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 the northwest part of the county and encompasses 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, with light growth beginning in 2010. An estimated 842 acres, or approximately 50 percent of the reservoir, was covered with hydrilla by October of 2010, with areas of dense mats of hydrilla, 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 would severely limit 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. This report is intended as an update on management progress and to support reasoned management planning.

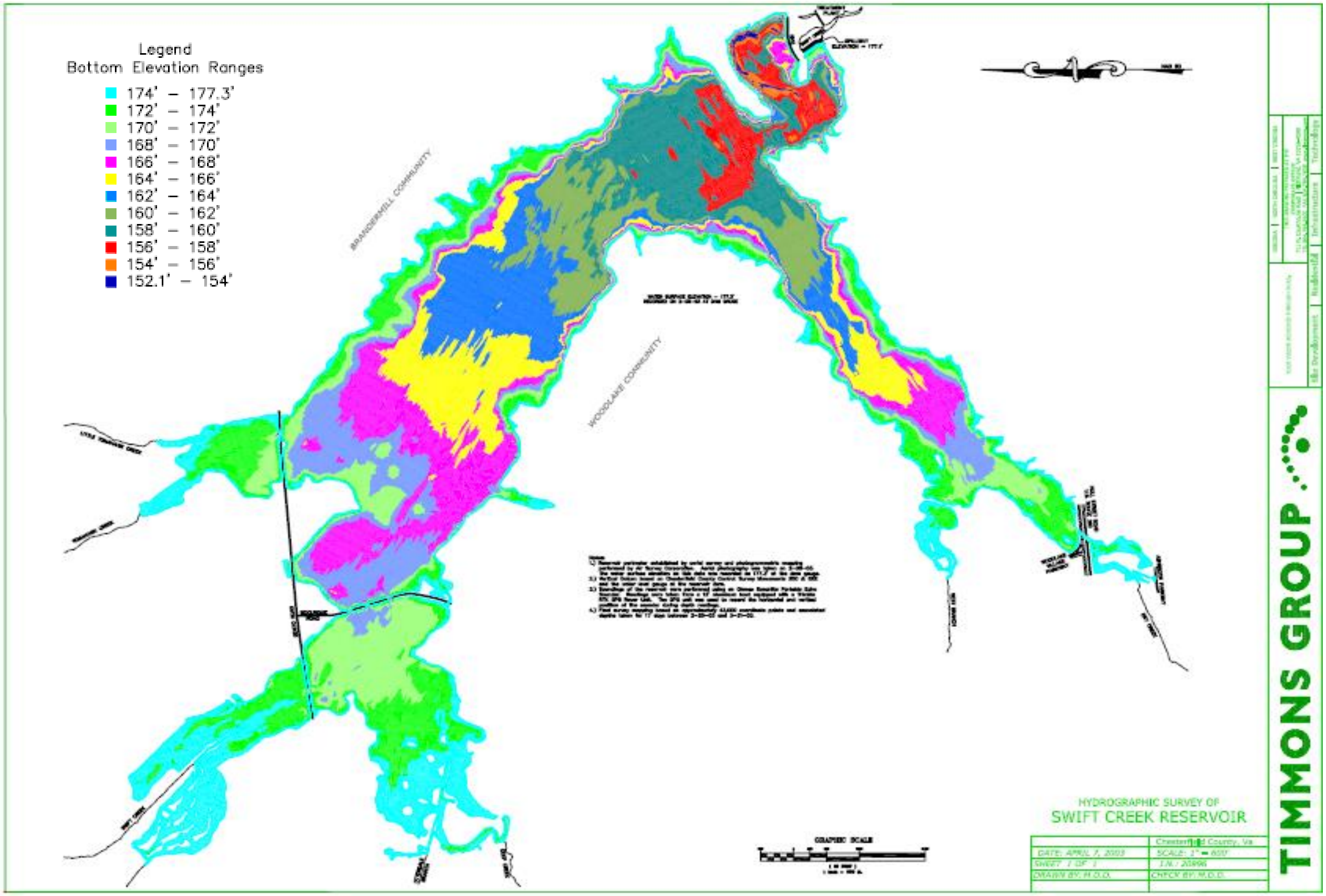

Figure 1. Bathymetry of Swift Creek Reservoir (2003)

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 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, near the high end of the normal range, 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 completely 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 a one year after stocking, approximately 16 months after initial stocking the reservoir had no hydrilla present and started to be void 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.

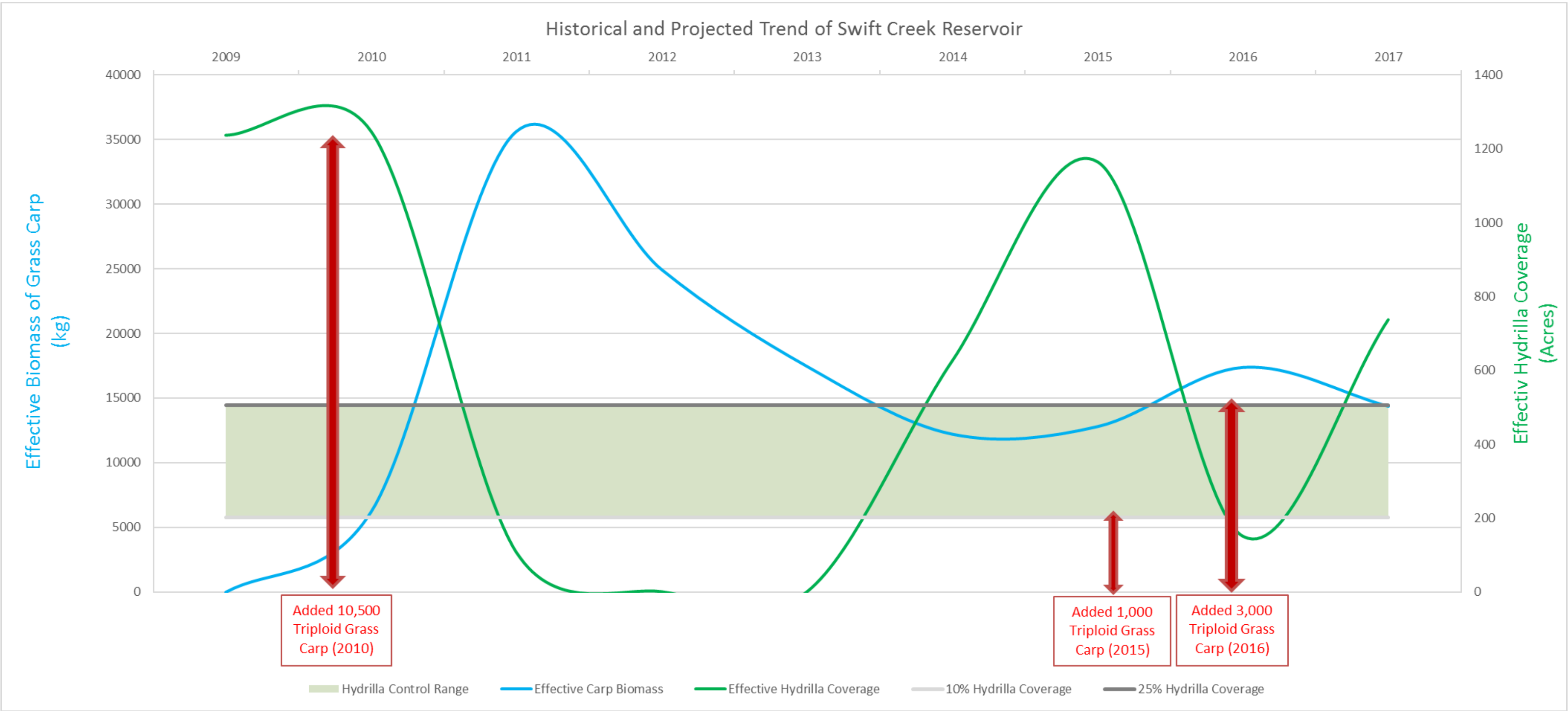

Figure 2. Hydrilla and estimated grass carp biomass in Swift Creek Reservoir, 2009-2017.

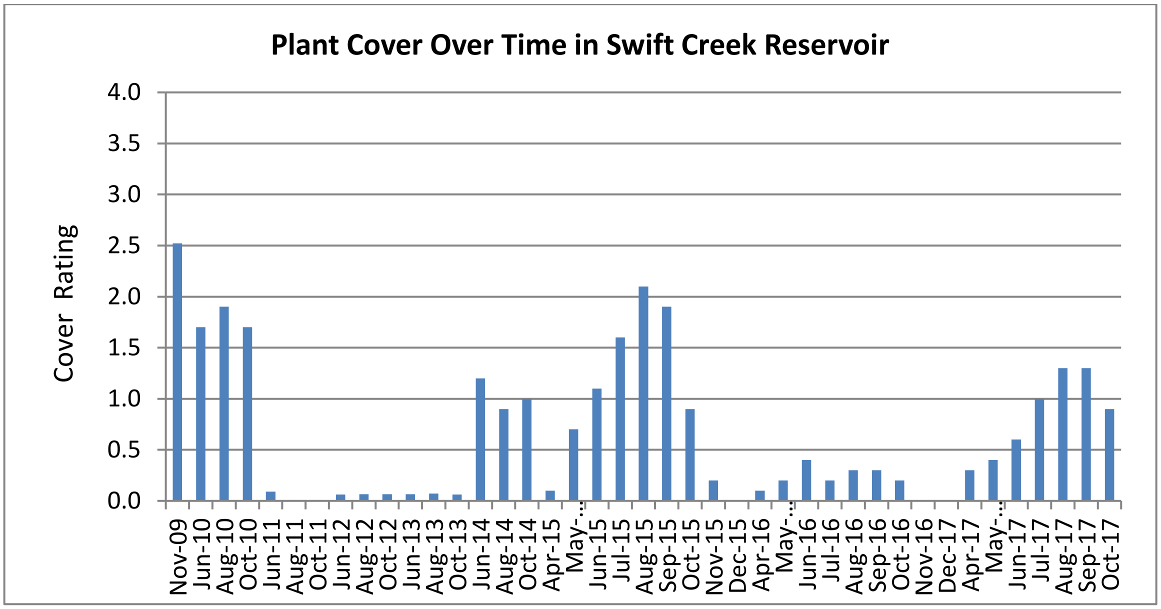

Figure 3. Total plant cover in Swift Creek Reservoir, 2009-2017.

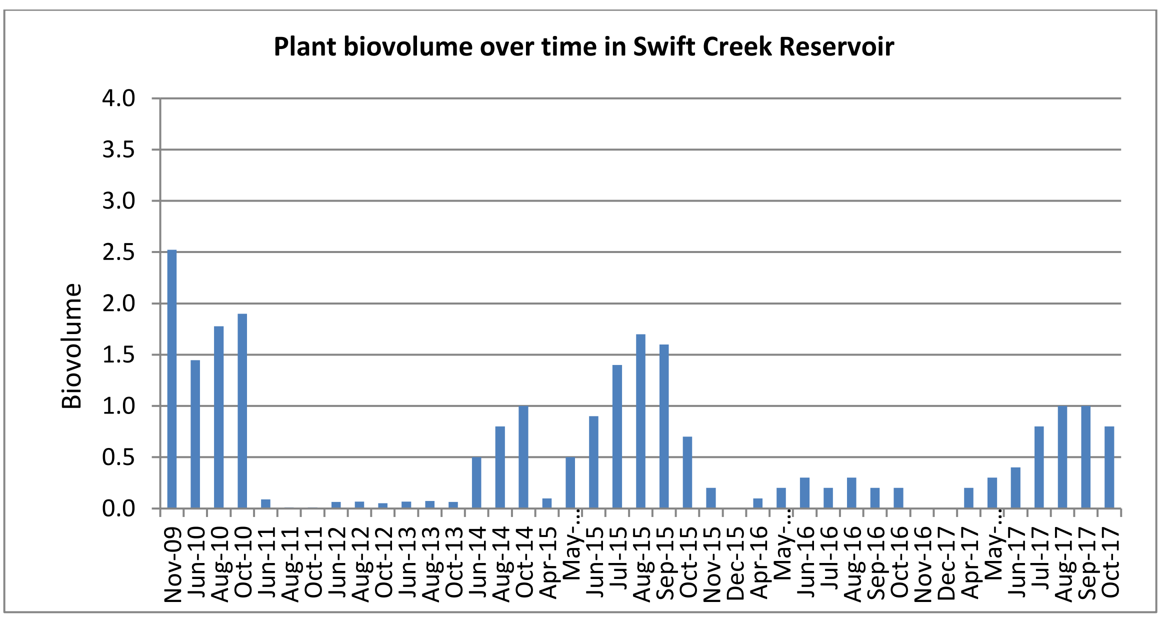

Figure 4. Total plant biovolume in Swift Creek Reservoir, 2009-2017.

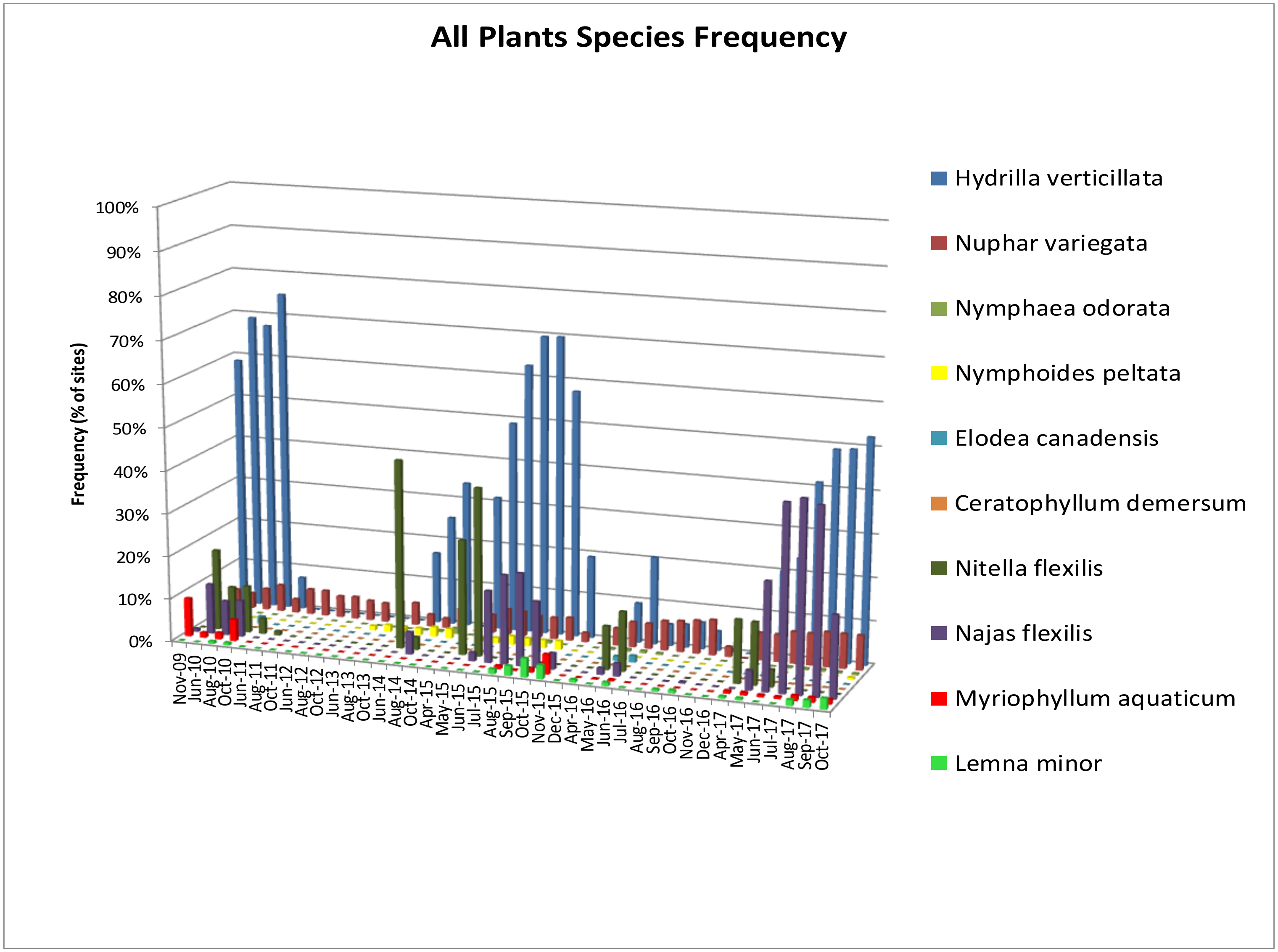

Figure 5. Frequency of plant species occurrence in SCR, 2009-2017.

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, but concern over excessive stocking and complete plant loss lead to only 1000 juvenile grass carp being stocked in April 2015. However, as newly stocked grass carp tend to exert very limited pressure on plant biomass, hydrilla continued to resurge and covered as much or more of the reservoir by late 2015 than it had before any grass carp were stocked (Figures 2-5). Hydrilla died back again near 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 would be 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 fairly 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 in 2017 was higher than 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.

Over the course of the 7-year period since initial grass carp stocking, few plants other than hydrilla have been observed (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. *Nitella* (stonewort, actually a form of algae) or *Naja*s (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 is therefore encouraging.

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. But grass carp stocked in 2015 and 2016 continue to grow, and unless scarce plants cause starvation, the biomass can be expected to achieve a level that exerts more control within a year or two. The trick is balancing grass carp stocking and growth with normal mortality and avoiding starvation induced losses.

The weather in 2016 was warmer and more favorable to plant growth than in 2017, so that does not explain lower plant abundance in 2016 and increased abundance in 2017. Turbidity was higher in 2016, a combination of increased algae abundance with warm weather and possibly more resuspension of bottom sediments by wind or boats with lower water levels. 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, however.

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 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 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 approximately 35%, above the target range of 10 to 25 percent. The more recently stocked grass carp will continue to grow and should reach peak grazing capacity in 2018 or 2019; monitoring of the plant community should continue to ensure there is not a collapse related to excessive grass carp addition. The maximum number of grass carp, if any addition is considered in 2018, is 500, based on a model of carp biomass over time and its relation to hydrilla abundance.

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 future grass carp 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.

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. 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 survey was conducted each year after 2010 (2011-2017). 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) before surveys in those years were conducted. 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.

Table 1. Grass carp data, 2010-2017.

Year	Grass Carp # caught	CPUE fish/hr	Avg Length mm	Avg Weight 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 2010-2017.

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

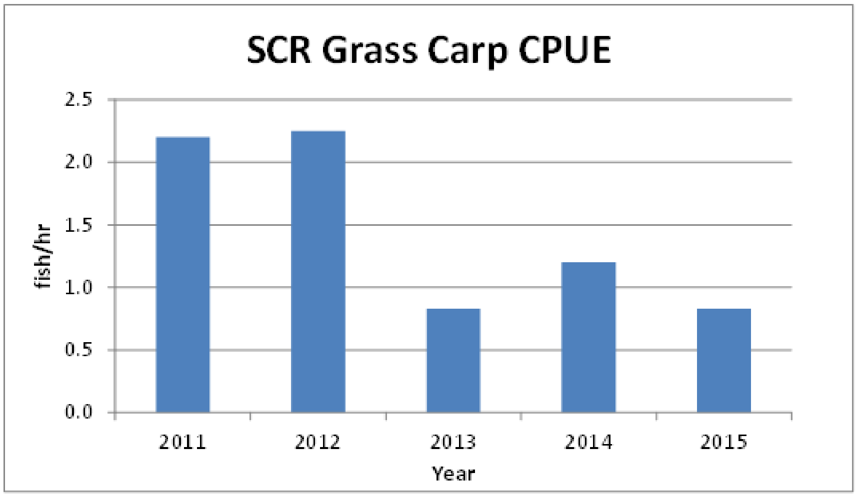

Figure 6. Catch per unit effort for grass carp in SCR, 2010-2015.

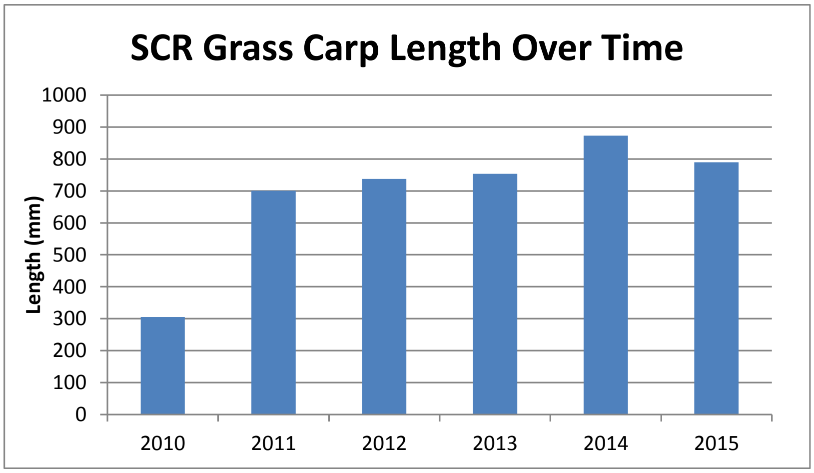

Figure 7. Length of grass carp in SCR, 2010-2015.

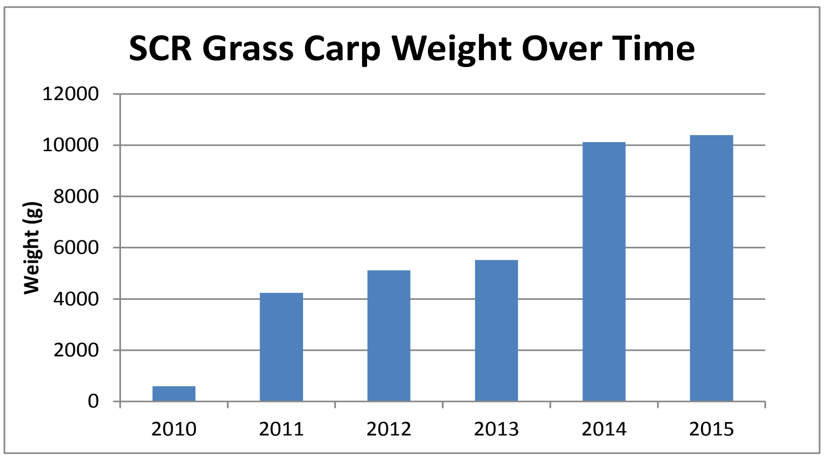

Figure 8. Weight of grass carp in SCR, 2010-2015.

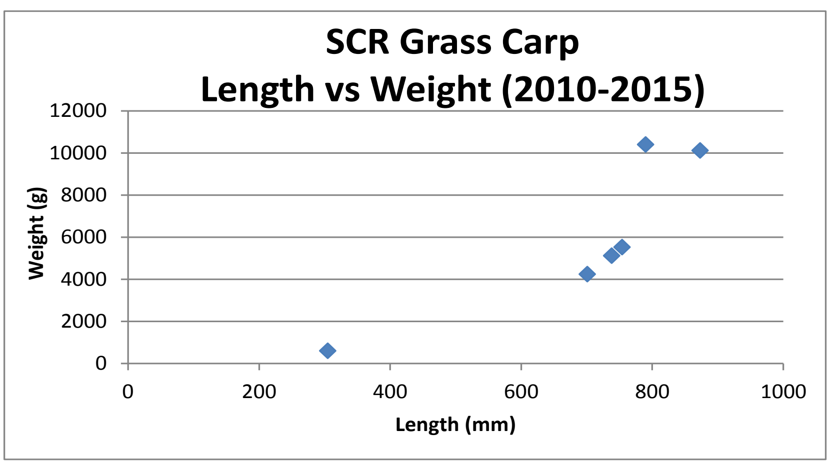

Figure 9. Average length vs weight for grass carp in SCR, 2010-2015.

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 possibly 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 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. This 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 3-12ac).

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 insights.

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 dense hydrilla growth and several years of higher fish metric values despite lower plant abundance, it is not at all clear that these declines relate to plant community fluctuations. Catch per unit effort remained low in 2017, but 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, but it is evident 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

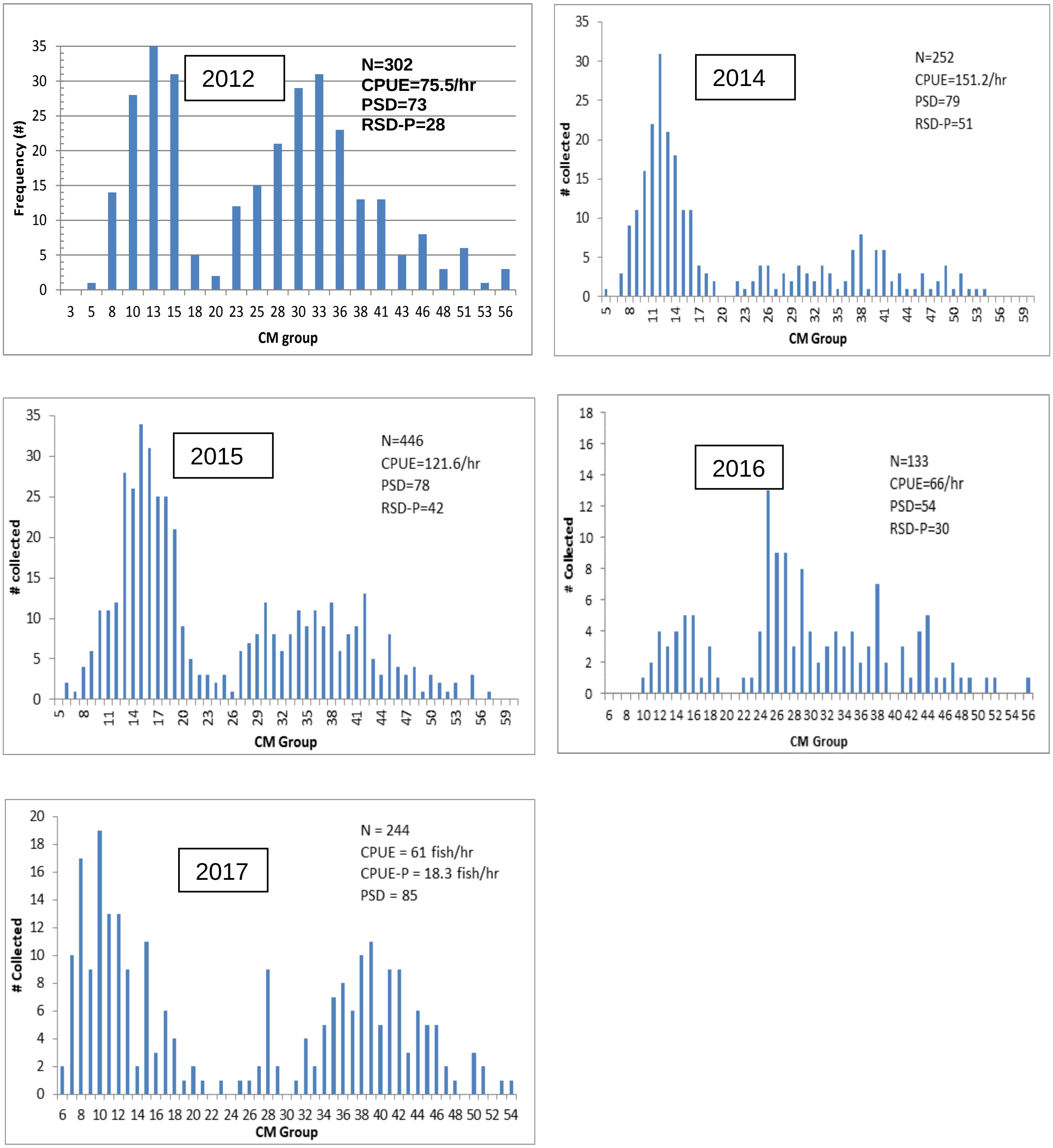

Figure 10. Largemouth bass length distribution in SCR over time.

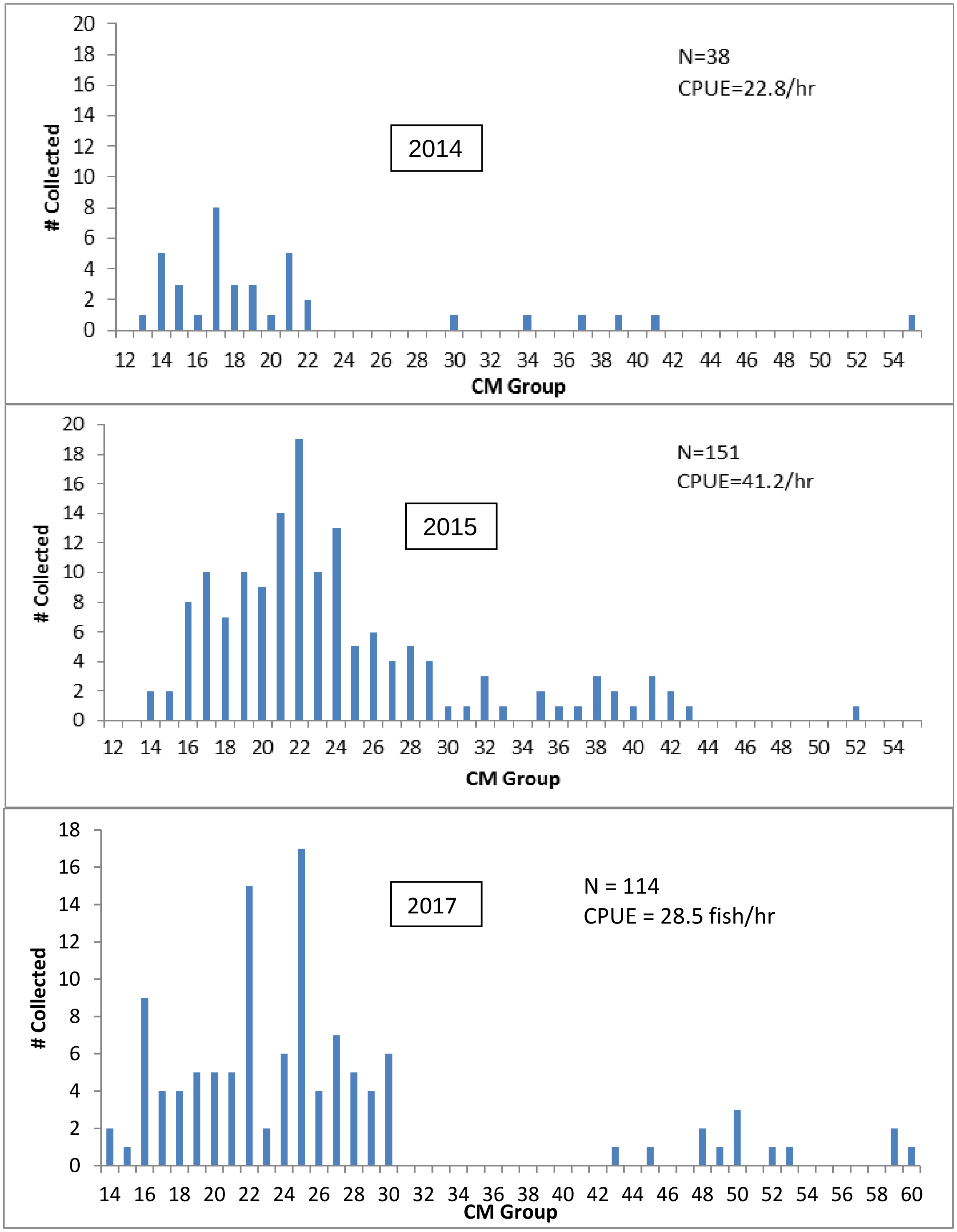

Figure 11. Chain pickerel length distribution in SCR over time.

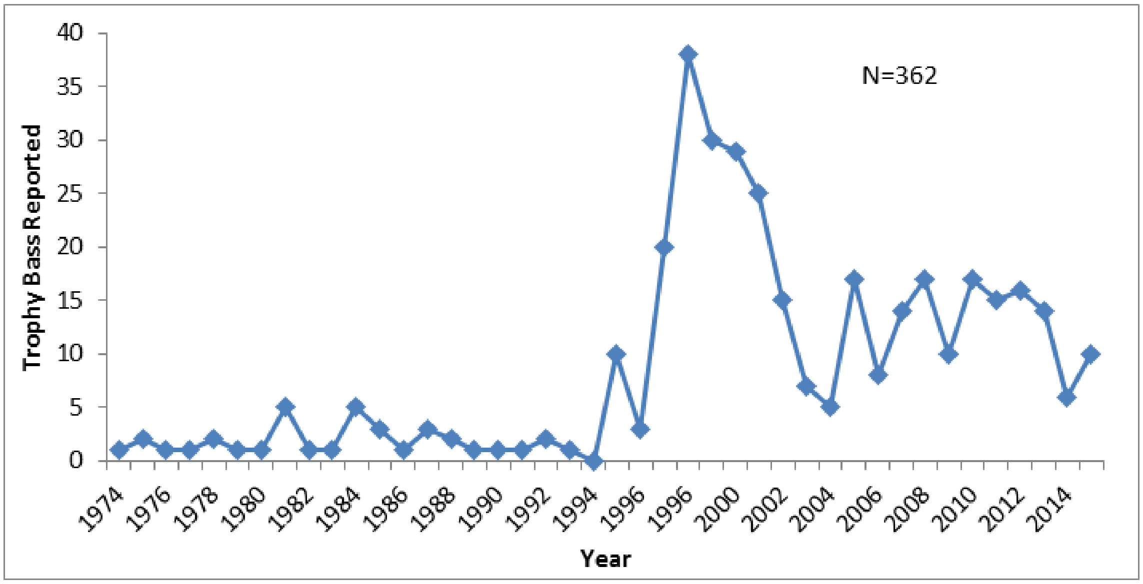

Figure 12. Trophy largemouth bass citations from Swift Creek Reservoir.

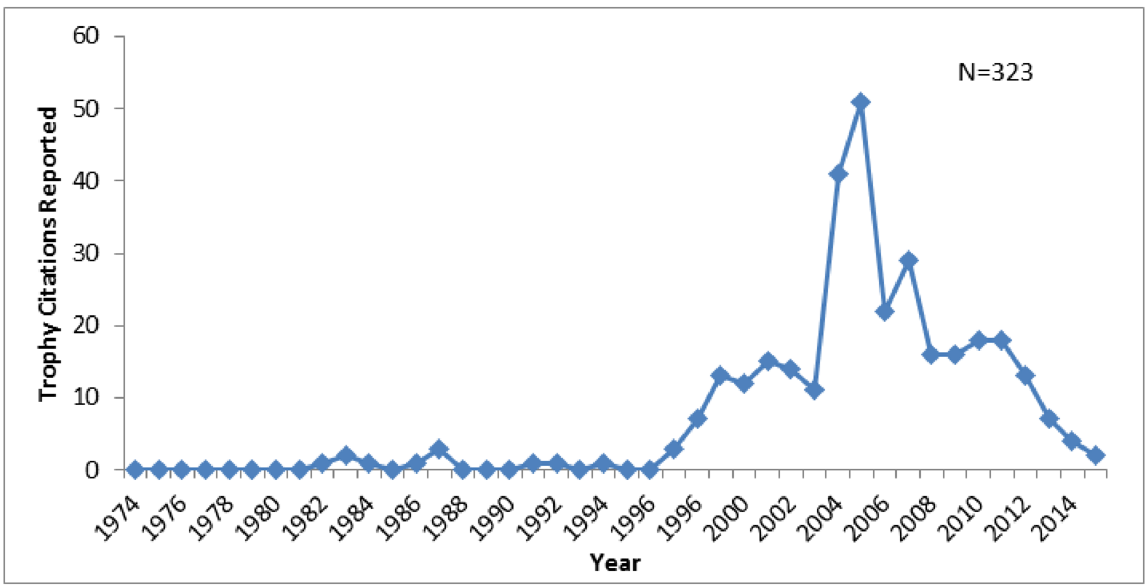

Figure 13. Trophy chain pickerel citations from Swift Creek Reservoir.

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 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, and may relate to the plant community, although it is certainly 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 decline through 2015. Since hydrilla was not a major component of the plant community until at least 2009, neither the increase nor decrease appears linked strongly to hydrilla, but a pattern of improved chain pickerel populations has 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 eliminated by grass carp. Chain pickerel are usually associated with weedy conditions, for spawning, juvenile cover, and feeding reasons. Hydrilla provided high pickerel habitat value and the loss of most 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, but the population appears to be declining. 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 need to 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. Certainly grass carp have altered the landscape within Swift Creek Reservoir, and after 7 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 banks of 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). Average values have not been significantly higher since grass carp stocking as a result of substantial interannual variability, and averages remain below the targeted upper threshold level of 0.040 mg/L. The observed levels since 2010 could represent an increase caused by grass carp, but it is not a major increase and cannot be unequivocally attributed to grass carp at this time. The average phosphorus concentration for 2017 (Figure 16) is considerably higher than in past years, however, but the reason is not currently known.

Consideration of median levels for various commonly measured water quality variables (Figure 16) also indicates a slight increase in phosphorus since stocking of grass carp, and slight increases in nitrogen, turbidity, and total suspended solids are discernible as well. Secchi transparency reflects water clarity and is related to turbidity and suspended solids, and has decreased slightly since grass carp were stocked. Chlorophyll concentration, indicative of algae abundance, is distinctly elevated since grass carp have been stocked. Likewise, annual average cell counts for algae in the reservoir (Figure 17) have increased noticeably since grass carp were stocked, although there is a decrease between 2013 and 2015 that coincides with hydrilla regrowth and apparent reduction in grass carp abundance.

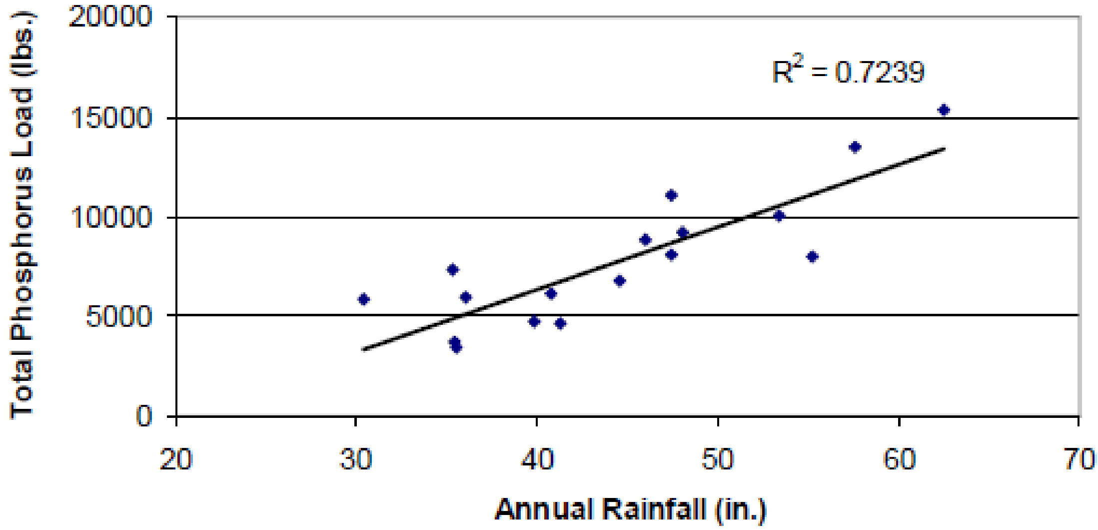

Figure 14. Correlation of phosphorus load to rainfall for Swift Creek Reservoir.

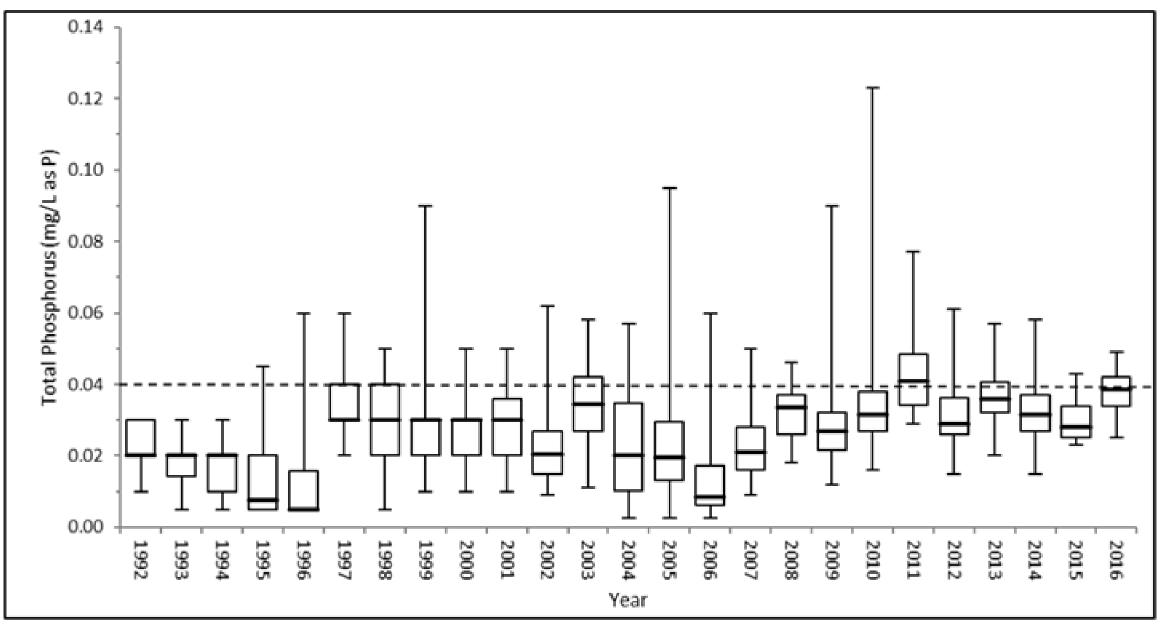

Figure 15. Annual phosphorus concentration statistics for SCR, 1992-2016.

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

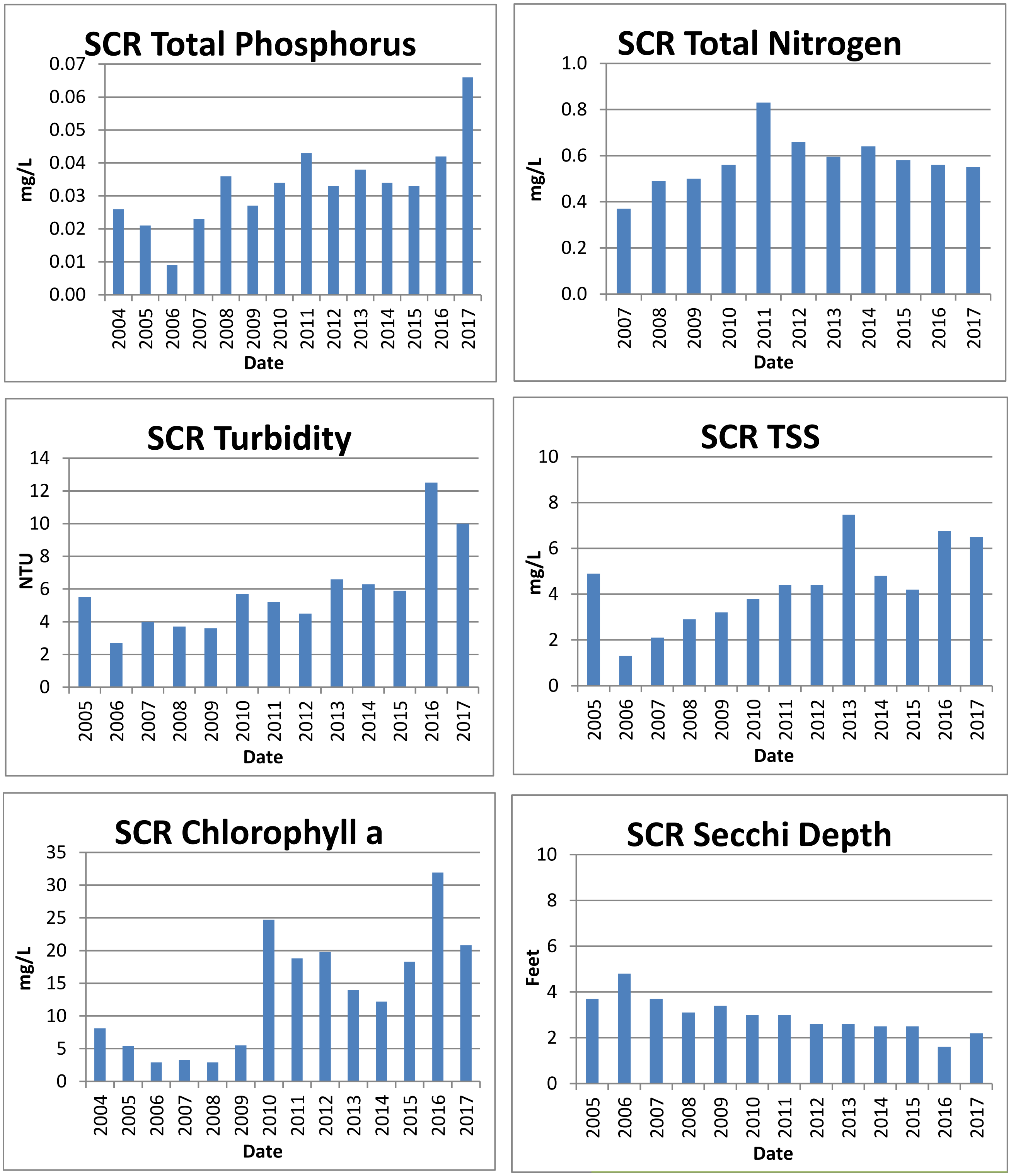

Figure 16. Annual median concentrations for key water quality variables in SCR.

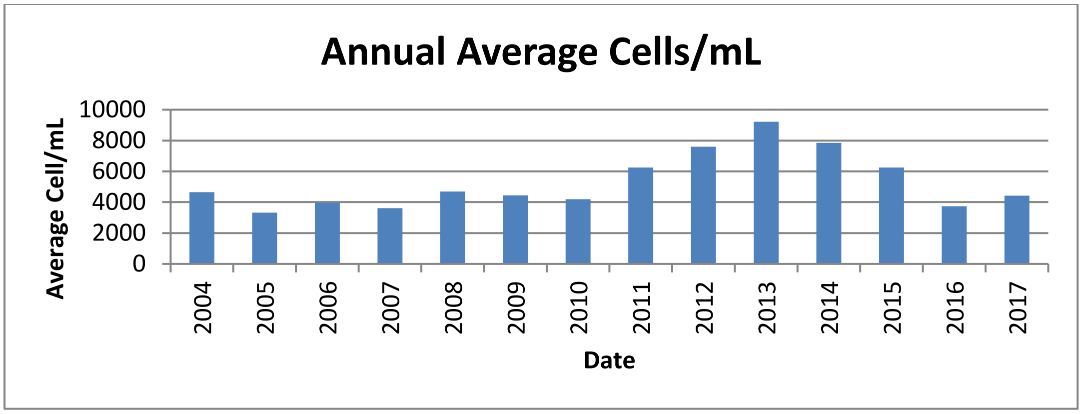

Figure 17. Annual average algae cell count in Swift Creek Reservoir, 2004-2017.

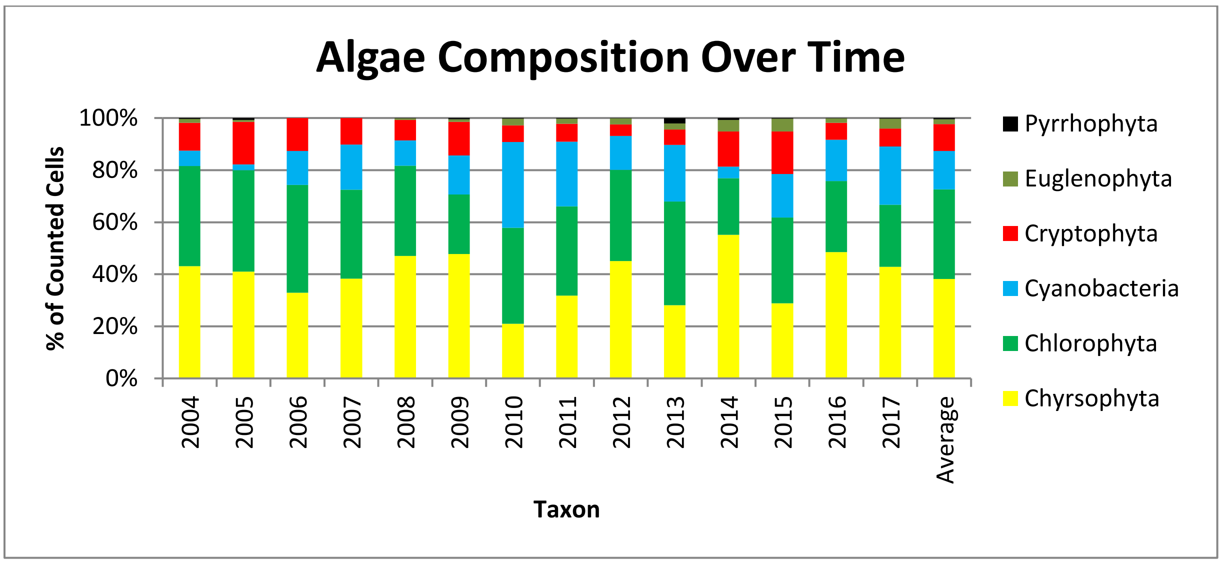

Figure 18. Algal community composition in Swift Creek Reservoir, 2004-2017.

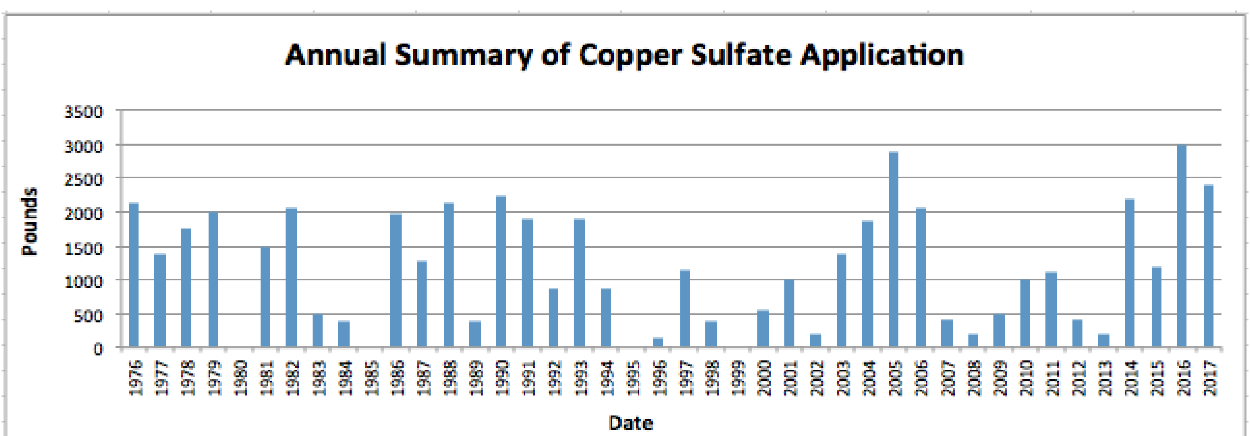

Figure 19. Annual total copper application to Swift Creek Reservoir, 1976-2017.

Increases in algae as indicated by chlorophyll and cell counts with only small increases in turbidity and solids and a small decrease in water clarity suggest that algae represent only one source of the turbidity and suspended solids in Swift Creek Reservoir. As the load of fine silt to this reservoir is evident, much of the elevated turbidity and solids concentration may be linked to non-living material. Slight decreases in turbidity and suspended solids since the resurgence of hydrilla suggest the filtering potential of dense vegetation. However, it should be noted that median chlorophyll in 2016 was the highest of the graphed values and Secchi transparency was the lowest value; algae can be a major source of turbidity in the reservoir.

Based on algal community composition assessed by Chesterfield County staff, there has been no major shift in the algal assemblage in terms of annual relative abundance of the various algal divisions (Figure 18). Relative abundance of observed algal divisions has fluctuated somewhat but has not changed appreciably in any direction since grass carp were stocked. 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. Chrysophytes (golden algae) and Chlorophytes (green algae) are the most abundant algae divisions based on annual averages. There have been cyanobacteria blooms that are not well reflected in annual average algae composition data, and algae are abundant enough to require attention as part of the water supply operation. That attention, in the form of copper sulfate applications, alters algae abundance and affects composition, and the data in Figures 17 and 18 are not independent of those treatments. Consequently, algae data alone are not sufficient to assess grass carp impact.

Application of copper to control algae levels in the reservoir, especially in the embayment where water is withdrawn for treatment and supply, may be a better measure of 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 19). 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. As a result, the average for 2010-2017 is 14% higher than the average from 1976-2009 and 21% higher than the average from the immediately preceding 8 years (2002-2009). The general 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 it does appear that more treatment has been necessary since grass carp were stocked. Variability is high, however, so factors other than grass carp (e.g., warmer temperatures) are likely influential as well.

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 2009 and 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 resurgence of hydrilla beyond the desired range of 10 to 25% coverage and biovolume was observed in 2017. This suggests that other factors besides just grass carp stocking influenced the plant community in 2016 and that grass carp biomass is still not high enough to exert the desired level of control. Conditions in 2017 were generally favorable for both habitat and recreation in most areas at the beginning of the summer, although the coverage area did exceed the target range of 10 to 25% later in the growth season. Overall coverage area was considerably lower than 2010 and slightly lower than 2015.

Impacts of grass carp on other plants besides hydrilla were also extreme between 2011 and 2014, and possibly in 2016, but growths were at least detectable in many areas in 2014, 2015 and 2017. 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, is also less edible by grass carp, and is present in only small amounts, 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. Plant shoots undoubtedly spring from buried roots or seeds periodically, but the existing grass carp population prevented any substantial growth until 2014. The resurgence of 2014 lasted through early 2016, after which plant growth in general was low, but increased again in 2017. While the stocking of 3000 grass carp in spring 2016 would have been expected to have more impact in 2017 than in 2016, there is variability inherent in biological systems that will make exact predictions difficult. Overall expectations for control should fall between what was experienced in 2014 and 2016 to ensure plant community stability in the reservoir. Stocking grass carp to a level that guarantees reservoir-wide control at very low plant density will result in unstable conditions and will not allow long-term control. This means that there will be occasional plant patches that are denser than some reservoir users may like and may require some alternative means of control.

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. It is difficult to adequately assess a grass carp population, and we do not have estimates of population size for each year since stocking. 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 declining 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.

Loss of plants alters habitat for many species, to the benefit of some and detriment of others. Fish surveys indicate possible negative impacts on largemouth bass after 7 years, but no extreme impacts that are clearly caused by grass carp. Bass remain abundant and exhibit a generally desirable size distribution, but there are fluctuations in population metrics that might be longer term consequences of grass carp stocking; more fish survey effort will be needed to better define possible impacts. Chain pickerel would be expected to decrease as a function of spawning difficulty (they need submerged plants), loss of cover as juveniles (cormorant predation may be an issue), and foraging challenges (they sit in weed beds and attack passing prey). Swift Creek Reservoir was not the biggest producer of trophy pickerel in Virginia in 2013, while it had been in 2004-2012, and there has been steady decline in reported trophy catches since 2010. Relatively few pickerel were captured in 2016, but the population appeared to increase in 2017, which could be a function of plant abundance and/or sampling method. Other fish populations show no clear signs of decline, but the data are not sufficient for a complete analysis.

Near complete loss of plants allows fine sediment to enter the reservoir and become more easily resuspended, as rooted plants provide both filtering and stabilization functions. Conversion of plant biomass into fish and potentially available nutrients is expected to increase phosphorus and algae, with related decreases in water clarity and increases in turbidity and suspended solids. An increase in chlorophyll, an algal pigment, and increased algae cell counts were indeed observed, although there has not been a major change in the types or relative abundance of major algae groups. However, copper treatments to control algae abundance limit indications from the algae data, and copper use has increased by about 21% since grass carp were stocked.

Slight increases in phosphorus, nitrogen, turbidity and suspended solids appear to have occurred, and water clarity is slightly lower. The changes in most water quality features are small, however, compared to the changes in algal abundance, suggesting that non-living material suspended in the water is a major source of turbidity and solids. This underscores the filtering value of plant assemblages and a potential negative effect of any plant control technique.

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 turbidity. 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 suggest intermediate control of hydrilla, and grazing would not be expected to decrease in 2018, but the biomass of grass carp surviving through 2016 when plant abundance was low is unknown. 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.

Maintaining an Appropriate Grass Carp Population

For many artificially created waterbodies there is no true native plant community, so while hydrilla is an invasive species that can have detrimental impacts on many aspects of aquatic systems, all colonizing plants are potentially "invasive" in such a situation and can cause problems. While it would be desirable to selectively build a plant community through planting and early intervention when undesirable species are detected, this can be impractical and experience with "aquascaping" is limited. Hydrilla is viewed by many lake users as a beneficial component of the aquatic system in comparison to having no plants, but hydrilla control by chemical or mechanical means can be too expensive to sustain when hydrilla becomes too abundant. Biological controls such as grass carp are therefore attractive, but can be difficult to manage and usually provide more variable results than chemical or physical methods. Using grass carp effectively is considerably more complicated than just some intermittent stocking.

The literature on grass carp stocking and impacts is extensive but not conclusive. Dibble and Kovalenko (2009, J. Aq. Plant Manage. 47:1-14) summarized almost 2000 publications and concluded that there were not enough long-term studies of impact to draw clear conclusions about the details of grass carp interaction with the rest of the aquatic community. Recommended stocking rates varied considerably among state programs, with a range of 1 to 20 grass carp per acre of waterbody, and often no clear distinction between total acres of water and vegetated acres. The most common recommendations are 3-5 fish for "maintenance" of low to moderate density plant communities, 6-9 fish for strong control without complete vegetation elimination, and 10-15 fish for eradication of plants. More fish are needed in more northern climates to achieve the desired level of control, but risk of starvation or other impacts is also higher. In most cases stocking recommendations are based on the number of vegetated acres, not total reservoir area, but that is not always clear. The associated variation in results is high, as is common for biological control techniques.

Lake Gaston was investigated as a possible model for management of Swift Creek Reservoir as grass carp have been stocked in Lake Gaston since 1995 and considerable effort has been expended to evaluate results and adjust to limit but not eliminate aquatic vegetation including hydrilla. Grass carp are not the only plant control method applied, and the stocking rate in recent years was 18.5 fish per vegetated acre, higher than initially applied to Swift Creek Reservoir. The plan calls for reduction of stocking to a low of 5 fish per vegetated acre as plant community features reach established targets for biomass and composition, but those have not yet been approached in this large reservoir. The key lesson from this case history applicable to Swift Creek Reservoir is to adjust stocking in response to plant community features as assessed in the fall before plant die back.

Review of many programs using grass carp to manage plants reveals several general trends:

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 direct 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 at 9-12 inches 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.

Further discussion of acceptable target conditions may be warranted, but the range encountered in 2014 is probably the closest we can come to an appropriate range for a multi-use reservoir. The overall conditions documented for 2014 (see for example Figures 2 and 5) do not appear too restrictive for boating and would provide enough plants to support habitat and water quality functions, especially near inlets. Some localized control with benthic barriers or harvesting might be needed in selected shoreline segments, and the exact pattern of abundance from October 2014 cannot be expected every year, but this condition appears to represent an appropriate compromise between elimination of plants and excessive hydrilla abundance. There was less vegetation in 2016, but conditions in 2017 were similar to those of later 2015, suggesting that the grass carp population and biomass during 2017 was slightly below the desired level. With careful management, we may be able to minimize unacceptable fluctuations without causing a collapse in the plant community, but there will be fluctuations.

Stocking 3000 fish in April 2016 after the stocking of 1000 fish in spring of 2015 was expected to increase the 2016 biomass to more than 17,000 kg. Spreadsheet calculations in 2016 explored possible population trajectories (see 2016 report). It was concluded that a biomass of 15,000 kg was probably inadequate to control hydrilla, while a biomass of 25,000 kg would likely eliminate vegetation. Based on system response, the model has been updated to diminish the effectiveness of the biomass of the mature carp to account for the decreased amount of pressure the older grass carp will exert on hydrilla. A biomass target somewhere between 14,000 and 17,000 kg appears appropriate from the updated model, but it may be hard to keep it in that range, as growth and mortality can vary substantially.

Based on the spreadsheet program, with no mortality induced by food shortage and no further stocking, 2017 would be followed by 4 years of biomass slightly below the lower end of the target range, after which there is a sharper decrease (Table 3). This suggests that without stocking, conditions will not be much worse in 2018-2021 than in 2017, but that may not be acceptable. Too much stocking in 2018 and beyond could cause a plant community crash within a year or two, so we have to estimate the right number of grass carp to stock in each year to keep the cumulative grass carp biomass in the right range. This has to be done with recognition of growth and mortality, each of which will vary based on a variety of conditions (including plant abundance, individual fish genetics, and weather), most of which are not controllable.

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 will remain in the range of 14,000 to 17,000 kg over the period of 2018-2022 with annual stocking of 500 grass carp in 2018 and 250 grass carp in 2019-2022. The grass carp biomass in 2018 will be near the low end of the target range, but will climb steadily in subsequent years into 2021, when the biomass would be near the upper end of the target range. After then, the advanced age and diminished contribution of fish stocked in 2015 and 2016 will cause a slight decline in 2022 and a major decline in 2023. Conditions in 2022 would be acceptable, but those in 2023 would not be, according to the model. A larger stocking would be needed in 2022 to have adequate grass carp biomass in 2023.

If more than 500 fish are stocked in 2018, there is a significant risk of collapsing the plant community. If we stock more than 250 fish in 2019-2021, similar risk is presented, so the "aging out" of fish stocked in 2015 and 2016 will cause a loss of control in 2023 that cannot be avoided by slightly greater stocking in previous years. 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 14,000 and 17,000 kg is between 250 and 500 fish, depending on mortality or growth limitation, which in turn depends on plant abundance. 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. Such adjustment must remain within a fairly narrow range of stocking, however, to avoid the "aging out" phenomenon some years later.

While additional fish surveys would be helpful, 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.

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.

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

Original Stocking of Grass Carp										Second Stocking				Third Stocking			
Year after stocking	Year	Low Range	High Range	Total Biomass	Effective Carp Biomass	Fish Assuming 20%/Yr Mortality	Fish with Additional 30% Loss after Plant Elimination	Average Weight (g)	Original Biomass (kg)	Added Stocked Fish	Fish Assuming 20%/Yr Mortality	Average Weight (g)	Total Effective Biomass (kg)	Added Stocked Fish	Fish Assuming 20%/Yr Mortality	Average Weight (g)	Total Effective Biomass (kg)
0	2010	14,000	17,000	6,206	6,206	10,500		591	6,206								
1	2011	14,000	17,000	35,616	35,616	8,400		4240	35,616								
2	2012	14,000	17,000	24,931	24,931	6,720	4,704	5300	24,931								
3	2013	14,000	17,000	17,452	17,452	3,763	2,634	6625	17,452								
4	2014	14,000	17,000	12,216	12,216	2,107	1,475	8281	12,216								
5	2015	14,000	17,000	25,024	12,807	1,180	826	10352	12,216	1000	1000	591	12807				
6	2016	14,000	17,000	45,206	17,381	944	661	12939	12,216		800	4240	15608	3000	3000	591	17381
7	2017	14,000	17,000	43,505	14,369	755	529	14000	10,574		640	5300	4193		2400	4240	14369
8	2018	14,000	17,000	52,851	13,864	604	423	14000	8,459		512	6625	3392		1920	5300	13568
9	2019	14,000	17,000	67,971	15,412	483	338	14000	6,767		410	8281	3392		1536	6625	13568
10	2020	14,000	17,000	67,318	16,260	387	271	14000	5,414		328	10352	3392		1229	8281	13568
11	2021	14,000	17,000	66,235	17,256	309	217	14000	4,331		262	12939	3392		983	10352	13568
12	2022	14,000	17,000	49,521	16,964	247	173	14000	3,465		210	14000	222		786	12939	10398
13	2023	14,000	17,000	9,681	14,531	198	139	14000	2,772		168	14000	0		629	14000	667
14	2024	14,000	17,000	6,458	15,264	158	111	14000	2,218		134	14000	0		503	14000	0
15	2025	14,000	17,000	2,844	-	127	89	14000	1,774		107	14000	0		403	14000	0

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. Stocking more than 250 grass carp per year after the April 2018 stocking of 500 fish may be appropriate at some point, but the current model suggest that approximately 250 fish should be adequate on an annual basis until 2022 when the influence of greater numbers of fish stocked in 2015-2016 will wane.

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.

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 slightly below those observed prior to control with grass carp. Restocking of grass carp in 2015 and 2016 appears to have been part of the reason for reduced hydrilla in 2016, but did not result in continued control in 2017. This may be a function of inadequate growth when plants were scarce in 2016 or even mortality over the winter of 2016-2017. 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. Data for the fish community is less extensive but still quite useful. 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 would seem appropriate. Data for grass carp are too limited to allow reliable estimation of population size or even average fish length and weight in most years since stocking. Analysis of grass carp dynamics and development of a desirable stocking rate therefore requires some assumptions and modeling which brackets probable values for fish size and population losses.

Consideration of plant conditions suggests that the features of the 2014 plant community represent an acceptable target condition, including presence of hydrilla at up to 33% of plant growth zone survey sites with up to 25% of sites having dense cover at peak growth. Late spring conditions included coverage by hydrilla at about 17% of sites without dense patches, but other plant species may be locally abundant. This represented 15-30% bottom cover by plants in the reservoir overall, desirable for fish and wildlife needs and tolerable to boaters in most cases. 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.

A range of stocking rates was examined after 2015, and based on the best available projections, 3000 grass carp were stocked in April 2016, equating to about 3.3 fish per vegetated acre when stocked. This level of stocking corresponded to significant reduction in the aquatic vegetation community and no vegetation was present in the December plant growth survey for 2016. It is not certain that the decline in plant abundance was entirely a function of grass carp grazing, as more plants were observed in 2017 when grass carp grazing pressure should have increased over the 2016 level. Uncontrollable variation in results is to be expected with biological controls, but it is intended that the range of conditions be narrow enough to meet user expectations while maintaining valued habitat for fish and wildlife.

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 suggest that the stocking of 500 grass carp in 2018 is reasonable. Annual stocking of approximately 250 grass carp per year is currently envisioned as a long-term approach that should provide a more stable population and more even control. However, aging of larger numbers of fish stocked in 2015 and 2016 will cause a substantial reduction in effective grass carp biomass in about 2023, such that stocking will need to increase in 2022 to avoid a lapse in plant control. Yet increasing stocking prior to 2022 will overshoot the capacity of the reservoir to support grass carp and would be expected to collapse the plant community and cause reduced increased grass carp mortality, increasing instability and reducing predictability. The model can be fine-tuned with additional data as management proceeds, but stocking should err on the low side of predicted needs to avoid decimating the plant community, and localized physical controls should be allowed and facilitated to supply access for reservoir users when higher plant density and coverage are encountered.

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, and an increase in copper use to maintain acceptable levels of algae has occurred since grass carp were stocked. Non-algal turbidity appears to be a greater issue, and may be reduced by more plant growth, especially near the inlets.