suggest moderate levels of this important plant nutrient on average, with high peaks in some years (Figure 15). Until 2017 average values had not been significantly higher since grass carp stocking (mainly as a result of substantial interannual variability) and averages remained below the targeted upper threshold level of 0.040 mg/L in all but one year (2011). The average phosphorus concentrations for 2017 and 2018 (Figures 15 and 16) were considerably higher than in past years, however. Both 2017 and 2018 were relatively wet years with elevated turbidity in the reservoir (Figure 16). The observed levels since 2011 suggest a phosphorus increase caused by grass carp, but it is not a major increase and cannot be unequivocally attributed to grass carp at this time. The strong relation between precipitation and phosphorus concentration appears to remain the main determinant of phosphorus concentration in Swift Creek Reservoir.

Consideration of median levels for various commonly measured water quality variables (Figure 16) indicates increases in phosphorus, nitrogen, turbidity, and total suspended solids since stocking of grass carp. Chlorophyll concentration, indicative of algae abundance, is distinctly elevated since grass carp have been stocked. Secchi transparency reflects water clarity and is related to turbidity and suspended solids and has decreased since grass carp were stocked. 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 very weak (Figure 17), suggesting that non-algal turbidity is the primary determinant of light penetration in this waterbody.

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 Chesterfield County staff. Annual average cell counts for algae in the reservoir (Figure 18) have increased noticeably since grass carp were stocked, although there has been a decrease since 2014 that coincides with hydrilla regrowth and apparent reduction in grass carp abundance. The average annual composition of the phytoplankton community (Figure 19) 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 commonly 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.

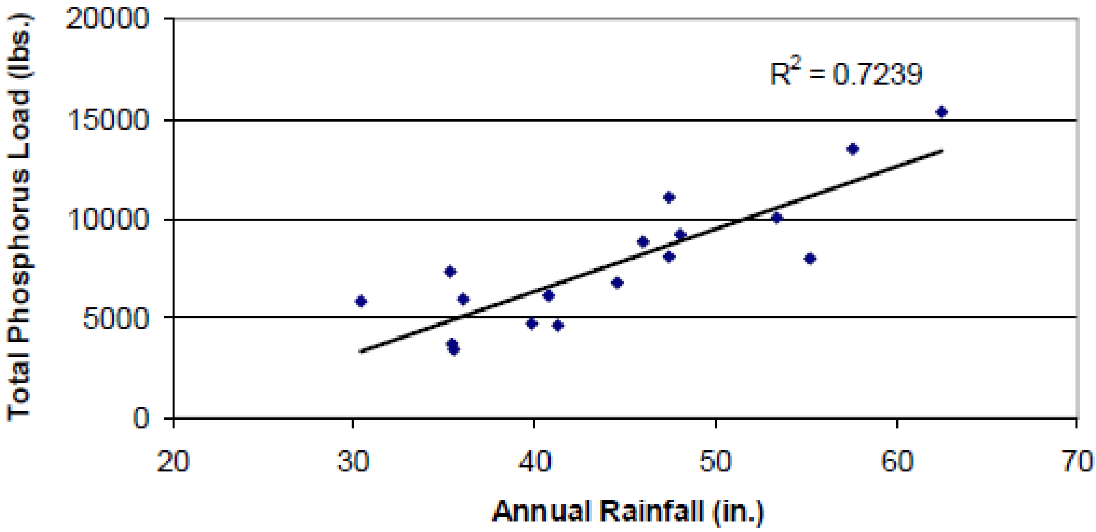

Figure 14. Correlation of phosphorus load to rainfall for Swift Creek Reservoir.

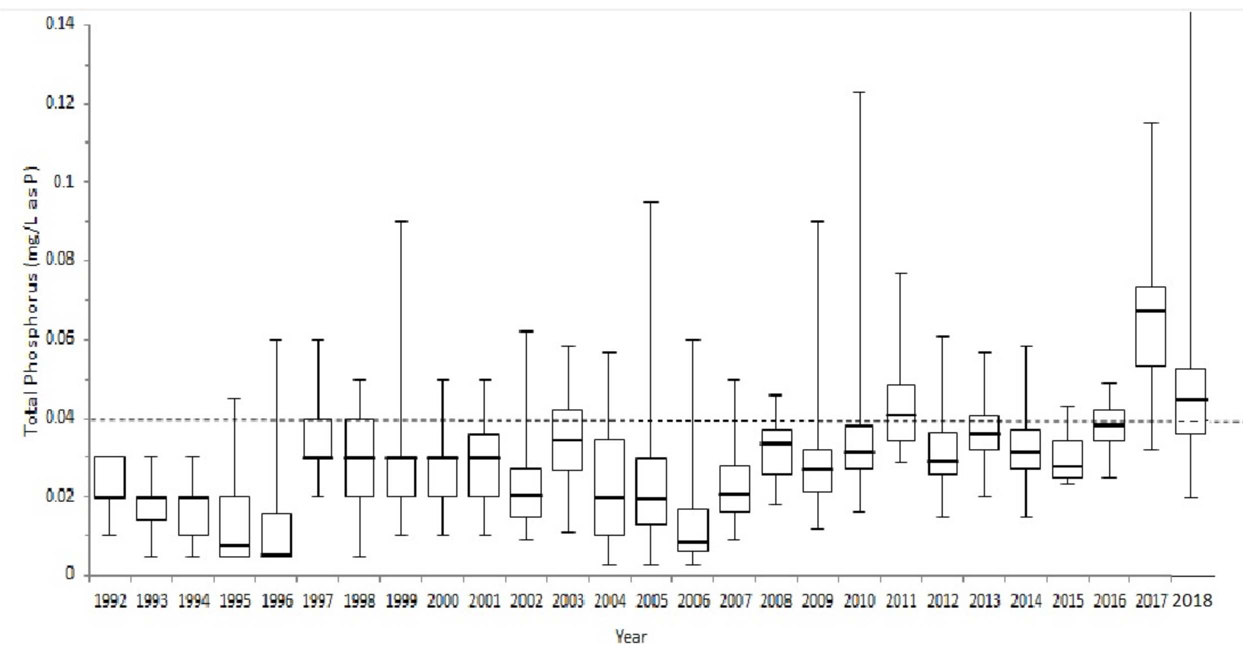

Figure 15. Annual phosphorus concentration statistics for SCR, 1992-2018.

(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.)

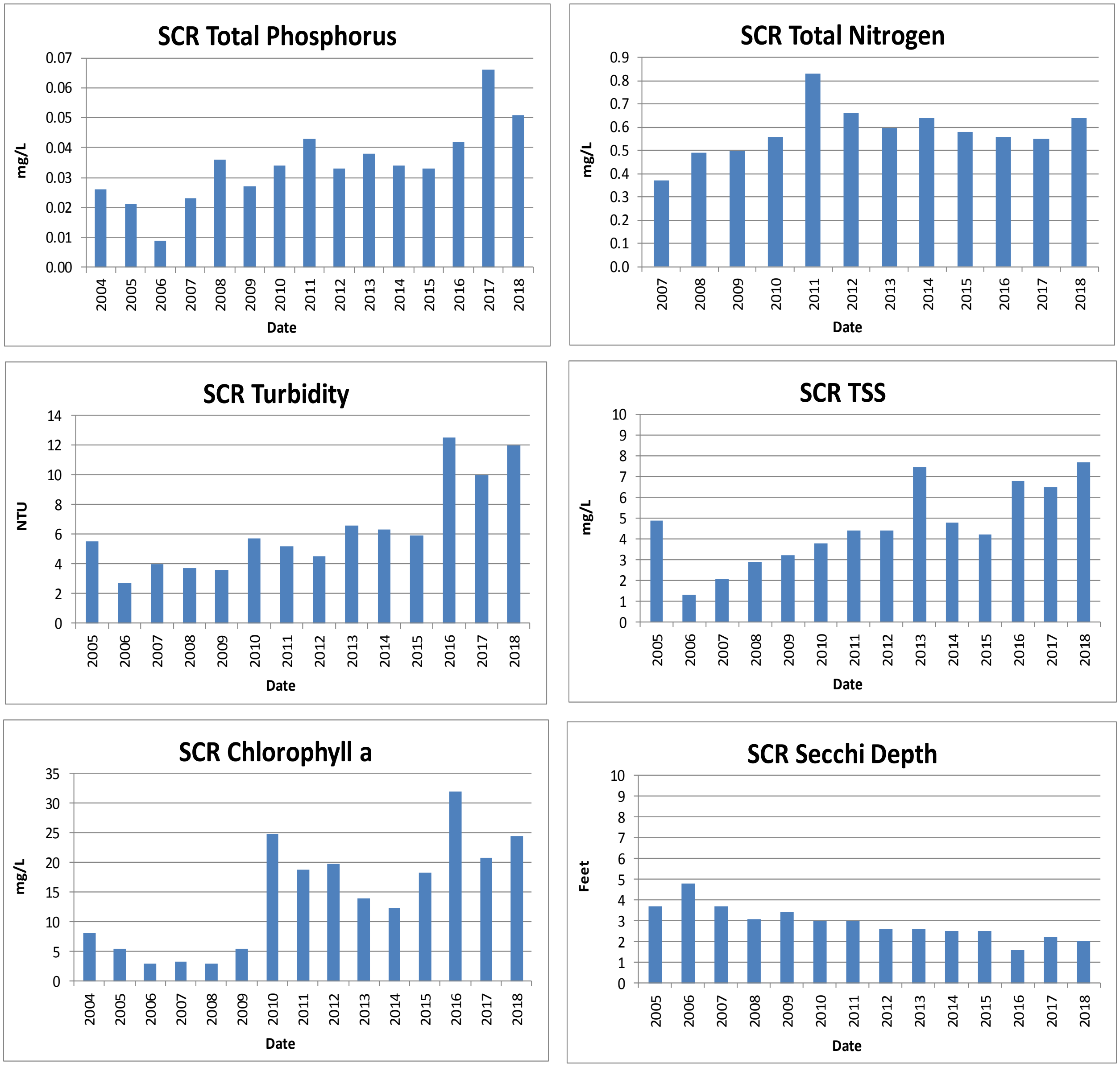

Figure 16. Annual median concentrations for key water quality variables in SCR.

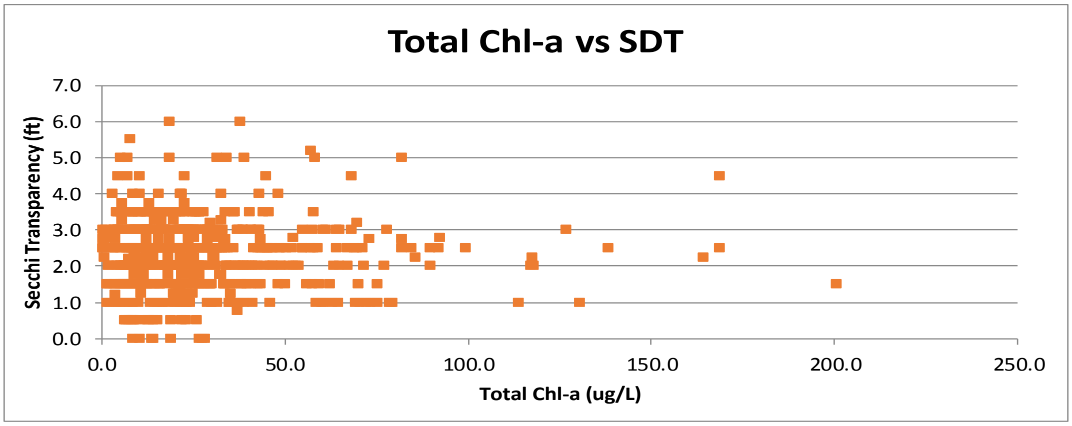

Figure 17. Total chlorophyll-a vs Secchi disk transparency from 2013-2018.

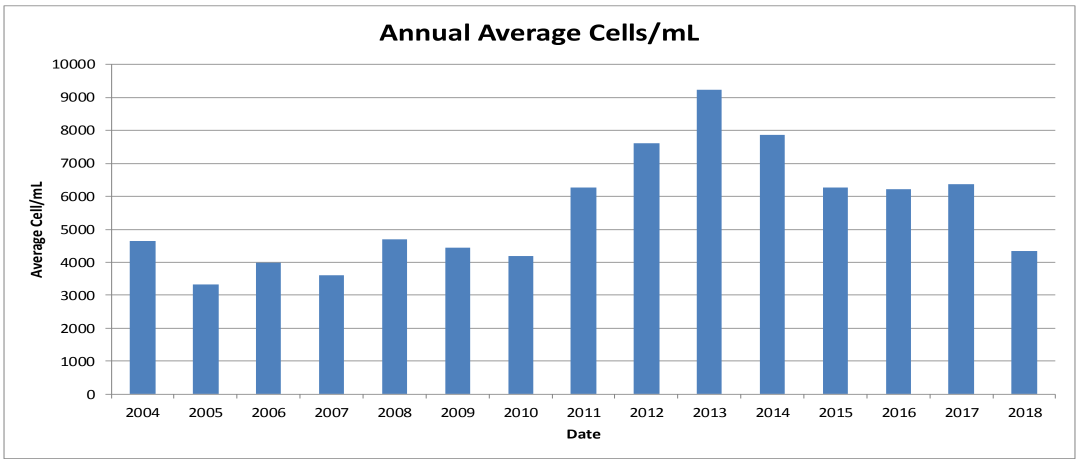

Figure 18. Annual average algae cell count in Swift Creek Reservoir, 2004-2018.

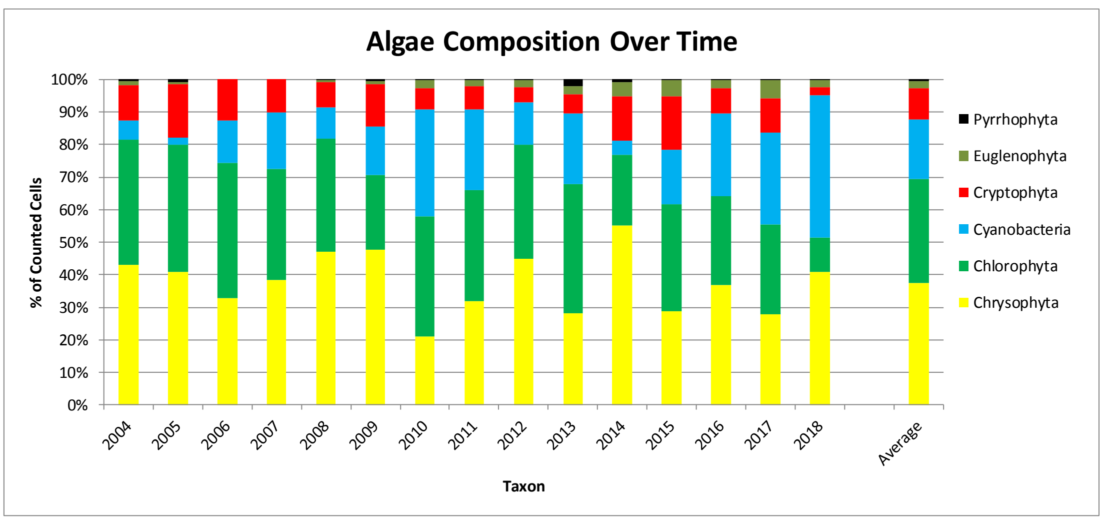

Figure 19. Algal community composition in Swift Creek Reservoir, 2004-2018.

The monthly pattern for chlorophyll-a (Figure 20) 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 county has to be ready to address algae issues at all times but 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 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. There are more algae in the water on average, 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.

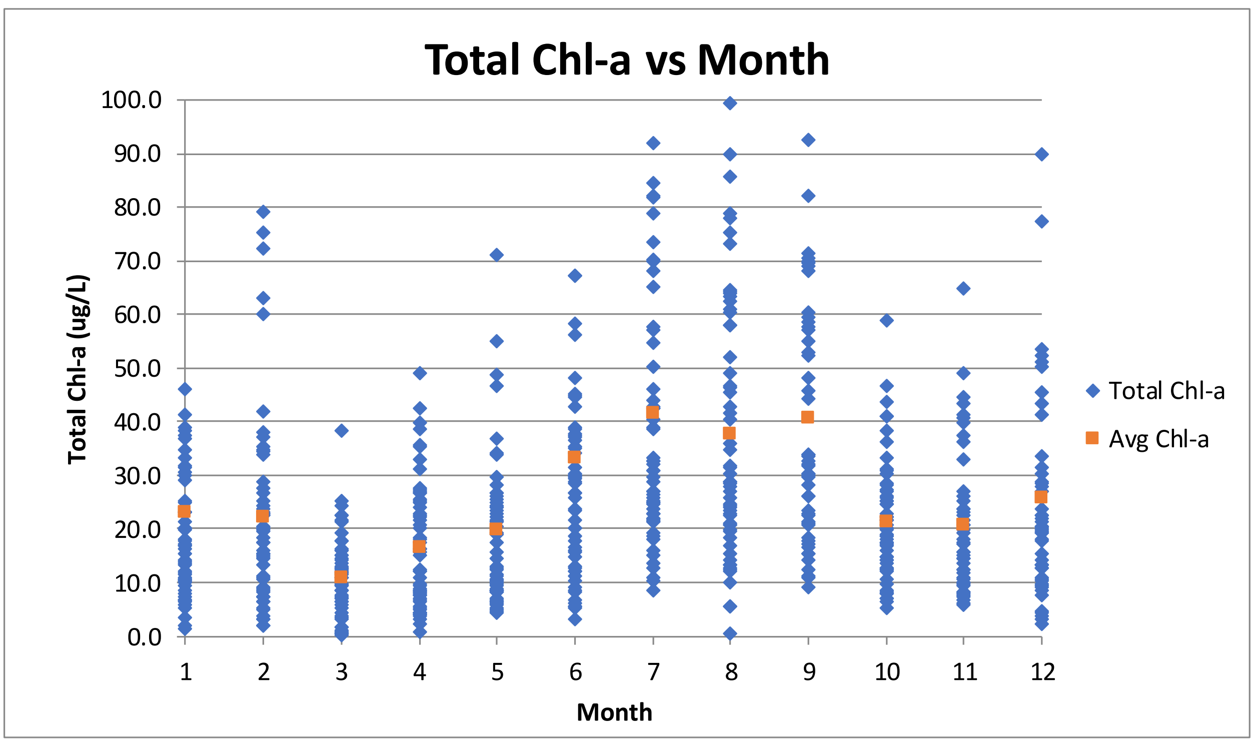

Figure 20. Total chlorophyll-a for 2013-2018 divided among months.

Algae control efforts in Swift Creek Reservoir focused on application of low dose copper-based algaecides for many years. 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 (400 lbs total in each year, with two applications of 200 lbs each to the intake embayment), but cyanobacteria were not abundant at the time of treatment. A temporary effect on other types of algae may have occurred, but as spring normally yields the lowest algae abundance in Swift Creek Reservoir, the overall impact of peroxides is not clear. There is no clear indication of any decrease in algae from the sonic devices yet but high variability within and among stations in the reservoir limits comparison.

Application of copper to control algae levels in the reservoir, especially in the embayment where water is withdrawn for treatment and supply, might reflect grass carp impact on algae abundance. The amount of copper applied varies considerably among years but has not increased markedly relative to historic levels (since 1976) since the grass carp were stocked (Figure 21). More copper was applied in 2016 than in any other year for which data are available, and the total applied in 2017 was the third highest on record, but no copper was applied in 2018. As a result, the average for 2010-2018 is almost identical to the average from 1976-2009 and is <10% higher than the average from the immediately preceding 9 years (2001-2009). Variability is high, however, so factors other than grass carp (e.g., non-algal turbidity, temperature) are likely influential on algal abundance and the need for control. The county treatment practice is to track algal abundance and treat before algae reach major bloom proportions, limiting impacts on and fluctuations in water quality. This is the most appropriate way to use algaecides but increases variation in how often copper is applied.

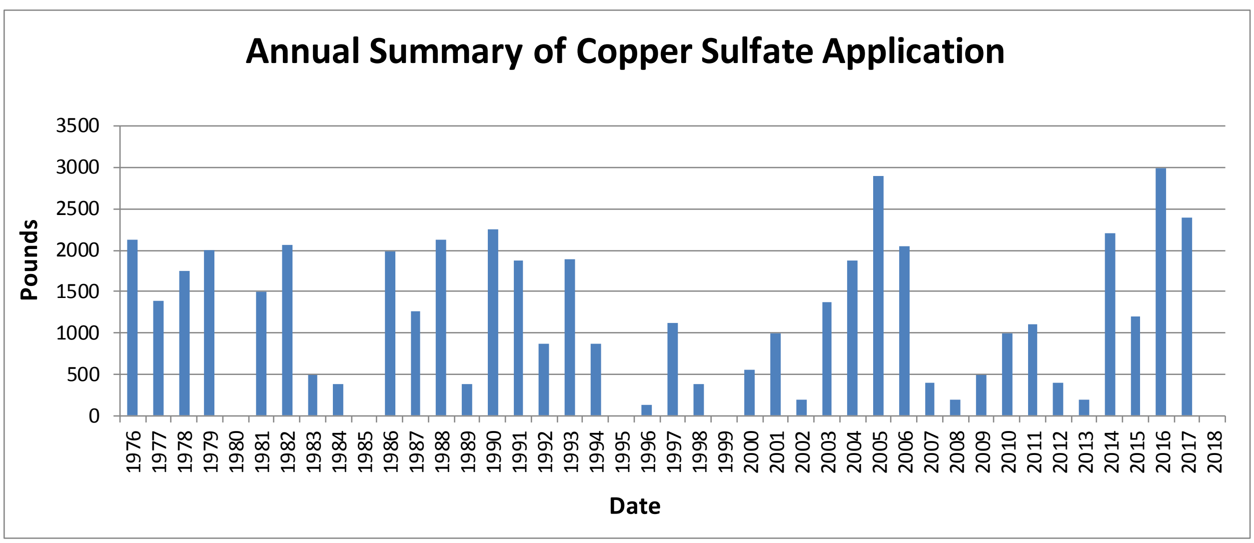

Figure 21. Annual total copper application to Swift Creek Reservoir, 1976-2018.

(Note that 400 lb of peroxide-based algaecide was applied in both 2017 and 2018)

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, 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 risk to resident eagles of allowing hydrilla to remain in the reservoir remains low at this time. 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 would be appropriate.

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 over 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 700 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 (1000 fish at 12-15 inches) and 2016 (3000 fish at 12-15 inches) contributed to low abundance of hydrilla in 2016, but other factors such as low light are believed to 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 and 500 fish of 12-15 inches in length were stocked in 2018. 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 but appears to be a worthwhile effort.

Resurgence of hydrilla to slightly beyond the desired range of 10 to 25% coverage and biovolume was observed in 2017 and 2018. This suggests that other factors besides just grass carp stocking influenced the low abundance plant community in 2016 with less grass carp biomass present than in 2017 or 2018. It also suggests that grass carp biomass is still not high enough to exert the desired level of control, although conditions in 2017 and 2018 were generally favorable for both habitat and recreation in most areas until later in the growth season. Overall coverage area in 2017 and 2018 was considerably lower than 2010 and slightly lower than 2015. Annual stocking of about 600 grass carp appears appropriate based on a model created for this system and accounts for the potential minor losses of carp due to escape through the barriers because of flood damage. Annual adjustment of stocking rate may be necessary, however, given variability in results and factors influencing both the grass carp and reservoir vegetation.

Impacts of grass carp on other plants besides hydrilla were extreme between 2011 and 2014, and possibly in 2016 (other factors may have been more influential in that year), but growths were at least detectable in many areas in 2014, 2015, 2017 and 2018. Except for yellow water lily, which has a growth habit that minimizes grazing by grass carp, and yellow floating heart, which invaded the reservoir relatively recently and is also less edible by grass carp, there were no detectable growths of rooted plants in the reservoir from mid-2011 until 2014 when desirable *Nitella* and *Najas* became moderately abundant in some areas. *Elodea* appeared briefly in 2016. *Najas* was widespread but not dense in 2017. Parrotfeather, which is an invasive species that is not a preferred food of grass carp, has been present at low frequency in some years but became moderately abundant in 2018. The plant community has not been very stable in this reservoir but seems to have been further destabilized by grass carp.

Plants may arise from buried seeds or roots periodically and may arrive at the reservoir from upstream or with boats and birds, but the existing grass carp population prevented any substantial growth until 2014. The species and abundance shifts observed since then 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 very low plant density will not result in even conditions. There will be occasional plant patches that are denser than some reservoir users may like and may require some alternative means of control. On a lakewide basis the conditions of 2017 and 2018 may be about as consistent as can be expected, but continued effort to improve stability is encouraged. To achieve greater success, we need to understand grass carp dynamics and adjust the stocking program accordingly, but this is no easy task.

The grass carp population can be expected to decrease in number over time after any stocking, as these fish are sterile, and declines of up to 20% per year are postulated but not documented. They can live for over two decades and reach lengths near 5 feet and weights over 50 pounds, but where stocked to minimize vegetation, they will be food limited and growth will be slower and longevity shorter. The added stress of low food availability can be expected to increase mortality, and winter die back of plants may cause grass carp to try to escape from the waterbody. The reservoir has a dual-layer containment barrier in place to minimize the potential for grass carp to leave the reservoir, but containment is not guaranteed and floods in 2018 may have allowed some escape. It is difficult to adequately assess a grass carp population, and we do not have estimates of population size for any year after the initial stocking in 2010. Yet inferences from fish surveys do not suggest a gradual decline in the population. Limited data and observations indicate that there was a substantial decrease in the number of grass carp between 2012 and 2014, coincident with complete loss of plants in the reservoir. Perhaps the best evidence of reduced grass carp abundance is the regrowth of plants in the reservoir, with hydrilla reaching pre-grass carp levels in 2015.

Individual grass carp weight increases substantially after fish are stocked, and while growth slows appreciably after the first year, the increase in weight can offset any decrease in numbers between years, up to the point where fish grow slows due to age or where food resources become limiting. There was no indication that grazing pressure on hydrilla was reduced by any decrease in grass carp numbers between 2010 and the start of 2014, and fish surveys documented the substantial but waning increase in individual grass carp biomass. However, there was an increase in average length and weight in 2014 suggestive of increased food availability that coincided with increased plant growth. The combination of number of grass carp and size (relating to individual grazing pressure, which can be 1/3 of body weight per day) appears to have dropped below the threshold for maintaining control over plants by spring 2014.

From the perspective of hydrilla control, the stocking of grass carp has been a major but not constant success. Impacts on fish and water quality are not positive, but the data do not indicate negative impacts that can be clearly linked to grass carp at this time, other than possibly pickerel abundance and increased algae. The first stocking has run its course and additions of 1000 more grass carp in spring 2015 and 3000 grass carp in spring 2016 have raised the number and biomass of carp, although not as much as from the initial stocking. Conditions in 2017 and 2018 suggest intermediate control of hydrilla, and grazing would not be expected to decrease in 2019 unless many fish escaped the reservoir during flood flows. Consequently, there is uncertainty about the current biomass of grass carp in the reservoir and the need for stocking to enhance hydrilla control. As the current management philosophy is to build a multi-age population of sterile grass carp to maximize the stability of grazing influence on plants, annual stocking is desirable as long as it does not overshoot the carrying capacity of the plant community in the reservoir. Determining what that stocking rate should be is an exercise in estimation, monitoring and adaptive management. The conclusion at the start of 2018 (see WRS 2018 for more details) was to stock 500 grass carp in 2018 with adjustment as warranted by plant monitoring and any available information on the grass carp population.

Maintaining an Appropriate Grass Carp Population in 2019 and Beyond

The 2017 update report (WRS 2018) described the issues presented when managing artificially created waterbodies, including that lack of a truly native plant community, experience with hydrilla management elsewhere, general ranges of target densities for grass carp, inherent variation in conditions, and several general trends gleaned from experience and repeated here:

1. Grass carp have definite food preferences; consumption of less desirable forms occurs after more desirable forms have been reduced to minimal levels. Fortunately, hydrilla is a preferred food resource, so it is possible to have other plant species survive in the presence of grass carp where hydrilla is abundant and represents the primary target of control.
2. Partial control projects have often not been considered successful, but this relates to targeting some threshold of acceptable plant cover and not accepting that biological controls will have inherent variability. To achieve success, the target needs to be a range of cover or biomass levels, possibly fairly wide to accommodate the variation in feeding that is affected by temperature, fish size, fish age, plant food choices and movement among reservoir areas.
3. If the target of plant control is a preferred food source and a range of plant abundance is adopted as acceptable, there is still the issue of spatial distribution of plants that will make some reservoir users unhappy. Grass carp cannot easily be directed to address key areas and to stay out of other areas where higher plant density is acceptable. Some shallow areas where boating may be impaired by elevated plant density will have dense growths. Inlet areas where dense growths could supply water quality benefits may be popular with grass carp as a function of flow and temperature in summer.
4. Common stocking protocols include stocking fish of at least a foot in length to minimize predation by larger predatory fish or birds and stocking in the spring to provide the most hospitable conditions for grass carp acclimation and initial growth.

5. It routinely takes a full year before reduced plant abundance can be detected, at which point plant consumption per fish or unit of biomass is maximal and the greatest impact is observed in year #2 after stocking. From that point on, control is largely a matter of balance between number of fish and biomass. Loss of grass carp can be offset by growth and increased plant consumption by remaining fish to a point. However, older, larger fish may not eat as much as younger, faster growing fish, and fewer fish cannot cover as much area as more fish per unit time. Grazing pressure is therefore never constant, and is additionally affected by temperature, oxygen, clarity, flow, and other reservoir variables which cannot be easily managed.
6. Fish may overwinter with limited stress when plants die back and food resources are scarce if it is cold but may die or seek to escape the reservoir if food remains scarce. Fish unable to store sufficient food reserves between spring and fall are less able to overwinter successfully.

Based on the above insights, a successful program will have to establish acceptable target conditions, an initial stocking rate that will potentially achieve those conditions, a monitoring program that provides enough notice to react in time to maintain the desired conditions, and a supplemental stocking program that embodies appropriate contingencies for adjusting the grass carp population. A target condition of 10-25% frequency for hydrilla over the many monitoring stations established in Swift Creek Reservoir was set, equating to coverage over an average of about 400 acres. There is a preference for minimizing areas of dense growth but recognition that not all growths will be sparse and that additional, localized control techniques will be needed in some high use areas of the reservoir.

Keeping hydrilla at an acceptably low level of occurrence in Swift Creek Reservoir appears to correspond to grass carp biomass between 13,500 and 18,000 kg from the updated model, but it may be hard to keep it in that range, as growth and mortality can vary substantially. The number of fish matters as well, as the biomass cannot be invested in fewer large fish to provide effective control. The plan is therefore to have a multi-age population of grass carp averaging about 4000 fish at a range of 0.5 to 14 kg each, averaging about 4 kg per fish, and to maintain this population by stocking each year such that fish that have died, escaped, or aged out of the effective feeding range are replaced. As past stocking has been inconsistent, a period of phased in consistency was envisioned, but with adjustment as warranted by monitored reservoir conditions.

Applying the spreadsheet model with mortality that reduces the number of grass carp by 20% each year and assuming minimal contribution to plant grazing by grass carp larger than 14 kg (about age 8), grass carp biomass were projected to remain in the range of 13,500 to 18,000 kg over the period of 2018-2021 with annual stocking of 500 grass carp in 2018 and 600 grass carp in 2019-2021. The grass carp biomass in 2018 was estimated to be near the low end of the target range and will be similar in 2019 based on the model, but will climb steadily in 2020 and 2021, when the biomass would be near the upper end of the target range. The advanced age and diminished contribution of fish stocked in 2015 and 2016 will cause a decline in 2022 and thereafter without a larger stocking of grass carp. Based on current conditions and modeling, stocking of 2000 grass carp would be needed in 2022 to have adequate grass carp biomass. A return to 600 grass carp per year is anticipated in 2023, but this is too far in the future for any certainty and recommendations will be adjusted annually.

If more than 600 fish are stocked for more than a year or two, there is a significant risk of collapsing the plant community. It is especially critical to avoid stocking more than 600 in 2019-2021, due to the elevated expected biomass of fish stocked in 2015 and 2016 (4000 total fish), unless further escape of other increased loss of grass carp is documented. Ideally, we would get to a point where roughly the same number of grass carp would be stocked every year, but even if we had not created a larger population in 2015 and 2016, there are other factors that will induce variation and require annual adjustment.

Stocking decisions should be based on the plant community in the fall of the previous year, modified by ongoing updates of the grass carp-hydrilla model that has been created. It is advisable to stock smaller numbers of grass carp either every year or every other year, to improve population stability while maintaining adequate biomass to keep hydrilla in check. The alternative of stocking more grass carp to get more rapid results causes instability that should be avoided to the extent possible. Allowing the plant community to collapse will increase mortality and decrease the accuracy of projections in subsequent years. Having too many fish in one year class will have a similar effect, as those fish will cease to provide significant grazing pressure over a short time period, mimicking a mortality event. And since fish must grow for about a year before they provide substantial grazing pressure, lead time for stocking must be factored in. While we cannot control all sources of variation, stocking smaller numbers of grass carp more frequently allows for more effective adjustment.

If the spreadsheet model represented in Table 3 is accepted as sufficiently reliable, the annual stocking rate that maintains a grass carp biomass between 13,500 and 18,000 kg and accounts for the additional loss in 2018 is estimated at 600 fish for the next three years, depending on mortality, escape or growth limitation, which in turn depends on plant abundance and the integrity of the outlet barrier. Any fluctuation in plant abundance, which could be a function of weather that induces colder or warmer temperature, higher or lower rainfall and associated turbidity, or higher or lower water levels, could alter the trajectory of the grass carp population and warrant some adjustment in stocking rate. Likewise, any mass escape of grass carp may necessitate increased stocking, but adjustment must remain within a fairly narrow range to avoid the “aging out” phenomenon some years later.

Given an assumption of some escape of grass carp due to flooding and barrier compromise in 2018, the model was used to bracket possible adjustment in 2019 stocking. Figure 2 shows the projected conditions based on the currently prescribed stocking regime, both actual through 2018 and projected through 2023. Table 3 provides a numeric tabulation of projected grass carp biomass which shows the biomass to be in the targeted zone for the next few years with the stocking of 600 new fish each year. Biomass was a little lower than desired in 2018, but the intention was to leave room for annual stocking in subsequent years without exceeding about 18,000 kg.

For the current model we have estimated that an additional 10% more fish were lost in 2018 than the original model assumed (30% vs. 20%). Stocking 600 fish in 2019-2021 keeps the projected grass carp biomass in the desired range (Table 4). The model suggests that stocking 600 grass carp in 2020 and 2021 will also achieve goals, but a major infusion of grass carp will be needed in 2022 to compensate for the fish from the 2015 and 2016 stockings aging out and becoming ineffective feeders.

Table 3. Projected change in grass carp population in response to multiple stocking events

			Original Stocking of Grass Carp				2015 Stocking				2016 Stocking				2017 Stocking				2018 Stocking				2019 Stocking				2020 Stocking				2021 Stocking			
Year after stocking	Year	Effective Carp Biomass (kg)	Fish @ 20%/Yr Loss (kg)	Fish @ 30% More Loss after Plant Elim.	Average Weight (g)	Original Biomass (kg)	Added Stocked Fish	Fish @ 20%/Yr Loss (kg)	Average Weight (g)	Total Effective Biomass (kg)	Added Stocked Fish	Fish @ 20%/Yr Loss (kg)	Average Weight (g)	Total Effective Biomass (kg)	Added Stocked Fish	Fish @ 20%/Yr Loss (kg)	Average Weight (g)	Total Effective Biomass (kg)	Added Stocked Fish	Fish @ 20%/Yr Loss (kg)	Average Weight (g)	Total Effective Biomass (kg)	Added Stocked Fish	Fish @ 20%/Yr Loss (kg)	Average Weight (g)	Total Effective Biomass (kg)	Added Stocked Fish	Fish @ 20%/Yr Loss (kg)	Average Weight (g)	Total Effective Biomass (kg)	Added Stocked Fish	Fish @ 20%/Yr Loss (kg)	Average Weight (g)	Total Effective Biomass (kg)
-1	2009	0																																
0	2010	6,206	10,500		591	6,206																												
1	2011	35,616	8,400		4240	35,616																												
2	2012	24,931	6,720	4,704	5300	24,931																												
3	2013	17,452	3,763	2,634	6625	17,452																												
4	2014	12,216	2,107	1,475	8281	12,216																												
5	2015	12,807	1,180		10352	12,216	1000	1000	591	12807																								
6	2016	17,381	944		12939	12,216		800	4240	15608	3000	3000	591	17381																				
7	2017	14,369	755		14000	10,574		640	5300	4193		2400	4240	14369	0	0	591	14369																
8	2018	13,864	604		14000	8,459		512	6625	3392		1920	5300	13568		0	4240	13568	500	500	591	13864												
9	2019	13,711	483		14000	6,767		358	8281	2968		1344	6625	11872		0	5300	11872		350	4240	13356	600	600	591	13711								
10	2020	15,746	387		14000	5,414		287	10352	2968		1075	8281	11872		0	6625	11872		280	5300	13356		480	4240	15391	600	600	591	15746				
11	2021	17,781	309		14000	4,331		229	12939	2968		860	10352	11872		0	8281	11872		224	6625	13356		384	5300	15391		480	4240	17426	600	600	591	17781

(Assumptions as listed in labels. Blue shaded cells indicate 30% loss instead of 20% as shown in label to account for escapes in 2018. Biomass for any given year shown in yellow highlight. Target biomass is 13,500-18,000 kg.)

Table 4. Projected changes in grass carp population with different 2018 loss levels

	Previous Assumptions		10% Higher Loss in 2018	
Year	Added Stocked Fish	Total Effective Biomass (kg)	Added Stocked Fish	Total Effective Biomass (kg)
2018	500	13864	500	13864
2019	250	15412	600	13711
2020	250	16260	600	15746
2021	250	17108	600	17781
2022	2500	16116	2000	17870

Overall control of hydrilla was somewhat lower than desired in 2017 and 2018 and a rise in parrotfeather, a non-preferred food for grass carp, was also observed in 2018. This suggests that there is adequate preferred food (mainly hydrilla) for the current grass carp population and that increasing biomass slightly would be appropriate. The original model projected that grass carp biomass would exceed the desired level and might lead to a collapse of the plant community with annual stockings of >250 fish in 2019-2021, but re-running that model with an additional 10% loss in just 2018 from presumed escape indicates that grass carp biomass would remain in the desired range with 600 grass carp stocked per year. And with the additional stocking in 2019-2021 the potential need for more fish to replace aged out 2015-2016 stocked fish would be lessened. It would seem entirely reasonable to increase the stocking rate from the previously projected 250 to 600 fish for 2019 and 2020, re-evaluating results based on plant data and reconsidering the stocking rate for 2021 and beyond.

While experience over multiple years will be needed to fine tune any approach, an initial target of no more than 15% coverage by hydrilla in June is appropriate, with very few areas of dense hydrilla growth. Note that other plants may be abundant, and in fact some dense growths of other plants such as *Nitella*, *Najas* and water lilies (*Nuphar* and *Nymphaea*) would be preferred for fish habitat in June or even earlier. At the peak of hydrilla growth, which can be between August and October depending on overall plant density and weather, no more than 25% of the reservoir should have hydrilla and no more than 25% of those sites should have dense hydrilla growth. If these values are exceeded, stocking adjustment may be needed the following April, although the magnitude of any increase will not be large to avoid collapsing the plant community. An oscillating pattern of plant abundance is expected, with a target frequency range for hydrilla of 10-25%. This means that there will be areas of greater coverage on a localized basis, and additional physical controls may be needed in those areas; an even distribution over the growth zone of the reservoir should not be expected.

For any annual stocking program, grounds for adjusting the stocking rate may take more time to solidify, as the presence of other species may be particularly important. If hydrilla is not abundant (<15% presence with very few dense patches) but neither are other plant species that provide valued fish and wildlife habitat, stocking might be decreased. However, if hydrilla is not abundant and other species are common, there would be less impetus to reduce the stocking rate. This seems like an unlikely situation, as hydrilla appears capable of expanding coverage and increasing density at a much greater rate than nearly all other species in Swift Creek Reservoir, but it should be kept in mind when stocking decisions are made. If hydrilla increases beyond the early and late season target abundances, stocking could be increased, but not to any extreme level unless we are expecting a major reduction in grass carp biomass by fish reaching about 8 years old, when reduced grazing is expected.

It is critical that stocking not err on the side of overstocking, as collapses of the plant community have undesirable consequences for reservoir ecology and water supply. Given expected natural variation, there will be patches of dense vegetation if the ongoing stocking program works as desired. Some of these patches may pose no issue for human access and reservoir use and should be left in place as habitat. Where such growths do interfere with access, however, having one or more localized techniques for plant control could allow access to be created while not substantively impacting conditions on a reservoir-wide basis.

Where the hydrilla growth pattern is acceptable on a reservoir-wide basis, but shoreline access is restricted by denser growths, residents or property owner groups should be allowed to apply benthic barriers or manually rake areas to provide boat access. Application to an area up to 10 feet wide and long enough to reach water >10 feet deep should be allowed. Loss of plant cover will be nominal over the area of the reservoir, and the edge effect that is created by such action will actually improve fish habitat. Consideration may also be given to using a mechanical harvester to clear areas of excessive vegetation. Mechanical harvesting is not feasible on a large scale in SCR, but with successful moderation of hydrilla abundance with grass carp, it could be an appropriate back-up technique if an electric powered machine is available to meet reservoir boat use requirements.

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 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 similar to those observed prior to control with grass carp. Restocking of grass carp in 2015 and 2016 appears to have been regained some vegetation control, but slightly more control is desired. No stocking occurred in 2017 and 500 grass carp were added in 2018, and while conditions in 2017 and 2018 were similar to those in 2014, somewhat more grass carp biomass appears warranted. Additional stocking is therefore needed, but care must be taken to avoid future collapse of the plant community.

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. Analysis of data by WRS after completion of monitoring in 2013 suggested that as few as a third of the current monitoring points are needed to get an adequate appraisal of the plant community, but the original program of nearly 600 survey points (over 500 of them in the expected plant growth zone) has been maintained and provides an excellent database for comparisons over space and time.

Data for the fish community is less extensive but still quite useful. While additional fish surveys would be helpful in evaluating progress and model assumptions, the difficulty in capturing enough grass carp to adequately estimate average length and weight or 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 2-3 years) and expend more effort to collect more and better data, especially for grass carp size distribution and condition.

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 working toward a more stable plant community at an intermediate density is appropriate. Data for grass carp are too limited to allow reliable estimation of population size or even average fish size in most years since stocking. Analysis of grass carp dynamics and development of a desirable stocking rate therefore requires assumptions and modeling which brackets probable values for fish size and population losses.

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 is about as narrow as can be expected. That range was slightly exceeded in 2017 and 2018, but considerable control by grass carp appears evident. However, elevated turbidity in 2016-2018 is believed to have depressed plant growth, so control by grass carp is likely to be somewhat lower than desired.

Decisions on how many fish should be stocked each spring should be based on plant data from the prior year and the current biomass model. Use of prior year plant data should be adequate to guide stocking in 2018 and beyond. The 2017 plant data suggested that the stocking of 500 grass carp in 2018 was reasonable and that stocking was accomplished. Annual stocking of approximately 250 grass carp per year was previously projected as appropriate for 2019-2021. However, flooding during 2018 is believed to have allowed escape of grass carp from the reservoir and no fish survey was conducted, increasing uncertainty regarding the grass carp population as of 2019. Applying the model and altering assumptions regarding loss of grass carp in 2018 (10% additional loss), it appears that the current level of control might be maintained in 2019-2021 with annual stocking of 250 fish/yr, but grass carp biomass will be at the low end of the targeted range and current control at slightly higher biomass is considered lower than desired.

Based on the current update of the model, stocking of 600 grass carp in 2019 and 2020 should not cause a collapse of the plant community and can be supported as a modification of the previous 2018 recommendation for stocking in 2019-2020 (250 fish per year). Stocking 600 grass carp in 2021 is projected to increase fish biomass close to the upper limit of the target range, but progress can be evaluated, and stocking can be adjusted at the end of 2019 and 2020 based on plant community monitoring to ensure the plant community does not collapse.

Aging of larger numbers of fish stocked in 2015 and 2016 will cause a substantial reduction in effective grass carp biomass in about 2022, such that stocking will need to increase in 2022 to avoid a lapse in plant control. Increasing stocking to more than 600 grass carp per year prior to 2022 may overshoot the capacity of the reservoir to support grass carp and would be expected to collapse the plant community, but stocking of more grass carp will be necessary in 2022 to replace aged out fish.

Chesterfield County should continue to maintain its fish escape prevention practices and should continue to carefully monitor water quality and the algae community, with treatment as needed to minimize harmful algae blooms. The probability of such blooms increases with grass carp control of the plant community, so a balance between plant control and water quality is needed but is difficult to achieve and maintain.