# Binational Ecological Risk Assessment of Bigheaded Carps (*Hypophthalmichthys* spp.) for the Great Lakes Basin

# Évaluation du risque écologique posé par les carpes à grosse tête (*Hypophthalmichthys* sp.) dans le bassin des Grands Lacs

Becky Cudmore[1], Nicholas E. Mandrak[1], John M. Dettmers[2], Duane C. Chapman[3], and Cynthia S. Kolar[4]

[1] Fisheries and Oceans Canada, Centre of Expertise for Aquatic Risk Assessment
867 Lakeshore Road, Burlington, ON  L7R 4A6

[2] Great Lakes Fishery Commission
2100 Commonwealth Blvd, Ste 100, Ann Arbor, MI  48105

[3] U.S. Geological Survey, Columbia Environmental Research Center
4200 New Haven Road, Columbia, MO 65201

[4] U.S. Geological Survey - Ecosystems
12201 Sunrise Valley Drive, MS-301, Reston, VA  20192

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

La présente série documente les fondements scientifiques des évaluations des ressources et des écosystèmes aquatiques du Canada. Elle traite des problèmes courants selon les échéanciers dictés. Les documents qu'elle contient ne doivent pas être considérés comme des énoncés définitifs sur les sujets traités, mais plutôt comme des rapports d'étape sur les études en cours.

Research documents are produced in the official language in which they are provided to the Secretariat.

Les documents de recherche sont publiés dans la langue officielle utilisée dans le manuscrit envoyé au Secrétariat.

This document is available on the Internet at:

Ce document est disponible sur l'Internet à:

http://www.dfo-mpo.gc.ca/csas/

# TABLE OF CONTENTS

## ABSTRACT

Bigheaded carps (Bighead and Silver carps) are considered a potential threat to the Great
Lakes basin. A binational ecological risk assessment was conducted to provide scientifically
defensible advice for managers and decision-makers in Canada and the United States. This risk
assessment looked at the likelihood of arrival, survival, establishment, and spread of bigheaded
carps to obtain an overall probability of introduction. Arrival routes assessed were physical
connections and human-mediated releases. The risk assessment ranked physical connections
(specifically the Chicago Area Waterway System) as the most likely route for arrival into the
Great Lakes basin. Results of the risk assessment show that there is enough food and habitat
for bigheaded carp survival in the Great Lakes, especially in Lake Erie and productive
embayments in the other lakes. Analyses of tributaries around the Canadian Great Lakes and
the American waters of Lake Erie indicate that there are many suitable tributaries for bigheaded
carp spawning. Should bigheaded carps establish in the Great Lakes, their spread would not
likely be limited and several ecological consequences can be expected to occur. These
consequences include competition for planktonic food leading to reduced growth rates,
recruitment and abundance of planktivores. Subsequently this would lead to reduced stocks of
piscivores and abundance of fishes with pelagic, early life stages. Overall risk is highest for
lakes Michigan, Huron, and Erie, followed by Lake Ontario then Lake Superior. To avoid the
trajectory of the invasion process and prevent or minimize anticipated consequences, it is
important to continue to focus efforts on reducing the probability of introduction of these species
at either the arrival, survival, establishment, or spread stage (depending on location).

# RÉSUMÉ

Les carpes à grosse tête (y compris la carpe argentée) sont considérées comme un risque potentiel pour le bassin des Grands Lacs. Une évaluation binationale des risques écologiques a été réalisée afin de pouvoir formuler des conseils scientifiques crédibles à l'intention des gestionnaires et des décideurs du Canada et des États-Unis. Dans le cadre de cette évaluation, on s'est intéressé à la probabilité de l'arrivée, de la survie, de l'établissement et de la propagation des carpes à grosse tête afin de parvenir à une probabilité globale d'introduction. Les voies d'arrivée qui ont été étudiées sont les connexions physiques ainsi que les rejets dont les humains sont à l'origine. Selon les conclusions de l'évaluation des risques, les connexions physiques (et en particulier la voie maritime du secteur de Chicago) sont la voie d'arrivée la plus probable des carpes à grosse tête dans le bassin des Grands Lacs. Les résultats de l'évaluation montrent aussi qu'il y a assez de nourriture et d'habitats pour que les carpes à grosse tête survivent dans les Grands Lacs, surtout dans le lac Érié et dans les échancrures productives des autres lacs. Des analyses des tributaires des Grands Lacs canadiens et des eaux américaines du lac Érié ont révélé que de nombreux tributaires sont propices à la fraie des carpes à grosse tête. Si les carpes à grosse tête devaient s'établir dans les Grands Lacs, leur propagation ne s'y limiterait probablement pas, et plusieurs conséquences écologiques seraient à escompter. Ces conséquences sont notamment la concurrence des espèces pour l'accès au plancton, ce qui entraîne la réduction des taux de croissance et du recrutement ainsi qu'une abondance des planctophages. L'établissement des carpes à grosse tête dans les Grands Lacs mènerait par la suite à la diminution des stocks de piscivores et à une abondance de poissons pélagiques et dans leurs premiers stades de vie. Le risque global est le plus élevé pour les lacs Michigan, Huron et Érié, puis le lac Ontario, et enfin le lac Supérieur. Afin d'éviter la trajectoire du processus d'invasion et de prévenir ou minimiser les conséquences anticipées, il est important d'axer les efforts sur la réduction de la probabilité de l'introduction de ces espèces au stade de l'arrivée, de la survie, de l'établissement ou de la propagation (selon l'endroit).

# 1.0 INTRODUCTION

The establishment of nonnative aquatic species can have negative, sometimes significant, consequences to the invaded ecosystem (Moyle and Light 1996, Rahel 2002), leading to considerable challenges for resource managers. Nonnative species can cause severe reduction or extirpation of native species (Dextrase and Mandrak 2006, Mandrak and Cudmore 2010), reduction in the abundance or productivity of sport, commercial, or culturally important species, and can result in significant habitat alteration (Rahel 2002). Consequently, these invasive, nonnative species are considered a threat to aquatic biodiversity at the same level as habitat loss and alteration (Light and Marchetti 2007).

The Great Lakes have not been immune to the arrival of aquatic invasive species. At least 69 nonnative fish species have been introduced to the Great Lakes, half of which are considered established (Mandrak and Cudmore 2010). The invasion of destructive aquatic invasive species (AIS) (e.g., Sea Lamprey (*Petromyzon marinus*)) into the Great Lakes, and the resulting necessity for intensive management activities and associated costs, has promoted management strategies that now focus on the prevention of establishment by new aquatic invasive species (Ricciardi et al. 2011). The mandate of Fisheries and Oceans Canada's (DFO) Centre of Expertise for Aquatic Risk Assessment (CEARA) is to identify potential invaders to all parts of Canada, assess their ecological risk, and provide science advice towards preventing the introduction of those species considered to be high risk. As noted by Kolar et al. (2007), Chapman and Hoff (2011), and Cudmore and Mandrak (2011), two species that currently threaten to invade the Great Lakes are Bighead Carp (*Hypophthalmichthys nobilis*) and Silver Carp (*H. molitrix*), herein referred to as bigheaded carps. The term Asian carps in this document is used to refer collectively to Grass Carp (*Ctenopharyngodon idella*), Bighead Carp, Silver Carp, and Black Carp (*Mylopharyngodon piceus*).

Bigheaded carps were first imported into the United States in the 1970s for use as water quality control agents and for foodfish culture. They subsequently escaped intended areas of introduction into natural waters (Chapman and Hoff 2011). For a detailed history on the use and introductions of these species in the United States, see Kelly et al. (2011). Previous risk assessments identified broad, potential risks to Canada and the United States, including the Great Lakes (Mandrak and Cudmore 2004, Kolar et al. 2007). While these risk assessments provided insight into the risk faced by broad areas of North America, knowledge gaps were identified as a result of the lack of information, at the time, on these species in established populations outside of their native range. As bigheaded carps have moved farther north up the Mississippi River basin, concern for movement into the Great Lakes has increased (see Figure 1 for current distribution). Now that further research has been conducted on the species in their introduced range, more available knowledge can be applied to our understanding of the risks associated with an invasion by these species. The purpose of this risk assessment is to determine the risk to the Great Lakes and to provide useful, scientifically defensible advice on subsequent prevention, monitoring, early detection, and management actions that are underway, or could be taken.

**a**



Map produced by the U.S. Geological Survey, Nonindigenous Aquatic Species Database, October 25, 2011.

**b**



Map produced by the U.S. Geological Survey, Nonindigenous Aquatic Species Database, October 25, 2011.
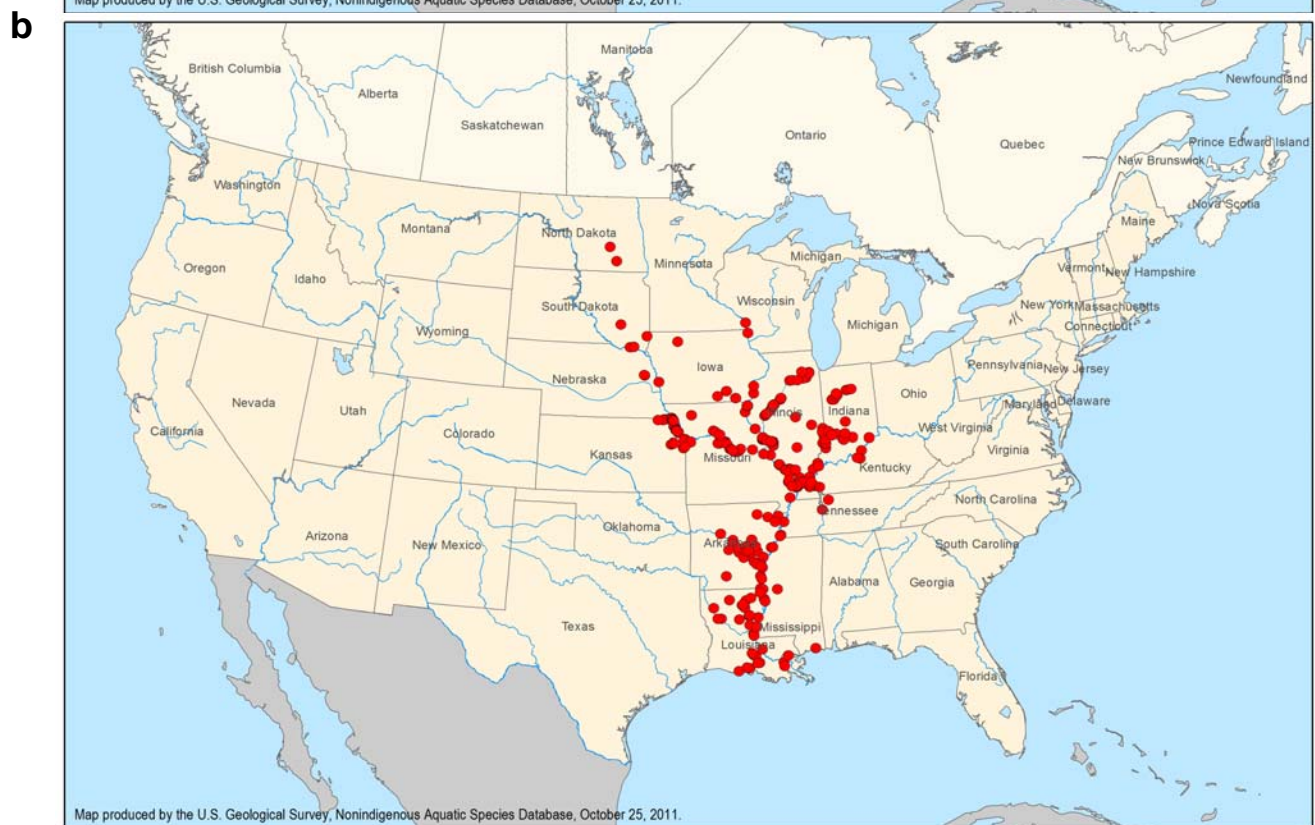
Figure 1. Nonnative occurrences of a) Bighead Carp (Hypophthalmichthys nobilis) and b) Silver Carp (H. molitrix) in the United States. Dots represent confirmed sightings and collections, not necessarily established populations. Maps courtesy of the U.S. Geological Survey.

The scope of this risk assessment was determined by workshop participants consisting of Great Lakes researchers, managers, and decision-makers (see Section 1.1). The risk assessment considers the available information known about bigheaded carps to assess the likelihood of arrival, survival, establishment, and spread within 20 years, and the magnitude of the ecological consequences (up to 20 years and up to 50 years) to the connected Great Lakes basin (defined as the Great Lakes and its tributaries up to the first impassable barrier (Figure 2)). For this assessment, Lake St. Clair is considered to be part of the Lake Erie basin. We recognize that Grass Carp and Black Carp, two other Asian carp species, also pose a concern for the Great Lakes (Nico et al. 2005, Cudmore and Mandrak 2011, Nico and Jelks 2011); however, due to resource and time limitations, it was determined that the scope of this risk assessment would focus on the Great Lakes managers' two highest priority Asian carp species, Bighead and Silver carps. Largescale Silver Carp (*Hypophthalmichthys harmandi)*, although a bigheaded carp species, was not assessed due to the low level of risk this species poses to the Great Lakes (Mandrak and Cudmore 2004, Kolar et al. 2007).
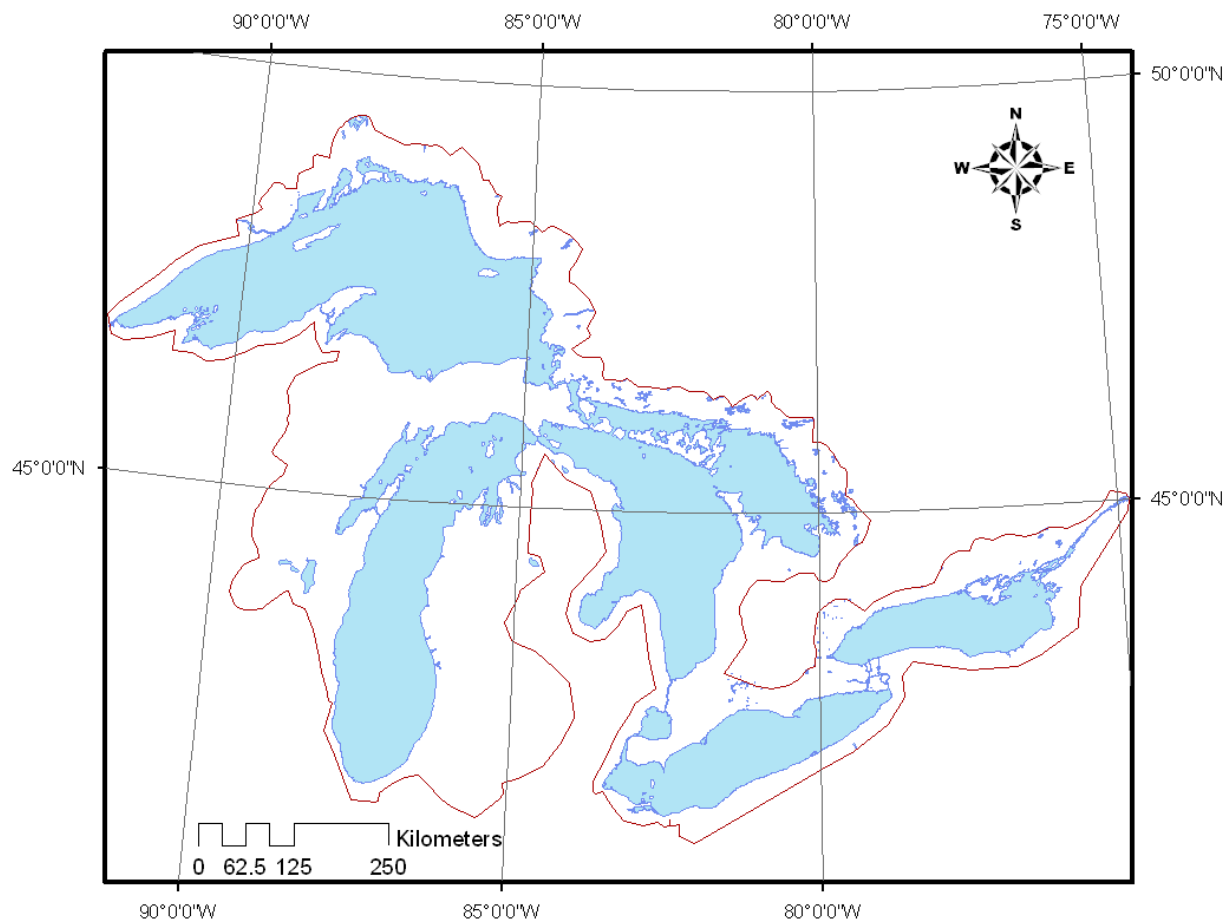


*Figure 2. The connected Great Lakes basin, defined as the Great Lakes and its tributaries up to the first impassable barrier (outlined in red). Modified from Hedges et al. (2011).*

This ecological risk assessment focuses only on the ecological consequences; the socio-economic consequences will be assessed separately using the results of the ecological risk assessment. It also addresses only the current state, with management measures that were in place during the scoping of the risk assessment (November 2010). It does not assess

effectiveness of measures in place nor the level of risks associated with a variety of potential mitigating factors that are not currently in place.

Targeted management questions were obtained from Great Lakes managers and decision-makers at the outset of the risk assessment process. This was done to ensure this risk assessment provides the most useful advice possible to address the needs of managers and decision-makers throughout the Great Lakes basin.

## 1.1  THE RISK ASSESSMENT PROCESS

The format of the binational ecological risk assessment for bigheaded carps in the Great Lakes basin follows guidance provided in the "*National Detailed-Level Risk Assessment Guidelines: Assessing the Biological Risk of Aquatic Invasive Species in Canada*" (Mandrak et al. 2012). This process serves to summarize the best available information and identify the relative risks posed to a specified area within a specified timeframe by a nonnative species. Risk assessments provide a framework for organizing and reviewing relevant information to provide scientifically defensible advice to managers and decision-makers.

As a first step in conducting an ecological risk assessment, the known biological information of the species is compiled into a biological synopsis. Kolar et al. (2007) provided biological information on bigheaded carps, and documented instances where they have impacted aquatic communities. To update Kolar et al. (2007), which used information published up to 2006, Kipp et al. (2011) used information published from 2006 to early 2011. Both of these documents relied heavily on available English literature. Naseka and Bogutskaya (2011) annotated the available Russian language literature on bigheaded carps, which was also used as a source of background information on the biology of these species for this risk assessment.

Other documents were developed to support the risk assessment and include ecosystem modelling (Currie et al. 2011) and a Canadian tributary analyses (Mandrak et al. 2011). Primary literature and publicly available reports were also used to inform the risk assessment. In some cases, personal communication, personal observation, and other draft information supplied to the risk assessment authors were used. This was done to utilize as much up-to-date, if not yet, published, information as possible to inform the risk assessment. ***Researchers who provided draft information or personal communication/observation/data retain the intellectual property of that work and their information should not subsequently be cited outside of the risk assessment work presented here. Permission for use was provided for this process and product only.***

Workshops were held in November 2010, May 2011, and June 2011 to develop the scope of the risk assessment, obtain management questions, and to understand the research occurring on both sides of the border that could provide input into the risk assessment.

After the risk assessment parameters were scoped, the definitions for risk ratings (Table 1), certainty (Table 2), and consequences (Table 3), as used in this risk assessment, were determined by the authors (and agreed upon by peer review experts), following guidance provided in Mandrak et al. (2012).

*Table 1. Likelihood as probability categories.*

| Likelihood | Probability Category |
|---|---|
| Very Unlikely | 0.00 - 0.05 |
| Low | 0.05 - 0.40 |
| Moderate | 0.40 - 0.60 |
| High | 0.60 - 0.95 |
| Very Likely | 0.95 - 1.00 |

*Table 2. Relative certainty categories.*

| % Level | Certainty Category |
|---|---|
| ± 10% | Very high certainty (e.g., extensive, peer-reviewed information) |
| ± 30% | High certainty (e.g., primarily peer reviewed information) |
| ± 50% | Moderate certainty (e.g., inference from knowledge of the species) |
| ± 70% | Low certainty (e.g., based on ecological principles, life histories of similar species, or experiments) |
| ± 90% | Very low certainty (e.g., little to no information to guide assessment) |

*Table 3. Description of ecological consequence ratings.*

| Consequence Rating | Description |
|---|---|
| Negligible | Undetectable changes in the structure or function of the ecosystem. |
| Low | Minimally detectable changes in the structure of the ecosystem, but small enough that it would not change the functional relationships or survival of species. |
| Moderate | Detectable changes in the structure or function of the ecosystem. |
| High | Significant changes to the structure or function of the ecosystem leading to changes in the abundance of native species and generation of a new food web. |
| Extreme | Restructuring of the ecosystem leading to severe changes in abundance of ecologically important species (those considered dominant or main drivers in the ecosystem) and significant modification of the ecosystem. |

Although the risk assessment targets the Great Lakes basin as a whole, to accommodate resource managers who wished to better understand the risk to a particular lake, the risk assessment does take into account each Great Lake separately. This risk assessment does not address a finer geographic scale, such as specific impacts within a particular bay or lake sub-region, as this is beyond the scope of the current project.

Mandrak et al. (2012) divided the risk assessment process into two steps: 1) estimating the probability of introduction (using likelihood of arrival, survival, establishment, and spread); and, 2) the determination of the magnitude of the ecological consequences once the species has been introduced, established, and has spread. The evaluation of the probability of introduction and the magnitude of the ecological consequences are based on a qualitative scale (see Tables 1 and 3, respectively), and includes a corresponding ranking of certainty (see Table 2). For this risk assessment (as the basin is interconnected), the overall probability of introduction was determined by taking the highest ranking between overall arrival and spread, then evaluating this rank with the ranks of survival and establishment, and using the lowest rank of the three. This is represented by the following formula:

Probability of Introduction = Min [Max (Arrival, Spread), Survival, Establishment]

The probability of introduction and the magnitude of the ecological consequences are combined into a risk matrix to obtain an overall risk (see Figure 3 for a species-specific example). To combine certainties between the risk assessment elements, the certainty associated with the highest rank was used or, if two or more certainties were the same, the certainty associated with the highest rank was used. Each lake was assessed for two different time periods, within 20 years and within 50 years, to show any increase in consequences over time. Therefore, two matrices are presented at the end of the risk assessment, one for 20 years and one for 50 years. The ellipse illustrates the amount of certainty associated with the point.
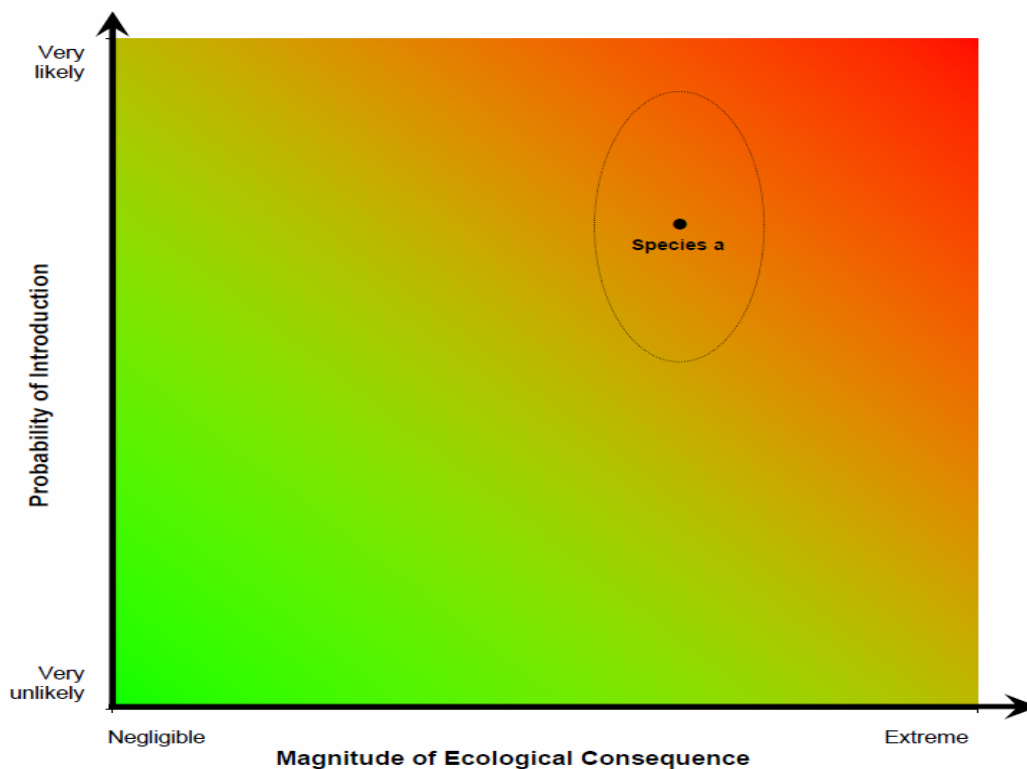


*Figure 3. Graphic representation to communicate the overall risk. Matrix combined probability of introduction and magnitude of consequences for a species-specific risk assessment. From Mandrak et al. 2012.*

A draft of this risk assessment was presented to expert peer reviewers who attended a peer review meeting November 8-10, 2011. Participants of the peer review included the authors of the risk assessment and bigheaded carp experts. Freshwater invasive fish or invasive modelling experts also participated. Some participants who had not been strongly engaged in the scoping of the risk assessment were included to maximize objectivity in the process. The peer review process followed the guidelines set out by Fisheries and Oceans Canada's Canadian Science Advisory Secretariat (CSAS). Documentation of the proceedings (DFO 2012a) of the peer review meeting that reviewed this risk assessment and a science advisory report (DFO 2012b) have been completed in support of this risk assessment. The risk assessment contains the body of information used to develop the overall risk, across all risk assessment elements, by

consensus of the peer review participants.  It is the definitive science document of this process and includes science advice.  The science advisory report is essentially an executive summary of the risk assessment coupled with science advice, and may be most appropriate for those who do not wish to read all the details in the risk assessment.  The proceedings document serves as a record of the discussions and decisions at the peer review meeting.  For further information and details about this peer review, science advisory process, see http://www.dfo-mpo.gc.ca/csas-sccs/index-eng.htm.

The risk assessment rankings are the product of consensus at a peer review meeting (DFO 2012a), not rankings of individuals.


# 2.0  PROBABILITY OF INTRODUCTION

To determine the probability of bigheaded carp introduction to the Great Lakes basin information related to the likelihood of arrival (Section 2.1), survival (Section 2.2), establishment (Section 2.3), and spread (Section 2.4) was used.

## 2.1 LIKELIHOOD OF ARRIVAL

Arrival of a nonnative species occurs through various forms of pathways and vectors, implying transit survival. Potential entry routes for bigheaded carps into the Great Lakes were identified and assessed where information was available. Entry routes discussed in this section are physical connections (e.g., canals and waterways, and intermittent or occasional connections around the watershed boundaries) and human-mediated release (e.g., bait use and trade). Arrival is considered the presence of at least one Bighead Carp or Silver Carp in at least one part of the Great Lakes basin The likelihood of arrival was evaluated for each Great Lake using the available information for entry routes to each lake.

### 2.1.1  Physical Connections

2.1.1.1  Chicago Area Waterway System (CAWS)
The CAWS provides a direct, artificial connection between Lake Michigan and the Mississippi River basin at Chicago, Illinois and includes natural and artificial waterways, locks and dams (Figure 4; Moy et al. 2011). Bigheaded carps are well-established in the Illinois River (Irons et al. 2011). A system of electric barriers (hereafter called the electric dispersal barrier) has been built in the Chicago Sanitary and Ship Canal (CSSC) near Lemont, IL, the portion of the CAWS that connects to the Mississippi River basin.  The electric dispersal barrier serves to deter movement of fishes upstream across the barrier. Initially constructed as a demonstration barrier that became operational on April 18, 2002, the electrical dispersal barrier now includes the original demonstration barrier (Barrier I) and two more barriers in close proximity (Barrier IIA and Barrier IIB) with the primary purpose of preventing upstream movement of bigheaded carps towards the Great Lakes. Currently, Barrier I and Barrier IIB are operating, with Barrier IIA in stand-by mode. Reversal of flow in the canal is a rare event of short duration and low velocity compared to the flow in the downstream direction.  Fishes are not likely to be swept into, or through, the electric dispersal barrier during flow reversals (Holliman 2011). Evidence to date using Common Carp (*Cyprinus carpio*) and other large-bodied surrogates for bigheaded carps
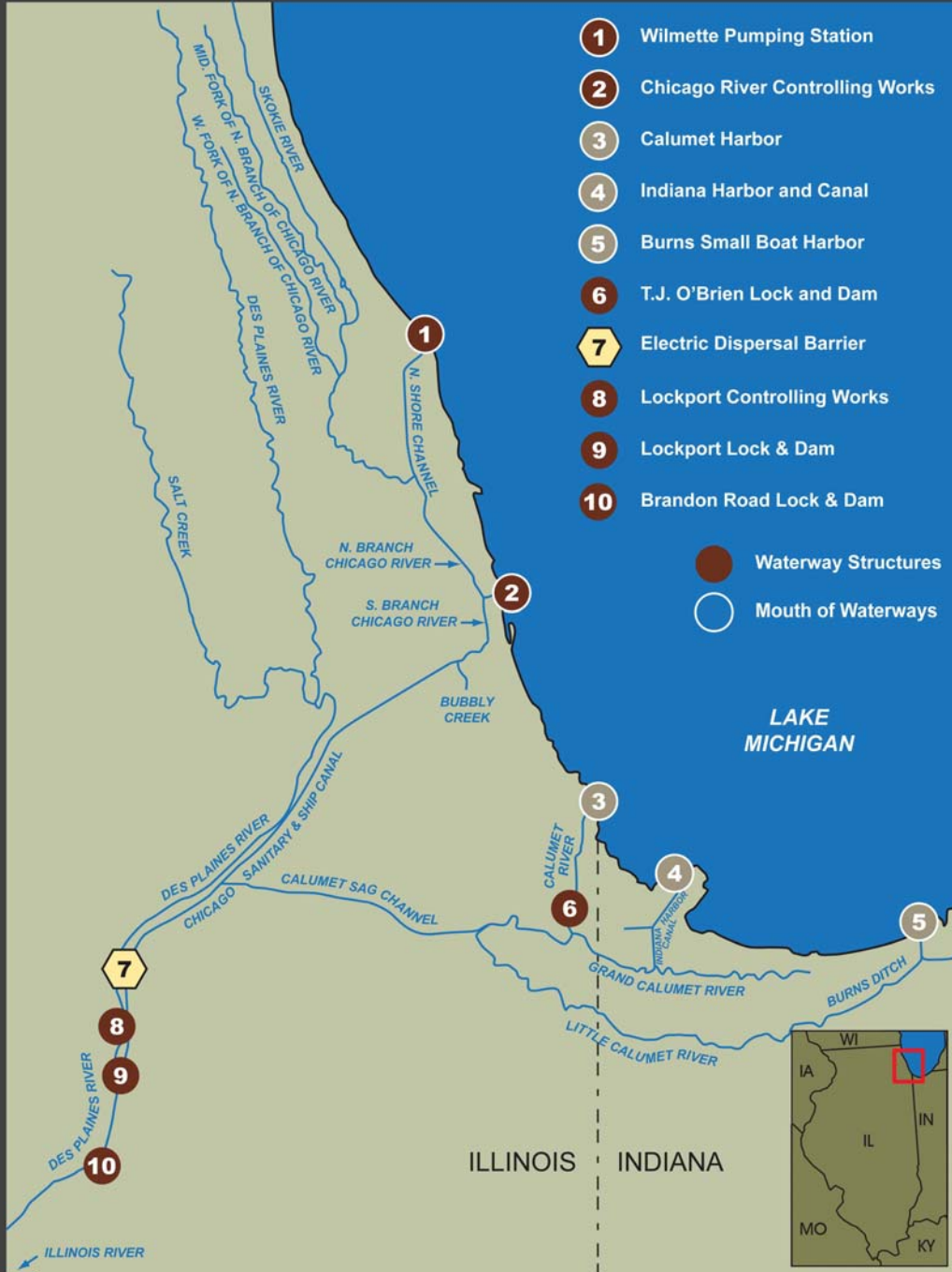
*Figure 4. The Chicago Area Waterway (CAWS) system. Map courtesy of U.S. Army Corps of Engineers.*

indicates that large fishes are deterred from crossing the electric dispersal barrier (Sparks et al. 2011). A radio-tagged Common Carp did pass through Barrier I on April 3, 2003. It was subsequently tracked approximately 2.5 km upstream of Barrier I, where it did not move again (Sparks et al. 2011). It is suspected that either the transmitter was expelled or that the fish died. Subsequent evaluation of fish movement in the vicinity of the electric dispersal barrier during 2011 also indicated that a transmitter from a Common Carp was found about 4 km upstream of the electric dispersal barrier on August 11, 2011. Since then, this transmitter has not moved (K. Baerwaldt, USACE, pers. comm.). Although the mechanism by which this transmitter moved above the electrical dispersal barrier is not known, it is highly unlikely that it was due to natural movement. The transmitter was regularly tracked by receivers below the electric dispersal barrier since its implantation into a Common Carp on October 27, 2010. The transmitter was tracked moving upstream early on July 5 and then moving downstream, where contact was lost at 7:31 AM. The transmitter was not heard again until August 11, 2011 as described above. Twelve receivers were between the point of last contact and where the tag was detected, with no detections on any of those receivers. One possible explanation is that the Common Carp was caught by an angler who then disposed of the tag several kilometers upstream of the electric dispersal barrier. Further studies of greater numbers of tagged fishes would provide stronger information.

Current information indicates the electric dispersal barrier deters small fishes (less than 137 mm). In tests of the effect of operational parameters of the electric field on Bighead Carp (51-76 mm), the optimal settings to immobilize small fishes were 0.91 V/cm, 30 Hz pulse frequency, and 2.5 ms pulse duration (Holliman 2011). Small Bighead Carp repeatedly challenged a model barrier, although they recognized the downstream edge of the electric field. They would continue to challenge the barrier even after recovering from immobilization. Based on the suite of operational settings explored and behavior of small (51-76 mm) Bighead Carp, Holliman (2011) recommended that electric dispersal barrier operational parameters be set at these levels to deter small fishes. Thus, while operating, the electric dispersal barrier effectively deters large fishes and, based on laboratory experiments, immobilizes small fishes (< 76 mm).

A Bighead Carp was collected approximately 100 m below electric dispersal Barrier IIA (11 km below Barrier I) in December 2009 (Moy et al. 2011; outside of the connected Great Lakes basin) as part of a rotenone operation to allow the US Army Corps of Engineers (USACE) to conduct required maintenance of Barrier IIA. One Bighead Carp was also collected from Lake Calumet, on the Lake Michigan side of the electric dispersal barrier, in June 2010. Organisms shed some of their DNA into the environment (termed eDNA). The presence of bigheaded carp eDNA has been used as an indicator that bigheaded carps are or have been potentially present (Jerde et al. 2011). Bigheaded carp eDNA was collected in the CAWS upstream of the electric dispersal barrier (see http://www.lrc.usace.army.mil/AsianCarp/eDNA.htm) during 2009 and 2011. In addition to the collections in the CAWS, in 2011 one sample tested positive for silver carp within Lake Michigan.  This was one of 13 samples taken by Notre Dame researchers in Calumet Harbor, adjacent to the locks leading to the CAWS.   It is important to note that the rate of false positives of eDNA (detecting bigheaded carp DNA when not present) is at or near zero (Battelle Memorial Institute 2010, USEPA 2010), but that eDNA can degrade quickly and that false negatives (no indication of a bigheaded carp when species is present) for this and traditional capture methods may be high (see Darling and Mahon 2011, Jerde et al. 2011). However, collection of bigheaded carp eDNA is not incontrovertible evidence of the presence of a live bigheaded carp, because eDNA can be transported without a live fish. It remains unclear whether small numbers of bigheaded carps have traversed or bypassed the electric dispersal barrier, whether these eDNA reports are false positives or from sources other than living fishes, or whether bigheaded carps have been

present in the CAWS for some time or if they have already escaped the CAWS and entered Lake Michigan. We thus assume for the purposes of this risk assessment that the invasion process is at "pre-arrival" for Lake Michigan.

The electric dispersal barrier only deters upstream movement through the canal at that location; it does not prevent downstream movement or movement bypassing the electric dispersal barrier by other means. Uncertainty exists about whether bigheaded carps may have moved across Barrier I before Barrier IIA was operational in 2009. It is possible that Bighead and Silver carps were in the vicinity of Barrier I long before biologists suspected they might be present. During this period, Barrier I was renovated and power fluctuations may have kept Barrier I from operating at optimal effectiveness (Moy et al. 2011). Further, Barrier IIA and IIB require regular maintenance at intervals of approximately one year.

Two known avenues by which bigheaded carps could bypass the electric dispersal barrier include the Des Plaines River and the Illinois & Michigan Canal (I&M Canal). The Des Plaines River joins the CSSC immediately below the Lockport Lock and Dam, about 13 km downstream of the electric dispersal barrier. The river parallels the CSSC for about 24 km upstream, within about 400 m of one another. During flood conditions, the Des Plaines River can be overtopped and water from the Des Plaines River will flow over land into the CSSC. Further, DNA sampling in the Des Plaines River between the Hoffmann Estates Dam and the confluence with the CSSC has detected bigheaded carp DNA since 2010, suggesting that bigheaded carps could move from the Des Plaines River into the CSSC during flooding. During 2010, the USACE installed a combination jersey barrier and mesh fence along the nearly 21 km stretch of close proximity to reduce the potential of bigheaded carps entering the CSSC from the Des Plaines River during flooding (USACE 2010a).

Similarly, the I&M Canal connects to the CSSC downstream of the Lockport Lock and Dam. The I&M Canal flows intermittently and there is a small drainage divide that sends water toward the Cal-Sag Channel upstream of the electric dispersal barrier. This divide could be overtopped during flooding such that water from downstream of the electric dispersal barrier could move upstream of the electric dispersal barrier. The USACE has enhanced the divide and plugged outflows from the I&M Canal into the CSSC upstream of the electric dispersal barrier (USACE 2010a).

The USACE also has installed screens on its sluice gates at the O'Brien Lock and Controlling Works (USACE 2010b). The USACE also recommended that the Metropolitan Water Reclamation District of Greater Chicago install screens on the sluice gates of the Chicago River Controlling Works and to modify operations at the Wilmette Pumping Station for diversion water intake if requested (USACE 2010b).

Another possible pathway for moving past the electric dispersal barrier is movement of small bigheaded carps in leaking barges. Reports of barges pumping water from void spaces are common throughout the Illinois Waterway, including the CSSC. To investigate this potential, a study to investigate the efficacy of bigheaded carp transport by barges was conducted (Heilprin et al. 2011). This study of water quality in barge voids found that dissolved oxygen levels and water temperatures were well within limits for fish survival, even during the hot months of the year (Heilprin et al. 2011). In 2011, attempts to entrain bigheaded carp larvae into voids by simulating a punctured barge hull were not successful due to difficulties associated with proper river conditions and the timing of bigheaded carp spawning, but survival of bigheaded carp larvae in cages within void spaces was high (Heilprin et al. 2011). This study also found that

survival of larval and small bigheaded carps (< 80 mm TL) was unlikely when passed through pumps commonly used on barges to remove water from voids.

2.1.1.2  Other Connections

The USACE is conducting a five year Great Lakes – Mississippi River Interbasin Study (GLMRIS) to comprehensively analyze the options, technologies, and alternatives for preventing the interbasin transfer of aquatic nuisance species between the two basins (USACE 2011a). The study, led by the USACE with a variety of other American agencies, is divided into two focus areas: one examining options for the CAWS; and, a second focus area that examines 19 potential natural and artificial hydrologic connections between the basins. The connection through the CAWS is considered higher risk within the GLMRIS study than the remaining 18 connections examined in Focus Area 2. Of these 18 possible connections, the authors felt three had stronger hydrological connections with implications for bigheaded carps: 1) Eagle Marsh in Indiana; 2) Ohio-Erie Canal in Ohio; and, 3) the Libby Branch connection to Lake Superior (Figure 5).
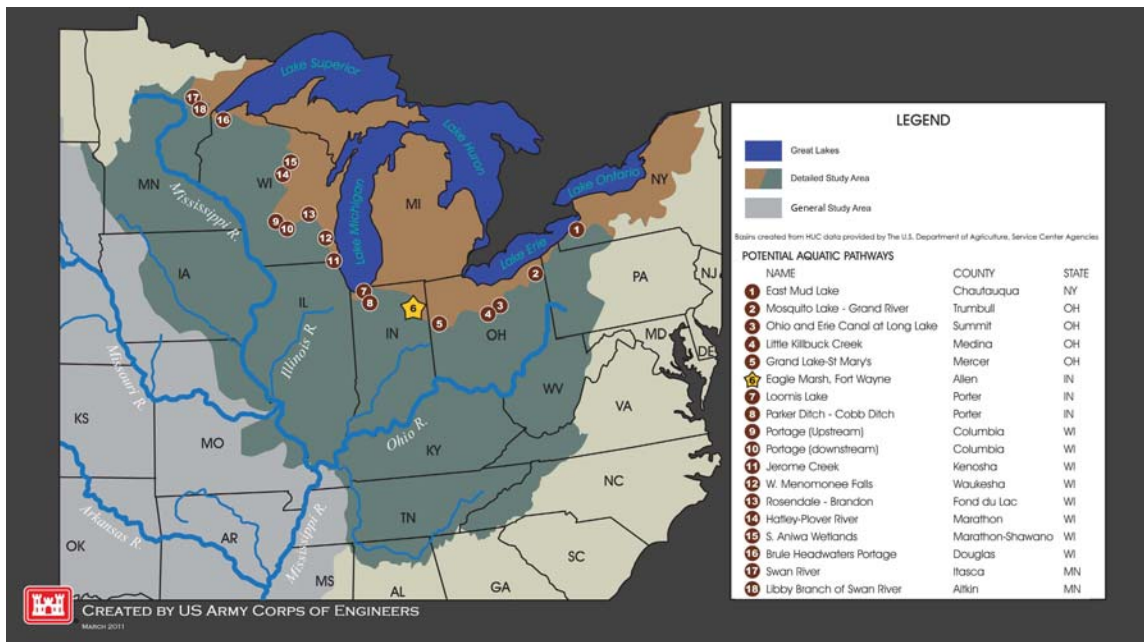


*Figure 5. Identified hydrological connections for aquatic invasive species transfer between the Mississippi River and Great Lakes basins. Map courtesy of U.S. Army Corps of Engineers.*

The Eagle Marsh in northwestern Indiana is an area that joins the Wabash River system with the Maumee River system under some flood conditions. This site has been rated the highest risk of aquatic invasive species transfer among the 18 locations evaluated in Focus Area 2 of GLMRIS. Bighead Carp have been reported about 35 km (22 river miles) downstream of Eagle Marsh in the Wabash River (USACE 2010b). One dam upstream of Huntington IN on the Little River (an older fixed crest approximately 2 m high) stands between bigheaded carps and eventual arrival in the Eagle Marsh area. Indiana deployed a large-mesh fence to deter movement of adult fishes between the two basins. During spring 2011 flooding, adult Common Carp attempted, but were not able, to cross this fence.

There is potential for bigheaded carps, should they move from the Ohio River up the Tuscarawas River, to enter the Lake Erie drainage from Long Lake into the Ohio-Erie Canal and

from there into the Little Cuyahoga River. The connection points are only 91 m from each other across a 1.5 m embankment (USACE 2010b). Bigheaded carps are known to be in the Ohio River at Pittsburgh, PA. It is unclear if these fishes originated in the area from a release or if they made their way up the river through Ohio (John Navarro, Ohio Department of Natural Resources, pers. comm.). The Tuscarawas River is a tributary of the Muskingum River and connects to the Muskingum River above Coshocton, Ohio. The start of the Tuscarawas River is about 161 km from the Ohio River and there are eight dams on the lower Muskingum River between the Ohio River and the Tuscarawas River. The head of these dams range from 3.5 - 7 m; therefore, it would be very difficult for bigheaded carps to make it up to this area (John Navarro, Ohio Department of Natural Resources, pers. comm.), but should they make it there, the connection to the Lake Erie drainage is close.

Another connection identified in the GLMRIS project as high risk for aquatic invasive species transfer was the Libby Branch connection to Lake Superior; however, this connection is characterized by many dams that would inhibit the dispersal of bigheaded carps past these barriers.

There are many ponds and artificial lakes in the Chicago metropolitan area. They are commonly stocked for fishing with Channel Catfish (*Ictalurus punctatus*). Channel Catfish are often purchased from southern fish farmers, where it is possible for the stock to be contaminated with small Bighead Carp. For instance, in September 2011, 17 large Bighead Carp were collected from Flatfoot Lake in the Beaubien Forest Preserve (K. Irons, Illinois Department of Natural Resources, pers. comm.). Flatfoot Lake is located about 180 m from the Calumet River, downstream of the O'Brien Lock and Dam. Three Bighead Carp were also found from Schiller Pond. Neither of these waterbodies have a direct connection to either Lake Michigan or the Cal-Sag Channel, but escapes of another Asian carp, Grass Carp, have occurred in similar circumstances (Maceina et al. 2011).

While it is unclear if any of these ponds could connect with the Lake Michigan watershed during flooding events, it does provide a source of individuals in close proximity for illegal movement (see Section 2.1.2).

Since its opening in 1959, the St. Lawrence Seaway/River continues to be an important route for the introduction of aquatic invasive species, such as the copepod, *Eurytemora affinis*, and White Perch (*Morone americana)* (Scott and Christie 1963, Hebert et al. 1989). Should bigheaded carps gain access to the St. Lawrence River, this would provide a direct route to Lake Ontario.

Unlike the ballast water in freighters that originate outside of the Great Lakes-St. Lawrence River basin, ballast water in freighters that remain in the basin (known as "lakers") is not treated for AIS in any way (see Section 2.4.1.3 for more details). If bigheaded carps were to become established first in the St. Lawrence River, laker movement may facilitate the arrival of the species into the Great Lakes basin. Over 2 million metric tonnes (mt) of ballast water is taken in by lakers in St. Lawrence ports each year (Table 4). This ballast water was transported primarily to other ports in the St. Lawrence River, and lakes Superior, Erie, Ontario, Huron and Michigan (Figure 6 - see also Section 2.4.1.3).

*Table 4. Estimated ballast water transfer volumes between basins associated with commercial laker traffic based on data used in Rup et al. 2010. Annual average volume (mt) data are provided as received and donated by a Great Lake and the St. Lawrence River. A small fraction (< 2.5%) of trips from Rup et al. (2010) were excluded due to uncertain ballasting procedures as were transfers within a basin.*

| Basin | Annual Average (mt) | |
| --- | --- | --- |
| | Recipient | Donor |
| Erie | 3,114,797 | 27,806,506 |
| Huron | 8647344 | 12,792,195 |
| Michigan | 7,166,444 | 19,975,152 |
| Ontario | 1,139,413 | 5,338,245 |
| St. Lawrence | 2,956,685 | 2,883,148 |
| Superior | 35,212,014 | 1,772,893 |
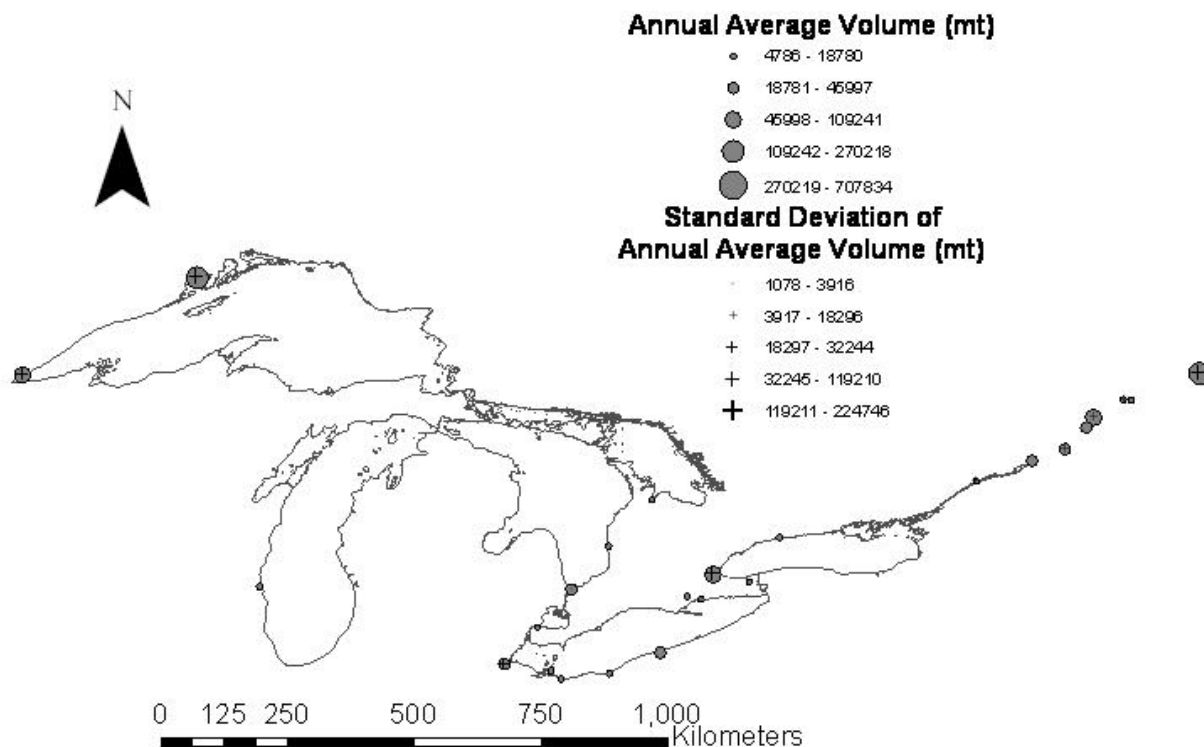


*Figure 6. Destination of ballast water discharge for trips originating from any port within St. Lawrence River. Annual averages and standard deviations of ballast discharge volumes, 2005 – 2007, are summarized from Rup et al. (2010).*

## 2.1.2 Human-mediated Release

The potential for purposeful, human-mediated releases of bigheaded carps into the Great Lakes basin does exist. Humans have illegally released freshwater fishes for sport opportunities (Crossman and Cudmore 1999a, Bradford et al. 2008) or spiritual/ethical reasons (Crossman and Cudmore 1999b, Severinghaus and Chi 1999, Shiu and Stokes 2008). This human behavior of illegally releasing nonnative fishes into the aquatic environment is difficult to characterize and quantify (Bradford et al. 2008). For this reason, we are unable to qualify the risk of intentional release, but should note its existence as a potential source of introduction of

bigheaded carps into the Great Lakes basin. Within this risk assessment, we assessed the human-mediated release from bait use and from trade.

<u>2.1.2.1 Bait</u>
The live baitfish pathway is a potential entry route for the arrival of small bigheaded carps into the Great Lakes. Baitfishes are used for angling in all states and provinces surrounding the Great Lakes, although specific regulations and the degree of baitfish activity vary by state/province (Table 5). The term 'baitfish' generally refers to a variety of small fishes with species dependent on local regulations, supply, and angler preference. Within most Great Lakes jurisdictions, baitfish supply may occur through angler self-harvesting (i.e., angler capture of small baitfishes using minnow traps, seines, or dip nets) or baitfish may be commercially harvested or cultured. Although culture does not occur within Great Lakes jurisdictions due to limited growing seasons, cultured baitfishes from American states outside of the basin (e.g., Arkansas, parts of Minnesota, North Dakota, South Dakota; Gary Whelan, Michigan DNR, pers. comm.) may be transported to Great Lakes states for sale to retailers and anglers. It is illegal to bring in live baitfish from the U.S. into Canada. Following harvest or culture, baitfishes are purchased by anglers at angling retail stores or, in the case of self-harvest, are transported directly to the angling destination. Despite legislation, anglers may release undesirable or left-over baitfishes into the destination waterbody following angling (Litvak and Mandrak 1993;1999, Dextrase and MacKay 1999, Kulwicki et al. 2003, Drake 2011), although the prevalence of release may be declining (A. Drake, DFO, unpubl. data).

*Table 5. Summary of 2011 recreational angling regulations for states and provinces in the Great Lakes basin related to potential Asian carp entry through the baitfish pathway. Although each jurisdiction has specific movement regulations (e.g., certain significant waterbodies may exhibit no-baitfish rules to protect sensitive game stocks), movements listed below concern noteworthy baitfish movement restrictions within each jurisdiction as they relate to pathway operations and the potential for Asian carp movement or entry into the pathway. In many cases, generic restrictions against 'carp' (presumably Common Carp) were made; these are listed simply as 'carp' unless specifically defined as Asian carps.*

| State / Province | Regulation (Possession / Use) | Regulation (Movement) |
|---|---|---|
| Minnesota | General white list (list of species permissible to use), with prohibition on using whole or parts of 'Carp' for bait (MNDNR 2011; p. 11). Specific prohibition about possessing or transporting Asian carps (MNDNR 2011; p. 10). | Statewide movement restrictions in response to viral hemorrhagic septicemia (VHS) concerns; anglers required to exchange bait water when leaving infected zone. |
| Wisconsin | General white list allows for all species in the minnow family, but with specific prohibition against 'Carp' (WDNR 2011; p. 7, 14). | Species-specific regulations (e.g., Alewife restrictions within Great Lakes) govern most statewide movement restrictions. |
| Illinois | Generic list of legal baitfish species; includes 'minnows' but does not specifically preclude 'Carp' (ILDNR 2010; p. 2). | Few statewide restrictions to baitfish movement. |
| Indiana | Generic list of legal baitfish species; specific prohibition against 'Carp' (IDNR 2011; p. 2). | Few statewide restrictions to baitfish movement. |

| Michigan | White list of legal baitfishes, with specific prohibition against Asian carps and other known invaders (MDNR 2011; p. 6, 14-15). | Movement zones vary in response to VHS concerns; movement to outside of GL drainages generally restricted or reduced. |
|---|---|---|
| Ohio | White list of legal baitfish species; prohibits use of fish species that are not already established in Ohio waters (ODNR; 2011). | Generally, movement of baitfish out of Lake Erie drainage prohibited in response to VHS concerns. |
| Pennsylvania | General use of baitfishes allowed; the use or possession of Common Carp as baitfish while fishing is prohibited (PFBC 2011; p. 7, 30). | Certain baitfish species prohibited from movement out of Lake Erie drainage in response to VHS concerns. |
| New York | Green (list of species permissible to use) list of legal species for widespread angler use in the state. Additional list of species for use in waters only where currently found (e.g., Alewife in Great Lakes). 'Carp' collection or use as bait is prohibited. (NYDEC 2011; p. 19-20). | Commercial catch VHS-free certification process determines the degree of allowable movement. Uncertified bait (some commercial catches and all self-harvested fishes) may not be transferred overland and must be used at point of harvest. |
| Québec | Very limited use of live baitfishes is allowed. Where allowed, only native species may be used; collection or use of 'Carp' and non-indigenous fish species for bait is prohibited (Ressources naturelles et faune Québec 2011; p. 8-9). | Substantial restrictions to baitfish movement, with use limited to a very few waterbodies exhibiting strict species regulations. |
| Ontario | White list of baitfish species; specific prohibition of use and possession of Asian carps (OMNR 2011; p. 8-10). | Restricted movement of Great Lake commercial baitfish catches to inland waters in response to VHS concerns; anglers encouraged to comply with commercial movement restrictions. |

The likelihood of the baitfish pathway as an entry route for bigheaded carps is dependent upon: 1) the distribution and intensity of baitfish harvest activity in relation to the distributional co-occurrence of bigheaded carps and target baitfishes in the wild; 2) the ability of commercial harvesters, baitfish retailers, and anglers to effectively sort or 'cull' bigheaded carps (presumably juveniles) from target catches; and, 3) the nature and prevalence of angling activities (e.g., long-distance transport and corresponding baitfish release) that allow for bigheaded carp entry into the Great Lakes basin.

All states and provinces within the Great Lakes basin designate certain baitfish species, usually deemed to be of low ecological risk, for angling use. Species listings provide a legal mechanism to prohibit the capture, use, and movement of invasive fishes, such as bigheaded carps, during baitfish operations. For example, in Ontario, a list of allowable target baitfishes legally precludes

undesirable species from the pathway (OMNR 2011). Yet, because the industry in Ontario and other jurisdictions within the Great Lakes basin rely on wild harvest, potential for non-target fish by-catch exists. A recent study of the Ontario baitfish pathway indicated the existence of invasive and other non-target fish by-catch during baitfish harvest operations in Great Lakes nearshore waters and tributaries (Drake 2011).The prevalence of invasive and other non-target fishes within retail tanks and angler purchases was generally much lower than that of harvest operations, indicating a substantial degree of species culling following harvest. However, even low prevalence of non-target species in angler purchases was sufficient for non-target species introductions, as low prevalence was offset by a large number of angler trips (4.12 million yearly events involving live fishes) (Drake 2011). The spatial distribution of live bait angling events in Ontario indicated that even the shortest trips involving live baitfishes were sufficient to surpass drainage basin boundaries, with the longest trips further emphasizing spread potential (Drake and Mandrak 2010).

Using results from a study (Drake 2011) of the baitfish industry and AIS in Ontario suggest that the entry route of bigheaded carps into the Great Lakes basin through the baitfish pathway will be largely dependent on the specifics of baitfish activity  within each jurisdiction such as: characteristics of harvest activity in relation to bigheaded carp source populations; angler use, movement patterns, release rates; and, the yearly volume and spatial distribution of angling events within and outside of the Great Lakes basin.

Most states prohibit the use of "carp" as baitfish with Michigan and Ontario specifically prohibiting the use of "Asian carps" (Table 5). Most states and Ontario have restrictions on the within-jurisdiction movement of baitfishes, with Ontario prohibiting the importation of baitfishes (Table 5). For most jurisdictions, knowledge is lacking about: the degree to which these regulations are followed; which bait originates in areas of bigheaded carp populations; angler use, movement, and release patterns; and, annual volume and distribution of angling events.

A survey of bait shops in the Chicago area was conducted in 2010 to determine presence of bigheaded carps in bait tanks using both visual and eDNA surveillance methods (Jerde et al. 2012). Fifty-two bait shops in nine northeastern Illinois counties were assessed. Visual inspections and eDNA water samples (n = 136 from 94 bait tanks) were conducted. No Bighead or Silver carps were observed or detected by visual inspections or eDNA analysis. Although this study provided no evidence that bigheaded carps are part of the Chicago area bait trade, it was a brief snapshot in time.

2.1.2.2  Trade
Bigheaded carps, which are listed under the injurious wildlife provisions of the *Lacey Act*, cannot be legally imported into the United States or moved interstate live without a permit. Since 2005, the eight Great Lakes states have amended their rules and regulations to prohibit movement and/or possession of live bigheaded carps across their jurisdictions. Even with these regulations, enforcement could be improved, given that live Bighead Carp were transported through U.S. states before these fishes were seized in Canada in 2010-2011 (see below).

In Canada, there is no federal legislation in place regarding import of aquatic species that may pose an invasion risk. At the time this risk assessment was written, the Province of Quebec did not have provincial regulations regarding prohibition of possession or sale of live Asian carps. The Ontario Ministry of Natural Resources (OMNR) banned the live sale of Asian carps through the *Fish and Wildlife Conservation Act* in 2004 and banned the live possession of Asian carps through the *Ontario Fishery Regulations* in 2005.

Prior to these rules and regulations being developed by Great Lakes jurisdictions, some individuals of Bighead Carp were caught in Lake Erie (see Cudmore and Mandrak 2011). The body condition of these individuals was healthy, but for those individuals dissected, their reproductive organs were not viable (B. Cudmore, Fisheries and Oceans, pers. comm.). It is likely these individuals were released from the live food trade prior to 2004, but there is no evidence that Bighead Carp established in Lake Erie (Cudmore and Mandrak 2011). Therefore, with the removal of these few non-reproductive individuals, the invasion process would be considered reset back to 'pre-arrival' for the Great Lakes.

Caution must be used with analyzing import records into Canada. For January 1, 2010 to August 17, 2011 data, only Harmonization System codes were available, which group live fish imports into very broad categories. Importers are relied upon to accurately place their imports into the correct categories; however, during border inspections of live aquatic species into Toronto and Niagara Falls, several discrepancies were noted among import records, import invoices, and the actual specimen/commodity being imported (B. Cudmore, N. Mandrak, DFO, pers. obs.).

Importation records of fishes entering Canada must be considered with caution. For January 2010 through August 2011, 11,573 import transactions for live fishes were recorded by Canada Border Services Agency (CBSA) across Canada. 73.2% of total live fishes imported into Canada were for aquarium or ornamental purposes, while 26.8% were imported for food. Of the 26.8% destined for the live food industry, 81.7% came from the United States (B. Cudmore, unpubl. data).

The United States was the primary exporter of all fishes to Canada (72.3% of total live fishes imported). The majority of these fishes were exported from California (31.9%), Florida (26.3%), Arkansas (4.9%), Pennsylvania (4.0%), and North Carolina (3.7%). Of the live fishes exported to Canada, most were imported into Ontario (46.7%) followed by British Columbia (18.7%), Alberta (16.5%), and Quebec (13.2%) (Figure 7) (B. Cudmore, unpubl. data).
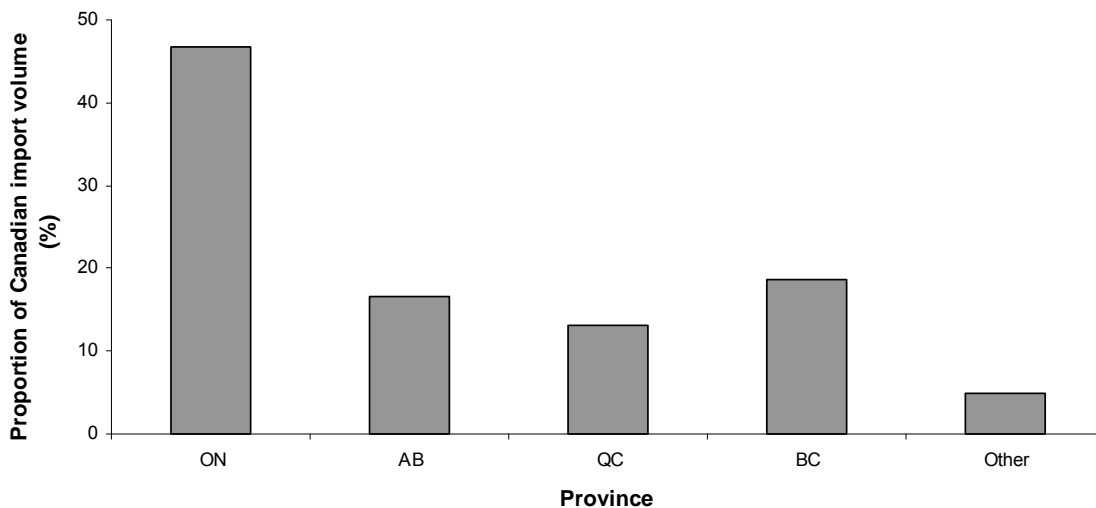


Figure 7. Proportion of total import of live fishes into Canada, by province (2010-2011), recorded by port of entry, as reported by Canada Border Services Agency. ON=Ontario; AB=Alberta; QC=Quebec; BC=British Columbia

Species-specific information is lacking with the 2010-2011 data; however, there is a category for 'carp' that importers were relied upon to use for all carp species, including bigheaded carps. Florida is responsible for exporting 23% of the total live carp into Canada, with Indiana (16.2%) and Arkansas (10.3%) representing other significant states of export.

Of the 46.7% of total live fishes imported into Ontario, 4.95% were represented by 'carp'. Primary entry locations into Ontario included Toronto Pearson International Airport (23.4% of Canadian imports, 50.1% Ontario imports), Niagara Falls-Queenston Lewiston Bridge (11.1% Canadian imports, 23.7% Ontario imports), and Windsor-Ambassador Bridge (5.8% Canadian imports, 12.3% Ontario imports) (B. Cudmore, unpubl. data).

Food industry import shipments are often, but not always, reported as units of weight in the shipping transaction. From January 1, 2010 to August 17, 2011, import data using weight indicate that approximately 13,774 metric tonnes (mt) of aquatic organisms classified as 'live fish' were imported into Canada (B. Cudmore, unpubl. data). Of this, 872 mt were classified as 'carp'. Border officials identified a further 19 mt as "probable carp", meaning imports that were not officially classified as carp but had carp in their "additional info/species" field. Therefore, we can surmise from this information that, in total, 891 mt of 'carp' were reported as imported into Canada. Live fishes classified as 'carp/probable carp' were imported into Ontario (840 mt) for food and aquarium and Alberta (50 mt) for aquarium (Figure 8). Most of these carps would most likely be Common Carp or koi.
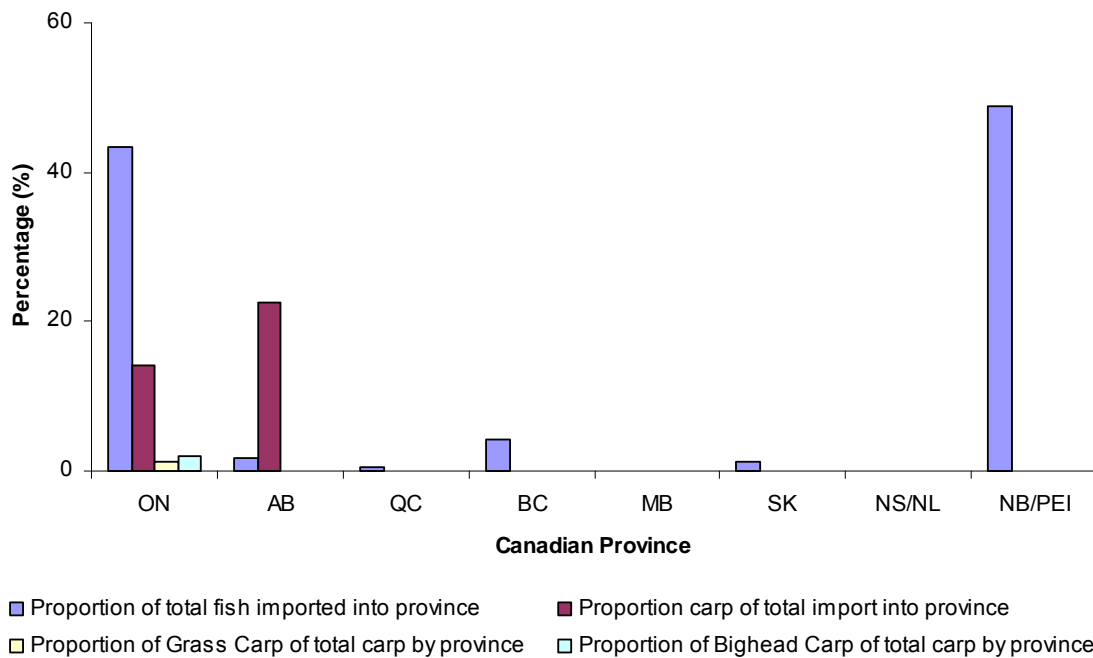


*Figure 8. Proportion of live fishes, "carps", Grass Carp and Bighead Carp imported into Canada by province/region. From B. Cudmore, unpubl. data; ON=Ontario; AB=Alberta; QC=Quebec; BC=British Columbia; MB=Manitoba; SK=Saskatchewan; NS/NL=Nova Scotia/Newfoundland and Labrador; NB/PEI=New Brunswick/Prince Edward Island.*

It is currently illegal to possess or sell live Asian carps in Ontario; however, despite this legislation, Bighead Carp and Grass Carp were documented in shipments for import into Ontario. Eight entry records were recorded from January 2010 to August 2011 that listed Grass

(9.8 mt) and Bighead (16.8 mt) carps as species descriptions. All of the shipments originated in Arkansas.

Some illegal shipment attempts into Ontario have been stopped by Canadian enforcement officers. In November 2010, there was a seizure at the Bluewater Bridge, Sarnia of 1,136 kg of Bighead Carp and 727 kg of Grass Carp after officers from both Canada Border Services Agency and OMNR inspected incoming shipments of live and fresh fishes (Sean Insley, OMNR, pers. comm.). In March 2011, a Markham (near Toronto, Ontario) fish importer was fined $50,000 for transporting live Bighead Carp (nearly 2,500 kg) from the U.S. across the Windsor-Detroit border. A few days later, an Indiana company, caught bringing live Bighead Carp (2,727 kg) into Canada, was fined $20,000. All fishes originated in Arkansas and were headed to live fish markets in the Toronto area (Sean Insley, OMNR, pers. comm.).

Feeder fishes (typically Goldfish (*Carassius auratus*) or "rosy reds" (colour variant of Fathead Minnow (*Pimephales promelas*)) shipped into the Great Lakes basin could be contaminated with bigheaded carps if they originated from fish farms in the Mississippi River basin. Fathead Minnows found in the bait industry in Michigan are known to originate from culture in Arkansas, Minnesota, North Dakota, and South Dakota (Gary Whelan, Michigan DNR, pers. comm.). However, the volume of such movement and the extent of contamination, if any, is unknown. Based on a subsample of live fish import records for 2006-2007, Fathead Minnows (likely rosy reds) imported for the aquarium trade originated primarily from Missouri and secondarily from North Carolina (B. Cudmore, DFO, unpubl. data).

The possession and sale of live Asian carps within the province of Quebec is currently legal, but prohibition regulations were recently posted for public consultation. However, import records into Canada (B. Cudmore, unpubl. data) indicate that carps are not entering into the province in large numbers (Figure 8).

### 2.1.3 Summary of Likelihood of Arrival

In summary, two pathways of potential entry into the Great Lakes basin were identified and assessed: physical connections; and, human-mediated release (Table 5). For this risk assessment the invasion process is considered at 'pre-arrival' for the Great Lakes.  With the removal of a few individuals over the past decade and positive eDNA samples, there is no sign the invasion process has moved to the next phases.

The most likely point of direct arrival into the Great Lakes basin is through the CAWS to Lake Michigan due to the proximity of established and invading bigheaded carp populations, the presence of positive eDNA samples, and the capture of one live Bighead Carp in the area above the electric dispersal barrier (Table 6).

Other physical connections to the Great Lakes basin were identified and ranked low, with the exception of Lake Superior, which was ranked very unlikely (Table 6). Of the hydrological connections considered high risk for aquatic nuisance species transfer (GLMRIS 2011), only one, Eagle Marsh IN, was considered by the authors as a high potential for bigheaded carp transfer to the Great Lakes (to Lake Erie). Eagle Marsh provides conditions suitable for bigheaded carp movement and is in proximity to bigheaded carp populations. However, this area is not suitable for spawning; therefore, the potential movement is limited to adults only. Direct transfer to the Great Lakes basin from the Chicago area ponds would be difficult due to the lack of natural connections. Also, fewer catfish farmers are raising Bighead Carp since the species was listed as 'injurious' under the Injurious Wildlife provisions of the *Lacey Act.* The Act

prohibits interstate transport of live Bighead Carp. Therefore going into the future, new stockings would have lowered potential for contamination. Sampling within the CAWS, both by eDNA and traditional sampling methods, provide for the ability to detect bigheaded carps early in the invasion process. Currently there are no bigheaded carps in or near the St. Lawrence River. Should they gain access to the St. Lawrence River, laker ballast water or natural dispersal would provide a direct route to Lake Ontario. However, the opportunities for the introduction of bigheaded carps to the St. Lawrence River are not well understood. Certainty for all lakes for physical connections was moderate, with the exception of Lake Michigan (high).

Potential for movement from the Mississippi River to the Great Lakes basin varies for each lake with respect to the human-mediated release pathway (Table 6). Variation in regulations for bait use and movement, as well as trade opportunities does vary by lake. In Lake Superior, it is very unlikely this pathway is of strong importance given the distance from established bigheaded carp populations and the time it will take before young specimens (e.g., from bait) could be found in nearby areas. There is also no international trade of bigheaded carps identified with the Lake Superior watershed. Lake Michigan was ranked low for human-mediated release; higher than for Lake Superior given the proximity of established populations as a source of available individuals. Lakes Huron and Ontario are associated with a low risk, taking into consideration the lack of movement of bait and trade from bigheaded carp areas and these lakes. However, these lakes are exposed to stronger fisheries from American anglers compared to Lake Superior, and Lake Ontario is also the location of live markets that could be involved in illegal trade. The risk of direct arrival to Lake Erie is also low, taking into consideration the presence of a higher number of anglers in lakes St. Clair and Erie, the frequent use of live bait in the area, and the potential for accidental release from illegal shipping of bigheaded carps coming from Windsor towards Toronto. Certainty associated with human-mediated releases varies by lake from low to moderate.

*Table 6. Overall probability of introduction rankings and certainties for each lake. Overall arrival is the combination of physical connections and overall human-mediated release. Greyed cells indicate "not applicable". (CAWS=Chicago Area Waterway System)*

| | Superior | | Michigan | | Huron | | Erie | | Ontario | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Element** | **Rank** | **Cert** | **Rank** | **Cert** | **Rank** | **Cert** | **Rank** | **Cert** | **Rank** | **Cert** |
| CAWS | | | Very Likely | High | | | | | | |
| Other Connections | Very Unlikely | Mod | Low | Mod | | | Low | Mod | | |
| **Overall Physical Connections** | **Very Unlikely** | **Mod** | **Very Likely** | **High** | | | **Low** | **Mod** | | |
| Bait | Very Unlikely | Low | Low | Low | Low | Low | Low | Low | Low | Low |
| Trade | Very Unlikely | Mod | Low | Mod | Very Unlikely | Low | Low | Low | Low | Mod |
| **Overall Human-Mediated Release** | **Very Unlikely** | **Low** | **Low** | **Low** | **Low** | **Low** | **Low** | **Low** | **Low** | **Low** |
| **OVERALL ARRIVAL (Combined Overall Physical Connections and Overall Human-mediated Release)** | **Very Unlikely** | **Mod** | **Very Likely** | **High** | **Low** | **Low** | **Low** | **Mod** | **Low** | **Mod** |

## 2.2 LIKELIHOOD OF SURVIVAL

The likelihood of survival (does not die upon arrival and lives over winter months) of bigheaded carps was based on available scientific knowledge of these species' biological requirements in terms of food resources and thermal tolerance, and the availability of such conditions within the Great Lakes basin.

At least three large adult Bighead Carp have been captured live from Lake Erie (Kolar et al. 2007, Cudmore and Mandrak 2011). Those fish are unlikely to have been recent escapes from aquaculture or live food trade because their size at capture (606 to 937 mm; Morrison et al. 2004) was much larger than the size at which cultured fish are harvested for sale (Engle and Brown 1999). Condition factor of those fish was extremely high (based on lengths and weights from Morrison et al. 2004). Aging structures from those fish indicated that the fish were growing rapidly (Morrison et al. 2004) and showed an early life history consistent with an aquaculture origin. It is clear that these fish were surviving and growing very well in Lake Erie. A live Bighead Carp was also captured from Lake Calumet, a portion of the CAWS, and environmental DNA from both Bighead and Silver carps has been collected from this system (USACE 2011b). While this particular habitat is not representative of the Great Lakes as a whole, it should be noted that the Great Lakes are not a uniform habitat and a variety of habitat types exist in all of the lakes. Bigheaded carps are mobile fishes (DeGrandchamp et al. 2008) and capable of selecting habitat types conducive to their survival.

### 2.2.1  Food Resources

 A bioenergetics model (Cooke and Hill 2010) suggested that bigheaded carps could survive in Lake Erie and in some embayments of the remaining Great Lakes, but that planktonic resources would be insufficient to support growth of Bighead and Silver carps in the open waters of the larger Great Lakes. Further research to refine and evaluate that model has been performed and continues at the time of this writing. Recently completed, but unpublished, data on Bighead Carp (K. Massagounder, Univ. of Missouri, pers. comm.) indicates that the Cooke and Hill (2010) model appears to overestimate growth at high food abundances and underestimate growth at low food abundance. Error rates were higher at the higher food abundances than at low food abundances, and higher at warmer temperatures (>18°C) than at cooler temperatures. This recent research indicates that respiration/maintenance costs used in the model are higher than measured costs, and that energy content of bigheaded carps is substantially lower than that used in the model. It is unclear at this time whether these improvements to the Cooke and Hill (2010) model would substantially increase the zones where bigheaded carps could survive, but they clearly support the conclusion that sufficient planktonic food exists in parts of the Great Lakes to provide for their survival and growth.

The degree to which non-planktonic sources of food in the Great Lakes may enhance survival of bigheaded carps is unclear but, in some cases, alternative foods may allow survival of bigheaded carps in regions where planktonic resources are inadequate. Bigheaded carps are primarily filter-feeders on plankton, but they are known to consume detritus (Anwand and Kozianowski 1987, Chen and Liu 1989, Cremer and Smitherman 1980, Takamura 1993). In studies in Dagestan, Russia (Lazareva et al. 1977) and in the lower Missouri River (D. Chapman, U.S. Geological Survey, pers. obs.) where planktonic food sources were in short supply, detritus often constituted more than 90% of the diet. However, the value of detritus as a food source for bigheaded carps is unclear and is probably highly variable depending on the origin of the detritus. Takamura (1993) found that detritus enriched by Grass Carp feeding was sometimes an important source of food for Silver Carp, but Lin et al. (1981) found that detritus

formed by the degradation of *Microcystis aeruginosa* (a blue-green algae common in the Great Lakes) was not an adequate diet to support growth of bigheaded carps. In addition, the energetic demands of detrital feeding, compared to pelagic filtering, are not understood, and may vary depending on detritus or substrate type. Nevertheless, the fact that bigheaded carps, at times, consume substantial detritus leads to the conclusion that they can benefit from the behaviour. Consumption of detrital food would open larger parts of the Great Lakes to invasion by bigheaded carps or allow bigheaded carps to disperse across areas with less than adequate planktonic resources.

Two likely sources of enriched sediment detritus in the Great Lakes are dreissenid mussel feces and pseudofeces and attached algae such as *Cladophora* and *Lyngbia*. Dreissenids remove plankton and organic material from the water and excrete feces and pseudofeces that collect in depositional areas (D. Chapman, USGS, unpubl. data). Attached algae have become more abundant in the Great Lakes because of increased water clarity and enhanced available inorganic nutrient concentrations resulting from dreissenid feeding on plankton (D. Chapman, USGS, unpubl. data). These attached algae break from their attachments and can become a part of the detritus. Studies on the nutritional value of enriched sediment detritus in the Great Lakes are incomplete at the time of this writing, but may also contribute to the survival or dispersal of bigheaded carps.

## 2.2.2  Thermal Tolerance

The Asian range of Bighead and Silver carps extends northward to the Amur River basin (Kolar et al. 2007). Bighead Carp are not thought to be native to the Amur basin, but they are present and established there. Herborg et al. (2007) compared environmental characteristics (including temperature) between the Asian range and North America, and found that the entire Great Lakes region, as well as a large portion of Canada, was well within the potential range of both species (Figure 9).

## 2.2.3 Summary of Likelihood of Survival

Information on food availability and thermal tolerance was used to assess the likelihood of survival of bigheaded carps in each of the Great Lakes. Alternative foods may allow for survival when planktonic food sources are inadequate. Modeling of environmental characteristics from the native range of bigheaded carps indicates that there is a strong match to environmental characteristics in the Great Lakes. For all lakes, likelihood of survival was ranked very likely with high certainty (Table 7). The certainty exception being for Lake Erie (very high) due to the greater volume of research associated with that lake in particular, and the existing records of the capture of healthy Bighead Carp individuals in this lake, thereby, indicating proven ability to survive in Lake Erie.
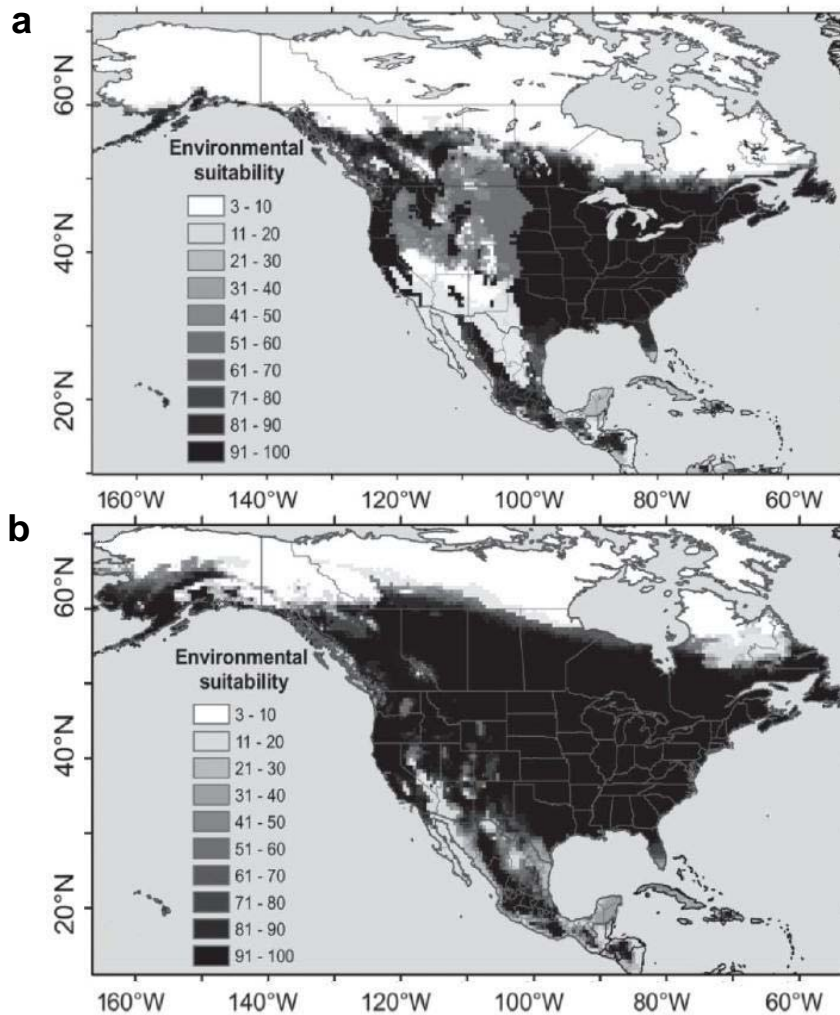
*Figure 9. Potential distribution of a) Bighead Carp (*Hypophthalmichthys nobilis*) and b) Silver Carp (*H. molitrix*) in North America based on environmental suitability, or the number out of a maximum of 100 niche-based models that predicted a certain area as appropriate. Modified from Herborg et al. (2007).*

*Table 7. Likelihood of survival rankings and certainties for each lake.*

|  | Superior | | Michigan | | Huron | | Erie | | Ontario | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Element** | **Rank** | **Cert** | **Rank** | **Cert** | **Rank** | **Cert** | **Rank** | **Cert** | **Rank** | **Cert** |
| Survival | Very Likely | High | Very Likely | High | Very Likely | High | Very Likely | Very High | Very Likely | High |

## 2.3  LIKELIHOOD OF ESTABLISHMENT

Assessment of the likelihood of establishment (evidence of the ability to reproduce, which would lead to a self-sustaining population) assumes that arrival and survival have occurred, and that the number of adult bigheaded carps present in the system is sufficient for spawning to potentially occur. The establishment of bigheaded carps in the Great Lakes would then be

dependent upon availability of suitable spawning and nursery habitats, survival of early life stages, stock size required for effective recruitment, and positive population growth.

## 2.3.1  Spawning and Nursery Habitat

A study of Silver Carp indicated they seem to require an average of 2,685 total annual degree-days (ADD; sum of mean daily water temperatures for all days above $0^{o}C$) each year over several years to mature (Krykhtin and Gorbach 1981). In a northern native population, males matured at 4-10 years and females at 6-10 years (Gorbach and Krykhtin 1981 in Naseka and Bogutskaya 2011), which incorporates delay of maturity up to 2 year in the coldest years (gorbach and Krykhtin 1980 in Naseka and Bogutskaya 2011).  In North America, maturity was reached in 2-3 years (Kipp et al. 2011). Once mature, bigheaded carps required a minimum number of total annual degree-days based on water temperature above $15^{o}C$ to reach spawning condition: 655 ADD for onset of spawning; and, 933 ADD for mass spawning (Gorbach and Krykhtin 1981 in Naseka and Bogutskaya 2011). Bigheaded carps are only known to spawn in rivers and it is believed that a rising hydrograph (flood event) is a primary spawning cue (Kolar et al. 2007). In its native range, Bighead Carp has a fecundity ranging from 280,000-1.1 million eggs (Kolar et al. 2007). In North America, fecundity ranged from 4,792-1.6 million eggs (Kipp et al. 2011). In its native range, Silver Carp has a fecundity ranging from 299,000-5.4 million eggs (Kolar et al. 2007). In North America, it has ranged from 26,650- 3.7 million eggs (Kipp et al. 2011).

Once the eggs are released and fertilized, the semi-buoyant, fertilized eggs may need to remain suspended in current until they hatch (Kolar et al. 2007). Hatching time is related to temperature (Kolar et al. 2007 and references therein). Larvae move to productive habitats (e.g., wetlands) for feeding and/or protection (Kryzhanovsky et al. 1951, Abdusamadov 1987, D. Chapman, unpub. data).

Bigheaded carp spawning has been documented to occur in tributaries generally longer than 100 km (Krykhtin and Gorbach 1981, Kolar et al. 2007). Kolar et al. (2007) identified 22 American tributaries of the Great Lakes that were unimpounded from the mouth to at least 100 km upstream to lakes Superior (three tributaries), Michigan (seven tributaries), Huron (four tributaries), and Erie (eight tributaries). There were no tributaries identified by Kolar et al. (2007) for Lake Ontario. Cudmore and Mandrak (2011) identified over 80 Canadian tributaries to the Great Lakes that were unimpounded from the mouth to at least 50 km upstream (Superior (30 tributaries), Huron (28), Erie (9), Ontario (19)). Fifty-two Canadian tributaries are unimpounded from the mouth to at least 80 km upstream (Superior (22 tributaries), Huron (16), Erie (6), Ontario (8)), and forty-one tributaries to at least 100 km upstream (Superior (16 tributaries), Huron (14), Erie (5), Ontario (6)) (Mandrak et al. 2011). The shortest flowing body of water in which bigheaded carps are known to have spawned is in an 87-km reach of the Kara Kum Canal in Turkmenistan (Aliev 1976).

Two recent studies have examined the suitability of Great Lakes tributaries for bigheaded carp spawning based on more detailed considerations of reproductive biology. Kocovsky et al. (2012) examined eight American tributaries in the central and western basins of Lake Erie. They considered: the thermal conditions of the tributaries and Lake Erie, the minimum total degree-days required for maturation, onset of spawning and mass spawning, timing of flood events as triggers for spawning, and length of stream required for egg hatching based on stream velocity and estimated incubation time. They concluded that the three larger tributaries were thermally and hydrologically suitable to support spawning of bigheaded carps, four tributaries were less suited, and that one was ill suited. Mandrak et al. (2011) conducted a similar analysis for the

Canadian tributaries of the Great Lakes. They concluded suitable spawning conditions were present in nine of 14 tributaries to Lake Superior with sufficient data; however, only one of the nine tributaries had a mean annual total degree-days exceeding 2,685. Therefore, bigheaded carps are unlikely to mature within Lake Superior tributaries, but may encounter sufficient growing degree-days to mature in some parts of Lake Superior such as near shore and bays. Further analysis is required to identify such areas. Mandrak et al. (2011) concluded suitable spawning conditions, including growing degree-days required for maturation, were present in 23 of 27 tributaries to Lake Huron, nine of 10 tributaries to Lake Erie, and 16 of 28 tributaries to Lake Ontario. Neither Kocovsky et al. (2012) nor Mandrak et al. (2011) incorporated the scale (e.g., minimum stream width) and nature of spawning habitat (e.g., turbulence) because the detailed characteristics required for bigheaded carp spawning are poorly understood. Furthermore, these studies rely on velocity measurements at few locations and are thus coarse drift models. More precise modeling would require extensive field data that are currently unavailable. Similar studies have not been conducted for US tributaries in lakes Michigan, Huron, Superior, Ontario, nor the eastern basin of Lake Erie, but the analyses of Kocovsky et al. (2012) and Mandrak et al. (2011) suggest that access to tributaries with suitable thermal and hydrologic regimes in the Great Lakes should not limit spawning by bigheaded carps.

A particle tracking model and estimated incubation times were used to examine the spawning suitability of St. Clair and Detroit rivers (N. Mandrak, Fisheries and Ocieans, unpubl. data). The model indicated that fertilized eggs in the St. Clair River would be deposited in Lake St. Clair before hatching, and those in the Detroit River would be deposited in Lake Erie before hatching. As there are no verified records of bigheaded carp eggs hatching in lentic waters and the currents of lakes St. Clair and Erie are generally less than 0.1m/s (Ibrahim and McCorquodale 1985; Leon et al. 2005), the eggs would likely not survive. The potential for lentic spawning (i.e., where eggs fall to substrate) is a knowledge gap that needs to be further investigated, particularly for locations with strong currents, clean substrates, and few Round Goby (*Neogobius melanostomus*) populations (e.g., Lake Superior). These results may be conservative as Chapman and George (2011) developed models showing faster hatching rates and hatching success on sediment.

Cudmore and Mandrak (2011) concluded that there were ample wetlands throughout the Great Lakes basin, including those associated with unimpounded tributaries greater than 50 km, which would be suitable nursery habitats for bigheaded carps. Mandrak et al. (2011) similarly concluded that many of the Canadian tributaries with suitable spawning habitat for bigheaded carps also had suitable nursery habitat. Although not assessed for suitability as nursery habitats for bigheaded carps, numerous coastal wetlands also exist throughout the Great Lakes in the United States (Simon and Stewart 2006).

### 2.3.2 Estimated Spawning Population Needed for Establishment

Because no data are available on the number of bigheaded carps needed to establish a population, it was assumed for the purposes of this risk assessment that sufficient numbers of adult bigheaded carp were present to potentially spawn. However, managers at a workshop held in November 2010 to identify management questions of concern asked to know the number of bigheaded carps needed to establish a population. Currie et al. (2011) addressed this question by modeling the probability of successful spawning of bigheaded carps in the Great Lakes based on a small founder population using a variant of the 'birthday problem' (Wendl 2003). They modeled the probability of successful spawning in three scenarios: (1) assuming bigheaded carps use environmental cues to identify rivers suitable for spawning, that once in a river, pheromone cues make encounter between male and female unproblematic, fish

are ready for spawning at about the same time, and several suitable spawning rivers are available and found by fish; (2) assuming that not all fish present in the lake arrive at suitable spawning rivers (i.e., fish have some difficulty in locating rivers); and, (3) assuming variability about spawning time of individuals. Common assumptions across scenarios are a 1:1 male:female sex ratio, spawning could occur between one male and one female, and suitable conditions for spawning occurred each year (i.e., hydrographs were conducive to spawning).

They concluded that when adults were able to accurately cue into suitable rivers for spawning, a founder population of 10 females and 10 males had a greater than 50% chance of successfully spawning. The minimum number of bigheaded carp required to have a 50% chance of spawning increased to 20 mated pairs if maturation time varied, or if fish only had a 20% success rate at choosing suitable spawning rivers. Similarly, number of fish required further increased if there was a larger number of suitable rivers, or if the fish have difficulty finding suitable spawning rivers. When factors that would limit successful spawning were combined, such as bigheaded carps being unable to accurately distinguish between suitable and unsuitable rivers, and that they must be present in a river over a very short time interval, the expected probability of a spawning was small.  Multiple spawning events can occur in a given year, however, if hydrologic conditions are conducive (Papoulias et al. 2006).

### 2.3.3  Survival of Early Life Stages

High fecundity, as found in bigheaded carps, is typically associated with high mortality in early life stages (Kolar et al. 2007). To date, there have been no specific studies on mortality rates of early life stages of bigheaded carps. Survival would be related to feeding, predation, and overwinter mortality. Newly hatched bigheaded carp larvae can move vertically and, as a result, do not need to remain in the current (Chapman and George 2011). Given high fecundity rates, they would encounter high intraspecific competition likely resulting in an initial high density-dependent mortality. Competition for food resources with other species has not been studied for early life stages, but is highly likely not to be limiting given the success of bigheaded carps in the Mississippi River watershed.

Bigheaded carp larvae in the drift that are younger than the gas bladder inflation stage do not appear to strongly avoid capture by nets or siphon tubes, and thus probably have poor predator avoidance strategies (D. Chapman, USGS, pers. obs.). However, older larvae did strongly attempt to avoid aquarium nets and siphon tubes. At that age, larvae begin to move toward wetland nursery habitats where they would be less susceptible to pelagic ichthyoplanktivores (D. Chapman, USGS, unpublished data.). However, there have not been any North American studies of predation on bigheaded carp juveniles (Kipp et al. 2011). Given the high fecundity strategy of the bigheaded carps and that most native species must go through a similar predation-prone period, it is unlikely that such predation would limit bigheaded carp population growth. Bigheaded carps undertake rapid growth, with Bighead Carp averaging 273 mm at age-1 (back calculated) and Silver Carp averaging 318 mm at age-1 in the Mississippi River (Nuevo et al. 2004). Growth would likely be slower in the Great Lakes and, even if the growth was 33% slower within their first year, the bigheaded carps would quickly exceed the gape size of most fish predators in the Great Lakes.

Overwinter mortality is an important limiting factor in temperate fishes (e.g., Shuter et al. 1980). It can typically result from prolonged starvation or extended periods of low dissolved oxygen concentrations (known as winterkill), the latter not typically occurring in the Great Lakes and its tributaries. Overwinter mortality as a result of starvation occurs when, going into their first winter, fishes have insufficient energy reserves (typically correlated to size) to survive until

resources become available the following spring (Holm et al. 2009). Because overwinter mortality is correlated to length of winter, it becomes more important with increasing latitude. It is not known to be an issue for bigheaded carps in the Mississippi River basin; bigheaded carp fingerlings are collected from floodplain wetlands in the spring in years when those wetlands were not connected to the river (D. Chapman, USGS, pers. obs.). Overwinter mortality may influence the northern limits of the native range of bigheaded carps, but has not been modelled specifically for these species in North America. However, ecological niche modeling based on their native range would implicitly incorporate such mortality. Ecological niche modeling predicting the potential North American distribution of bigheaded carps indicated that they could survive well north of the Great Lakes basin (Herborg et al. 2007); therefore, overwinter mortality will likely not be a limiting factor in most years.

### 2.3.4  Stock Required for Effective Recruitment

No data was located on stock size for effective recruitment of bigheaded carps in environments similar to the Great Lakes. A stock-recruitment model has been developed, however, for Bighead Carp in large rivers of the United States. The Asian Carp Working Group (2007) of the Aquatic Nuisance Species Task Force recommended development of stock-recruitment models for Bighead Carp and other Asian carps to assist in management and control of feral populations. Hoff et al. (2011) developed a Ricker stock-recruitment model using Bighead Carp population data collected in the LaGrange Reach of the Illinois River and Pool 26 of the Mississippi River during 2001-2004 to guide management and control efforts there. The modeled functional relationship explained 83% of the recruitment (during July through October of the first year of life) variation using stock size and river discharge (Figure 10). Seventy-two percent of recruitment variation was explained by stock-size abundance, while an additional 11% was explained by the coefficient of variation of discharge in July. Assuming the stock-recruitment relation in the Illinois and Mississippi rivers is similar to one that would develop in the Great Lakes, the risk of establishment of Bighead Carp, and probably Silver Carp, would increase rapidly with small increases in adult stock size (Figure 11).

$$R = S\,e^{\,1.46133-16.0356\,S}$$

$r^2 = 72\%,\ df = 5,\ F = 10.23,\ P = 0.03$

Where: R = recruit CPUE and S = stock CPUE
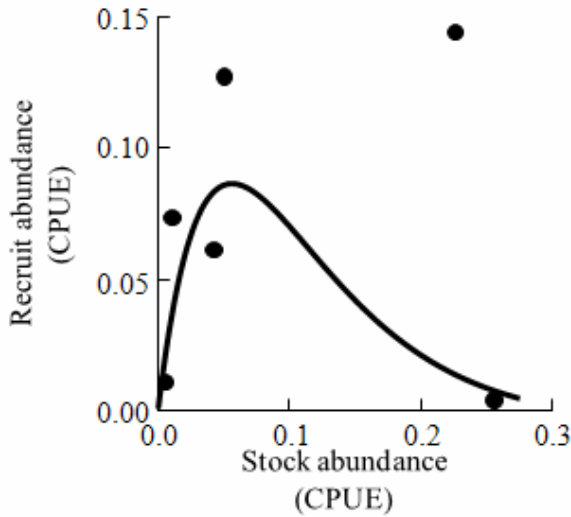
Figure 10. Functional relationship, from the trivariate stock-recruit model for Bighead Carp, of recruitment to stock size abundance and river discharge coefficient of variation during July. From Hoff et al. (2011).

$$R = S\,e^{\,5.62869-18.8237\,S-0.10746\,D}$$

adj. $R^2 = 83\%,\ df = 2,\ 3,\ F = 13.42,\ P = 0.03$

Where: R = recruit CPUE, S = stock CPUE, and D = river discharge coefficient of variation in July
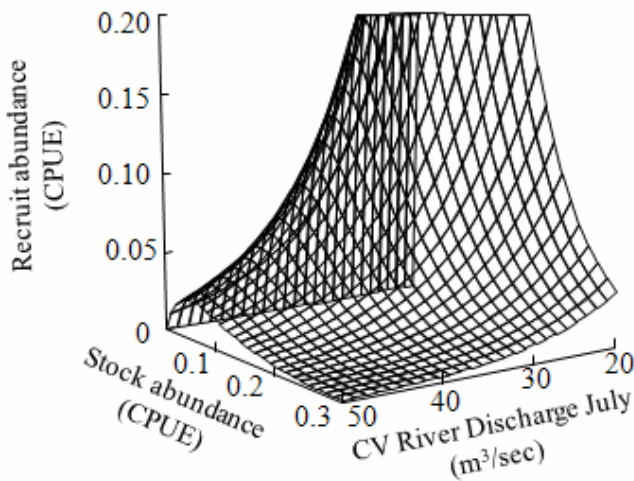
Figure 11. Empirical stock and recruitment data and the stock-recruit model for Bighead Carp in the LaGrange Reach of the Illinois River and Pool 26 of the Mississippi River, 2001-2004. From Hoff et al. (2011).

### 2.3.5  Positive Population Growth

Population growth and establishment models are lacking in the literature for bigheaded carps. The need for such modeling was identified at a workshop attended by those conducting research on bigheaded carps in November 2010. Currie et al. (2011) developed stage-structured deterministic and stochastic population growth models for bigheaded carps in the Great Lakes under various scenarios to fill this information gap.

The deterministic model incorporated four life stages: juvenile (eggs, larvae, Age-0); first subadult stage (Age-1); second subadult stage (Age-2); and adult (Age-3+) and was parameterized using data from the literature where available. Once a stable stage distribution was reached, the model predicted large population growth rate ($\lambda$) of $\lambda$=2.18 per year. A second version of the model was developed with sexual maturity at age 5 rather than age 3. Using this model, the annual population growth rate was slower ($\lambda$=1.36). In both versions of the model, population growth was most sensitive to the survivorship of juveniles followed by those in the first subadult stage.

The stochastic model incorporated environmental stochasticity (years with poor reproductive success), likelihood of adults finding a suitable spawning river, and variation in number of initial females (10-30) and spawning rivers (1, 5, and 10). The model predicted the probability of population establishment (population size of 1000 adult females within 20 years) and growth under three release scenarios (where the number of fish released varied from 2-60): a single release of adults; a single release of subadults; and a slow release of subadults. Currie et al. (2011) conservatively assumed mated pairs of males and females and one spawning event per season. The model predicted that under the worst-case scenarios (maturity at 3 years and a high ability to locate suitable spawning rivers) as few as 10 mated pairs of bigheaded carps present in one Great Lake would result in a very high probability of establishment in that lake within 20 years. This probability was lower and the number of fish required was higher for a single release of subadults than the other two scenarios. Probability of establishment decreased and time to establishment increased if fish cannot accurately identify suitable spawning rivers.. For example, the probability of establishing a population within 20 years in a Great Lake under a low probability of finding a spawning river varied between 0 and 35% as the number of spawning rivers varied (see Figure 3-3 in Currie et al. 2011). Models predicted substantially longer than 20 years to establishment regardless of number of spawning pairs, spawning rivers, or environmental stochasticity if age at maturity was raised from 3 to 5 years (see Figure 3.4 in Currie et al. 2011).

### 2.3.6  Summary of Likelihood of Establishment

Research on the establishment of bigheaded carps indicates lakes Huron, Erie, and Ontario have suitable spawning tributaries based on thermal and hydrologic regimes, some of which have adjacent suitable nursery habitat. Nine tributaries were identified in the Lake Superior basin with amenable hydrologic regimes; however only one was sufficiently warm. The ability for bigheaded carps to mature in the Lake Superior basin needs to be examined further. Thermal and hydrologic regimes of potential spawning tributaries of Lake Michigan have not been examined, but Lake Michigan does have  tributaries that exceed 100 km that might have the minimum requirements for Asian carp spawning and recruitment.  Although little published information exists, competition, predation and overwinter mortality of early life stages would likely not limit establishment of these species. Little published information exists regarding population growth for bigheaded carps. A stock-recruitment model suggests that the risk of establishment may increase rapidly with small increases in adult stock size. Deterministic and

stochastic population growth models predicted positive population growth in the Great Lakes, but that it would be slower if fish reached sexual maturity at age 5 rather than age 3. In the scenarios examined, the most conservative likelihood of establishment was estimated to be 100% with 10 mated pairs of a species of bigheaded carp in a single Great Lake basin (given a single release of adult fish and high ability of fish to locate appropriate tributaries for spawning). Time to population establishment wass dependent upon age of maturity and was likely to be relatively short (i.e., within 20 years) in the southern portion of the Great Lakes basin.

Given that access to suitable spawning and nursery habitat should not be limiting, nor should survival of early life stages, the high likelihood of recruitment and positive population growth, the likelihood of establishment for all but Lake Superior was ranked very likely with high certainty. It is likely that age of maturity will be older in Lake Superior and that establishment would take longer. Given the likely older age of maturity, fewer suitable spawning tributaries, and uncertainty related to ability to mature in the Lake Superior basin, the likelihood of establishment for Lake Superior was ranked moderate with moderate certainty (Table 8). Likelihood of establishment for the rest of the Great Lakes was ranked very likely with high certainty.

*Table 8. Likelihood of establishment rankings and certainties for each lake.*

|  | **Superior** |  | **Michigan** |  | **Huron** |  | **Erie** |  | **Ontario** |  |
|---|---|---|---|---|---|---|---|---|---|---|
| **Element** | **Rank** | **Cert** | **Rank** | **Cert** | **Rank** | **Cert** | **Rank** | **Cert** | **Rank** | **Cert** |
| Establishment | Moderate | Moderate | Very Likely | High | Very Likely | High | Very Likely | High | Very Likely | High |

## 2.4  LIKELIHOOD OF SPREAD

Following successful establishment within the Great Lakes basin, the likelihood of spread into other areas of basin was assessed based on the best available scientific information about dispersal (i.e., volitional swimming of individual fish, through canals or via ballast water) or human-mediated vectors (i.e., baitfish introductions). Ballast water is considered in spread with dispersal rather than with human-mediated vectors. Subsequently, each of the Great Lakes has been considered separately since the likelihood of spread via these vectors may differ among lakes.

### 2.4.1  Dispersal

2.4.1.1 Natural Dispersal
Few studies have assessed the movement of bigheaded carps in natural environments. Those that have been completed were conducted in rivers or ponds (Konagaya and Cai 1989, Peters et al. 2006, Kolar et al. 2007, DeGrandchamp et al. 2008), habitats that differ significantly from those available in much of the Great Lakes basin. Movement rates of bigheaded carps reported from riverine telemetry studies have varied. Peters et al. (2006) conducted telemetry of Bighead Carp on the Illinois River (May-July 2003 and 2004) and found a mean movement rate of 1.7 km/day but, in some cases, individual fish moved longer distances (up to 14 km/day). Kolar et al. (2007) reported results of a telemetry study of Bighead Carp in the Missouri River that found individual Bighead Carp did not travel long distances (<15 km) except during high water where some fish moved more than 80 km. DeGrandchamp et al. (2008) conducted telemetry on Bighead Carp and Silver Carp in the lower Illinois River during spring-summer 2004 and 2005 using mobile and stationary receivers and found that Bighead Carp moved a mean of 3.6 km/day while Silver Carp moved an average of 3.2 km/day. Further, results from stable carbon

isotope analysis of otoliths of bigheaded carps by Ernat et al. (2010) suggested that individual fish inhabiting the area below the electric dispersal barrier moved long distances, originated from within the Illinois River, the middle Mississippi River, and floodplain lakes along the lower Illinois River valley. Because of a lack of information from the peer-reviewed literature on natural movement of bigheaded carps via natural dispersal in lacustrine environments, we must rely on modeling efforts to predict potential spread through the Great Lakes by this vector.

Two studies have been completed to date that address potential spread of bigheaded carps in the Great Lakes. Currie et al. (2011) assessed the potential spread of bigheaded carps from various entry points around the Great Lakes using the Fish Foraging and Movement model, an individual-based, Markov process movement model. The model allowed habitat use to be affected by zooplankton abundance and distribution and current patterns (i.e., fishes would stay in more profitable areas longer before moving on) and simulations were run for 1, 2, 5, 10, and 20 years. Cooke and Hill (2010) developed bioenergetics models for bigheaded carps based on empirically derived parameters from the literature. They assessed the potential of bigheaded carps to colonize habitats in the Great Lakes based on plankton biomass and surface water temperature data. Their models indicated that many open-water regions of the Great Lakes could not support growth of bigheaded carps. The models indicated, however, that more productive regions, such as Green Bay, western Lake Erie, and some other wetlands and embayments, did contain sufficient planktonic resources. It is noteworthy that this study was based solely on empirically derived data and considers only plankton as food resources for bigheaded carps (and does not include many rotifers which are known to be important in the diets of bigheaded carps; Bardach et al. 1972; Berday et al. 2005). Results of these studies are discussed below as they apply to individual Great Lakes.

2.4.1.2 Canals
Studies are largely lacking that quantify the movement of invasive species through canals, as well as lock and dam structures. Brooks et al. (2009) implanted several fish species, including bigheaded carps, with sonic tags from 2006 through 2008 to assess passage of fishes through the Lock and Dam complexes of the Upper Mississippi River System using stationary data logging receivers. They documented both upstream and downstream passages of bigheaded carps through each Lock and Dam complex from 19 (Keokuk, IA) through 26 (Alton, IL). See also work by Knights et al. (2003) documenting upstream fish passage at dams. Sauger (*Sander canadensis*) (Pegg et al. 1997) and Silver Carp (Calkins et al. 2011) have been documented moving through lock structures.

Artificial waterway connections, canals, are known to be important pathways that facilitate the spread of AIS between waterbodies (Mandrak and Cudmore 2010). Sea Lamprey (*Petromyzon marinus*), Alewife (*Alosa pseudoharengus*) Bigmouth Buffalo (*Ictiobus cyprinellus*), and White Perch (*Morone americana*) are examples of species that expanded their range to the upper Great Lakes through the Welland Canal, the portion of the St. Lawrence Seaway connecting Lake Ontario to Lake Erie (Mandrak and Cudmore 2010).

2.4.1.3 Laker Ballast
Unlike the ballast water in freighters that originate outside of the Great Lakes-St. Lawrence River basin, ballast water in freighters that remain in the basin (known as "lakers") is not treated for AIS. Therefore, lakers may facilitate the movement of organisms between ports and Great Lakes, particularly small early life stages such as eggs, larvae, and juveniles. To date, there have been no quantitative studies on the role of laker ballast water specific for the movement of fishes, including bigheaded carps. Therefore, findings of Rup et al. (2010) were used as a surrogate for potential propagule pressure between lakes. To determine the potential for

between-lake ballast movement, primary port-to-port trips (i.e., single trips involving a single ballast-in ballast-out sequence) were plotted by Rup et al. (2010) for each donor region. Trips display annual average ballast volume (mt) and variability (standard deviation) received at the port level and originating from each donor region (Figure 12). To describe overall lake-wide patterns of ballast movement, the annual average and proportion of ballast water transferred from each donor region was calculated (Table 9). All analyses describing directional ballast movement, volume and variability were based on data from Rup et al. (2010), describing all joint American and Canadian laker traffic within the Great Lakes-St. Lawrence River basin, 2005–2007. A small fraction (< 2.5%) of trips was excluded due to uncertain ballasting procedures. Ports in lakes Erie, Michigan, and Huron are the greatest donors of ballast water to ports in the other lakes, and ports in lakes Superior, Michigan, and Huron are the greatest recipients of ballast water from ports in the other lakes (Table 4).

### 2.4.2  Human-mediated Dispersal

If bigheaded carps became established in some portion of the Great Lakes basin, their spread to other areas of the basin could be facilitated by human-mediated dispersal mechanisms. For the purposes of this risk assessment, baitfish introductions are the only mechanism of human-mediated dispersal that can be qualified.
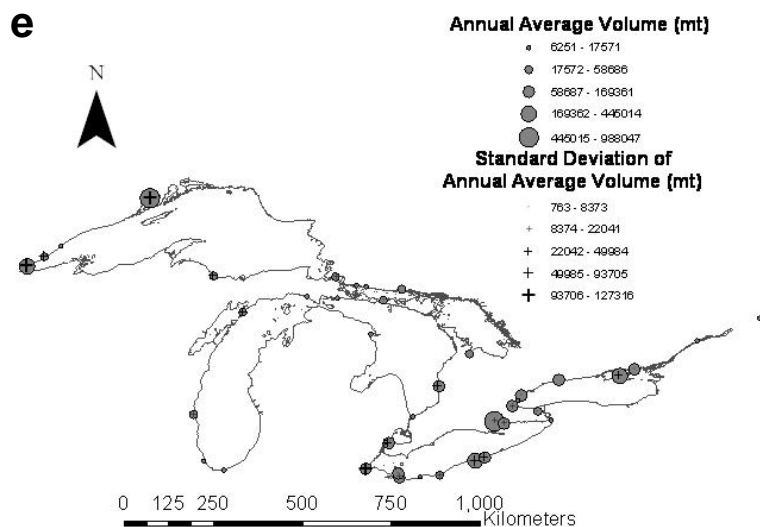
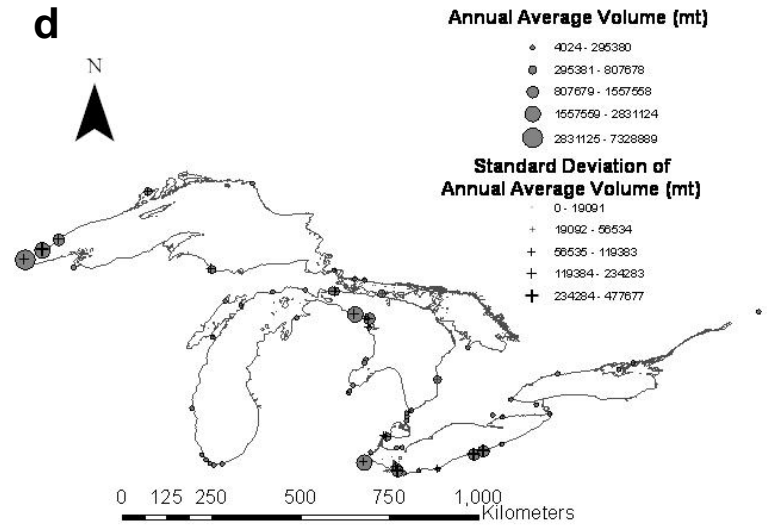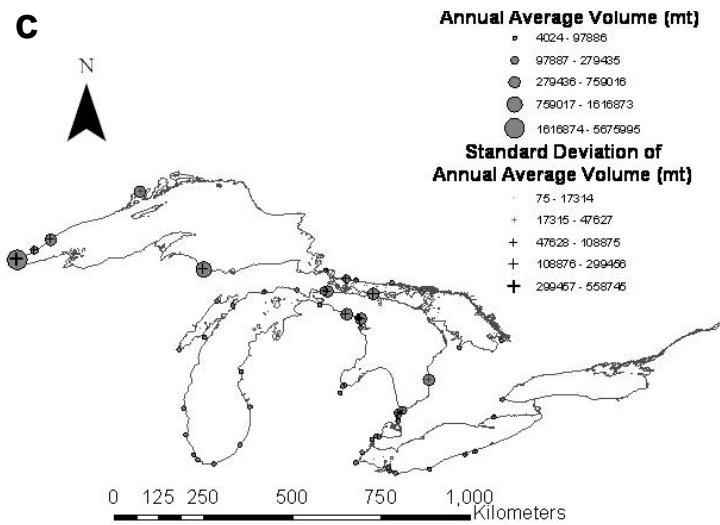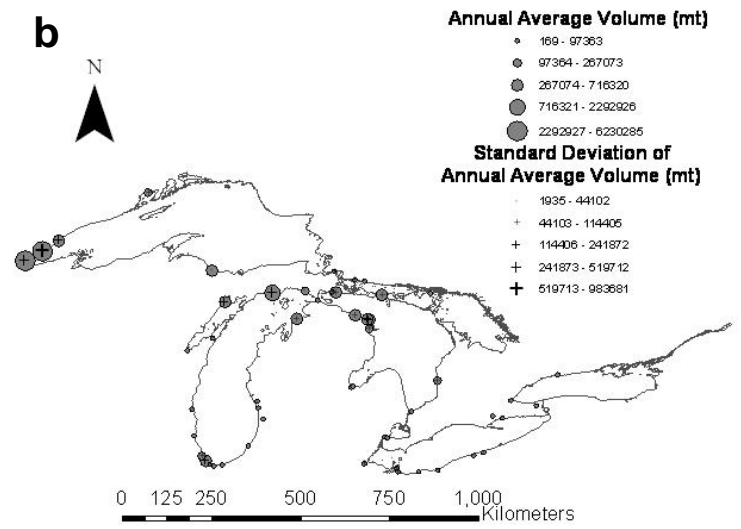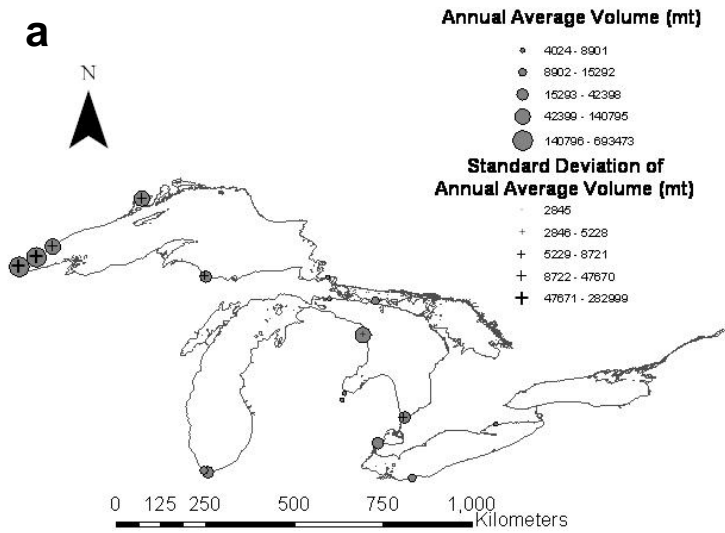*Figure 12. Destination of ballast water discharge for trips originating from any port within a) Lake Superior, b) Lake Michigan, c) Lake Huron, d) Lake Erie, and e) Lake Ontario. Annual averages and standard deviations of ballast discharge volumes, 2005 – 2007, are summarized from Rup et al. (2010).*

*Table 9. Origin of ballast water discharge for trips between Great Lakes and the St. Lawrence River. Annual averages of ballast discharge volumes, 2005 – 2007, summarized from Rup et al. (2010). A small fraction (< 2.5%) of trips from Rup et al. (2010) were excluded due to uncertain ballasting procedures.*

| Recipient Region | Donor Region | Recipient Annual Average (mt) | Recipient Proportion |
|---|---|---|---|
| Superior | Superior | 1,461,949 | 0.041 |
| | Michigan | 11,444,781 | 0.322 |
| | Huron | 8,443,756 | 0.238 |
| | Erie | 12,518,207 | 0.353 |
| | Ontario | 1,343,321 | 0.038 |
| | St. Lawrence | 290,411 | 0.008 |
| | Total | 35,502,425 | 1 |
| Michigan | Superior | 55,607 | 0.007 |
| | Michigan | 5,039,678 | 0.614 |
| | Huron | 1,046,856 | 0.127 |
| | Erie | 1,941,544 | 0.236 |
| | Ontario | 123,051 | 0.015 |
| | St. Lawrence | 6,564 | 0.001 |
| | Total | 8,213,300 | 1 |
| Huron | Superior | 205,391 | 0.018 |
| | Michigan | 3,050,252 | 0.261 |
| | Huron | 2,906,624 | 0.248 |
| | Erie | 5,194,303 | 0.444 |
| | Ontario | 290,418 | 0.025 |
| | St. Lawrence | 50,608 | 0.004 |
| | Total | 11,697,596 | 1 |
| Erie | Superior | 49,945 | 0.005 |
| | Michigan | 414,114 | 0.038 |
| | Huron | 347,734 | 0.032 |
| | Erie | 7,917,597 | 0.718 |
| | Ontario | 2,159,917 | 0.196 |
| | St. Lawrence | 143,088 | 0.013 |
| | Total | 11,032,394 | 1 |
| Ontario | Superior | 0 | 0.000 |
| | Michigan | 11,589 | 0.010 |
| | Huron | 7,800 | 0.007 |
| | Erie | 180,490 | 0.157 |
| | Ontario | 827,523 | 0.719 |
| | St. Lawrence | 123,599 | 0.107 |
| | Total | 1,151,002 | 1 |
| St. Lawrence | Superior | 0 | 0.000 |
| | Michigan | 14,738 | 0.005 |
| | Huron | 39,425 | 0.013 |
| | Erie | 54,366 | 0.018 |
| | Ontario | 594,016 | 0.200 |
| | St. Lawrence | 2,268,879 | 0.764 |
| | Total | 2,971,423 | 1 |

There is the potential for bigheaded carps, if they arrive in the Great Lakes basin, to be spread through the use of baitfish (see Section 2.1.5 for discussion of baitfishes as an arrival route). For most jurisdictions, knowledge is lacking on the degree to which these regulations are adhered and to which baitfish originated in areas of bigheaded carp populations, on angler use, movement, and release patterns, and on annual volume and distribution of angling events. A recent study (Drake 2011) examined these issues in Ontario and can be used to assess the potential spread of bigheaded carps through baitfish in the Great Lakes basin (see Section 2.1.2.1 for details).

### 2.4.3  Lake Superior

2.4.3.1  Natural Dispersal
If bigheaded carps colonized Lake Huron, individuals could disperse through the St. Marys River, passing its locks and compensating works, to reach Lake Superior. Several invasive fishes, including Alewife, Sea Lamprey, White Perch, and Rainbow Smelt (*Osmerus mordax*) have used the St. Marys River to colonize the lake (Mandrak 2009). Nonnative fishes initially found only in Lake Superior (Fourspine Stickleback (*Apeltes quadracus*), Ruffe (*Gymnocephalus cernua*)) have not yet colonized other Great Lakes naturally from Lake Superior, and have yet to be found in proximity to the St. Marys River; therefore, they are not a good test as to whether fishes can colonize Lake Huron from Lake Superior through natural dispersal. In Lake Superior, tagged Lake Trout (*Salvelinus namaycush*) have been known to leave the lake through the St. Marys River within a year (M. Hoff, USFWS, pers. comm.).

Modeling by Currie et al. (2011) predicted that given an entry point into the Great Lakes of the CAWS, very few bigheaded carps would make it to Lake Superior in 20 years, but those that did would be attracted to northern embayments, including Black and Thunder bays and the western-most arm near the St. Louis estuary. No bigheaded carps were predicted to enter Lake Superior within 20 years when the entry point was in lakes St. Clair or Erie. When the starting point was western Lake Superior, bigheaded carps tended to remain in that region because of higher production, but were also attracted to Black and Thunder bays and the Keweenaw Peninsula. However, this model does not take into account characteristics of the system that may serve as an attractant for bigheaded carps, such as turbulence of the St. Marys River; therefore, the Currie et al (2011) results may underestimate visits over time to Lake Superior. Bioenergetics modeling by Cooke and Hill (2010) predicted a maximum travel distance in 30 days for Bighead and Silver carps to be 0.8-7.5 and 2.1 km, respectively (predicted movement was dependent on location of colonization and size of individual).

Given that lock and dam structures in the St. Marys River did not inhibit the movement of several invasive fishes, such as Alewife, Sea Lamprey, White Perch, and Rainbow Smelt from Lake Huron to Lake Superior (Mandrak 2009) and that bigheaded carps have been documented to move upstream and downstream through lock and dam structures (Brooks et al. 2009), it is not expected that these structures would impede the movement of bigheaded carps to or from Lake Superior. Likely, the turbulence of the area may serve as an attractant for bigheaded carps to move towards Lake Superior.

Based on the analysis of ballast water from lakers presented from Rup et al. (2010), Lake Superior is primarily a recipient of inter-lake ballast water, with a high proportion of ballast it receives deriving from lakes Michigan, Erie, and Huron (Table 9). The two nonnative fishes, Fourspine Stickleback and Ruffe, initially found only in Lake Superior, are thought to have arrived in ballast water (Mandrak and Cudmore 2010). The larger ports in Lake Superior are also those likely to contain sufficient planktonic resources to sustain bigheaded carps (Cooke

and Hill 2010); therefore, these ports may also serve as sources for potential spread by inter-lake ballast water, should early life stages of bigheaded carps be present.

### 2.4.3.2  Human-mediated Dispersal

Lake Superior was the sixth most popular destination for Ontario anglers using live baitfishes (Drake 2011). These baitfishes would originate primarily from the Canadian nearshore waters and tributaries of lakes Huron, Erie, and Ontario, and secondarily from inland lakes in southern Ontario (Drake 2011).

## 2.4.4  Lake Michigan

### 2.4.4.1  Natural Dispersal

Several invasive fishes have spread to Lake Michigan from adjacent Great Lakes (e.g., Alewife, Sea Lamprey, White Perch). In addition, Rainbow Smelt have spread from the Lake Michigan basin to other Great Lakes (Stewart et al. 1981). Also, models by Beletsky et al. (2007) indicated small fishes are transported by currents of the lake; Yellow Perch larvae were transported from southwestern Lake Michigan to Traverse Bay in approximately 2-3 months. If bigheaded carps were present in Lake Michigan, they could disperse into Lake Huron via natural dispersal through the Straits of Mackinac. Likewise, if they were present in Lake Huron, they would have access to Lake Michigan.

As discussed in 2.1.1.1, the CAWS and surrounding waterways are potential sites of bigheaded carp introduction into the Great Lakes basin. Currie et al. (2011) modeled the potential spread of bigheaded carps with an entry site into Lake Michigan at the CAWS. Models predicted that the most likely sites in Lake Michigan that would attract bigheaded carps in the first five years after introduction would be the Muskegon River, Grand Traverse Bay, and Green Bay. Predicted potential spread after 20 years, with introduction at the CAWS, varied with parameters describing movement of individual fish, but included lakes Huron and Erie in the default model tested. After influences of food limitation and currents were added into the model, lakes Huron, Erie, and either Ontario or Superior were predicted to be visited by bigheaded carps, depending on fish movement rates. Lake Michigan was predicted to not be visited by bigheaded carps within 20 years of introduction when entry points were modeled from lakes Erie (including Lake St. Clair) or Superior. Bioenergetics modeling by Cooke and Hill (2010) predicted relatively high maximum distance traveled over 30 days from Green Bay, compared with other Great Lakes areas (27.0-33.4 km for 10 g and 28.8-35.0 km for 2,400 g Bighead Carp; 29.8-31.4 km for 10 g and 22.8-24.4 km for 2,400 g Silver Carp, in spring and summer).

Lake Michigan is not connected to other Great Lakes by artificial waterways. Therefore, if bigheaded carps become established in some portion of the Great Lakes, they could not spread to or from Lake Michigan via artificial pathways.

Based on the analysis of ballast water from lakers presented in Rup et al. (2010), Michigan ports are the second leading donor of laker ballast water to the other Great Lakes (Table 4). Western Lake Superior, northern Lake Michigan, and northern Lake Huron are the destinations receiving the greatest volume (Figure 12). The proximity of bigheaded carps to the southern basin of Lake Michigan and the high proportion of inter-lake ballast derived from this lake contribute to risk of spread via this pathway should bigheaded carps become established in port areas of Lake Michigan . Lake Michigan ports receive the third greatest amount of lake ballast water, primarily from Lake Erie ports (Table 4).

### 2.4.4.2  Human-mediated Dispersal
No studies on angler behavior related to baitfish movement along the coasts of Lake Michigan were identified.

### **2.4.5  Lake Huron**

### 2.4.5.1  Natural Dispersal
Several invasive fishes have spread to Lake Huron from adjacent Great Lakes (e.g., Alewife, Sea Lamprey, White Perch, Rainbow Smelt). If bigheaded carps were present in Lake Huron, they could likely disperse through the St. Marys River to Lake Superior or through the Detroit River, Lake St. Clair, and the St. Clair River to Lake Erie. Similarly, it is expected that bigheaded carps present in either Lake Superior or Lake Erie could move via natural dispersal into Lake Huron.

Using an introduction point at the entrance to the CAWS, dispersal modeling by Currie et al. (2011) predicted that 30-50% bigheaded carps would visit Lake Huron within 10 years of introduction under each set of model simulation assumptions. Also given this introduction point, those models predicted that bigheaded carps would be attracted to Saginaw Bay and the North Channel of Georgian Bay five years after introduction, across the range of swimming speeds and lake current influence.

The Fish Movement Model in Currie et al. (2011) suggested approximately 5% (± 2%) of bigheaded carps were predicted to enter Lake Huron by year 2 when the starting point was Lake St. Clair. This was under conditions where swimming rates were 14 cm/s and a 25% influence of lake currents. Under slower movement rates, this 5% value was reached in 5-10 years. If the fishes ignore lake currents or swim against flow, a slightly higher percentage of fishes enter Lake Huron. Cooke and Hill (2010) did not include analysis of Lake Huron in their study.

Given the historical use of the St. Marys River by invasive fishes to spread from Lake Huron to Lake Superior (Mandrak 2009) and the documented upstream and downstream movement of bigheaded carps through locks (Brooks et al. 2009), it is not thought that these connecting waters would impede movement of bigheaded carps in either direction.

Based on the analysis of ballast water from lakers presented in Rup et al. (2010), Lake Huron donates more inter-lake ballast water than it receives (Table 4), but the destination of about a quarter of the laker ballast water derived from Lake Huron is received by ports within that same lake (Table 9). Lake Superior is the major recipient of laker ballast from Lake Huron, followed by Lake Michigan (Table 9, Figure 12). Lake Huron ports receive the second greatest amount of lake ballast water, primarily from ports in lakes Erie, Michigan, and Huron (Table 9).

### 2.4.5.2  Human-mediated Dispersal
Lake Huron and Georgian Bay ranked, respectively, the third and fifth most popular destinations for Ontario anglers using live baitfishes (Drake 2011). These baitfishes would originate primarily from the Canadian nearshore waters and tributaries of lakes Erie, Huron and Ontario, and secondarily from inland lakes in southern Ontario (Drake 2011).

## 2.4.6  Lake Erie

2.4.6.1  Natural Dispersal
The connecting channels between Lake Huron and the western basin of Lake Erie (St. Clair River, Lake St. Clair, and the Detroit River) would not impede the spread of bigheaded carps from one lake to the other; this pathway has previously been used by invasive fishes to move between basins (e.g., Alewife, Sea Lamprey, White Perch, and Rainbow Smelt). Instead, the warm and productive waters of the Huron-Erie Corridor may act as attractants for bigheaded carps and facilitate further dispersal.

Using an introduction point at the entrance to the CAWS, modeling by Currie et al. (2011) predicted that bigheaded carps would visit Lake Erie within 20 years of introduction under each set of model simulation assumptions. Models also predicted that Lake St. Clair, the western basin of Lake Erie, and Sandusky Bay could become potential sites for establishment, but that almost every location in Lake Erie would be suitable for bigheaded carps. Given, instead, an entry point of bigheaded carps into Lake St. Clair, fishes remained primarily in Lake Erie because of the high abundance of food resources; although, by 20 years, there were visits to lakes Huron and Ontario. Similarly, given an entry point of bigheaded carps into the Great Lakes at the mouth of the Maumee River, models predicted that bigheaded carps would remain primarily in Lake Erie, with some visits to Lake Ontario by 20 years after introduction. Overall, Cooke and Hill (2010) predicted bigheaded carps could swim greater maximum distances in the western basin of Lake Erie without losing biomass than other areas simulated in the Great Lakes. In the western basin, maximum distances that could be traveled were higher in the spring (26.7-33.7 km) than summer (3.9-14.8 km). Predicted maximum distances traveled before beginning to lose mass in the central and eastern basin were similar to those of the western basin in the summer.

Although movement rates of fishes through the Welland Canal have not been studied, this route has resulted in the establishment of fishes from Lake Ontario into Lake Erie (e.g., Sea Lamprey, and White Perch). Preliminary results of a study on the movement of fishes in Welland Canal lock chambers using hydroacoustics, conducted in October 2011, indicated that there were many small and large fishes present (N. Mandrak, unpubl. data) further suggesting that fishes likely move directly through the Welland Canal. Given that bigheaded carps have been documented to move upstream and downstream through lock and dam structures (Brooks et al. 2009), the Welland Canal may slow, but may not curtail, the movement of bigheaded carps between lakes Erie and Ontario.

Based on the analysis of ballast water from lakers presented in Rup et al. (2010), Lake Erie is primarily a donor of inter-lake ballast water throughout the basin (Table 4). Lake Erie is the source of 35-72% of inter-lake ballast for lakes Superior, Huron, and Michigan (Table 9, Figure 12). In addition, 72% of inter-lake ballast received in Lake Erie originates from that same lake (Table 9). The proximity of bigheaded carps to the Lake Erie drainage, the abundance of food resources and suitable habitat for bigheaded carps, and the fact that Lake Erie is a source of much of laker ballast water both within Lake Erie and the other Great Lakes, with western Lake Superior, northern Lake Huron and Lake Erie ports being the destinations receiving the greatest volume (Figure 12), contribute toward the risk of laker ballast for spreading bigheaded carps in the basin. Lake Erie ports receive the fourth greatest amount of lake ballast water, primarily from ports in lakes Huron and Erie (Table 7).

2.4.6.2  Human-mediated Dispersal
Lake Erie and Lake St. Clair ranked, respectively, the second and ninth most popular destinations for Ontario anglers using live baitfishes (Drake 2011). These baitfishes would originate primarily from the Canadian nearshore waters and tributaries of lakes Erie, Huron and Ontario, and secondarily from inland lakes in southern Ontario (Drake 2011).

## 2.4.7  Lake Ontario

2.4.7.1  Natural Dispersal
The only natural dispersal pathway for bigheaded carps to get from the other Great Lakes into Lake Ontario is survival over Niagara Falls. No field study of fish survival (of any life stage) going over Niagara Falls could be located; however, we know of one muskellunge (*Esox masquinongy*) that was tagged above the falls in the Niagara River that was recovered below the falls (K. Kapucinski, SUNY-Syracuse, pers. comm.) and presumably survived going over the falls. Potential survival of any life stage of bigheaded carps over Niagara Falls remains a knowledge gap.

Given an introduction point at the entrance of the CAWS, the Fish Movement Model of Currie et al. (2011) predicted that very few (<2%) bigheaded carps would visit Lake Ontario after 20 years, but those that did would be attracted to sites such as the Genessee River and Bay of Quinte, under the standard swimming rates of 14 cm/s and a 25% influence of lake currents. This percentage is higher, and arrival times are earlier, if fishes swimming speed was greater, or the fishes were more passively transported by lake currents.

Approximately 5% (± 2%) of bigheaded carps were predicted to get to Lake Ontario within 10 years when the starting point was in Lake Erie or Lake St. Clair, using the standard swimming parameters. When the starting point was Montreal, it took more than 5 years for fishes to arrive at Lake Ontario under the same model conditions. Relative to the other Great Lakes, Cooke and Hill (2010) predicted high maximum distances traveled in 30 days without losing biomass in Lake Ontario. They predicted biomass loss would begin in adult Silver Carp before adult Bighead Carp in all three areas of Lake Ontario examined (16-21 km and 26-33 km, respectively).

Although movement rates of fishes through the Welland Canal have not been studied, this pathway has resulted in the establishment of fishes from Lake Ontario into Lake Erie (e.g., Sea Lamprey and White Perch). Preliminary results of a study on the movement of fishes in Welland Canal lock chambers using hydroacoustics, conducted in October 2011, indicated that there were many small and large fishes present (N. Mandrak, unpubl. data) further suggesting that fishes likely move directly through the Welland Canal. Given that bigheaded carps have been documented to move upstream and downstream through lock and dam structures (Brooks et al. 2009), the Welland Canal may not curtail the movement of bigheaded carps between lakes Erie and Ontario.

According to the analysis of ballast water from lakers presented in Rup et al. (2010), Lake Ontario donates almost five times the amount of inter-lake ballast water as it receives (Table 4). Most of the laker ballast from Lake Ontario makes its way to either lakes Erie or Superior, though some is received at other ports within Lake Ontario (Figure 12). About 72% of laker ballast coming into Lake Ontario originated within the lake (Table 9). Lake Ontario ports receive the least amount of lake ballast water from ports in other lakes, primarily from Lake Erie and the St. Lawrence River (Table 9).

2.4.7.2  Human-mediated Dispersal
Lake Ontario was the most popular destination for Ontario anglers using live baitfishes (Drake 2011). These baitfishes would originate primarily from the Canadian nearshore waters and tributaries of lakes Erie, Huron and Ontario, and secondarily from inland lakes in southern Ontario (Drake 2011).

## 2.4.8 Summary of Likelihood of Spread

Based on history of movement of fishes in the Great Lakes, there is evidence that fish move from lake to lake (both upstream and downstream) (Mandrak and Cudmore 2010). Habitat and food are two factors to be taken into consideration regarding fish movement, along with availability of suitable physical routes for movement. As Currie et al. (2011) indicated, there is little incentive for bigheaded carps to move themselves from locations with suitable habitat and sufficient food abundance. For lakes Superior and Ontario, spread to and from these lakes are similar, being at the upstream-most and downstream-most locations, respectively. It is unlikely that spread of bigheaded carps to and from these lakes through dispersal will be strongly limited; however, movement from the central lakes (lakes Michigan, Huron, and Erie) to lakes Superior and Ontario would be limited by the abundant food source and suitable habitat found in those central lakes; there would be little incentive to move from these areas.

Inter-lake ballast water transfer and bait movement between lakes are potential vectors of spread, but likely have low probability of facilitating the movement of bigheaded carps.

For lakes Superior, Michigan, Huron and Erie, likelihood of spread (Table 10) is very likely due to lack of structures preventing movement to and from these lakes; high for Lake Ontario. Certainty for all lakes was high.

*Table 10. Likelihood of spread rankings and certainties for each lake.*

|  | Superior | | Michigan | | Huron | | Erie | | Ontario | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Element** | **Rank** | **Cert** | **Rank** | **Cert** | **Rank** | **Cert** | **Rank** | **Cert** | **Rank** | **Cert** |
| Spread | Very Likely | High | Very Likely | High | Very Likely | High | Very Likely | High | High | High |

## 2.5 SUMMARY OF PROBABILITY OF INTRODUCTION

In summary, the likelihood of arrival, survival, establishment and spread of bigheaded carps within the Great Lakes basin were assessed using the best available information. As the Great Lakes basin is so interconnected, the overall probability of introduction was ascertained by first determining the highest ranking between overall arrival and spread (Table 11), then taking this with the ranks of survival and establishment and using the lowest rank of the three. This is represented by the following formula:

Probability of Introduction = Min [Max (Arrival, Spread), Survival, Establishment]

The certainty associated with the highest rank was used or, if two or more certainties were the same, the certainty associated with the highest rank was used.

Probability of introduction (Table 12) was considered to be very likely for lakes Michigan, Huron, and Erie, high for Lake Ontario, and moderate for Lake Superior, with the level of certainty as high for all lakes, with the exception of Lake Superior (moderate).

*Table 11. Maximum rank of overall arrival and spread (Max(Arrival, Spread)) for each lake.*

| | Superior | | Michigan | | Huron | | Erie | | Ontario | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Element** | **Rank** | **Cert** | **Rank** | **Cert** | **Rank** | **Cert** | **Rank** | **Cert** | **Rank** | **Cert** |
| **Overall Arrival** | Very Unlikely | Mod | Very Likely | High | Low | Low | Low | Mod | Low | Mod |
| **Spread** | Very Likely | High | Very Likely | High | Very Likely | High | Very Likely | High | High | High |
| **Max(Arrival, Spread)** | Very Likely | High | Very Likely | High | Very Likely | High | Very Likely | High | High | High |

*Table 12. Overall probability of introduction rankings and certainties for each lake.*

| | Superior | | Michigan | | Huron | | Erie | | Ontario | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Element** | **Rank** | **Cert** | **Rank** | **Cert** | **Rank** | **Cert** | **Rank** | **Cert** | **Rank** | **Cert** |
| **Max(Arrival, Spread)** | Very Likely | High | Very Likely | High | Very Likely | High | Very Likely | High | High | High |
| **Survival** | Very likely | High | Very Likely | High | Very Likely | High | Very Likely | Very High | Very Likely | High |
| **Establishment** | Mod | Mod | Very Likely | High | Very Likely | High | Very Likely | High | Very Likely | High |
| **P(Intro)=Min [Max(Arrival, Spread), Survival, Establish]** | Mod | Mod | Very Likely | High | Very Likely | High | Very Likely | High | High | High |

# 3.0 MAGNITUDE OF ECOLOGICAL CONSEQUENCES

Kolar et al. (2007) and Kipp et al. (2011) reviewed the effects of bigheaded carps on invaded environments. Bigheaded carps are capable of inducing -dramatic changes in planktonic composition. Plankton is the base of the Great Lakes food web, and changes to plankton composition are likely to have substantial repercussions. A great deal of information is available on effects by Silver Carp, or Silver and Bighead carps in combination, on plankton.  Much less information is available on the effects of Bighead Carp alone. The most common effect of bigheaded carp feeding is a strong decline in crustacean zooplankton populations, even though bigheaded carps are not thought to be primarily crustacean consumers. Kolar et al. (2007) described the methods by which bigheaded carps can have this effect. Bigheaded carps also cause substantial changes in phytoplankton composition. This likely occurs from the removal of larger phytoplankton, which can often lead to an increase in picophytoplankton (0.2-2 μm) and smaller nanophytoplankton (2-20 μm), which are not susceptible to grazing by Silver Carp. Bigheaded carp effects on rotifer abundances have been variable, with some studies showing a decrease in rotifers, but Sass et al. (2010) found an increase in rotifer abundance (possibly due to release from predation by crustacean zooplankton) after the bigheaded carp invasion into the Illinois River.

In the United States, where bigheaded carps are established primarily in large rivers and not in lakes, effects of the bigheaded carp invasion on native species are not fully understood. Effects on populations of fishes are difficult to document in highly dynamic systems such as large rivers. Irons et al. (2007) reported that filter feeding fishes of the Illinois River were lower in condition factor after the bigheaded carp invasion, and Gutreuter et al. (2011) reported that lipids,

especially essential Omega-3 lipids, are reduced in pelagic fishes (but not littoral fishes) in portions of the Mississippi River where bigheaded carps are abundant. Gutreuter et al. (2011) also reported that reproductive success of Sauger and Bigmouth Buffalo declined substantially when Silver Carp were abundant. Such perturbations could be expected to have population effects at some level, but Gutreuter et al. (2011), using long-term monitoring data, did not find population-level effects on resident fishes of the Mississippi and Illinois rivers that could be attributed to the bigheaded carp invasion. Populations of large river fishes are highly dependent on physical variables such as hydrographs, and those variables are likely to mask population-level effects.

In lentic systems, undesirable population-level effects of bigheaded carp introductions on native fishes have often been described in the literature. Effects on native planktivorous fish species are most commonly described (Spataru and Gophen 1985, Natarajan 1988, Wilkonska 1988, Shetty et al. 1989, Costa-Pierce 1992, DeIongh and VanZon 1993, Pavlovskaya 1995, Yang 1996, Li 2001, Li and Xie 2002), but some papers have documented effects beyond planktivores. The International Lake Environment Committee (2001) documented declines in fish diversity after stocking bigheaded carps and Grass Carp. Costa-Pierce (1992) reported that Silver Carp introductions into German lakes caused steep declines in populations of several species with pelagic early life stages, including Zander (*Sander lucioperca*), a close relative of the Walleye. In that study, fishes with littoral early life stages were not affected. Svirsky and Barabanshchikov (2010) noted that at high densities of bigheaded carps in Lake Khanka, Russia, that reproduction of native pelagic fishes whose eggs develop in the water column was limited. If bigheaded carps were to become established with abundant populations in the Great Lakes, they will likely have effects in the lakes similar to the effects that have been documented worldwide.

## 3.1 LAKE SUPERIOR

Consequences of established populations of bigheaded carps are projected to include competition for planktonic food resources, with nearshore, planktivorous fishes in Lake Superior. That competition may result in reduced growth rates, recruitment, and abundance of Cisco (*Coregonus artedi*), Bloater (*Coregonus hoyi*), and Rainbow Smelt in the nearshore habitats of Lake Superior. Thus, those species are at risk to become less abundant and grow more slowly after establishment of bigheaded carp populations in Black Bay, Thunder Bay, Nipigon Bay, Chequamegon Bay, Whitefish Bay, Keweenaw Bay, the western arm of Lake Superior, and other nearshore habitats. Reduced abundance of nearshore, planktivorous forage fishes are projected to result in slower growth, reduced recruitment, and lower abundance of adult piscivores, such as Lake Trout, that rely on planktivorous forage fishes in nearshore habitats (Conner et al. 1993, Bronte et al. 2003).

## 3.2 LAKE MICHIGAN

The food web of Lake Michigan is dominated by pelagic primary production. Since 1995, dreissenid mussels have increased in abundance exponentially, with maximum densities recorded at $19,000/m^2$ in 2008 (Nalepa et al. 2010). Resultant changes in the food web include a reduced spring diatom bloom (Evans et al. 2011), reduced deep chlorophyll layer (Fahnenstiel et al. 2010), substantial reduction of *Diporeia* (Barbiero et al. 2011), and reduced zooplankton abundance (Johannsson et al. 2000). If the potential impacts of bigheaded carps to the offshore of Lake Michigan are similar to those predicted for Lake Ontario (see Section 3.5; Currie et al. 2011), bigheaded carps are likely to establish in the offshore of Lake Michigan, but at uncertain population levels. The resultant impacts to planktivorous fishes can be expected to be generally

similar to those in Lake Ontario (see Section 3.5), with Alewife biomass likely being reduced, with a greater potential for additional top-down reduction of Alewife biomass by the Pacific salmonine-dominated predator community.

In the nearshore waters of Lake Michigan, it could be expected that Green Bay, southern Lake Michigan, and the drowned river mouths of the eastern shoreline would be affected more strongly by bigheaded carps due to the warmer and more productive waters. Bigheaded carp abundance would likely be higher in these areas, with stronger potential for bigheaded carps to spawn successfully in one or more tributaries to these areas using spawning tributary characteristics noted in Kocovsky et al. (2012). Depending on the biomass of bigheaded carps achieved in these waters, there could be negative effects on fish species such as Yellow Perch (*Perca flavescens*) and Lake Whitefish (*Coregonus clupeaformis*). Nearshore populations of Alewife also likely would be strongly negatively affected.

## 3.3 LAKE HURON

Consequences of established populations of bigheaded carps are projected to include competition for planktonic food resources, with the nearshore, planktivorous fishes in Lake Huron. That competition may result in reduced growth rates, recruitment, and abundance of Alewife, Bloater, Cisco, Rainbow Smelt, Yellow Perch, and various centrarchids (*Centrarchidae*) in nearshore habitats of Lake Huron. Thus, forage fish stocks are at risk of becoming less abundant and growing more slowly following the establishment of bigheaded carp populations in Saginaw Bay, Georgian Bay, the southern basin of Lake Huron, and other nearshore habitats. Reduced abundance of nearshore forage fishes are projected to result in slower growth, reduced recruitment, and lower adult abundance of adult Chinook Salmon (*Oncorhynchus tshawytscha*), Walleye, Northern Pike (*Esox lucius*), and Lake Trout stocks that rely on planktivorous forage fishes in nearshore habitats (Diana 1990, Bence et al. 2008).

## 3.4 LAKE ERIE (INCLUDING LAKE ST. CLAIR)

Lakes Erie and St. Clair are the warmest and most eutrophic of the Great Lakes, and they are supplied by rivers such as the Maumee and the Thames, which are possibly the most likely rivers in this system to provide for spawning and recruitment of bigheaded carps (Kocovsky et al. 2012; Mandrak et al. 2011). Three individual Bighead Carp have already been demonstrated to survive and grow rapidly in the western basin of Lake Erie (Morrison et al. 2004). A large population of bigheaded carps would likely have highly detrimental effects on populations of planktivorous fishes and fishes with pelagic early life stages such as Walleye and Yellow Perch. Emerald Shiner (*Notropis atherinoides*), Gizzard Shad (*Dorosoma cepedianum*), Rainbow Smelt, Spottail Shiner (*Notropis hudsonius*), and White Perch are important planktivorous fishes of Lake Erie and Lake St. Clair. These species form the majority of the prey base for pelagic piscivorous fishes, and which would likely decrease in abundance in response to changes in plankton composition resulting from feeding by bigheaded carps.

Many of these planktivorous species are important prey fishes for Lake Trout, Rainbow Trout (*Oncorhynchus mykiss*), Walleye, and Yellow Perch. Loss of prey species would have undesirable effects on growth and survival of predator species, unless juvenile bigheaded carps or other species could replace those prey species in the diet of predators. Juvenile bigheaded carps are not pelagic during the life stages at which they are small enough to be preyed upon by those pelagic predators (Naseka and Bogutskaya 2011, D. Chapman, USGS, pers. comm), and so are unlikely to represent an alternative food source. Bigheaded carps also quickly outgrow the gape size of most native predators in the Great Lakes.

## 3.5 LAKE ONTARIO

The food web of Lake Ontario is dominated by pelagic primary production. Recent food web changes associated with dreissenid mussels have reduced zooplankton production by about half between the period 1987-1991 and 2001-2005 (Stewart et al. 2010). This reduction in zooplankton production is of concern to fishery managers because Alewife, although it can compensate to a degree for this reduced production by feeding more heavily on *Mysis*, may be at greater population risk for overconsumption by salmonines. When considering potential effects of bigheaded carps on the Lake Ontario ecosystem, preliminary food web modeling suggests that these invaders can establish in the offshore foodweb (Currie et al. 2011). Under conditions of low dreissenid mussel biomass, bigheaded carp biomass would increase at the expense of Alewife biomass; whereas, under conditions of high dreissenid biomass, Alewife biomass would not decrease to the same degree. Thus, depending on dreissenid biomass, the establishment of bigheaded carps could reduce Alewife biomass by up to 90%, although the threat to salmonine populations may not be as strong (see Currie et al. 2011).

## 3.6 SUMMARY OF MAGNITUDE OF ECOLOGICAL CONSEQUENCES

In Lake Superior, most significant ecological impacts of bigheaded carps are projected in Thunder Bay, Black Bay, Nipigon Bay, Chequamegon Bay, Keweenaw Bay, Whitefish Bay, the western arm of Lake Superior, and other nearshore habitats because temperature and food resources in those locations are most likely to support high-density populations. In Lake Michigan, current high abundance of dreissenid mussels is projected to result in Alewife biomass likely being reduced, and a greater potential for additional top-down reduction of Alewife biomass by the Pacific salmonine-dominated predator community. Fish species in the nearshore waters of Lake Michigan could be exposed to negative effects considering the high establishment potential in these areas. In Lake Huron, most significant impacts are projected for Saginaw Bay, Georgian Bay, the southern basin of Lake Huron, and other nearshore habitats because temperature and food resources in those locations are most likely to support high-density populations. In these two Great Lakes, initial impacts are projected to result in reductions in abundance of nearshore, planktivorous forage fishes. Those reductions are subsequently projected to result in slower growth, reduced recruitment, and lower abundance of adult Lake Trout that rely on planktivorous forage fishes in nearshore habitats. In lakes Erie and St. Clair, a large population of bigheaded carps would likely have highly detrimental effects on populations of planktivorous fishes and fishes with pelagic early life stages. Loss of prey species would have undesirable effects on growth and survival of predator species, unless juvenile bigheaded carps or other species could replace those prey species in the diet of predators. In Lake Ontario, the impact of bigheaded carps depends on dreissenid biomass. If such establishment happens, Alewife biomass could be reduced by up to 90%. However, the threat to salmonine populations may not be as strong.

Overall, with no new additional prevention or management actions, the magnitude of ecological consequences of a bigheaded carp invasion in the Great Lakes was ranked as moderate for all lakes over a period of 20 years, with the exception of Lake Superior (low) (Table 13). This suggests a similar invasion process as what has occurred within the Mississippi River basin where the consequences of this invasion that started two decades ago is reaching higher levels. Within 50 years, the magnitude of consequences will be high for all lakes. Certainty for all lakes in both times periods was ranked as moderate.

*Table 13. Magnitude of the ecological impacts and certainties to each lake within a 20-year and a 50-year timeframe.*

| Element | Superior Rank | Superior Cert | Michigan Rank | Michigan Cert | Huron Rank | Huron Cert | Erie Rank | Erie Cert | Ontario Rank | Ontario Cert |
|---|---|---|---|---|---|---|---|---|---|---|
| ~20 years | Low | Mod | Mod | Mod | Mod | Mod | Mod | Mod | Mod | Mod |
| ~50 years | Mod | Mod | High | Mod | High | Mod | High | Mod | High | Mod |

# 4.0 OVERALL RISK ASSESSMENT

As noted in Section 1.1, the overall probability of introduction (Section 2.5) and the magnitude of the ecological consequences (Section 3.6) were combined to obtain a final risk and was completed for each lake taking into account both a 20 year (Figure 13a) and 50 year (Figure 13b) timeframe.

# 5.0 CONSIDERATIONS

Risk assessments are based on best available information, and should identify knowledge gaps and uncertainties. These knowledge gaps and uncertainties can be reduced through further research. Prioritized knowledge gaps were compiled by the authors and the peer review participants and can be found in the proceedings of the peer review (DFO 2012a). Key areas of uncertainty (where certainty was ranked very low to low) identified in this risk assessment are:
- human-mediated releases into all lakes. This is a key area of uncertainty where more information and data would strengthen the advice surrounding arrival from this potential entry route; and,
- overall arrival into Lake Huron.

Risk analysis is composed of risk assessment, risk management, and risk communication (Mandrak et al. 2012). This risk assessment might be helpful as future mitigation plans for bigheaded carps are developed.  The results of the risk assessment will be communicated with the public, resource managers, and decision makers in both countries.

Bighead and Silver carps are only two of four Asian carp species that currently threaten the Great Lakes basin. Due to time and resource constraints, Grass Carp and Black Carp were not be included in this targeted risk assessment. A binational risk assessment, following a similar process for the bigheaded carps, could be conducted for Grass and Black carps focusing on the Great Lakes.
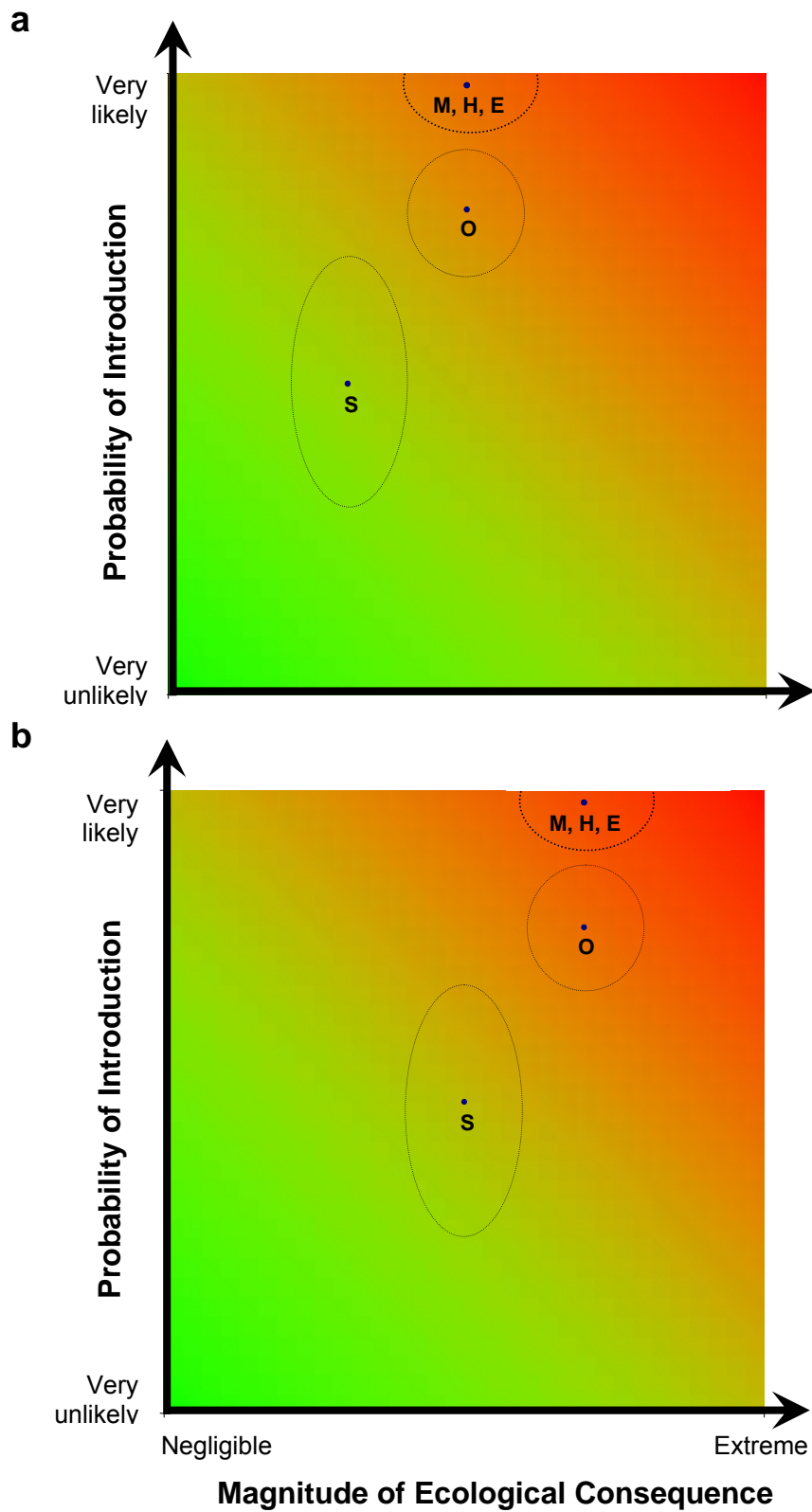
*Figure 13. Probability of introduction and magnitude of the ecological consequences over a) 20 years and b) 50 years as a graphic representation to communicate risk. S=Lake Superior, M=Lake Michigan, H=Lake Huron, E=Lake Erie, O=Lake Ontario; ellipses are representative of amount of certainty around rank.*

Aquatic invasions can be considered natural disasters (Ricciardi et al. 2011).  The further into the invasion process (pre-arrival, arrival, survival, establishment, or spread), the more difficult and costly it is to halt or manage (Leung et al. 2002).  Preventing arrival is therefore the most feasible and effective management effort that can be taken (Mack et al. 2000, Leung et al. 2002).  As time passes, bigheaded carps continue moving toward the Great Lakes and the time to prevent their arrival shrinks. Therefore, activities that specifically target pre-arrival, such as some of those being implemented by the Asian Carp Regional Coordinating Committee in the United States, continue to be important (see ARCC 2011 and ARCC-MRRWG 2011 for complete descriptions).  Likewise, given that the number of individuals entering an ecosystem (i.e., propagule pressure) is paramount to establishment (Lockwood et al. 2005) and that prompt removal of initial individuals detected from a system is key to effective control (Simberloff 2010), additional actions targeting arrival, survival, establishment, and spread provide additional opportunities to interrupt the invasion process (on-going efforts in the US described in ARCC 2011 and ARCC-MRRWG 2011).

There is an expected time lag associated with seeing the full consequences of an established population of bigheaded carps in the Great Lakes, however, this should not be interpreted that there is time to wait before acting. The opportunity to prevent these predicted consequences may not persist. Management options exist and are ongoing in the United States, and further research can be conducted, to interrupt the trajectory to minimize the risk predicted within this assessment. We can, with effective prevention and control actions, continue to delay when these consequences would occur if bigheaded carps became established in the Great Lakes. This delay will provide time to conduct further research into eradication and control options, as well as minimize and postpone overall costs of high control and management efforts, and costs associated with impacts.


## 6.0 TARGETTED MANAGEMENT QUESTIONS


At three workshops (November 2010, May 2011, and June 2011) held for managers and decision-makers around the Great Lakes from both sides of the border, specific management questions were compiled. These questions represent the key information needs by managers and decision-makers to be supported from this risk assessment. The summary of advice to these questions stemming from this risk assessment is presented in Table 14 and was not developed by the authors for review, but rather by consensus at the peer review meeting.

*Table 14. Summary of advice to management questions presented by Great Lakes managers and decisions makers and location within the risk assessment where the advice can be found.*

| Management Question | Summary of Answer |
|---|---|
| How risky are the various points of arrival? | In general, the physical connections represent higher likelihood than human-mediated releases; however, there is much lower certainty associated with the ranks of human-mediated releases. The highest likelihood of arrival into the basin is from the CAWS into Lake Michigan. |
| How effective is the barrier? | A detailed evaluation of the effectiveness of the electric dispersal barrier was not conducted in this risk assessment. |
| Are the Great Lakes too cold? | No. |
| Are the right environmental conditions available? | Yes. |
| Is there enough food and where? | Yes. There is enough food, especially in Green Bay, Saginaw Bay, Lake St. Clair, and Lake Erie. Warm embayments in lakes Superior and Ontario should also provide suitable amounts of food. |
| What number of individuals is needed to establish a population? | Modeling suggests that under ideal conditions (assuming fish locate suitable rivers, a low spawning failure rate, and that sexual maturity is reached at 3 years of age), as few as 10 mature females and 10 mature males in the basin of a single Great Lake have a greater than 50% chance of successfully spawning (Currie et al. 2011). |
| What is the potential biomass? | Bigheaded carps have the potential to become a dominant biomass in favourable locations. |
| Where will they be most abundant? | Lake Erie, including Lake St. Clair, and high productivity embayments of lakes Superior, Michigan, Huron and Ontario. |
| What characteristics make for suitable spawning tributaries? | Some general knowledge exists on the characteristics of suitable spawning tributaries; however, specific characteristics are identified as a critical knowledge gap within this risk assessment. |
| What/how many tributaries would support spawning and recruitment? | Suitable spawning tributaries are found in all lakes.<br><br>**United States:** 21 suitable spawning tributaries in the American Great Lakes basin are unimpounded from mouth to at least 100km upstream. More detailed analyses of tributary characteristics for Lake Erie suggest that 3 out of 8 tributaries examined could provide suitable spawning habitat and that 4 others appeared moderately suitable (Kocovsky et al. 2012).<br><br>**Canada:** 41 suitable spawning rivers in the Canadian Great Lakes basin are unimpounded from mouth to at least 100km upstream. More detailed analyses of tributary characteristics suggest that suitable spawning conditions exist in at least 49 Canadian Great Lake tributaries (Mandrak et al. 2011). |
| Could they spawn directly in the Great Lakes? | This is identified as a critical knowledge gap within the risk assessment. See the proceedings document from the peer review meeting (DFO 2012a) for a list of prioritized (by consensus of the peer review participants) knowledge gaps. |
| What is the timeframe and direction of spread? | Varies depending on arrival point within the basin, but predicted to be less than 10 years with direction likely Michigan to Huron to Erie. |
| How long before they | Less than 5 years after arrival into the connected Great Lakes |

| reach Canadian waters? | basin via Lake Michigan. |
|---|---|
| What level of population would be an acceptable level of risk/impact? | This is outside the scope of this risk assessment. |
| What are the impacts to recruitment – food, behavioural disruption? | Recruitment of fishes with pelagic early life stages are expected to decline. Mechanisms are unclear. |
| Will a fishery be lost? Loss of diversity, richness or production? | Fish community responses would be variable and difficult to predict. Accordingly, impact on fisheries are difficult to predict and outside the scope of this risk assessment. |
| Is there a variation of impacts with variation in abundance levels of bigheaded carps? | Yes. Higher abundance of bigheaded carps would lead to greater ecological consequences. |
| Will there be a cumulative impact of two more planktivorous invaders? | Different changes in plankton communities are predicted than have been seen with planktivores that have previously invaded the Great Lakes. Cumulative impacts are difficult to predict. |
| Need links of ecological impacts to use for socio-economic uses and activities | Select qualitative consequences have been identified; some specific quantitative information could not be completed within this risk assessment timeframe. |
| What is the timeframe of risk for each element? | Beyond current efforts underway, if no additional management actions around the entire basin are taken:<br>▪ Arrival – impending;<br>▪ Survival – immediate upon arrival;<br>▪ Establishment – 5 to 20 years (short in southern basin, longer in Lake Superior);<br>▪ Spread – 5 to 20 years; and,<br>▪ Consequences – will build over time. |
| What are the confounding issues? | Question is too broad to provide meaningful advice. |
| Where are the most vulnerable areas? | Lake Erie, including Lake St. Clair, and high productivity embayments of lakes Superior, Michigan, Huron (including the Huron-Erie corridor), and Ontario. Overlap of identified spawning tributaries and potential points of arrival. |
| Help inform rapid response? | See above points of arrival, abundant areas, spawning tributaries, and vulnerable areas. |
| What are some mitigation options? | A discussion of mitigation options is outside the scope of this risk assessment; however, potential entry routes have been identified to inform prevention activities. |

# 7.0 REFERENCES

Abdusamadov, A. S. (1987). "Biology of white amur, *Ctenopharyngodon idella* silver carp, *Hypophthalmichthys molitrix*, and bighead, *Aristichthys nobilis*, acclimatized in the Terek Region of the Caspian Basin." Journal of Ichthyology 26: 41-4

Aliev, D.S. 1976. The role of phytophagous fish in the reconstruction of commercial ichthyofauna and biological melioration of water reservoirs. Journal of Ichthyology 162:216.

Anwand, K., Kozianowski, A. 1987. Stocking experiments with herbivorous carps in natural lakes. Z. BINNENFISCH. DDR. 34: 342-355.

Asian Carp Regional Coordinating Committee (ARCC). 2011. Asian carp control strategy framework. 63 pp.

Asian Carp Regional Coordinating Committee - Monitoring and Rapid Response Workgroup (ARCC-MRRWG). 2011. Monitoring and rapid response for Asian carp in the Upper Illinois River and Chicago Area Waterway System. 111 pp.

Asian Carp Working Group. 2007. Management and control plan for bighead, black, grass, and silver carps in the United States. Aquatic Nuisance Species Task Force, Arlington, VA (http://anstaskforce.gov/control.php; accessed September 22, 2011).

Bardach, J.E., Ryther, J.H., and McLarney, W.O. 1972. Aquaculture: the farming and husbandry of freshwater and marine organisms. Wiley-Interscience, New York. 868 p.

Barbiero, R.P., Schmude, K., Lesht, B.M., Riseng, C.M., Warren, G.J., and Tuchman M.L. 2011. Trends in *Diporeia* populations across the Laurentian Great Lakes, 1997-2009. J. Great Lakes Res. 37: 9-17.

Battelle Memorial Institute. 2010. Revised final independent external peer review report environmental DNA (eDNA) science and methodology. Prepared for U.S. Army Coprs of Engineers, Rock Island District. Contract #W911NF-07-D-0001. 19 p.

Beletsky, D., Mason, D.M., Schwab, D.J., Rutherford, E.S., Janssen, J., Clapp, D.F., and Dettmers, J.M. 2007. Biophysical model of larval yellow perch advection and settlement in Lake Michigan. J. Great Lakes Res. 33(4): 842-866.

Bence, J. R., Dobiesz, N.E., Madenjian, C.P., Argyle, R., Barbiero, R., Bowlby, J.N., Claramunt, R.M., O'Gorman, R., and Schaner, T. 2008. Top-down effects of open-water salmonine predators in the Great Lakes. Michigan State University, Quantitative Fisheries Center Technical Report T2008-07, East Lansing, MI.

Berday, N., Zaoui, D., Lamrini, A., and Abi, M. 2005. Impact of feeding activity of silver carp on plankton removal from a high-rate pond effluent. Water Qual. Res. J. Canada. 40: 191-201.

Bradford, M.J., Tovey, C.P., and Herborg, L.M. 2008. Biological risk assessment for yellow perch (*Perca flavescens*) in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc 2008/073: vi + 21 p.

Bronte, C.R., Ebener, M.P., Schreiner, D.R, DeVault, D.S., Petzold, M., Jensen, D.A., Richards, C., and Lozano, S.J. 2003. Fish community change in Lake Superior, 1970-2000. Can. J. Fish. Aquat. Sci. 60: 1552-1574.

Brooks, R.C., Garvey, J.E., Hill, M., Tripp, S.J., and Calkins, H.A. 2009. Fish passage in the Upper Mississippi River system, Fisheries and Illinois Aquaculture Center, Southern Illinois University, Carbondale, IL.

Calkins, H.A., Tripp, S.J., and J.E. Garvey. 2011. Linking silver carp habitat selection to flow and phytoplankton in the Mississippi River. Biol. Inv. p. 1-10.

Chapman, D.C., and George, A.E. 2011. Developmental rate and behavior of early life stages of bighead carp and silver carp, U.S. Geological Survey Scientific Investigations Report 2011-5076.

Chapman, D.C. and Hoff, M.H. (eds). 2011. Invasive Asian carps in North America. Am. Fish. Soc. Symp. 74. Bethesda. MD.

Chen, S., and Liu, X. 1989. Study on the digestion and utilization of fish feces by Silver Carp and Bighead Fingerlings. Acta Hydro. Sin. 13: 250-259.

Conner, D.J., Bronte, C.R., Selgeby, J.H., and Collins, H.L. 1993. Food of salmonine predators in Lake Superior 1981-87. Great Lakes Fish. Comm. Tech. Rep. 59, Ann Arbor, MI.

Cooke, S.L. and Hill, W.R. 2010. Can filter-feeding Asian carp invade the Laurentian Great Lakes? A bioenergetic modelling exercise. Freshw. Biol. 55: 2138-2152.

Costa-Pierce, B.A. 1992. Multiple regression analysis of plankton and water quality relationships as affected by sewage inputs and cage aquaculture in a eutrophic, tropical reservoir, *In* Reservoir Fisheries of Asia. *Edited by* S. De Silva. International Development Research Centre (IDRC), Ottawa, Canada. p. 38-48.

Cremer, M.C. and Smitherman, R.O.1980. Food habits and growth of silver and bighead carp in cages and ponds. Aquaculture. 20: 57-64.

Crossman, E.J., and Cudmore, B.C. 1999a. Summary of fishes intentionally introduced in North America, *In* Nonindigenous Freshwater Organisms: Vectors, Biology, and Impacts. *Edited by* Claudi, R., and J.H., Leach. Lewis Publishers. Boca Raton. Florida. p. 99-112.

Crossman, E.J., and Cudmore, B.C. 1999b. Summary of North American introductions of fish through aquaculture vector and related human activities, *In* Nonindigenous Freshwater Organisms: Vectors, Biology, and Impacts. *Edited by* Claudi, R., and J.H., Leach. Lewis Publishers. Boca Raton. Florida. p. 297-303.

Cudmore, B., and Mandrak, N.E. 2011. Assessing the biological risk of Asian carps to Canada. *In* Invasive Asian carps in North America. *Edited by* Chapman, D.C. and Hoff, M.H. Am. Fish. Soc. Symp. 74. Bethesda. MD. p. 15-30.

Currie, W.J.S., Cuddington, K., Stewart, T.J., Zhang, H., and Koops, M.A. 2011. Modelling spread, establishment and impact of Bighead and Silver carps in the Great Lakes. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/113: vii + 71 p.

Darling, J.A., and Mahon, A.R. 2011. From molecules to management: adopting DNA-based methods for monitoring biological invasions in aquatic environments. Environ. Res., doi:10.1016/j.envres.2011.02.001.

DeGrandchamp, K.L., Garvey, J.E., and Colombo, R.E. 2008. Movement and habitat selection by invasive Asian carps in a large river. Trans. Am. Fish. Soc. 137: 45-56.

DeLongh, H.H., and VanZon, J.C.J. 1993. Assessment of impact of the introduction of exotic fish species in north-east Thailand. Aquac. Res. 24: 279-289.

Dextrase, A.J., and MacKay, B. 1999. Evaluating the effectiveness of aquatic nuisance species outreach materials in Ontario. Abstracts from the 9th International Zebra Mussel and Aquatic Nuisance Species Conference. Duluth, Minnesota, 26-30 April 1999. The Professional Edge, Ottawa, Ontario. p. 103.

Dextrase, A.J., and Mandrak, N.E. 2006. Impacts of alien invasive species on freshwater fauna at risk in Canada. Biol. Inv. 8: 13-24.

DFO. 2012a. Proceedings of the CSAS peer review of the binational ecological risk assessment of bigheaded carps (*Hypophthalmichthys* spp.) for the Great Lakes basin; November 8-10, 2011. DFO Can. Sci. Advis. Sec. Proceed. Ser. 2011/060.

DFO. 2012b. Binational ecological risk assessment of the bigheaded carps (*Hypophthalmichthys* spp.) for the Great Lakes basin. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2011/071.

Diana, J.S. 1990. Food habits of angler-caught salmonines in western Lake Huron. J. Great Lakes Res. 16: 271-278.

Drake, D.A.R. 2011. Quantifying the likelihood of human-mediated movements of species and pathogens: the baitfish pathway in Ontario as a model system. Thesis (PhD), Department of Ecology and Evolutionary Biology, University of Toronto. 295 p.

Drake, D.A.R., and Mandrak, N.E. 2010. Least-cost transportation networks predict spatial interaction of invasion vectors. Ecol. Appl. 20: 2286-2299.

Engle, C.R., and Brown, D.W. 1999. Growth, Yield, Dressout, and net returns of Bighead Carp *Hypophthalmichthys nobilis* stocked at three densities in fertilized earthen ponds. Journal of the World Aquac. Soc. 30: 371-379.

Ernat, D.R., Phelps, Q.E., and Whitledge, G.W. 2010. Stable isotope indicators of population structure and natal habitats of Asian carps threatening to invade the Great Lakes, Fisheries and Illinois Aquaculture Center. Southern Illinois University, Carbondale. IL. (http://opensiuc.lib.siu.edu/reach_posters/7; accessed September 2010).

Evans, M.A., Fahnenstiel, G., and Scavia, D. 2011. Incidental oligotrophication of North American Great Lakes. Environ. Sci. Technol. 45: 3297-3303.

Fahnenstiel, G., Pothoven, S., Vanderploeg, H., Klarer, D., Nalepa, T., and Scavia, D. 2010. Recent changes in primary production and phytoplankton in the offshore region of southeastern Lake Michigan. J. Great Lakes Res. 36: 20-29.

Gorbach E.I., Krykhtin M.L. 1980. Optimal parameters of the main factors determing maturation and reproduction of grass carp and silver carp in the Amur. pp. 152-154 *In:* Kamilov G.K. (Ed.). *Phytophagous fishes in industrial fish culture. Book of Abstracts of the 9th All-Union Conference.* [Rastitel'noyadnye ryby v promyshkennom rybovodstve. Tezisy dokladov IX Vsesoyuznogo Soveshchaniya.] Izdatel'stvo AN USSR, Tashkent. (in Russian)

Gorbach E.I., Krykhtin M.L. 1981. Rate of maturation in grass carp *Ctenopharyngodon idella* (Val.) and silver carp *Hypophthalmichthys molitrix* (Val.) in Amur River. J.of Ichthy. 21(5): 835-843. (in Russian)

Great Lakes and Mississippi River InterBasin Study (GLMRIS). 2011. (http://glmris.anl.gov/documents/index.cfm; accessed October 24, 2011).

Gutreuter, S., Vallazza, J.M., Knights, B.C., Bartsch, M.R., Bartsch, L.A., and Richardson, W.B. 2011. Early evidence of effects of invasive Asian carps on selected fishes of the Upper Mississippi River system. Project completion report to the U.S. Fish and Wildlife Service. Project number 3210APN11. 107 p.

Hebert, P.D.N., B.W. Muncaster and G.L. Mackie. 1989. Ecological and genetic studies on *Dreissena polyrnorpha* (Paltas): a new mollusc in the Great Lakes. Can. J. Fish. Aquat. Sci. 46: 587-1591.

Heilprin, D., Main, T., Herring, P. 2011. Water Transport during Normal Operations of Towboats and Barges in the Illinois River. United States Environmental Protection Agency. Technical Report Documentation Report# CG-D-08-11. 40p.

Herborg, L-M., Mandrak, N.E., Cudmore, B., and MacIsacc, H.J. 2007. Comparative distribution and invasion risk of snakehead and Asian carp species in North America. Can. J. Fish. Aquat. Sci. 64: 1723-1735.

Hedges, K.J, Mandrak, N.E., Koops, M.A., and Johannsson, O.E. 2011. Great Lakes aquatic protected areas. White paper for the Great Lakes Fishery Commission. Ann Arbor, MI. 57 p.

Hoff, M.H., Pegg, M.A., and Irons, K.S. 2011. Management implications from a stock-recruit model for Bighead Carp in portions of the Illinois and Mississippi rivers, *In* Invasive Asian Carps in North America. *Edited by* Chapman, D.C., and Hoff, M.H. Am. Fish. Soc. Spec. Symp. 74. Bethesda. MD. p. 5-14

Holliman, F.M. 2011. Operational protocols for electric barriers on the Chicago Sanitary and Ship Canal: influence of electrical characteristics, water conductivity, fish behavior, and water velocity on risk for breach by small silver and bighead carp. Final Report to U.S. Army Corps of Engineers.

Holm, E., Burridge, M., and Mandrak, N.E. 2009. The ROM Field Guide to the Freshwater Fishes of Ontario. Royal Ontario Museum, Toronto. 462 p.

Ibrahim, K.A., and McCorquodale, J.A.. 1985. Finite element circulation model for Lake Erie. J. Great Lakes Res. 11(3):208-222.

Illinois Department of Natural Resources (ILDNR). 2010. 2010 Illinois fishing information. Illinois Department of Natural Resources. 71 p.

Indiana Department of Natural Resources (IDNR). 2011. 2011 Indiana fishing regulations. Indiana Department of Natural Resources. 6 p.

Irons, K.S., Sass, G.G., McClelland, M.A., O'Hara, T.M. 2011. Bigheaded carp invasion of the La Grange Reach of the Illinois River: insights from the long term resource monitoring program. Am. Fish. Soc. Symp. 74:31-50.

Irons, K.S., Sass, G.G, Mcclelland, M.A. and Stafford, J.D. 2007. Reduced condition factor of two native fish species coincident with invasion of non-native Asian carps in the Illinois River, USA - Is this evidence for competition and reduced fitness? J. Fish Biol. 71: 258-273.

International Lake Environment, Committee. 2001. World lake database (http://www.ilec.or.jp/database/database.html.; accessed October 24, 2011).

Jerde, C.L., Mahon, A.R., Chadderton, W.L., and Lodge, D.M. 2011. "Sight-unseen" detection of rare aquatic species using environmental DNA. Conservation Letters 4: 150-157.

Jerde CL, Bundy ML, Barnes MA, Mahon AR, Galaska MP, Deines JM, Chadderton WL, and Lodge DM.  2012. Environmental DNA surveillance of the Chicago area bait trade for juvenile bighead and silver carp contamination. Final report to the Illinois Department of Natural Resources. Great Lakes Protection Fund. 36pp.

Johansson, O, Dermott, R., Graham, D.M., Dahl, J., Millard, E.S., Myles, D., and LeBlanc, J. 2000. Benthic and pelagic secondary production in Lake Erie after the invasion of dreissenid spp. with implications for fish production. J. Great Lakes Res. 26: 31-54.

Kelly, A.M., Engle, C.R., Armstrong, M.L., Freeze, M., and Mitchell, A.J. 2011. History of introductions and governmental involvement in promoting the use of Grass, Silver, and Bighead Carps, *In* Invasive Asian Carps in North America. *Edited by* Chapman, D.C., and Hoff, M.H. Am. Fish. Soc. Spec. Symp. 74. Bethesda. MD. p. 163-174.

Kipp, R., Cudmore, B., and Mandrak, N.E. 2011. Updated (2006-early 2011) biological synopsis of Bighead Carp (*Hypophthalmichthys nobilis*) and Silver Carp (*H. molitrix*). Can. Manuscr. Rep. Fish. Aquat. Sci. 2962: vi + 50 p.

Knights, B.C., Wlosinski, J.H., Kala, J.A., and Bailey, S.W. 2003. Upstream fish-passage opportunities at Ohio River mainstem dams. Completion report for the U.S. Army Corps of Engineers, Nashville District. U.S. Geological Survey, Upper Midwest Environmental Sciences Center, La Cross, Wisconsin. 96 p.

Kocovsky, P.M., D.C.Chapman., and McKenna, J.E. 2012. Thermal and hydrologic suitability of Lake Erie and its major tributaries for spawning of Asian carps. J. Great Lakes Res. 38(1): 159-166.

Kolar, C.S., Chapman, D.C, Courtenay, W.R., Housel Jr., C.R., Williams, J.D., and Jennings, D.P. 2007. Bigheaded carps: a biological synopsis and environmental risk assessment. Am. Fish. Soc. Spec. Publ. 33. Bethesda. MD.

Konagaya, T., and Cai, Q.H. 1989. Telemetering of the swimming movements of silver and bighead carp in Lake Donghu in summer. Nipp. Suis. Gakk. 55: 1139-1144.

Krykhtin, M.L., and Gorbach, E.I. 1981. Reproductive ecology of the Grass Carp, *Ctenopharyngodon idella*, and the Silver Carp, *Hypophthalmichthys molitrix*, in the Amur Basin. J. Ichthy. 21: 109-123.

Kryzanovskiy, S.G., A.I. Smirnov, and S.G. Soin. 1951. Data on development of fishes in the Amur River. *In* G.V. Nikol'skiy (Ed.). Proceedings of the Amur Ichthyological Expedition in 1945-1949. Vol. 2, pp. 5-233.

Kulwicki, M.M., Rosenthal, S.K., and Lodge, D.M. 2003. Aquatic nuisance species awareness of anglers in northern Wisconsin and the upper peninsula of Michigan. Abstracts from the 12th International Conference on Aquatic Invasive Species. Windsor, Ontario, 9-12 June 2003. The Professional Edge, Ottawa, Ontario. p. 129.

Lazareva, L.P., Omarov, M.O., and Lezina, A.N. 1977. Feeding and growth of the bighead, *Aristichthys nobilis*, in the waters of Dagestan. J. Ichthy. 17: 65-71.

León1, L.F. Imberger, J., Smith, R.E.H., Hecky, R.E., Lam, D.C.L., and Schertzer, W.M. 2005 Modeling as a tool for nutrient management in Lake Erie: a hydrodynamics study. J. Great Lakes Res. 31(Suppl. 2):309–318.

Leung, B., Lodge, D.M., Finnoff, D., Shogren, J.F., Lewis, M.A., Lamberti, G. 2002. An ounce of prevention or a pound of cure, bioeconomic risk analysis of invasive species. Proc. R. Soc. Lond. B 269:2407-2413.

Li, S. 2001. The impact of large reservoirs on fish biodiversity and fisheries in China, *In* Reservoir and culture-based fisheries: biology and management. *Edited by* S. De Silva. Proceedings of an International Workshop, February 15-18, 2000, Bangkok, Thailand. Australian Centre for International Agriculture Research, Canberra. p. 22-28.

Li, Z-Y., and Xie, Y. (eds). 2002. Invasive alien species in China. China Forestry Publishing House, China. 211 p.

Light, T., and Marchetti, M.P. 2007. Distinguishing between invasions and habitat changes as drivers of diversity loss among California's freshwater fishes. Cons. Biol. 21: 434-446.

Lin, W.L., Liu, X.Z., and Liu, J.K. 1981. Detritus Formation of Two Plankters and Query on the Role of Their Detritus in the Nutrition of the Silver Carp and Bighead. Proc. Int. Assoc. Theor. Appl. Limnol. 21.

Litvak, M.K., and Mandrak, N.E. 1993. Ecology of freshwater baitfish use in Canada and the United States. Fisheries. 18: 6-13.

Litvak, M.K., and Mandrak, N.E. 1999. Baitfish trade as a vector of aquatic introductions, *In* Nonindigenous Freshwater Organisms: Vectors, Biology, and Impacts. *Edited by* Claudi, R., and J.H., Leach. Lewis Publishers. Boca Raton, Florida. p. 163-180.

Lockwood, J.L., P. Cassey, and T. Blackburn. 2005. The role of propagule pressure in explaining species invasions. Trends in Ecology and Evolution 20:223-228.

Maceina, M.J., Slipke, J.W., and Grizzle, J.M. 2011. Effectiveness of three barrier types for confining grass carp in embayments of Lake Seminole, Georgia. N.A. J. Fish. Mangagm. 19: 968-976.

Mack, R.N., Simberloff, D., Lonsdale, W.M., Evans, H., Clout, M., Bazzaz, F.A. 2000. Biotic invasions: causes, epidemiology, global consequences, and control. Ecol. Appl. 10:689-710.

Mandrak, N.E. 2009. Fish fauna of Lake Superior: past, present and future, *In* State of Lake Superior: Health, Integrity & Management, Ecovision World Monograph Series, *Edited by* Munawar, M. and I.F. Munawar. 2009. Backhuys Publ., Leiden, The Netherlands, p. 645-663.

Mandrak, N.E., and Cudmore, B. 2004. Risk assessment for Asian carps in Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2004/103. ii + 48 p.

Mandrak, N.E., and Cudmore, B. 2010. The fall of native fishes and the rise of non-native fishes in the Great Lakes Basin. Aquat. Ecosyst. Health Manage. 13: 255-268.

Mandrak, N.E., Cudmore, B and Chapman, P.M. 2012. National Detailed-Level Risk Assessment Guidelines: Assessing the Biological Risk of Aquatic Invasive Species in Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/092. vi + 15 p.

Mandrak, N.E., Grafe, S., Lewin, A., and Hunter, P. 2011. Preliminary assessment of the suitability of Canadian Great Lakes tributaries for Asian carp spawning. Can. Manuscr. Rep. Fish. Aquat. Sci. 2965: vi + 44 p.

Michigan Department of Natural Resources (MDNR). 2011. 2011 Michigan fishing guide. Michigan Department of Natural Resources. 40 p.

Minnesota Department of Natural Resources (MNDNR). 2011. Minnesota fishing regulations 2011. Minnesota Department of Natural Resources. 82 p.

Morrison, B.J., Casselman, J.C., Johnson, T.B., and Noakes, D.L. 2004. New Asian carp genus (*Hypophthalmichthys*) in Lake Erie. Fisheries. 29: 6-7.

Moy, P.B., Polls, I., and Dettmers, J.M. 2011. The Chicago Sanitary and Ship Canal aquatic nuisance species dispersal barrier. Am. Fish. Soc. Symp. 74: 121-137.

Moyle, P.B., and Light, T. 1996. Biological invasions of freshwater, empirical rules and assembly theory. Biol. Cons. 78: 149-161.

Nalepa, T.F., Fanslow, D.L., and Pothoven, S.A. 2010. Recent changes in density, biomass, recruitment, size structure, and nutritional state of *Dreissena* populations in southern Lake Michigan. J. Great Lakes Res. 36: 5-19.

Naseka, A. and Bogutskaya, N. 2011. Annotated bibliography of Bighead (*Hypophthalmichthys nobilis*) and Silver (*Hypophthalmichthys molitrix*) carps from Russian-Language literature. Can. Manuscr. Rep. Fish. Aquat. Sci. 2964: vi + 76 p.

Natarajan, A.V. 1988. Ecological and aquacultural roles of exotic fishes in aquatic productivity in India-a risk benefit analysis, *In* Exotic aquatic species in India. *Edited by* Mohan Joseph, M. Proceedings of the workshop on exotic aquatic species in India 25–26 April, 1988. Asian Fish. Soc. Spec. Publ.1, Mangalore, India. p. 11-17.

New York Department of Environmental Conservation (NYDEC). 2011. New York freshwater fishing 2010 – 2011 regulations guide. New York Department of Environmental Conservation. 3: 1-76.

Nico, L.G., Williams, J.D., and Jelks, H.L. 2005. Black Carp: biological synopsis and risk assessment of an introduced fish. Am. Fish. Soc. Spec. Publ. 32. Bethesda. MD.

Nico, L.G., and Jelks, H.L. 2011. The Black Carp in North America, *In* Invasive Asian carps in North America. *Edited by* Chapman, D.C., and Hoff, M.H. Am. Fish. Soc. Spec. Symp. 74. Bethesda. MD. p. 89-104.

Nuevo, M., Sheehan, R.J., and Wills, P.S. 2004. Age and growth of the bighead carp *Hypophthalmichthys nobilis* (Richardson 1845) in the middle Mississippi River. Arch. Hydrogiologia. 160: 215-230.

Ohio Department of Natural Resources (ODNR). 2011. Fish bait collection regulations (http://www.dnr.state.oh.us/Default.aspx?tabid=18644; accessed September, 2011).

Ontario Ministry of Natural Resources (OMNR). 2011. Ontario recreational fishing regulations summary. Ontario Ministry of Natural Resources. 104 p.

Papoulias, D. M., D. C. Chapman, and D.E. Tillit. 2006. "Reproductive condition and occurrence of intrasex in bighead carp and silver carp in the Missouri River." Hydrobiologia 571: 355-360.

Pavlovskaya, L.P. 1995. Fishery in the lower Amu-Darya under the impact of irrigated agriculture. FAO Fisheries Circular. 894. Rome, FAO. p. 42-57.

Pegg, M.A., Bettoli, P.W., and Layzer, J.B. 1997. Movement of saugers in the Lower Tennessee River determined by radio telemetry, and implications for management. N.A. J. Fish. Managem. 17: 763-768.

Pennsylvania Fish and Boat Commission (PFBC). 2011. 2011 Pennsylvania fishing summary: summary of fishing regulations and laws. Pennsylvania Fish and Boat Commission. 41 p.

Peters, L.M., Pegg, M.A., and Reinhardt, U.G. 2006. Movements of adult radio-tagged Bighead Carp in the Illinois River. Trans. Am. Fish. Soc. 135: 1205-1212.

Rahel, F.J. 2002. Homogenization of freshwater faunas. Ann. Rev. Ecol. Syst. 33: 291-315.

Ressources naturelles et faune Québec. 2011. Sport fishing in Québec 2011. Gouvernement du Québec. 135 p.

Ricciardi, A., Palmer, M.E., and Yan, N.D. 2011. Should biological invasions be managed as natural disasters? BioScience. 61: 312-317.

Rup, M.P., Bailey, S.A., Wiley, C.J., Minton, M.S., Miller, A.W., Ruiz, G.M., and MacIsaac, J.J. 2010. Domestic ballast operations on the Great Lakes: potential importance of lakers as a vector for introduction and spread of nonindigenous species. Can. J. Fish. Aquat. Sci. 67: 256-268.

Sass, G., Cook, T., Irons, K., Mcclelland, M., Michaels, N., and Stroub, M. 2010. A mark-recapture population estimate for invasive silver carp (*Hypophthalmichthys molitrix*) in the La Grange Reach, Illinois River. Biol. Invasions. 12: 433-436.

Scott, B.W., and Christie, W.J. 1963. The invasion of the Great Lakes by the White Perch, *Roccus americanus* (Gmelin). J. Fish. Res. Bd. Canada. 20: 1189-1195.

Severinghaus, L.L., and Chi, L. 1999. Prayer animal release in Taiwan. Biol. Conserv. 89: 301-304.

Shetty, H.P., Nandeesha, M.C., and Jhingran, A.G. 1989. Impact of exotic species in Indian waters, *In* Exotic aquatic organisms in Asia. *Edited by* S. De Silva. Proceedings of the workshop on introduction of exotic aquatic organisms in Asia. Asian Fish. Soc. Spec. Publ. 3. Manila, Philippines. p. 45-55.

Shiu, H., and Stokes, L. 2008. Buddhist animal release practices: historic, environmental, public health and economic concerns. Contemporary Buddhism: An Interdisciplinary Journal. 9: 181-196.

Simberloff, D. 2010. Invasive species management: a handbook of principles and techniques. The Quarterly Review of Biology 85:495-496.

Simon, T.P. and P.M. Stewart. 2006. Coastal Wetlands of the Laurentian Great Lakes: Habitat, Health, and Indicators. Authorhouse Press, Bloomington, Indiana. 540p.

Shuter, B.J., Maclean, J.A., Fry, F.E.J, and Regier, H.A. 1980. Stochastic simulation of temperature effects on first-year survival of smallmouth bass. Trans. Am. Fish. Soc. 109: 1-34.

Spataru, P., Gophen, M. 1985. Feeding-behavior of the Silver Carp *Hypophthalmichthys-molitrix* and its impact on the food web in Lake Kinneret, Israel. Hydrobiologia.120: 53-61.

Sparks, R.E., Barkley, T.L., Creque, S.M., Dettmers, J.M., and Stainbrook, K.M. 2011. Evaluation of an electric fish dispersal barrier in the Chicago Sanitary and Ship Canal. Am. Fish. Soc. Symp. 74: 139-161.

Stewart, D.J., Kitchell, J., and Crowder, L. 1981. Forage fishes and their salmonid predators in Lake Michigan. Trans. Am. Fish. Soc. 110(6): 751-763.

Stewart, T.J., Johannsson, O.E., Holeck, K., Sprules, W.G., and O'Gorman, R. 2010. The Lake Ontario zooplankton community before (1987-1991) and after (2001-2005) invasion-induced ecosystem change. J. Great Lakes Res. 36: 596-605.

Svirsky, V.G. and E.I. Barabanshchikov. 2010. Biological invasions as an element of anthropogenic pressure upon the aquatic biotic communities in Lake Khanka. Russ. J. Bio. Inv. 1: 21-25.

Takamura, N. 1993. A novel approach to evaluate feeding by mixed cyprinid species in a Chinese integrated fish culture pond using measurements of chlorophyll derivatives and photosynthesis in gut contents. Can. J. Fish. Aquat. Sci. 50: 946-952.

U.S. Army Corps of Engineers (USACE). 2010a. Dispersal barrier efficacy study: interim I – dispersal barrier bypass risk reduction study and integrated environmental assessment. 57 p.

U.S. Army Corps of Engineers (USACE). 2010b. Dispersal barrier efficacy study: interim III – modified structures and operations, Illinois and Chicago area waterways risk reduction study and integrated environmental assessment. 504 p.

U.S. Army Corps of Engineers (USACE). 2011a. Dispersal barrier efficacy study: efficacy study interim report IIA, Chicago Sanitary and Ship Canal dispersal barriers – optimal operating parameters laboratory research and safety tests. 294 p.

U.S. Army Corps of Engineers (USACE). 2011b. eDNA Results Map 2011. (Accessed October 28, 2011).

U.S. Environmental Protection Agency (USEPA). 2010. Laboratory audit report – Lodge Laboratoy, Department of Biological Sciences, University of Notre Dame. 22 p.

Wendl, M. 2003. Collision probability between sets of random variables. Statistics and Probability Letters 64:249-254.

Wilkonska, H. 1988. The effect of the introduction of herbivorous fish in the heated Lake Goslawskie (Poland) on the fry of the local ichthyofauna. Pol. J. Ecol. p. 275-281.

Wisconsin Department of Natural Resources (WDNR). 2011. Guide to Wisconsin hook and line fishing regulations 2011–2012. Wisconsin Department of Natural Resources. 72 p.

Yang, J. 1996. The alien and indigenous fishes of Yunnan: A study on impact ways, degrees and relevant issues, *In* Conserving China's biodiversity (II). *Edited by* Schei, P.J., Wang, S., and Xie, Y. China Environmental Science Press, Beijing, China. p. 157-168.