Common Carp Assessment in Six Mile Creek
Final Report: June 2014 – December 2016

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Project Overview

This report presents the results of the Six Mile Creek Common Carp Assessment which was funded by the Minnehaha Creek Watershed District (MCWD) and conducted by the University of Minnesota (UMN) from July 2014 through March 2017. The stated purpose of this study was to "determine the abundance, seasonal movements, and recruitment patterns of common carp (*Cyprinus carpio*) in the Six Mile Creek Subwatershed to enable development of carp control strategies for restoration of the Six Mile Creek subwatershed". The UMN was contracted to (1) estimate adult carp abundance in at least 7 of the Six Mile Creek lakes, (2) determine the movement patterns and seasonal distributions of at least 100 adult carp throughout the subwatershed, (3) determine the recruitment patterns of carp throughout the subwatershed via annual netting surveys and age determination of at least 200 carp, and (4) to report and interpret all findings and provide recommendations for future carp management strategies.

The UMN has completed all tasks as outlined in the Project Scope of Work. Specifically, the UMN has estimated adult carp abundance and biomass in 15 lakes, implanted radio-tags in 120 carp across the subwatershed, located radio-tagged carp at least once per month for 2 full years, conducted annual trap-net surveys in 23 water bodies, and determined the age structure of carp across the subwatershed based on 378 individuals from 11 lakes. Additionally, the UMN calculated a supplemental mark-recapture population estimate for Parley and Mud Lakes. All findings obtained by December 2016 are presented herein and discussed in the framework of possible carp management strategies specific to the Six Mile Creek subwatershed. Genetic and microchemical analyses of carp in the Six Mile Creek subwatershed are ongoing as part of a M. S. thesis and final results will be made available as appendices to this report. The results of a planned supplemental study on carp winter seining in Lake Wassermann will also be made available as an appendix to this report.

Executive Summary

The common carp (*Cyprinus carpio*; hereafter 'carp'), a benthivorous fish native to Eurasia, is highly invasive in the North American Midwest and many other regions around the world. Invasive populations of carp are often associated with declines in the abundance and diversity of submersed aquatic vegetation as well as invertebrates and can trigger sustained increases in water turbidity, algal growth, and nutrient loading. For these reasons, carp have been the subject of many research and management activities in watersheds throughout the Midwest. In the Six Mile Creek subwatershed, a diagnostic study identified carp as one of the major drivers of its poor water quality and recommended carp assessment and control (Wenck 2013). In 2014, the MCWD partnered with the UMN to initiate a three-year study to obtain a better understanding of carp in the Six Mile Creek subwatershed to inform sustainable control strategies. This study sought to determine patterns in carp abundance, movement, and recruitment across the entire subwatershed.

Three field seasons of data collection are now complete and reveal that the total biomass of carp in the Six Mile Creek subwatershed is approximately five times greater than a threshold value previously identified to cause severe ecological impacts in Midwestern lakes. The study also identified areas in the subwatershed where carp have reproduced successfully in recent years, indicating that the carp population is presently growing. South Lundsten Lake in the middle portion of the subwatershed is of primary concern because it can produce many young carp and is well-connected to other lakes. South Lundsten Lake appears to be the primary source of carp for North Lundsten, West Auburn, and East Auburn Lakes and also contributes low numbers of carp downstream to Parley Lake and as far upstream as Wassermann Lake. Several additional basins throughout the subwatershed appear to have functioned as carp nurseries in the past (i.e. Marsh, Sunny, Turbid, and Mud Lakes), but successful recruitment in these locations has been limited to only five years since the 1960's and has not occurred in the past 15 years.

Movement patterns and age structures of adult carp across the subwatershed suggest there are multiple sub-populations of carp that could function as 4 management units: 1) Piersons-Marsh-Wassermann, 2) Auburn-Lundsten-Turbid, 3) Parley-Mud-Halsted's, and 4)

Carver Park Reserve Lakes (i.e. Steiger, Zumbra, Sunny, & Stone). Each of the lakes in the eastern Carver Park Reserve contains its own isolated subpopulation of carp, but these lakes could be grouped together as a single management unit given their similar ecological conditions, carp management goals, and common jurisdiction within the Three Rivers Park District.

Control of carp in the Six Mile Creek subwatershed may be possible, but will require a strategic, adaptive management framework that is implemented over several years. A possible first step would be to suppress ongoing carp recruitment in South Lundsten Lake and to put measures in place to prevent future recruitment in the locations identified as past carp nurseries. Once this is accomplished, management activities might then focus on reducing the existing carp biomass below 100 kg/ha in each management unit. Specific goals and possible management strategies vary by management unit and are detailed in the management section of this report. As management activities are implemented, ongoing monitoring is recommended to evaluate carp recruitment failure and adult biomass decline.

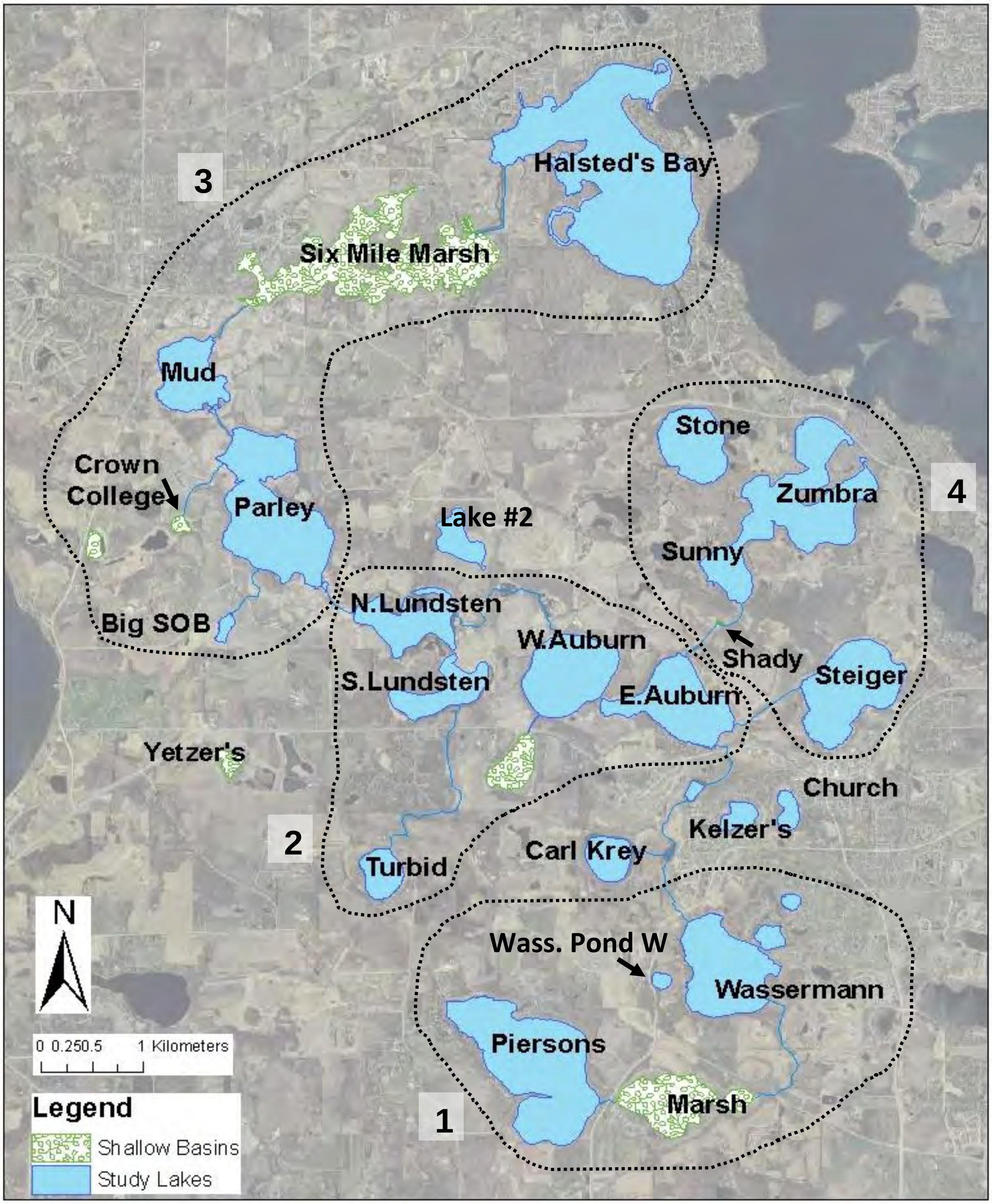

Figure 1. An overview map of the Six Mile Creek subwatershed with possible carp management units outlined: 1) Piersons-Marsh-Wassermann, 2) Auburn-Lundsten-Turbid, 3) Parley-Mud-Halsted's, and 4) Carver Park Reserve Lakes.

1.0 Background

1.1 Site overview

Located in the southwest corner of the Minnehaha Creek Watershed District (MCWD), the Six Mile Creek subwatershed spans roughly 27 square miles and encompasses a chain of 17 lakes (Piersons, Marsh, Wassermann, Carl Krey, Kelzer's, Church, East Auburn, West Auburn, Steiger, Sunny, Zumbra, Stone, North Lundsten, South Lundsten, Turbid, Parley, and Mud) and over a dozen ponds and wetlands (Figure 1). This system has its headwaters at Piersons Lake in Laketown Township and eventually drains north via Six Mile Creek into Halsted's Bay of Lake Minnetonka in Minnetrista, MN. Land use in the subwatershed is predominately agricultural and parkland, but is becoming increasingly developed.

Water quality in the Six Mile Creek subwatershed varies by lake, but many lakes are highly degraded and devoid of healthy native submersed plant communities. In the absence of submersed plants, poor water clarity and nuisance algal blooms are common. Additionally, several lakes currently fail to meet state nutrient standards and are classified as impaired for excess nutrients (phosphorus). Because common carp activity was observed throughout much of this system and internal loading was identified as a significant driver of in-lake phosphorus concentrations, further assessment and management of carp was recommended by Wenck Associates (2013).

1.2 The common carp

The introduction of common carp to Minnesota waters in the 1880s was one of the greatest ecological tragedies to befall our freshwater ecosystems. Being long-lived, mobile, extremely fecund, and tolerant of environmental extremes, the common carp has come to dominate the fish biomass in many lakes in the Upper Midwest (Sorensen & Bajer 2011). Common carp disrupt freshwater ecosystems by uprooting submersed vegetation, altering food webs, and often negatively impacting water quality by increasing turbidity and sometimes nutrient loading (Parkos et al. 2003; Bajer et al. 2009; Weber & Brown 2009; Vilizzi et al. 2015; Bajer et al. 2016). The effects of carp are most pronounced in shallow lakes that do not stratify. In deeper, thermally-stratifying lakes, large decreases in water clarity and reductions in submersed aquatic plant growth in littoral zones have also been observed, but the impacts of carp on nutrient cycling are less straightforward (Bajer & Sorensen 2015). In both shallow and dimictic Midwestern lakes, when adult carp biomass approaches approximately 100 kg/ha, 50% reductions in submersed aquatic vegetation coverage, significant decreases in water clarify, and declines in waterfowl use have been observed (Bajer et al. 2009; Bajer and Sorensen 2015). In a recent review of 73 studies across a variety of freshwater systems worldwide, extreme impacts by carp were observed, on average, at a critical biomass of 198 kg/ha (Vilizzi et al. 2015). Similarly, Bajer et al. 2016 suggest that a carp biomass of about 200 kg/ha causes a 90% reduction in plants in Midwest lakes. This report uses 100 kg/ha as a target value for carp management goals given the high value of these lakes.

Efforts aimed at improving water quality and restoring fish and wildlife habitat are typically futile in carp–infested lakes until densities of carp can be sustainably reduced to levels approaching 100 kg/ha (Bajer et al. 2009, Bajer and Sorensen 2015, unpublished data). Unfortunately, reducing carp biomass in a sustainable manner has proven very difficult due to the complex life history strategies employed by carp. For example, adult carp have a tendency to exploit outlying predator-free ponds and wetlands for breeding, where young carp often thrive and can then disperse to connected waters. This influx of young carp counteracts adult carp removal efforts (Bajer & Sorensen 2010; Sorensen & Bajer 2011; Osborne 2012; Koch 2014). Additionally, carp are very long-lived (up to 64 years; Koch 2014) and have low natural annual mortality rates estimated between 4 and 26% (Brown et al. 2005; Donkers et al. 2011; Bajer et al. 2015). Due to the longevity of carp, it is usually necessary to reduce existing carp biomass through removal of adults in addition to preventing new recruitment (production of young carp) in order to meet management goals.

1.3 Generalized common carp research & management approach

Despite the complex life history of carp, research conducted by the Sorensen Laboratory at the UMN over the past decade has revealed a possible way forward to sustainably control carp in many watersheds without relying on fish poisons such as rotenone. This management approach has three components; (1) understanding carp movement patterns to identify sub-populations and delineate appropriate management units, (2) identifying carp nurseries and suppressing recruitment, and (3) quantifying adult carp abundance and reducing existing biomass below a target of 100 kg/ha.

First, appropriate management units must be defined. Characterizing carp movement patterns along with age structures and/or genetic structures can elucidate sub-populations of carp (i.e. groups that function as a unit across space and time) and inform the delineation of appropriate management units. Presently, carp behavior is too poorly understood to predict when and where they will move across any particular watershed. Further, these fish can migrate large distances and often appear to home to specific spawning areas that may be unknown (Koch 2014). Consequently, in developing a management scheme, it is necessary to collect detailed site-specific demographic data to develop sustainable control strategies at appropriate spatial scales.

Next, the source(s) of juvenile carp (i.e. recruitment) in each management unit should be identified and subsequently remediated, isolated, or eliminated (Bajer & Sorensen 2010; Bajer et al. 2012; Koch 2014). Remediation may be possible if carp nurseries can be restored to support healthy native fish communities comprised of species that consume carp eggs and young (e.g. bluegill sunfish; Silbernagel & Sorensen 2013). Alternatively, nurseries may be isolated from connected lakes using barriers so that adult carp cannot reach them to breed and/or to prevent young carp from dispersing. If isolation is not feasible, control strategies such as water drawdowns or poisonings at regular intervals can be used to eliminate the young carp before significant numbers disperse.

Lastly, existing adult carp should be removed in large enough numbers to improve to ecosystem function. A target biomass of less than 100 kg of carp per hectare is appropriate for shallow Midwestern systems (Bajer et al. 2009) and can also be applied to deeper, dimictic lakes as a conservative threshold (Vilizzi et al. 2015; Bajer et al. 2016). Removal of carp is often possible through the use of multiple tools such as commercial seining, trapping spawning migrants, baited traps, water drawdowns, or piscicides. Seining can sometimes be an efficient means of removal because adult carp often aggregate during winter months where they may be targeted by commercial fishermen if the bottom is free of obstacles and the substrate is amenable to netting. The use of radio-tagged 'Judas' fish can increase the success rate of such seining efforts (Bajer et al. 2011). Seining may not always be feasible because carp can quickly learn to avoid nets, bottom topography can be uneven, or carp may not form wintertime aggregations. Adult carp may also form springtime spawning aggregations which can be targeted, trapped, and removed. If natural aggregations cannot be exploited, aggregation behavior can be induced by training carp to feed in a particular area using baited traps (Bajer et al. 2010). If these strategies are not feasible, whole-lake drawdowns or poisonings can also be used to reduce carp biomass although these methods are not species-specific and therefore require careful evaluation of non-target impacts.

2.0 Research Findings in the Six Mile Creek Subwatershed

2.1 Deliverable 1: Estimates of adult common carp abundance in all accessible lakes

Methods

Adult common carp abundance was estimated by conducting standardized boat electrofishing surveys in each accessible lake (i.e. Piersons, Wassermann, Turbid, Kelzer's, Steiger, Zumbra, Sunny, Stone, East Auburn, West Auburn, North Lundsten, South Lundsten, Parley, Mud, and Halsted's Bay; see Table 1) to calculate mean catch per unit effort values (CPUE; number of carp sampled per hour) and extrapolate to population size using known relationships. Briefly, surveys consisted of sampling the entire littoral area of each lake using a boat electrofisher with pulsed DC current. Estimates of carp density were then calculated from measured CPUE values using published mathematical relationships of electrofishing efficiency from similar locations (Bajer & Sorensen 2012). In lakes in which multiple surveys were conducted, 95% confidence intervals were generated as a measure of precision. Carp biomass (kg/ha) was estimated by multiplying abundance by the average weight of carp in each lake and then dividing by lake surface area.

During the course of our electrofishing surveys, all carp sampled were also marked with external plastic T-bar anchor tags (Hallprint co., Australia) before being released. These fish were tagged to allow for possible supplemental mark-recapture population estimates in the event that enough tagged fish (few percent of the population) were recaptured.

Results

At least four electrofishing surveys were conducted in each of the 15 accessible lakes between June 2014 and October 2016, with most lakes having between 8 and 10 surveys completed (Table 2). Because catch rates were comparable between years and no young fish recruited to the adult populations during the study period, we combined all years to maximize sample size and thus increase the precision of abundance and biomass estimates. Carp throughout the system grew substantially during the 3 year study period (roughly 13% by weight), so although abundance estimates did not change much between 2014 and 2016, biomass estimates increased in each lake (see Table 2, top panel versus bottom panel). We used the average weight of carp sampled in 2016 in our final table (Table 2, bottom panel) to best reflect the present biomass of carp in the system.

Carp biomass in individual study lakes ranged widely from 26 to 1,264 kg/ha, with an average biomass of 491 kg/ha across the entire subwatershed (Table 2). Twelve of the 15 accessible lakes had biomass levels above 100 kg/ha; a threshold known to be ecologically damaging in shallow Midwestern lakes (Bajer et al. 2009). Carp biomass was very high in Wassermann, Turbid, W. Auburn, E. Auburn, Parley, Mud, and Halsted's Bay ranging from 253 to 1,264 kg/ha. Notably, Halsted's Bay was estimated to contain 64,441 (57,769-71,113) individuals with a biomass of 1,264 (1,133-1,394) kg/ha based on nine whole-lake surveys. This exceeds the damaging threshold twelvefold and is the highest carp biomass ever observed by the Sorensen Lab. Carp biomass was moderate (156-204 kg/ha) in N. Lundsten, S. Lundsten, Steiger, Sunny, and Zumbra. Carp biomass was low (≤99 kg/ha) in Piersons, Stone, and Kelzer's. No electrofishing surveys were conducted in Marsh or Carl Krey Lakes due to inaccessibility.

During the course of all electrofishing surveys conducted from 2014 to 2016, 1,763 common carp were tagged with T-bar tags and released. As of December 2016, 87 of these tagged fish have been recaptured. Of the recaptured carp, 37 were sampled relatively evenly throughout the subwatershed and thus represent low recapture rates that do not allow for the statistical computation of supplemental mark-recapture estimates. However, the remaining 50 were recaptured during the commercial seine haul that took place in Parley Lake on March 10th, 2015. This recapture rate allowed us to calculate population estimates for Parley and Mud lakes combined (the lakes could not be separated because all carp from both lakes formed a single large wintertime aggregation in Parley Lake). In total, 6,206 carp were captured in the seine haul, of which 5,564 were individually checked for tags and 50 tagged fish were observed. Given that there were 211 carp tagged in Parley and Mud Lakes before the seining occurred, this recapture rate results in an estimated population size of 23,591 carp based on the Lincoln-Peterson method (i.e. $N=Kn/k$ where N = number of individuals in the population, K = number of marked animals in the population, n = number of animals captured, and k = number of recaptured individuals). This mark-recapture population estimate for Parley and Mud Lakes combined is comparable to the sum of estimates generated from electrofishing surveys in both lakes (i.e. 19,006-23,625) despite violating assumptions of a closed population.

2.2 Deliverable 2: Seasonal distribution and movement patterns of adult carp

Methods

The seasonal distributions and movement patterns of adult carp across the Six Mile Creek subwatershed were determined by implanting carp with radio-tags and manually bi-angulating their locations at least once per month. In October of 2014, 102 radio-tags were implanted in carp throughout the subwatershed (5-15 tags per lake; see Table 1). In the spring of 2015, 18 more radio-tags were implanted in 3 additional lakes for a total of 120 radio-tagged carp. Each tagged carp was given a unique fish identification number ranging from 1 to 120.

In addition to tracking the radio-tagged carp, movement patterns were also elucidated by recapturing carp previously tagged with individually numbered T-bar tags during routine electrofishing surveys. As discussed above, 1,763 carp had been sampled, tagged with T-bar tags, and released since the onset of the study in June 2014.

Results

Radio-tagged carp were located throughout the subwatershed at least once per month for two full years from November 2014 through October 2016 (See Figures 2-29). During April, May, and June, the carp were located twice per month to increase the resolution of data during the pre-spawning and spawning periods. From November 2014 through April 2015, 99% of the tagged fish were located successfully each month. Beginning in late May 2015 and continuing through October 2016, an average of 13 tagged carp were missing each month, primarily from Parley, Mud, and Halsted's Bay. The several missing carp from Parley, Mud, and Halsted's Bay were presumed to be somewhere in greater Lake Minnetonka, but due to time constraints, it was not feasible to search all of Lake Minnetonka. Large portions of Lake Minnetonka were searched on occasion and radio-tagged carp have been located in Priest's Bay, Cook's Bay, West Upper, West Arm, and as far east as Jenning's Bay near the inlet of Painter Creek (see Figure 18).

The first mortality of a radio-tagged carp occurred in May 2015 in Mud Lake. Since then, 32 additional radio-tagged adult carp have died or lost their transmitters for a total mortality rate of 27.5% over two years which is comparable to published annual natural mortality rates in systems with high carp densities (Brown et al. 2005; Bajer et al. 2015). Mortalities were distributed relatively evenly across the subwatershed (i.e. 2 in Halsted's, 4 in Mud, 5 in Parley, 5 in Wassermann, 3 in Lundsten, 2 in Steiger, 1 in Zumbra, 3 in East Auburn, 3 in West Auburn, 2 in Turbid, and 3 in Piersons) and thus did not diminish the scope or resolution of the movement study.

As for movement of carp between lakes, approximately half of the radio-tagged carp (59 of 120; 49%) were located in a lake other than where they were originally tagged at least once during the two-year movement study. A summary of movement corridors, rates, and timing can be found in Table 3 and is summarized on a map in Figure 30. Most carp traveled between just a few lakes and usually returned to their lake of origin. Most movements occurred from deeper lakes to shallow habitats during the spawning season (e.g. from Auburn to South Lundsten and from Parley and Halsted's to Mud) or from shallow lakes to deeper lakes in late fall before ice cover (e.g. from Mud to Parley; Table 3).

The highest average annual movement rates occurred between Parley and Mud Lakes in both directions (81%), between Mud and Halsted's Bay in both directions (47%), and between East and West Auburn Lakes in both directions (73%). Most of these movements occurred from Mud Lake to Parley Lake in late fall each year (see Figures 2-3 & 17-19) or between Parley, Mud, and Halsted's Bay in all directions between late May and August in 2015 (see Figures 10-14) and between late May and October in 2016 (see Figures 24-29). Additionally, 13 of the 45 carp originally tagged in Parley, Mud, or Halsted's Bay have been located in other bays of Lake Minnetonka year-round despite low sampling effort in greater Lake Minnetonka. This high rate of movement to and from the rest of Lake Minnetonka (22%, annually) likely explains our inability to locate some of the tagged carp each month. Several radio-tagged carp have also moved from Wassermann Lake, Auburn Lakes, and North Lundsten Lake into South Lundsten Lake (5%, 43%, & 46%, annually) in May and June of both years and then returned to their respective lakes of origin by late summer (see Figures 11 & 23-25). No movement of radio-tagged carp in or out of Turbid, Zumbra, Sunny, Steiger, or Piersons Lakes was observed during the 2 year study period.

In addition to radio-tagged carp moving between lakes, there have also been seasonal patterns in the spatial distribution of carp within lakes. Specifically, wintertime aggregations of carp (identified by at least 50% of radio-tagged carp being found within a 10 hectare area) formed in both 2014-15 and 2015-16 in all but one of the study lakes (i.e. Steiger Lake). The timing of aggregation formation and location varied, but in general, aggregations formed by December and persisted through February (Table 4). These aggregations contained as many as 100% of radio-tagged carp in some lakes (i.e. Parley-Mud, N. Lundsten, S. Lundsten, Turbid, W. Auburn, E. Auburn, Sunny, Zumbra, and Wassermann), whereas in other lakes (i.e. Halsted's Bay, Piersons), multiple aggregations comprised of roughly 40-60% of tagged fish each were observed. Interestingly, winter aggregations in some lakes formed in same location between years (i.e. Parley, West Auburn, East Auburn, Zumbra, and Piersons) whereas they formed in different places in Wassermann Lake and Halsted's Bay (See Figures 5 and 20).

Recaptures of T-bar tagged carp and visual observations of spawning migrations confirmed the patterns observed during the radio-tag study (i.e. movement between Parley, Mud, and Halsted's Bay and movement between Auburn Lakes and Lundsten Lakes) and contributed some additional information on carp movement patterns. Specifically, recaptures of T-bar tagged carp revealed that it is possible for carp to move through the Parley Lake dam in a downstream direction as evidenced by one carp that was originally tagged in West Auburn Lake in June 2014 that was recaptured in the commercial seine haul in Parley Lake in March 2015. To date, there has been no evidence that the Parley Lake dam is passable by fish in an upstream direction. Mass spawning migrations of carp were also observed prior to deploying radio-tags throughout the system during the spring flooding of 2014. Large numbers of migrating carp were observed downstream of culverts in Turbid Creek at Laketown Road, in Six Mile Creek at the Parley Dam, and in Six Mile Creek at Marsh Lake Road upstream of Wassermann Lake. These observations were consistent with past anecdotal reports of carp spawning migrations (Wenck 2013).

2.3 Deliverable 3: Identification of sources of juvenile carp across the watershed

Carp recruitment during the study period was characterized by sampling for juvenile carp using trap-nets (section 2.3.1) while historic patterns of recruitment were examined by ageing adult carp to determine when they hatched (section 2.3.2). Ongoing work using genetic and biochemical markers is presently being conducted to further investigate past nursery contributions (appendix 2).

2.3.1 Distribution and relative abundance of juvenile common carp in 2014-2016

Methods

To assess the distribution and relative abundance of young-of-the-year carp (YOY; spawned that year) and bluegill sunfish (*Lepomis macrochirus*; a predator of carp eggs and larvae; Bajer at al. 2011; Silbernagel & Sorensen 2013), we conducted standardized trap-net surveys across the subwatershed. Trap-nets are a common type of sampling gear used to survey small fishes in the littoral zone of lakes (e.g. YOY fishes and panfish). Trap-nets consist of a long wall of net (30 ft x 3 ft) that is staked close to shore and directs fish to an underwater frame with a series of hoops and funnels that trap fish in a holding cage at the rear of the net. Five nets were set equidistantly around the perimeter of each accessible lake and pond and were left in place overnight for approximately 24 hours. Trap-net surveys were conducted in August and September, when YOY fishes were large enough to sample, but before lake temperatures dropped. Trap-nets reliably sample YOY carp (<150 mm in total length) and one-year-old carp, but rarely sample older juveniles or adults (Osborne 2012).

Results

Trap-net surveys targeting juvenile common carp were completed in fall 2014, 2015, and 2016 in each of the 15 accessible study lakes along with numerous additional connected ponds (Table 1). Of the 21 sites sampled in 2014, YOY carp were only captured in three locations: Mud Lake (0.2 per net), Crown College Pond (1.0 per net), and Big SOB Lake (19.8 per net). Additionally, one-year-old carp were sampled in 2 locations: Shady Pond (0.67 per net) and Carl Krey Lake (2.0 in a gillnet; Table 5). In 2015, YOY carp were sampled in 4 out of 22 locations: Crown College Pond (332.3 per net), North Lundsten (3.2 per net), South Lundsten (311.2 per net), and Wassermann Lake (0.2 per net). Additionally, one-year-old carp were sampled in 2 locations: Big SOB Lake (1.8 per net) and Wassermann Pond West (0.3 per net). In 2016, no YOY carp were sampled throughout the entire subwatershed, but one-year-old carp were sampled in South Lundsten (0.4 per net) and Crown College Pond (2.3 per net). In total, juvenile carp were sampled at 9 unique sites, but mostly in very low numbers (i.e. <3 per net; Table 5). Extremely high numbers of carp were however observed in South Lundsten Lake and Crown College Pond in 2015 (i.e. >300 per net) and trap-netting in 2016 revealed that at least some portion of these carp successfully overwintered in both locations. Catch rates of YOY carp and one-year-old carp cannot be compared directly because one-year-old carp are not sampled as well in trapnets.

Bluegill sunfish were abundant throughout much of the watershed (Table 6). Bluegill sunfish were sampled in all locations where juvenile carp were sampled except for in Crown College Pond in 2014 and 2015, Shady Pond, and Wassermann Pond West (Table 6). Shady Pond and Wassermann Pond West experience summer and winter hypoxia as evidenced by large numbers of dead fish in August trapnet surveys and low dissolved oxygen readings in February (Table 7). It should be noted that the presence of bluegill sunfish during fall trapnet surveys does not indicate that bluegills were present in the spring during the carp spawning season; it is possible that some basins experienced winterkill conditions that went undetected due to bluegill sunfish recolonization from connected waters.

2.3.2 Historical patterns of carp recruitment via ageing analysis

Methods

To elucidate historical trends in common carp recruitment, ageing studies were conducted throughout most of the subwatershed (Table 1). In 2014, otoliths were collected from Halsted's Bay (n=51), Mud Lake (n=51), Parley Lake (n=51). In 2015, otoliths were collected from North Lundsten Lake (n=31), West Auburn Lake (n=28), East Auburn Lake (n=28), Wassermann Lake (n=37), and Piersons Lake (n=34). In 2016, otoliths were collected from Turbid Lake (n=24), Steiger Lake (n=15), and Zumbra Lake (n=28). Common carp were sampled via electrofishing, removed from the system, and frozen for subsequent analysis following established protocols for common carp outlined in Bajer and Sorensen (2010). Specifically, the asterisci otoliths (i.e. ear bones) were extracted, embedded in epoxy, and sectioned using a slow speed saw. Annual growth rings were counted using a compound microscope by two independent observers.

Results

In total, 378 common carp were collected across the subwatershed for age determination. Carp ages ranged from 2 to 54 years old with just five year-classes (i.e. 2001-2002 and 1990-1992) accounting for 68% of total recruitment system-wide (Figure 31). The age structures of common carp sampled across the subwatershed were not consistent between all study lakes, but were similar between some groups of adjacent lakes (Figure 32). Lakes with similar age structures were grouped as follows: 1) Piersons and Wassermann, 2) East Auburn, West Auburn, North Lundsten, and Turbid, 3) Parley, Mud, and Halsted's Bay, and 4) Steiger and Zumbra Lakes (Figure 33). The age structure results coupled with the results of the movement study (see section 2.2) seem to suggest that there are several sub-populations of carp within the subwatershed (discussed in detail in section 2.4 below).

At the headwaters of the system in Lakes Piersons and Wassermann, there have only been two strong year classes of common carp since the 1960s (i.e. 1991 & 1992; figure 33). These two year classes account for 54% of all carp sampled in these two lakes combined. Aside from a couple of individuals every few years, there is a noticeable lack of young fish in this sub-population indicating that carp recruitment has been largely unsuccessful in recent years. In contrast, in Lakes Auburn and Lundsten, there are relatively consistent year classes almost every year for the past 15 years and a notable absence of older individuals (Figure 33). The strongest year classes were from 2001 and 2002 which accounted for 50% of recruitment in Auburn, Lundsten, and Turbid Lakes combined. This age structure, along with extremely high catch rates of YOY carp in South Lundsten in 2015, indicates that South Lundsten is serving as an active and highly productive carp nursery. In Parley, Mud, and Halsted's Bay, 75% of all carp sampled assigned to the same strong year classes mentioned above (i.e. 1990, 1991, 1992, 2001, & 2002; Figure 33). Similarly, these five years classes accounted for 84% of recruitment in Zumbra and Steiger Lakes as well (Figure 33).

Interestingly, the seven strongest year classes of carp observed in the Six Mile Creek subwatershed (i.e. 1990-92, 2001-02, & 2009-10) closely matches the patterns of carp recruitment observed in the Phalen Chain subwatershed in Saint Paul, MN (Figure 34). The similarities in carp year class strength between the two isolated chains of lakes indicates that whatever is driving carp recruitment in the Six Mile Creek subwatershed is likely not system-specific, but is instead related to outside factors such as climate. Historical water level records for Parley Lake dating back to the 1980s reveal that extended periods of low water preceded both 1991 and 2001 (Figure 35). It is possible that such drought conditions increased the likelihood and severity of winterkills in many of the shallow basins throughout the Six Mile Creek subwatershed and the state during these years.

2.4 Overall conclusions of research findings & resulting management units

Based on the abundance estimates, size structures, movement patterns, and age structures of carp in the Six Mile Creek subwatershed, there appears to be multiple sub-populations of carp throughout the subwatershed and consequently multiple management units. Carp sub-populations are: Piersons-Marsh-Wassermann, Auburn-Lundsten-Turbid, Parley-Mud-Halsted's, and the rest of the isolated lakes individually (i.e. Stone, Zumbra-Sunny, and Steiger). These sub-populations are not entirely independent as there is evidence of low levels of movement between Lundsten and Parley and between Lundsten and Wassermann. Although ongoing carp recruitment in South Lundsten appears to impact both upstream and downstream sub-populations to some degree, dispersal of carp recruits from South Lundsten to other sub-populations appears to be minimal based on the prevailing recruitment patterns observed in each sub-population elucidated from age structures and preliminary genetic analyses (See Figure 33 and Appendix 2). Dispersal from South Lundsten to North Lundsten and Auburn Lakes is common. Cutting off dispersal of new carp recruits from South Lundsten is integral to managing carp throughout the entire Six Mile Creek subwatershed and is likely a prerequisite to dividing the system up into clear manageable units.

If MCWD were to suppress the ongoing recruitment in South Lundsten, the resulting management units would be: 1) Piersons-Marsh-Wassermann, 2) Auburn-Lundsten-Turbid, 3) Parley-Mud-Halsted's, and 4) Carver Park Reserve Lakes (Steiger Lake, Zumbra-Sunny, and Stone). The area between Wassermann and East Auburn (i.e. the wetland complex that includes Carl Krey, Kelzer's Pond, and Church Lake) is not included in any management unit as no carp management activities are recommended there due to a lack of carp movement in and out of these systems and very low numbers of carp in the locations that were sampled. It should be noted that we have a poor understanding of this portion of the system due to limited access with sampling gear. Below is the rationale for delineating each management unit:

Piersons-Marsh-Wassermann

It appears that carp inhabiting Piersons Lake, Marsh Lake, and Wassermann Lake likely comprise a single sub-population that might be managed together. There are multiple lines of evidence that Piersons and Wassermann share a common primary carp nursery. Specifically, the age structures are similar between lakes and are both dominated by the 1991-92 year classes (55% & 51% of total recruitment; Figure 32) and the average size of carp is similar in both lakes (3.3kg & 3.4kg) and is in contrast to connected lakes (Table 2). Additionally, there is evidence of spawning migrations to Marsh Lake from both lakes and pilot studies indicate that genetic structures also appear similar between lakes and are in contrast to downstream lakes (Appendix 2). Although no movement of radio-tagged carp into Marsh Lake was observed during the study period, there are past reports of spawning migrations to Marsh Lake from Piersons Lake (Wenck 2013) and hundreds of carp from Wassermann Lake were observed attempting to migrate towards Marsh Lake at the Marsh Lake Road crossing during spring of 2014.

Although it is possible for carp to move between Wassermann and downstream lakes as evidenced by 2 of 15 radio-tagged carp moving from Wassermann to East Auburn and back again and one moving as far as South Lundsten, movement seems relatively uncommon given the stark contrast between the age structures of carp in Piersons-Wassermann compared to that of Auburn-Lundsten-Turbid (Figure 33). Low levels of connectivity between South Lundsten and Wassermann Lake could explain the elevated presence of the 2001-02 year class in Wassermann Lake (17% of total recruitment) compared to that in Piersons Lake (3%) as well as the higher levels of genetic differentiation in Wassermann Lake (Appendix 2).

Auburn-Lundsten-Turbid

In the central portion of the subwatershed, carp inhabiting East Auburn, West Auburn, North Lundsten, South Lundsten, and Turbid Lakes might also be managed as a single sub-population. There are multiple lines of evidence that these lakes share two common nurseries (i.e. South Lundsten & Turbid Lakes). South Lundsten Lake appears to be the primary nursery for both of the Lundstens and Auburns as evidenced by high catch rates of YOY carp in South Lundsten in 2015 (Table 5), spawning-season migrations of radio-tagged to South Lundsten from North Lundsten and Auburn (Table 3), similar age structures in Lundsten and Auburn dominated by the 2001-02 year classes (34% and 42% of total recruitment, respectively) and lacking the 1990-92 year classes (Figure 32), and similar average sizes of carp in the Lundstens and Auburns ranging from 1.9 kg to 2.6 kg (Table2).

In Turbid Lake, every single carp analyzed assigned to the 2001-02 year classes (Figure 32) and there is some evidence of a genetic bottleneck (Appendix 2). It is possible that Turbid experienced a near complete winterkill in 2001, followed by recolonization by a small number of carp and/or repopulation by a small number of surviving carp. Given this unique situation, carp spawned in Turbid Lake have a distinctive genetic signature that can be used to track their dispersal. Based on the genetic signatures of carp sampled in Lundsten and Auburn Lakes, it appears that roughly 5% of these carp were spawned in Turbid Lake (Appendix 2). There is no evidence of successful recruitment in Turbid Lake since 2002.

Despite the presence of two additional inflowing creeks to East Auburn (i.e. Steiger Lake outflow and Sunny Lake outflow), no radio-tagged fish have been observed moving upstream or downstream in either of these creeks. Additionally, carp in these connected systems (i.e. Zumbra-Sunny, Stone, & Steiger) are significantly larger (> 3.0 kg; Table 2) and older (Figure 32) which provides further evidence that these sub-populations can be managed separately.

Parley-Mud-Halsted's

In the lower portion of the subwatershed, carp inhabiting lakes Parley, Mud, and Halsted's Bay should also be managed as a single sub-population. It would be incredibly difficult to manage any of these lakes individually due to extremely high rates of carp movement between all three lakes (Figure 30). There is also evidence that these lakes share one or more common nurseries. Specifically, between Parley, Mud, and Halsted's Bay, the average size of carp is similar (4.0, 4.1, & 4.4 kg, respectively; Table 2) and the age structures are dominated by the same five year classes (i.e. 2001-02, & 1990-92). Notably, Parley Lake contains more younger carp (spawned post 2000; Figure 32) relative to the other lakes downstream, suggesting that at least a portion of carp in this subpopulation may have originated from nursery areas in closer proximity to Parley Lake (i.e. Crown College Pond and/or South Lundsten Lake). Although carp are not able to move upstream through the Parley Lake dam to access South Lundsten to spawn, carp from above can move downstream as evidenced by one carp originally tagged with a T-bar tag in West Auburn later being recaptured in Parley. The occurrence of spawning migrations below the Parley Lake dam provides further evidence that some carp were likely spawned upstream of the dam because common carp have a tendency to exhibit natal site homing (Koch 2014).

This possible management unit presents challenges because large numbers of carp move readily between Parley-Mud-Halsted's and other bays of Lake Minnetonka (Figure 30). Understanding and quantifying carp movement outside of the Six Mile Creek subwatershed was beyond the scope of this study, but will be important to guide sustainable carp control in this management unit. Presently, this management unit cannot be separated from the rest of Lake Minnetonka without taking actions to isolate Parley-Mud and/or Halsted's Bay from the other bays (e.g. installing a carp barrier between Mud Lake and Halsted's Bay or between Halsted's Bay and Priest's Bay).

Carver Park Reserve Lakes

The rest of the study lakes (i.e. Steiger, Zumbra, Sunny, & Stone) each seem to contain their own isolated sub-population of carp, but we grouped them together as a possible single management unit given their similar ecological conditions, carp management goals, and shared location within the eastern Carver Park Reserve in the jurisdiction of the Three Rivers Park District. Although there was no carp movement in or out of any of these lakes during the study period, it should be noted that man-made barriers were in place in the connections between Stone and Sunny Lakes and between Zumbra and Sunny Lakes. Without these barriers, it is likely that Stone, Sunny, and Zumbra would function as one sub-population.

3.0 Management Recommendations

The overarching aim of the common carp assessment in the Six Mile Creek subwatershed was to develop a rigorous scientific understanding of the carp in this system to develop sustainable control strategies. The first step in any sustainable carp control program is to delineate appropriate management units by determining the spatial and temporal scales at which local carp population dynamics are operating. In the Six Mile Creek subwatershed, four possible management units have been tentatively identified: 1) Piersons-Marsh-Wassermann, 2) Lundsten-Auburn-Turbid, 3) Parley-Mud-Halsted's, and 4) Carver Park Reserve Lakes (see Section 2.4 for details and justifications).

Next, appropriate management objectives and measurable targets must be established for each unit. To achieve long-term, sustainable control of carp populations, ongoing recruitment must be suppressed and future recruitment must be prevented owing to the extreme fecundity and longevity of carp. To mitigate or prevent detrimental impacts to aquatic habitats and water quality, the biomass of carp might then be reduced and/or maintained below thresholds where ecological damage occurs. Specific targets for each management unit are discussed below in Sections 3.1 and 3.2.

Finally, realistic strategies must be identified to meet the specific targets identified for each management unit and these strategies must be implemented in a strategic order. There are multiple ways to approach carp control in the Six Mile Creek subwatershed depending on management priorities. For example, one option would be to suppress recruitment system-wide and then proceed with biomass reduction in each individual management unit. Another approach would be to start in the headwaters of the system by meeting all of the objectives identified in the Piersons-Marsh-Wassermann management unit (i.e. recruitment suppression and existing biomass reduction) and then repeat for the remaining management units. A third approach would be to first eliminate carp movement between the subwatershed and Lake Minnetonka and then proceed with either of the first two options. A fourth approach would be to implement individual management strategies opportunistically where they make sense with other district planning initiatives (e.g. installation of a carp barrier when a road crossing is being rebuilt).

Each of the management approaches outlined above has its own benefits and pitfalls. We recommend the first approach of suppressing carp recruitment system-wide be strongly considered. The rational for choosing this approach is because there is presently ongoing, continuous, and likely large-scale recruitment in South Lundsten Lake that should be addressed immediately to stop the overall carp population from growing. It is also important to address the sporadic recruitment that has occurred in all of the other management units to prevent successful large year classes of carp in the future – a single recruitment event can have devastating consequences. These actions should be prioritized because MCWD is currently in the unique position of having accurate, up-to-date estimates of carp abundance and biomass across the entire subwatershed (see Table 2). If recruitment is not suppressed and the carp population continues to grow, new estimates of carp biomass will be required to adjust the management targets developed in this report. After recruitment is suppressed system-wide, any of the remaining three management approaches seem reasonable. The following sections outline possible carp control strategies specific to each management unit regardless of the order they are implemented.

3.1 Strategies to suppress recruitment

Given the fecundity of adult common carp (2-3 million eggs per large female), suppression of recruitment is the cornerstone of sustainable long-term carp management. After three years of trap-netting for YOY carp and determining the age structure of carp in 11 lakes, a few carp nurseries have been identified in the Six Mile Creek Subwatershed, with South Lundsten Lake being a management priority. Strategies to suppress recruitment are less clear in Piersons-Marsh-Wassermann, Parley-Mud-Halsteds, and the Carver Park Reserve Lakes because the age structures in these lakes suggest that carp recruitment has only been successful in a few years since the 1960s (Figure 33). It is difficult to determine the precise source(s) of carp that were spawned decades ago, but it is possible to speculate on the likely sources based on our study findings, our knowledge of common carp life history, and historical climatic records. It is plausible that Mud Lake and the Marsh Lake both served as carp nurseries in the past because of the large number of carp that move towards them during the spawning season and because they are likely susceptible to winterkill conditions due to their shallow depths.

3.1.1 Piersons-Marsh-Wassermann

In the Piersons-Marsh-Wassermann management unit, aside from one YOY carp sampled in Wassermann Lake and two Age-1 carp sampled in Wassermann Pond West in 2015, no juvenile carp have been sampled during the study period. The age structure of carp in Piersons and Wassermann also confirms that there is very little ongoing successful recruitment as most of the carp were spawned in 1990-92 (54% of total recruitment) compared to only 5% spawned during the past 10 years (Figure 33). Although there has not been any movement of tagged fish from Piersons or Wassermann into Marsh Lake during the study period, past reports of mass spawning migrations to Marsh Lake from both of these lakes indicate that it likely functioned as a nursery in the past. The dissolved oxygen content in Marsh Lake remained high (>9 mg/L; Table 7) during the winters of 2014-15 and 2015-16 and bluegill sunfish catch rates were also very high in fall of 2014, 2015, and 2016 (131.4, 113.5, & 108.6 per net, respectively; Table 6). Based on these findings, it does not appear that Marsh Lake has a tendency to winterkill often, but perhaps extreme climatic conditions (e.g. harsh winters, above average snowfall, drought) could cause periodic winterkills. This could explain the recruitment success of carp in 1990-91 in this system because a winterkill likely occurred in Marsh Lake in 1988-89 due to severe drought conditions across the state causing water levels to drop an average of three feet (MN DNR 1989).

To prevent future successful carp recruitment in Marsh Lake, winter aeration should be considered to mitigate the risk of future winterkills. The feasibility of aerating Marsh Lake is presently unknown and should be explored. If aeration is not feasible, barriers should be installed to block adult carp from accessing Marsh Lake from both Piersons and Wassermann Lakes. Multiple barrier technologies exist, each with their own strengths, weaknesses, and limitations (see Table 8). A barrier between Piersons and Marsh must block carp swimming in the downstream direction whereas a barrier between Wassermann and Marsh must block carp swimming in an upstream direction.

In Wassermann Lake, there is also evidence of some recruitment inputs from the Auburn-Lundsten-Turbid sub-population downstream. Specifically, the 2001-02 year class which is well-represented in Auburn-Lundsten-Turbid, accounts for 17% of total recruitment in

Wassermann Lake compared to 3% in Piersons (Figure 32). The elevated presence of this year class in Wassermann coupled with evidence of radio-tagged carp moving from Wassermann to Auburn and South Lundsten and back confirms that dispersal of carp from South Lundsten to Wassermann is possible. To suppress ongoing recruitment inputs from downstream, recruitment in the Auburn-Lundsten-Turbid sub-population would need to be suppressed (See Section 3.1.2) or a barrier would need to be installed at the outlet of Wassermann Lake. This barrier would only need to be a 1-way barrier that prevented carp from entering Wassermann from downstream waters. Depending on the site specifications, a velocity barrier, vertical drop barrier, or an electric barrier may be effective (see Table 8).

3.1.2 Auburn-Lundsten-Turbid

In this management unit, it appears that South Lundsten Lake is a very productive and active carp nursery. South Lundsten supports extremely high densities of YOY carp and is well-connected to other lakes as evidenced by high catch rates of YOY carp in trapnets in 2015 (>300 per net), movement of radio-tagged carp between North and South Lundsten (56%, annually) and between Auburn and South Lundsten (43%, annually), and the prevalence of young carp inhabiting Lundsten and Auburn Lakes (Figure 33). Although moderate numbers of bluegill sunfish were sampled in South Lundsten Lake during fall trapnet surveys (17.4, 34.2, & 68.8 per net in 2014, 2015, & 2016 respectively; Table 6), the maximum dissolved oxygen content measured by MCWD staff during winter of 2014-15 was 1.5 mg/L (Table 7), just slightly above a level that is lethal to bluegill sunfish (Moss & Scott 1961; Petrosky & Magnuson 1973; Bajer & Sorensen 2010). The dissolved oxygen concentration was measured by MCWD staff in February of 2015 at the deepest point in the lake; it is likely that oxygen levels fell below 1.5 mg/L in shallower parts of the lake or later in the winter resulting in at least a partial winterkill of bluegill sunfish in South Lundsten. It is possible that bluegill sunfish were then able to recolonize South Lundsten from connected waters before our fall surveys were conducted. In winter of 2015-16, the maximum dissolved oxygen content was 10.0 mg/L (Table 7) and trap-netting in South Lundsten in 2016 revealed that many bluegills survived the winter (108.6 and 68.8 fish per net in April and September, respectively) and no YOY carp were present in fall of 2016.

Interestingly, there is a lack of older carp in this sub-population indicating that South Lundsten Lake has not always been an active, productive nursery. Specifically, the 1990-92 year classes that are well-represented everywhere else throughout the subwatershed are missing from Auburn-Lundsten-Turbid (Figure 33). This lack of old carp may be explained by the former presence of a riprap dam between West Auburn and North Lundsten that washed out in the late 1990's (Wenck 2013). This dam (and probable fish barrier) was replaced by a culvert that is easily passable by carp as evidenced by our radio-tagging study results and may have allowed unprecedented access to the prime spawning habitats in South Lundsten.

To suppress ongoing recruitment in Auburn-Lundsten-Turbid, aerating South Lundsten during the winter months is recommended to promote the survival of a robust panfish community year-round in order to increase predation pressure on carp eggs and larvae. The feasibility of aeration in South Lundsten Lake is presently unknown, but it may be increased by manipulating water levels to be higher in the winter via the water control structure at the outlet of North Lundsten Lake (aka the Parley Lake Dam). It should be noted that future aeration will do nothing to address the juvenile carp that are already in South Lundsten, including the sizeable 2015 year class. These carp could be removed as adults later using a variety of techniques (see section 3.2.2) or actions could be implemented in 2017 to eliminate them from South Lundsten Lake before large numbers start dispersing to connected lakes (e.g. whole-lake poisoning or water drawdown).

Although South Lundsten is the primary carp nursery for this sub-population, there is also some evidence that low levels of successful recruitment has occurred in North Lundsten and Turbid Lakes as well. Specifically, small numbers of YOY carp were sampled in trap-nets in North Lundsten in 2015 (3.2 carp per net; Table 6) and preliminary genetic evidence indicates that roughly 5% of the carp in Auburn and Lundsten Lakes originated from Turbid Lake (Appendix 2). To prevent future sporadic recruitment in North Lundsten and Turbid Lakes, wintertime aeration is recommended to promote dissolved oxygen concentrations adequate for bluegill sunfish survival.

If aeration is not feasible in South Lundsten, North Lundsten, and/or Turbid Lakes, barriers could be installed to isolate one or more of these lakes. It would be difficult to isolate

South Lundsten from North Lundsten due to their close proximity and minimal separation by a low-lying horse path that is prone to flooding. A better place for a barrier may be the culvert between North Lundsten and West Auburn, the site of the former riprap dam. If isolation is not feasible, these lakes could be monitored annually for successful recruitment (see section 3.3) and then regularly drawdown and/or poisoned to eliminate juvenile carp before they are able to disperse to connected lakes. Additionally, it may be possible to manipulate water levels during the spawning season to decrease carp recruitment rates (Shields 1958). This may be accomplished by operating the North Lundsten outlet structure to lower water levels immediately following peak carp spawning behavior in attempts to desiccate vulnerable eggs and larvae. This feasibility of this strategy depends on the outlet structure design and lake bathymetry.

3.1.3 Parley-Mud-Halsted's

In this possible management unit, carp may be coming from multiple sources including South Lundsten, Mud, or one or more peripheral ponds where YOY carp have been sampled during the study period (i.e. Big SOB Lake and/or Crown College Pond). Based on the age structure of carp in these lakes, with roughly half of all individuals assigning to the 1990-92 year classes and a very low representation of these year classes in Auburn-Lundsten-Turbid (Figure 33), it seems likely that most of these older fish were spawned in locations below the Parley lake dam (i.e. not South Lundsten). In contrast, roughly 20% of carp in this management unit assigned to the 2001-02 year classes (Figure 33), with these younger fish being twice as prevalent in Parley compared to Mud or Halsted's Bay (Figure 32). Because these year classes are more prevalent in Parley Lake and were also well-represented in Auburn-Lundsten, it follows that these individuals may have been spawned in South Lundsten Lake. Observations of carp moving successfully through the Parley Lake Dam in the downstream direction and past occurrences of large spawning migrations of carp trying to pass through the Parley Lake dam in an upstream direction coupled with the homing tendencies of carp support this hypothesis (Koch 2014).

To suppress the ongoing recruitment inputs to Parley-Mud-Halsted's from South Lundsten Lake, recruitment would have to be suppressed in Auburn-Lundsten-Turbid (strategies discussed above in section 3.1.2) or carp movement through the Parley Lake Dam would have to be prevented. Preventing future recruitment below the Parley Lake Dam is more complicated due to the uncertainty surrounding where exactly young carp were historically produced. Due to the statewide drought conditions in 1988-89, it is possible that Mud Lake winterkilled in 1989-90 creating ideal carp spawning conditions the next spring for the same reasons discussed above for Marsh Lake. Specifically, water levels in Parley Lake reached record lows during 1988-1990 (2.5ft lower than average conditions; Figure 35), which would have made Mud Lake approximately 1 foot deep on average during those years. It is also possible that carp were spawned in one or more of the peripheral basins where YOY carp were sampled during the study period as these basins would have likely winterkilled that year as well. The role that these peripheral basins have in contributing carp recruits to the greater sub-population is however unclear. The YOY carp that were sampled in Big SOB Lake in 2015 were likely an artifact of a rotenone poisoning carried out by the property owner the preceding fall which mimicked winterkill conditions and was followed by high spring water levels which facilitated recolonization by adult carp from Parley. Crown College Pond likely suffers partial or complete winterkills most years as evidenced by it freezing solid to the bottom in winter 2014-2015 and experiencing very low dissolved oxygen concentrations in winter 2015-16 (1.85 mg/L) despite mild conditions (Table 7). Although very high numbers of YOY carp were sampled in Crown College Pond in fall of 2015 (>300 per net), few one-year-old carp were sampled in April of 2016 (2.6 per net) indicating relatively high overwinter mortality rates. Nevertheless, at least some carp did survive the winter in Crown Pond despite suboptimal oxygen conditions, indicating that Crown Pond could serve as a source of carp to connected waters if emigration is possible.

To prevent future recruitment in Parley-Mud-Halsted's, wintertime aeration of Mud Lake is recommended. If aeration of Mud Lake is not feasible, isolating Mud Lake from both Parley and Halsted's Bay using barriers is recommended. Isolating Mud Lake would be difficult because carp frequently move through these corridors in both directions (Table 3). Because 100% of our radio-tagged carp left Mud Lake by December 2015 to overwinter in Parley, there should be a window of time between December and ice-out to install barriers while Mud Lake does not contain many carp. As for the peripheral potential carp nurseries, it is unknown if Big

SOB Lake experiences winter hypoxia under natural conditions, but it is currently being aerated by the private landowner and should continue to support a healthy panfish community if aeration continues. In Crown College Pond, aeration is likely not feasible due to its tendency to freeze solid in some years, so isolation of this pond is recommended instead. The creek flowing from Crown Pond to Parley flows intermittently and is not passable by carp most of the year; a simple physical barrier blocking adult carp from accessing Crown from Parley may be sufficient.

3.1.4 Carver Park Reserve Lakes

No YOY carp were sampled in any of the lakes within the Carver Park Reserve management unit (i.e. Steiger, Zumbra, Sunny, and Stone) and the age structures in Zumbra and Steiger lakes indicate that successful recruitment has largely been restricted to the 2001-02 and 1990-92 year classes (Figure 33). Furthermore, all of these lakes contain low to moderate numbers of carp which indicates that population abundance has not been increasing rapidly. It is difficult to determine where the carp were produced in past years, but reports of a history of winterkill in Sunny Lake (Wenck 2013) along with very low dissolved oxygen concentrations measured in Sunny in February 2015 (0.9 mg/L; Table 7) draw attention to Sunny as a potential carp nursery. No signs of winterkill were observed in Sunny Lake during the study period (i.e. bluegill catch rates > 38.0 fish/net each year) and no movement of carp was observed in or out of any of these lakes towards Sunny although manmade barriers were in place at the outlets of Stone and Zumbra during the entire study period.

As a precautionary measure to prevent possible future recruitment in Sunny Lake, aeration of Sunny should be considered. Additionally, the barrier at the Stone outlet should be maintained and the barrier at the Zumbra outlet should be fortified. The current barrier at the Zumbra outlet is not very robust and is also prone to flooding (See Figure 36). The wide spacing of the Zumbra outlet barrier should be maintained to promote recolonization of Sunny Lake by bluegill sunfish in the event of a winterkill.

3.1.5 Summary of recruitment suppression strategies

- To suppress the consistent, ongoing carp recruitment occurring in South Lundsten Lake, winter aeration of South Lundsten should be a management priority. Aerating South Lundsten should not only eliminate the primary source of carp in Auburn-

Lundsten-Turbid, but it will also reduce recruitment inputs to Wassermann Lake and Parley-Mud-Halsted.

- To prevent additional strong year classes of carp in areas that were identified as past productive carp nurseries, wintertime aeration should be considered for Marsh, Mud, Sunny, Turbid, and North Lundsten Lakes. These lakes contained robust populations of bluegill sunfish during the study period, but are vulnerable to climatic extremes that may induce winterkill. Supplemental stocking of bluegill sunfish is likely not necessary because native fishes appear to readily repopulate all locations.
- The feasibility of winter aeration in the aforementioned lakes is unknown and should be determined. It is presently unclear whether aeration can prevent carp recruitment if it is only partially successful because the critical density of bluegill sunfish required to control carp eggs and larvae is unknown.
- In locations where aeration is not feasible or practical, barriers may be deployed in attempts to isolate nurseries from connected waters.
    - Simple physical barriers (e.g. fences or culvert screens) may be appropriate for sites with low discharge, little debris, and well-defined channels. Simple physical barriers are already in place at the outlets of Stone and Zumbra Lakes to block access to Sunny Lake. The barrier at the Zumbra Lake outlet should be enhanced if Sunny Lake is not aerated as it is currently prone to flooding.
    - A simple physical barrier should be considered at the outlet of Crown College Pond to prevent access by carp from Parley Lake.
    - Specialized site-specific barriers would be required to isolate Marsh, Mud, North Lundsten, and/or South Lundsten Lake in the event that aeration is not feasible or practical. Barriers at these locations would need to be designed to accommodate moderate to high discharge rates, considerable amounts of debris, and the need to prevent carp movement in upstream, downstream, or both directions.

- In locations where neither aeration nor isolation is feasible, recruitment prevention may not be possible, but recruitment mitigation may be possible. This may be accomplished through whole-lake manipulations such as water drawdowns or poisonings to eliminate existing juvenile carp before they disperse to connected waters.
    - This type of strategy could be considered to address the 2015 year class in South Lundsten Lake that recruited during the study period. Alternatively, these fish could be removed as adults throughout the Auburn-Lundsten-Turbid management unit in the future (see Section 3.2.2).
- As recruitment suppression management actions are implemented, there will be a need for ongoing monitoring of carp recruitment (see Section 3.3)
- Emergency response contingency plans should be developed to be able to respond quickly to unplanned events such as aeration failure.

3.2 Strategies to reduce the biomass of adult carp

Once recruitment is under control, it is reasonable to remove adult carp with the goal of reducing carp biomass below damaging levels (i.e. 100 kg/ha). Based on multiple electrofishing surveys conducted across the subwatershed over three years, it is clear that there are locations that both warrant and do not warrant adult carp removal to meet a carp biomass target of 100 kg/ha (See Table 2). The only lakes that will likely not require any adult carp removal are Piersons, Stone, and Kelzer's. The total abundance of carp in the Six Mile Creek subwatershed is approximately 130,459 individuals with an average weight of 3.63 kg for a total biomass of 491 kg/ha. This estimate should be considered slightly conservative because it only applies to the 15 study lakes that were accessible with electrofishing boat and thus excludes Marsh, Carl Krey, Church, Big SOB, Crown, and Wassermann Pond West although numbers of resident adult carp in these locations are expected to be minimal. The Six Mile Creek subwatershed would need an overall reduction of 80% of its existing adult carp biomass (roughly 100,000 individuals) in order to meet a target threshold of 100 kg/ha. Specific carp removal goals for each management unit (see Table 9) and possible strategies to achieve them are discussed below (Sections 3.2.1-3.2.4) after a brief overview of carp removal options.

There are multiple different strategies to reduce carp abundance, each with its own strengths, weaknesses, and limitations. These strategies are not mutually-exclusive and can often be employed in combination. Under-ice commercial seining can be a useful strategy to remove large numbers of carp with very little non-target impacts. The feasibility and success of seining depends on ice conditions, substrate conditions at the aggregation site, bathymetry at the aggregation site, as well as the level of commercial fishing expertise and funds available (the relative cost of removing fish increases as their number decreases). It is very likely that multiple systematic seining attempts over many years will be necessary to significantly reduce existing adult biomass in most locations. Where seining is not possible or practical, trapping and removal of spawning migrants may be another viable management strategy. For example, this method has been very successful in removing adult carp from Piersons Lake where roughly 4,000 carp have been removed at the outlet to Marsh Lake (Wenck 2013), bringing the current estimated carp biomass below 100 kg/ha. High rates of carp movement have been observed in Six Mile Creek between Halsted's Bay and Mud Lake, between Mud and Parley Lakes, between West Auburn and North Lundsten Lakes, and between East Auburn and West Auburn. Bidirectional traps in these locations could be very effective in removing large numbers of migrating carp. Another option for removing carp is via baited traps such as box nets baited with corn. This method is useful when natural aggregations do not occur or when carp abundance is low because it can induce carp to aggregate in a desired location by training them to come to a food source (Bajer et al. 2010). This method only works during the summer and fall when carp are actively feeding and requires several days of baiting to induce an aggregation. Average harvest rates depend on net size and food availability, but catch rates of roughly a few hundred individuals can typically be expected. It is also possible to reduce carp numbers by inducing whole lake fish kills through water level drawdown and freeze out or by using poisons such as rotenone. These strategies are often the most economical, but also have the greatest impacts to non-target species. There are also some emerging technologies currently under development such as species-specific fish toxin delivery systems and engineered diseases, but these methods will likely not be available for use in natural systems for decades.

3.2.1 Piersons-Marsh-Wassermann

This management unit presently contains approximately 13,611 carp with a total biomass of 247 kg/ha. To achieve 100 kg/ha of carp, the sub-population would need to be reduced by 60% or 8,107 carp (Table 9). Because the carp biomass in Piersons Lake is already below 100 kg/ha, removal should occur in Wassermann Lake.

Removing 8,107 carp from Wassermann may be possible with a combination of techniques including seining, baited nets, and/or installing a one-way fish barrier at the outlet of Wassermann Lake. A large portion of these fish could be removed in a few successful seine hauls given the tendency of 100% of the radio-tagged carp to tightly aggregate in this lake from December through February. It should however be noted that under-ice seining has failed in Wassermann in the past apparently due to unfavorable substrate conditions in some portions of the lake (muck and debris). Repeated strategic seining attempts would likely be required and debris removal may also be necessary. A baited box net would likely be another viable option to remove carp from Wassermann Lake. It would be incredibly labor-intensive to remove ~8,000 carp using a box net, but it could be an efficient option if only a few thousand carp remained in the lake. The box net would need to be deployed in an area with sandy substrate (e.g. most of the eastern or southern shorelines). Another option to reduce the carp abundance in Wassermann Lake would be to install a one-way barrier at the outlet designed to let carp leave Wassermann, but not return (e.g. electric, velocity, or vertical drop barrier). Based on the annual movement rates of radio-tagged carp that left Wassermann to travel to Auburn or Lundsten Lakes downstream and then later returned, a roughly 22% reduction in carp abundance could be expected if reentry to Wassermann Lake was blocked. This type of barrier would have the added benefit of protecting Wassermann Lake from downstream recruitment inputs, but would also require the adult carp from Wassermann Lake to be removed from the system downstream in the Auburn-Lundsten-Turbid management unit. It is possible that a trap could be installed in conjunction with a one-way barrier to block reentry into Wassermann while also removing fish from the system. One example of an electric barrier paired with a trap that had success blocking and removing invasive sea lamprey is discussed in Johnson et al. (2016). This technology has not yet been tested on common carp.

3.2.2 Auburn-Lundsten-Turbid

This management unit presently contains approximately 20,802 carp with a total biomass of 286 kg/ha. To achieve 100 kg/ha of carp, the sub-population would need to be reduced by 65% or 13,527 carp (Table 9). Carp are distributed relatively evenly across these lakes and therefore all will need adult carp removal to achieve targets. Because carp move readily between East Auburn, West Auburn, North Lundsten, and South Lundsten, they cannot be managed independently. The number of carp in this sub-population will likely continue to increase given the ongoing recruitment observed in South Lundsten, including the 2015 year class. Because this sub-population is comprised of young, fast-growing carp, it likely has not been experiencing damaging levels of carp for long which might explain its relatively good water quality despite its high carp biomass. Removal of roughly 12,000 carp from Auburn and Lundsten Lakes combined along with another 1,500 carp from Turbid would be necessary to achieve targets.

In Auburn-Lundsten, under-ice seining is likely feasible in both East and West Auburns, but not in North or South Lundsten. Tight aggregations of 100% of radio-tagged carp formed in West Auburn from January through February and in East Auburn from December through February. Under-ice seining may not be feasible in Lundsten Lake due to limited access and its shallow depth with dense vegetation growth. In addition to seining, trapping carp that are migrating between West Auburn and North Lundsten could also be effective because an average of 43% of radio-tagged carp from East and West Auburn Lakes passed through this corridor annually (~4,500 carp). The site of the former riprap dam in the Carver Park Reserve might be a good location to trap carp in this corridor because the channel is restricted to a ~4 foot culvert. Baited box nets may be a useful tool to supplement removal in West Auburn Lake, but the substrate in East Auburn or either of the Lundstens is too mucky and not likely amenable to box-netting. Another possible option for reducing carp in Auburn-Lundsten would be to drawdown and freeze out North and South Lundsten if the North Lundsten outlet structure (aka Parley Lake Dam) could be operated to reduce water levels enough to promote winterkill. Whole-lake poisonings of South and North Lundsten could also be conducted (applying toxins in conjunction with a drawdown would reduce dosage requirements). These strategies could eliminate the resident adult population of carp in North and South Lundsten combined (~5,000 carp) as well as any juvenile carp that were present (e.g. the 2015 year class). In attempting whole-lake fish kills, precautions should be taken to avoid creating conditions that instead promote increased carp recruitment. For example, incomplete kills of adult carp or recolonization of adult carp before panfish populations rebound could create ideal carp spawning conditions.

Although Turbid Lake has the highest carp biomass (514 kg/ha) within the Auburn-Lundsten-Turbid management unit, it only contains 2,300 carp. A removal target of 1,500 carp is appropriate and could be achieved through under-ice seining, open water seining (a seine net could cover the vast majority of the lake due to its small size), or via baited box-netting along the sandy Eastern shoreline. Permission from a local landowner would be required for access.

3.2.3 Parley-Mud-Halsteds

This management unit presently contains approximately 85,759 carp with a total biomass of 981 kg/ha. To achieve 100 kg/ha of carp, abundance would need to be reduced by 90% or 77,014 individuals (Table 9). The biomass of carp is incredibly high in all three lakes and movement rates are also very high between all lakes. This management unit is complicated by its connection to the rest of Lake Minnetonka (an average of 22% of the carp radio-tagged in Parley, Mud, or Halsted's Bay moved to other bays of Lake Minnetonka annually) and presently cannot be managed independently from Lake Minnetonka. Because managing carp in Parley, Mud, and all of Lake Minnetonka combined is likely not realistic, these locations could be divided up into smaller management units using barriers to isolate portions of the system.

Parley and Mud Lakes could be isolated from Lake Minnetonka by installing a barrier between Mud Lake and Halsted's Bay. Carp in Parley and Mud Lakes are vulnerable to removal via under-ice seining because all of the radio-tagged carp from both lakes formed a single tight aggregation in Parley Lake during both years of the study. Additionally, there is a history of successful seining in Parley Lake as evidenced by 6,206 of 21,315 carp (29% of the total carp population in Parley-Mud) being captured in one seine haul in March of 2015 and tens of thousands of pounds of carp being captured and removed in the early 2000's (MN DNR Carver County commercial fishing records). It should be noted that most of the carp captured in the

2015 seine haul escaped back into Parley Lake as they were awaiting transport because the holding pens were vandalized. In addition to seining, carp could be removed from Parley and Mud Lakes by trapping spawning migrants at one or more locations. Carp could be removed in traps between Parley and Mud Lake, especially in late November/early December as carp leave Mud Lake to overwinter in Parley or in spring as carp return to Mud Lake after ice-out. An average of 81% of radio-tagged carp from Parley or Mud Lakes moved through this corridor annually. Additionally, carp from Parley and Mud could be removed between Mud Lake and Halsted's Bay if traps were installed in conjunction with the barrier recommended at this location. This barrier/trap system could be designed to remove carp moving in both directions which would reduce the numbers of carp in Halsted's Bay as well. An average of 47% of radio-tagged carp from Parley, Mud, or Halsted's Bay moved through this corridor annually during the study period.

If a barrier was installed between Mud Lake and Halsted's Bay as discussed above, Halsted's Bay could be managed with the rest of Lake Minnetonka. Given the high rates of carp movement between Halsted's Bay and other bays, it would need to be isolated from the rest of Lake Minnetonka to be managed for carp independently. Isolating Halsted's Bay from the other bays would be challenging given the need for a navigable channel between Halsted's and Priest's Bays. The only safe, available fish deterrence technology that would not impede boat traffic would be a Bio-Acoustic Fish Fence system (BAFF; http://www.fish-guide.com/baff-system.html). A BAFF system optimized to deter carp is currently being designed and tested by the Sorensen Lab group at the UMN. This type of system would likely work best installed at an angle to deflect carp into traps versus as a cross-stream barrier to impede movement. If Halsted's Bay could be successfully isolated from the rest of Lake Minnetonka, carp could be removed via seining, stream traps, or baited box nets although box nets would be impractical until carp abundance was drastically reduced.

3.2.4 Carver Park Reserve Lakes

This management unit presently contains approximately 10,247 carp with a total biomass of 180 kg/ha. To achieve 100 kg/ha of carp, abundance would need to be reduced by 45% (Table 9). Because the lakes in this management unit (i.e. Steiger, Zumbra, Sunny, and

Stone) each contain their own sub-population of carp, adult removal strategies can be implemented independently. In Stone Lake, carp biomass is already below the target threshold and immigration of new carp is prevented by a barrier at the outlet, so no carp removal is necessary. Modest amounts of carp removal would be required to meet the 100 kg/ha target in Steiger, Zumbra, and Sunny Lakes (approximately 1000, 3000, and 400 individuals, respectively).

In Steiger Lake, because the radio-tagged carp never formed winter aggregations during the study period, under-ice seining is probably not feasible. A baited box net could likely be used to remove ~1,000 carp in just a few good hauls. Preliminary baiting experiments conducted in Steiger Lake by Drs. Ratna Ghosal and Jessica Eichmiller of the UMN as part of an unrelated study demonstrated that 23 of 25 (92%) radio-tagged common carp aggregated by a corn baiting station within 7 days (Ghosal, Eichmiller, et al., in prep). In Zumbra Lake, 3,000 carp could be removed via under-ice seining or baited box nets. The radio-tagged carp in Zumbra Lake formed tight winter aggregations in the Northwest bay from January through February in both years of the study. In Sunny Lake, adult carp removal would be difficult due to limited access, mucky substrate, and dense coontail growth.

3.2.5 Summary of adult removal strategies

- To meet a target carp biomass threshold of 100 kg/ha, removal of adult carp is necessary in all locations throughout the subwatershed except Piersons Lake, Stone Lake, and Kelzer's Pond.
- Removal methods are not mutually-exclusive; implementing a combination of methods over several years or possibly decades will likely be required to achieve biomass targets system-wide.
- Whenever possible and practical, the most efficient way to remove carp without severely impacting non-target species is to exploit naturally occurring aggregations of carp such as winter aggregations or spawning migrations.
    - Targeting winter aggregations via under-ice commercial seining may be feasible in Wassermann, East Auburn, West Auburn, Turbid, Zumbra, Parley, and Halsted's Bay.

    - Targeting migrating carp using stream traps may be feasible in the corridors between Wassermann and East Auburn, West Auburn and North Lundsten, Parley and Mud, Mud and Halsted's Bay, and Halsted's Bay and Preist's Bay.
- If aggregations do not occur naturally or if individuals are in low abundance, it may be possible to induce targetable aggregations via baiting.
    - Removing carp via baited box nets may be feasible in Wassermann, West Auburn, Turbid, Steiger, Zumbra, Parley, and Halsted's Bay.
- When physical removal of adults is not possible or practical, whole-lake manipulations to eliminate fish such as water drawdowns or poisonings could be considered.

3.3 Monitoring recommendations

When implementing management strategies using an adaptive management approach, ongoing monitoring is necessary to measure progress and evaluate success. In terms of carp management in the Six Mile Creek subwatershed, it will be necessary to monitor all putative carp nurseries (i.e. Marsh, South Lundsten, North Lundsten, Turbid, Sunny, Mud, and Crown) for successful recruitment and to monitor carp biomass levels as adults are removed.

To monitor carp recruitment, winter dissolved oxygen in all putative carp nurseries should be measured monthly every year and visual observations for fish carcasses should be conducted each spring immediately following ice-out. Monitoring dissolved oxygen content is especially important in the event that aeration systems are installed. If any signs of winterkill are observed (i.e. dissolved oxygen <1.5 mg/L, fish carcasses present), standardized trap-net surveys should be carried out in the spring to assess bluegill sunfish survival and in the fall to assess YOY carp production and bluegill sunfish recolonization. In the event that putative nurseries are isolated with barriers, regular visual observations at barrier sites should be conducted throughout the open water season and after all rainfall events. In the event that a barrier is breached, fall trap-net surveys should be conducted in all relevant nurseries to assess YOY carp production.

To monitor adult carp biomass, boat electrofishing surveys should be conducted following the protocols established in Bajer and Sorensen (2012). Adult carp biomass should be monitored as needed in the event of successful recruitment causing population growth or to verify population decline as a result of management actions (e.g. winter seining, stream trapping, box netting, poisoning). Additionally, where adult carp removal is successful, MCWD should be prepared to monitor the response of aquatic plants and nutrients.

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Tables & Figures

Table 1. Overview of study design -- Attributes of study lakes in the Six Mile Creek Subwatershed and available sampling data collected by the University of Minnesota. X's denote sampling that has occurred each year and asterisks (*) denote sampling conducted by MCWD staff.

Location	Surface Area (ac)	Max Depth (ft)	Electrofishing Survey			Trapnet Survey			Aging Studies			Radio Telmetry (# of Tags)	Winter Dissolved Oxygen*
			2014	2015	2016	2014	2015	2016	2014	2015	2016		
Halsted's Bay	552	30	X	X	X		X	X	X			15	
Mud	144	6	X	X	X	X	X	X	X			15	X
Parley	257	19	X	X	X	X	X	X	X			15	
Crown College	6	3				X	X	X					
Big SOB	7.5	25			X	X	X	X					X
Yetzer's Pond	12	2				X							
N. Lundsten	114	7	X	X	X	X	X	X		X		5	X
S. Lundsten	77	9	X	X	X	X	X	X				5	X
Turbid	40	35	X	X	X	X	X	X			X	5	
Lake #2	36	N/A				X							
W. Auburn	145	80	X	X	X	X	X	X		X		7	
E. Auburn	148	40	X	X	X	X	X	X		X		8	
Shady Pond	0.5	>5				X	X	X					X
Sunny	48	N/A	X	X	X	X	X	X				3	X
Zumbra	193	50	X	X	X	X	X	X			X	7	
Stone	99	30	X	X	X	X	X	X					
Steiger	166	37	X	X	X	X	X	X			X	10	
Kelzer's	21	34	X	X	X	X	X	X					X
Church	16	54					X	X					X
Carl Krey	50	16				X	X	X					X
Wassermann	164	41	X	X	X	X	X	X		X		15	
N. Wassermann Pond	6	27											X
S. Wassermann Pond	13.3	27											X
W. Wassermann Pond	6.5	18					X	X					X
Marsh	143	5				X	X	X					X
Piersons	297	40	X	X	X	X	X	X		X		10	

Table 2. Attributes of 15 assessable study lakes, mean catch rates of common carp from whole-lake boat electrofishing surveys (CPUE), and resulting estimates of carp abundance and biomass in the Six Mile Creek Subwatershed. Electrofishing surveys were conducted between June and October and are shown for 2014 alone (top) and 2014, 2015, and 2016 combined (bottom).

2014

Lake Name	Area (ha)	# of Surveys	CPUE (SE) (# / hr)	Abundance, mean (95%CI)	Average Weight (kg)	Biomass (kg/ha) (95%CI)
Halsted's Bay	223.4	4	61.3 (4.6)	65,225 (55,803-74,646)	3.74	1,093 (935-1,251)
Mud	37.6	6	26.3 (5.2)	4,782 (2,969-6,595	3.89	495 (307-683)
Parley	104.4	6	30.4 (1.6)	15,265 (13,709-16,820)	3.51	513(461-566)
North Lundsten	43.7	2	21.3 (9.2)	4,515 (795-8,234)	1.98	204 (36-372)
South Lundsten	29.9	1	9.7 (NA)	1,268 (NA)	2.29	97 (NA)
West Auburn	53.8	3	31.3 (3.1)	8,097(6,552-9,641)	1.92	290 (234-345)
East Auburn	46.9	3	36.6 (12.6)	8,237 (2,761-13,712)	1.84	323 (108-538)
Turbid	16.2	2	29.4 (2.1)	2,290 (1,983-2,597)	3.09	436 (378-495)
Wassermann	66.0	4	38.4 (5.2)	12,141 (8,956-15,326)	3.01	555 (409-700)
Piersons	120.1	5	3.6 (0.7)	2,400 (1,661-3,140)	3.33	66 (46-87)
Steiger	67.1	4	9.5 (3.3)	3,214 (1,175-5,254)	3.24	155 (57-254)
Sunny	19.4	1	2.8 (NA)	314 (NA)	2.61	42 (NA)
Zumbra	89.4	4	8.7 (1.8)	3,931 (2,472-5,390)	2.46	108 (68-148)
Stone	39.3	1	4.4 (NA)	924 (NA)	4.40	104 (NA)
Kelzer's	8.0	1	2.5 (NA)	118 (NA)	4.77	70 (NA)
All Six Mile	**965.2**	**47**		**132,721**	**3.01**	**414**

2014-2016 Combined

Lake Name	Area (ha)	# of Surveys	CPUE (SE) (# / hr)	Abundance, mean (95%CI)	Average Weight (kg)	Biomass (kg/ha) (95%CI)
Halsted's Bay	223.4	9	60.6 (3.2)	64,441 (57,769-71,113)	4.38	1,264 (1,133- 1,394)
Mud	37.6	10	28.4 (3.3)	5,148 (4,019-6,277)	4.12	564 (440-687)
Parley	104.4	10	32.2 (1.2)	16,167 (14,987-17,348)	4.02	623 (577-668)
North Lundsten	43.7	7	12.9 (3.1)	2,793 (1,557-4,029)	2.56	164 (91-236)
South Lundsten	29.9	4	16.5 (3.8)	2,414 (1,354-3,474)	2.54	204 (115-295)
West Auburn	53.8	9	27.8 (1.9)	7,201 (6,267-8,136)	2.33	311 (271-352)
East Auburn	46.9	10	27.0 (3.9)	6,121 (4,421-7,820)	1.94	253 (183-323)
Turbid	16.2	8	29.2 (1.5)	2,273 (2,051-2,496)	3.66	514 (464-564)
Wassermann	66.0	10	31.6 (3.1)	10,031 (8,149-11,912)	3.44	523 (425-621)
Piersons	120.1	11	5.7 (0.8)	3,580 (2,644-4,516)	3.32	99 (73-125)
Steiger	67.1	10	8.5 (1.6)	2,886 (1,915-3,857)	3.62	156 (103-208)
Sunny	19.4	4	10.1 (3.3)	981 (398-1,565)	3.26	165 (67-263)
Zumbra	89.4	10	13.5 (1.6)	5,953 (4,630-7,276)	2.99	199 (155-243)
Stone	39.3	5	1.7 (0.9)	427 (108-746)	4.77	52 (13-91)
Kelzer's	8.0	5	0.5 (0.4)	43 (11-74)	4.77	26 (7-45)
All Six Mile	**965.2**	**122**		**130,459**	**3.63**	**491**

Table 3. Summary of radio-tagged common carp movement patterns across the Six Mile Creek subwatershed over the 2 year study period. Year 1 is from November 2014 to October 2015 and Year 2 is from November 2015 to October 2016. Movement rates (% living radio-tagged carp that moved from where they were originally tagged [origin] to any other location [destination]) are shown for each year, each movement path, and both directions. The average annual movement rates are reported here and are shown for each movement path on a map in Figure 30.

Movement Path: origin to destination **↔: moved there and back** **→: Move there & stayed or died**	**% radio-tagged carp that moved**			**Timing**
	Year 1	**Year 2**	**Annual Avg.**	
Wassermann ↔ East Auburn	7%	27%	17%	left May-June, returned July-Sept
Wassermann ↔ South Lundsten	0%	9%	5%	left June, was most of the way back in Oct 2016
Auburns/Lundstens ↔ Wassermann	0%	0%	0%	
East Auburn ↔ West Auburn	63%	88%	75%	Throughout open water season
West Auburn ↔ East Auburn	57%	86%	71%	Throughout open water season
Auburns ↔ Lundstens	27%	33%	30%	left May-June, returned June-July
Auburns → Lundstens	0%	27%	13%	left May-June, died in June-Aug
Lundstens ↔ Auburns	0%	0%	0%	
North Lundsten ↔ South Lundsten	25%	67%	46%	left May, returned June
South Lundsten ↔ North Lundsten	20%	0%	10%	left Nov, returned May
Parley ↔ Mud	73%	56%	64%	Throughout open water season
Parley → Mud	13%	11%	12%	Throughout open water season
Mud ↔ Parley	100%	62%	81%	Left Dec, returned April-June
Mud → Parley	0%	8%	4%	Left Nov, stayed in Parley
Parley/Mud ↔ Halsted	13%	32%	23%	Left May-June, returned July-Oct
Parley/Mud → Halsted	23%	18%	21%	Left June-August
Hasted↔ Parley/Mud	33%	50%	42%	Left May-June, returned July-Oct
Hasted → Parley/Mud	13%	0%	7%	Left May-June
Parley/Mud/Halsted's ↔ Greater Minnetonka	11%	21%	16%	Year-round
Parley/Mud/Halsted's → Greater Minnetonka	9%	3%	6%	Year-round

Table 4. Summary of winter aggregation occurrence and timing in the Six Mile Creek study lakes from November 2014 through March 2016. An aggregation is defined as when at least 50% of radio-tagged carp were confined to an area of less than 10 hectares. Note that radio-tags were implanted in four additional lakes in spring of 2015.

Location	Year	November	December	January	February	March
Halsted's Bay	2014-15				x	
	2015-16		x		x	
Mud	2014-15					
	2015-16					
Parley	2014-15		x	x	x	x
	2015-16			x	x	x
N. Lundsten	2014-15	NA	NA	NA	NA	NA
	2015-16		x	x	x	x
S. Lundsten	2014-15	NA	NA	NA	NA	NA
	2015-16	x	x	x	x	x
W. Auburn	2014-15			x	x	
	2015-16			x	x	
E. Auburn	2014-15	x	x	x	x	x
	2015-16		x	x	x	
Zumbra	2014-15			x	x	x
	2015-16			x	x	
Sunny	2014-15	NA	NA	NA	NA	NA
	2015-16		x	x	x	x
Steiger	2014-15					
	2015-16					
Wassermann	2014-15		x	x	x	
	2015-16		x	x	x	x
Turbid	2014-15	NA	NA	NA	NA	NA
	2015-16		x	x	x	x
Piersons	2014-15	x	x	x	x	x
	2015-16				x	x

Table 5. Catch rates of young-of-year (YOY) and age-1 carp from standardized trap-net surveys conducted in the Six Mile Creek subwatershed. Asterisks (*) denote catch rates from gill net surveys. NS denotes locations that were not sampled that year.

Location	YOY carp catch rate (#/net)			Age-1 carp catch rate (#/net)		
	2014	2015	2016	2014	2015	2016
Halsted's Bay	NS	0.0	0.0	NS	0.0	0.0
Mud	0.2	0.0	0.0	0.0	0.0	0.0
Parley	0.0	0.0	0.0	0.0	0.0	0.0
Crown College	1.0	332.3	0.0	0.0	0.0	2.3
Big SOB	19.8	0.0	0.0	0.0	1.8	0.0
Yetzer's Pond	0.0	NS	NS	0.0	NS	NS
N. Lundsten	0.0	3.2	0.0	0.0	0.0	0.0
S. Lundsten	0.0	311.2	0.0	0.0	0.0	0.4
Turbid	0.0	0.0	0.0	0.0	0.0	0.0
Lake #2	0.0	NS	NS	0.0	NS	NS
W. Auburn	0.0	0.0	0.0	0.0	0.0	0.0
E. Auburn	0.0	0.0	0.0	0.0	0.0	0.0
Shady Pond	0.0	0.0	0.0	0.7	0.0	0.0
Sunny	0.0	0.0	0.0	0.0	0.0	0.0
Zumbra	0.0	0.0	0.0	0.0	0.0	0.0
Stone	0.0	0.0	0.0	0.0	0.0	0.0
Steiger	0.0	0.0	0.0	0.0	0.0	0.0
Kelzer's	0.0	0.0	0.0	0.0	0.0	0.0
Church	NS	0.0	0.0	NS	0.0	0.0
Carl Krey	0.0	0.0	0.0	2.0*	0.0	0.0
Wassermann	0.0	0.2	0.0	0.0	0.0	0.0
Wassermann Pond W.	NS	0.0	0.0	NS	0.3	0.0
Marsh	0.0	0.0	0.0	0.0	0.0	0.0
Piersons	0.0	0.0	0.0	0.0	0.0	0.0

Table 6. Catch rates (#/net) of bluegill sunfish from standardized annual fall trap-net surveys conducted in the Six Mile Creek subwatershed from 2014 to 2016. Asterisks (*) denote catch rates from gill net surveys. NS denotes locations that were not sampled that year.

Location	Bluegill Catch Rate (# /trapnet)		
	2014	2015	2016
Halsted's Bay	NS	122.0	94.2
Mud	84.0	32.8	132.8
Parley	19.2	38.4	25.0
Crown College	0.6	1.3	22.0
Big SOB	32.6	52.0	107.6
Yetzer's Pond	0.0	NS	NS
N. Lundsten	38.0	113.2	109.0
S. Lundsten	17.4	34.2	68.8
Turbid	32.8	81.4	47.6
Lake #2	0.0	NS	NS
W. Auburn	29.4	203.0	66.2
E. Auburn	55.2	74.2	122.8
Shady Pond	6.9	0.0	0.0
Sunny	38.0	45.6	59.6
Zumbra	12.7	128.6	55.8
Stone	0.0	0.0	0.0
Steiger	20.6	90.5	98.2
Kelzer's	23.2	75.7	103.3
Church	NS	0.0	0.0
Carl Krey	15.0*	98.2	101.3
Wassermann	12.5	96.0	67.5
Wassermann Pond W.	NS	0.0	0.2
Marsh	131.4	113.5	108.6
Piersons	24.0	102.0	54.8

Table 7. Dissolved oxygen maxima (mg/L) measured by Minnehaha Creek Watershed District staff in select study sites in the Six Mile Creek subwatershed. Measurements were taken in late February just beneath the ice surface at approximately the deepest point in the waterbody. “NS” denotes locations that were not sampled that year; “Frozen” denotes locations that were frozen solid to the bottom.

Location	Dissolved oxygen (mg/L)	
	2015	**2016**
Marsh	12.9	9.4
Turbid	5.7	NS
Carl Krey	9.9	8.9
Crown College	Frozen	1.9
Mud	6.1	9.4
South Lundsten	1.5	10.0
North Lundsten	1.6	NS
Sunny	0.9	NS
Shady	0.8	NS
Wassermann Pond West	1.3	3.8
Kelzer's	7.2	NS
Church	1.6	NS

Table 8. An overview of possible barrier options to deter the movements of fishes. The upper panel is a summary of non-physical barriers from table 1 in Noatch & Suski (2012). The lower panel is a summary of physical barriers generated for this report.

Table 1. Summary of different non-physical barriers that could be implemented to deter the movements of fishes. Also listed are deployment conditions where barriers are likely to be successful, advantages and disadvantages of different barrier types, and representative citation showing the barrier in use.

Barrier/Deterrent	Deployment conditions	Advantages	Disadvantages	Relevant citations
Electricity	Site with adequate power source; appropriate water conductivity	Flexible deployment, very effective against recruited fish	May not affect smaller fish	Bullen and Carlson 2003; Savino et al. 2001; Clarkson 2004
Strobe lights	Consistent low water turbidity	Less infrastructure, potentially lower cost	Lower effectiveness, especially in daytime	Johnson et al. 2005*a*; Hamel et al. 2008
Sound (AFD)	Site with adequate acoustic characteristics	Effective across a wide range of environmental conditions	Variable effectiveness; frequencies must be chosen per species	Maes et al. 2004; Sonny et al. 2006
Bubble curtains	Low water turbidity, relatively shallow water	Few as a stand-alone deterrent; may enhance other deterrents	Low effectiveness, may not work under all conditions	Patrick et al. 1985; Stewart 1981
Water velocity	Target species that is a weak swimmer; narrow channel with adequate water flow	Selectively excludes nuisance species	Major modification to channel; few sites meet criteria	Hoover et al. 2003; Katopodis et al. 1994
Hypoxia and hypercapnia	Relatively shallow water, space needed for bulk gas storage	Potential to exclude virtually all fish	Large investment of research time and capital	
Pheromones	Confined spaces and (or) short term application	Potential to selectively exclude particular fish	Time and effort to procure pheromones in bulk quantity	Little and Calfee 2006; Johnson et al. 2005*b*
Chlorine	Highly constricted deployment space	Potential to exclude virtually all fish	Deleterious to almost all aquatic fauna; negative public perception	Giattina et al. 1981; Wilde et al. 1983
Electromagnetism	Constricted areas, choke points	Cost effective, low environmental impact	May not work on all teleost fishes	Northcutt et al. 1994; Gibbs and Northcutt 2004

Barrier	Deployment conditions	Advantages	Disadvantages
Fence or screen	Low discharge & minimal debris	Can be highly effective, cost effective	Requires regular cleaning, not species-specific
Vertical drop/dam	Sufficient vertical relief	Can be highly effective	Only deters upstream movement, may require major modification to channel, not species-specific

Table 9. Common carp abundance and biomass for all Six Mile Creek Lakes combined and broken down by management unit. Also included is the number and percent of carp required to be removed in order to meet the 100 kg/ha biomass threshold.

Management Unit	Surface area (ha)	Total carp abundance	Mean carp weight (kg)	Mean carp biomass (kg/ha)	# Carp removal required to achieve 100 kg/ha	% carp removal required to achieve 100 kg/ha
All Six Mile Creek Study Lakes	965.2	130,459	3.63	491	103,869	80%
Piersons-Wassermann	186.0	13,611	3.38	247	8,107	60%
Auburn-Lundsten-Turbid	190.6	20,802	2.62	286	13,527	65%
Parley-Mud-Halsted	365.4	85,759	4.18	981	77,014	90%
Carver Park Reserve Lakes	215.2	10,247	3.79	180	4,568	45%

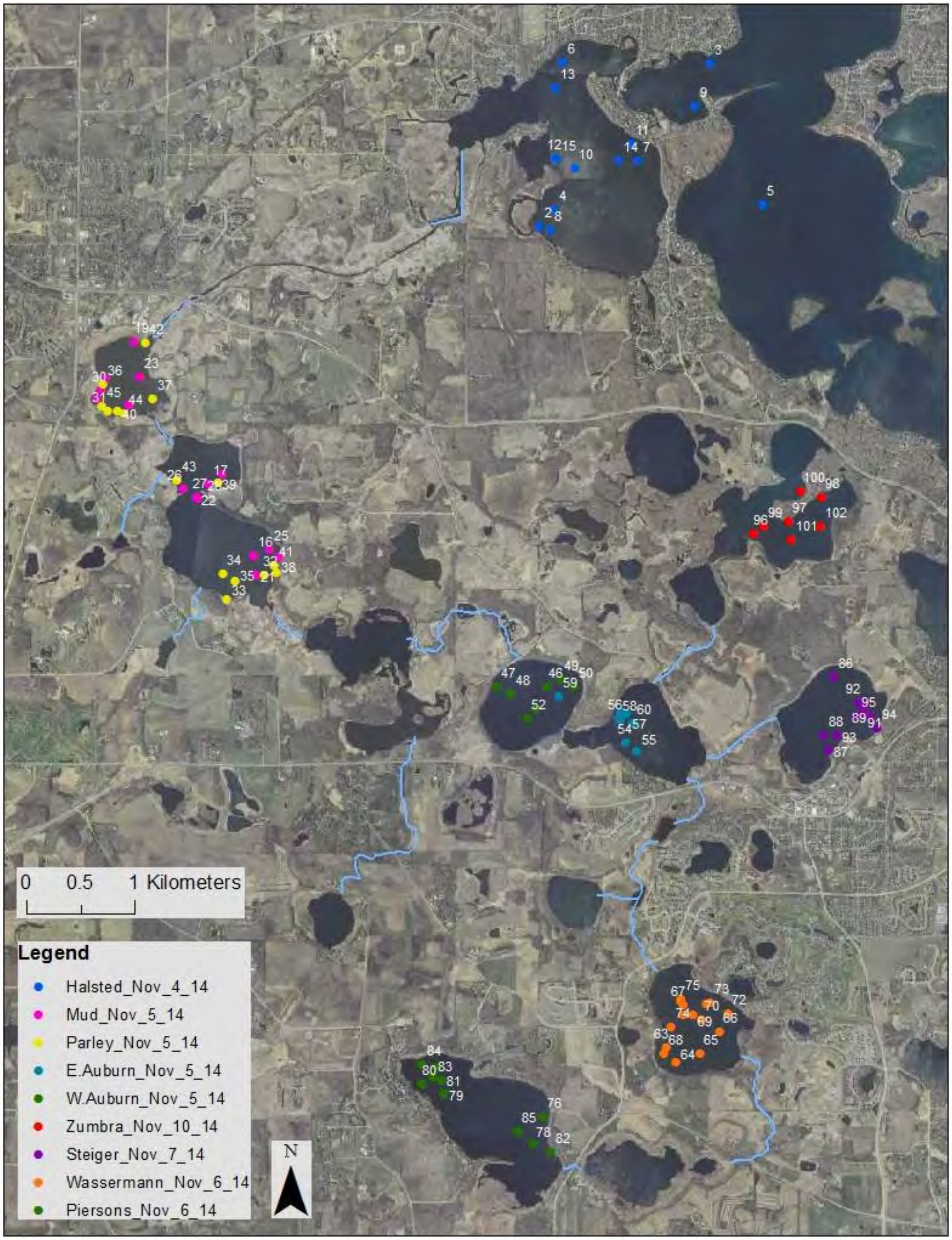


Figure 2. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in November 2014. Individuals are labeled with unique identification numbers (white).

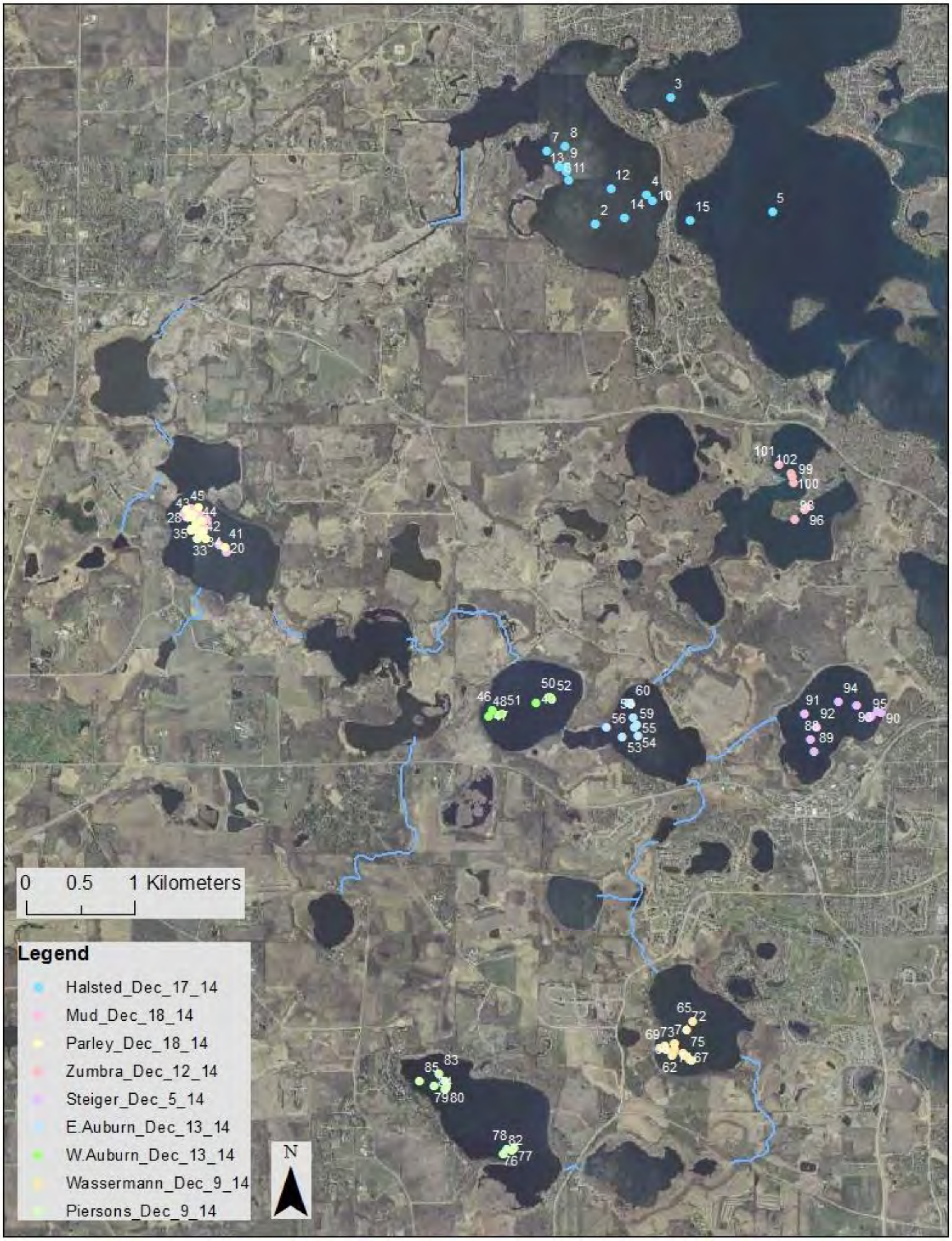


Figure 3. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in December 2014. Individuals are labeled with unique identification numbers (white).

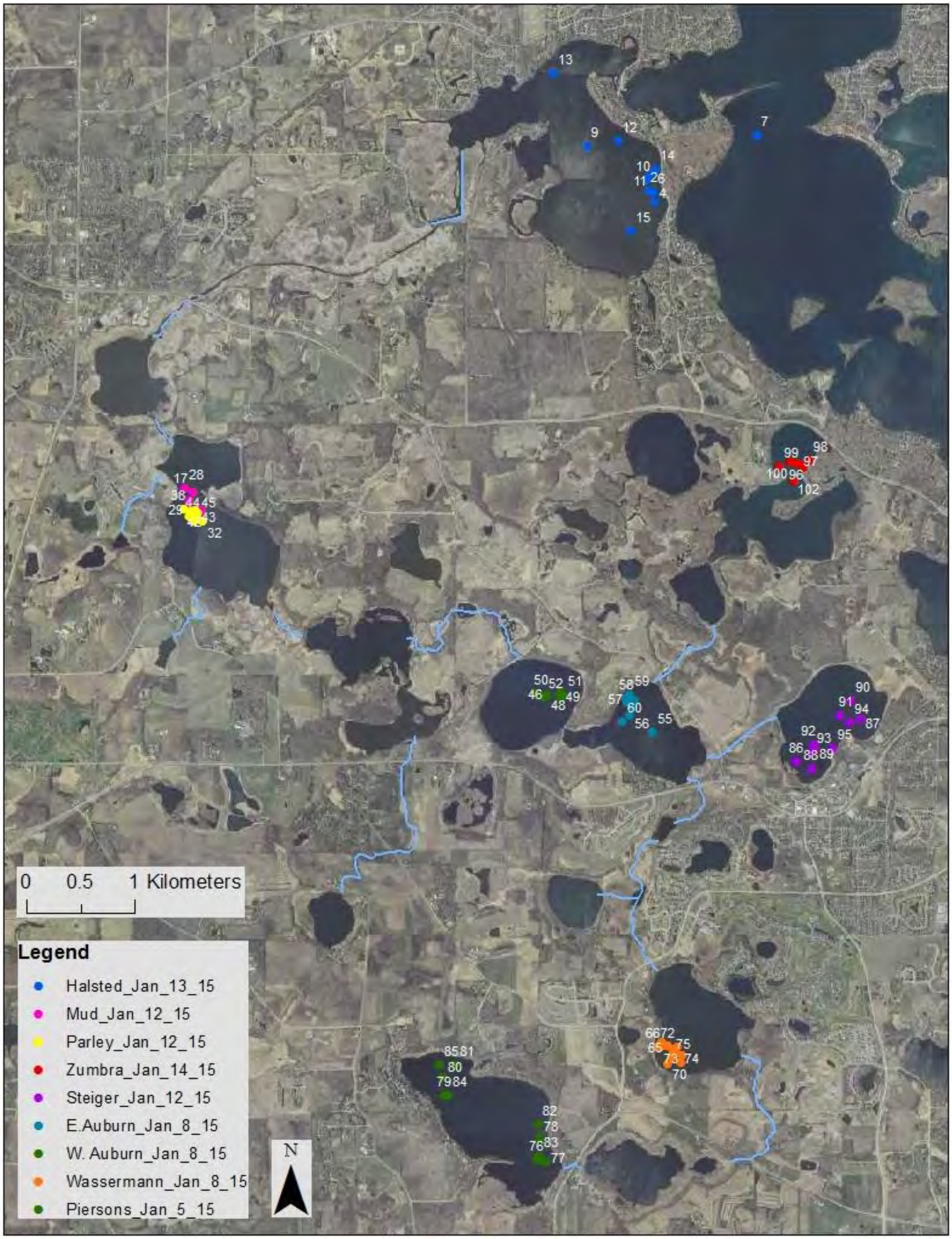


Figure 4. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in January 2015. Individuals are labeled with unique identification numbers (white).

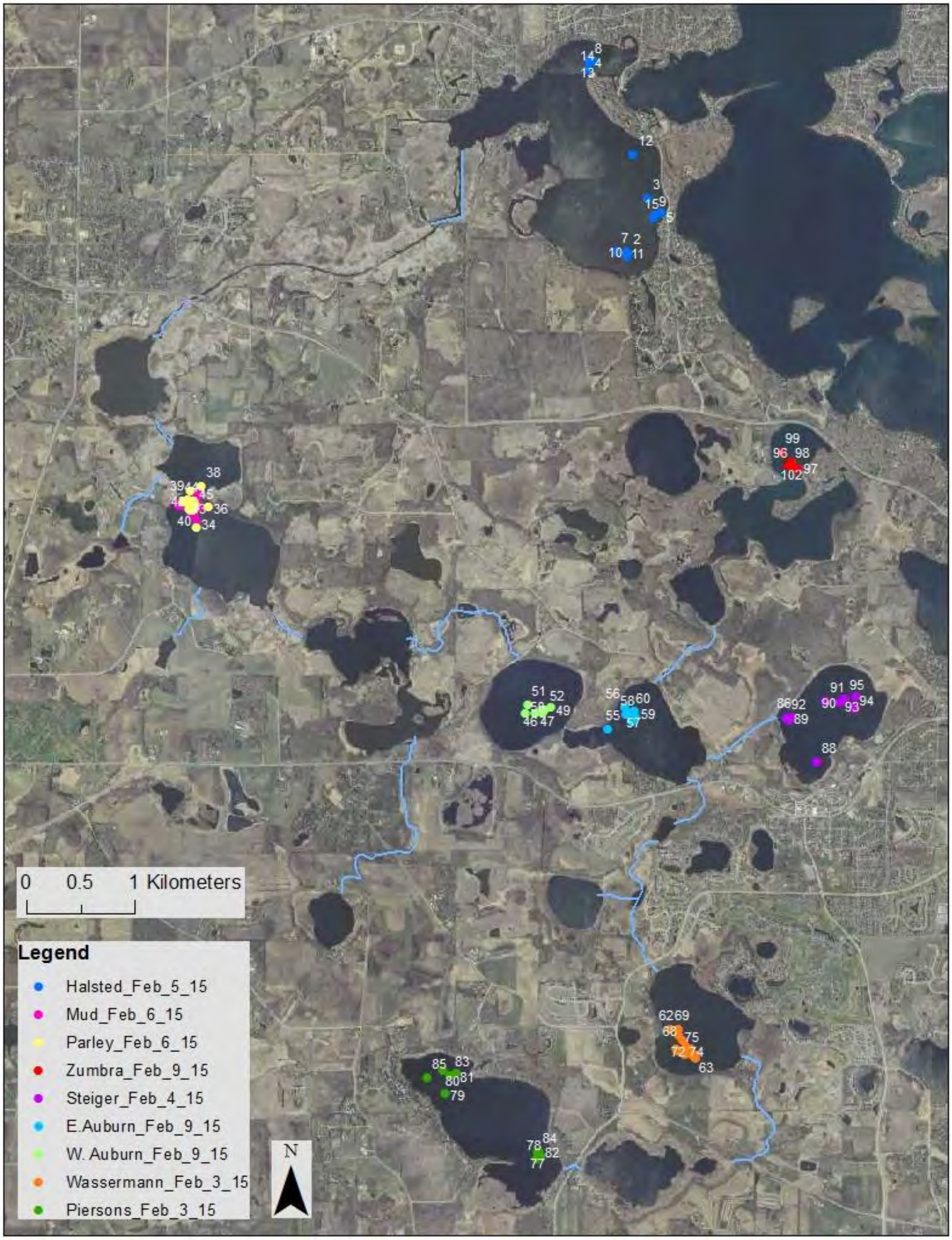


Figure 5. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in February 2015. Individuals are labeled with unique identification numbers (white).

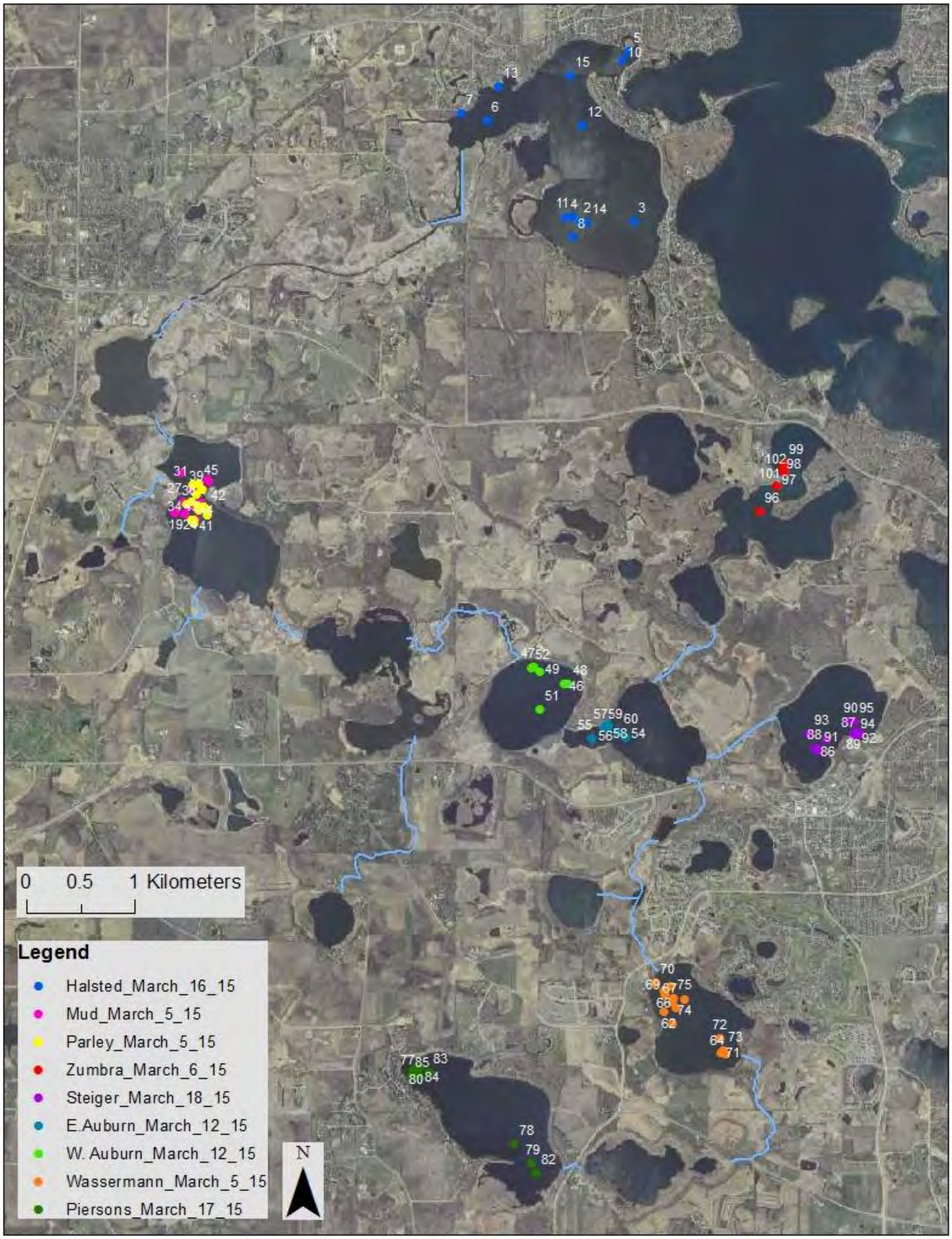
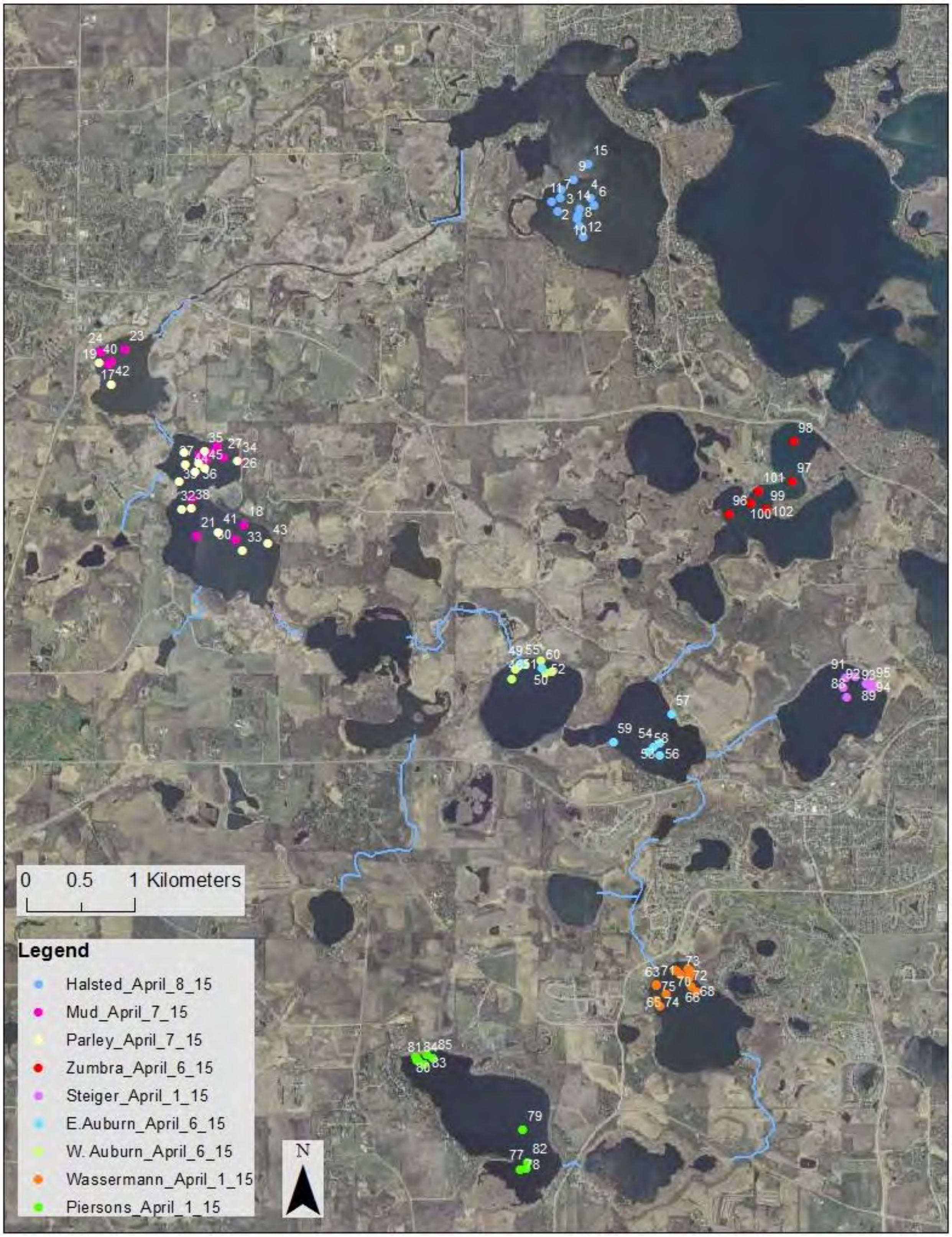


Figure 6. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in March 2015. Individuals are labeled with unique identification numbers (white).



0 0.5 1 Kilometers
Legend
Halsted_April_8_15
Mud_April_7_15
Parley_April_7_15
Zumbra_April_6_15
Steiger_April_1_15
E.Auburn_April_6_15
W. Auburn_April_6_15
Wassermann_April_1_15
Piersons_April_1_15
N

Figure 7. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in early April 2015. Individuals are labeled with unique identification numbers (white).

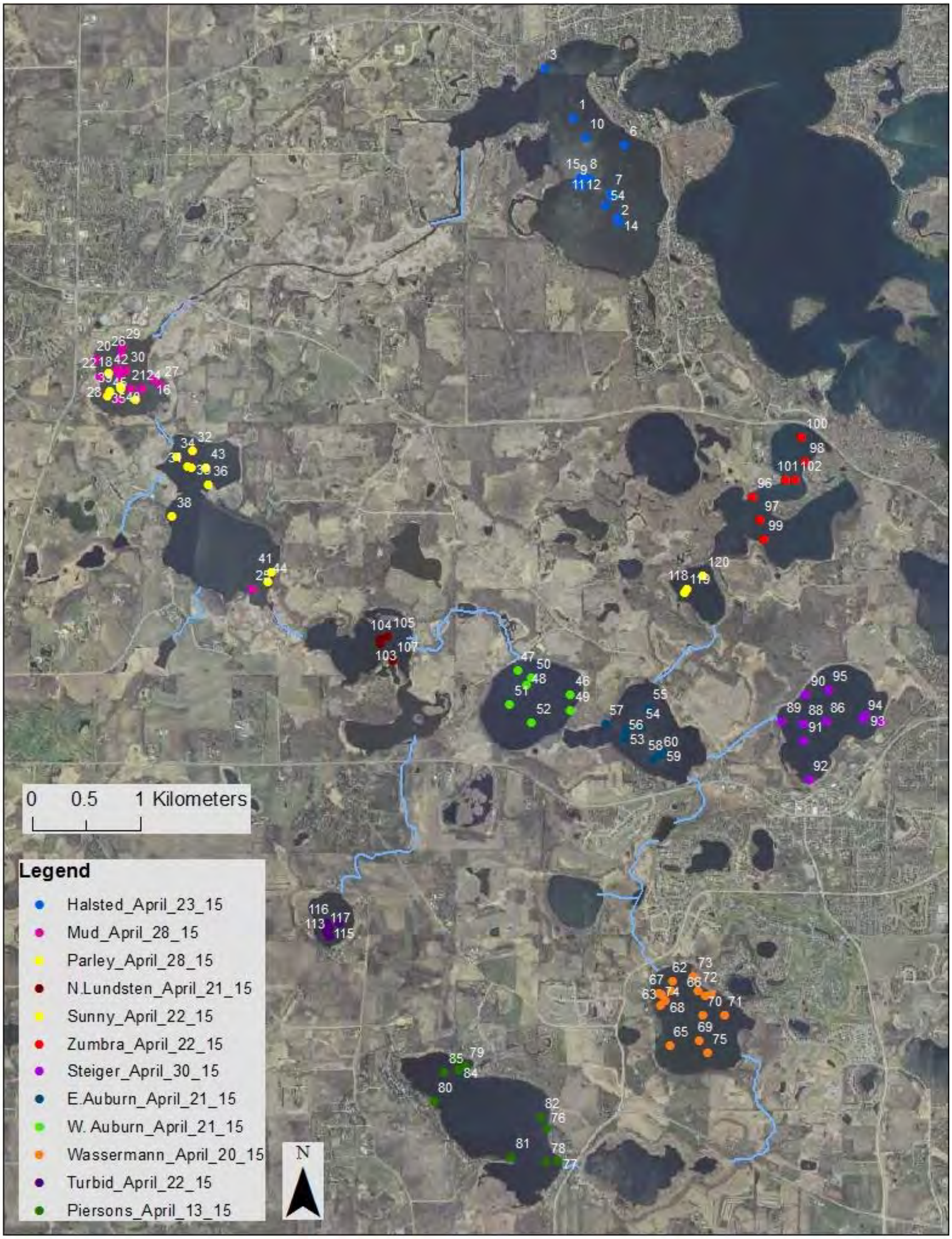
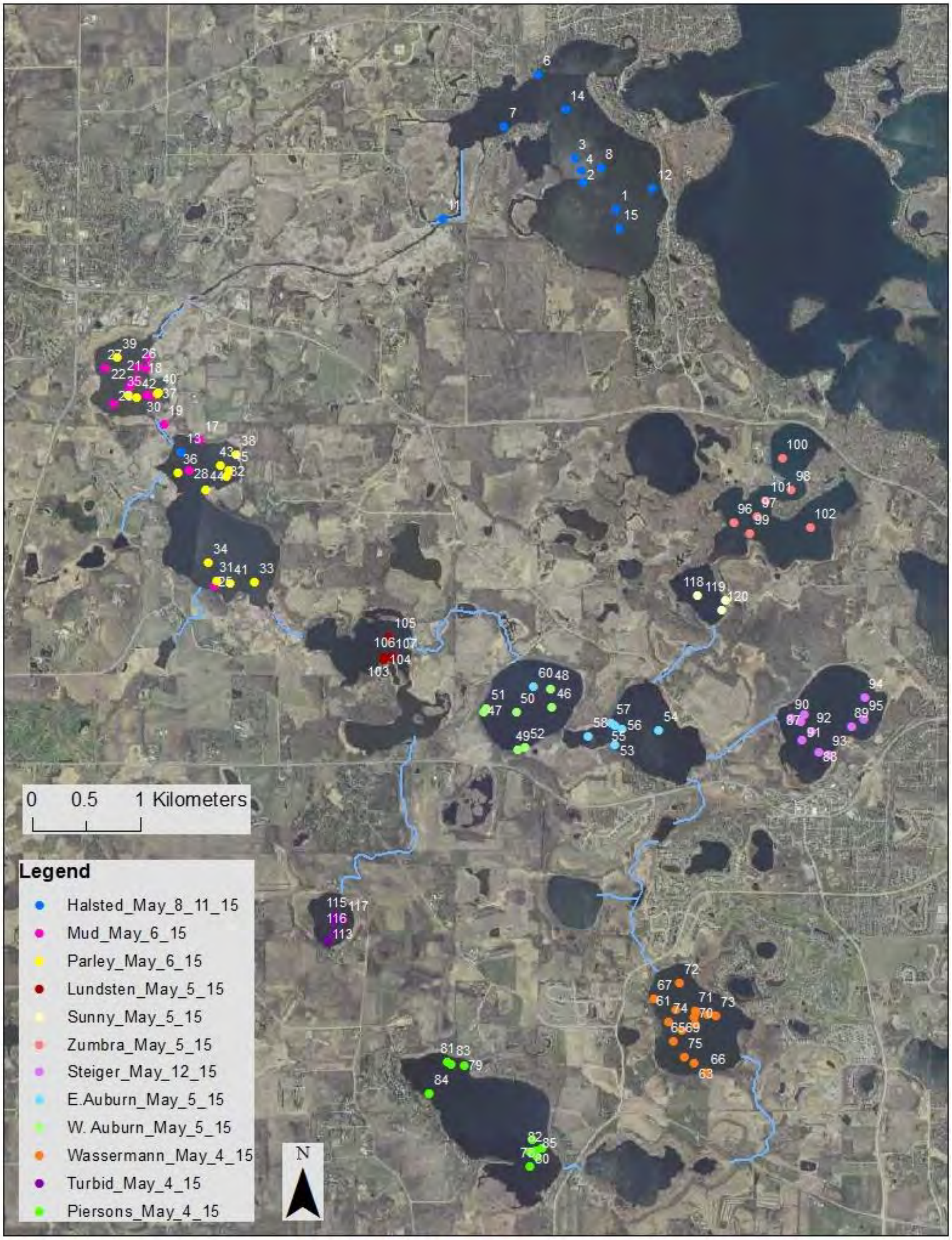

0 0.5 1 Kilometers
Legend
Halsted_April_23_15
Mud_April_28_15
Parley_April_28_15
N.Lundsten_April_21_15
Sunny_April_22_15
Zumbra_April_22_15
Steiger_April_30_15
E.Auburn_April_21_15
W. Auburn_April_21_15
Wassermann_April_20_15
Turbid_April_22_15
Piersons_April_13_15
N

Figure 8. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in late April 2015. Individuals are labeled with unique identification numbers (white).



0 0.5 1 Kilometers
Legend
Halsted_May_8_11_15
Mud_May_6_15
Parley_May_6_15
Lundsten_May_5_15
Sunny_May_5_15
Zumbra_May_5_15
Steiger_May_12_15
E.Auburn_May_5_15
W. Auburn_May_5_15
Wassermann_May_4_15
Turbid_May_4_15
Piersons_May_4_15
N

Figure 9. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in early May 2015. Individuals are labeled with unique identification numbers (white).

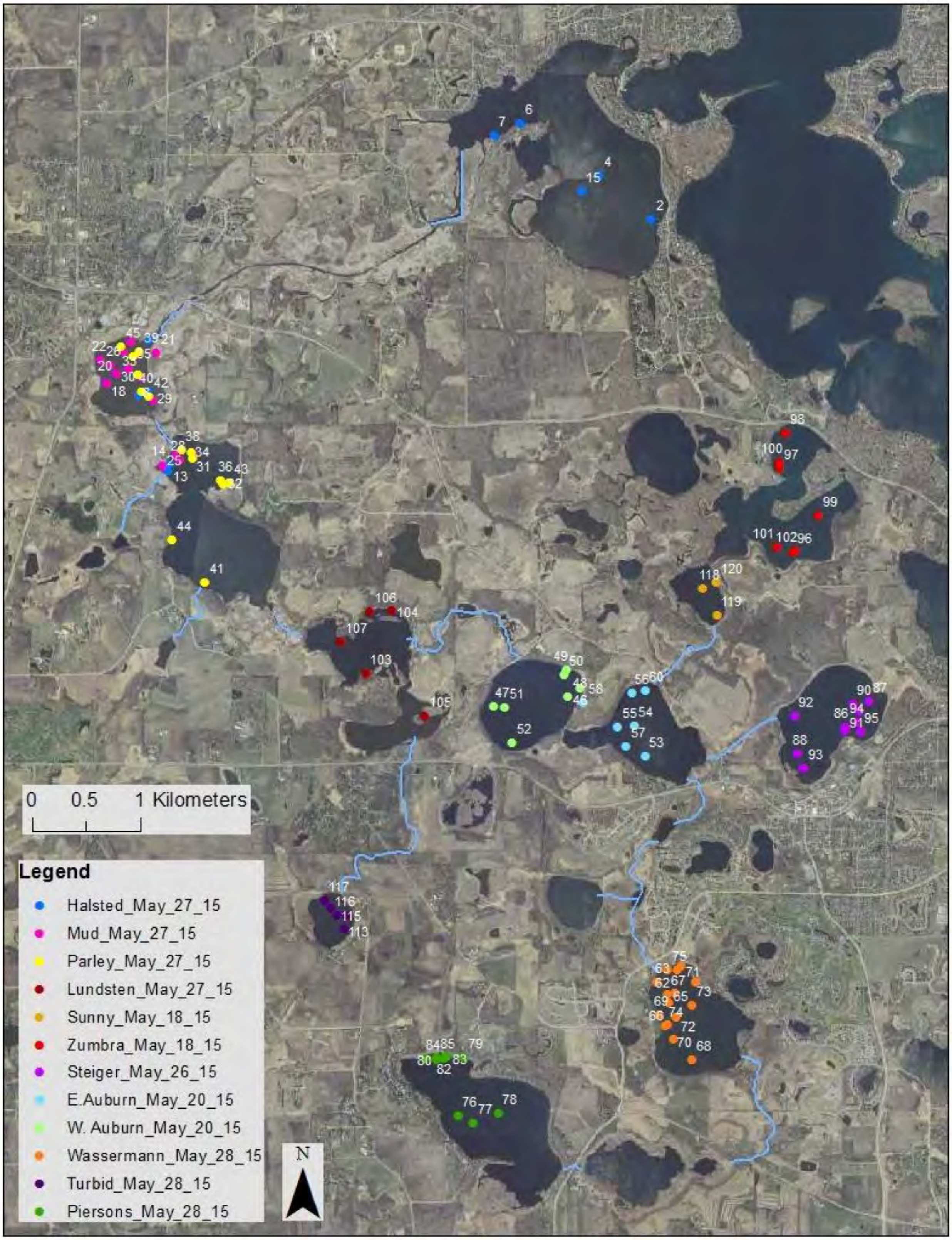

0 0.5 1 Kilometers
Legend
Halsted_May_27_15
Mud_May_27_15
Parley_May_27_15
Lundsten_May_27_15
Sunny_May_18_15
Zumbra_May_18_15
Steiger_May_26_15
E.Auburn_May_20_15
W. Auburn_May_20_15
Wassermann_May_28_15
Turbid_May_28_15
Piersons_May_28_15
N

Figure 10. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in late May 2015. Individuals are labeled with unique identification numbers (white).

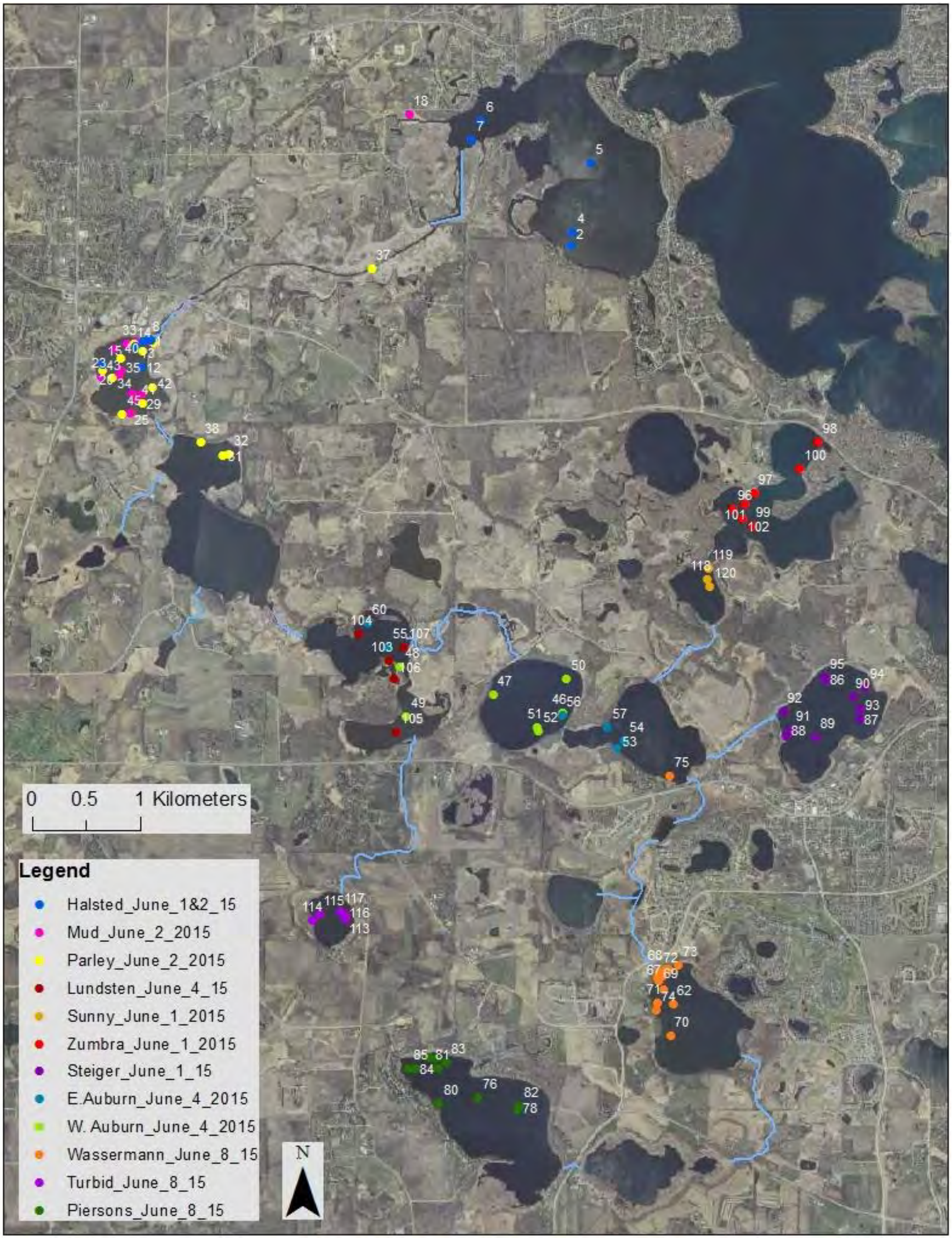


Figure 11. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in early June 2015. Individuals are labeled with unique identification numbers (white).

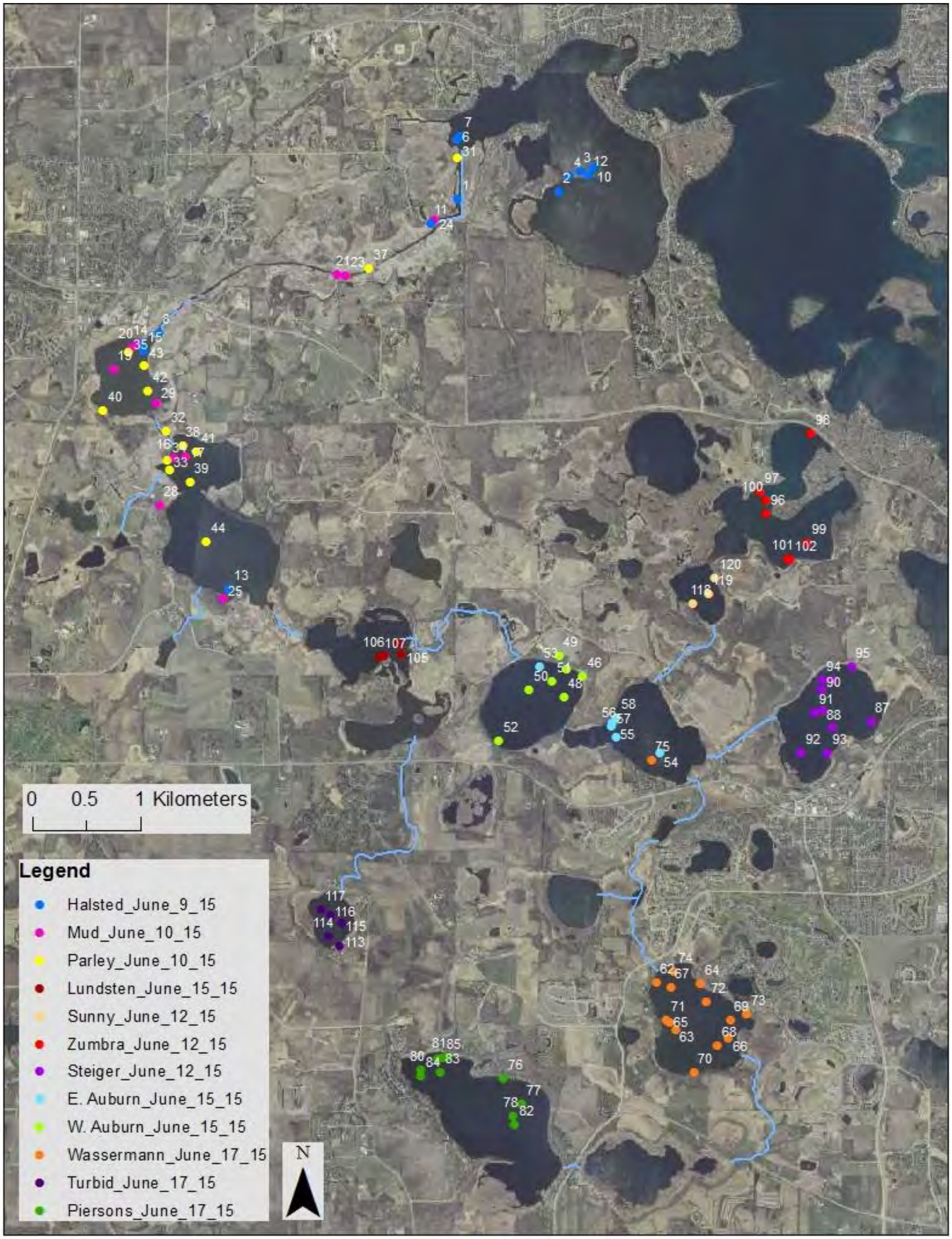


Figure 12. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in late June 2015. Individuals are labeled with unique identification numbers (white).

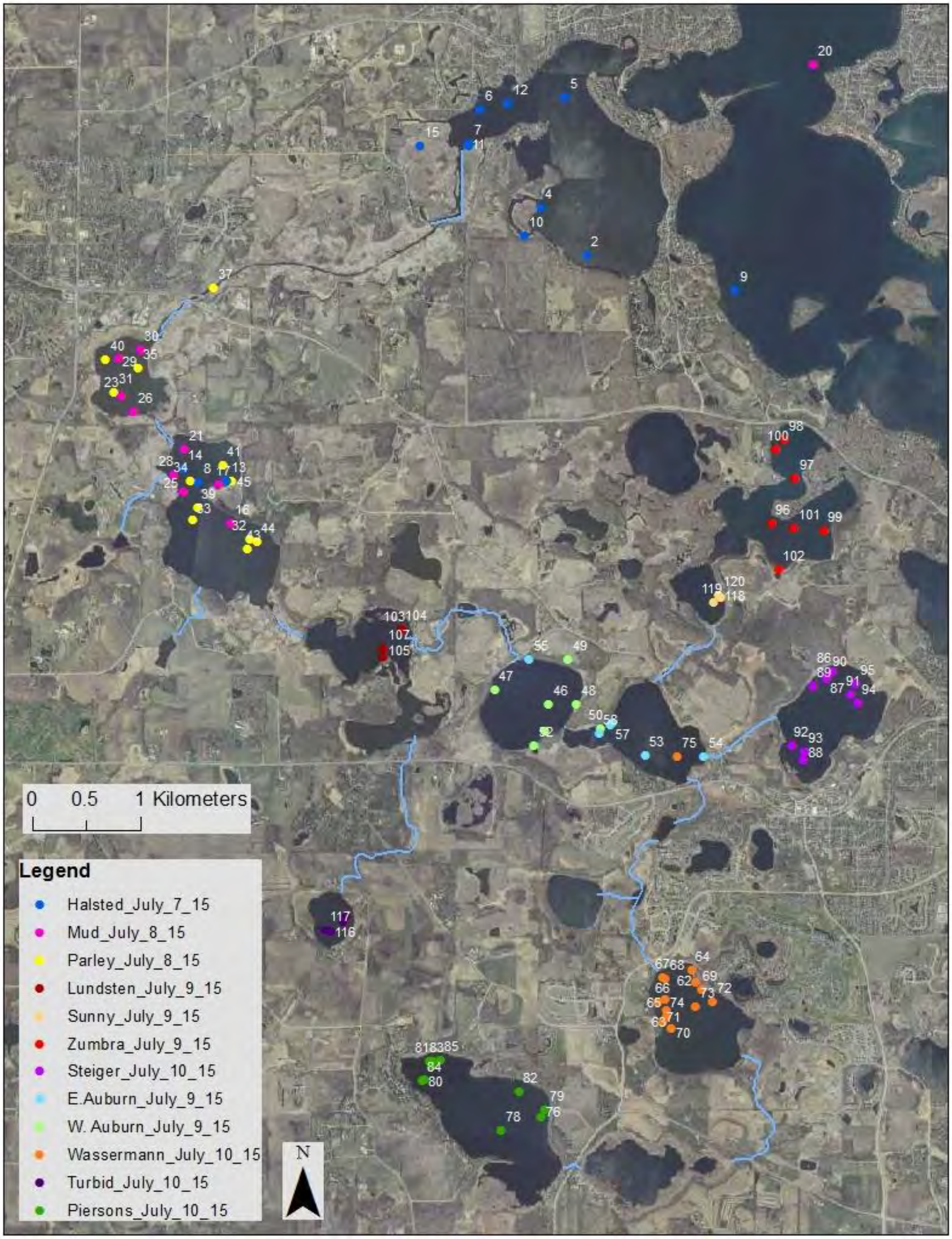

0 0.5 1 Kilometers
Legend
Halsted_July_7_15
Mud_July_8_15
Parley_July_8_15
Lundsten_July_9_15
Sunny_July_9_15
Zumbra_July_9_15
Steiger_July_10_15
E.Auburn_July_9_15
W. Auburn_July_9_15
Wassermann_July_10_15
Turbid_July_10_15
Piersons_July_10_15
N

Figure 13. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in July 2015. Individuals are labeled with unique identification numbers (white).

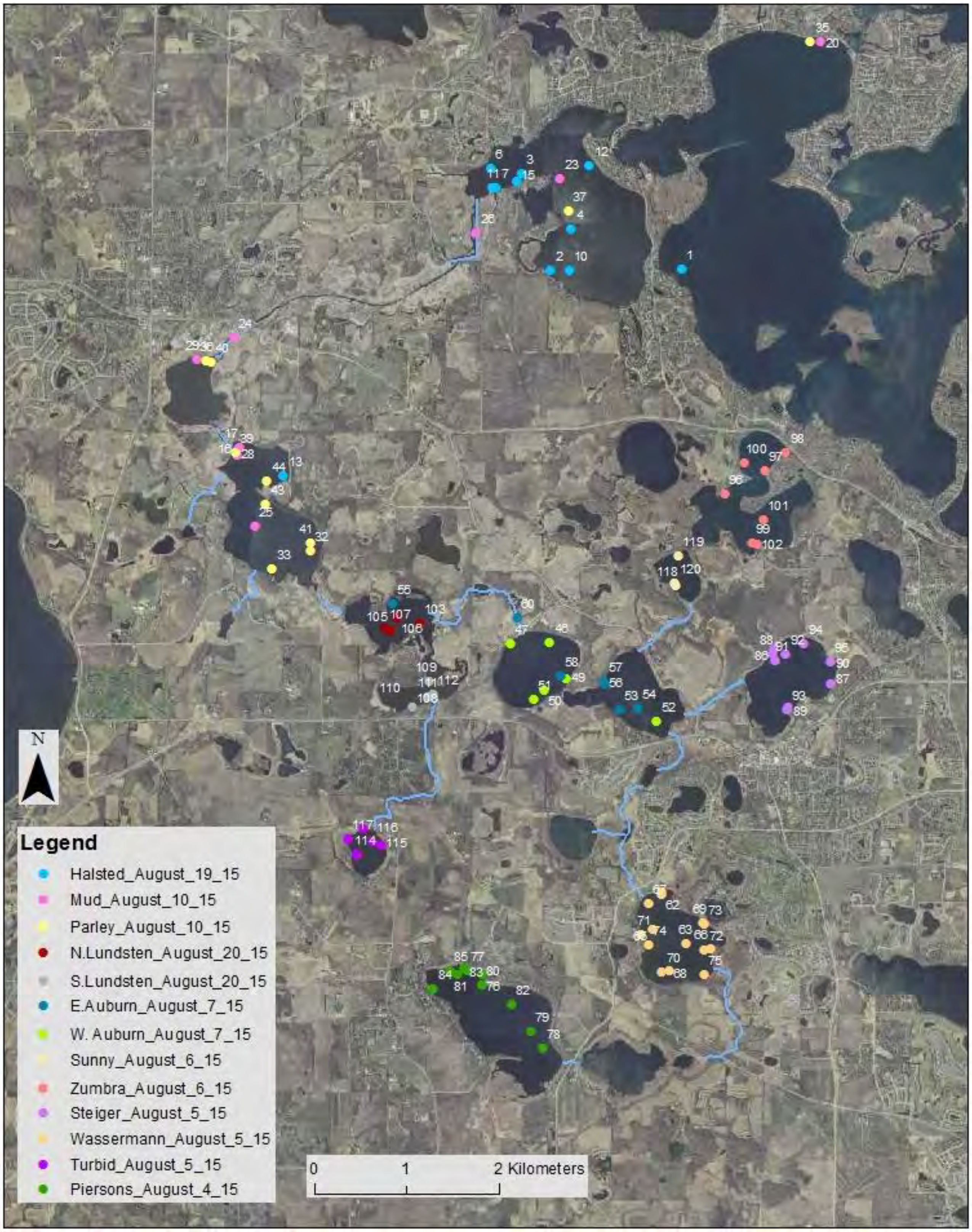


Figure 14. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in August 2015. Individuals are labeled with unique identification numbers (white).

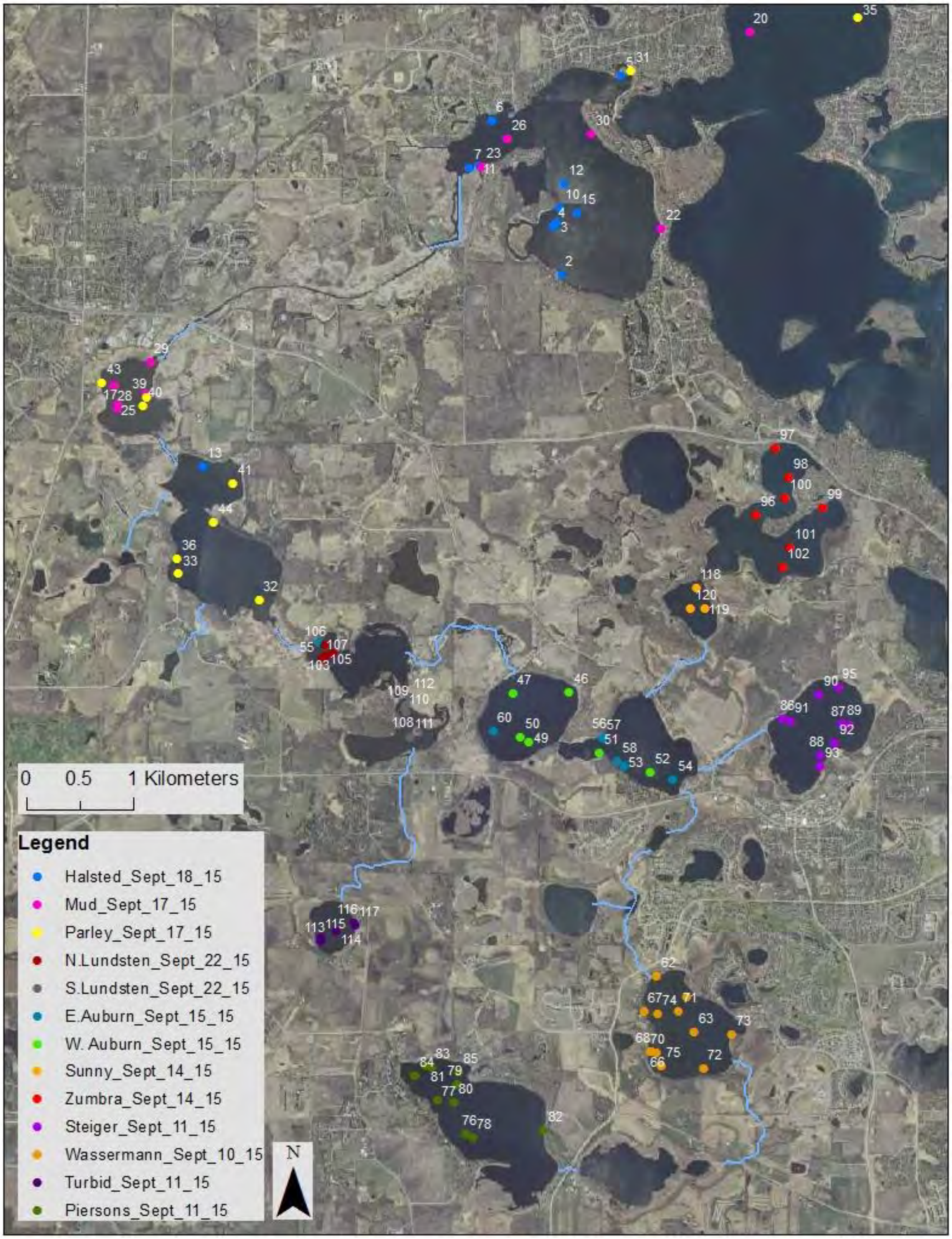


Figure 15. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in September 2015. Individuals are labeled with unique identification numbers (white).

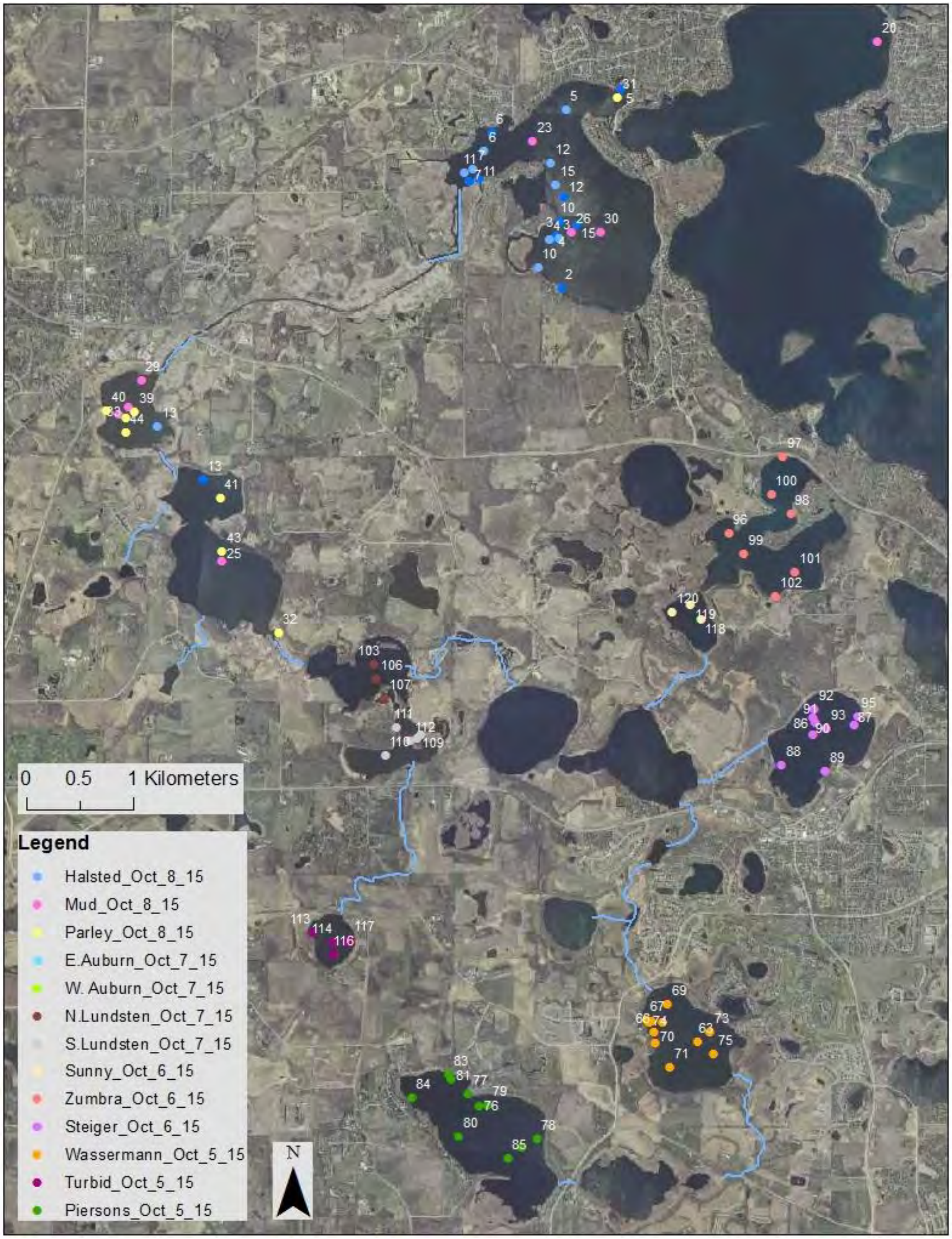


Figure 16. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in October 2015. Individuals are labeled with unique identification numbers (white).

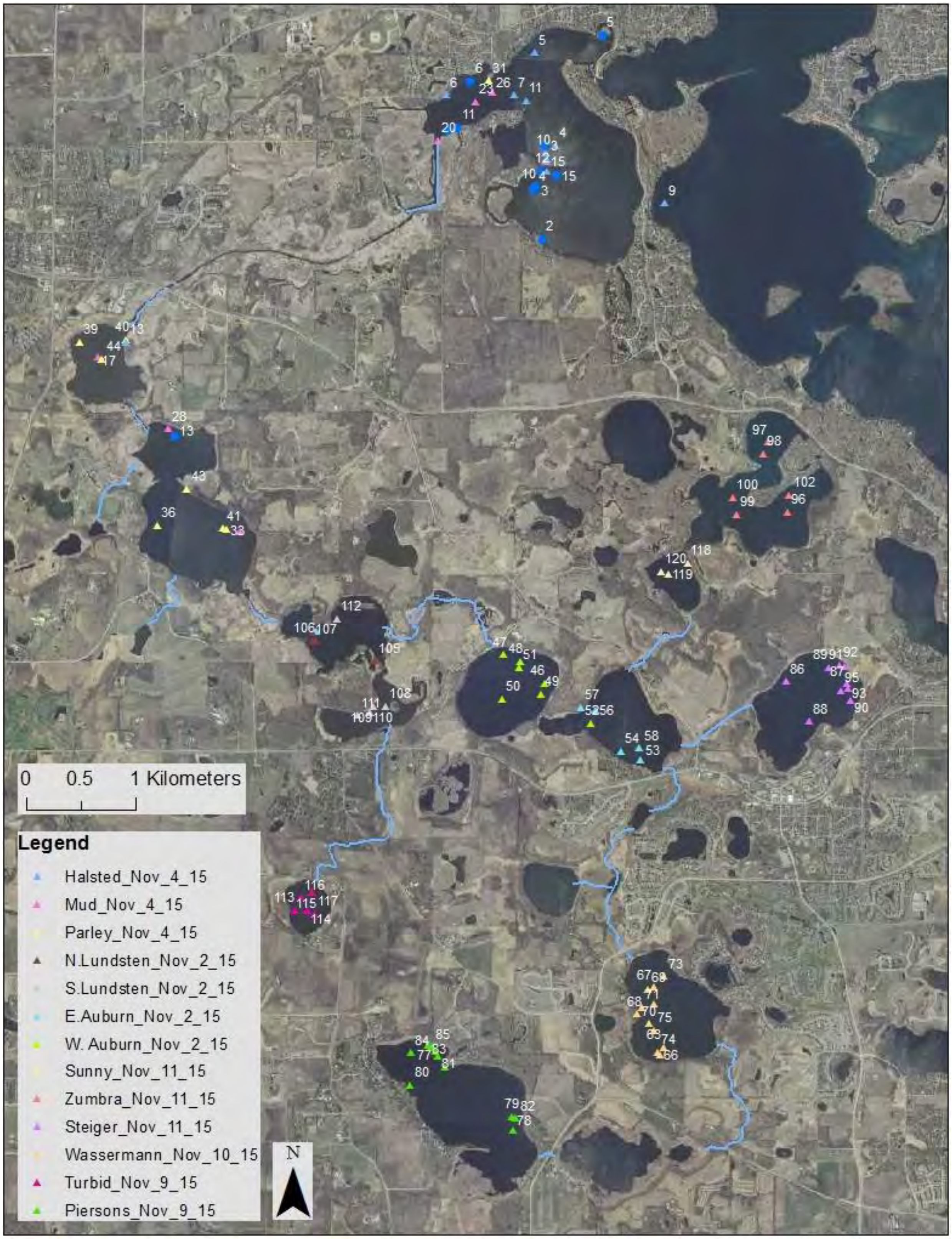


Figure 17. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in November 2015. Individuals are labeled with unique identification numbers (white).

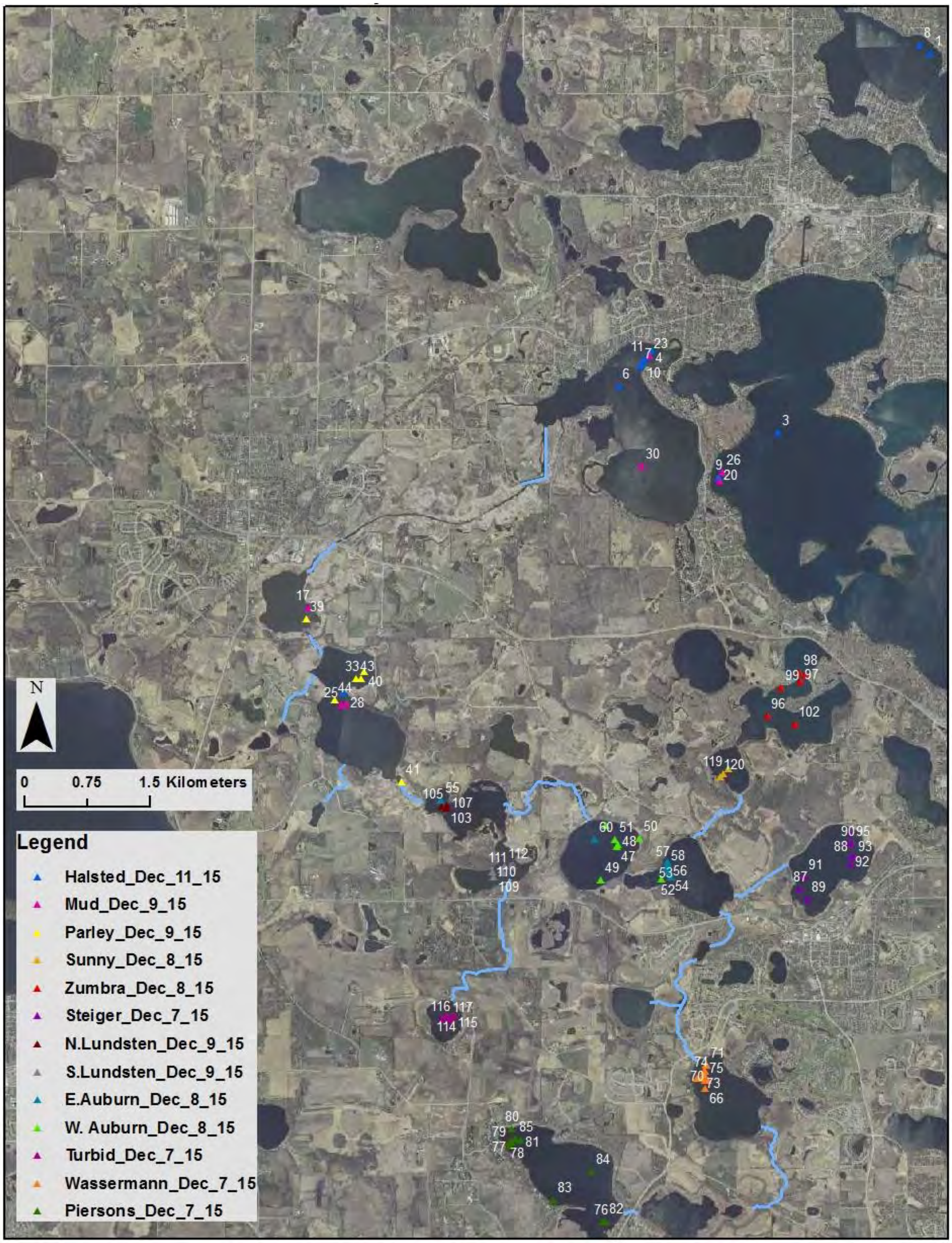


Figure 18. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in December 2015. Individuals are labeled with unique identification numbers (white).

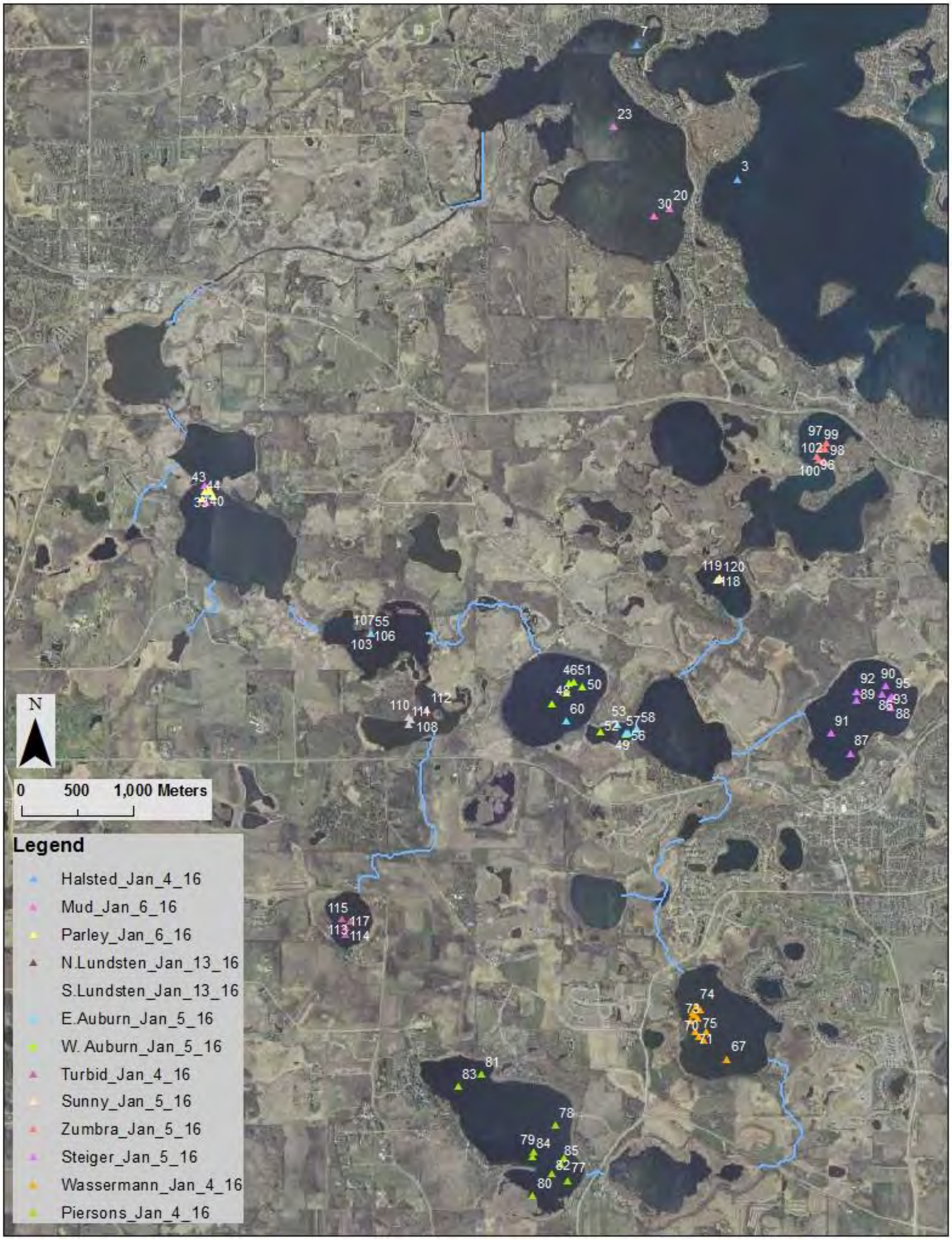

N
0 500 1,000 Meters
Legend
Halsted_Jan_4_16
Mud_Jan_6_16
Parley_Jan_6_16
N.Lundsten_Jan_13_16
S.Lundsten_Jan_13_16
E.Auburn_Jan_5_16
W. Auburn_Jan_5_16
Turbid_Jan_4_16
Sunny_Jan_5_16
Zumbra_Jan_5_16
Steiger_Jan_5_16
Wassermann_Jan_4_16
Piersons_Jan_4_16

Figure 19. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in January 2016. Individuals are labeled with unique identification numbers (white).

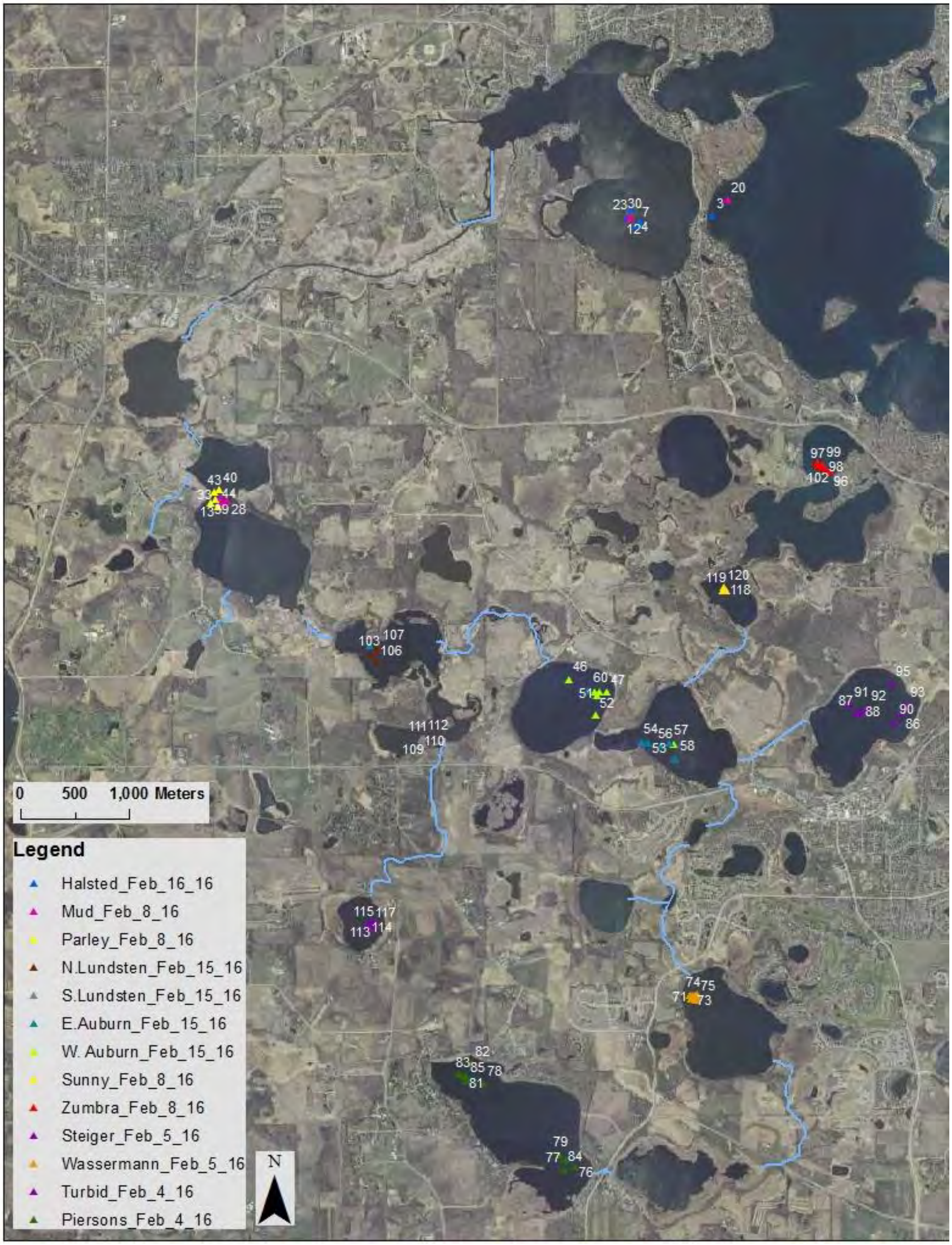

0 500 1,000 Meters
Legend
Halsted_Feb_16_16
Mud_Feb_8_16
Parley_Feb_8_16
N.Lundsten_Feb_15_16
S.Lundsten_Feb_15_16
E.Auburn_Feb_15_16
W. Auburn_Feb_15_16
Sunny_Feb_8_16
Zumbra_Feb_8_16
Steiger_Feb_5_16
Wassermann_Feb_5_16
Turbid_Feb_4_16
Piersons_Feb_4_16
N

Figure 20. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in February 2016. Individuals are labeled with unique identification numbers (white).

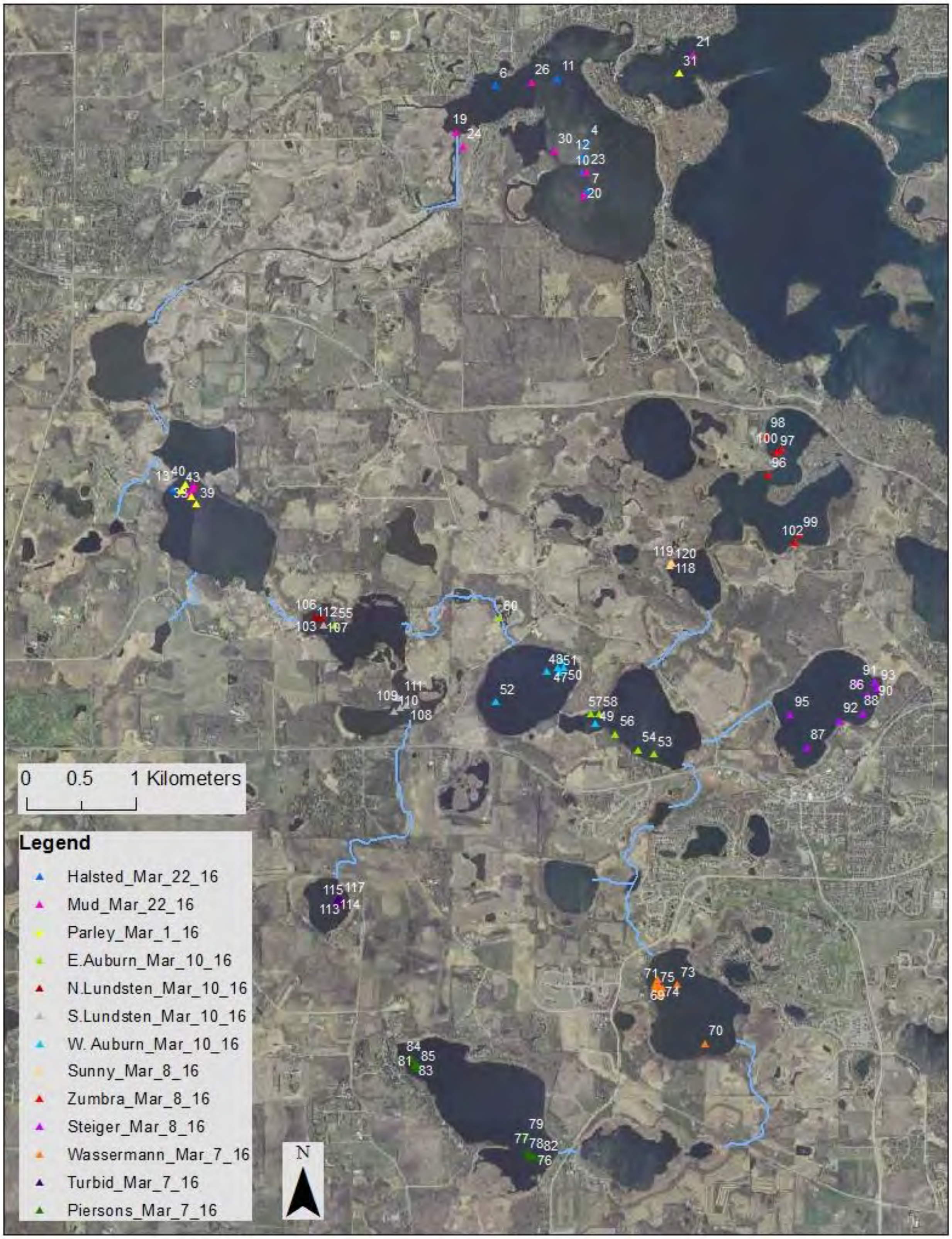

0 0.5 1 Kilometers
Legend
Halsted_Mar_22_16
Mud_Mar_22_16
Parley_Mar_1_16
E.Auburn_Mar_10_16
N.Lundsten_Mar_10_16
S.Lundsten_Mar_10_16
W. Auburn_Mar_10_16
Sunny_Mar_8_16
Zumbra_Mar_8_16
Steiger_Mar_8_16
Wassermann_Mar_7_16
Turbid_Mar_7_16
Piersons_Mar_7_16
N

Figure 21. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in March 2016. Individuals are labeled with unique identification numbers (white).

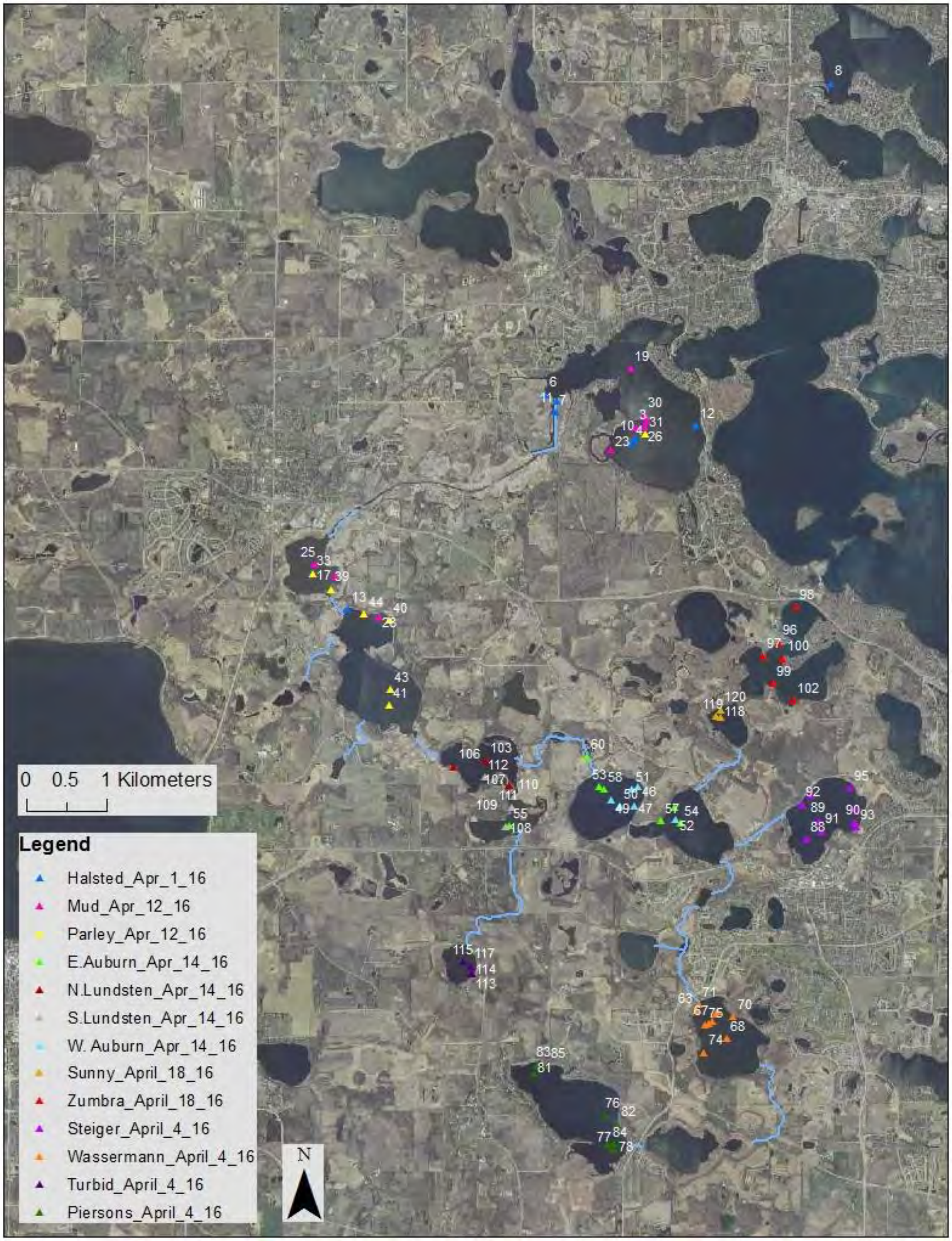


Figure 22. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in April 2016. Individuals are labeled with unique identification numbers (white).

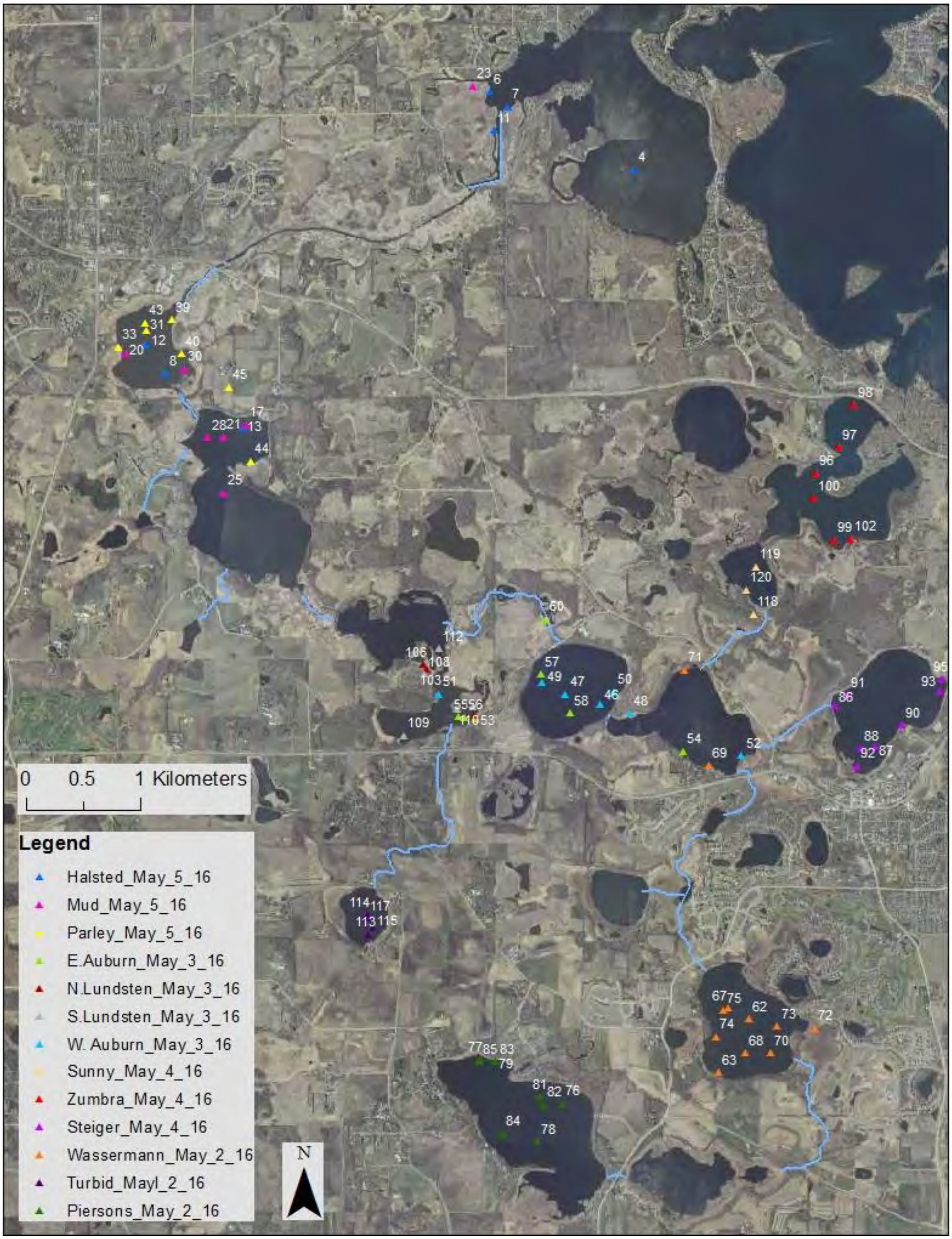


Figure 23. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in early May 2016. Individuals are labeled with unique identification numbers (white).

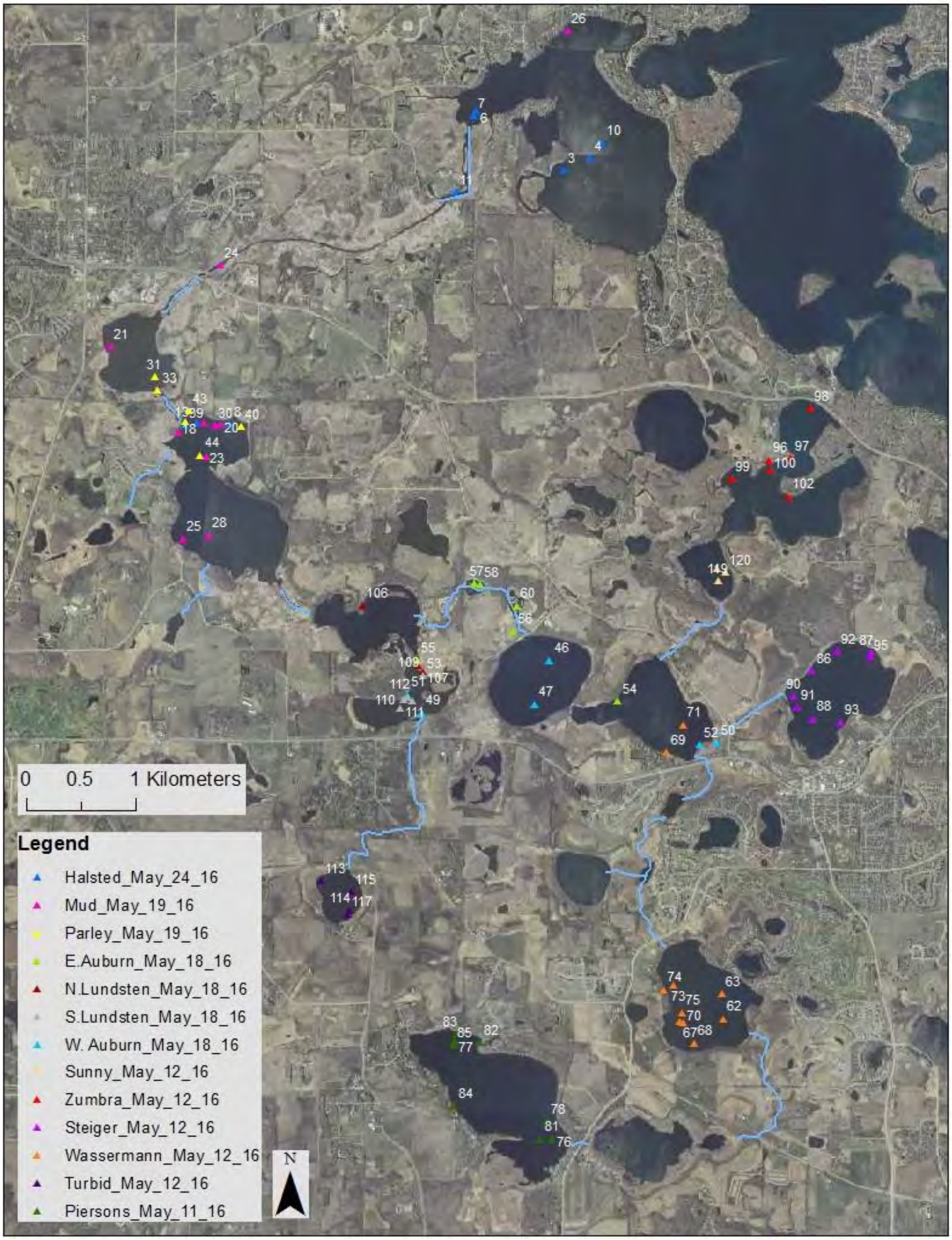


Figure 24. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in late May 2016. Individuals are labeled with unique identification numbers (white).

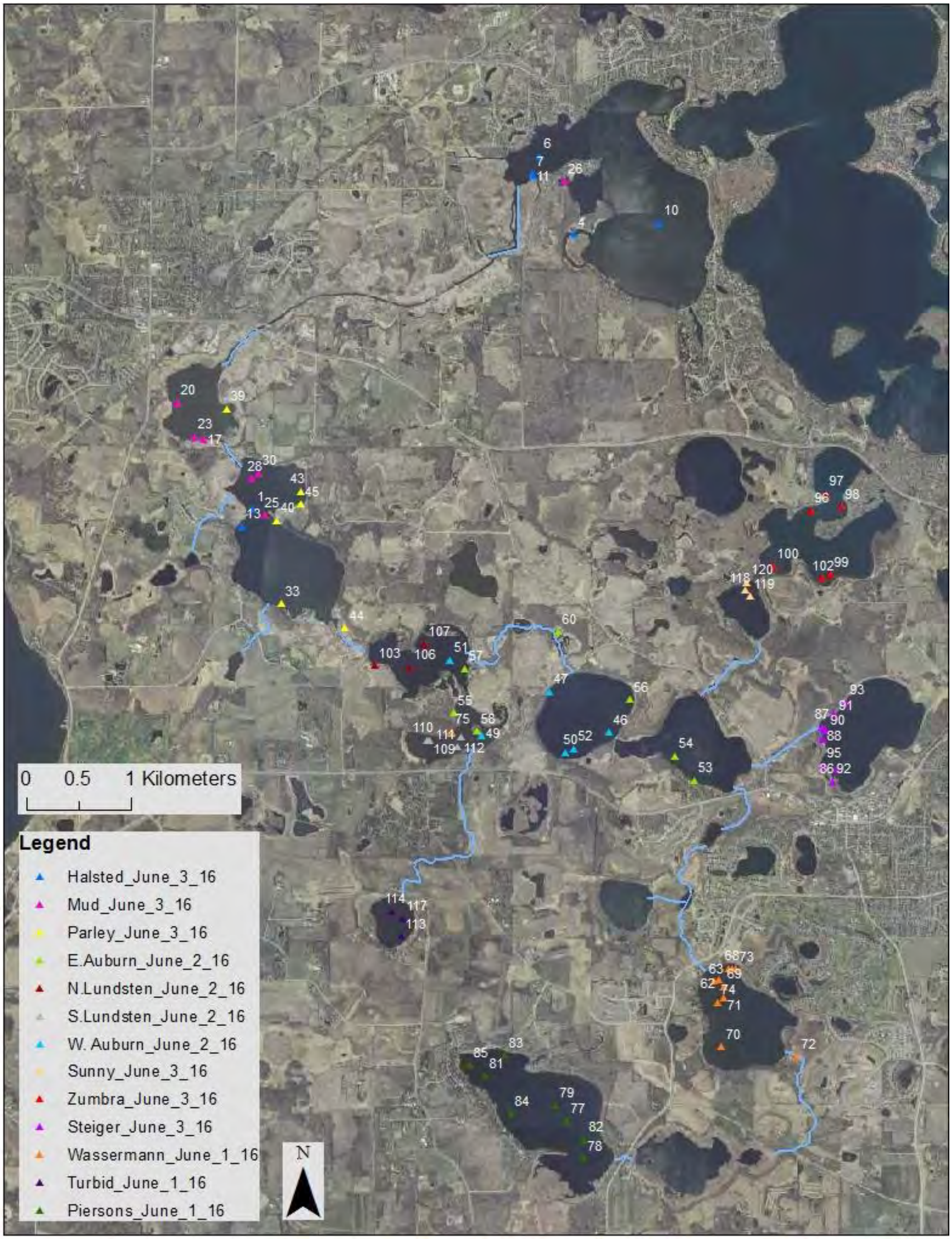


Figure 25. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in June 2016. Individuals are labeled with unique identification numbers (white).

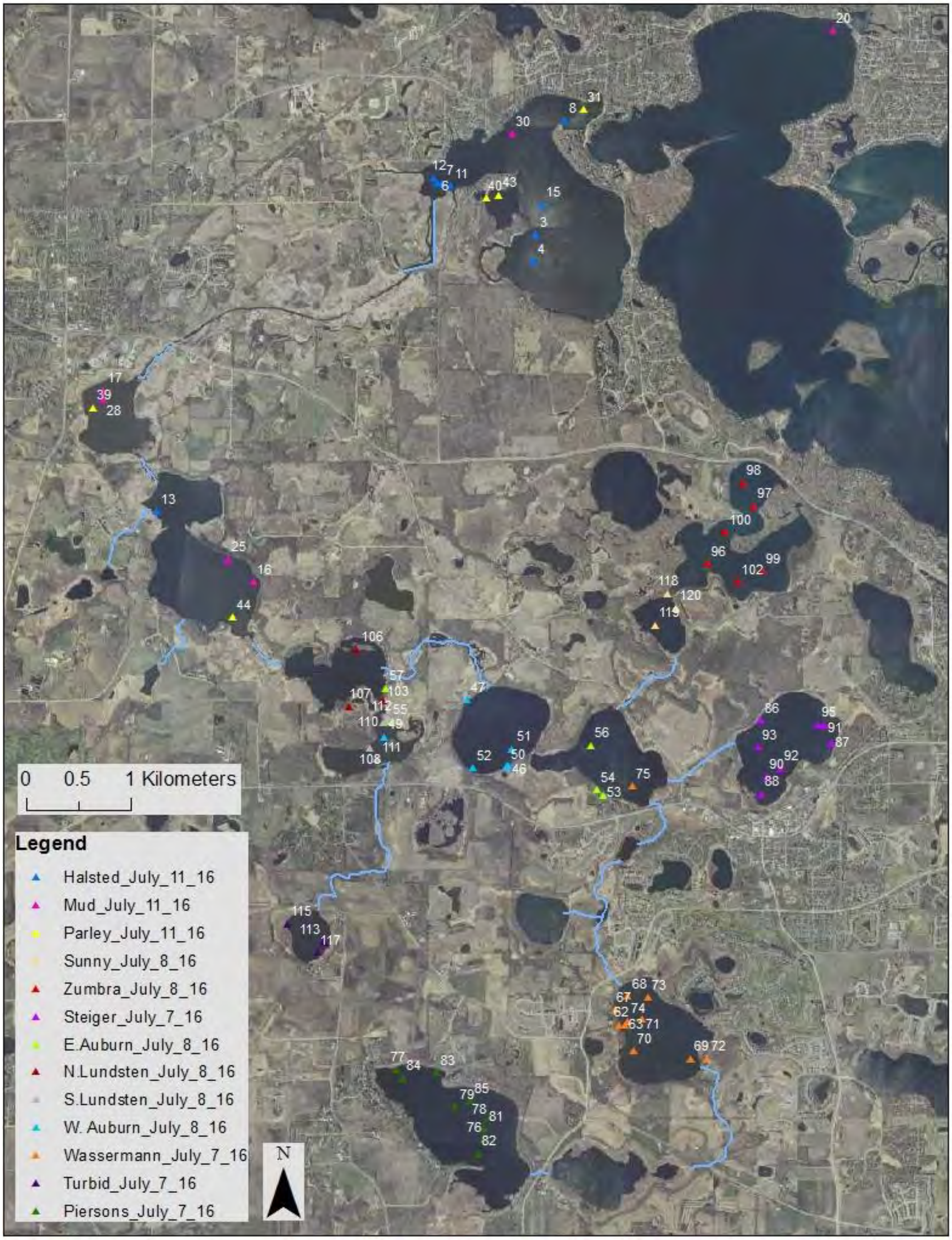


Figure 26. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in July 2016. Individuals are labeled with unique identification numbers (white).

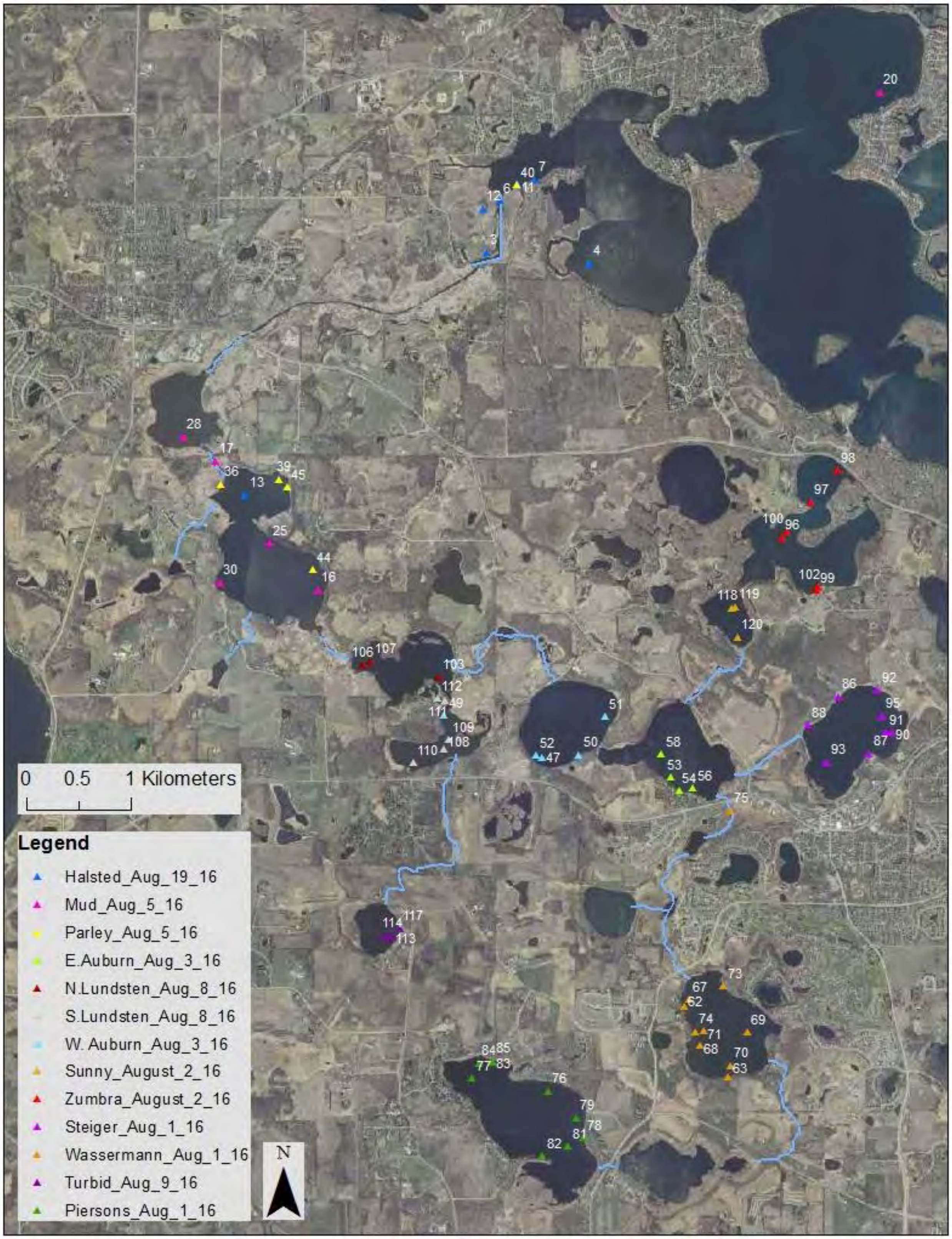


Figure 27. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in August 2016. Individuals are labeled with unique identification numbers (white).

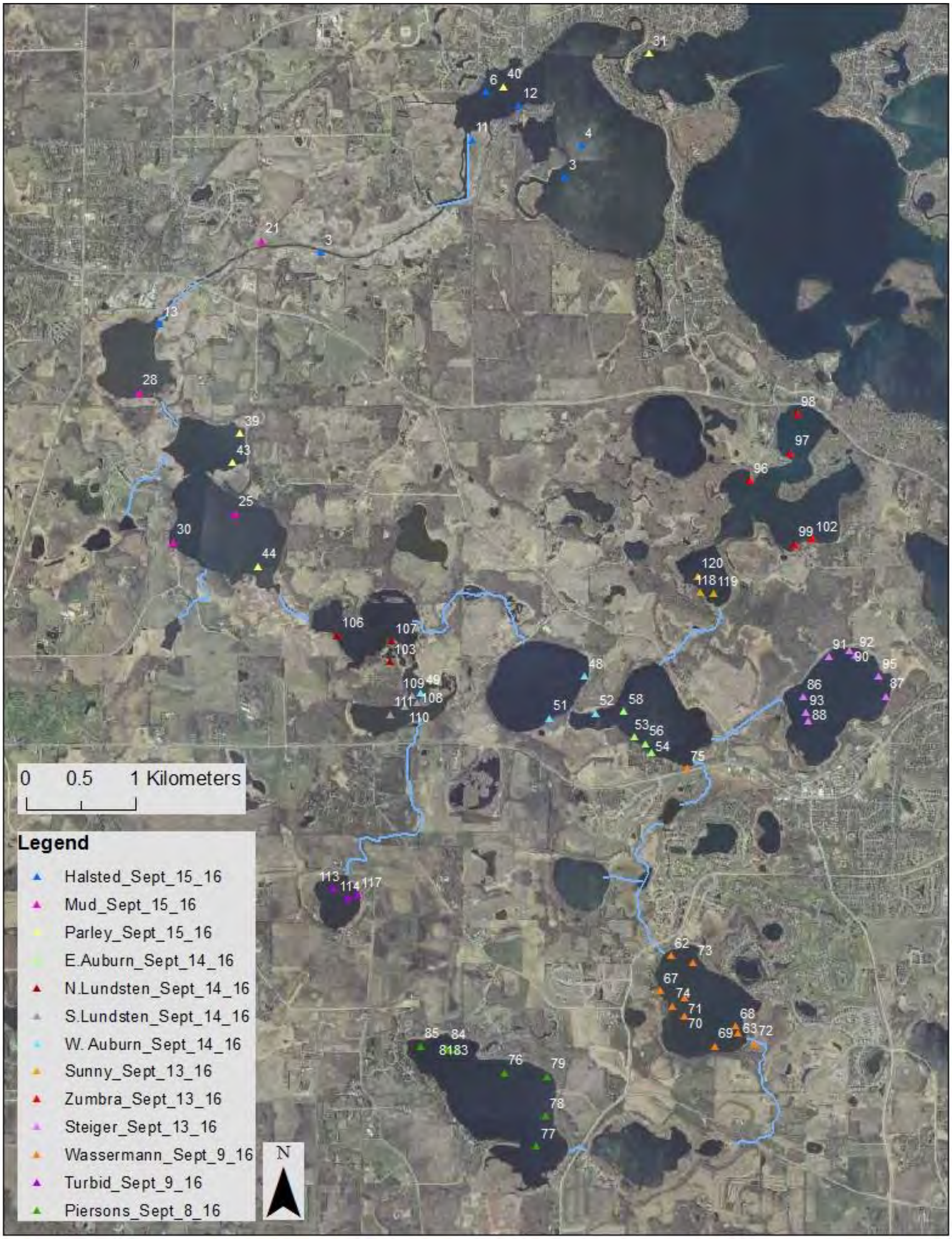


Figure 28. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in September 2016. Individuals are labeled with unique identification numbers (white).

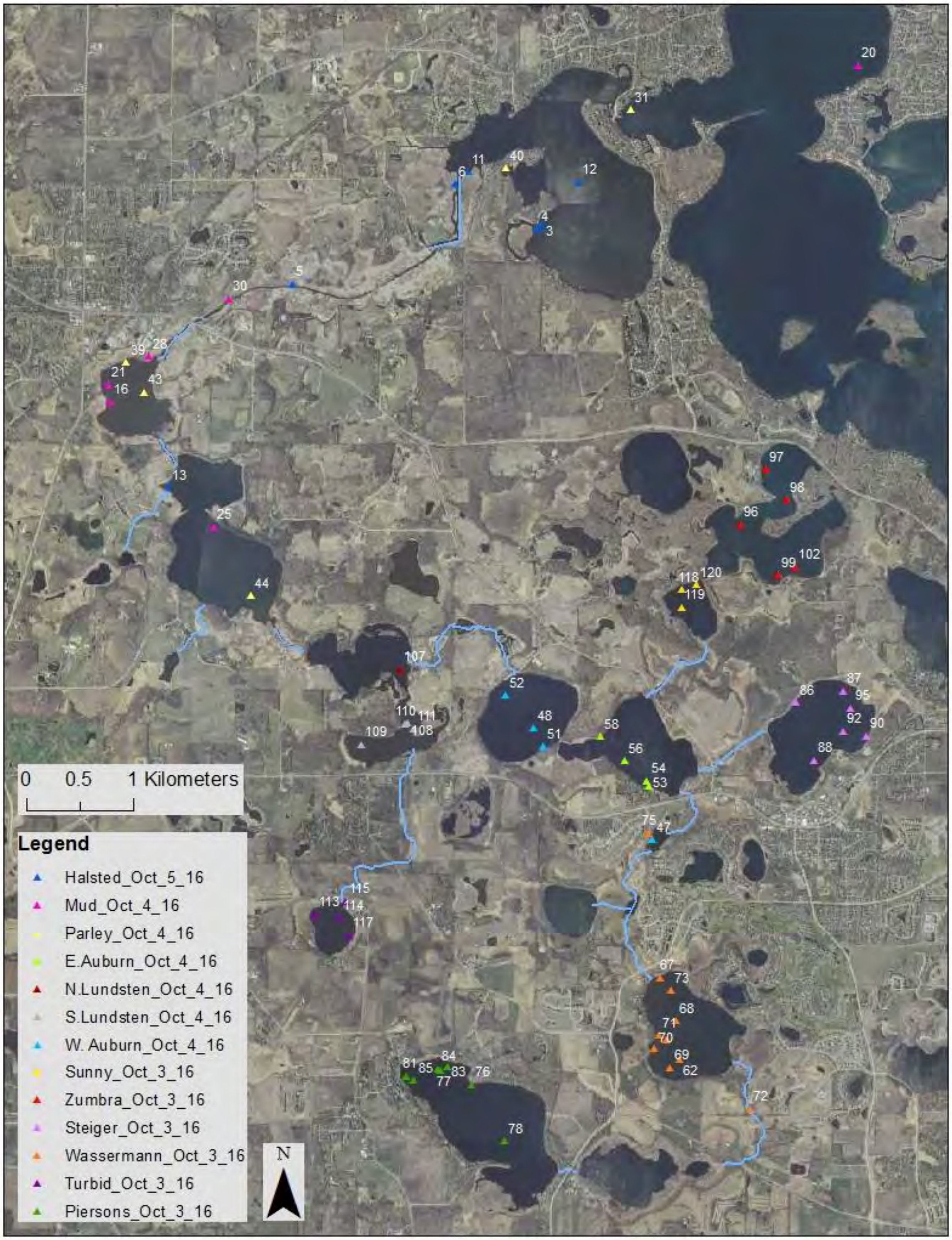


Figure 29. Locations of radio-tagged common carp in the Six Mile Creek Subwatershed in October 2016. Individuals are labeled with unique identification numbers (white).

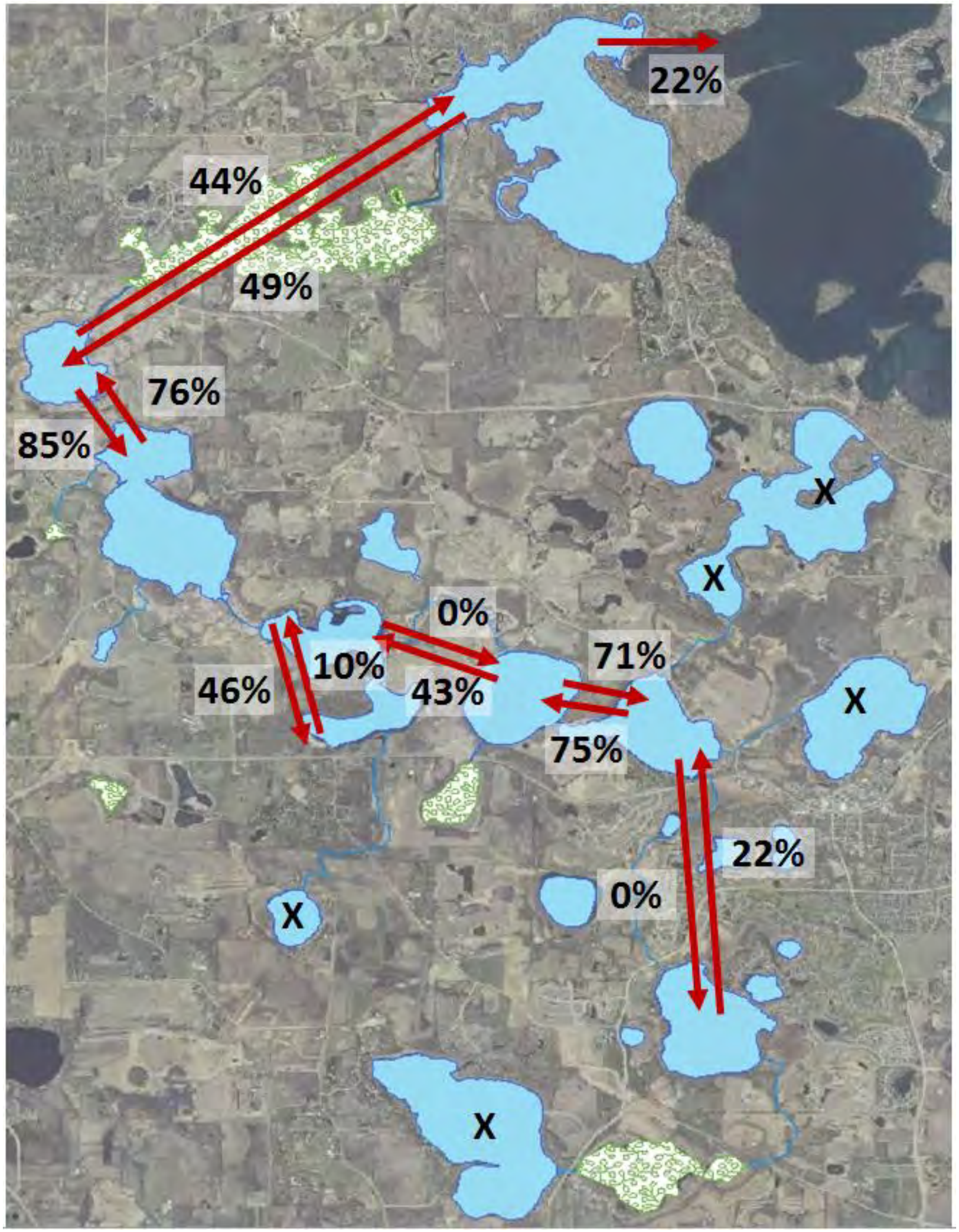


Figure 30. Summary of radio-tagged common carp movement patterns across the Six Mile Creek subwatershed from November 2014 through October 2016. Mean annual movement rates (% living radio-tagged carp that moved from origin to destination) are shown for each movement path indicated by a red arrow. An "X" indicates lakes with radio-tagged carp where

no carp movement was observed during the study period. A detailed breakdown of movement rates and timing by year can be found in Table 3.

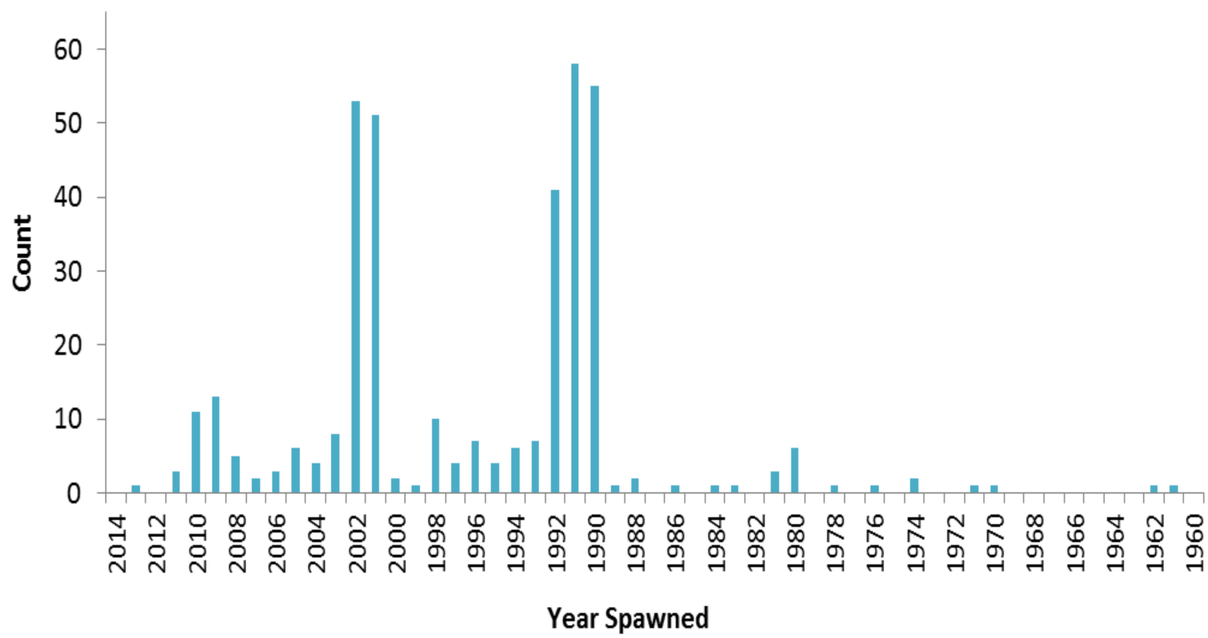


Figure 31. The age structure of common carp (n=378) across the Six Mile Creek Subwatershed. Common carp were sampled from Halsted's Bay (n=51), Mud Lake (n=51), and Parley Lake (n=51) in 2014, North Lundsten Lake (n=31), West Auburn Lake (n=28), East Auburn Lake (n=28), Wassermann Lake (n=37), and Piersons Lake (n=34) in 2015, and Turbid Lake (n=24), Steiger Lake (n=15), and Zumbra Lake (n=28) in 2016.

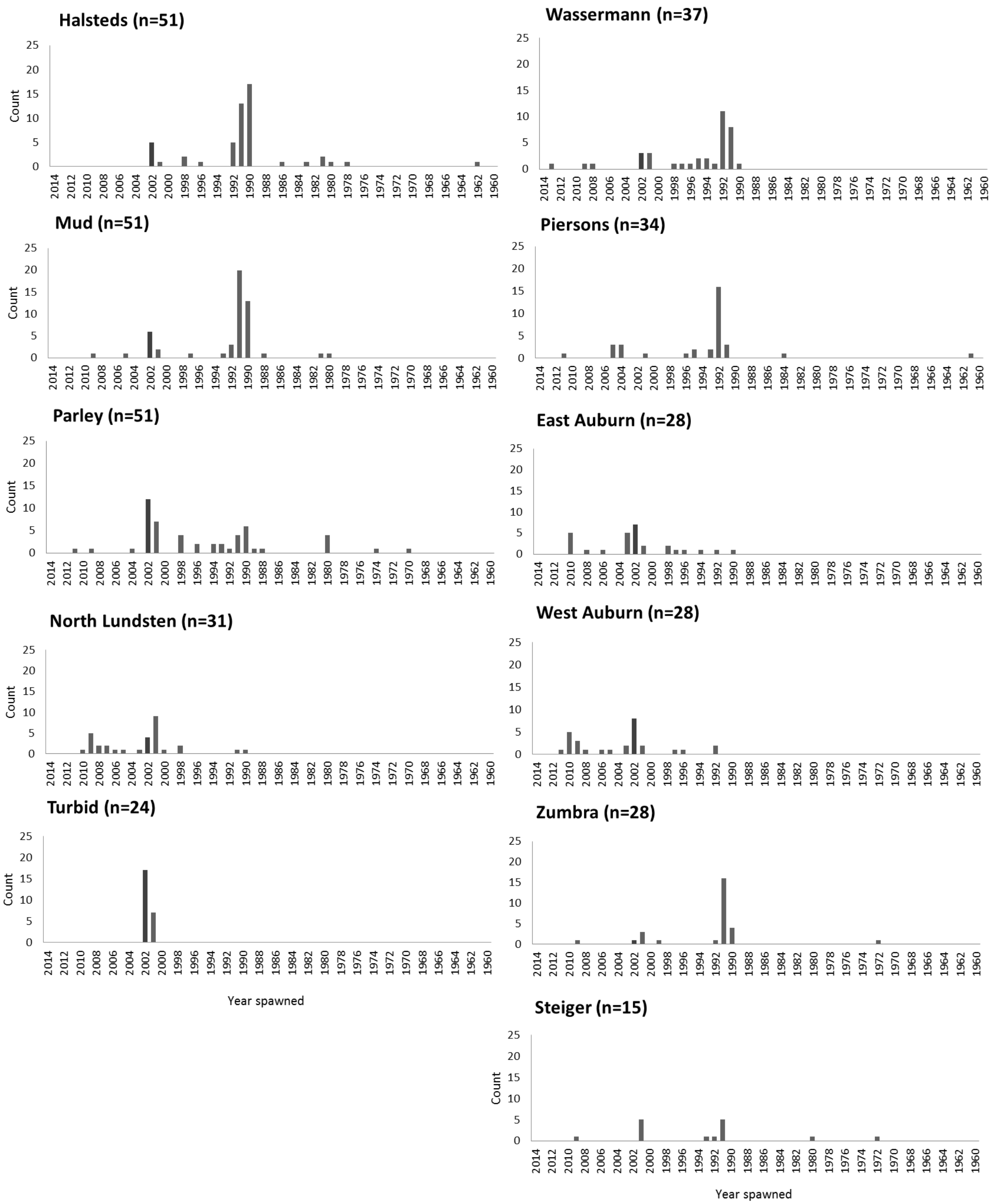


Figure 32. The age structures of common carp sampled across the Six Mile Creek Subwatershed shown individually by lake. Sample sizes are shown parenthetically.

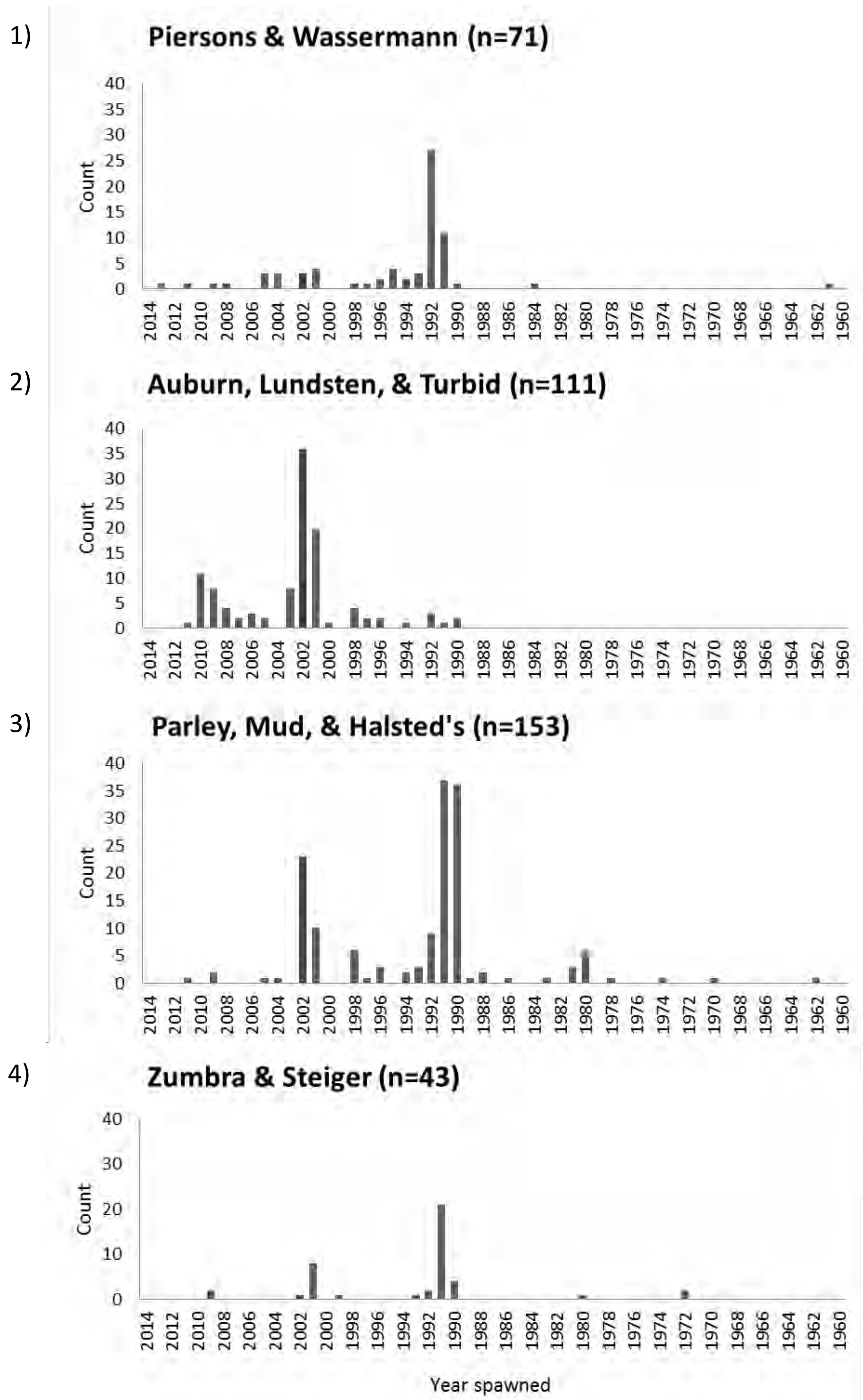


Figure 33. The age structures of common carp sampled across the Six Mile Creek Subwatershed shown by sub-population: 1) Piersons & Wassermann, 2) Auburn, Lundsten, & Turbid, 3) Parley, Mud, & Halsted's Bay, and 4) Zumbra & Steiger. Sample sizes are indicated parenthetically.

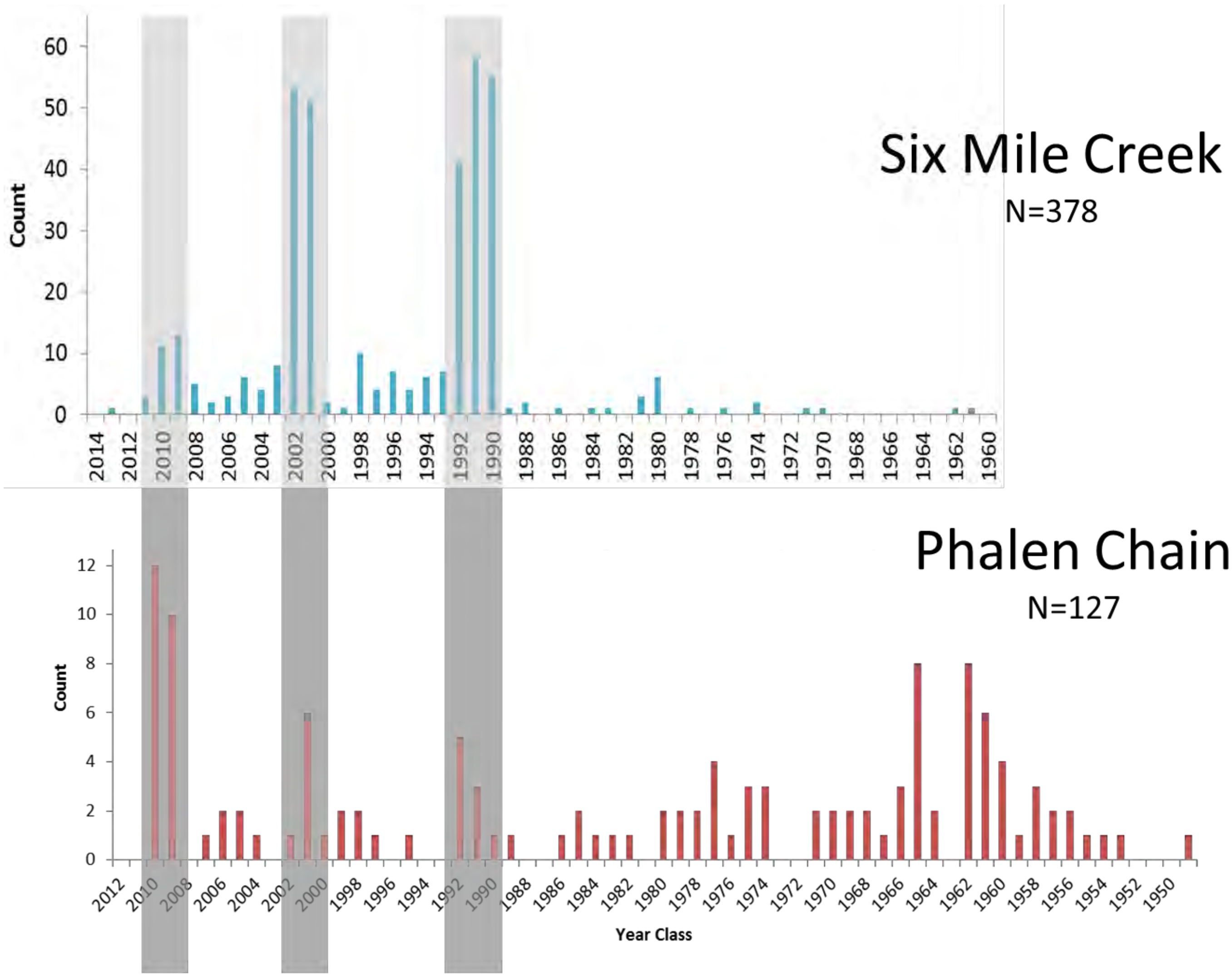


Figure 34. The age structure of common carp sampled in the Six Mile Creek subwatershed in the southwestern twin cities metropolitan area from 2014-2016 (n=378) compared with that of common carp sampled in the Phalen Chain subwatershed in the northeastern twin cities metropolitan area from 2011-2013 (n=127). The shaded rectangles highlight the similarities in year class strength between the two isolated systems.

Figure 35. Parley Lake surface water elevation from April 1981 through November 2015. The average surface water elevation for this time period (929 feet) is shown by the dashed line. Note the extended periods of low water prior to 1991 and 2001. Source: MN DNR; http://www.dnr.state.mn.us/lakefind/showlevel.html?downum=10004200

Figure 36. A photograph of the barrier in place at the Zumbra Lake outlet to Sunny Lake in the Carver Park Reserve. Lake levels were observed overtopping this barrier in August of 2016.