Northern Snakehead Control and Management Plan for the Chesapeake Bay Watershed

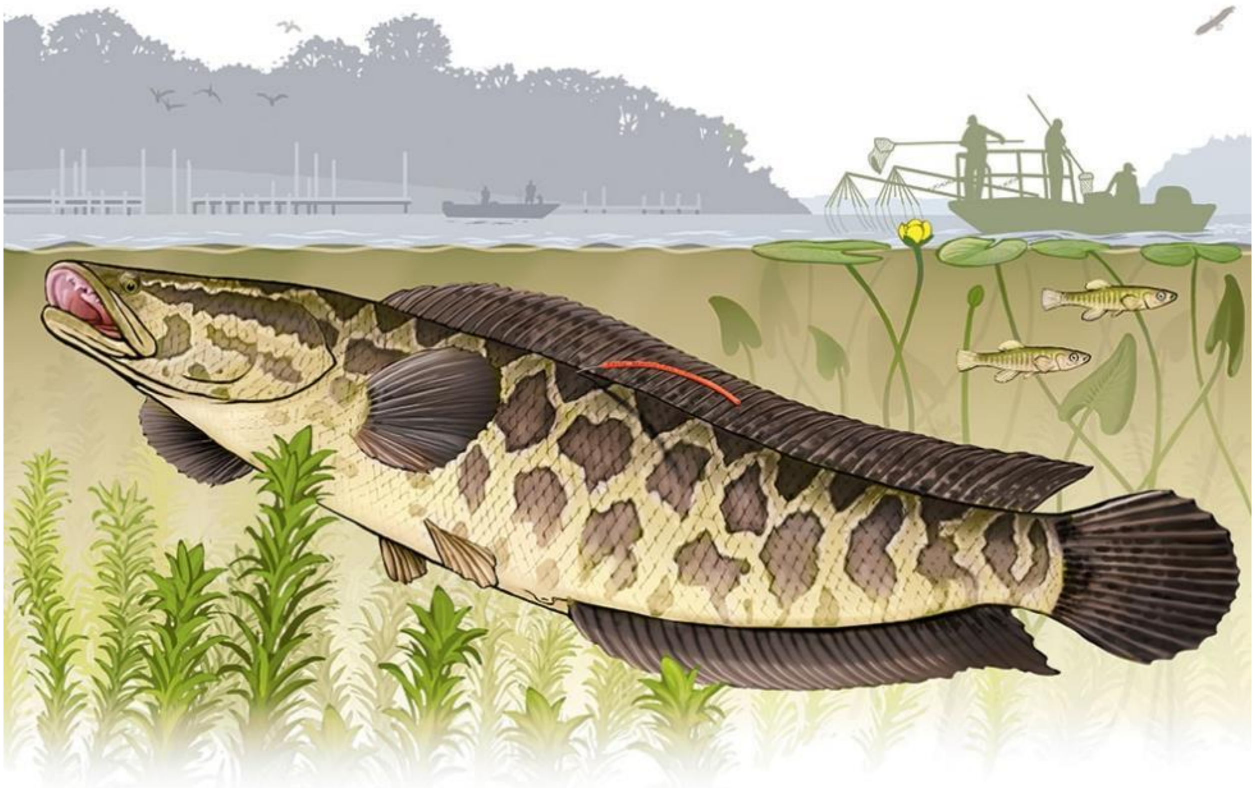

Illustration courtesy of Patterson Clark and The Washington Post.

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Prepared by the Chesapeake Bay Northern Snakehead Plan Working Group

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I. Executive summary

The Northern Snakehead (*Channa argus*) is a predatory fish species native to Russia, China, and the Korean peninsula. In their native range, Northern Snakehead are a popular food fish and were present in live-food markets in the United States (U.S.) until their 2002 importation and interstate transport ban under the Lacey Act. Unfortunately, this did not prevent their introduction into U.S. waters. Since their discovery in the Potomac River in 2004, Northern Snakehead have spread (both naturally and due to human transport) to all major rivers connected to the Chesapeake Bay, as well as numerous smaller tributaries and reservoirs. Their introduction in the U.S. generated an immense deal of public attention owing to uncertainty regarding their impact on humans and native wildlife. Initial fears regarding widespread ecological devastation appear to be unwarranted. However, much uncertainty remains owing to the potential for time-lags before any negative effects might become apparent, and their potential ecological impacts in newly colonized waterbodies.

In 2005, Congress requested that the U.S. Fish and Wildlife Service (USFWS) address concerns about the introduction of Northern Snakehead into U.S. waters. In response, a working group was assembled, and this eventually led to the creation of a National Control and Management Plan for Members of the Snakehead Family (*Channidae*), published in 2014. As Northern Snakehead continue to spread throughout the Chesapeake Bay watershed, and beyond, there has been recent political interest in creating a control and management plan to address concerns specific to this watershed in light of all that has been learned regarding Northern Snakehead biology over the past 20 years. This plan, meant to complement the national plan, differs in several ways. First, unlike the national plan it is focused on a single species of snakehead – the Northern Snakehead – and is limited geographically to the Chesapeake Bay watershed, which includes parts of six states (Delaware, Maryland, New York, Pennsylvania, Virginia, and West Virginia) and Washington D.C. Second, given the growing number of studies on Northern Snakehead in the Chesapeake Bay watershed, this plan goes into greater detail reviewing the state of knowledge and areas of uncertainty (i.e., future research needs), discussing and evaluating the costs, benefits, and feasibility of different control and management options for Northern Snakehead, and giving specific recommendations. The guiding principles in developing this plan were an emphasis on practical or workable solutions, cost-effectiveness, and control and management practices that can be sustained.

Overall plan goal: Within the Chesapeake Bay watershed, use the best-available science and management practices to prevent new Northern Snakehead introductions, limit spread, and control abundance to prevent adverse effects on aquatic communities.

Objective 1. Prevent new Northern Snakehead introductions into waterbodies within the Chesapeake Bay watershed, and into adjacent watersheds.

Objective 2. Detect new (distinct) Northern Snakehead populations at an early stage.

Objective 3. Limit the spread of Northern Snakehead within connected waterways of the Chesapeake Bay watershed.

Objective 4. In established areas, minimize Northern Snakehead population size through control and management actions.

Objective 5. Conduct research to better understand Northern Snakehead biology, population dynamics, and impacts, and develop more effective detection, surveillance, and control methods.

Objective 6. Implement public outreach to prevent additional introductions of Northern Snakehead, limit spread, and aid in control efforts.

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<u>Acronyms</u>

ANSTF	Aquatic Nuisance Species Task Force
C&O Canal	Chesapeake and Ohio Canal
C&D Canal	Chesapeake and Delaware Canal
CPUE	Catch Per Unit Effort
eDNA	Environmental Deoxyribonucleic Acid (DNA)
EDRR	Early Detection and Rapid Response
GSI	Gonadosomatic Index
LMBV	Largemouth Bass Virus
MDDNR	Maryland Department of Natural Resources
NEFC	Northeast Fishery Center (USFWS)
NYDEC	New York State Department of Environmental Conservation
PCBs	Polychlorinated Biphenyls
PFBC	Pennsylvania Fish and Boat Commission
SRAFRC	Susquehanna River Anadromous Fish Restoration Cooperative
SRBC	Susquehanna River Basin Commission
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
VDWR	Virginia Department of Wildlife Resources

II. The biology of Northern Snakehead

The Northern Snakehead (*Channa argus*) is a robust, air-breathing, freshwater, predatory fish in the family Channidae. This species, native to China, the Korean peninsula, and Russia, has the northernmost distribution of the otherwise tropical and sub-tropical snakehead family. Northern Snakehead have broad temperature tolerance ranging from 0 to >30 °C. They are obligate air-breathers, except during very cold temperatures when metabolism slows and oxygen demand is greatly reduced – such as when surviving under ice. The species attains a maximum size of approximately 900 mm (36 in) and 9 kg (20 lb). They can be found in streams, rivers, canals, reservoirs, and lakes, and their preferred habitat is stagnant shallow waters with mud substrate and aquatic vegetation. In their native range, Northern Snakehead reportedly reach sexual maturity and start spawning after 2 or 3 years at a size of 300–350 mm. Females spawn 1 to 5 times per year during the warmer months. During spawning, 22,000–51,000 floating eggs are released into a 1-meter diameter nest cleared of vegetation. Fry hatch 1–5 days later, depending on water temperature. Eggs and fry are guarded by both parents. Juveniles consume plankton, small crustaceans, insects, and fish larvae and the adult diet consists primarily of fish but also frogs, crustaceans, and aquatic insects. For a more thorough review of Northern Snakehead biology and distribution please see Courtenay and Williams (2004), from which the above information is derived.

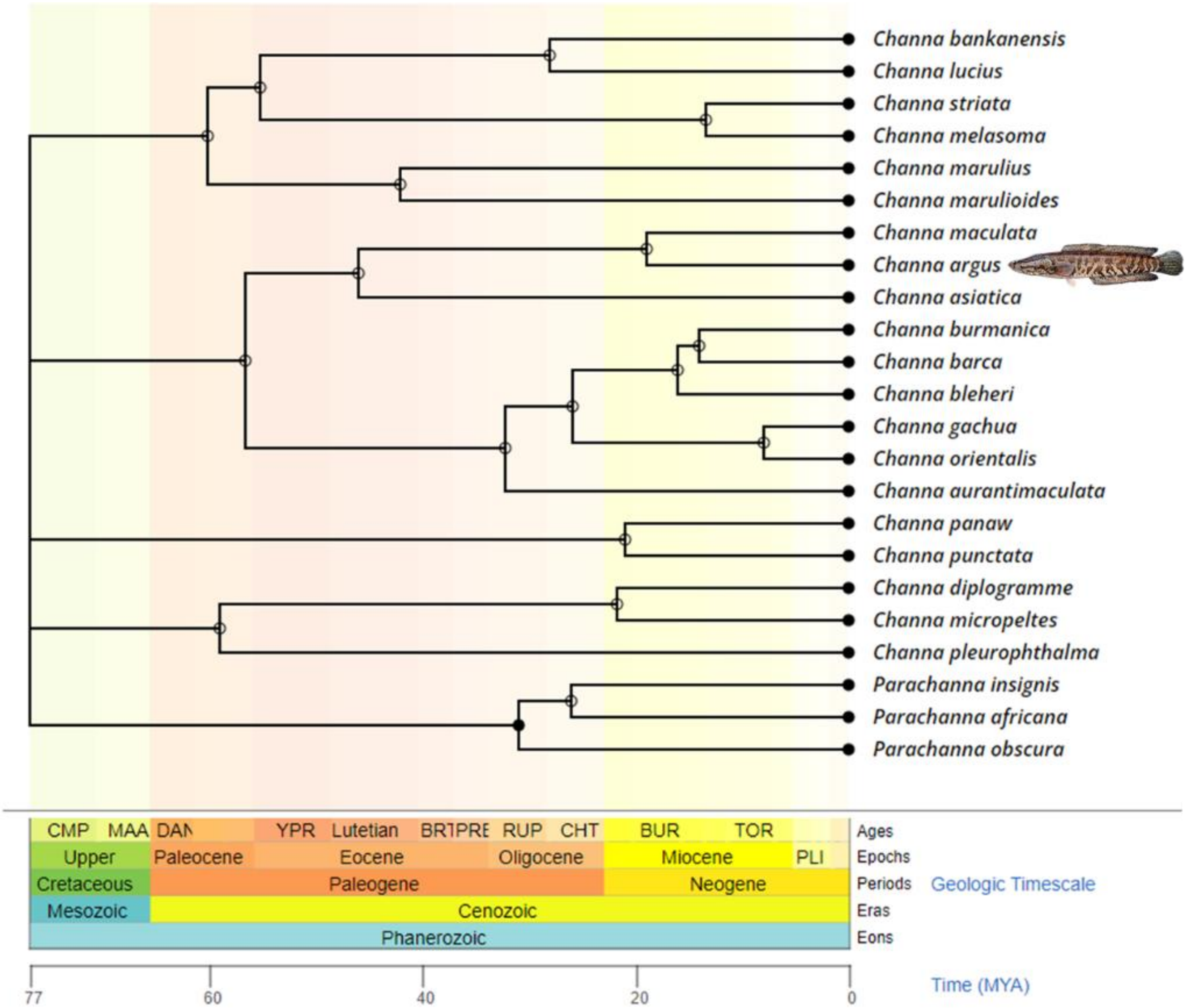

Figure 1. The Northern Snakehead, *Channa argus*, is a member of the family Channidae. Illustration by Susan Trammell. Phylogenetic tree from http://www.timetree.org/

III. History of introduction into U.S. waters

In much of their native range Northern Snakehead are considered a delicacy and are cultured for food (Courtenay and Williams 2004, ANSTF 2014, Benson 2019). For example, in China the Northern Snakehead is the commercially most important snakehead species and is cultured in ponds, rice paddies, and reservoirs (Courtenay and Williams 2004). Likewise, in Korea it is considered a valuable commercial fish (Courtenay and Williams 2004, Choi and Kim 2021). Northern Snakehead have been widely introduced outside their native range. Established populations are found throughout Japan where they were introduced from Korea in the early 20th century as an aquaculture food resource (Nakai 2009). They are established in the Aral Sea basin including rivers, reservoirs, and ponds of Kazakhstan, Uzbekistan, and Turkmenistan. This accidental introduction occurred in the early 1960s when Northern Snakehead, likely originating from China, were included with shipments of carp (Courtenay and Williams

2004). Finally, and most recently, Northern Snakehead have become established in the U.S., likely intentionally released into multiple water bodies after having been acquired at live food markets (Courtenay and Williams 2004, ANSTF 2014, Wegleitner et al. 2016, Benson 2019).

Before 2002, there were sporadic isolated reports of Northern Snakehead being caught in various locations around the U.S. (California, Florida, Massachusetts, North Carolina), but there was no evidence of reproducing populations (Courtenay and Williams 2004, ANSTF 2014, Benson 2019). In May 2002, a reproducing population was discovered in a pond in Crofton, Maryland. This population was eradicated using rotenone. However, in May 2004 Northern Snakehead were discovered in the Potomac River near Mount Vernon, Virginia (Odenkirk and Owens 2005). Eradication was not possible, but it was initially thought that higher salinity in the lower Potomac River might prevent spread to neighboring rivers. However, that was not the case, and over subsequent years Northern Snakehead colonized all major Chesapeake Bay tributaries (Love and Newhard 2018, Bunch et al. 2019, Fuller et al. 2022). Much of the colonization is inferred to be natural range expansion outward from the Potomac River through brackish water and into new river systems, particularly in the spring and early summer following heavy rain and flooding when salinity is lower. However, secondary human transport and illegal release of Northern Snakehead has aided and accelerated expansion (Benson 2019, Bunch et al. 2019). For example, introduction into Delaware's portion of the Nanticoke River around 2010 facilitated their spread within Delaware and Maryland's eastern shore (Love and Newhard 2018). Within the Chesapeake Bay watershed, Northern Snakehead have also been found in numerous ponds and reservoirs with no obvious connection to sources of natural colonization strongly suggesting human introduction (Bunch et al. 2019). Independently of the Potomac River introduction, Northern Snakehead were found in Meadow Lake in Philadelphia in July 2004, and from this area expanded outward in waters of the Schuylkill and Delaware Rivers (Delaware River watershed) in Pennsylvania, Delaware, New Jersey, and most recently New York. Finally, (since 2005) established populations of Northern Snakehead have been found in several lakes and ponds in New York City. Thus, within the mid-Atlantic and northeast, Northern Snakehead are now established in Virginia, Maryland, Delaware, Pennsylvania, New Jersey, and New York.

In 2008, Northern Snakehead were discovered in Arkansas's Big Piney Creek, apparently escapees from a fish farm culture operation. A massive eradication attempt using rotenone proved unsuccessful, and subsequent flooding eventually led to their expansion into the Mississippi River (Barnett 2019). In this region, Northern Snakehead are now established in both Arkansas and Mississippi. Finally, there have been several successful rotenone eradication efforts of small Northern Snakehead populations including in the Hudson River drainage in New York (Catlin Creek and Ridgebury Lake in 2008–2009) (Wegleitner et al. 2016, Benson 2019) and in 2019, of a population discovered in a private pond in Georgia (Roop et al. 2020).

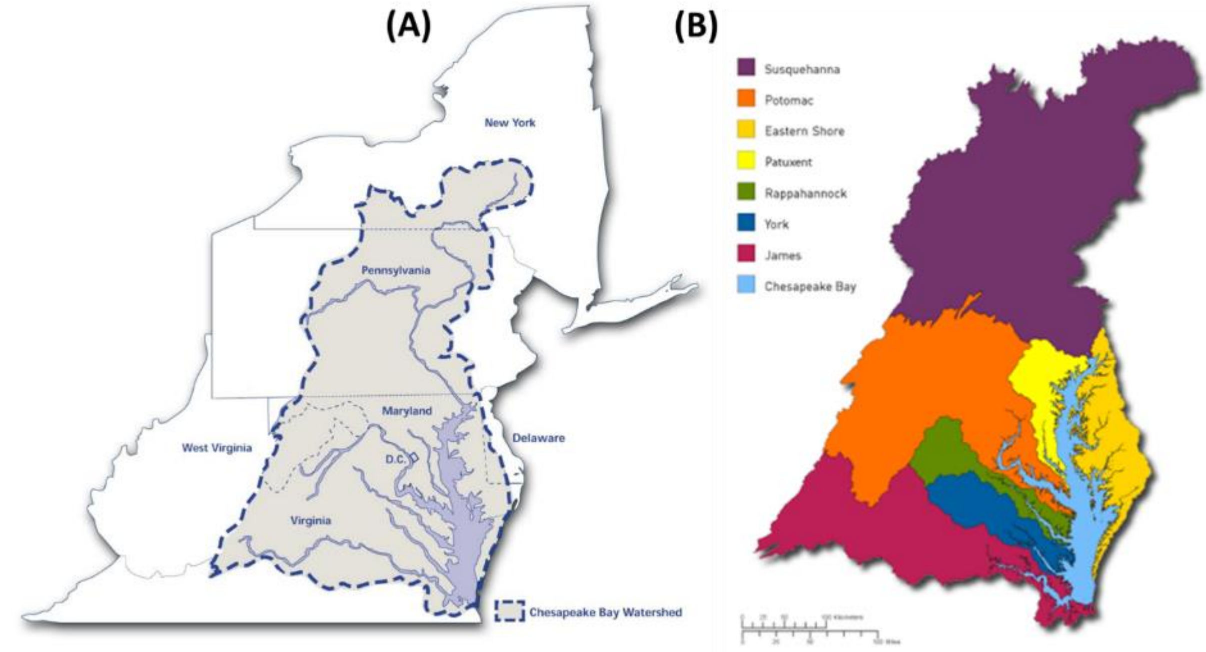

Figure 2. (A) The Chesapeake Bay watershed includes waters in six states (Delaware, Maryland, New York, Pennsylvania, Virginia, and West Virginia) plus all of Washington D.C. (B) Major river drainages of the Chesapeake Bay watershed. Sources of maps (A): https://dof.virginia.gov/water-quality-protection/learn-about-water-quality-protection/chesapeake-bay-watershed-and-virginia/ and (B): https://web.arch.virginia.edu/baygame/thebay/

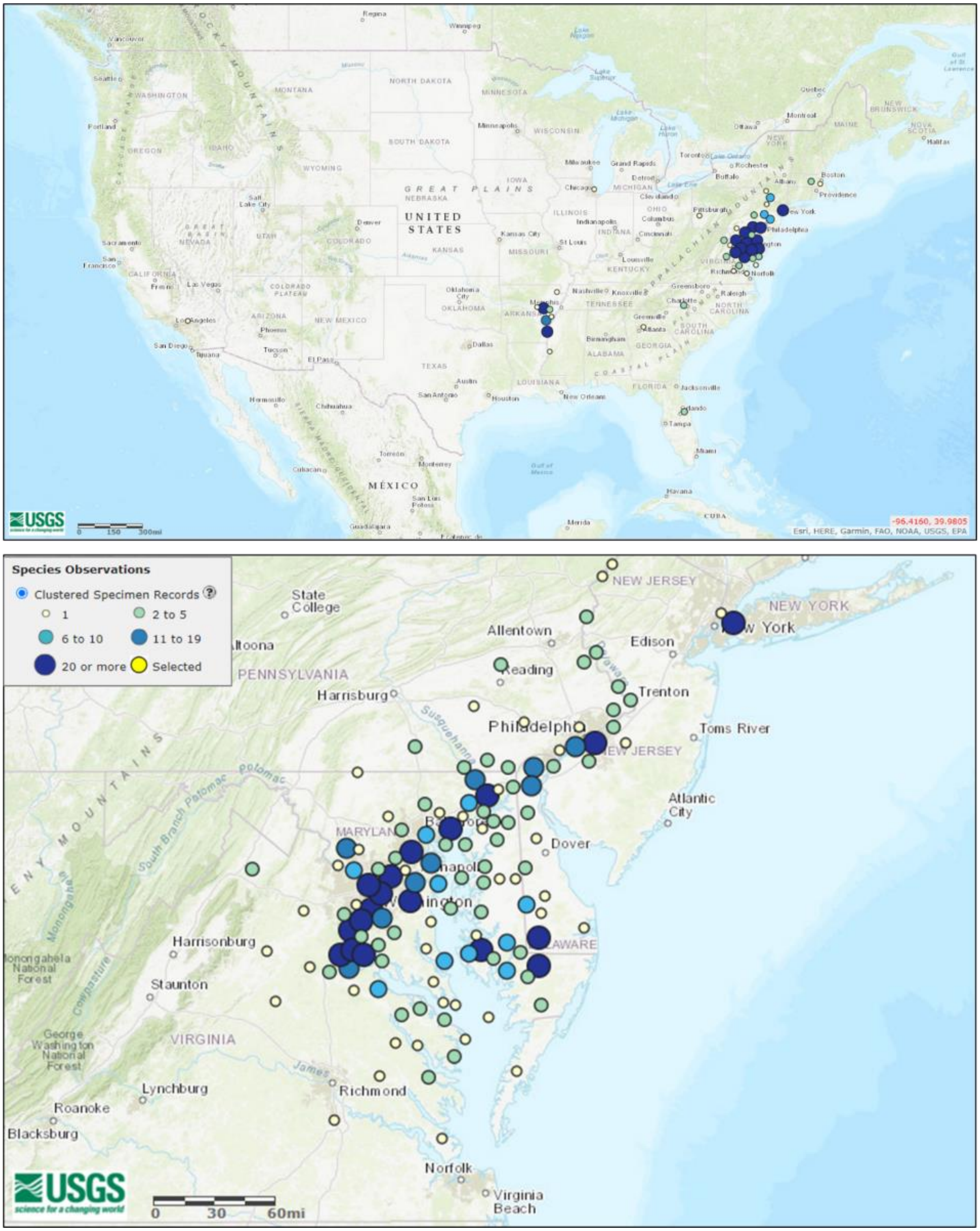

Figure 3. Distribution of Northern Snakehead in the United States and the Chesapeake Bay watershed (as of May 2022). Source: https://nas.er.usgs.gov/viewer/omap.aspx?SpeciesID=2265

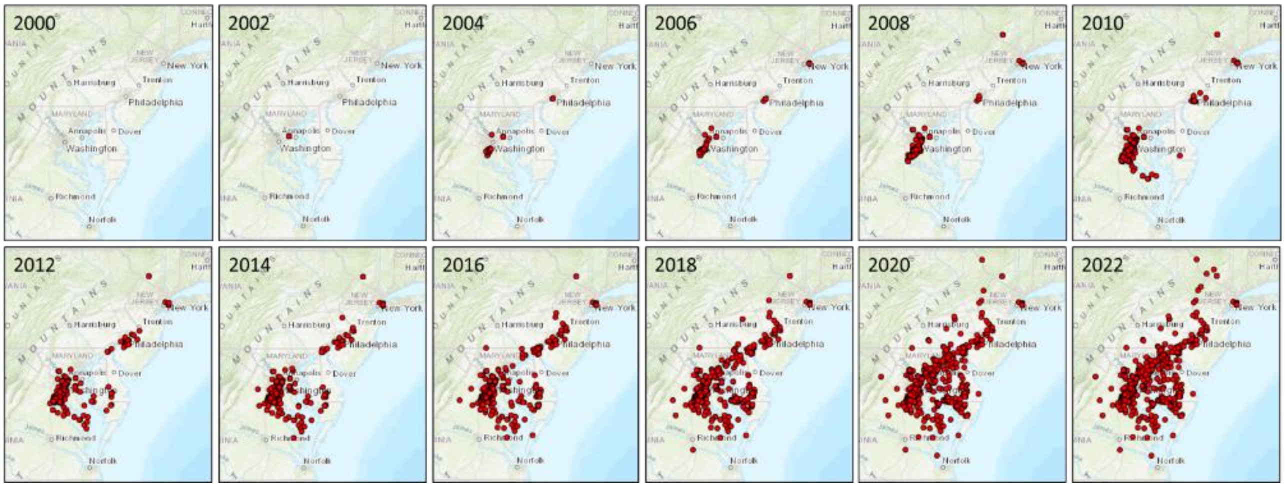

Figure 4. The spread of Northern Snakehead across the Chesapeake Bay watershed and beyond, between the years of 2000 and 2022. Cumulative occurrence data compiled by United States Geological Survey (USGS). https://nas.er.usgs.gov/queries/SpeciesAnimatedMap.aspx?speciesID=2265

IV. State of knowledge

In the 20 years since Northern Snakehead were first discovered in Crofton Pond, much has been learned about their biology in the Chesapeake Bay watershed. Below, is a summary of the state of knowledge and areas of uncertainty. This information is important background for setting realistic control and management goals and informing the potential effectiveness of various approaches.

Source, origin, genetics

Genetic sequencing of Northern Snakehead samples from various locations across space and time can help determine (i) if geographically distinct Northern Snakehead populations in the U.S. were independently introduced from different sources or originated from the same source population, (ii) the source of new colonizations (i.e., whether outward spread from original introduction site, or independent introduction from different source than original), and (iii) where in the native range original introductions into U.S. waters were derived from.

Genetic evidence indicates the Crofton Pond and Potomac River populations were the result of independent introductions, as no haplotype was shared between them (Orrell and Weigt 2005). Furthermore, the identification of six age-classes in the Potomac River population, suggests it may have preceded the introduction into Crofton Pond (Odenkirk and Owens 2005). Finally, genetic analyses of a subset of Northern Snakehead from the Potomac River suggest the source was likely a small number of founders (Orrell and Weigt 2005). The presence of unique haplotypes, with none shared between areas, supports the hypothesis that there were several independent introductions of Northern Snakehead into different waters (i.e., Crofton Pond in Maryland, Potomac River, Pine Lake in Maryland, Meadow Lake in Philadelphia, and Newton Pond in Massachusetts), and no two introductions came from the same original parental source (Orrell and Weigt 2005). Genetic evidence indicates Northern Snakehead from Meadow Lake in New York City resulted from multiple introductions (King and Johnson 2011). Wegleitner et al. (2016) found that the population in the Upper Hudson River – Catlin Creek and Ridgebury Lake (successfully eradicated) – was most genetically similar, and likely derived from, the New York City population. They further found that individuals from the Potomac River and some other rivers connected to the Chesapeake Bay represented a single genetic population indicating natural dispersal out of the Potomac River and/or human transport of individuals from this population into adjacent rivers. However, some individuals from the eastern shore of the Chesapeake Bay were found to be more closely related to individuals from the Hudson and Delaware Rivers than to those from the Potomac River (T. King, USGS, personal communication; cited in Love and Newhard 2018). Resh et al. (2018) found five distinct geographic and genomic clusters of Northern Snakehead in the U.S. – the Potomac River and Chesapeake basin, the Upper Hudson River basin, New York City and the Chinatown (Manhattan) fish market, Philadelphia, and Arkansas. Building on their earlier work, Resh et al. (2021) performed genomic scans on additional Northern Snakehead samples from the U.S. as well as specimens from their native range in China. They concluded that the Yangtze River basin in China is a likely source of the Northern Snakehead introductions into multiple areas of the U.S. including New York City, Catlin Creek and Ridgebury Lake (Upper Hudson River basin), and Philadelphia (Lower Delaware River basin).

Environmental tolerances, habitat modelling, and terrestrial locomotion

Northern Snakehead have broad temperature tolerance (0 to >30 °C), and habitat models suggest most, if not all, of the U.S. represent suitable habitat for colonization and establishment (Herborg et al. 2007, Poulos et al. 2012, ANSTF 2014, Kramer et al. 2017, Smith et al. 2019). They are obligate air-breathers, except during very cold temperatures when metabolism slows and oxygen demand is greatly reduced – such as when surviving under ice (Frank 1970 cited in Courtenay and Williams 2004). Water chemistry parameters including dissolved oxygen levels appear to be of little concern, and they are found in a broad range of conditions, though the need to come to the surface to respire effectively limits them to waters less than 2 meters deep. Northern Snakehead exhibit intermediate salinity tolerance. They have been observed resting in 10–12‰ in the Chesapeake Bay (Love and Newhard 2018) and caught at the mouth of the Potomac River where salinities range from 10–12‰ (ANSTF 2014). The upper salinity tolerance for Northern Snakehead is 18‰ (S. Minkinnen cited in ANSTF 2014, Bunch et al. 2019). The propensity for terrestrial overland movement was heavily emphasized in early media reports (Mason 2003). However, a laboratory study found Northern Snakehead voluntarily leave water only under extreme conditions including low pH (4.8), high salinity (30 ‰), and high dCO_2 (10% seltzer solution) (Bressman et al. 2019). Larger individuals placed on land exhibited axial-appendage-based terrestrial locomotion (i.e., crawling behavior) and this improved on complex substrates like grass (Bressman et al. 2019). Furthermore, if placed on land by humans or accidently by predators, and kept moist, they are capable of surviving for very long periods (i.e., several days). Nonetheless, natural over-land movement is an unlikely colonization pathway, unless greatly aided by flooding and/or driven by extreme environmental circumstances and over very short distances.

Abundance, density, population size, and expansion

In the Potomac River, Northern Snakehead were first collected in Dogue Creek, a small tributary near Mount Vernon, Virginia (Odenkirk and Owens 2005, 2007). Estimated relative abundance (fish/hour while boat electrofishing) from four Virginia creeks up and downstream of the original area of colonization in the Potomac River, indicate a dramatic increase (2004–2010) followed by a levelling off (2011–2015) and a recent decline (Odenkirk and Isel 2016, J. Odenkirk, VDWR, personal communication). Density estimates of Northern Snakehead in tributaries of the Potomac River ranged from 12 to 22 fish/hectare (ha) in Little Hunting Creek (Odenkirk and Isel 2016) to three fish/ha in both Nanjemoy and Chopawamsic Creek (Love et al. 2015a). Based on an estimate of habitat suitability across 44 major tidal tributaries of the Potomac River (7,093 ha of suitable habitat) and an extrapolated density estimate of three adult fish/ha, a preliminary estimated population size for the Potomac River was 21,279 (Love et al. 2015a).

In the Chesapeake Bay watershed, Northern Snakehead have expanded their range at a rate of approximately 2.7 sub-watersheds per year since 2004 (Love and Newhard 2018). If the observed rate of colonization remains constant, it is predicted it will take approximately 52 years to colonize the entire Chesapeake Bay watershed (Love and Newhard 2018). The number of sub-watersheds colonized increased with increasing May precipitation (Love and Newhard 2018), suggesting high spring rainfall and flooding may act as a spring-time dispersal trigger. Heavy rainfall increases connectivity of waterbodies and decreases salinities at the mouths of rivers increasing the likelihood that Northern Snakehead, and other freshwater species, may exit a river into the Chesapeake Bay and swim up adjacent rivers.

Diet and prey preference

Several diet studies of Northern Snakehead in the Potomac River have been conducted (Odenkirk and Owens 2007, Saylor et al. 2012, Isel and Odenkirk 2019). Odenkirk and Owens (2007) examined gut contents of 219 Northern Snakeheads from the Potomac River. Of the 15 fish species present, Banded Killifish (*Fundulus diaphanus*) were the most commonly encountered prey item (27% frequency of occurrence), followed by Bluegill (*Lepomis macrochirus*), Pumpkinseed (*Lepomis gibbosus*), and White Perch (*Morone americana*) (each 5% frequency of occurrence). Saylor et al. (2012) compared the diet of Northern Snakeheads (n=403) with that of Largemouth Bass (*Micropterus salmoides*), American Eel (*Anguilla rostrata*), and Yellow Perch (*Perca flavescens*) in the lower Potomac River. Over 97% of Northern Snakehead gut contents were fish, including 14 different species. Banded Killifish were the most common prey item by frequency (25.4%) and abundance (33.7%) but Bluegill were the most common prey item by weight (20.3%). Largemouth Bass, Yellow Perch, and American Eel were all present in Northern Snakehead gut contents, but represented a small portion of the total diet. Dietary overlap was significant only between Northern Snakehead and Largemouth Bass. The primary dietary difference between these two species was that Largemouth Bass consumed invertebrates (primarily crayfish) 10–20 times more frequently than Northern Snakehead. Although, recent diet analysis indicates crayfish are now more commonly observed in gut contents of Northern Snakehead collected from the Potomac River (J. Love, MDDNR, personal communication).

Isel and Odenkirk (2019) analyzed gut contents for 2,260 Northern Snakeheads from tidal rivers within the Virginia portion of the Potomac watershed (n=2,057, collected from 2004–2017) and Virginia lakes (n=203, collected from 2015–2017). Overall, fish accounted for 98% of Northern Snakehead diet items. A total of 30 prey types were identified from Northern Snakehead stomachs taken from rivers, whereas seven prey types were identified from lakes. In rivers, Banded Killifish (31%), Bluegill (31%), and crayfish (7%) were the most abundant prey types based on frequency of occurrence; while the most important prey based on the percent (%) wet weight were Bluegill (40%), Gizzard Shad (*Dorosoma cepedianum*) (10%), and Banded Killifish (8%). In lakes, Bluegill (68%), frogs (12%), and Yellow Perch (11%) were the most common prey items; similarly, Bluegill (65%), Yellow Perch (12%), and frogs (11%) contributed the most mass. Largemouth Bass accounted for only 2.3% of food items from rivers (ranking as the 9th most common food item by number) and 2.5% by wet weight (ranking as 11th). In lakes, no Largemouth Bass were found in the diets of Northern Snakehead.

Finally, Love and Newhard (2021) examined Northern Snakehead prey preference or electivity in a series of 10 controlled outdoor pond experiments. In each experiment, known numbers of a variety of prey species were added to a semi-covered pond containing a single Northern Snakehead; 14–24 days later the pond was drained and the remaining prey species were counted to determine which had been eaten and hence calculate prey preference. Prey fish species included in the experiment were those found in the diet of Northern Snakehead in the Potomac River including multiple representatives of four categories: (i) broad-bodied spiny-rayed fishes, (ii) fusiform, spiny-rayed fishes, (iii) golden, soft-rayed fishes, and (iv) other soft-rayed minnows or killifishes. Prey were eaten in approximately equal proportions indicating no evidence for strong prey preference in Northern Snakehead.

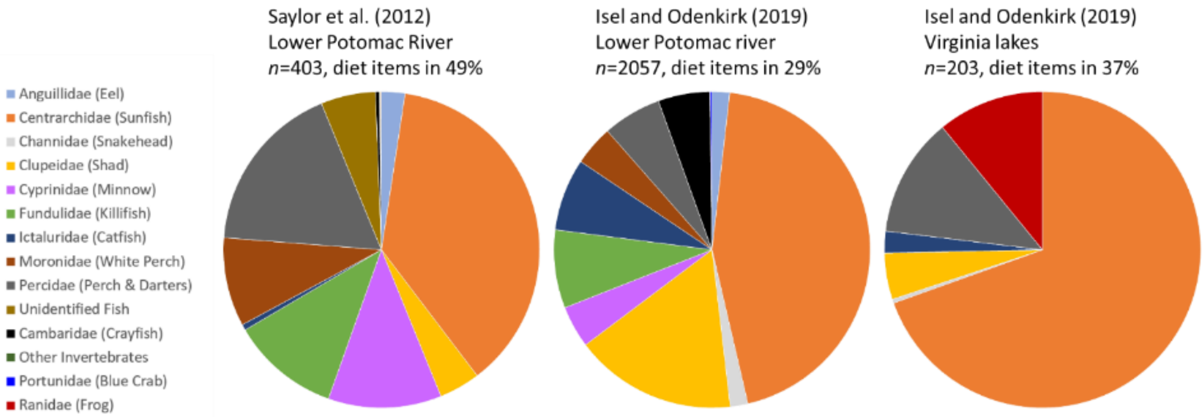

Figure 5. Summary of Northern Snakehead diet composition by percent wet weight.

Impacts in U.S. waters

An "aquatic nuisance species" or "invasive species" can be defined as *a non-native species whose introduction causes, or is likely to cause, economic or environmental harm or harm to human health* (Executive Order 13112[1]). There is no significant threat to humans from Northern Snakehead. To date, there have been three reports of people being bitten by Northern Snakeheads in the U.S. and sustaining minor injuries (Martin 2012, J. Newhard, USFWS, personal communication). All involved an individual placing their arm or leg into a school of fry and being bitten by an attending parent.

Another concern with the introduction of nonnative species is the potential for transmission of new diseases or pathogens. Health screenings of Northern Snakeheads captured in the Potomac River have revealed protozoal, monogenean, and trematode parasites, histological lesions consistent with helminths or trematodes, the presence of Largemouth Bass virus (LMBV), and mycobacterial infection (Iwanowicz et al. 2013, Densmore et al. 2016). LMBV has been isolated from 16 different fish species, including other non-centrarchids (Iwanowicz et al. 2013) and mycobacterial infection has previously been found in numerous fish species in the Chesapeake Bay watershed, most prominently Striped Bass (*Morone saxatilis*) (Densmore et al. 2016). Apart from one individual that exhibited abnormal swimming behavior and died three days post-capture, the Northern Snakehead with LMBV and mycobacterial infection did not show any signs of disease and appeared in good condition. The significance of these findings are unclear as the presence of LMBV and mycobacteria pre-dated Northern Snakehead arrival and the mechanism(s) of transmission between species are unknown. However, a concern is that Northern Snakehead dispersal or illegal introduction to new areas will introduce these pathogens or add to the number of vectors through which disease transmission is possible.

The greatest concern regarding the introduction and spread of Northern Snakehead within the U.S. is their potential negative impact on native or beneficial naturalized wildlife and aquatic communities through competition and predation (Courtenay and Williams 2004). Diet studies (summarized above) are consistent in indicating Northern Snakehead are highly piscivorous and opportunistic, consuming prey items most commonly encountered in their habitat. However, their actual impact on prey abundance, and indirectly on competitor species, can only be assessed empirically through comparisons of fish community abundance pre-and post- introduction.

Isel and Odenkirk (2019) compared relative abundance of Bluegill in two Virginia lakes (Burke and Brittle) for several years before and after Northern Snakehead were illegally introduced. Bluegill abundance was estimated using catch per unit effort (CPUE: in fish/hour) while boat electrofishing

[1] https://www.invasivespeciesinfo.gov/executive-order-13112

shoreline transects. Data did not support a decline in Bluegill abundance following Northern Snakehead introduction.

Cohen and MacDonald (2016) compared fish species abundance and CPUE in two connected New York City lakes (Meadow and Willow) following the discovery of Northern Snakehead. In June 2005, three Northern Snakeheads were captured in a fyke net in Meadow Lake. From July 2006 to October 2013, night-time boat electrofishing surveys were used to calculate CPUE for all fish species (including Northern Snakehead). Since discovery, Northern Snakehead CPUE fluctuated annually but did not show any trend, either increasing or decreasing. Furthermore, relative abundance of other fish species varied over time but have not progressively declined. Finally, overall species richness remained stable or increased over time.

Since 1984, George Mason University researchers have performed detailed aquatic monitoring in Gunston Cove, an embayment of the tidal freshwater Potomac River (de Mutsert et al. 2017, Jones et al. 2021), and one of the first Potomac River sites colonized by Northern Snakehead (Odenkirk and Owens 2005). Over this period there have been major shifts in the fish community concomitant with a substantial reduction in nutrient loading by a local water treatment plant, an increase in water quality, a decrease in harmful algal blooms, and the return of submerged aquatic vegetation. Specifically, although overall fish abundance did not change, there has been a decrease in abundance of open-water species, such as White Perch, and an increase in abundance of species that utilize submerged aquatic vegetation, particularly Banded Killifish. The shift in fish community somewhat coincided with the arrival of Northern Snakehead in the early 2000s, however, the authors attributed the fish community changes to the dramatic environmental changes (i.e., return of substantial submerged aquatic vegetation) that occurred over the same time period rather than impacts of Northern Snakehead or other invasive species.

Finally, Newhard and Love (2019) conducted fish community surveys in the Blackwater River drainage on Maryland's eastern shore from 2006 to 2008 and again in 2018–2019, before and after Northern Snakehead were first found in 2012. Fyke net surveys revealed that five of six sites had significantly different fish communities pre- and post-snakehead surveys. There was a reduction in biomass for most fish species (24 fish species decreased in relative abundance and 8 increased). The largest declines in relative abundance were observed for White Perch (*Morone americana*), Brown Bullhead (*Ameiurus nebulosus*), Atlantic Silverside (*Menidia menidia*), and Black Crappie (*Pomoxis nigromaculatus*), and the largest increases in relative abundance were observed for Common Carp (*Cyprinus carpio*), Atlantic Menhaden (*Brevoortia tyrannus*), Bay Anchovy (*Anchoa mitchilli*), and Gizzard Shad (*Dorosoma cepedianum*). Thus in 2018–2019 the fish community became dominated by Common Carp and Gizzard Shad, as the first and second most abundant species, compared to 2006 and 2007 when White Perch and Brown Bullhead were most abundant. Potential causes of the significant change in aquatic community could include the following, alone or in combination: the introduction and establishment of Northern Snakehead, the installation of a water control structure by the USFWS to limit saltwater intrusion into the watershed (Love et al. 2008), the substantial increase in relative abundance of Common Carp (+286%) causing habitat alteration, or unexplained interannual variability in the abundance of different species. Notably, much of the Blackwater region is protected as a National Wildlife Refuge and, besides the water control structure, land use and development appeared largely unchanged in the decade between fish surveys.

Largemouth Bass are an important recreational fishery in the Potomac River, and a series of papers addressed the potential for population decline in Largemouth Bass due to predation and competition with Northern Snakehead (Love and Newhard 2012, and Love et al. 2015b). Using age-structured population models of Largemouth Bass, Love and Newhard (2012) concluded that, given current levels of habitat co-occurrence between these two species (i.e., 10.6%) and measured predator-prey interactions, a 3.8% reduction in Largemouth Bass abundance might be expected. This minimal level of estimated population impact was consistent with Largemouth Bass surveys which did not find declines in abundance since the introduction of Northern Snakehead. However, their model also suggested that if Northern Snakehead continued to expand their range (leading to 100% habitat overlap with Largemouth Bass), and in the absence of control measures, there could be a 35.5% reduction in Largemouth Bass abundance. Love et al. (2015b) updated their earlier age-structured population model by including more refined estimates of Largemouth Bass fishing mortality in the Potomac River, recruitment compensation, and a parameter representing competition for spawning habitat. Model output indicated that the equilibrium Largemouth Bass abundance was, on average, 20% lower when Northern Snakehead were included.

In the Chesapeake Bay watershed, Largemouth Bass have been widely introduced as a game fish beginning in the 1880s, with Northern Snakehead establishment within the past 20 years. Japan's situation may be informative because it somewhat mirrors that of the Chesapeake Bay region, with the order of species introduction being reversed. Northern Snakehead were introduced to Japan 100 years ago and spread throughout the country to all prefectures except Okinawa, while Largemouth Bass were introduced much more recently (Nakai 2019). Some quotes from Nakai's (2019) review article on the history of snakehead introductions in Japan are interesting: "Some publications on local fish fauna documented that *C. argus* gradually declined following introductions of Largemouth Bass and Bluegill, likely through competition and predation (e.g. Tajima 1995, Maehata 2002)", "… all three snakeheads naturalized in Japan were excluded from this new list [Ecologically Invasive Species in Japan] suggesting minimal ecological invasiveness in Japan in comparison with other nonindigenous species selected in the list [including Largemouth Bass]", and finally, "According to Maehata (2002) and Nakai (2002), *C. argus* was often witnessed to coexist with small native fish, especially in comparison with dramatic faunal changes caused by intrusion of Largemouth Bass." In short, Japan's experience suggests introduced Largemouth Bass can have detrimental impacts on the native fish community. In the Chesapeake Bay watershed, we might expect this species to have already had impacts on the fish community, although how this affects the potential impact of another, more recently introduced, predatory fish species (Northern Snakehead) is unclear.

Examination of Northern Snakehead impacts in their native range may also be informative. Choi and Kim (2021) examined fish and cladoceran community structure in 30 wetlands in South Korea. Northern Snakehead are native to this region and both Largemouth Bass and Bluegill have been introduced. These authors found heavy fishing pressure in lowland wetlands led to reduced Northern Snakehead density and an abundance of Largemouth Bass and Bluegill, which subsequently reduced fish species diversity and altered the cladoceran community. In contrast, in more undisturbed upland wetlands, Northern Snakehead attained higher abundance, Largemouth Bass and Bluegill numbers were reduced, and fish species diversity was higher. This suggests that (native) Northern Snakehead can reduce the abundance of (introduced) Largemouth Bass and Bluegill populations, and fishing pressue can be an effective means of snakehead population control.

Can any general conclusions be derived from the body of work examining impacts of Northern Snakehead introduced into U.S. waters and beyond? Based on studies and information to date, initial concerns regarding widespread ecological devastation from Northern Snakehead introduction and expansion appear to be unwarranted. In general, Northern Snakehead may be more likely to have a discernable negative effect on the fish community in areas in which (i) they can obtain high density due to an abundance of suitable habitat, (ii) other top predator fish species (which may act as competitors and fill a similar ecological role) are absent or at low population density, and (iii) fishing pressure is minimal. The converse is that Northern Snakehead may have minimal, if any, discernable impact on the fish community in water bodies (i) where they remain at low overall density due to a mix of suitable and unsuitable habitat (which would also provide refugia for prey species), (ii) other top predator species are already abundant, and (iii) with intense fishing pressure. Moreover, the ability to detect impacts depends on (i) monitoring and (ii) factors affecting the ecosystem and its populations. In unreplicated natural systems, isolating the effect of Northern Snakehead impacts can be challenging, especially when aquatic communities are simultaneously responding to biotic disturbance, anthropogenic factors, and the establishment of other invasive species. As Northern Snakehead continue to expand their range, seemingly unabated, one concern is that they may have a negative impact in more pristine ecosystems or those less affected by other introduced fishes, for example vernal pool systems or shallow marshes. Another general concern is that introduced species are notorious for showing lags – lags before they begin to spread, lags before they attain high population density, and lags before their negative impacts are felt (Crooks 2005). A final concern is their potential impact in areas containing threatened or endangered fish, amphibian, and crustacean species (Appendix A; Courtenay and Williams 2004, ANSTF 2014).

Growth and reproduction

Northern Snakehead grow faster in the Potomac River than in their native range (average size of 394 mm in the first year) and appear to attain sexual maturity within a year (Odenkirk et al. 2013). No difference in growth rate was observed between males and females (Landis et al. 2011) although males may attain larger maximum size; the largest collected female, based on presence of ovaries, was 782 mm compared to the largest confirmed male, based on presence of testes, at 871 mm (Newhard 2015). The oldest individuals in the Potomac River, based on otolith annuli, were estimated to be 10 years (Odenkirk and Owens 2007, Phelps et al. 2019). Total annual mortality of adults was estimated to be 38% (Odenkirk and Owens 2007). Natural mortality may be caused by predation and disease. Predators of young include fishes (e.g., Eastern Mosquitofish *Gambusia holbrooki*; Landis and Lapointe 2010) and predators of adults include birds of prey (e.g., Osprey; Owens et al. 2008). Some diseases have been observed (Iwanowicz et al. 2013, Densmore et al. 2016) though fatality from them has not been documented in the wild.

Trends in female gonadosomatic index (GSI: gonad mass as a proportion of total body mass) suggest repeat spawning from May to September (Odenkirk and Owens 2007); female GSI rose rapidly in early April, peaked in early June when water temperatures reached 26° C, and gradually declined through August/September (Odenkirk and Owens 2007, Landis et al. 2011). The data on GSI of preserved fish preclude definitively distinguishing between asynchronous single spawns by multiple fish versus multiple spawns by individual fish spread over several months (Landis et al. 2011). However, synchronous patterns in GSI were not observed indicating individuals spawned asynchronously (Landis et al. 2011). Furthermore, recently spawned females frequently contained small inchoate eggs, suggesting they were beginning to develop new eggs, so the potential for multiple spawning may exist (Landis et al. 2011). Females have an average of 40,786 eggs (Odenkirk and Owens 2007) with some containing over 100,000 depending on female size (J. Love, MDDNR, personal communication). Counts of daily rings on otoliths from age-0 Northern Snakehead indicate hatching began in mid-June and lasted until early September (Odenkirk and Owens 2007).

The first Northern Snakehead nest was found on September 7, 2006 in a bed of *Hydrilla* in 1.5 meters of water and a temperature of 25° C. More than 500 juveniles of 20 mm in length were collected and an adult was removed while boat electrofishing (Odenkirk and Owens 2007). Landis and Lapointe (2010) described a nest and the nesting habits of Northern Snakehead in the Potomac River in detail. The nest was a circular disk, 1.8 meters in diameter with sand substrate amongst dense *Hydrilla* at a depth between 25 and 125 cm, depending on the tide. *Hydrilla* stems, clipped by the parents floated to the surface above the nest and created a matrix in which the eggs rested. The eggs hatched within three days at 3.4 mm total length and after transition to exogenous feeding in approximately the third week after hatching gained 2.3 mm of length per day (Landis et al. 2011). Both parents guard their eggs and the school of fry, after they leave the nest, for at least four weeks (Landis and Lapointe 2010) and up to nine weeks (Ling 1977 cited in Landis et al. 2011).

Adult body condition, as measured by residual weight, was above average in spring and fall, but below average in summer, corresponding to periods of spawning activity (Landis et al. 2011). Both sexes exhibited this pattern. This pattern was also evident in feeding; the number of fish without food in their stomach peaked mid-summer. These patterns suggest costs associated with reproduction and bi-parental nest guarding may limit feeding and cause reduced body condition. Most somatic growth by Northern Snakehead in the Potomac River occurred after the spawning season (Landis et al. 2011).

Habitat, daily activity cycle, and seasonal movement patterns

Northern Snakehead macrohabitat preferences are well understood; they prefer shallow, soft-bottomed, vegetated habitats (Courtenay and Williams 2004). In the Potomac River, primary habitat is shallow waters with floating or emergent vegetation (Odenkirk and Owens 2005), although they tended not to be captured in complete cover (Love et al. 2015a). They also were frequently captured near docks, shorelines, and in the upper ends of tidal freshwater streams (Love et al. 2015a). Tide had a relatively minor role on habitat selection (Lapointe et al. 2010). In the Potomac River, Northern Snakehead are diurnal (Lapointe et al. 2019); movement (based on individuals implanted with radio-transmitters and tracked for 24 hour period) and feeding data (gut content and level of digestion) indicated greater activity during daylight hours. Finally, individuals exhibited home ranges that overlapped substantially suggesting a lack of territoriality (Lapointe et al. 2013). However, they did not aggregate or shoal (i.e., they were solitary with pairs only found during the spawning period) (Lapointe et al. 2013, Love et al. 2015a).

Radio-tracking of Northern Snakehead in the Potomac River revealed most fish exhibited stable home ranges with an average size of 1.2 km^2 (Lapointe et al. 2013). That is, most fish stayed in the same embayment in which they were released after tagging for the entire study period and moved less than 1 km between seasons. However, some individuals exhibited long-distance spring-time dispersal. In the spring, 13 individuals, or 31% of fish dispersed an average distance of 18 km upstream (Lapointe et al. 2013). At least 10 dispersing fish crossed the Potomac River and 12 of 13 dispersers travelled upstream, with the greatest distance travelled being 39 km. However, upstream dispersal was limited by dams and Great Falls, so even longer upstream dispersal is likely (Lapointe et al. 2013), and has been subsequently confirmed (J. Newhard, USFWS, personal communication). Dispersing fish were consistently found in the same area post-dispersal, indicating they established a new home range (Owens et al. 2008, Lapointe et al. 2013). Together these results suggest the Potomac River represents a single patchy population with one third of individuals dispersing between patches each year. Fish crossed the main Potomac River channel which is 9–12 meters deep, much greater than their preferred habitat of <2 meters, suggesting deliberate dispersal behavior rather than generalized exploration of suitable habitat.

Despite having well understood habitat preferences and relatively limited home ranges, Lapointe et al. (2013) found that Northern Snakehead occupied different parts of the study area during four distinct seasons (pre-spawn, spawn, post-spawn, and winter). During the spring pre-spawn period, Northern Snakehead moved upstream into creek mouths and inner bays (Lapointe et al. 2010). At this time, a subset of the population exhibited natural long-distance (primarily upstream) dispersal (Lapointe et al. 2013, Love and Newhard 2018) and have been found congregating below dams (Bunch et al. 2019, Normandeau Associates 2021). It has been suggested that movement into upstream habitats may be triggered in response to precipitation and flooding (Lapointe et al. 2010, Love and Newhard 2018). Based on radio telemetry, Northern Snakehead appeared to move little during summer spawning months when they showed a preference for aquatic plants (Owens et al. 2008, Lapointe et al. 2013). The post-spawn period is characterized by heavy feeding and growth (Landis et al. 2011), greater movement than during the spawning period (Owens et al. 2008), and a shift to deeper water (Lapointe et al. 2013).

Lastly, in winter, fish moved into deeper downstream habitats and selected the warmest available water (Lapointe et al. 2010, 2013) with 10–30% of Northern Snakeheads completely inactive when water was less than 10° C (Lapointe et al. 2013). Cold water may cause a state of torpor in which Northern Snakehead cease movement for more than eight hours. Observations of Northern Snakehead burying in sediment when ponds dried (Courtenay and Williams 2004) and behavioral observations in the field while electrofishing, combined with the winter habitat preference for the softest substrate suggest they may burrow in the sediment as a means of cover.

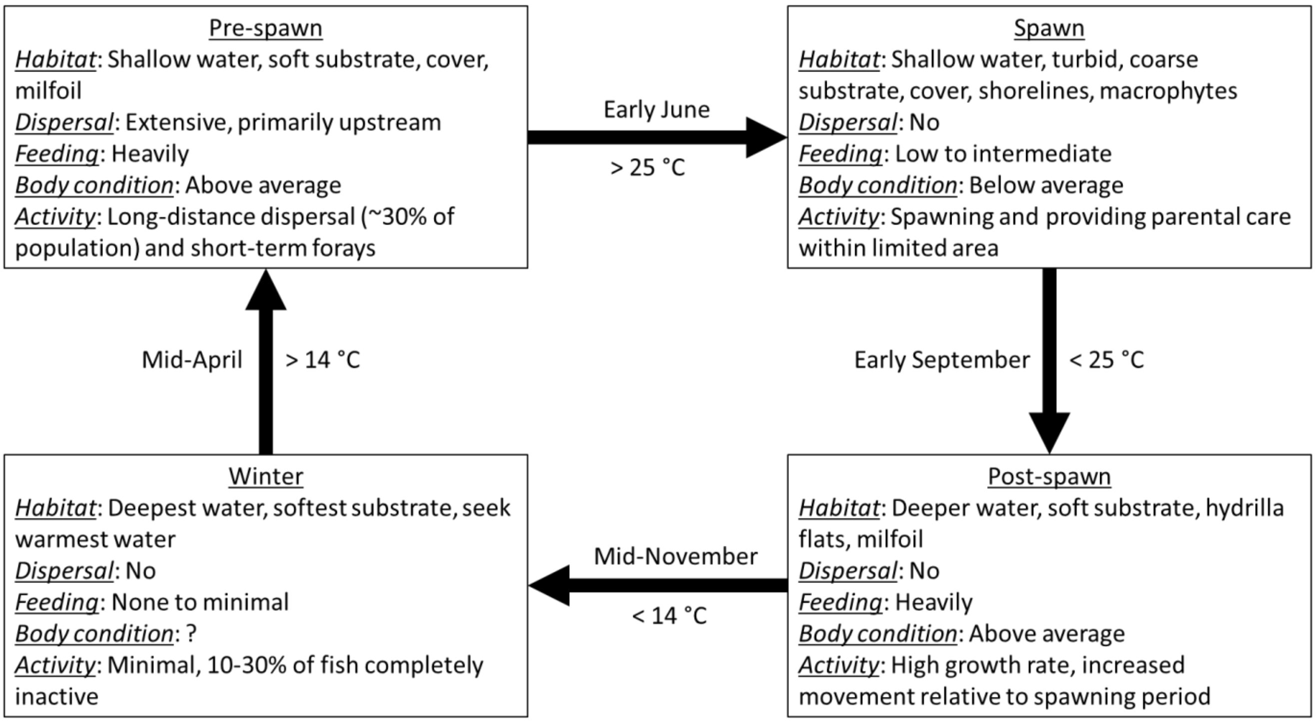

Figure 6. Summary of Northern Snakehead behavior across seasons in the Potomac River. Figure after Lapointe et al. (2010) with habitat data summarized from Lapointe et al. (2010), dispersal data from Lapointe et al. (2013), feeding and body condition data from Landis et al. (2011), and activity data from Owens et al. (2008), Lapointe et al. (2010), Landis et al. (2011), Lapointe et al. (2013), and Lapointe et al. (2019).

Angler, manager, and public attitude toward Northern Snakehead

There are a diverse set of constituents interested in Northern Snakehead which make development of a management plan for this species challenging. As Orth (2019) put it: “A Northern Snakehead management plan, to be effective, must anticipate that the multiple parties involved will have strong opinions and values and, therefore, will most certainly clash over management objectives.” Conflict is likely to arise because of (i) existing uncertainty regarding ‘harm’ resulting, or that may result, from Northern Snakehead introduction, and (ii) conflicting values including ecosystem health, biodiversity, naturalness, animal welfare, and anthropocentric values of nature (recreational and economic values). Furthermore, conflicting stakeholder values will confound management goals if not explicitly recognized and considered (Orth 2019).

Although data are rare, there is undoubtedly an increasing range of perspectives regarding Northern Snakehead. Lapointe et al. (2012) recognized that “Attitudes toward nonnative species may differ significantly among stakeholder groups, including resource managers and scientists, with different weightings applied to ecological and social considerations.” These authors compared five approaches to quantifying the impact of 73 nonnative fishes in the Mid-Atlantic. Interestingly, Northern Snakehead were given the highest socioeconomic impact rating and fourth-highest ecological impact rating (out of 73 nonnative species) by fish biologists, despite their recent introduction and (at the time) limited distribution, which the authors suggest was due to widespread negative media attention rather than empirical evidence of undesirable social or economic consequences (Lapointe et al. 2012).

In the summer of 2014, a survey of angler attitudes (n=113 interviews) toward the introduction of Northern Snakehead was conducted at six different Potomac River boat ramps (Agarwal et al. 2016). Of the anglers surveyed, 46.9% reported Northern Snakehead had a positive impact on their fishing enjoyment, 7.1% reported a negative impact, 1.8% were neutral, and 44.2% did not respond. The popularity of Northern Snakehead fishing in the Chesapeake Bay watershed is further reflected in popular-press articles[2], a Facebook group dedicated to snakehead fishing ‘Snakeheadlife’ that has over 10,000 members[3], and the growing number of privately organized Northern Snakehead fishing tournaments[4]. Although angler harvest is encouraged by state resource agencies (Love and Genovese 2019), some anglers view Northern Snakehead as a resource to be protected (Mathwin 2018), and there is worry amongst managers that the growing popularity of this fishery may encourage further illegal introductions (Pasko and Goldberg 2014, Love and Genovese 2019, Bunch et al. 2019).

V. Legal and regulatory framework

Prior to an importation ban, smaller species of snakehead were present in the U.S. in the aquarium trade and larger species in live-food ethnic markets (Courtenay and Williams 2004, Benson 2019). For example, Northern Snakehead were sold in ethnic live-food fish markets in New York City, St. Louis, Houston, Miami, Pembroke Pines (FL), and Orlando (Courtenay and Williams 2004) and were likely present in many others. Northern Snakehead populations in the eastern U.S. likely originated as releases from numerous live-food market shipments at different times and locations and possibly different sources in Asia (Benson 2019). An investigation revealed the population in Crofton Pond, Maryland resulted from the release of three live fish by a local resident who purchased them at a food market in New York City in 2000 and released them shortly thereafter (Boesch 2002 cited in ANSTF 2014, Benson 2019).

The snakehead family (Channidae) was given a rating of ‘high’ with respect to probability of establishment, consequence of establishment, and organism risk potential (Courtenay and Williams 2004). In October 2002, the USFWS added all species of snakehead to the list of injurious wildlife (Federal Register: 67 FR 62193) thereby prohibiting their live importation and interstate transport under the Lacey Act (18 U.S.C. 42). A 2017 D.C. Circuit Court decision held that the Lacey Act (18 U.S.C. 42) prohibits importation of listed species but does not prohibit transport of listed species between states of the continental U.S.[5] To this day, live snakehead or their eggs can only be imported with a permit for scientific, medical, educational, or zoological purposes or by federal agencies. For knowing violations, the Lacey Act imposes criminal penalties of up to five years’ imprisonment and a maximum fine of $250,000 for individuals and $500,000 for organizations for each offense. Importation records show that live snakehead imports to the U.S. increased from 1997 to 2002 then declined precipitously beginning in 2003 (ANSTF 2014).

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[2] https://www.in-fisherman.com/editorial/super-bass-aka-snakeheads/378545
[3] https://www.facebook.com/groups/snakeheadlife
[4] https://www.blackwatersedge.com/tournaments
[5] https://www.fws.gov/Implementation-USARK-V-Zinke

The Lacey Act does not regulate within-state possession, transportation, and sale of wildlife. However, under the Lacey Act additional charges may be filed for violating state laws prohibiting import and transport of snakehead (16 U.S.C. 3372). Fourteen U.S. states had laws prohibiting the possession of live snakehead that preceded the federal listing of snakehead under the Lacey Act (Courtenay and Williams 2004), and today all states legally manage snakehead to some extent, although violation penalties vary greatly from state to state (Appendix B; ANSTF 2014).

Love and Genovese (2019) provide an overview of Maryland's regulatory framework. In 2003, Maryland adopted a regulation prohibiting the selling, breeding, or possession of live Northern Snakehead (Code of Maryland Regulations 08.02.19.06). For Northern Snakehead, there are no regulations defining a season, a minimum size, or creel limit – thereby allowing for open harvest. Maryland's Natural Resources Police was tasked with enforcing the regulation that Northern Snakehead must be dead if held in possession. In 2013, the penalty for live possession of snakehead was increased to \$2,500 per fish, for up to 10 live fish per person (i.e., a maximum \$25,000 fine). Finally, in 2016, Maryland Department of Natural Resources (MDDNR) initiated a new commercial Northern Snakehead bowfishing license that allows holders to harvest and sell unlimited Northern Snakehead taken within tidal waters of the state[6].

The regulatory state of affairs, and public messaging in Maryland consists of three parts: (i) if Northern Snakehead are to be harvested they must be killed immediately, (ii) if Northern Snakehead are to be released they must be released immediately at point of capture, and (iii) the possession (and transport) of live Northern Snakehead is illegal. This tripartite regulatory framework, if followed by all individuals, would prevent Northern Snakehead from being introduced to new waterways by humans. Notably, it also accommodates catch and release anglers, or others who may be opposed to killing Northern Snakehead, by allowing them to release the fish immediately from where it was caught. This framework works for a state/area in which Northern Snakehead are firmly established and eradication is no longer a feasible goal, and the primary management objective is to prevent introduction to new areas, and a secondary management objective is to reduce biomass. In this framework, harvest can still be encouraged by authorities but it avoids potential conflicts and pitfalls associated with compulsory destruction policies (i.e., caught snakehead must be killed, DO NOT return to water) (Rice 2016, Orth 2019). Although live possession and transport of Northern Snakehead is prohibited in all states encompassing the Chesapeake Bay watershed, the language, messaging, and penalties for violation vary (Appendix B).

Implementation strategies and considerations

The 'National Control and Management Plan for Members of the Snakehead Family (Channidae)' listed six objectives, the first of which was to "Prevent importation into the U.S. by refining the Lacey Act and other regulations and improving the compliance and enforcement of this legislation" (ANSTF 2014). Although importation as a source of illegal introductions has not been eliminated, the Lacey Act listing and its continued enforcement has substantially lowered the probability of new snakehead introductions into the U.S. via this pathway (ANSTF 2014). However, once Northern Snakehead began reproducing in U.S. waters, this created significant secondary dispersal pathways – namely, the unintentional or intentional transport and release of captured Northern Snakehead by naïve individuals who are unable to identify snakehead or are unaware of the legal penalties for doing so, and the intentional illegal release to new areas to create fisheries either for human consumption or sport fishing.

As Northern Snakehead expand their range, more people will come into contact with them. It is likely that at least some of these individuals will be unable to identify Northern Snakehead or be aware of applicable laws and regulations. Fortunately, given the amount of media attention and time since

[6] https://law.justia.com/codes/maryland/2016/natural-resources/title-4/subtitle-7/section-4-701.1

establishment, Northern Snakehead are a highly visible and recognizable species. An angler survey at Potomac River boat launches indicated 78.4% of total anglers and 98.4% of anglers who reportedly had caught a Northern Snakehead were able to successfully identify them by picture (Agarwal et al. 2016). This survey was conducted in 2014, and since then these numbers are likely to have increased. The National Snakehead Plan recommended the need to conduct surveillance monitoring of unintentional transport pathways including eggs, juveniles, or adults being transported amongst live bait, fish stocks, and plants derived from areas with established snakehead populations (ANSTF 2014). Though not impossible, the biology of Northern Snakehead may make these pathways less likely compared to deliberate transport. Northern Snakehead eggs are bright yellow, clump together, are found atop distinctive looking nests, and have a relatively short incubation period before hatching (1–3 days); both eggs and juveniles are guarded zealously by their parents, juveniles travel in schools, and juveniles have the same body shape as adults. One challenge with enforcement of existing snakehead laws is anglers who wish to harvest Northern Snakehead being uninformed on how to kill the fish, or unable to do so, and therefore keeping live snakehead in their possession while fishing or transporting them home (Love and Genovese 2019). The solution to each of these issues is public outreach and communication efforts (Section X).

Being aware of existing snakehead laws and regulations, and yet deliberately flouting them by catching and introducing Northern Snakehead into new waterways for the express purpose of creating new fisheries represents a different problem that requires different approaches. This is undoubtedly a pressing concern as the popularity of Northern Snakehead fishing increases, and Northern Snakehead continue to turn up in isolated ponds and lakes (Benson 2019). Cases have been uncovered on social media of individuals filmed keeping captured Northern Snakehead in tubs in their backyard, and marketing live Northern Snakehead for the purpose of expanding the population (Love and Genovese 2019). To deter this illegal behavior, public outreach is needed that clearly and honestly explains the rationale behind existing laws and regulations while also acknowledging uncertainties and knowledge gaps (Section X). Other components might include ensuring existing penalties are proportionate to the seriousness of the offense and comparable across jurisdictions, finding new ways to enforce these laws and regulations, and further disincentivizing this behavior through community engagement and peer pressure.

Johnson et al. (2009) suggested that, in addition to hefty fines, a continent-wide lifetime fishing ban is an appropriate penalty for 'illegal stocking'. This would ensure that the perpetrator does not personally reap any benefit of their action. Another suggestion is creating mechanisms (toll-free hotline or website) in which anglers and the general public can report illegal fish stocking, and offering rewards for pertinent information (Johnson et al. 2009). Monitoring social media may be another means in which to identify and thwart illegal stocking activities. In concert with legal deterrence and penalties, it is encouraging to see new organizations devoted to Northern Snakehead fishing publicly advise their members of applicable law (i.e., do not transport live snakehead). Resource agencies could reach out to such snakehead angling groups in order to develop a good relationship, address any concerns regarding laws and regulations, and answer any questions.

VI. Early detection, potential for eradication, and rapid response

Early Detection and Rapid Response (EDRR) is defined as a coordinated set of actions to find and eradicate potential invasive species in a specific location before they spread and cause harm[7]. Northern

[7] https://www.usgs.gov/programs/invasive-species-program/science/early-detection-and-rapid-response

Snakehead early detection can come from public observations, angler reports, commercial fishery capture, appearance in fish passage structures at dams, fishery surveys by resource agencies, and environmental DNA (eDNA) presence. Eradication of newly discovered Northern Snakehead populations have been successful in small, isolated waterbodies (i.e., ponds) and when detected early in small, flowing, connected waters (i.e., marshes and creeks), but have not been successful in large waterbodies (i.e., rivers, extensive system of marshes and canals, and a reservoir). In the Chesapeake Bay watershed, Northern Snakehead are an established member of the fish community. Given the extent of distribution, there may be relatively few areas left within the lower portion of the watershed where eradication of a newly discovered Northern Snakehead population would be feasible. However, there are areas (particularly the upper Susquehanna River basin) where Northern Snakehead are not established and EDRR is of higher priority.

Early detection methods

State resource agencies have mechanisms in place (toll free number and/or website) to report observations or captures of Northern Snakehead (Appendix B). In states where Northern Snakehead are well established and the number of captures is very large, such reporting systems may no longer be actively maintained or anglers may no longer be requested nor inclined to make such reports. However, at the invasion front, or in previously uncolonized watersheds, such reporting systems are very important as they are often the first means of detection. Such was the case with Crofton Pond, Maryland; in 2002 a Northern Snakehead was caught by an angler, photographed, and this image was given to the MDDNR. This set into motion a chain of events that led to a lot of media attention and the eradication of this population. Public reporting systems should include the solicitation of as much detail as possible, including GPS coordinates and, where possible, photographs of the fish. Finally, such reports should be carefully vetted, prioritized, and followed up on by seeking additional information and, if necessary, conducting fisheries surveys. Electrofishing has become the primary method used by resource agencies to physically confirm the presence of Northern Snakehead. At the national level, the USGS maintains a central repository of Northern Snakehead occurrence data. This resource has been used in several research papers analyzing the spread of Northern Snakehead across geographic regions and through time. All agencies should report confirmed Northern Snakehead occurrence data to this website (https://nas.er.usgs.gov/SightingReport.aspx).

Environmental DNA (eDNA) is the DNA of an organism shed into the environment from feces, slime, mucus, gametes, shed scales, skin, or carcasses. eDNA can be detected by filtering water samples, and then sequencing the samples to determine the presence or absence of DNA of the target organism[8]. Detection of eDNA of the target organism could trigger additional verification steps, including traditional fishery sampling. This is important because eDNA presence in a waterbody could potentially be due to transport by birds or boats and may not indicate physical presence of the target organism. Due to its potential to detect organisms at low abundances compared to traditional sampling gear, it is an efficient method to screen and detect Northern Snakehead in waterbodies of concern and newly invaded areas. Researchers at the USFWS Northeast Fishery Center (NEFC) have developed and validated a Northern Snakehead specific genetic marker to verify presence of Northern Snakehead DNA in a water sample[9].

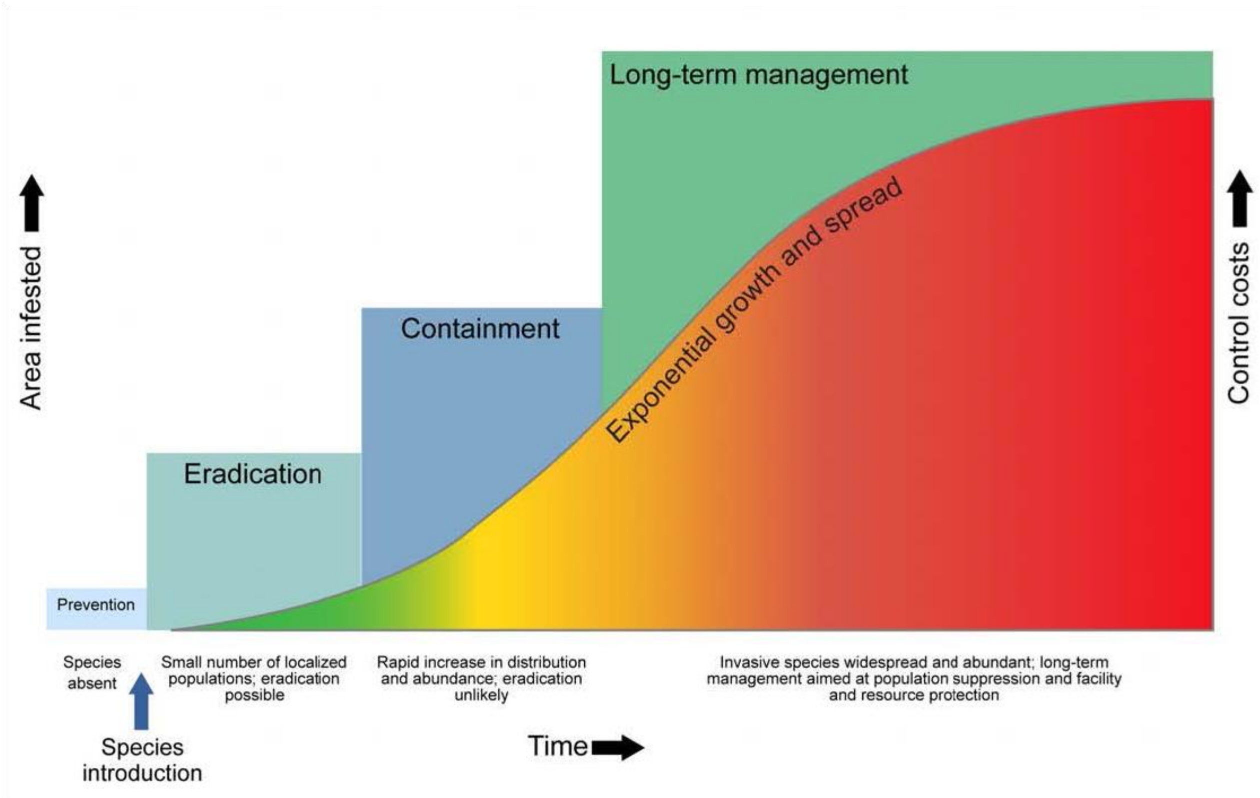
The NEFC genetics lab has been working with several partner agencies to perform Northern Snakehead eDNA detection in some regions of the Chesapeake Bay and adjacent watersheds. Since 2019, the Susquehanna River Basin Commission (SRBC), partnering with the NEFC, has conducted eDNA surveillance for Northern Snakehead in the Susquehanna River downstream of Harrisburg. There have been positive detections in the lower Susquehanna River downstream and upstream of Conowingo Dam

[8] https://www.usgs.gov/special-topics/water-science-school/science/environmental-dna-edna
[9] https://www.fws.gov/project/edna-and-next-gen-species-identification-northeast-fishery-center

(i.e., in Conowingo Reservoir), but not further upstream (A. Henning, SRBC, personal communication). The New York State Department of Environmental Conservation (NYDEC), in collaboration with the NEFC, is currently performing fine-scale eDNA sampling in New York's Basha Kill marsh in order to delimit the boundary of Northern Snakehead spread in the Delaware River watershed (S. Pearson, NYDEC, personal communication). They are also performing broader-scale sampling in the Upper Delaware River watershed focusing on suitable habitat areas for Northern Snakehead. However, they have no current plans to sample in the upper Susquehanna in New York, part of the Chesapeake Bay watershed – where Northern Snakehead are not currently found (S. Pearson, NYDEC, personal communication). This leaves the majority of the Chesapeake Bay watershed unsampled using eDNA technology.

Examples of eDNA sampling strategies include broad landscape-scale surveys as a means of early detection, targeted sampling after receiving a credible public report, or fine-scale mapping of an area of particular interest to delimit distribution. Given how widespread Northern Snakehead are in the Chesapeake Bay watershed (Figure 4), performing eDNA sampling in areas where Northern Snakehead are established is generally not warranted. Instead, the technology is better suited as a means of early detection on the fringes of distribution, where Northern Snakehead are not currently established but may do so in the future. Positive eDNA detection would initiate additional monitoring and verification steps (i.e., sampling effort to confirm physical presence of fish) followed by appropriate early control and management actions when they have the highest likelihood of succeeding (Figure 7). Additional eDNA sampling can also be used as a means to ascertain the effectiveness of existing prevention and control strategies by monitoring colonization and spread to new areas (i.e., metric of success). Focus areas could include isolated waterbodies (i.e., ponds, lakes, and reservoirs), areas above and below natural and artificial dispersal barriers such as waterfalls and dams, and yet uncolonized, upstream reaches where Northern Snakehead are expected to be found in the future (i.e., leading edge surveys). eDNA in aquatic environments lasts 7–21 days depending on environmental conditions[10]. It is more likely to accumulate and be detected in slow flowing or stagnant waters and can be carried away and distributed by currents. Therefore, putting prior thought into hydrological processes of potential sampling sites, as well as Northern Snakehead habitat, is important. Finally, there is the need to seek input from partners regarding sampling strategy and sites of particular concern or interest.

[10] https://www.usgs.gov/special-topics/water-science-school/science/environmental-dna-edna



Sources: National Invasive Species Council; U.S. Department of Agriculture; National Park Service; U.S. Fish and Wildlife Service; Rodgers, L, South Florida Water Management District; Department of Primary Industries, State of Victoria, Australia; and GAO. | GAO-16-49

Figure 7. The invasion curve for invasive species. Control costs increase as invasion spreads.

Review of past eradication efforts

Information from past Northern Snakehead eradication efforts, summarized in Appendix C, can provide a roadmap for future efforts. In most instances (six out of nine), the first discovery and report of Northern Snakehead in a new area came from an angler. In only two cases were they first detected by resource agencies. This emphasizes the importance of public reporting systems as a means of early detection. Following the initial reporting, the next step, in all cases, was for assessment by resource agencies. This typically involved electrofishing and/or use of nets to determine whether the population was reproducing, whether multiple age or size classes were present, the geographic extent of spread, and the nature and connectedness of the water body. This step could properly be described as information gathering. After considering costs versus benefits and likelihood of success a decision was then made whether to attempt eradication. In three cases eradication was not attempted (Appendix C). In Meadow and Willow lakes in New York City, it was evidently decided that eradication would not be attempted since these lakes drained to the sufficiently saline Flushing Bay, and there was no concern that the populations would expand to contiguous freshwater bodies. In Meadow Lake in Philadelphia, Pennsylvania Fish and Boat Commission (PFBC) biologists decided eradication would not be feasible, as Northern Snakehead had probably accessed adjoining waters of the nearby lower Schuylkill and Delaware Rivers through a maze of interconnected embayments and tidal sloughs. Finally, in the Nanticoke River it was determined that eradication would not be feasible due to the size of the system, tidal flows, and possible continued immigration from other areas (Martin 2012). In the other six instances, resources and personnel were mobilized, and an eradication attempt was mounted. Reproducing populations have been successfully eradicated from small, closed waterbodies (1/1: Crofton Pond) and relatively small, open waterbodies (2/2: Ridgebury Lake and Catlin Creek in New York state, and a series of private ponds and surrounding tributaries and marshes in Gwinnett County, Georgia). Eradication of reproducing populations from large, open waterbodies has not been successful (0/2: Potomac River, Big Piney Creek), nor has eradication from large, closed waterbodies (0/1: Conowingo Reservoir).

The greatest likelihood of successfully eradicating a population is when it is first discovered, and the population is small and geographically isolated (Simberloff 2009). This is especially true for Northern Snakehead given how quickly they reach maturity, and, in connected waters, their propensity for dispersal. Successful eradication efforts have often used low-tech, brute-force, scorched-earth approaches relying on mechanical, physical, or chemical means (Simberloff 2005, 2009). To date, every successful Northern Snakehead eradication effort has used rotenone, a general piscicide that kills all species of fish and size classes in treated waters. Drawbacks to the use of rotenone include that it kills non-target fish species, difficulty in obtaining use permits, and financial costs. The *double* rotenone treatment at Ridgebury Lake / Catlin Creek proved key in eliminating Northern Snakehead from the Hudson River watershed. Just over a year after the initial rotenone treatment, and following the discovery of two adult Northern Snakehead, a follow-up treatment was performed over a portion of the original treatment area using Marsh Master vehicles to more efficiently treat areas of difficult terrain (Flaherty 2019). This was apparently effective as follow-up surveys using electrofishing and eDNA resulted in no evidence of Northern Snakehead. Flaherty (2019) also credits New York State declaring an environmental emergency which prioritized resources and funding. In a similar vein, the National Snakehead Plan emphasizes the importance of having the plans in place ahead of time, to be able to react quickly to the discovery of a new population, when eradication efforts are most likely to succeed (ANSTF 2014).

<u>Rapid response</u>

The rapid response component of EDRR refers to a systematic effort to eradicate an invasive species while the infestation is localized. An effective rapid response requires having clearly defined agency responsibility and action paths, exchange of information between agencies and stakeholders, and appropriate roles and leadership – all of which may be facilitated by use of the Incident Command System (ANSTF 2014). There is a National Framework for EDRR (U.S. Department of Interior 2016), the National Snakehead Plan contains considerable detail describing each of the rapid response phases and their various sub-components (ANSTF 2014), and many states have rapid response protocols in state aquatic invasive species plans and sometimes in separate documents (Appendix E).

The rapid response can be divided into three phases: the response trigger, rapid response operations, and reverse trigger (ANSTF 2014). The response trigger is the threshold or incident that initiates the rapid response. This might include (i) agency observation or capture of one or more Northern Snakehead from a new location, (ii) one or more credible reports or sightings of Northern Snakehead from a new location, or (iii) eDNA detection and subsequent verification in a new area. Regardless of the trigger, information gathering (i.e., rapid assessment) should follow any credible report to help inform the next steps (U.S. Department of Interior 2016). If the cost-benefit ratio is favorable and there is reasonable likelihood of success then the eradication effort would enter the rapid response operations phase. This consists of, among numerous steps and actions, preparation and mobilization of resources and personnel, stakeholder notification, treatment selection and application, and follow-up monitoring. Finally, the reverse trigger is the point at which the lead agency and partners agree that the incident has been addressed thereby concluding the rapid response. Such triggers might include the compete detoxification of treatment area, conclusion of cleanup, or conclusion that eradication is not possible.

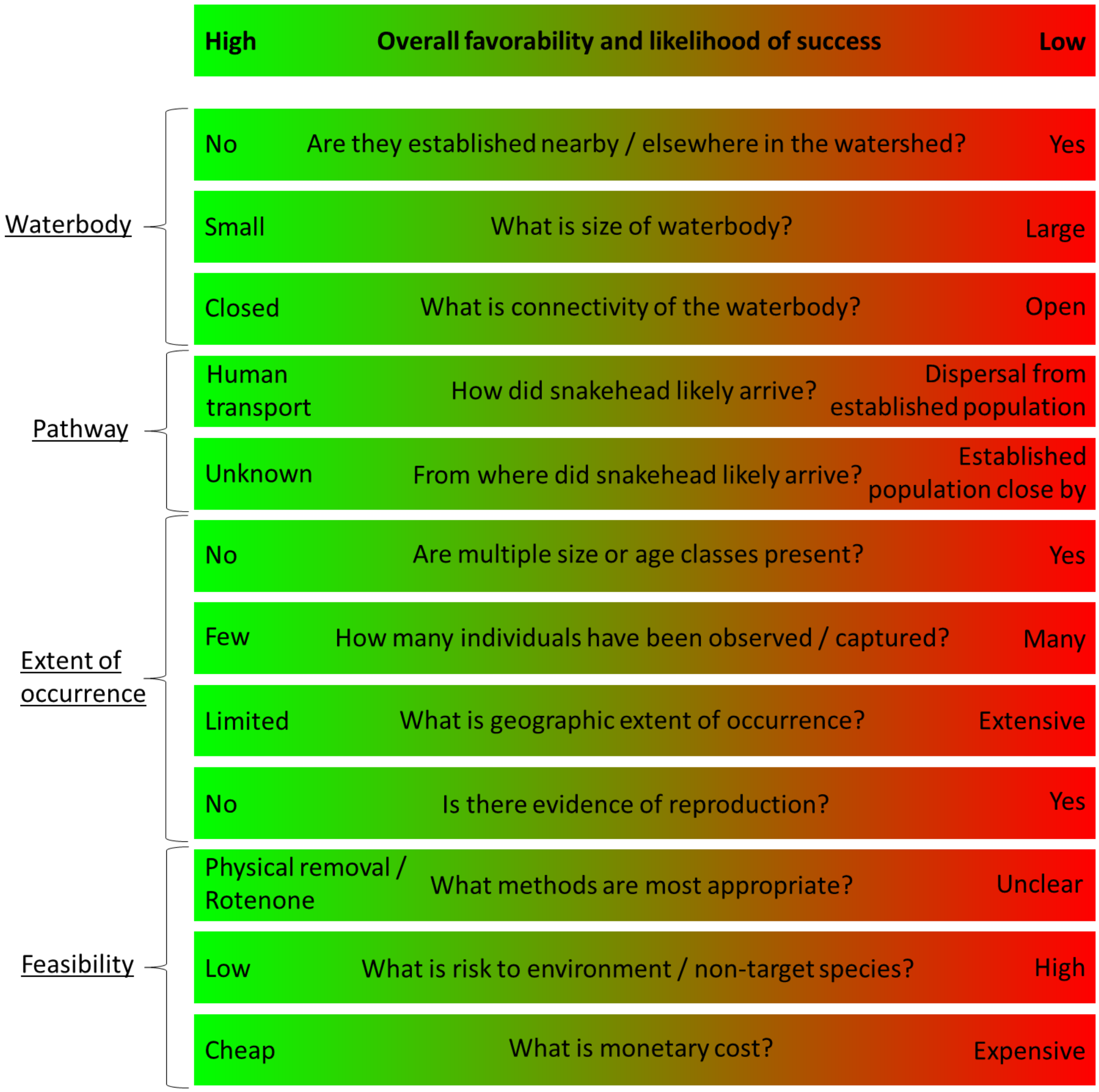


Figure 8. Diagram illustrating some of the key questions to be asked when deciding whether to attempt to eradicate a newly discovered Northern Snakehead population. These questions could be further formalized into a decision tree, tiered response matrix, or rubric with cutoff values or thresholds that guide the course of action, in concert with existing national, regional, and state rapid response plans.

Whether to attempt eradication following a new Northern Snakehead detection has become an increasingly important question given Northern Snakehead continued range expansion (Figure 8). In general, rapid response and a subsequent eradication attempt is likely less applicable to the lower Chesapeake Bay watershed given that Northern Snakehead are established and widespread in many regions, and more applicable to the Susquehanna River basin, where a series of hydroelectric dams has prevented Northern Snakehead upstream colonization. The Susquehanna River basin encompasses parts of three states: Maryland, Pennsylvania, and New York. Each of these states has its own aquatic invasive species plan and rapid response protocols (Appendix E). For Northern Snakehead, state resource agencies have initiated the rapid response and decided what if any action is to be taken following detection in state waters (see prior section for discussion of various responses). Moving forward, it may be desirable to have coordination between agencies with respect to what rapid response actions are desirable, feasible, and who is available to conduct which actions, particularly when dealing with Northern Snakehead detection around state boundaries.

Figure 9. Potential general actions in response to verified Northern Snakehead detection, as a function of invasion stage (see also Appendix D).

Summary and recommendations

Northern Snakehead are in an expansion phase within the Chesapeake Bay watershed, within adjacent watersheds (i.e., the Delaware River), and in other regions of the U.S. (the Mississippi River watershed). Several features make Northern Snakehead particularly effective at both colonizing and spreading, while also limiting the effectiveness of eradication efforts. They have broad environmental tolerances (temperature, salinity) and because they breathe air they are not limited by oxygen availability. They exhibit rapid growth and, in the Potomac River, sexual maturity is likely reached in their first year. They produce large numbers of eggs and potentially spawn multiple times per year while also providing extensive parental care to their offspring, thus likely ensuring relatively high survival. This combination of features is rather unusual; in general, fish species either invest heavily in a small number of offspring and provide extensive care, or produce numerous small offspring and provide limited care. In open waterbodies, a portion of the population disperses long distances, primarily upstream in the spring, and can quickly set up new home ranges in different areas. During this dispersal period they are willing to cross deep water and high flow. Their preferred habitat (i.e., shallow, muddy-bottomed, and highly vegetated) makes them fairly cryptic and not particularly susceptible to traditional commercial fishing gear. Netting and/or electrofishing is too selective on larger size classes to completely remove a population, even in an isolated situation (Courtenay and Williams 2004) and using chemical means of eradication (i.e., rotenone) has several limitations which limit its effectiveness to small waterbodies.

Finally, Northern Snakehead tend to be solitary, and do not school or aggregate, with the exception of when they form pairs during the spawning season and when multiple individuals can sometimes be found congregating below dams in the spring.

As boldly stated with respect to snakehead species introduced into U.S. waters: "Eradication from flowing waters or large lakes with connecting drainages is physically and fiscally impossible…." (Courtenay and Williams 2004). A compilation of eradication attempts of newly discovered reproducing Northern Snakehead populations in the U.S. mostly bears this out (Appendix C). Northern Snakehead are an established member of the U.S. fish fauna. Within the Chesapeake Bay watershed there are dozens of isolated waterbodies with established Northern Snakehead populations (Benson 2019, Bunch et al. 2019, Isel and Odenkirk 2019, Fuller et al. 2022) and they are found in, at least the lower reaches, of all major rivers connected to the Chesapeake Bay. Their continued expansion within the Chesapeake Bay watershed undoubtedly changes the calculation regarding whether to attempt eradication of a newly discovered population. One of several considerations is how geographically separated a newly discovered Northern Snakehead population is from existing established populations (Figure 9). The further from an established population, the greater the benefit of preventing establishment by attempting eradication. When Northern Snakehead are first detected in a new area or watershed the cost-benefit ratio of eradication is most favorable and the likelihood of success the greatest. However, given the extent of distribution, there may be relatively few areas in the lower Chesapeake Bay watershed that fit this criteria. This suggests the need to be realistic in how success is defined given what is practical. Considerable effort should be directed at preventing their colonization and establishment in new waterways, and potentially utilizing natural and existing artificial barriers to limit their spread.

VII. Limiting spread from established areas

With respect to limiting the spread of Northern Snakehead, there is a distinction to be drawn between closed waterbodies such as isolated ponds, lakes, and reservoirs, and open waterbodies including rivers and marshes connected to the Chesapeake Bay. In closed water bodies, the primary goal should be preventing the initial introduction of Northern Snakehead through human transport (Section V and X). Eradication may be feasible in some instances if several conditions are met including early detection, small waterbody size, favorable cost-benefit ratio, and if sufficient resources can be quickly amassed (Section VI). However, if established in closed waterbodies the spread of Northern Snakehead is limited and can only be brought about through human transport or heavy flooding. In contrast, within open waterbodies, Northern Snakehead can naturally disperse up and downstream. Here, focus should be maintaining natural and existing artificial barriers to upstream dispersal to limit their continued expansion within the watershed. These are realistically the areas in which measurable success can be achieved given Northern Snakehead proclivities for long-distance dispersal.

Natural barriers to fish dispersal include waterfalls and artificial barriers include dams and weirs. Canals, human-made waterways that connect two waterbodies (or even watersheds), might also represent reasonable targets for limiting dispersal, if no longer used for boat passage. The past several decades have brought increasing recognition of the costs artificial barriers impose by preventing native migratory fishes from reaching spawning grounds and the need to, where logistically and fiscally possible, eliminate these barriers from rivers and/or create mechanisms that allow fishes to pass. However, Northern Snakehead have repeatedly been found congregating below small dams in lower tidal creeks (Bunch et al. 2019), and below large dams in the springtime. Therefore, a tradeoff potentially exists between native migratory fish restoration efforts and preventing the upstream spread of Northern Snakehead and other invasive fish species. In such situations there may be differing perspectives, with different stakeholders or resource agencies coming to different conclusions after weighing the benefits of native fish passage versus the potential costs of invasive species spread. The continued expansion of Northern Snakehead within the Chesapeake Bay watershed is continually bringing this issue to the forefront.

Hydroelectric dams on the Susquehanna River

The Susquehanna River is the largest river on the U.S. Atlantic coast, supplies 50% of the freshwater input into the Chesapeake Bay, and its watershed covers 71,000 km^2 that span parts of three states: Maryland, Pennsylvania, and New York. There are four hydroelectric dams (Conowingo, Holtwood, Safe Harbor, and York Haven) on the lower Susquehanna within the first 65 miles of where the river empties into the Chesapeake Bay (Figure 10). Three of these dams have been complete barriers to upstream fish migration since their construction in the early 1900s. However, since the 1960s, the Susquehanna River has been the focus of multi-agency migratory fish restoration efforts under the aegis of the Susquehanna River Anadromous Fish Restoration Cooperative (SRAFRC)[11]. The hydroelectric dams on the lower Susquehanna River have operating licenses with the Federal Energy Regulatory Commission, and these licenses include provisions for upstream fish passage. The most downstream dams (Conowingo, Holtwood, and Safe Harbor) have fish lifts to facilitate the upstream movement of fish, while York Haven Dam has a passive fish ladder. For each dam, upstream fish passage efficiency standards have been developed for American Shad (a native anadromous species). At Conowingo and Holtwood these targets are included in the project licenses and gradual improvements have been made over the years. The fish lifts operate from late March to mid-June each year to support passage of American Shad (*Alosa sapidissima*) and River Herring (Blueback Herring *Alosa aestivalis* and Alewife *Alosa pseudoharengus*).

[11] https://www.srbc.net/srafrc/

Figure 10. The Susquehanna River, the largest of the Chesapeake Bay watershed, traverses three states: Maryland, Pennsylvania, and New York. There are four hydroelectric dams (Conowingo, Holtwood, Safe Harbor, York Haven) on the lower Susquehanna within the first 65 miles of where this river empties into the Chesapeake Bay. Source of map: Pennsylvania Fish and Boat Commission (https://www.fishandboat.com/Fish/PennsylvaniaFishes/Pages/SusquehannaShad.aspx)

Conowingo Dam, located approximately 10 miles from the Chesapeake Bay, is the first barrier fish face as they travel upstream in the Susquehanna River (Figure 11). Conowingo's East Fish Lift, operated since 1991, passes all fish that enter the lift into the Conowingo Reservoir above the dam. The lift operates in an elevator-like manner. Fish, attracted by flowing water released from the dam, enter a water-filled hopper or chamber. A gate closes and the chamber is lifted upwards to the upper edge of the dam. The water-filled chamber, and all fish contained within, is emptied into a runway. This runway contains a clear underwater viewing window and narrow choke-point through which all fish pass before entering the Susquehanna River. Thus all fish, having been lifted over the dam are identified and counted, through the viewing window, as they exit into the Susquehanna River to continue their upstream journey. The lift operates approximately every half hour during daylight hours during the spring. Conowingo's West Fish Lift, operated since 1972, works in a similar manner except fish are lifted upward a short distance (not over the dam), placed into holding tanks, sorted, and shad are either used in tank spawning efforts or transported by truck and released upstream of hydroelectric dams.[12]

Northern Snakehead were first observed in the lower Susquehanna River around 2015 (Figure 4). In 2017, a single Northern Snakehead was observed passing from the East Fish Lift into Conowingo Reservoir. Following this first arrival of Northern Snakehead, practices were modified to try to reduce or eliminate the passage of Northern Snakehead through the lifts. In 2018, no Northern Snakehead were observed in the lifts. In 2019, 81 Northern Snakehead were caught in the dam's lifts and prevented from being released into the reservoir[13]. In 2020, the fish lifts began operating late in the season (i.e., May 12th) due to the Covid pandemic. The following day, one Northern Snakehead was observed passing into Conowingo Reservoir. In subsequent days, 35 Northern Snakehead were observed (21 passed into Conowingo Reservoir, and 14 were collected out of the hopper). On May 15th the fish lifts were shut down for the season to prevent further passage of Northern Snakehead (Normandeau Associates 2021). Resource agencies electrofished Conowingo Reservoir and, combined with angler captures, removed 6 of the 21 Northern Snakeheads that passed upstream that season.

When the lifts reopened the following year (i.e., spring 2021) modified procedures were in place to manually sort all fish and thereby prevent the passage of Northern Snakehead, as well as Blue Catfish (*Ictalurus furcatus*) and Flathead Catfish (*Pylodictis olivaris*). In 2021, only the West Fish Lift operated at Conowingo. That year 952 Northern Snakeheads were removed, dispatched, and processed and all American Shad and River Herring were transported upstream. In 2022, both the East and West Fish lifts were in operation. However, the East Fish Lift stopped half-way up the dam and all fish were emptied into a holding tank. American Shad and River Herring were manually removed (i.e., netted) for truck transport and release in spawning habitat upstream of hydroelectric dams, invasive fishes were manually netted for dispatch and processing, and all other native fishes were returned to the tailrace. In 2022, 866 Northern Snakeheads were removed between the two fish lifts.

To date, eDNA sampling by the Susquehanna River Basin Commission suggests Northern Snakehead are present in Conowingo Reservoir, likely at low density. However, the next dam (i.e., Holtwood) is likely preventing natural upstream dispersal in the Susquehanna, as eDNA samples have been negative for all areas upstream of Holtwood Dam and below Harrisburg (A. Henning, SRBC,

[12] https://www.srbc.net/srafrc/docs/2012/Conowingo%20West%20Fish%20Lift%20Passage%202012.pdf

[13] https://news.maryland.gov/dnr/2019/06/13/northern-snakeheads-caught-in-conowingo-dam-fish-lift/

personal communication). Fish sorting facilities are only available at Conowingo Dam. Upstream dams do not have any means in place to selectively sort fishes, and are all that is preventing further upstream dispersal. For this reason, the fish lifts at Holtwood and Safe Harbor dams have not been in operation for the past two years.

The process of manual sorting of all native and invasive fishes at Conowingo Dam is not an optimal long-term solution. The sorting of the millions of fish that enter the lifts each spring and the associated amount of effort, cost, and handling stress imposed on the fish limit the feasibility of this as a permanent practice. There is a clear need for resource agencies and hydroelectric companies to work together and create a long-term strategy that adequately resolves these complex issues. In theory, selective fish passage offers a solution. This is a process that allows for the upstream passage of native anadromous species (American Shad, Alewife, and Blueback Herring) while simultaneously precluding the passage, or allowing for the removal, of invasive species (Northern Snakehead, Blue Catfish, Flathead Catfish). Ideally such a process would be i) accurate, ii) minimize handling of fish, iii) as automated as is feasible, iv) contain few steps, and v) can handle very large quantities of fish quickly.

Figure 11. Conowingo Dam on the Susquehanna River. The East and West Fish Lifts are indicated (A). From the vantage point of the East Fish Lift, five Northern Snakehead could be seen swimming against the dam's eastern wall (B & C). Photos taken May 18th, 2022.

Potomac River: Great Falls and the Chesapeake and Ohio Canal

From their presumed point of origin in Dogue Creek, a small tributary of the Potomac River near Mount Vernon, Virginia, Northern Snakehead rapidly spread upstream and downstream within the tidal portion of the Potomac River (Odenkirk and Owens 2005, 2007, Bunch et al. 2019). Approximately 10 miles northwest of Washington D.C. and 30 miles upstream of Dogue Creek is the fall line where the Potomac River transitions from the soft sediment of the Coastal Plain to the hard bedrock of the Piedmont. Here the Potomac River drops 60 feet in a dramatic series of waterfalls and rapids known as Great Falls. This marks the transition between the tidal or lower Potomac and the upper Potomac River. It was thought Great Falls would act as an insurmountable natural barrier to upstream dispersal (Starnes et al. 2011, Lapointe et al. 2013, ANSTF 2014, Love and Newhard 2018). This barrier also prevented boat passage thus limiting commerce and trade, hence between 1828 and 1850 the Chesapeake and Ohio Canal (hereafter C&O Canal) was constructed. This 184.5-mile canal runs parallel to the Potomac River and circumvents Great Falls with a series of locks and dams yet maintains numerous connections with the Potomac River both below and above the fall line. The canal stopped being used for boat passage in 1924, and today uses a series of weirs, spillways, and overflow areas to regulate water-levels and mitigate flood damage[14]. Starnes et al. (2011) recognized the potential of the C&O Canal to provide a slack-water conduit for Northern Snakehead to bypass Great Falls and colonize the upper Potomac River:

> *"The C&O Canal, with its iconic status as a major historical symbol and curiosity in the Potomac River area, will probably be maintained by the U.S. National Park Service in its present state for the foreseeable future. However, how it is managed in coming decades may determine its ability to function as both an isolated swath of lowland fish habitat and as a conduit for passage of fish upstream beyond Great Falls. With the invasion of such nonnative predators as Northern Snakeheads and perhaps Flathead Catfishes, this passage is of concern. It will be important, even in the face of river flood stages, to attempt to permanently maintain some completely dewatered reaches of the canal below Great Falls, especially given the Northern Snakehead's capacity, as an air breather, to survive for periods in habitats consisting of little more than deep mud."*

The National Snakehead Plan reiterated this concern: "Cascading water at Great Falls block upstream movement of snakehead in the Potomac, but there is concern that the adjacent C&O Canal could allow fish to bypass the falls" (ANSTF 2014). No Northern Snakehead were captured in targeted surveys of the C&O Canal in 2008 (MDDNR cited in Starnes et al. 2011). However, angler reports of Northern Snakehead being caught in the C&O Canal (between mile marker 19 and 22) occurred in 2014. USFWS and MDDNR personnel followed up these reports by surveying eight miles of canal between Great Falls and Violettes Lock. They found a juvenile Northern Snakehead, and later a park visitor photographed a Northern Snakehead guarding a school of fry in the canal within the surveyed area[13]. Finally in 2016, came the first confirmed report of a Northern Snakehead in the non-tidal portion of the Potomac River above Great Falls[15]. It likely colonized this area by travelling through the C&O Canal (Love and Newhard 2018). To date, there have been several observations of Northern Snakehead in the C&O Canal and main-stem Potomac River upstream of Great Falls (Fuller et al. 2022).

[14] https://news.maryland.gov/dnr/2015/07/21/invasive-snakeheads-found-above-great-falls/
[15] https://dnr.maryland.gov/fisheries/Documents/UpperPotomacRiverSnakehead.pdf

Figure 12. Great Falls represents a significant natural dispersal barrier in the Potomac River. The C&O Canal runs parallel to the Potomac River and has likely provided a means for Northern Snakehead to travel around this barrier and reach the Upper Potomac River. Photos taken June 18th, 2022.

Chesapeake and Delaware Canal: A conduit between watersheds

The Chesapeake and Delaware Canal (hereafter C&D Canal) is a 14-mile long, 450-foot wide, and 35-foot deep shipping canal that connects the upper Chesapeake Bay to the lower Delaware River[16]. The canal, completed in 1829, is now a major commercial waterway. By 2011, Northern Snakehead were present in tributaries of the lower Delaware River, close to the C&D Canal entrance on the Delaware side, having likely spread downward from their point of origin in Meadow Lake Philadelphia (Figure 4; Fuller et al. 2022). By 2015, Northern Snakehead were present in the upper Chesapeake Bay, near the C&D Canal entrance on the Maryland side, having spread upward from their point of origin in the Potomac River and eastern shore of Maryland (Figure 4; Fuller et al. 2022). It was known that many migratory fishes, including Shortnose Sturgeon (*Acipenser brevirostrum*) (Welsh et al. 2002) and Striped Bass (*Morone saxatilis*) (Koo and Wilson 1972) migrate through the C&D Canal. Additionally, Northern Snakehead are capable of traveling long distances in the Potomac River. For example, Lapointe et al. (2013) tracked movement of Northern Snakehead in the Potomac over 150 km of river and suggested that they could likely travel even farther upstream than the maximum observed distance of 40 km if not for barriers to dispersal such as dams and Great Falls. Similarly, a tag and recapture study in the Potomac River documented a maximum migration distance of 88 km (J. Newhard, USFWS, personal

[16] https://www.nap.usace.army.mil/Missions/Civil-Works/Chesapeake-Delaware-Canal/Canal-History/

communication). Finally, tributaries to the C&D Canal appear to contain suitable long-term Northern Snakehead habitat and kayak anglers target them in these areas (M. Steiger, Delaware Department of Natural Resources and Environmental Control, personal communication). This all suggests that the C&D Canal allows for Northern Snakehead movement between the Chesapeake Bay and Delaware River watersheds.

Preliminary results of a tagging program in the Upper Chesapeake Bay confirmed use of the canal to migrate between watersheds (J. Newhard, USFWS, personal communication). A Northern Snakehead tagged on 5/11/2022 in the vicinity of Elk River Park near Elkton, MD was reported caught by a fly fisherman on 5/23/2022 in Darby Creek on John Heinz National Wildlife Refuge, next to the Philadelphia International Airport. Assuming some other person did not move the fish, the most likely scenario is this fish swam from the Elk River, of the Upper Chesapeake Bay, through the C&D Canal and up the Delaware River to Darby Creek. This fish swam approximately 86 river km in 12 days, or at least 7.2 river km per day. Finally, a genomic analysis found evidence for low levels of genetic admixture (i.e., gene flow) between Northern Snakehead samples from the Chesapeake Bay and Delaware River watersheds (Resh et al. 2018), and 1 of 54 Northern Snakeheads from the Chesapeake Bay watershed clustered genetically with fish collected from Philadelphia in the Delaware River watershed (Resh et al. 2021). The apparent movement of Northern Snakehead through the C&D Canal reinforces lessons learned from earlier studies in the Potomac River, namely that in open river systems some Northern Snakehead are willing long-distance dispersers and can travel quickly through non-preferred habitat, such as a deep shipping channel.

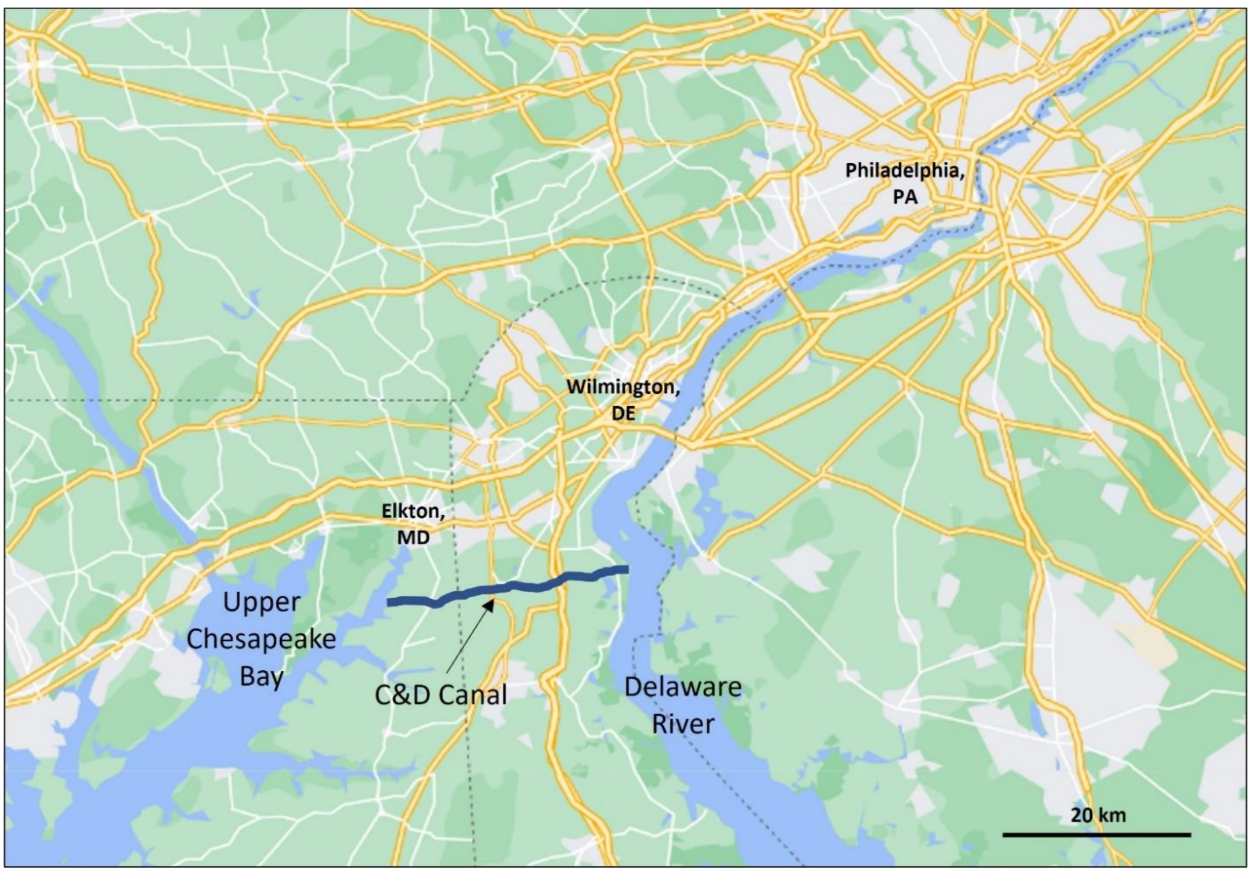


Figure 13. The Chesapeake and Delaware (C&D Canal) connects the Chesapeake Bay and Delaware River watersheds. It is proving to be a pathway in which Northern Snakehead can travel.

Summary and Recommendations

Preventing establishment in new isolated waterbodies should be a priority within the Chesapeake Bay watershed. This is best brought about through education, outreach, and law enforcement efforts designed to disincentivize illegal stocking. Limiting the spread of Northern Snakehead within connected, flowing waterbodies – for example, rivers connected to the Chesapeake Bay – is a challenging proposition. Perhaps the best chance for measurable success is to take a landscape-level approach and identify the existence of natural or artificial dispersal barriers and utilize these to slow or stop progression. Waterfalls and dams represent strategic chokepoints limiting upstream dispersal, and in spring, Northern Snakehead have repeatedly been found congregating below such barriers. Maintaining dams as barriers to upstream fish movement simultaneously prevents native anadromous species from reaching their traditional spawning grounds and prevents access of invasive species to upstream river reaches. This creates a tradeoff that puts native migratory fish restoration efforts in conflict with invasive species control measures. Selective fish passage at dams – a process that allows passage of native species but excludes non-native species – represents one potential solution to this complex issue, and research on this front is urgently needed.

In addition to major dams on the mainstem Susquehanna, there are numerous smaller dams on tributaries to the Susquehanna, and most other rivers in the Chesapeake Bay watershed. The ability of Northern Snakehead to traverse small low-head dams and those with fish ladders is not well known. However, dam size and structure may be a key factor in spread limitation and there may be a distinction in strategy depending on dam size. For example, a small dam on a tributary may not be a blockage to Northern Snakehead when water levels are high, in which case it would not make sense to maintain the dam as a barrier to Northern Snakehead spread if it was otherwise beneficial to remove this barrier.

There currently is no feasible way to limit spread within open waterbodies when dispersal barriers are not present. However, there may be opportunity to stem spread in adjacent watersheds by eliminating potential for dispersal through abandoned canals subject to occasional flooding. Finally, there is a place for broad public involvement in reducing Northern Snakehead biomass in established areas, through harvest, and potentially targeted control and management efforts by resource agencies in specific areas most likely to achieve measurable successes and/or of conservation concern.

VIII. Control and Management

"*Each instance where snakehead are managed will be unique as to whether the costs of control are greater than the possible harm of snakehead to the environment*" (ANSTF 2014).

"*To institute a control program that cost-effectively minimizes negative impacts from ANS [Aquatic Nuisance Species], the negative impacts from ANS must be well-documented*" (MDDNR, Maryland Aquatic Nuisance Species Management Plan).

The two most extensive control and management programs for invasive fish species in the U.S. are for Sea Lamprey (*Petromyzon marinus*) in the Great Lakes, and invasive carp in the Mississippi River watershed and Great Lakes basin. Sea Lamprey entered the Great Lakes in 1920 and by 1947 devastated commercial and recreational fisheries. Since 1954, Sea Lamprey populations have been intensively managed by the Great Lakes Fishery Commission, which currently employs an Integrated Pest Management strategy that includes chemical control using lampricides, trapping spawning adults, sterile male release, physical and electric barriers to prevent upstream migration, and use of pheromones as an attractant or deterrent (Schloesser et al. 2019). Invasive carp, including four species – Black

(*Mylopharyngodon piceus*), Grass (*Ctenopharyngodon idella*), Bighead (*Hypophthalmichthys nobilis*), and Silver (*Hypophthalmichthys molitrix*), all native to Asia – escaped aquaculture ponds in the Southeast U.S. in the 1970s and made their way into the Mississippi River. They have subsequently spread throughout much of the Mississippi River watershed to the doorstep of the Great Lakes (Invasive Carp Regional Coordinating Committee 2022). They outcompete native species for food often attaining extremely high densities, can lower water quality, and have negative ecosystem impacts. The Invasive Carp Regional Coordinating Committee, composed of over 25 member agencies, performs a variety of actions including monitoring and preventative measures such as creating and maintaining an electric barrier in the Chicago Sanitary and Ship Canal to prevent movement from the Mississippi River watershed to Lake Michigan. Control and management activities include researching new technologies and gear for capturing invasive carp and contracting commercial fisherman to remove massive numbers of carp from the upper Illinois and lower Des Plaines Rivers[17,18]. The cost of implementing each of these control and management approaches ranges from tens to hundreds of millions of dollars annually (lamprey, over 10 million annually[19]; invasive carp, 283 million in 2022: Invasive Carp Regional Coordinating Committee 2022). The biology and impacts of Northern Snakehead differ compared to both Sea Lamprey or invasive carp, and as such the management approach must also differ.

Control and management practices are designed to reduce population size, and minimize potential negative effects, when eradication is no longer a realistic goal (Britton et al. 2011). When devising control and management strategies for Northern Snakehead two primary questions need to be considered. First, what are the negative effects of Northern Snakehead? Until negative effects are demonstrated, labor and cost-intensive management practices designed to greatly depress abundance seem unwarranted. Instead, resources may be better directed toward (i) preventing their transport to new watersheds, (ii) limiting their spread within the Chesapeake Bay watershed, and (iii) within the control and management realm, encouraging angler harvest as a cost-effective means of reducing Northern Snakehead biomass across the entire watershed. Second, how is success defined in terms of measurable outcomes? If costly and labor-intensive control and management measures were to be implemented clear metrics of success are needed to judge their effectiveness. This raises many issues, some of which have been addressed using modelling, and others for which information is currently lacking. A key question in determing the effectiveness of control and management efforts is how a population is defined (e.g., the entire watershed, each sub-watershed or major river basin, each tributary, or each local site within a tributary). In an open system, this scale matters given the interconnectedness of populations and the question as to whether localized effort in reducing population size would have any lasting impact. As Lapointe et al. (2013) note: "Northern Snakehead in all Potomac River habitats likely interact and function as a single population of both mobile and sedentary individuals. This may limit the success of efforts to eradicate or control the species locally, because any given area could quickly be recolonized from other habitats."

Overview of management options

Three categories of methods for population control include biological, physical, and chemical (Kolar et al. 2010). The use of biological agents to control an unwanted fish species – including releasing a predator or disease agent that affects the target species, or genetic manipulation and release of sterile triploid or transgenic individuals – are inherently risky due to the potential for unintended consequences and/or require significant research and testing. Biological agents have not been used to eradicate or control existing populations of Northern Snakehead. Physical control refers to any mechanical means by

[17] https://invasivecarp.us/control.html
[18] https://www.doi.gov/ocl/asian-carp-control-0
[19] https://2001-2009.state.gov/g/oes/ocns/inv/cs/2305.htm

which fish are removed from the waterbody (e.g., angling, bowfishing, removal at dams, netting, electrofishing, or draining). Such physical methods have been widely employed for Northern Snakehead control. Finally, chemical control refers to the use of fish toxicants (e.g., ichthyocides, piscicides, or fish poisons). The general piscicide rotenone has been used in several Northern Snakehead eradication attempts.

Below, existing control and management options are reviewed in light of Northern Snakehead biology. All methods have limitations and drawbacks and are likely to be most effective under certain conditions or seasons. Specifically, some methods are better suited to eradiation attempts and others to reoccurring long term population control. In general, winter seems to be a 'dead period' in terms of control and management because Northern Snakehead are largely immobile, non-feeding, in deeper water, not coming to the surface for air, and apparently non-congregated thus making them difficult to find and target. Demographic modelling suggests control efforts immediately prior to spawning and/or juvenile dispersal would be most effective compared to year-round control efforts (Jiao et al. 2009). For Northern Snakehead this corresponds to April through September and coincidentally overlaps substantially with when Northern Snakehead are most 'visible' and probably more easily targeted (Lapointe et al. 2013).

Hook and line angling

Angler harvest, the predominant current form of population control, is seemingly moderately effective at reducing Northern Snakehead numbers in areas in which they are established (Odenkirk and Isel 2016, Newhard et al. 2019) but has seemingly not slowed the spread to new areas, which has been linear to exponential in the Chesapeake Bay watershed (Love and Newhard 2018). From 2009–2017, Northern Snakehead population size and fishing mortality were concurrently estimated in two tributaries of the Potomac River (Little Hunting Creek and upper Anacostia River) using electrofishing and angler returns (Newhard et al. 2019). The Upper Anacostia population showed a negative relationship between population size and fishing mortality, suggesting increased fishing pressure reduced population size. In contrast, the Little Hunting Creek population changed little in response to fishing mortality, except for a single year (2016) which had the lowest population estimate and highest fishing mortality. This suggests recreational fishing may be a viable means of controlling population size, but well-established populations are likely to require high (>25%) exploitation rates (Newhard et al. 2019). Similarly, a modeling approach suggested annual fishing mortality of 30% may be required for recruitment overfishing of Northern Snakehead in the Potomac River (Newhard unpublished manuscript). Hoff and Odenkirk (2019) developed a stock-recruit model using Northern Snakehead population data collected in northern Virginia tidal tributaries from 2009–2015. Model predictions indicated management efforts to reduce adult stock size from 2–4 fish/hour (captured while boat electrofishing) to <0.5 fish/hour would effectively reduce recruitment and hence adult abundance over the long-term. Finally, Jiao et al. (2009) applied a demographic model, parameterized using trait data from their native range, to Northern Snakehead population growth under different harvesting scenarios. They concluded that intensive control efforts that limit the number of spawning adults is the most effective strategy.

Angler harvest of Northern Snakehead is probably the most intensive and cost-effective available approach to reduce biomass across the entire established range (Love and Genovese 2019). In Maryland, and surrounding states, there is essentially open harvest for Northern Snakehead meaning minimal to no regulations on gear, season, size, or creel limits (Love and Genovese 2019). The primary benefit of this control and management approach is that it engages the public and may be sustained with minimal agency input.

However, this approach has several limitations. The minimum size Northern Snakehead reportedly captured by hook and line anglers is 250 mm (Newhard et al. 2019), so angling is ineffective at capturing juveniles. In addition, it can be difficult to overharvest a river system because the harvested areas are quickly repopulated with fish that migrate from other parts of the river (US Army Corps of Engineers 2012). A final concern is that even if harvest locally reduces Northern Snakehead numbers it does not seem to be preventing their spread throughout the Chesapeake Bay watershed (Love and Newhard 2018).

All the above suggest that angler harvest is not a viable means of eradication or necessarily even slowing spread. However, at least in some cases, it appears effective at reducing abundance, but this likely requires sustained high angler harvest rates of adults and may be dependent on site-specific factors. Nonetheless, even if population reduction is not achieved (i.e., overharvesting / overfishing targets are not reached) the removal of large mature fish could still potentially have positive ecosystem effects by removing the largest consumers of other species and reducing the average size of individuals in the population, and hence total biomass (Pasko and Goldberg 2014, Newhard et al. 2019).

Bowfishing

Bowfishing at night, using boats capable of traveling in shallow waters and outfitted with high-powered lights, can be an effective means of targeting Northern Snakehead. Furthermore, this fishery appears to be growing in popularity. For example, in a study on the effect of angler harvest on Northern Snakehead populations – that relied on anglers to return tags taken from captured fish – Newhard et al. (2019) found that initially ~90% of tag returns were from hook and line captures. But, the number of tag returns from bowfishers increased each year and in 2016 made up almost 85% of tag returns from the Potomac River (Newhard et al. 2019). Unlike hook and line angling, catch and release is not possible when bowfishing, thus guaranteeing that all Northern Snakehead are harvested. Some limitations are it can be done only when fish are in shallow water, cannot be conducted in very turbid water, is most effective at night, requires specialized equipment, and only effectively targets adults. There is also potential conflict with waterfront property owners over night-time noise and bright lights[20]. Finally, bowfishing could lead to increased targeting of native fishes such as gar, bowfin, and suckers – which are typically not taken for food but simply discarded[21]. In 2016, the MDDNR developed an inexpensive ($15) commercial bowfishing license that allows holders to harvest and sell unlimited Northern Snakehead taken within tidal waters of the state, and by July 2018, 55 were sold statewide (Love and Genovese 2019). It may be worthwhile performing targeted surveys, within well-defined areas, to determine the efficacy of sustained bowfishing at causing population declines in Northern Snakehead.

Incentivized harvest programs

Incentive programs encourage the pubic to harvest and use (often eat) species as a means of control or eradication (Nuñez et al. 2012, Pasko and Goldberg 2014). The implementation of such programs raise several issues. Incentivized harvest initiatives that have not been carefully considered or lack an exit strategy can cause more harm than good. Unintended consequences of harvest incentives include the public developing an appreciation or preference for the species, even without economic incentives, that drive illegal stocking activities (Pasko and Goldberg 2014). Harvest incentive programs could create a source of income and thereby generate pressure to sustain the species (Pasko and Goldberg 2014). Finally, if such programs are oversold, a lack of success can cause public frustration and skepticism toward all invasive species control programs (Nuñez et al. 2012).

Pasko and Goldberg (2014) give four examples of programs that may use incentives to encourage harvest of invasive species: (i) bounty program, (ii) contract operation, (iii) commercial market, and (iv) recreational harvest. A bounty program is when a predetermined amount of money is

[20] https://monkeywire.org/pa-wants-more-rules-for-popular-night-bow-fishing-outside/
[21] https://blog.nature.org/science/2020/10/21/an-overlooked-threat-to-freshwater-fisheries-bowfishing/

paid to an individual upon evidence of collection of the organism. A contract operation provides payment to a service provider to remove or harvest a species. Commercial market incentives aim to encourage individuals or businesses to sell the harvested species. Finally, recreational harvest incentives are actions that encourage fishing, hunting, or trapping of the species through outreach, tournaments, changing license requirements, or modifying seasons or bag limits.

Bounty programs are undoubtedly the most direct and controversial harvest incentive program. Offering money for harvested individuals (i.e., a bounty) can encourage illegal introductions, lead to animals being propagated in captivity, or contribute to the protection of some individuals so as to not completely eliminate a source of income. They can also be expensive. A Northern Snakehead bounty program offered by Bass Pro Shops in Hanover, Maryland, begun in 2004, quickly ended because too many fish were being traded in for money (Love and Genovese 2019). Furthermore, government-run bounties are illegal in Maryland, and several other states (Pasko and Goldberg 2014). Finally, there may be public disapproval of bounty programs for moral and ethical reasons, including requiring the presentation of dead bodies or body parts for payment (Pasko and Goldberg 2014).

Contract fishing, paying a service provider – often commercial fisherman – to harvest a species is a component of invasive carp control and management strategy in the Mississippi River watershed. Given their habitat preferences for shallow weedy waters, Northern Snakehead are not particularly susceptible to traditional commercial fishing gear (i.e., nets). Furthermore, this strategy may be more appropriate for a species generally deemed undesirable as a food source, such as carp, where the market does not generate sufficient demand to encourage large-scale commercial harvest. At high market prices, financial incentives may not be needed to encourage harvest, as market price alone is incentive enough (Pasko and Goldberg 2014).

Commercial fishing for Northern Snakehead relies on the consumption for conservation message “If you can’t beat them, eat them” (Pasko and Goldberg 2014, Love and Genovese 2019). Northern Snakehead yield large firm white fillets that can be prepared in a variety of ways[22]. The MDDNR requires commercial watermen to report sale of Northern Snakehead, and since 2011 the biomass taken from tidal freshwaters of the Potomac River has increased annually, reaching over 2000 kg in 2017 (Love and Genovese 2019). Yet, this remains small relative to that of other freshwater fishes such as Blue Catfish (197,868 kg harvested from Maryland portion of Potomac River in 2017) (Love and Genovese 2019). In 2018, Virginia joined Maryland and Washington D.C. in allowing legalized commercial harvest (Newhard et al. 2019). The high market price for Northern Snakehead will likely encourage continued growth of this fishery for the foreseeable future.

Recreational harvest incentives that encourage anglers to fish for and consume Northern Snakehead can take a variety of forms including social media initiatives, fishing awards, and tournaments (Love and Genovese 2019). The MDDNR Angler’s Log contest allowed participants to submit photos of harvested Northern Snakehead and be entered into a year-end drawing for prizes (Love and Genovese 2019). In 2012, an invasive species award category was added to Maryland’s notable catch program; harvested Northern Snakehead (above 762 mm) were eligible for an award. Also in 2012, Maryland created an invasive species state record category that included harvested Northern Snakehead. The current state record is just under 20 pounds (Love and Genovese 2019). Finally, Northern Snakehead fishing tournaments, which require harvest of caught snakehead, began in 2011 on the Potomac River and have since been organized in different areas and by a growing number of resource agencies and private fishing clubs (ANSTF 2014, Love and Genovese 2019, Newhard et al. 2019).

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[22] https://www.washingtonpost.com/news/capital-weather-gang/wp/2015/05/20/snakehead-taste-test-can-a-fish-this-ugly-really-taste-that-good-photos/

Several key recommendations for incentivized harvest programs include: define the management plan and objectives, understand the costs, consider risks to human health and safety, and monitor unintended outcomes (Pasko and Goldberg 2014). These recommendations should be thoroughly considered before promoting recreational harvest of Northern Snakehead as a means of population control. Two of the main objectives of a recreational harvest program could include educating the public about the existence of the fishery and reducing biomass – but should not be oversold as a means of eradication. The most basic form of recreational harvest incentive is allowing open harvest (no closed season, length limits, or creel limits) by various means (hook and line angling and potentially bowfishing); this could be combined with encouragement to harvest Northern Snakehead through outreach and messaging. More elaborate and financially costly incentivized harvest programs may not always be necessary, for example, where Northern Snakehead have been established for nearly two decades and the fishery has been ongoing for over a decade (Newhard et al. 2019). Where Northern Snakehead fisheries do exist, resource agencies have sometimes promoted the palatability of snakehead fillets, and many anglers enjoy eating Northern Snakehead. In 2014, 55.8% of Potomac River anglers surveyed reported having caught a snakehead, 37.2% reported having eaten snakehead, and of those who had eaten it, 100% would recommend it (Agarwal et al. 2016). From a human health perspective, Northern Snakehead fillets from Potomac River tributaries contained acceptably low levels of Polychlorinated Biphenyls (PCBs) (Darkwah and Browder 2019) and, in general, relatively low levels of contaminant concentrations relative to other predatory species in the same waters (Pinkney 2018). In the Potomac and Anacostia Rivers, the current Maryland consumption advisory is three meals per month for the general population[23]. In the interest of public safety, examination of Northern Snakehead contaminants and meal advisories should be explored in new areas where fisheries will be promoted, and continue in regions with established fisheries. Unintended consequences are probably the greatest risk of encouraging recreational harvest through incentives. Sometimes the best option is doing nothing rather than promoting integration into local culture or creating economic markets that could be a problem for the future (Nuñez et al. 2012). In fact, the NYDEC considered and rejected the idea of promoting the Meadow/Willow Lake Northern Snakehead population in New York City as a recreational angling opportunity due to concerns that this would cause intentional spread or propagation to sustain the fishery (ANSTF 2014). Whether to encourage recreational harvest or not will likely depend upon invasion stage in the local area. Specifically, this strategy may be most appropriate in areas where Northern Snakehead are established and widespread – and population control is the primary management goal – yet rate of harvest remains low, perhaps due to anglers being unfamiliar with the fishery. At the leading edge, when first detected in brand new areas, or when confined to a single waterbody, containment and potential eradication take precedence and heavily promoting angling could potentially be counterproductive if it leads to further spread (Appendix D).

Physical removal at dams and natural barriers

"As more is learned about snakehead behavior in U.S. waters, it will be easier for resource managers to strategically target control actions when capture efficiency is high, possibly also reducing costs." (ANSTF 2014). During the spring, a substantial portion of Northern Snakehead found in rivers connected to the Chesapeake Bay move upstream long-distances (Lapointe et al. 2013, Love and Newhard 2018). During this time, Northern Snakehead are attracted to flowing water (J. Newhard personal, USFWS, communication) and congregate below dams (Bunch et al. 2019, Normandeau Associates 2021). This is demonstrated at the Conowingo Dam on the Lower Susquehanna River. Flowing water released from the dam is used to attract native anadromous fish to the entrance to the fish lifts.

[23] https://mdewin64.mde.state.md.us/WSA/FCA/index.html

Yet, it also attracts Northern Snakehead in substantial numbers. In 2021, 952 adult Northern Snakehead were collected from the fish lifts at Conowingo Dam and in 2022, 866 were collected. The middle of a large, deep, swiftly flowing river is not habitat Northern Snakehead are typically found in at most other times of the year, and strongly suggests they are actively attempting to disperse upstream. Although the fish lifts are incidentally collecting Northern Snakehead (along with native anadromous species), it would be highly desirable to exclude Northern Snakehead from entering. Research and development effort could be put into utilizing this information to develop the exact opposite system – a trap that utilizes flowing water to attract and collect Northern Snakehead (but excludes native anadromous species). Such traps could then be deployed in the springtime along likely Northern Snakehead dispersal routes or in places where they congregate.

Netting

Low numbers of Northern Snakehead have been caught with fyke nets (Cohen and MacDonald 2016, Newhard and Love 2019 unpublished), seine nets (Odenkirk and Owens 2005, 2007), dip nets / hand nets (Odenkirk and Owens 2005, 2007, Cohen and MacDonald 2016), trap nets (Odenkirk and Owens 2007, Cohen and MacDonald 2016), gill nets (Bourdon et al. 2022), and pound nets (ANSTF 2014). Although the effectiveness of these different nets has not been formally compared to each other or to other methods, such as electrofishing, none seem to capture large numbers of Northern Snakehead. This could be for several reasons, including Northern Snakehead are a solitary non-schooling species, they inhabit shallow heavily vegetated waters, and during the summer they may not move around very much. It has been suggested that passive nets, such as gill and trap, may be most effective in the spring when Northern Snakehead are moving the most (Lapointe et al. 2013).

Electrofishing

Electrofishing is a specialized technique in which electricity is placed into the water, temporarily immobilizing fish in the nearby area, and allowing them to be netted and removed. It can be implemented from backpack, barge, or boat. This method has been successfully employed by resource agencies to collect thousands of Northern Snakehead across the Chesapeake Bay watershed. Boat electrofishing of suitable habitat is frequently used by resource agencies to survey for Northern Snakehead, monitor population density, collect fish for use in research studies, and as a form of limited population control. However, this method does have limitations. Capture probabilities (percent of population captured) are relatively low and can be site-dependent. At two sites in the Potomac River, capture probability ranged between 2-12% across years (Newhard et al. 2019). Likelihood of capture can be improved by using electrofishing settings designed to attract Northern Snakehead to electrofishing anodes (Temple and Newhard 2019). However, while many fish species tend to stay immobilized at or near the water's surface, Northern Snakehead caught in the electrical field typically surface briefly, allowing a brief moment for them to be netted, before sinking to the bottom. Northern Snakehead near the edge of the electrical field often exhibit a violent escape reaction and sometimes leap from the water (Odenkirk and Owens 2005).

Another limitation of electrofishing is that it is a labor-intensive method that requires specialized equipment that must be authorized by resource agencies for public use. Historically, across the U.S., public use of electrofishing for harvest has not been allowed. However, in recent years, experimental electrofishing licenses have been granted to remove Blue Catfish in the James River in Virginia and other rivers of southeastern North Carolina (Reynolds and Dean 2020). It is not currently known to what extent, if any, commercial electrofishing has reduced those populations. In untrained hands, electrofishing can be harmful to many fish species (i.e., if proper settings are not used). In the Blue Catfish experiment, specialized equipment is provided, only allowing commercial users the ability to use low frequency settings, which specifically immobilize catfish and generally not other species

(Reynolds and Dean 2020). Such equipment designs may not be possible for Northern Snakehead, given the electrofishing waveforms suggested by Temple and Newhard (2019) are likely effective at immobilizing many other species, raising the concern of electrofishing impacts to non-target, native species.

Electrofishing is generally limited to freshwater habitats (<5,000 µS/cm) and can be inefficient in dense vegetation or in waterbodies that are very deep or shallow. Finally, it is not as effective on smaller individuals (<200 mm) (Kim et al. 2019, Newhard et al. 2019). Therefore, given the limitations of electrofishing and its relative inefficiencies, on its own it is probably an ineffective means of population control across large areas (i.e. whole river systems). However, it is also likely the best tool resource agencies have to capture and remove Northern Snakehead from target areas. Therefore, electrofishing is likely most useful as a population control tool when combined with other management approaches designed to reduce Northern Snakehead populations.

Draining

Draining a waterbody ensures all fish are captured. In May 2004, shortly after an adult Northern Snakehead was captured by an angler in 4-acre Pine Lake in Wheaton, Maryland officials drained the lake with a pump. No other Northern Snakehead were found[24,25]. In October 2019, an angler caught a Northern Snakehead in a private pond in Gwinnett County, Georgia and Georgia DNR subsequently found numerous other individuals. DNR staff lowered the pond water level, and that of surrounding wetlands and canals utilizing existing irrigation infrastructure to cut off the pond's water supply. This reduced fishes access to vegetative cover and the amount of rotenone that was required. Survey work after rotenone treatment did not recover any live Northern Snakehead. The effectiveness of draining is probably limited to eradication attempts in small waterbodies, rather than as a means of reoccurring population control and management. However, draining some sections of disused canals to prevent inter-watershed spread could be a viable strategy (Section VII).

Chemical control

Piscicides are chemicals that kill fish. There are four chemical piscicides approved for use in the U.S. including antimycin A, rotenone, nicolsamide and TFM (US Army Corps of Engineers 2012). Antimycin A, a product of fungal fermentation, and rotenone, a plant flavonoid, are general piscicides that indiscriminately kill all species of fish. Niclosamide and TFM are lampricides used to target the larvae of lamprey in Great Lakes tributaries (US Army Corps of Engineers 2012). Rotenone has been used in at least four Northern Snakehead eradication attempts (Section VI, Appendix C). In a laboratory study, Lazur et al. (2006) found that the lowest rotenone concentration applied (0.075 mg/L) resulted in 100% mortality of juvenile Northern Snakehead within one hour, and the Crofton Pond rotenone treatment of 0.25 mg/L was effective at killing all Northern Snakehead (as well as all other fish). Given that rotenone treatment kills all fish species, requires appropriate training and permits, and can be financially costly, its use is limited to eradication efforts in small waterbodies, rather than as a means of recurrent population control.

Summary and recommendations

In large flowing waters where Northern Snakehead are established, including much of the lower Chesapeake Bay watershed, eradication is not possible. In such regions, the management objective thus

[24] https://www.washingtonpost.com/archive/local/2004/05/04/confidence-grows-that-wheaton-lake-is-snakehead-free/6fafc403-134f-4e27-8166-edfdc666cbe2/
[25] https://www.fredericknewspost.com/archives/river-wrecker-destructive-snakehead-found-at-wheaton-regional-park/article_d57e520b-a0c2-5be1-837b-0d0de6799966.html

becomes to limit Northern Snakehead biomass such that there are no discernable negative effects on aquatic communities. To date, evidence for the effect of Northern Snakehead on aquatic communities has ranged from negligible to measurable (Section IV), and such effects, if present, are likely to depend on the nature of the waterbody and local fish community. Therefore, each established northern snakehead population will have its own management goals and considerations. However, recreational harvest appears to be a moderately successful, cost-effective, and scalable control option. Recreational fisheries may grow organically as the fishing community seek to capture and harvest Northern Snakehead. Resource agencies may also seek to grow fishery sectors (commercial or recreational) with incentivized harvest programs and/or increased outreach encouraging harvest. One risk to this approach is that the growing popularity of the fishery may cause Northern Snakehead to be moved to new areas, which reiterates the importance of attempting to eliminate new illegal introductions (Section V and X). This also suggests that encouraging angling and harvest of Northern Snakehead is most applicable in areas in which they are both established and widespread, not necessarily at the invasion front where limitation of spread is the primary concern.

An adaptive management framework aims to use best-available management tools to restrict, reduce, and maintain the target species at levels of insignificant impact while minimizing risks to the environment, the economy, and human health. In the Chesapeake Bay watershed, the cornerstone of such an approach would likely rely on recreational harvest to reduce Northern Snakehead biomass cost-effectively across large geographic areas in which they are established, while allowing for targeted control and management efforts by resource agencies in the specific areas most likely to achieve measurable successes and/or of conservation concern. As additional information becomes available about the types of waters Northern Snakehead are more likely to have negative impacts, targeted efforts (e.g., electrofishing, netting, contract fishing) could be directed to these specific areas. Control and management efforts could also utilize natural topographic features to their advantage. In the spring a substantial portion of Northern Snakehead found in rivers disperse upstream and therefore congregate below natural and artificial barriers. These congregations may represent useful control points where they can be more readily captured than when otherwise spread across much greater areas at other times of the year. Another component of an adaptive management strategy is research. This could involve comparison of the effectiveness of different techniques through pilot studies in the field, and the research and development of new control and management methods.

IX. Research needs

What, if any, long-term impacts do Northern Snakehead have on aquatic communities?

Several studies have addressed this question in U.S. waters (Section IV). However, much uncertainty remains. Standardized surveys of fish community in different types of habitat are needed pre- and post- Northern Snakehead arrival. Ideally such studies would measure Northern Snakehead abundance, density, or CPUE and that of other species using standardized sampling designs and be repeated across multiple years. Sampling across multiple years is important to account for inter-annual fluctuation in the abundance of fish species due to environmental effects, and because when Northern Snakehead first arrive their numbers will necessarily be low and therefore any effect may not be apparent until they reach higher densities. Ideally, conducting such studies in various habitat types (e.g., small and large, open and closed, natural and disturbed, low fishing pressure and high fishing pressure) would determine if and where negative impacts are most likely to occur, and such areas could then be prioritized for control and management actions. Existing long-term fish community surveys, for example to determine the relative abundance of recreationally or commercially important species or monitor species of conservation concern, conducted in waterbodies in which Northern Snakehead are now found, could be used to address this question, even if not the original goal. The use of such re-purposed data to address potential impacts is more efficient and cost-effective compared to collecting such data from scratch. Finally, it may be worth strategically selecting some sites of potential conservation concern (e.g., shallow marshes that contain lots of suitable habitat, or those containing threatened or endangered fish species) not yet colonized by Northern Snakehead but likely to be imminently so, to do baseline surveys of fish community such that they can be compared post-snakehead invasion. This would allow for an assessment of Northern Snakehead impact on species of conservation concern (Appendix A). Finally, study of the economic impacts of Northern Snakehead introduction and expansion may be warranted.

What are effective and efficient means in which to allow native fish passage at dams while preventing Northern Snakehead from being passed (or collecting them for removal)?

This is a pressing research need because the alternatives to selective fish passage are to (i) maintain dams as complete dispersal barriers and allow no fish to pass, including desirable native anadromous species, (ii) allow all fish to freely pass through lifts, including Northern Snakehead, or (iii) enact costly and time-consuming manual sorting and transport procedures. This issue becomes most pressing when Northern Snakehead are abundant below a dam but not present above. This is the situation on the lower Susquehanna River where a series of hydroelectric dams are all that is preventing Northern Snakehead from colonizing a large upstream river basin that spans three states. A general research strategy could involve using a closed system (i.e., flume) to test the behavioral and biomechanical response of native anadromous and invasive fishes to a variety of stimuli (high-flow, turbulence, sound, air bubbles) in order to develop a combination of filters that facilitate the passage of native anadromous fishes through the system, and effectively exclude Northern Snakehead.

Are Northern Snakehead able to traverse small low-head dams and those with fish ladders?

In addition to major dams, there are numerous smaller dams on rivers, tributaries, and creeks throughout the Chesapeake Bay watershed. The ability of Northern Snakehead to traverse these small low-head dams, and those with fish ladders, is not well understood. However, this information could have implications for both limiting upstream spread of Northern Snakehead to new areas, and for dam removal projects. Specifically, if certain small dams are unlikely to block Northern Snakehead when water levels are high, it would not make sense to maintain them as potential barriers to Northern Snakehead spread if it was otherwise beneficial to remove them in the context of anadromous fish restoration efforts.

What triggers springtime Northern Snakehead dispersal?

An unexpected finding has been that, in rivers of the Chesapeake Bay watershed, a subset of Northern Snakehead disperse long distances, primarily upstream, in the spring. This phenomenon was not previously known or reported in reviews of Northern Snakehead biology in their native range or other introduced areas outside the U.S. (Courtenay and Williams 2004). There is much to learn about this phenomenon that could have implications for limiting the spread of Northern Snakehead and controlling population size. It has been suggested that spring-time dispersal is related to high rainfall and flooding (Love and Newhard 2018). This could be tested, along with other potential triggers (e.g., rainfall, flow rate, temperature) using Northern Snakehead arrival data at Conowingo Dam. At Conowingo Dam, the East Fish Lift operates approximately every 30 minutes during daylight hours from late March to mid-June. Every Northern Snakehead that enters the fish lift is collected, dispatched, and the date and time of day entering the lift is recorded. A subset of these fish are measured by MDDNR and have basic data recorded including total length and sex. This data has been collected for the past two years and will continue into the foreseeable future. A time-series or lag sequential analysis that includes data on daily number of Northern Snakehead arrivals, daily rainfall, daily flow-rate at the dam, and daily water temperature could be used to test the dispersal trigger. Data from Conowingo Dam could also be used to address whether there is sex or size-biased dispersal, and at what times of the day Northern Snakehead are most active and likely to enter the lift. Finally, high-reward tagging studies, designed primarily to estimate the rate of harvest through angling, can be used to study dispersal patterns across the watershed.

What steps should be taken when Northern Snakehead are detected and how does this differ depending upon invasion stage, detection method, and waterbody characteristics?

Structured decision making is an organized approach to making natural resource management decisions based in decision theory and risk analysis[26]. This approach may be useful in helping guide potential actions following a new Northern Snakehead detection because here time is of importance and appropriate actions likely differ depending upon a variety of factors such as invasion stage, detection method, and waterbody characteristics. Structured decision making could also be used in the context of how to allocate resources among competing control and management options in established areas. A first step in this process would be to organize a workshop among experts in which the problem is framed, objectives identified, and alternative options listed. This would then allow for the estimation of probable consequences of each alternative and evaluation of trade-offs among them.

What is the most effective way of capturing Northern Snakehead under different conditions?

It may be worth attempting to compare the catch rates of existing methods in a standardized way and figuring out under what conditions and times they are most and least effective. Research and development effort could be put into developing a trap that utilizes flowing water to attract and collect Northern Snakehead during the spring. Such traps could then be deployed along likely Northern Snakehead dispersal routes or in places where they congregate, such as below dams or waterfalls. A design challenge of such a trap would be minimizing by-catch of native anadromous species migrating upstream. Comparing the catch rates of existing methods in the field and developing new methods may be useful such that – if it is later found that Northern Snakehead are most likely to have negative impacts in a given habitat – then a suitable suite of effective control and management options have already been tested and are on the table for implementation.

Is harvest an effective means of watershed-wide population control?

Harvest is the primary control and management strategy for Northern Snakehead in established areas of the Chesapeake Bay watershed. In some states this includes angling, and in others both angling and bowfishing. Studies in two tributaries of the Potomac River suggest high harvest rates can reduce Northern Snakehead population size (Newhard et al. 2019). Furthermore, in the Potomac River, Northern Snakehead population size stabilized and then declined 10-years post discovery (Odenkirk and Isel 2016, J. Odenkirk, VDWR, personal communication). It is not definitively known whether the stabilization and subsequent decline is due to harvest and/or the population naturally reaching carrying capacity. However, it is known that large numbers of Northern Snakehead are taken each year (VDWR Potomac River Tributaries Creel Survey) and the perception of Virginia anglers is that the population is in decline due to bowfishing (J. Odenkirk, VDWR, personal communication, VDWR biannual regulation cycle comment period in 2022). The Potomac River is characterized by patches of suitable Northern Snakehead habitat in shallow embayments and creeks that bracket the deep and largely unsuitable mainstem Potomac River, whereas in other areas of the Chesapeake Bay watershed such as the Susquehanna Flats or Blackwater National Wildlife Refuge there is more extensive suitable habitat. It is

[26] https://www.usgs.gov/centers/eesc/science/structured-decision-making

likely that the rate of harvest will differ depending on habitat characteristics. It will be interesting to monitor whether a similar population trajectory (i.e., initial increase followed by stabilization and decline, over a 10-year timeframe) occurs in other more recently colonized rivers with similar habitat characteristics to the Potomac River, as well as very different habitat characteristics – and if such a population trajectory is dependent on the rate of harvest. This could be assessed by concurrently monitoring Northern Snakehead harvest rate (through high-reward tagging studies or creel surveys) and relative abundance or CPUE over time (through, for example, boat electrofishing). If a similar stabilizing and then decreasing population trajectory was consistently observed outside the Potomac River, and irrespective of harvest rate, then this would suggest limits to Northern Snakehead abundance without having to resort to labor-intensive or costly control options. If, instead, a stabilizing and then decreasing population trajectory were only observed with high harvest rates, then this would suggest measures to increase harvest rate be employed or other control options be considered.

What is the best way to assess abundance of Northern Snakehead?

Northern Snakehead range expansion is primarily determined by angler reports and agency capture, and abundance (in established areas) by boat electrofishing (Bunch et al. 2019). Boat electrofishing allows for the calculation of CPUE, often expressed as fish captured per hour fished. Electrofishing CPUE can be compared within sites across time, when conducted in a standardized manner, but it is unclear whether it can be readily compared across different sites. This is because there is currently no standardized protocol for Northern Snakehead sampling and therefore different resource agencies, or operators, may do things differently in different sites. Developing a standardized protocol would allow estimates of Northern Snakehead relative abundance to be more readily compared across different sites, rivers, and even watersheds. This could potentially also aid in determining the effectiveness of different control and management strategies.

Alternative ways of assessing relative abundance, in places where boat electrofishing is not suitable due to habitat characteristics, might include calculating CPUE from passive gears (i.e., fyke nets or fish traps), creel surveys (i.e., angler interviews), and night-time visual transect surveys from a boat or from shore. At night, Northern Snakehead are reportedly more easily spotted and less skittish – which is when they are frequently targeted during bowfishing[27]. It may be possible to utilize these features to estimate their abundance; such a procedure could involve setting up standardized transects of 100-meters (or any suitable length) that parallel the shore, in prime Northern Snakehead habitat, and then using high powered lamps to count the number of Northern Snakehead observed along these 100-meter stretches. Density estimates based upon visual transect surveys conducted at night could then be compared to electrofishing surveys conducted during the day, along the same transects.

What are angler attitudes, and that of general public, toward Northern Snakehead?

Ultimately the effectiveness of a control and management plan relies on the support of the public, therefore it may be worth tracking attitudes toward Northern Snakehead over time in different segments of society. One way this could be done is by periodically implementing a standard survey of attitudes toward this species (Agarwal et al. 2016). Results might reveal differences in attitude between Northern Snakehead anglers specifically and those who primarily target other species, or between anglers and the general public. Angler and public attitudes could help refine outreach messaging, inform harvest incentive strategies, determine the palatability of different control and management options, improve EDRR initiatives, or perhaps lead to the revision of existing regulations, statutes, or penalties.

What are contaminant levels in Northern Snakehead from the Chesapeake Bay watershed?

[27] https://fishandhuntmaryland.com/articles/snakehead-fishing-maryland

In Potomac River tributaries, Northern Snakehead fillets were found to contain relatively low levels of contaminant concentrations (Pinkney 2018, Darkwah and Browder 2019). Nonetheless, it will be important to continue to assess toxin accumulation (PCBs and mercury) for various size classes and geographic locations to help ensure safety and human health. As Northern Snakehead continue expanding their distribution, consumption advisories may change as well, depending on where populations become established.

Are there density-dependent responses to management actions?

It currently is not known whether spring-time dispersal is density dependent or independent. For example, is spring-time dispersal an innate feature of Northern Snakehead biology that occurs even at low population densities, or does it only occur at higher population densities in response to competition? It also is not known whether existing harvest levels cause recruitment compensation. That is, does lower density benefit survivors resulting in increased recruitment, thereby offsetting removal efforts? Addressing these questions through field population sampling could help refine control and management strategies or lead to a revision in expectations from control programs.

X. Public outreach and communication

Effective public outreach and communication is essential to the success of this plan. Since their discovery in Crofton Pond in 2002, Northern Snakehead have garnered substantial media attention, some of it sensationalized (Love and Genovese 2019, Orth 2019). When first found in a new area Northern Snakehead continue to draw headlines, as they did with the national media following their detection in Crofton Pond, just at a more regional scale (Bunch et al. 2019). This suggests the importance of having plans in place not only for how to respond to Northern Snakehead (Section VI) but how to respond to the resulting public and media attention. One suggestion is for each jurisdiction to have a designated knowledgeable point person for dealing with media inquiries (ANSTF 2014). Finally, it is important to have an honest and factual message that avoids emotionally charged language.

Identify the message

Before communicating with the public one must have a message – one which is honest, evidence-based, and coherent. Messaging that prohibits live possession and transport of Northern Snakehead has been clearly stated in regulation and statute. This message is simple, applicable watershed wide, and consistent with a long tradition of conservation and protection of native North American biota.

Catch and release angling is an issue with the potential to divide stakeholders because there is an apparent conflict between catch-and-release anglers, who may be morally opposed to killing a Northern Snakehead, and the state, who may wish to reduce their population by having all captured fish killed (Orth 2019). When considering the costs versus benefits of explicitly acknowledging catch and release angling, the message has sometimes been tailored to invasion stage and whether eradication is a realistic goal (Appendix D). In early stages of introduction, agencies have used messaging that advises anglers to ‘kill snakehead and do not return them to the water.’ States may lack legal authority to compel individuals to kill a caught fish, which could be challenged on religious freedom grounds (Rice 2016), although an alternative is giving it to authorities. Once established and eradication is no longer feasible, messaging that encourages harvest has been used. If one closely examines the public messaging of the MDDNR over time one can see the evolution of messaging (Appendix G). Initially public communications asked anglers to kill caught fish and do not return to the water (although they never explicitly stated this was against the law), then ambiguity (anglers encouraged to harvest caught fish without explicitly mentioning catch and release), and finally encouragement to harvest but with acknowledgement that immediate release at point of capture is acceptable. Throughout this time there was emphasis on the complete prohibition of live possession and transport. The shift in emphasis from killing all captured fish to accommodating (immediate) catch and release roughly tracked the likelihood of eradication. In waterbodies in which Northern Snakehead are firmly established, the success or failure of a control or management plan that relies on public harvest does not hinge on complete removal of all captured individuals. This is because here the realistic goal is not eradication but simply to reduce biomass and prevent negative effects on aquatic communities. In such areas it may make sense to accommodate differing values, by allowing immediate catch and release at point of capture, with a continued strong emphasis on preventing spread to new waterbodies. The language of compulsory destruction makes sense only where eradication is the primary goal (i.e., in locations in which snakehead are not established).

If the government (federal, state, local) is encouraging harvest, while simultaneously disallowing live possession and transport, then it would be advisable to provide the public with clear recommendations on the most humane and effective way to quickly, safely, and humanely dispatch Northern Snakehead. As Pasko and Goldberg (2014) state: "Humane protocols should be developed for the target species, taking into account the unique anatomical characteristics of the species and the likelihood that harvest will occur by a nonprofessional in a remote setting." This may seem like a trivial point, but can be a source of significant uncertainty, anxiety, and confusion amongst anglers who may wish to harvest Northern Snakehead. Northern Snakehead breathe air and are hardy; therefore, means of dispatch that work for most fish – such as putting them in an ice-filled cooler – simply do not work. Furthermore, the legal prohibition on live possession and transport requires that harvested fish must be actively dispatched by some means. The MDDNR has advised the public that removing the gill arches, head, or internal organs, or puncturing the skull with an awl are methods in which to dispatch Northern Snakehead for harvest (Appendix G, Figure 19). According to the Royal Society for the Prevention of Cruelty to Animals, percussive stunning or spiking, as soon as possible after capture, are the most humane ways of killing fish that are to be eaten[28]. With percussive stunning a hard blow is delivered to the top of the head just behind the eyes with a blunt object. With spiking (also known as pithing or iki-jime) a sharp, pointed object is driven through the skull and into the brain. After stunning and/or spiking, fish can be bled out by cutting the gill rakers, have the internal organs removed, or be put on ice. Methods of dispatch that are prolonged or less humane should be avoided.

Northern Snakehead have attracted a passionate following among some groups of anglers. In areas in which they are established, some anglers advocate Northern Snakehead should be managed as a game fish, with harvest limits, and catch and release should be encouraged. For example, an editorial in the Washington Post argued that in the Potomac River Northern Snakehead have become more difficult to catch, and this warrants special protections including designation as a game fish and limits placed upon the number that can be kept (Mathwin 2018). There are several reasons to oppose this. Insofar as they are getting more difficult to catch in certain areas (e.g., some tributaries of the Potomac River) then this may constitute evidence that the current control program is working. To reverse this would potentially undo this progress. Furthermore, even if some localized Northern Snakehead populations are being depressed by heavy angling pressure and harvest, this has not stopped their expansion. Finally, this would likely encourage illegal stocking. Implementing limits or regulations designed to protect them in some parts of their introduced range, would prematurely send the message that Northern Snakehead are a naturalized member of the fish community, at a time when a primary objective is to limit their spread.

[28] https://kb.rspca.org.au/knowledge-base/what-is-the-most-humane-way-to-kill-a-fish-intended-for-eating/

How to communicate the message

Communication about Northern Snakehead has occurred among agencies, and toward the public, recreational anglers and bowfishers, commercial harvesters, media, legislators, and local officials. The purpose of outreach and communication efforts has included identification of Northern Snakehead, informational (general, fishing, FAQs), laws and fishing regulations, and/or reporting requirements (Appendix G). In addition to these more traditional communications, there is a need for practical advice (from authoritative or official sources) on fishing for, handling, dispatching, and filleting of Northern Snakehead. The MDDNR produced several instructional YouTube videos[29,30] on these and other topics (Love and Genovese 2019). Finally, messages would ideally be given in multiple formats and places. Examples of places where messages may reach a large and/or targeted audience have included resource agency websites, posters in visible areas such as fishing piers and public boat launches, handouts or brochures for distribution at outreach events, and social media. Depending upon the audience it may be important to provide communications in multiple languages and provide clear links to where more detailed information can be found, as well as contact information. Communication materials also need to be regularly updated. Existing Northern Snakehead online resources are listed in Appendix F, with brief descriptions, and examples of various outreach materials are provided in Appendix G.

Summary and recommendations

Given the notoriety of Northern Snakehead, the importance of honest and well-crafted public communications cannot be overemphasized. The one message that should be emphasized across the entire watershed is the illegality of live possession and transport of Northern Snakehead. This message is both simple and well justified. When Northern Snakehead are first found in an area, and eradication is the goal, resource agencies may wish to strongly emphasize the importance of not returning any fish to the water, and reporting captures to the agency. Likewise, at the invasion front, strong encouragement to not return any captured Northern Snakehead is justified. However, in areas in which Northern Snakehead are established and widespread, and eradication is no longer a realistic goal, catch and release angling can be accommodated while still encouraging harvest to reduce Northern Snakehead biomass (Appendix D). Inter-agency communication and the periodic review and updating of communication materials based on new knowledge will be important moving forward.

[29] https://youtu.be/ljzNcBOqqHg
[30] https://youtu.be/Fzgvxyxwr-A

XI. Plan objectives, action items, and metrics of success

Overall plan goal: Within the Chesapeake Bay watershed, use the best-available science and management practices to prevent new Northern Snakehead introductions, limit spread, and control abundance to prevent adverse effects on aquatic communities.

Objective 1. Prevent new Northern Snakehead introductions into waterbodies within the Chesapeake Bay watershed, and into adjacent watersheds.

2.2 Continue enforcement of the Lacey Act prohibiting importation of live snakehead, and state laws and regulations prohibiting live possession and within-state transport.

1.2 Encourage state legislators to establish or increase penalties for violation of invasive species laws and regulations.

1.3 Liaise with angling groups, and snakehead angling groups specifically, to develop a good relationship and address any concerns regarding existing laws and regulations.

1.4 Publicize occasional enforcement actions to serve as deterrent.

Objective 1. Metric of success. Monitor cumulative number of colonized waterbodies across years to determine if rate of new introductions has slowed.

Objective 2: Detect new (distinct) Northern Snakehead populations at an early stage.

2.1 Ensure existing public reporting mechanisms remain in place as well as means to authenticate these records.

2.2 Report new, verified occurrences to a publicly available database (e.g., USGS Nonindigenous Aquatic Species database: https://nas.er.usgs.gov/SightingReport.aspx).

2.3 Identify areas containing species of conservation concern for priority detection.

2.4 Develop watershed wide eDNA sampling design in collaboration with partners that focuses on isolated waterbodies (i.e., ponds, lakes, and reservoirs), areas above and below natural and artificial dispersal barriers such as waterfalls and dams, and yet uncolonized, upstream reaches where Northern Snakehead are expected to be found in the future (i.e., leading edge surveys).

2.5 Develop coordination between state and federal agencies about appropriate rapid response actions.

2.6 Create decision tree that guides Northern Snakehead early detection and rapid response actions, to complement existing state and regional rapid response protocols.

Objective 2. Metric of success. Check whether all states / jurisdictions have emplaced early detection systems for Northern Snakehead.

Objective 3. Limit the spread of Northern Snakehead within connected waterways of the Chesapeake Bay watershed.

3.1 Where possible, maintain artificial barriers to Northern Snakehead dispersal (i.e., dams), while simultaneously allowing for native anadromous fish passage.

3.2 If canals connecting watersheds are unused for boat passage, and in state of disrepair, disconnect a section to prevent spread of Northern Snakehead to adjacent watersheds (i.e., ensure at least one section is permanently de-watered thereby eliminating the potential for dispersal through abandoned canals which are subject to occasional flooding).

Objective 3. Metric of success. Monitor cumulative number of colonized sub-watersheds across years to determine if the rate of spread has slowed.

Objective 4. In established areas, minimize Northern Snakehead population size through control and management actions.

4.1 Encourage harvest by having minimal recreational fishery regulations.

4.2 Allow bowfishing for Northern Snakehead.

4.3 Consider developing commercial market.

4.4 Implement recreational harvest initiatives (e.g., public communications, outreach, tournaments).

4.5 Focus electrofishing effort in high density areas or those of conservation concern.

4.6 Target Northern Snakehead below natural and artificial barriers when they congregate in the springtime.

Objective 4. Metric of success. In areas in which they are established, determine whether Northern Snakehead numbers (abundance or relative abundance) have stabilized or declined.

Objective 5. Conduct research to better understand Northern Snakehead biology, population dynamics, and impacts, and develop more effective detection, surveillance, and control methods.

5.1 Determine, what, if any, long-term impacts Northern Snakehead have on aquatic communities of various types.

5.2 Research selective fish passage to allow native anadromous species to bypass dams while preventing Northern Snakehead from doing so.

5.3 Determine Northern Snakehead ability to traverse small low-head dams and navigate fish ladders.

5.4 Research Northern Snakehead upstream dispersal triggers in the springtime.

5.5 Utilize structured decision making to evaluate potential management actions following Northern Snakehead detection.

5.6 Perform targeted studies on effectiveness of various management approaches.

5.7 Further evaluate recreational harvest as an effective means of population control.

5.8 Determine effective and standardized ways of assessing abundance of Northern Snakehead that can be applied across watersheds / jurisdictions.

5.9 Periodically assess angler attitudes, and that of general public, toward Northern Snakehead.

5.10 Conduct studies on the contaminant levels in Northern Snakehead from across the Chesapeake Bay watershed, and develop consistent strategy for consumption guidance.

5.11 Assess how control measures might affect population level dynamics (emigration, recruitment, natural mortality, etc.)

Objective 5. Metric of success. Track whether the research items identified here have been addressed.

Objective 6. Implement public outreach to prevent additional introductions of Northern Snakehead, limit their spread, and aid in control efforts.

6.1 Designate a knowledgeable point person for Northern Snakehead communications and messaging in each state / jurisdiction.

6.2 Present message on the illegality of live possession and transport of Northern Snakehead as the primary message across all states and jurisdictions.

6.3 Tailor emphasis of additional messages to invasion stage in local area and the management goal (i.e., eradication versus biomass control).

6.4 Provide recreational anglers practical advice on rapid and humane ways of dispatching fish for harvest.

6.5 Regularly review websites and communication materials to make sure they are up to date as new information becomes available and control and management goals change.

6.6 Create a new website, or designate one of the existing ones (see Appendix F), as a single centralized 'hub' for Northern Snakehead information.

6.7 Make all Northern Snakehead papers, reports, book chapters, and symposium proceedings open access and freely available online (i.e., as downloadable pdfs) in a single location.

Objective 6. Metric of success. The success of outreach efforts will result in a more engaged and informed public. This can be assessed using surveys, website and video view counts, engagement metrics, and comments on articles, press releases, and policy proposals.

XII. Implementation table

Strategy	Objective	Action	Current Status	Lead Agency	Cooperating Agency	Timeframe	Comments
Prevention	Prevent new Northern Snakehead introductions into waterbodies within the Chesapeake Bay watershed, and into adjacent watersheds.	1.1 Continue enforcement of the Lacey Act prohibiting importation of live snakehead, and state laws and regulations prohibiting live possession and within-state transport.	Ongoing	USFWS (Lacey Act), State Resource Agencies (State laws and regulations)	-	Continue indefinitely	
		1.2 Encourage state legislators to establish or increase penalties for violation of invasive species laws and regulations.	Variable by state	State Resource Agencies	USFWS	2-years	
		1.3 Liaise with angling groups, and snakehead angling groups specifically, to develop a good relationship and address any concerns regarding existing laws and regulations.	Ongoing	USFWS & State Resource Agencies	-	6-months and then continue indefinitely	
		1.4 Publicize occasional enforcement actions to serve as deterrent.	Ongoing	State Resource Agencies	-	Continue indefinitely	
Early Detection & Rapid Response	Detect new (distinct) Northern Snakehead populations at an early stage.	2.1 Ensure existing public reporting mechanisms remain in place as well as means to authenticate these records.	Ongoing	State Resource Agencies	-	Continue indefinitely	
		2.2 Report new, verified occurrences to a publicly available database (e.g., USGS Nonindigenous Aquatic Species database: https://nas.er.usgs.gov/SightingReport.aspx).	Ongoing	State Resource Agencies & USFWS	-	Continue indefinitely	
		2.3 Identify areas containing species of conservation concern for priority detection.	To be initiated	State Resource Agencies	USFWS	1-year	
		2.4 Develop watershed wide eDNA sampling design in collaboration with partners that focuses on isolated waterbodies (i.e., ponds, lakes, and reservoirs), areas above and below natural and artificial dispersal barriers such as waterfalls and dams, and yet uncolonized, upstream reaches where Northern Snakehead are expected to be found in the future (i.e., leading edge surveys).	Initiated in 2023	USFWS	SRBC, State Resource Agencies	Continue as needed	This action is particularly relevant to the Susquehanna River basin upstream of Conowingo Reservoir
		2.5 Develop coordination between state and federal agencies about appropriate rapid response actions.	Ongoing	USFWS & State Resource Agencies	-	Continue indefinitely	

Strategy	Objective	Action	Current Status	Lead Agency	Cooperating Agency	Timeframe	Comments
		2.6 Create decision tree that guides Northern Snakehead early detection and rapid response actions, to complement existing state and regional rapid response protocols.	To be initiated	USFWS	State Resource Agencies	1-year	
Spread Limitation	Limit the spread of Northern Snakehead within connected waterways of the Chesapeake Bay watershed.	3.1 Where possible, maintain artificial barriers to Northern Snakehead dispersal (i.e., dams), while simultaneously allowing for native anadromous fish passage.	Variable by state	State Resource Agencies	SRAFRC, USFWS	Variable	For hydroelectric dams on the Susquehanna, power companies are responsible for costs associated with fish passage, under guidance of SRAFRC
		3.2 If canals connecting watersheds are unused for boat passage, and in state of disrepair, disconnect a section to prevent spread of Northern Snakehead to adjacent watersheds (i.e., ensure at least one section is permanently de-watered thereby eliminating the potential for dispersal through abandoned canals which are subject to occasional flooding).	Variable by state	State Resource Agencies	USFWS	Variable	Likely to apply in limited circumstances
Control and Management	In established areas, minimize Northern Snakehead population size through control and management actions.	4.1 Encourage harvest by having minimal recreational fishery regulations.	Ongoing / Variable by state	State Resource Agencies	-	Continue indefinitely	Action dependent on invasion stage
		4.2 Allow bowfishing for Northern Snakehead.	Ongoing / Variable by state	State Resource Agencies	-	Continue indefinitely	Action dependent on invasion stage
		4.3 Consider developing commercial market	Ongoing / Variable by state	State Resource Agencies	-	Continue indefinitely	Action dependent on invasion stage
		4.4 Implement recreational harvest initiatives (e.g., public communications, outreach, tournaments).	Ongoing / Variable by state	State Resource Agencies	USFWS	Dependent on initiative	Action dependent on invasion stage
		4.5 Focus electrofishing effort in high density areas or those of conservation concern.	Ongoing / Variable by state	State Resource Agencies, USFWS	-	Continue as needed	
		4.6 Target Northern Snakehead below natural and artificial barriers when they congregate in the springtime.	To be initiated	State Resource Agencies, USFWS	-	Continue as needed	
Research	Conduct research to better understand Northern Snakehead biology,	5.1 Determine, what, if any, long-term impacts Northern Snakehead have on aquatic communities of various types.	Ongoing	USFWS, State Resource Agencies	-	Longer-term, no definite timeframe	USFWS to add new long-term monitoring site
		5.2 Research selective fish passage to allow native anadromous species to bypass dams while preventing Northern Snakehead from doing so.	To be initiated	USGS, USFWS, MDDNR	-	5-years	

Strategy	Objective	Action	Current Status	Lead Agency	Cooperating Agency	Timeframe	Comments
	population dynamics, and impacts, and develop more effective detection, surveillance, and control methods.	5.3 Determine Northern Snakehead ability to traverse small low-head dams and navigate fish ladders.	To be initiated	USGS, USFWS	State Resource Agencies	5-years	This could be part of selective fish passage research (5.2, above) in which Northern Snakehead maximal swimming abilities and potential jumping abilities are tested in a closed system (and then this applied hypothetically to dams of various sizes to determine if the dam flow and height would preclude passage). This could also be tested empirically through eDNA sampling above and below existing barriers (see 2.4, above).
		5.4 Research Northern Snakehead upstream dispersal triggers in the springtime.	Ongoing	USFWS, MDDNR	-	3-years	Two ways to address this are through study of dispersal patterns from high-reward tagging study, and study of arrival time in relation to environmental conditions using data from Conowingo Dam fish lifts.
		5.5 Utilize structured decision making to evaluate potential management actions following Northern Snakehead detection.	Not initiated	USGS	USFWS, State Resource Agencies	Undefined	
		5.6 Perform targeted studies on effectiveness of various management approaches.	Ongoing	USFWS, State Resource Agencies	-	1-year	This includes a study of bowfishing effectiveness in reducing Northern Snakehead numbers and tagging study to assess harvest
		5.7 Further evaluate recreational harvest as an effective means of population control.	Ongoing	USFWS, VDWR, MDDNR	Other State Resource Agencies	3-years	This includes USFWS and MDDNR ongoing high reward tagging study to estimate rate of harvest in Upper Bay tributaries. VDWR continues long-term monitoring of Northern Snakehead density in rivers of northern Virginia.
		5.8 Determine effective and standardized ways of assessing abundance of Northern Snakehead that can be applied across watersheds / jurisdictions.	To be initiated	USFWS	State Resource Agencies	1-year	
		5.9 Periodically assess angler attitudes, and that of general public, toward Northern Snakehead.	Ongoing	State Resource Agencies	USFWS	Undefined	Could include open comment period on fishery regulations or surveys
		5.10 Conduct studies on the contaminant levels in Northern Snakehead from across the Chesapeake Bay watershed, and develop consistent strategy for consumption guidance.	Variable by state	State Resource Agencies and/or USFWS	-	5-years	States have their own fish consumption guidance in state waters and specific localities
		5.11 Assess how control measures might affect population level dynamics (emigration, recruitment, natural mortality, etc.)	To be initiated	USFWS	State Resource Agencies	5-years	

Strategy	Objective	Action	Current Status	Lead Agency	Cooperating Agency	Timeframe	Comments
Public Outreach	Implement public outreach to prevent additional introductions of Northern Snakehead, limit their spread, and aid in control efforts.	6.1 Designate a knowledgeable point person for Northern Snakehead communications and messaging in each state / jurisdiction.	Variable by state	State Resource Agencies	-	1-year	Could be state AIS coordinator, if such a position exists for each state
		6.2 Present message on the illegality of live possession and transport of Northern Snakehead as the primary message across all states and jurisdictions.	Ongoing	State Resource Agencies, USFWS	-	Continue indefinitely	
		6.3 Tailor emphasis of additional messages to invasion stage in local area and the management goal (i.e., eradication versus biomass control).	Ongoing	State Resource Agencies	-	Continue indefinitely	
		6.4 Provide recreational anglers practical advice on rapid and humane ways of dispatching fish for harvest.	Variable by state	State Resource Agencies	-	Continue indefinitely	
		6.5 Regularly review websites and communication materials to make sure they are up to date as new information becomes available and control and management goals change.	Ongoing	State Resource Agencies, USFWS, USGS	-	Continue indefinitely	
		6.6 Create a new website, or designate one of the existing ones (see Appendix E), as a single centralized 'hub' for Northern Snakehead information.	Ongoing	USGS	-	Continue indefinitely	The USGS Northern Snakehead website (https://nas.er.usgs.gov/queries/FactSheet.aspx?SpeciesID=2265) could be used and expanded on as it is currently updated and maintained.
		6.7 Make all Northern Snakehead papers, reports, book chapters, and symposium proceedings open access and freely available online (i.e., as downloadable pdfs) in a single location.	To be initiated	USGS, USFWS	-	1-year	These could be housed at the snakehead 'hub' (see action item 6.6).

XIII. Priorities for action

There are 36 actions identified in this plan. The following 12 are of high priority based on the aggregate prioritization by each state/agency. Actions within each strategy category (i.e., Prevention, Early Detection and Rapid Response, Spread Limitation, Control and Management, Research, and Public Outreach) were prioritized separately from other categories and the top one to three actions within each category are compiled below.

Prevention

- Liaise with angling groups, and snakehead angling groups specifically, to develop a good relationship and address any concerns regarding existing laws and regulations.

Early Detection and Rapid Response

- Identify areas containing species of conservation concern for priority detection.
- Develop watershed wide eDNA sampling design in collaboration with partners that focuses on isolated waterbodies (i.e., ponds, lakes, and reservoirs), areas above and below natural and artificial dispersal barriers such as waterfalls and dams, and yet uncolonized, upstream reaches where Northern Snakehead are expected to be found in the future (i.e., leading edge surveys).
- Develop coordination between state and federal agencies about appropriate rapid response actions.

Spread Limitation

- Where possible, maintain artificial barriers to Northern Snakehead dispersal (i.e., dams), while simultaneously allowing for native anadromous fish passage.

Control and Management

- Focus electrofishing effort in high density areas or those of conservation concern.
- Target Northern Snakehead below natural and artificial barriers when they congregate in the springtime.

Research

- Determine, what, if any, long-term impacts Northern Snakehead have on aquatic communities of various types.
- Research selective fish passage to allow native anadromous species to bypass dams while preventing Northern Snakehead from doing so.
- Conduct studies on the contaminant levels in Northern Snakehead from across the Chesapeake Bay watershed, and develop consistent strategy for consumption guidance.

Public Outreach

- Present message on the illegality of live possession and transport of Northern Snakehead as the primary message across all states and jurisdictions.
- Regularly review websites and communication materials to make sure they are up to date as new information becomes available and control and management goals change.

XIV. Plan review

Review of plan implementation progress will take place during an annual spring meeting of the ‘Chesapeake Bay Northern Snakehead Working Group’. Members of this group can be changed as needed dependent upon interests and expertise. USFWS will be responsible for organizing this meeting. An annual report summarizing this meeting and detailing plan implementation progress and challenges will be generated by USFWS for distribution to all partners.

XV. Literature cited

Agarwal, I., Amrhein, L., Fitzgerald, B., Golt, S., Gonzalez, Z., Hentati, Y., Kang, B., Mann, Y., Matthews, G., Mills, T., 2016. Angler perception and population dynamics of the Northern Snakehead (*Channa argus*) in the Potomac River & tributaries (Thesis). University of Maryland Honors College: Gemstone Program.

ANSTF (Aquatic Nuisance Species Task Force), 2014. National Control and Management Plan for Members of the Snakehead Family family (Channidae). Available: http://www.aquaticnuisance.org/wordpress/wp-content/uploads/2009/01/SnakeheadPlanFinal_5-22-14.pdf

Barnett, J., 2019. A history and distribution of Northern Snakehead in Arkansas, in: Proceedings of the First International Snakehead Symposium. American Fisheries Society, Symposium 89, Bethesda, Maryland, pp. 35–42.

Benson, A.J., 2019. Snakehead fishes (*Channa* spp.) in the USA, in: Proceedings of the First International Snakehead Symposium. American Fisheries Society, Symposium 89, Bethesda, Maryland, pp. 3–21.

Bourdon, R., Newhard, J., Minkkinen, S., Mangold, M., 2022. U.S. Fish & Wildlife Service Susquehanna River American Shad (*Alosa sapidissima*) Restoration: Potomac River Egg Collection, 2022. U.S. Fish and Wildlife Service. Maryland Fish & Wildlife Conservation Office. Technical Report.

Bressman, N.R., Love, J.W., King, T.W., Horne, C.G., Ashley-Ross, M.A., 2019. Emersion and terrestrial locomotion of the Northern Snakehead (*Channa argus*) on multiple substrates. Integrative and Comparative Biology 1, 1–20.

Britton, J.R., Gozlan, R.E., Copp, G.H., 2011. Managing non-native fish in the environment. Fish and Fisheries 12, 256–274.

Bunch, A.J., Odenkirk, J.S., Isel, M.W., Boyce, R.C., 2019. Spatiotemporal patterns and dispersal mechanisms of Northern Snakehead in Virginia, in: Proceedings of the First International Snakehead Symposium. American Fisheries Society, Symposium 89, Bethesda, Maryland, pp. 23–33.

Choi, J.-Y., Kim, S.-K., 2021. Effect of the human utilization of Northern Snakehead (*Channa argus* Cantor, 1842) on the settlement of exotic fish and cladoceran community structure. Sustainability 13, 2486.

Cohen, M.K., MacDonald, J.A., 2016. Northern Snakeheads in New York City. Northeastern Naturalist 23, 11–24.

Courtenay, Jr, W.R., Williams, J.D., 2004. Snakeheads (Pisces, Channidae): a biological synopsis and risk assessment. US Geological Survey Circular 1251.

Crooks, J.A., 2005. Lag times and exotic species: The ecology and management of biological invasions in slow-motion. Ecoscience 12, 316–329.

Darkwah, G., Browder, R., 2019. Symposium Abstract: Contaminant levels of Polychlorinated Biphenyls (PCBs) in edible fillets of Northern Snakehead *Channa argus* from Virginia Potomac River tributaries, in: Proceedings of the First International Snakehead Symposium. American Fisheries Society. Symposium 89, Bethesda, Maryland, p. 239.

De Mutsert, K., Sills, A., Schlick, C.J., Jones, R.C., 2017. Successes of restoration and its effect on the fish community in a freshwater tidal embayment of the Potomac River, USA. Water 9, 421.

Densmore, C.L., Iwanowicz, L.R., Henderson, A.P., Iwanowicz, D.D., Odenkirk, J.S., 2016. Mycobacterial infection in Northern Snakehead (*Channa argus*) from the Potomac River catchment. Journal of Fish Diseases 39, 771–775.

Flaherty, M.J., 2019. Symposium Abstract: Eradication of Northern Snakehead from the Catlin Creek watershed in Southeastern New York: a success story?, in: Proceedings of the First International Snakehead Symposium. American Fisheries Society. Symposium 89, Bethesda, Maryland, p. 232.

Fuller, P.L., Benson, A.J., Nunez, G., Fusaro, A., and Neilson, M., 2022, *Channa argus* (Cantor, 1842): U.S. Geological Survey, Nonindigenous Aquatic Species Database, Gainesville, FL, https://nas.er.usgs.gov/queries/FactSheet.aspx?SpeciesID=2265, Revision Date: 12/31/2019, Peer Review Date: 9/22/2015, Access Date: 5/22/2022

Herborg, L.-M., Mandrak, N.E., Cudmore, B.C., MacIsaac, H.J., 2007. Comparative distribution and invasion risk of snakehead (Channidae) and Asian carp (Cyprinidae) species in North America. Canadian Journal of Fisheries and Aquatic Sciences 64, 1723–1735.

Hoff, M.H., Odenkirk, J.S., 2019. Management implications from a stock-recruit model for Northern Snakehead in Virginia waters of the tidal Potomac River, in: Proceedings of the First International Snakehead Symposium. American Fisheries Society, Symposium 89, Bethesda, Maryland, pp. 173–182.

Isel, M.W., Odenkirk, J.S., 2019. Evaluation of Northern Snakehead diets in Virginia’s tidal rivers and lakes, in: Proceedings of the First International Snakehead Symposium. American Fisheries Society, Symposium 89, Bethesda, Maryland, pp. 83–93.

Iwanowicz, L., Densmore, C., Hahn, C., McAllister, P., Odenkirk, J., 2013. Identification of Largemouth Bass virus in the introduced Northern Snakehead inhabiting the Chesapeake Bay watershed. Journal of Aquatic Animal Health 25, 191–196.

Jiao, Y., Lapointe, N.W.R., Angermeier, P.L., Murphy, B.R., 2009. Hierarchical demographic approaches for assessing invasion dynamics of non-indigenous species: an example using Northern Snakehead (*Channa argus*). Ecological Modelling 220, 1681–1689.

Johnson, B.M., Arlinghaus, R., Martinez, P.J., 2009. Are we doing all we can to stem the tide of illegal fish stocking? Fisheries 34, 389–394.

Jones, R.C., De Mutsert, K., Fowler, A., 2021. An ecological study of Gunston Cove 2020. Available: https://perec.science.gmu.edu/wp-content/uploads/2021/11/GC-2020-Final-Entire-Report.pdf

Kim, H.H., Emmel, J.A., Phelps, Q.E., 2019. Proposed standard-weight (W_s) equation and size structure indices for Northern Snakehead, in: Proceedings of the First International Snakehead Symposium. American Fisheries Society, Symposium 89, Bethesda, Maryland, pp. 45–51.

King, T.L., Johnson, R.L., 2011. Novel tetra-nucleotide microsatellite DNA markers for assessing the evolutionary genetics and demographics of Northern Snakehead (*Channa argus*) invading North America. Conservation Genetics Resources 3, 1–4.

Kolar, C.S., Courtenay Jr, W.R., Nico, L.G., 2010. Managing undesired and invading fishes, in: Inland Fisheries Management in North America. American Fisheries Society, Bethesda, Maryland, pp. 213–259.

Koo, T.S.Y., Wilson, J.S., 1972. Sonic tracking Striped Bass in the Chesapeake and Delaware Canal. Transactions of the American Fisheries Society 101, 453–462.

Kramer, A.M., Annis, G., Wittmann, M.E., Chadderton, W.L., Rutherford, E.S., Lodge, D.M., Mason, L., Beletsky, D., Riseng, C., Drake, J.M., 2017. Suitability of Laurentian Great Lakes for invasive species based on global species distribution models and local habitat. Ecosphere 8, e01883.

Landis, A.M.G., Lapointe, N.W.R., 2010. First record of a Northern Snakehead (*Channa argus* Cantor) nest in North America. Northeastern Naturalist 17, 325–332.

Landis, A.M.G., Lapointe, N.W.R., Angermeier, P.L., 2011. Individual growth and reproductive behavior in a newly established population of Northern Snakehead (*Channa argus*), Potomac River, USA. Hydrobiologia 661, 123–131.

Lapointe, N.W.R., Odenkirk, J.S., Angermeier, P.L., 2013. Seasonal movement, dispersal, and home range of Northern Snakehead *Channa argus* (Actinopterygii, Perciformes) in the Potomac River catchment. Hydrobiologia 709, 73–87.

Lapointe, N.W.R., Thorson, J.T., Angermeier, P.L., 2010. Seasonal meso- and microhabitat selection by the Northern Snakehead (*Channa argus*) in the Potomac River system. Ecology of Freshwater Fish 19, 566–577.

Lapointe, N.W.R., Saylor, R.K., Angermeier, P.L., 2019. Diel feeding and movement activity of Northern Snakehead, in: Proceedings of the First International Snakehead Symposium. American Fisheries Society, Symposium 89, Bethesda, Maryland, pp. 69–81.

Lapointe, N.W.R., Pendleton, R.M., Angermeier, P.L., 2012. A comparison of approaches for estimating relative impacts of nonnative fishes. Environmental Management 49, 82–95.

Lazur, A., Early, S., Jacobs, J.M., 2006. Acute toxicity of 5% rotenone to Northern Snakeheads. North American Journal of Fisheries Management 26, 628–630.

Love, J.W., Genovese, P., 2019. Fishing for an invasive: Maryland's toolbox for managing Northern Snakehead, in: Proceedings of the First International Snakehead Symposium. American Fisheries Society, Symposium 89, Bethesda, Maryland, pp. 139–152.

Love, J.W., Gill, J., Newhard, J.J., 2008. Saltwater intrusion impacts fish diversity and distribution in the Blackwater River drainage (Chesapeake Bay watershed). Wetlands 28, 967–974.

Love, J.W., Newhard, J.J., 2012. Will the expansion of Northern Snakehead negatively affect the fishery for Largemouth Bass in the Potomac River (Chesapeake Bay)? North American Journal of Fisheries Management 32, 859–868.

Love, J.W., Newhard, J.J., 2018. Expansion of Northern Snakehead in the Chesapeake Bay watershed. Transactions of the American Fisheries Society 147, 342–349.

Love, J.W., Newhard, J.J., 2021. Using published information to predict consumption by Northern Snakehead in Maryland. Transactions of the American Fisheries Society 150, 425–434.

Love, J.W., Newhard, J.J., Greenfield, B., 2015a. A geospatial approach for estimating suitable habitat and population size of the invasive Northern Snakehead. Journal of Fish and Wildlife Management 6, 145–157.

Love, J.W., Newhard, J.J., Groves, M., 2015b. Risk of population decline for Largemouth Bass in a Potomac River fishery (USA): Effects from invasive Northern Snakehead, in: Black Bass Diversity: Multidisciplinary Science for Conservation. American Fisheries Society Symposium, pp. 207–222.

Martin, C.C., 2012. Action plan for Northern Snakehead (*Channa argus*) in Delaware. Delaware Division of Fish and Wildlife.

Mason, M.D., 2003. The saga of the snakehead fish. Natural Resources & Environment 17, 242–244.

Mathwin, J., 2018. Stop killing the Potomac's snakehead. The Washington Post. Available: https://www.washingtonpost.com/opinions/stop-killing-the-potomacs-snakehead/2018/07/13/c48ecf7e-7e3c-11e8-b660-4d0f9f0351f1_story.html

MDDNR (Maryland Department of Natural Resources), 2016. Maryland Aquatic Nuisance Species Management Plan. Annapolis. Available: https://dnr.maryland.gov/Invasives/Documents/Maryland_Aquatic_Nuisance_Species_Plan.pdf

Nakai, K., 2019. Historical review of snakeheads in Japan, in: Proceedings of the First International Snakehead Symposium. American Fisheries Society, Symposium 89, Bethesda, Maryland, pp. 185–202.

Newhard, J.J., 2015. Identification and location of testes in the invasive *Channa argus* Cantor (Northern Snakehead). Northeastern Naturalist 22, N15–N18.

Newhard, J.J., unpublished. How much effort is needed to overfish the invasive Northern Snakehead?

Newhard, J.J., Love, J.W., 2019. Comparison of fish community within the Blackwater River watershed before and after establishment of Northern Snakehead *Channa argus*. USFWS & MDDNR. Available: https://dnr.maryland.gov/fisheries/Documents/FINAL_Blackwater%20Fish%20Community%20Comparison.pdf

Newhard, J.J., Odenkirk, J.S., Lyon, L., 2019. Effects of fishing on select populations of Northern Snakehead in the Potomac River, in: Proceedings of the First International Snakehead Symposium. American Fisheries Society, Symposium 89, Bethesda, Maryland, pp. 159–171.

Normandeau Associates, 2021. Summary of Operations at the Conowingo Dam East Fish Passage Facility Spring 2020. Available: https://www.srbc.net/srafrc/docs/2020/conowingo-east-lift-fish-passage-2020.pdf

Nuñez, M.A., Kuebbing, S., Dimarco, R.D., Simberloff, D., 2012. Invasive species: to eat or not to eat, that is the question. Conservation Letters 5, 334–341.

Odenkirk, J., Lim, C., Owens, S., Isel, M., 2013. Insight into age and growth of Northern Snakehead in the Potomac River. North American Journal of Fisheries Management 33, 773–776.

Odenkirk, J., Owens, S., 2005. Northern Snakeheads in the tidal Potomac River system. Transactions of the American Fisheries Society 134, 1605–1609.

Odenkirk, J., Owens, S., 2007. Expansion of a Northern Snakehead population in the Potomac River system. Transactions of the American Fisheries Society 136, 1633–1639.

Odenkirk, J.S., Isel, M.W., 2016. Trends in abundance of Northern Snakeheads in Virginia tributaries of the Potomac River. Transactions of the American Fisheries Society 145, 687–692.

Orrell, T.M., Weigt, L., 2005. The Northern Snakehead *Channa argus* (Anabantomorpha: Channidae), a non-indigenous fish species in the Potomac River, USA. Proceedings of the Biological Society of Washington 118, 407–415.

Orth, D.J., 2019. Socrates opens a Pandora's box of Northern Snakehead issues, in: Proceedings of the First International Snakehead Symposium. American Fisheries Society, Symposium 89, Bethesda, Maryland, pp. 203–221.

Owens, S.J., Odenkirk, J.S., Greenlee, R., 2008. Northern Snakehead movement and distribution in the tidal Potomac River system, in: Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies. pp. 161–167.

Pasko, S., Goldberg, J., 2014. Review of harvest incentives to control invasive species. Management of Biological Invasions 5, 263–277.

Phelps, Q.E., Kim, H.H., Lim, C., Odenkirk, J.S., 2019. Marginal increment analysis of Northern Snakehead otoliths, in: Proceedings of the First International Snakehead Symposium. American Fisheries Society, Symposium 89, Bethesda, Maryland, pp. 153–158.

Pinkney, A.E., 2018. Contaminant Concentrations in Fish Tissue Collected from the Waters of the District of Columbia: 2017-2018. U.S. Fish and Wildlife Service. Publication No. CBFO-C18-02.

Poulos, H.M., Chernoff, B., Fuller, P.L., Butman, D., 2012. Ensemble forecasting of potential habitat for three invasive fishes. Aquatic Invasions 7, 59–72.

Resh, C.A., Galaska, M.P., Benesh, K.C., Gardner, J.P.A., Wei, K.J., Yan, R.J., Mahon, A.R., 2021. Using genomics to link populations of an invasive species to its potential sources. Frontiers in Ecology and Evolution 9, 575599.

Resh, C.A., Galaska, M.P., Mahon, A.R., 2018. Genomic analyses of Northern Snakehead (*Channa argus*) populations in North America. PeerJ 6, e4581.

Reynolds, J.B., Dean, J.C., 2020. Development of electrofishing for fisheries management. Fisheries, 45, 229-237.

Rice, J., 2016. The snakehead war: Administrative rule-making and legislative strategies to minimize destruction by the Northern Snakehead. William & Mary Environmental Law and Policy Review 40, 965–987.

Roop, H.J., Whelan, N.V., Williams, A.S., Page, J., 2020. First record of occurrence and genetic characterization of a population of Northern Snakehead *Channa argus* (Cantor, 1842) in Georgia, USA. Bioinvasions Records 9, 842–852.

Saylor, R.K., Lapointe, N.W.R., Angermeier, P.L., 2012. Diet of non-native Northern Snakehead (*Channa argus*) compared to three co-occurring predators in the lower Potomac River, USA. Ecology of Freshwater Fish 21, 443–452.

Schloesser, N., Erickson, R., Putnam, J., 2019. Symposium Abstract: Integrated pest management: Lessons learned from Sea Lamprey control, in: Proceedings of the First International Snakehead Symposium. American Fisheries Society. Symposium 89, Bethesda, Maryland, p. 231.

Simberloff, D., 2009. We can eliminate invasions or live with them. Successful management projects. Biological Invasions 11, 149–157.

Simberloff, D., Parker, I.M., Windle, P.N., 2005. Introduced species policy, management, and future research needs. Frontiers in Ecology and the Environment 3, 12–20.

Smith, S.C.F., Micah Tindall, Homan, J., Lochmann, S.E., 2019. Large-scale predictions of Northern Snakehead range expansion using maximum entropy modeling, in: Proceedings of the First International Snakehead Symposium. American Fisheries Society, Symposium 89, Bethesda, Maryland, pp. 97–114.

Starnes, W.C., Odenkirk, J., Ashton, M.J., 2011. Update and analysis of fish occurrences in the lower Potomac River drainage in the vicinity of Plummers Island, Maryland—Contribution XXXI to the natural history of Plummers Island, Maryland. Proceedings of the Biological Society of Washington 124, 280–309.

Temple, A.J., Newhard, J., 2019. Symposium Abstract: Defining electrical settings to increase sampling efficiency and precision for Northern Snakehead *Channa argus*, in: Proceedings of the First International Snakehead Symposium. American Fisheries Society. Symposium 89, Bethesda, Maryland, p. 235.

US Army Corps of Engineers, 2012. ANS Control Fact Sheets. Available: https://glmris.anl.gov/documents/docs/anscontrol/All27ANSControlFactSheets.pdf

US Department of the Interior. 2016. Safeguarding America's lands and waters from invasive species: A national framework for early detection and rapid response, Washington D.C. Available: https://www.doi.gov/sites/doi.gov/files/National%20EDRR%20Framework.pdf

Wegleitner, B.J., Tucker, A., Chadderton, W.L., Mahon, A.R., 2016. Identifying the genetic structure of introduced populations of Northern Snakehead (*Channa argus*) in Eastern USA. Aquatic Invasions 11, 199–208.

Welsh, S.A., Mangold, M.F., Skjeveland, J.E., Spells, A.J., 2002. Distribution and movement of Shortnose Sturgeon (*Acipenser brevirostrum*) in the Chesapeake Bay. Estuaries 25, 101–104.

Appendix A. Listed species potentially preyed upon by Northern Snakehead

Category	Common name	Scientific name	Federal	Delaware	Maryland	Pennsylvania	Virginia	Risk from snakehead
Amphibians	Eastern Cricket Frog	*Acris crepitans*				Endangered		minimal / moderate
Amphibians	Mabee's salamander	*Ambystoma mabeei*					Threatened	minimal
Amphibians	Eastern Tiger Salamander	*Ambystoma tigrinum*		Endangered	Endangered		Endangered	minimal
Amphibians	Eastern Hellbender	*Cryptobranchus alleganiensis*			Endangered			minimal
Amphibians	Barking Treefrog	*Hyla gratiosa*		Endangered	Endangered			minimal
Amphibians	Eastern Narrow-mouthed Toad	*Gastrophryne carolinensis*			Endangered			minimal
Amphibians	Cheat Mountain Salamander	*Plethodon nettingi*	Threatened (WV)					non-existent / minimal
Amphibians	Shenandoah Salamander	*Plethodon shenandoah*	Endangered (VA)				Endangered	non-existent / minimal
Amphibians	Mountain Chorus Frog	*Pseudacris brachyphona*			Endangered			minimal
Amphibians	Mud Salamander	*Pseudotriton montanus*		Endangered		Endangered		minimal
Amphibians	Eastern Spadefoot Toad	*Scaphiopus holbrookii*				Threatened		non-existent / minimal
Crustaceans	Madison Cave Isopod	*Antrolana lira*	Threatened (VA, WV)				Threatened	non-existent / minimal
Crustaceans	Franz's Cave Isopod	*Caecidotea franzi*			Endangered			non-existent / minimal
Crustaceans	Maus' Cave Isopod	*Caecidotea mausi*			Endangered			non-existent / minimal
Crustaceans	Vandel's Cave Isopod	*Caecidotea vandeli*			Endangered			non-existent / minimal
Crustaceans	Pennsylvania Cave Crangonyctid	*Crangonyx dearolfi*			Endangered			non-existent / minimal
Crustaceans	Friendly Cave Amphipod	*Stygobromus amicus*			Endangered			non-existent / minimal
Crustaceans	Biggers' Cave Amphipod	*Stygobromus biggersi*			Endangered			non-existent / minimal
Crustaceans	Cecil Groundwater Amphipod	*Stygobromus caecilius*			Endangered			non-existent / minimal
Crustaceans	Feller's Groundwater Amphipod	*Stygobromus felleri*			Endangered			non-existent / minimal
Crustaceans	Rappahannock Spring Amphipod	*Stygobromus foliatus*			Endangered			non-existent / minimal
Crustaceans	Shenandoah Valley Cave Amphipod	*Stygobromus gracilipes*			Endangered			non-existent / minimal
Crustaceans	Hay's Spring Amphipod	*Stygobromus hayi*	Endangered (DC, MD)					non-existent / minimal
Crustaceans	Rock Creek Groundwater Amphipod	*Stygobromus kenki*			Endangered			non-existent / minimal
Crustaceans	Prettyboy Groundwater Amphipod	*Stygobromus paxillus*			Endangered			non-existent / minimal
Crustaceans	Capital Area Groundwater Amphipod	*Stygobromus sextarius*			Endangered			non-existent / minimal
Crustaceans	Madison Cave Amphipod	*Stygobromus stegerorum*					Threatened	non-existent / minimal
Fishes	Shortnose Sturgeon	*Acipenser brevirostrum*	Endangered (DC, DE, MD, VA)	Endangered	Endangered		Endangered	minimal
Fishes	Atlantic Sturgeon	*Acipenser oxyrhynchus*	Endangered (DC, DE, MD, VA)	Endangered	Endangered		Endangered	minimal
Fishes	Northern Redbelly Dace	*Chrosomus eos*				Endangered		moderate / high

Category	Common name	Scientific name	Federal	Delaware	Maryland	Pennsylvania	Virginia	Risk from snakehead
Fishes	Blueridge Sculpin	*Cottus caeruleomentum*		Endangered				minimal
Fishes	Blackbanded Sunfish	*Enneacanthus chaetodon*		Endangered	Endangered		Endangered	high
Fishes	Maryland Darter	*Etheostoma sellare*	Endangered (MD)		Endangered			minimal / moderate
Fishes	Glassy Darter	*Etheostoma vitreum*		Endangered	Threatened			minimal / moderate
Fishes	American Brook Lamprey	*Lethenteron appendix*			Threatened			minimal
Fishes	Bridled Shiner	*Notropis bifrenatus*		Endangered		Endangered		moderate
Fishes	Ironcolor Shiner	*Notropis chalybaeus*		Endangered	Endangered			moderate
Fishes	Blackchin Shiner	*Notropis heterodon*				Endangered		moderate
Fishes	Blacknose Shiner	*Notropis heterolepis*				Endangered		moderate
Fishes	Orangefin Madtom	*Noturus gilberti*					Threatened	minimal / moderate
Fishes	Tadpole Madtom	*Noturus gyrinus*				Endangered		moderate / high
Fishes	Chesapeake Logperch	*Percina bimaculata*			Threatened	Threatened		minimal / moderate
Fishes	Stripeback Darter	*Percina notogramma*			Endangered			minimal / moderate

Species of conservation concern (i.e., Threatened or Endangered) found within the Chesapeake Bay watershed, and which may potentially be impacted by Northern Snakehead. Amphibians, crustaceans, and fishes were included since diet studies indicate these groups are preyed upon by Northern Snakehead (Section IV). Arachnids, birds, ferns and allies, flowering plants, insects, lichens, mammals, millipedes, mollusks, planarians, and reptiles were not included because species in these groups are either unlikely to be preyed upon by Northern Snakehead or make up a relatively small dietary component. The column 'Federal' indicates whether the species is federally listed under the Endangered Species Act, meaning it is threatened or endangered across its entire geographic range; states in which the species is found within the Chesapeake Bay watershed are indicated in parentheses. The columns for states indicate whether the species is threatened or endangered within a given state and found within the Chesapeake Bay watershed in that state. A species listed as threatened or endangered by a state refers only to its status within that state and not across the entire geographic range of the species – hence it is a common occurrence for a given species to be listed as threatened or endangered within a given state, but not listed federally. Washington D.C. and West Virginia apparently do not maintain a separate category of state listed species and hence are not represented. In New York, none of the state listed threatened or endangered amphibian, crustacean, or fish species are found within the Chesapeake Bay watershed in that state, hence it is not represented. The column 'Risk from snakehead' indicates the potential risk posed to the given species from Northern Snakehead predation. Risk assessment was based upon habitat preferences of the listed species in comparison to that of Northern Snakehead, and hence likelihood the two species would interact and the listed species would regularly be preyed upon. Most listed Amphibian species appear to be of minimal risk from Northern Snakehead due to habitat segregation (i.e., primarily terrestrial as adults and breed either terrestrially as in *Plethodon* salamanders, or in aquatic environments unlikely to be inhabited by Northern Snakehead including vernal pools, ephemeral pools, or fish-less ponds). All listed species of aquatic crustaceans were isopods or amphipods that inhabit subterranean waters and occasionally are found above ground in seepage springs where ground water reaches the surface; hence the risk posed by Northern Snakehead is likely minimal due to habitat segregation. However, several state listed fish species including Blackbanded Sunfish, Northern Redbelly Dace, Tadpole Madtom, and four species of shiners exhibit similar habitat preferences as Northern Snakehead and would likely be regularly preyed upon. Other listed fish species including three species of darters, Chesapeake Logperch, Orangefin Madtom, American Brook Lamprey, and Blueridge Sculpin would likely be preyed upon by Northern Snakehead occasionally but are typically found in the riffles of rocky-bottomed streams and rivers, which Northern Snakehead will pass through but which is not preferred habitat.

<u>Data sources</u>
Federal: https://ecos.fws.gov/ecp/report/species-listings-by-state-totals?statusCategory=Listed and https://www.fisheries.noaa.gov/species-directory/threatened-endangered
Delaware: https://dnrec.alpha.delaware.gov/fish-wildlife/conservation/endangered-species/
Maryland: https://dnr.maryland.gov/wildlife/Documents/rte_Animal_List.pdf
New York: https://www.dec.ny.gov/animals/7494.html
Pennsylvania: https://www.pacodeandbulletin.gov/Display/pacode?file=/secure/pacode/data/058/chapter75/chap75toc.html and https://www.pgc.pa.gov/Wildlife/EndangeredandThreatened/Pages/default.aspx
Virginia: https://dwr.virginia.gov/wp-content/uploads/media/virginia-threatened-endangered-species.pdf
Habitat Reference: https://explorer.natureserve.org/

Appendix B. Regulations summary

Northern Snakehead regulations by state, taken from publicly available online sources and communication with state resource agencies. NA = Not applicable. NL = not listed or specified.

State	Season	Gear restrictions	Bow-fishing	Size limit	Creel limit	Commercial license / market	Immediate release	Live possession	Dead possession	Penalty for violation	Reporting	Notes	State record	Reference(s)
Delaware	Open year round	Permissible by bowfishing, spear, or hook and line	Yes	None	None	NL	Yes	No	Yes	NL	If you catch Northern Snakehead, please send an e-mail to DNRECFisheries@delaware.gov or call 302-739-9914 or go to http://bit.ly/reportinvasivefish from your phone.	Official fishing regulations state that "If you catch a Northern Snakehead please do not return it to the water, but kill it and contact us."	12 lb 12 oz	https://www.eregulations.com/assets/docs/guides/22DEFW.pdf; https://fishspecies.dnrec.delaware.gov/FishSpecies.aspx?habitat=1&species=43; https://regulations.delaware.gov/register/december2004/proposed/8%20DE%20Reg%20858%2012-01-04.htm
Maryland	Open year round	Gigging is not allowed	Yes	None	None	Yes	Yes	No	Yes	$1000 maximum fine per fish for live possession, $2500 maximum fine for import, transport, or introduction	Anglers asked to report snakehead (with a picture) outside of the Potomac River and its tributaries or upstream of Great falls, to Maryland's Invasive Fish Tracker website (https://survey123.arcgis.com/share/bf026700cada433296cab48ab2a090b6), or by email (fishingreports.dnr@maryland.gov) or phone (410-260-8300).	Live possession and transport prohibited. If fish are to be harvested they must be killed immediately, or else released at spot of capture.	19.9 lb	https://www.eregulations.com/maryland/fishing/invasive-species; https://www.eregulations.com/assets/docs/guides/22MDFW.pdf; https://mdcourts.gov/sites/default/files/files/import/district/dcar/XVIII-AdmReg-042019.pdf; https://dnr.maryland.gov/fisheries/Documents/NorthernSnakehead_Sign_English.pdf; https://law.justia.com/codes/maryland/2019/natural-resources/title-4/subtitle-7/sect-4-701-1/
New York	NA	NA	No	NA	NA	No	No	No	No	NL	Report it to your regional NYS DEC fisheries office or to NYS DEC's Invasive Species Bureau at isinfo@dec.ny.gov or (518) 402-9425	In official fishing regulations nothing is listed regarding license, season, gear, limits, etc. except that "possession prohibited" and "Any snakehead caught while angling cannot be released back into the water. They must be immediately killed and reported to DEC."	NL	https://www.dec.ny.gov/docs/fish_marine_pdf/fishguide2022.pdf; https://www.dec.ny.gov/animals/45470.html

State	Season	Gear restrictions	Bow-fishing	Size limit	Creel limit	Commercial license / market	Immediate release	Live possession	Dead possession	Penalty for violation	Reporting	Notes	State record	Reference(s)
Pennsylvania	Open year round	Permissible by hook and line and bowfishing	Yes	None	None	No	Yes	No	Yes	$150 fine per fish for live possession	Anglers suspecting they have caught a Snakehead are encouraged to NOT release it, and report it to the Commission at 814-359-5163 or via email (sehartzell@pa.gov). They can also report to general AIS web reporting form: https://pfbc.pa.gov/forms/reportAIS.htm or call the PA Invasive Species Reporting Hotline (1-833-INVASIV).	In official fishing regulations nothing is listed regarding license, season, gear, limits, etc. except that it is unlawful to possess, introduce, or import, transport, sell, purchase, offer for sale, or barter live snakehead (all species) in Pennsylvania.	NL	https://www.fishandboat.com/Fish/FishingRegulations/Documents/2022summarybook.pdf; https://www.media.pa.gov/pages/fish-and-boat-commission-details.aspx?newsid=491
Virginia	Open year round	NA	Yes	None	None	NL	Yes	No	Yes	Class 1 misdemeanor	Anglers may possess snakeheads taken from Virginia waters if they immediately kill the fish and notify the headquarters or a regional office of the department; notification may be made by calling (804) 367-2925.	According to Virginia DWR website: "Anglers are required to report snakeheads kept but are not required to kill them if caught and immediately released. Snakeheads must be dead if in possession (contained in live well, cooler, etc.). However, the Department asks that all snakeheads be killed if possible."	None officially listed by state (unofficial: 19 lb 5 oz)	https://dwr.virginia.gov/wp-content/uploads/media/2022-fishing-regulations.pdf; https://dwr.virginia.gov/fishing/snakehead/; https://law.lis.virginia.gov/vacode/title18.2/chapter7/section18.2-313.2/; https://dwr.virginia.gov/fishing/trophy-fish/state-records/; https://chesapeakebaymagazine.com/wild-chesapeake-world-record-snakehead-caught-in-va/
West Virginia	NA	NA	NA	NA	NA	NA	NA	NA	NA	NL	It is requested that snakehead sightings be reported to ais@wv.gov or WVdnr.gov	Currently, there have been no live reports of Northern Snakehead in West Virginia.	NA	https://wvdnr.gov/wp-content/uploads/2022/01/2022.01.04-DNR_FishingRegulations.pdf
Washington D.C.	Open year round	Hook and line only	No	None	None	NL	Yes	No	Yes	NL	NL	Official fishing regulations state: "If you catch a Northern Snakehead DO NOT RETURN IT TO THE WATER. Snakeheads should be immediately killed by removing the head, removing all vital organs, or removing both gill arches." No information is listed regarding license, season, gear, limits, etc.	NL	https://doee.dc.gov/service/regulated-fishing-activities

Appendix C. Eradication attempts summary

Summary of response to the discovery of a reproducing Northern Snakehead population in a new region or area distinct from their prior distribution. Not included was the discovery of non-reproducing populations (often a single fish) or new incremental range extensions in watersheds in which they were already established. Although sample size is limited, these cases help address under what circumstances Northern Snakehead populations may be effectively eradicated.

Site	City/Region	State	Watershed	Date	Waterway	Waterbody size	Eradication attempted	Eradication successful	Method(s)	Cost	Number	Notes	Reference
Crofton Pond	Crofton	Maryland	Chesapeake Bay	2002	Closed	3 acres	Yes	Yes	Rotenone	Unknown but likely low	Over 1300	In May 2002, an angler captured an adult Northern Snakehead and sent pictures to MDNR. In June another angler caught an adult and eight juveniles. MDNR captured 100 young-of-year while electrofishing. In September, the pond was treated with rotenone and over 1200 Northern Snakeheads were found. Source of introduction determined to be release of three live fish by local resident who obtained them from live food market in New York.	Courtenay and Williams (2004), ANSTF (2014)
Potomac River	Dogue Creek near Mount Vernon	Virginia	Chesapeake Bay	2004	Open	Hundreds of km	Yes	No	Electrofishing, nets (gill, trap, seine, trawl, minnow traps), angling	Unknown but high in terms of personnel and time	20 during 2004	In May 2004, an angler captured an adult Northern Snakehead in Little Hunting Creek, a tributary of the tidal Potomac River. Over the next several months extensive sampling by Virginia Department of Game and Inland Fisheries, other agencies, commercial fisherman, and anglers captured 20 Northern Snakeheads of several different age/size classes within a 23-km reach of the Potomac River. 10 of the 20 fish collected during 2004 were from Dogue Creek, and multiple collections occurred in adjacent creeks both to the north and south of this point, suggesting it was the point of introduction.	Odenkirk and Owens (2005), ANSTF (2014)
Meadow Lake	Philadelphia	Pennsylvania	Delaware River	2004	Open	17 acres, but part of a maze of interconnected embayments and tidal sloughs	No	NA	NA	NA	Several size-classes including juveniles	In July 2004, an angler captured and preserved two adult Northern Snakeheads. A total of six were later captured from the lake. In 2005, sampling efforts captured several size-classes including juveniles. According to the National Snakehead Plan: "Given the openness of the system, Pennsylvania Fish and Boat Commission (PFBC) biologists concluded that the fish had probably accessed adjoining waters of the nearby lower Schuylkill and Delaware Rivers. As a result, PFBC biologists decided that they would monitor the pond and surrounding waters but eradication would not be feasible (PFBC press release, July 23, 2004)."	ANSTF (2014), Benson (2019)

Site	City/Region	State	Watershed	Date	Waterway	Waterbody size	Eradication attempted	Eradication successful	Method(s)	Cost	Number	Notes	Reference
Meadow & Willow Lakes	Queens	New York	Atlantic Ocean / Long Island Sound	2005	Closed	38.4 & 18.2 hectares	No	NA	NA	NA	3 initially, 62 between 2006 and 2013	In June 2005, three Northern Snakeheads were captured in a fyke net in Meadow Lake (one of two connected lakes in Flushing Meadows Corona Park). This lake system connects to the saline waters of Flushing Bay, so there was no concern that the population would expand to contiguous freshwater bodies. The population was monitored using boat electrofishing and fyke nets between July 2006 and October 2013. 62 Northern Snakeheads were captured in Meadow and Willow Lakes during the study period.	ANSTF (2014), Cohen and MacDonald (2016)
Big Piney Creek	White River System	Arkansas	Mississippi River	2008	Open	50,021 acres (20,234 hectares) covering approximately 700 km of creeks, ditches, and backwater areas	Yes	No	Rotenone	$429,359 not including labor of 7,000 person hours	Over 1000	In April 2008, a local farmer captured a Northern Snakehead and reported it to Arkansas Game and Fish Commission. A survey by AGFC biologists discovered an established Northern Snakehead population in the Big Piney Creek watershed that likely originated as escapees from farm ponds. In March 2009, a massive eradication effort was attempted using rotenone distributed from helicopters, Marsh Masters, boats, and ground teams. This eradication attempt ultimately proved unsuccessful as live Northern Snakehead were found during post-treatment monitoring.	ANSTF (2014), Barnett (2019)
Ridgebury Lake / Catlin Creek	Orange County	New York	Hudson River	2008	Open	28 acres + 2 miles of creek + 49 acres of wetland	Yes	Yes	Rotenone	Unknown	227	In May 2008, a private pond owner notified NY DEC of the capture of two Northern Snakeheads in Ridgebury Lake part of Catlin Creek, of the Wallkill River drainage, and a tributary of the Hudson River. In August, Ridgebury Lake, Catlin Creek, and adjacent ponds downstream were treated with rotenone. More than 200 Northern Snakeheads were recovered, most juveniles. In 2009, two adults were captured in Valentine's pond downstream of Ridgebury Lake. This system was again treated with rotenone. Subsequent monitoring failed to detect any Northern Snakehead.	ANSTF (2014), Flaherty (2019)

Site	City/Region	State	Watershed	Date	Waterway	Waterbody size	Eradication attempted	Eradication successful	Method(s)	Cost	Number	Notes	Reference
Nanticoke River	Broad Creek, Horseys Pond near Laurel	Delaware	Chesapeake Bay	2010	Open	Hundreds of km	No	NA	NA	NA	At least 8	In October 2010, an adult Northern Snakehead was captured by Delaware Division of Fish and Wildlife while electrofishing Broad Creek/Horseys Pond. Subsequent sampling failed to find additional Northern Snakehead but from 2010 to 2012 at least eight Northern Snakeheads were collected from Delaware portions of the Nanticoke River. It was determined eradication would not be feasible due to the size of the system, tidal flows, and possible continued immigration from other systems.	Martin (2012), ANSTF (2014), Love and Newhard (2018)
Private Pond	Gwinnett County	Georgia	Yellow River	2019	Open	Two ponds (0.61 ha), 5.5 km of first and second order tributaries connected to the pond, 36 ha of wetlands	Yes	Yes	Electrofishing (boat and backpack), seine nets, crayfish traps, rotenone	Unknown	34	In October 2019, an angler caught a Northern Snakehead in a private pond. Georgia DNR staff collected and removed 16 Northern Snakeheads within and near the pond and the surrounding channels and wetland using boat and backpack electrofishing. Rotenone applied to the area resulted in the recovery of 18 additional Northern Snakehead. Survey work after rotenone treatment did not recover any live snakehead.	Roop et al. (2020)
Conowingo Reservoir	Lower Susquehanna River	Maryland / Pennsylvania	Chesapeake Bay	2020	Closed	9,000 acres	Yes	No	Electrofishing, angling	Unknown	22	In 2017, a single Northern Snakehead passed through Conowingo Dam's East Fish Lift into Conowingo Reservoir. In 2020, 21 passed into Conowingo Reservoir and 14 were netted out of the hopper prior to release. The fish lifts were prematurely shut down for the season to prevent further passage of Northern Snakehead. Resource agencies electrofished Conowingo Reservoir. Combined with angler captures, six Northern Snakeheads were removed.	Normandeau Associates (2021), S. Eyler, USFWS, personal communication

Appendix D. Strategies for dealing with Northern Snakehead as a function of invasion stage

	Invasion stage of state or sub-region		
	Brand new area	**Leading edge**	**Established population**
Legal and regulatory framework	Live possession and transport prohibited		
Early Detection and Rapid Response (EDRR)	Verify detection (i.e., confirm physical presence). Gather information to determine if eradication attempt is feasible and favorable. Remove all captured individuals (resource agencies and public). Public communication including press release and/or posters in visible locations such as boat launches.	Verify detection (i.e., confirm physical presence). Continue monitoring. Public communication including press release and/or posters in visible locations such as boat launches. Shift to control and management if/as population becomes established.	NA, see control and management options (below).
Limiting spread from established areas	Curb human transport and illegal introductions through public outreach/communication and law enforcement, and in connected waterbodies utilize existing natural and artificial dispersal barriers to limit spread.		
Control and management	NA, see EDRR (above)	See EDRR (above) and shift to control and management (right) if/as population becomes established.	Viable options likely include: Allow hook and line angling, allow bowfishing, recreational harvest initiatives (e.g., public communications, outreach, tournaments, regulation change, etc.), develop commercial market (i.e., allowing people to sell catch), electrofishing by resource agencies in targeted areas, and physical removal below dams and natural barriers in the springtime.
Public outreach and communication	Aggressive messaging: Ask or advise public to not return any captured Northern Snakehead to water and emphasize illegality of live possession and transport	Encourage harvest of any captured Northern Snakehead and emphasize illegality of live possession and transport	Encourage harvest of Northern Snakehead (while potentially acknowledging immediate catch and release) and emphasize illegality of live possession and transport

The Chesapeake Bay watershed encompasses states and sub-regions of states that are at different invasion stages. These include (i) brand new areas where Northern Snakehead are not currently found but, if detected, would represent a new, distinct, small, and isolated population, (ii) leading edge, also known as the invasion front, which is directly adjacent to established areas, and finally (iii) established populations/areas where Northern Snakehead are already known and well-established. The legal and regulatory framework and strategies for limiting Northern Snakehead spread are relatively universal irrespective of invasion stage. In contrast, the optimal early detection and rapid response strategy and public messaging likely should differ as a function of invasion stage. Finally, control and management actions, by definition, are appropriate for established populations, but the specific actions taken must be informed by waterbody characteristics and logistical constraints in the local area.

Appendix E. State Aquatic Invasive Species Plans and Rapid Response Protocols

Below is a list of existing state plans that were consulted in the development of this plan.

Delaware

- Delaware Invasive Species Management Plan (2005)
- Action Plan for Northern Snakehead (*Channa argus*) in Delaware (2012)
- Delaware Aquatic Invasive Species Management Plan (in progress)

Maryland

- Rapid Response Planning for Aquatic Invasive Species: A Maryland Example (2009)
- Maryland Aquatic Nuisance Species Management Plan (2016)
- Maryland Emergency Response Plan for Invasive Pests (2018)

New York

- New York Aquatic Invasive Species Management Plan (2015)
- New York Rapid Response Plan (2016)

Pennsylvania

- Pennsylvania Aquatic Invasive Species Management Plan (2006)
- Pennsylvania Rapid Response Plan and Procedures (2022)
- Pennsylvania Aquatic Species Control Plan for Northern Snakehead (2023)

Virginia

- Virginia Invasive Species Management Plan (2018)

West Virginia

- West Virginia Invasive Species Strategic Plan and Voluntary Guidelines (2014)

Appendix F. Online Resources

Below is a list of some existing online resources about Northern Snakehead or aquatic invasive species generally. For some resources a brief description is given highlighting why it was included or notable features.

Federal

United States Department of Agriculture: https://www.invasivespeciesinfo.gov/aquatic/fish-and-other-vertebrates/northern-snakehead

United States Fish and Wildlife Service: https://fws.gov/project/northern-snakehead-control-and-management

United States Geological Survey: https://nas.er.usgs.gov/queries/factsheet.aspx?speciesid=2265
[Probably the closest to a central repository or hub website for Northern Snakehead information. The point map is particularly useful, and the website contains a 'Sightings Report Form' so data can be added.]

State

Delaware: https://dnrec.alpha.delaware.gov/fish-wildlife/fishing/invasive-species/snakeheads/
https://fishspecies.dnrec.delaware.gov/FishSpecies.aspx?habitat=1&species=43

Maryland: https://dnr.maryland.gov/fisheries/pages/snakehead.aspx
[Provides detailed information regarding Northern Snakehead identification, biology, and fishing. Notably, contains videos giving practical advice on snakehead fishing, regulations, and how to fillet.]

Pennsylvania: https://www.fishandboat.com/Fish/PennsylvaniaFishes/Pages/Snakehead.aspx
https://seagrant.psu.edu/topics/invasive-species/aquatic-invasive-species

New York: https://www.dec.ny.gov/animals/45470.html
https://nyis.info/invasive_species/northern-snakehead/#Introduction%20and%20Spread

Virginia: https://dwr.virginia.gov/fishing/snakehead/

Washington D.C.: https://doee.dc.gov/service/regulated-fishing-activities

West Virginia: https://wvdnr.gov/wp-content/uploads/2022/01/2022.01.04-DNR_FishingRegulations.pdf

Other relevant web resources

Animal Legal and Historical Center at Michigan State University's College of Law:
https://www.animallaw.info/article/detailed-discussion-laws-concerning-invasive-species
https://www.animallaw.info/article/overview-lacey-act-16-usc-ss-3371-3378

[Provides a comprehensive repository of information regarding invasive species laws and regulations.]

Aquatic Nuisance Species Task Force: https://www.fws.gov/program/aquatic-nuisance-species-task-force/documents

[Contains downloadable copies of many policy documents and state aquatic nuisance species management plans].

Great Lakes and Mississippi River Interbasin Study: https://glmris.anl.gov/controls/

[Provides detailed list and evaluation of Aquatic Nuisance Species control strategies.]

Gunston Cove Ecosystem Study: https://perec.science.gmu.edu/our-research/gunston-cove-study/

[Long-term ecosystem study of Gunston Cove, one of the first areas in the Potomac River where Northern Snakehead were found.]

Maryland Fish Consumption Advisories (DNR): https://mdewin64.mde.state.md.us/WSA/FCA/index.html

[Searchable, by species and waterbody, fish consumption advisories for state of Maryland.]

Mid-Atlantic Panel on Aquatic Invasive Species: http://www.midatlanticpanel.org/mapais_resources/

[Contains downloadable copies of Chesapeake Bay aquatic invasive species management plans.]

Appendix G. Examples of public outreach materials

Examples of Northern Snakehead outreach materials from the Chesapeake Bay watershed.

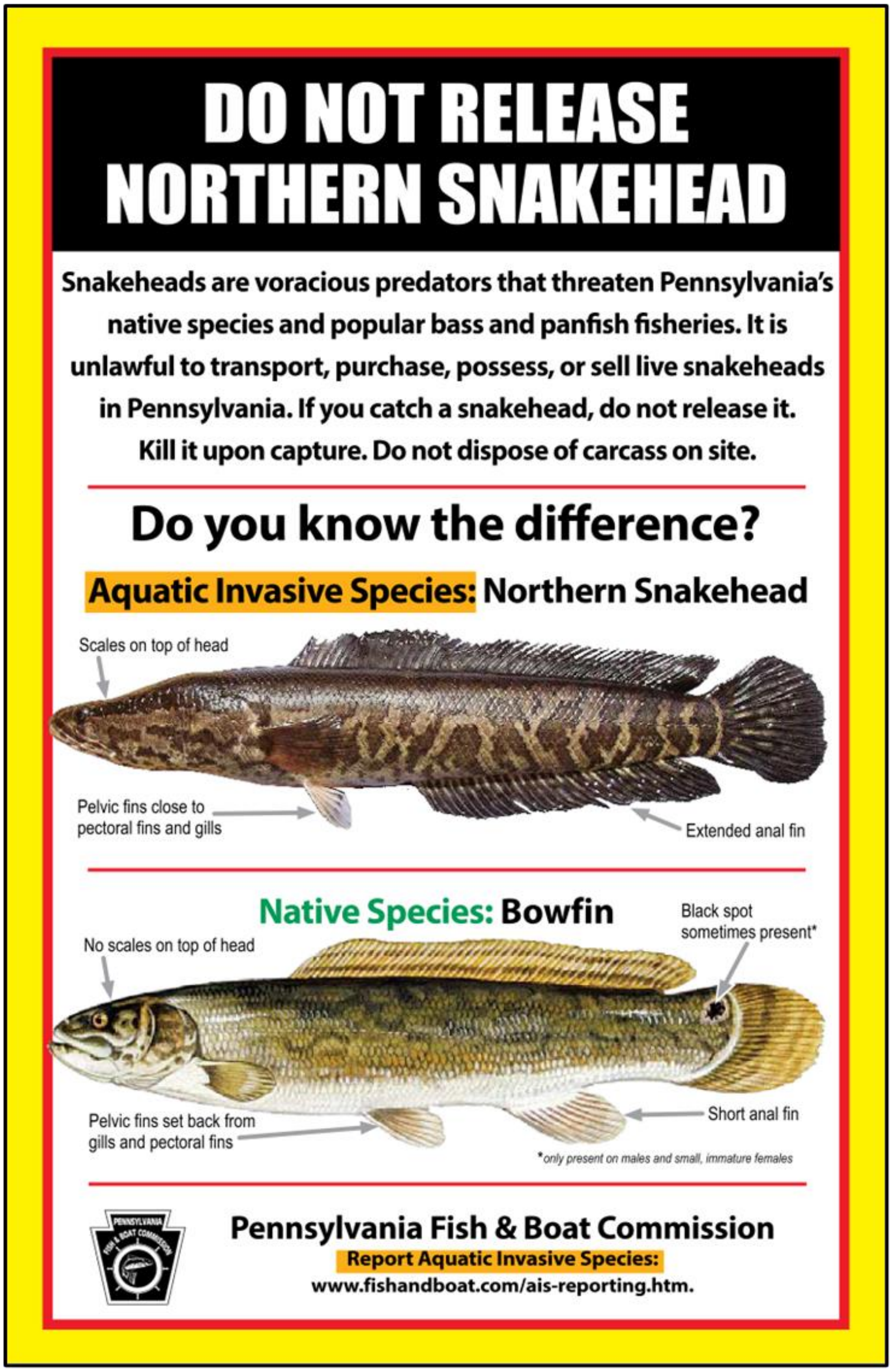

Figure 14. Poster on Northern Snakehead identification. Pennsylvania Fish and Boat Commission.

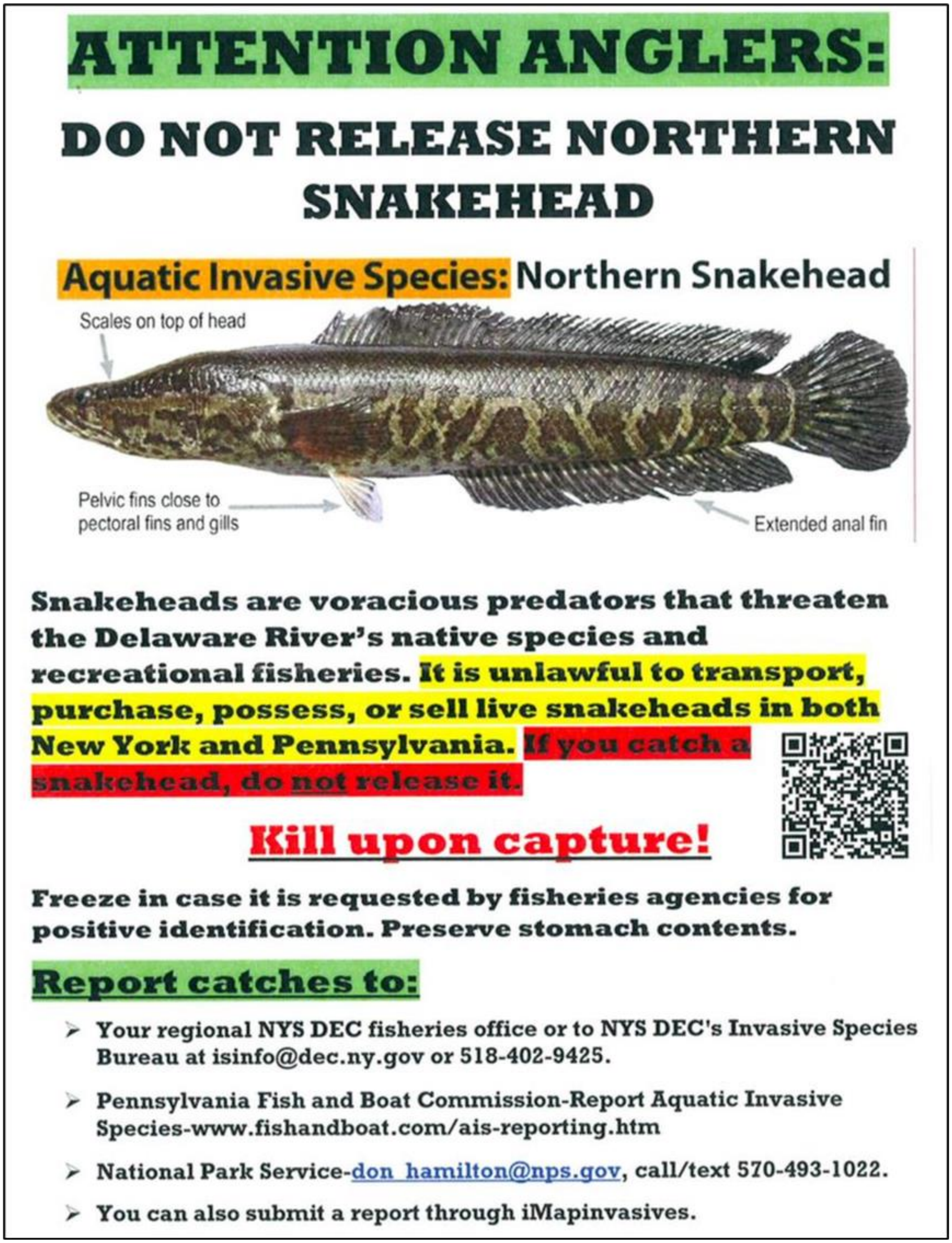

Figure 15. Poster (date unknown) advising the public on how to handle Northern Snakehead. The emphasis is upon identification of Northern Snakehead, not returning captured fish to the water (i.e., kill upon capture), and reporting catches to authorities. This strong messaging is typical when Northern Snakehead are first found in a given area and eradication is the goal.

Figure 16. Early poster (exact date unknown) advising the public on how to handle Northern Snakehead. Maryland Department of Natural Resources. The emphasis is upon identification of Northern Snakehead, not returning captured fish to the water (i.e., please kill), and reporting. This messaging is typical when Northern Snakehead are first found in a given area and eradication is the goal.

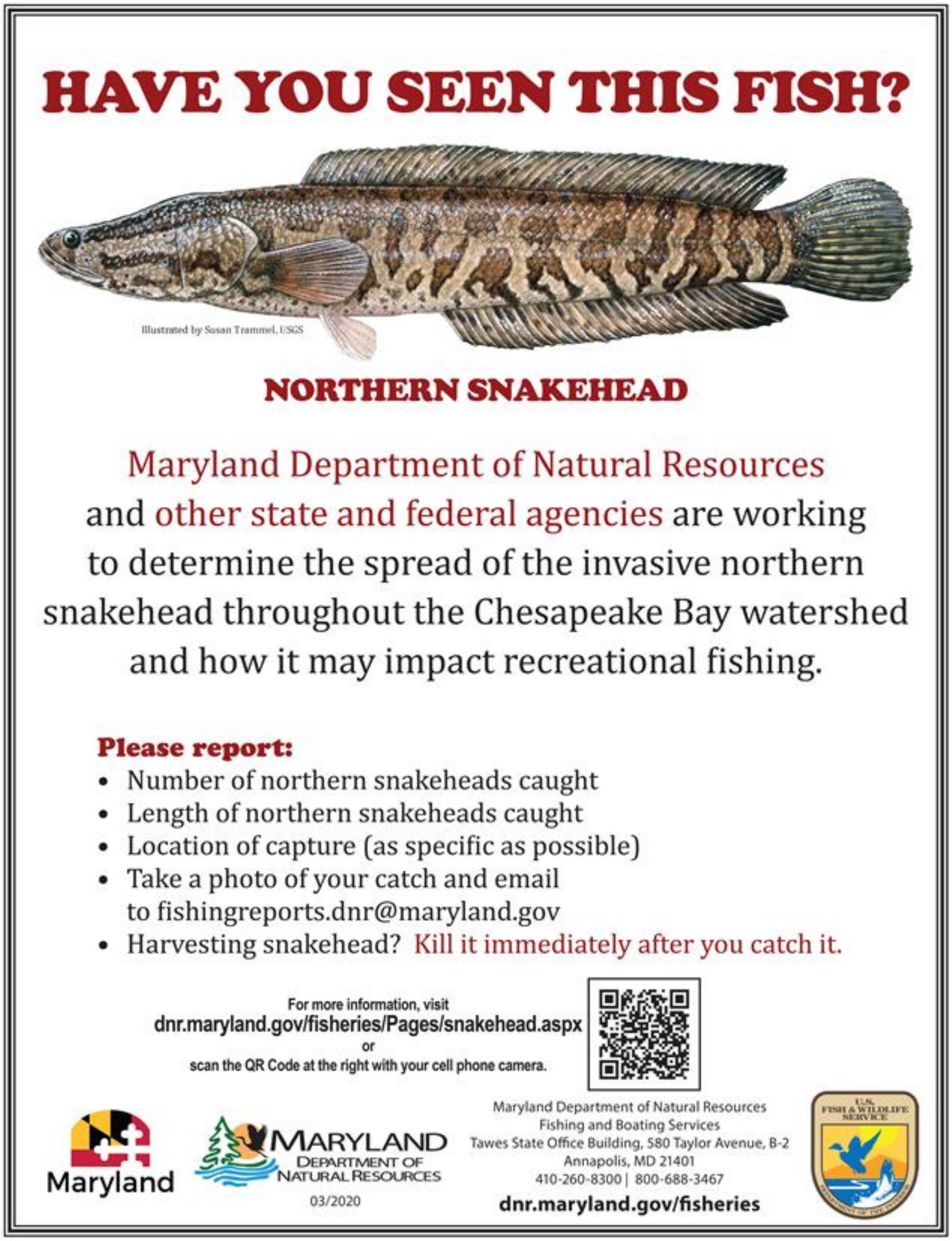

Figure 17. Poster (March 2020) advising the public on how to handle Northern Snakehead. Maryland Department of Natural Resources. The emphasis is upon reporting Northern Snakehead captures to help resource agencies determine spread, and advising that *if* Northern Snakehead are to be harvested they must be killed immediately. This messaging indirectly acknowledges catch and release angling and directly highlights the prohibition on live possession. This messaging is consistent with preventing spread and reducing biomass, while implicitly acknowledging that eradication is no longer a realistic goal.

Figure 18. Poster (present) advising the public on Northern Snakehead fishing regulations. Maryland Department of Natural Resources. Two clear alternatives are presented: if keeping (i.e., harvesting) kill the fish immediately, otherwise immediately release. This messaging is consistent with preventing spread and reducing biomass, while implicitly acknowledging that eradication is no longer a realistic goal in this area. It explicitly accommodates catch and release anglers.

Figure 19. Directions on how to harvest Northern Snakehead, from the Maryland Department of Natural Resources. This poster is one of the of the few authoritative sources (i.e., from a resource agency) providing specific guidance.

Northern Snakehead
Frequently Asked Questions
Fishing Information

Are snakehead easy to catch? Yes. Snakeheads can have large populations and can be targeted in a variety of ways with a variety of bait/tackle. Check out our how-to-target video/ information, ask the professionals at tackle shops, or find tips and tricks online or through social media.

Where can I catch them? It can depend on the season and time of day, but usually freshwater and marshy areas, along shorelines in water less than six feet deep. The department has several tools for anglers including: an Angler's Log with searchable reports of where snakeheads are being caught, a public access map that highlights places to fish for snakeheads and a weekly fishing report.

What specifically are Maryland regulations? Anglers targeting snakehead must possess a valid Maryland fishing license but there are no seasons, no size limits and no creel limits. Harvested snakehead must be killed immediately after being caught if there is intent to keep the fish. Possession and/or transport of live snakehead is illegal under state and federal law. If the angler does not intend on keep the fish, they may release it but must do so, immediately.

Are Snakehead fishing regulations in Maryland different than those in other states? No. Some of the terminology is different but live possession is illegal in all impacted states and live import from other countries is illegal.

Are snakehead safe to eat? Yes. Northern snakehead (Channa argus) are both nutritious and delicious. Studies routinely demonstrate that snakehead muscle contains insignificant levels of contaminants that are harmful to humans. Once filleted, their meat is similar to any flaky white fish such as halibut, haddock, whiting, or even striped bass (rockfish).

Are there worms in the fish? Potentially. Nearly any fish species can harbor intramuscular worms. Cutting the worms out is easy enough and they're even safe to eat if cooked completely.

Do I have to kill every snakehead I catch? No. Persons wishing to release a live snakehead may do so provided it is immediate and directly back into the waters from which it came. For those willing, we actively encourage the targeting and harvest of every snakehead caught.

Should snakehead be treated like other sportfish with seasons and limits? No. Snakeheads are an invasive species that can negatively impact native fishes here and across the country. Because of ongoing research, the department, along with its many colleagues, continue to categorize the fish as invasive, nuisance or injurious. Many of the properties that support those classifications will, unfortunately, allow the species to persist in Maryland, likely without any need of conservation strategies

MARYLAND
Larry Hogan, Governor

MARYLAND DEPARTMENT OF NATURAL RESOURCES
Jeannie Haddaway-Riccio, Secretary

Maryland Department of Natural Resources,
Fishing and Boating Services
Tawes State Office Building,
580 Taylor Ave., B-2, Annapolis, MD 21401-2352
800-688-3467 | dnr.maryland.gov/fisheries

DNR 17-041719-144

4/19

Figure 20. Informational handout (April 2019) of Northern Snakehead Frequently Asked Questions / Fishing Information. Maryland Department of Natural Resources.