POTENTIAL EFFECTS OF ALEWIFE RESTORATION IN CHINA LAKE

Prepared for:

The Kennebec Water District
Waterville, Maine

Prepared by:

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August 2015

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1.0 INTRODUCTION

China Lake is one of the designated Great Ponds of Maine. The lake consists of three basins, east, north, and west, located in the towns of South China, China, and Vassalboro. The west basin has been the source of water for the Kennebec Water District (KWD) since 1905, supplying drinking water to Waterville and the surrounding area. In the 1980s, the water quality in China Lake rapidly changed from good to poor with the onset of annual nuisance algal blooms. The U.S. Environmental Protection Agency has listed the lake as an impaired waterbody and a total maximum daily load (TMDL) study was completed to assess non-point source pollution in the watershed (DEP 2001a). The water level of China Lake is controlled at the outlet dam on the west side of the West Basin. The China Lake Outlet Stream passes five more dams before it discharges into the Sebasticook River near the confluence with the Kennebec River.

Construction of dams in the nineteenth century led to declining populations of migratory fish species across the northeast, including the Kennebec watershed and China Lake (Hall et al. 2011). One of these native, sea-run species whose population declined significantly is the alewife (*Alosa pseudoharengus*). Alewives were once an important ecological and economic species in Maine. When abundant, alewives provided a food source for birds, mammals, and other fish. Also, alewives were a food source and bait source for local residents. However, some lake managers have expressed concern that alewives may be detrimental to water quality.

In 1986, the Maine Department of Marine Resources (DMR) unveiled a strategic plan to restore American shad (*Alosa sapidissima*) and alewife to their historical range in the Kennebec watershed. Part of Phase II of this plan includes reintroducing alewife to China Lake. Since the removal of Edwards dam in 1999 and Fort Halifax dam in 2009, the six remaining dams on Outlet Stream are the only barriers to sea-run alewife migration to China Lake. Over the last two decades, DMR and local restoration advocates have proposed restoring the alewife population by providing fish passage at, or removing, the dams on outlet stream. Community support for the restoration project in China Lake has progressed from a strategic plan to imminent action because of the successful restoration of alewife in other parts of the Kennebec watershed and the associated benefits. The Alewife Restoration Initiative (a consortium of non-profits and governmental organizations) is currently developing fish passage plans for each of the barriers on the outlet stream.

The KWD is a quasi-municipal, public water supply company with the mission to produce and distribute safe, high-quality water for its customers economically and professionally. In response to the declining water quality in China Lake over the last few decades, the KWD has invested significant time and money to maintain the quality of its product by installing advanced water treatment infrastructure and becoming a steward of the China Lake watershed. The KWD operates the China Lake outlet dam and, before becoming a participant in the restoration project, needs to understand the potential risk to the quality of their drinking water source. The KWD's objective in commissioning this study is to investigate the potential effects of restoring alewife on the water quality of China Lake.

This report is organized into four main sections: a literature review, a regional analysis, a site-specific analysis, and conclusions regarding the probable effects relating to water quality of restoring alewife in China Lake. The goal of the literature review is to survey the current scientific understanding of the effect of alewife restoration on lakes. The regional analysis reports case studies in Maine that alewife has been restored that are analogous to China Lake. The site-specific analysis describes the attributes of China Lake that are relevant to alewife reintroduction. Information summarized in the first three sections was synthesized to develop an opinion of the probable effect on water quality of alewife restoration in China Lake as a risk management tool for the KWD.

2.0 LITERATURE REVIEW

A literature search and review was conducted to survey the current scientific understanding of the effects of alewife on lake ecosystems. Google Scholar and the URSUS catalog search engine at the University of Maine's Fogler Library were the primary sources for the literature search. Search keywords included *alewife, lakes, eutrophication, trophic status*, *diadromous fish*, *phosphorus*, *nutrients*, and *restoration*. Literature considered included peer-reviewed journal articles, government reports, and grey literature of various types. The geographic limitation of the search was North America with special emphasis on lake ecosystems hydrologically linked to the marine coast. The search resulted in hundreds of papers of which approximately 50 were reviewed beyond the abstract.

The most relevant literature involved discussions of alewife biology, nutrient cycling in lakes, food-web dynamics in lakes, alewife restoration in lakes, and alewives as invasive species. The following sections describe the significant findings regarding these topics across a range of sources.

2.1 ALEWIFE BIOLOGY

Alewife is a small (less than 14 inches) anadromous fish of the family Clupeidae. Anadromous fish spawn in freshwater and spend most their life in the ocean (Figure 1). The geographic range of the alewife spans from the southeast United States into Canada. The annual productivity estimate for alewife in Maine prior to the industrial revolution is 11 billion fish (Hall et al. 2012). Today only a small percentage of historical alewife habitat has been restored. The Sebasticook River is a dramatic success story in alewife, routinely passing more than a million upstream migrating alewives each year (DMR 2012).

Alewife is an iteroparous species that spawns multiple times during its life cycle. In Maine, adult alewives (3 to 8 years old) migrate up rivers to spawn in lentic[1] freshwater lakes and ponds typically from early May to mid-June, depending mostly on water temperature (Saunders et al. 2006). The sex ratio of the spawning run is around 1:1, although males sometimes dominate (Havey 1973). Adults typically spend less than 2 weeks in their spawning habitat and feed little or not at all before returning to the ocean (Cooper 1961). Alewife fecundity is high; females

[1] non-flowing water

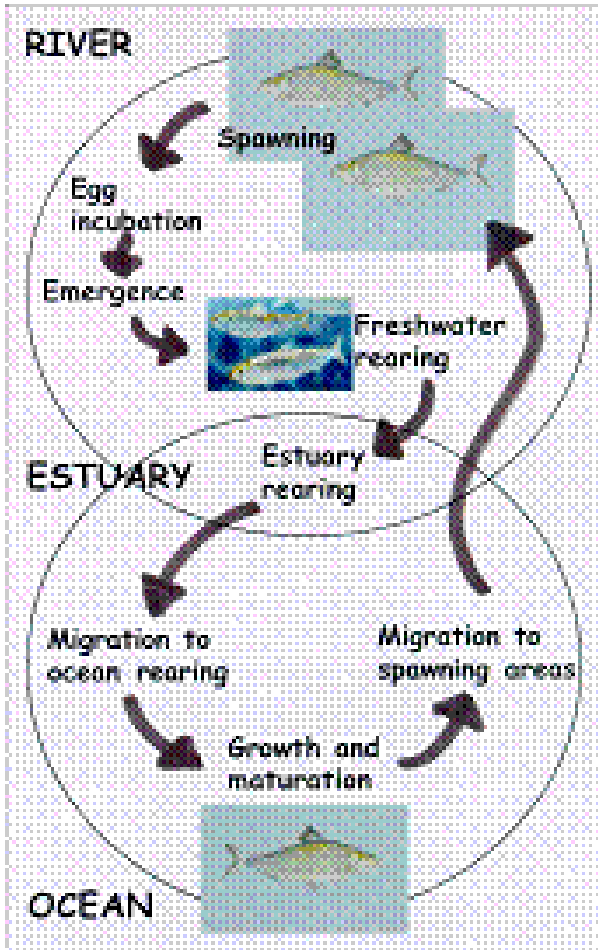

FIGURE 1 ALEWIFE LIFE CYCLE (COURTESY OF DMR)

produce approximately 60,000 to 100,000 eggs during each spawning run (Kircheis et al. 2004). Alewife spawns in near-shore environments but exhibits pelagic activity during the remainder of its life cycle (Cooper 1961). Juvenile alewives spend the first few months of their life growing in freshwater lakes before migrating to the ocean during late summer to early fall, usually following precipitation events (Gahagan et al. 2010).

The food habitats of adult alewives are not well understood but preferences are likely to include marine copepods, mysids, and other zooplankton (Neves 1981). Juvenile alewives are also planktivores feeding heavily on cladocerans and copepods. Alewives exhibit size-selective predation, and their prey increases in size as they grow; therefore, the presence of alewife often affects the population of large-bodied crustaceans (e.g., cladoceran) (Brooks and Dodson 1965). All life stages of alewife are important prey items for a variety of animals. Alewife eggs and juveniles are prey items of perch, bass, pickerel, sunfish, and numerous other fish species. Atlantic salmon, striped bass, and many other larger predatory fishes prey on adult and juvenile alewives (Loesch 1987). Adult alewives also are prey for a variety of birds including osprey, bald eagle, cormorants, gulls, and great blue heron (Dalton et al. 2009). Mammals that benefit prey on alewife include seals, mink, otters, raccoons, and fox.

2.2 EFFECTS OF ALEWIVES ON FRESHWATER ECOSYSTEMS

The presence of an abundant population of alewife affects freshwater ecosystems in ways attributable to the species' life cycle, numbers, feeding behavior, and benefit to predators. The following paragraphs describe the potential effects of alewife on nutrient cycling and food web dynamics. In general, research on the topic of the effects of alewife on freshwater ecosystems is limited, except for as an invasive or stocked species. The difference between reintroducing or restoring alewife to its historic habitat and introducing the species to non-native habitat is important; therefore, the closing paragraph of this section discusses the wealth of literature documenting alewife as a problematic introduced or invasive species.

2.2.1 EFFECTS ON NUTRIENT CYCLING

Anadromous fish carry important marine-derived nutrients into freshwater ecosystems (Moore et al. 2003). Much of the seminal research on marine-derived nutrients contributed by anadromous fish species involves Pacific salmon migrations in which all post-spawned adults die, releasing large amounts of carbon, nitrogen, and phosphorus to the freshwater ecosystem (Kline et al. 1990, 1993). The research on marine-derived nutrients from iteroparous species such as alewife in Atlantic coast freshwater ecosystems was limited prior to the twenty-first century (Kissil 1969; Durbin et al 1979). Recently, the role of alewife as a nutrient contributor has garnered more attention (MacAvoy et al. 2000; Post and Walters. 2009; West et al. 2010; Twining et al. 2013).

Two predictive modeling studies investigating marine-derived nutrients use a mass-balance approach to quantify the mechanisms of translocation of nutrients, including gamete release, mortality, and excretion (Durbin et al. 1979; West et al. 2010). Gamete release is the spawning activity of adult alewives releasing sperm or eggs in freshwater. Gametes have high concentrations of nutrients to support the early life stages of alewife offspring (Kissil 1969).

Mortality includes predation of adults during the spawning run, which is typically high. In a study of Love Lake in Washington County, Maine, the average mortality for adults was 90.7 percent with a range of 66 to 100 percent from 1960 to 1971(Havey 1973). The mass-balance approach also accounts for direct excretion of nutrients by adults; the excretion rate and nutrient concentration were determined from mesocosm experiments (Durbin 1976; Post and Walters 2009) or by weight loss during spawning (Durbin et al. 1979). The total marine-derived nutrients (in this case, phosphorus) being contributed to a freshwater ecosystem can be estimated by the following equation (adapted from West et al. 2010):

$$\text{Phosphorus Input} = n_A \text{ X } (P_M + P_G + P_E) - P_J$$

where:

n_A is the number of immigrating adults;
P_M is the phosphorus input from adult mortality;
P_G is the phosphorus input from adult gamete release;
P_E is the phosphorus input from adult excretion, and
P_J is the phosphorus output from juvenile emigration.

In the modeling studies, the net input of phosphorus into the ponds was estimated to be 115 kilograms a year (kg/yr) and 41.4 kg/yr, respectively (Durbin et al. 1979; and West et al. 2010); therefore, anadromous alewives are considered important suppliers of nutrients to freshwater ecosystems based on the modeling studies completed to date.

As suppliers of marine-derived nutrients to freshwater ecosystems, anadromous alewives affect nutrient cycling; however, whether this effect is detrimental to an ecosystem that was once part of the historical range of the species is debatable. According to a paleoecological study of southern New England lakes in which sediment cores and nutrient loading models were used to investigate how nutrient inputs have changed over the last 400 years, prior to Euro-American settlement, migrating alewives contributed up to 95 percent and 68 percent of the allochthonous[2] inputs of phosphorus and nitrogen, respectively(Twining et al. 2013). The researchers estimated that, before Euro-American settlement, the nutrient input into the study lakes contributed by historical alewife migrations was equal to or even greater than nutrient inputs attributed to current land use. Yet, these large inputs of marine-derived nutrients did not illicit the problematic

[2] from the watershed, not from internal cycling

ecosystem responses (e.g., algal blooms) commonly seen today, which typically are attributed to increased nutrient inputs resulting from altered land use. The authors provided the following explanations:

- Historic alewife immigration numbers were overestimated.
- Nutrient inputs from anadromous alewife and the landscape are supplied to the lake in different forms.
- Nutrient inputs from anadromous alewife occur when the water residence time in the lakes is short, suggesting that nutrient inputs are flushed from the ecosystem rapidly.
- The timing of nutrient inputs from anadromous alewife occurs when primary production is low.
- Compared to nutrient inputs from anadromous alewife, allochthonous inputs from the landscape are relatively constant throughout the year.

Therefore, magnitude of the alewife run, the timing of the alewife run, and the forms in which nutrients are supplied to a lake are key factors that ultimately determine whether anadromous alewives can affect water quality. The largest nutrient input from anadromous alewife is adult mortality, which contributes approximately 60 to 90 percent of the total nutrient supply (Durbin et al. 1979; West et al. 2010). The carcasses of adult alewife that remain in the lake are not bio-available forms of nutrients; rather these contributions require further decomposition to become inorganic nutrient forms that are readily assimilated by primary producers (Vanni, 2002). In contrast, nutrient forms derived from altered land use patterns (e.g., failing septic systems) are typically bio-available and are rapidly incorporated into primary producer biomass. Also, a percentage of adult mortality is the result of consumption by predators that translocate the nutrients to other areas of the watershed (e.g., ospreys that catch a spawning adult alewife and return to the nest to feed). No detailed accounting of adult mortality is available to better estimate the in-lake nutrient contribution from anadromous alewife.

The timing of the alewife migration also mitigates the risk of negative water quality effects in lakes. In Maine, alewife migrate in May and early June, when the flushing rate of lakes is fastest, offering less time for the marine-derived nutrients to be assimilated into the ecosystem. In addition, primary production (algal growth) typically is low in May; consequently, the small percentage of bio-available nutrients supplied by anadromous alewife is not readily incorporated into primary producers because of the suboptimal growing conditions (e.g., cold temperature, less sunlight).

2.2.2 Effects on Food Web Dynamics

A food web is a description of the natural flow of energy and nutrients through an ecosystem developed by defining interspecies grazing and predation relationships. A simplified aquatic food web includes sunlight (energy), nutrients, producers, consumers, and decomposers (Figure 2). The interactions between components of the food web are highly complex, but in the simplified form, the anadromous alewife belongs in the niche of the consumer that feeds on zooplankton (small aquatic crustaceans) and is preyed upon by piscivores (preys on fish). Because of the short time they spend in freshwater, adult anadromous alewives have minimal effect on food web dynamics other than providing a pulse of marine-derived nutrients for predators.

Juvenile anadromous alewives, on the other hand, have a significant effect on both piscivores (MacAvoy et al. 2000; Moring and Mink. 2002) and zooplankton (Brooks and Dodson. 1965; Bradt and Chungu 1999; Kircheis et al. 2004; Trout-Haney 2006; Toupin 2009; Walsh et al. 2012; Twining and Post 2013; Demi et al,. 2015). Piscivores benefit from the steady supply of pelagic prey species that juvenile alewives provide, particularly during the warm summer months, when metabolism and feeding rates are high (Yako et al. 2000; Dalton et al. 2009). Theoretically, juvenile anadromous alewives compete with other species for prey items, thus limiting their growth and survival. A study conducted in the St. Croix watershed looked at the potential for competition between age-zero smallmouth bass and age-zero alewife (Hanson and Curry 2005). Although the diets of the two species were similar, smallmouth bass often preyed on alewife once they became large enough, suggesting that competition effects, if present, are limited. Moring and Mink (2002) conducted a similar study with juvenile alewife and white perch and reached the same conclusion: the species compete at certain life stages, but predation by white perch on alewife is the dominant food web interaction. Rainbow smelt is another species that may be affected by the introduction of alewife. A study conducted in Echo Lake on Mount Desert Island, Maine, showed significant overlap in the diets of alewife and rainbow smelt, suggesting that competition may be affecting growth and survival of smelt (Gately 1978); however, no pre-introduction data were collected for the study, nor was evidence presented that food was limiting in the lake.

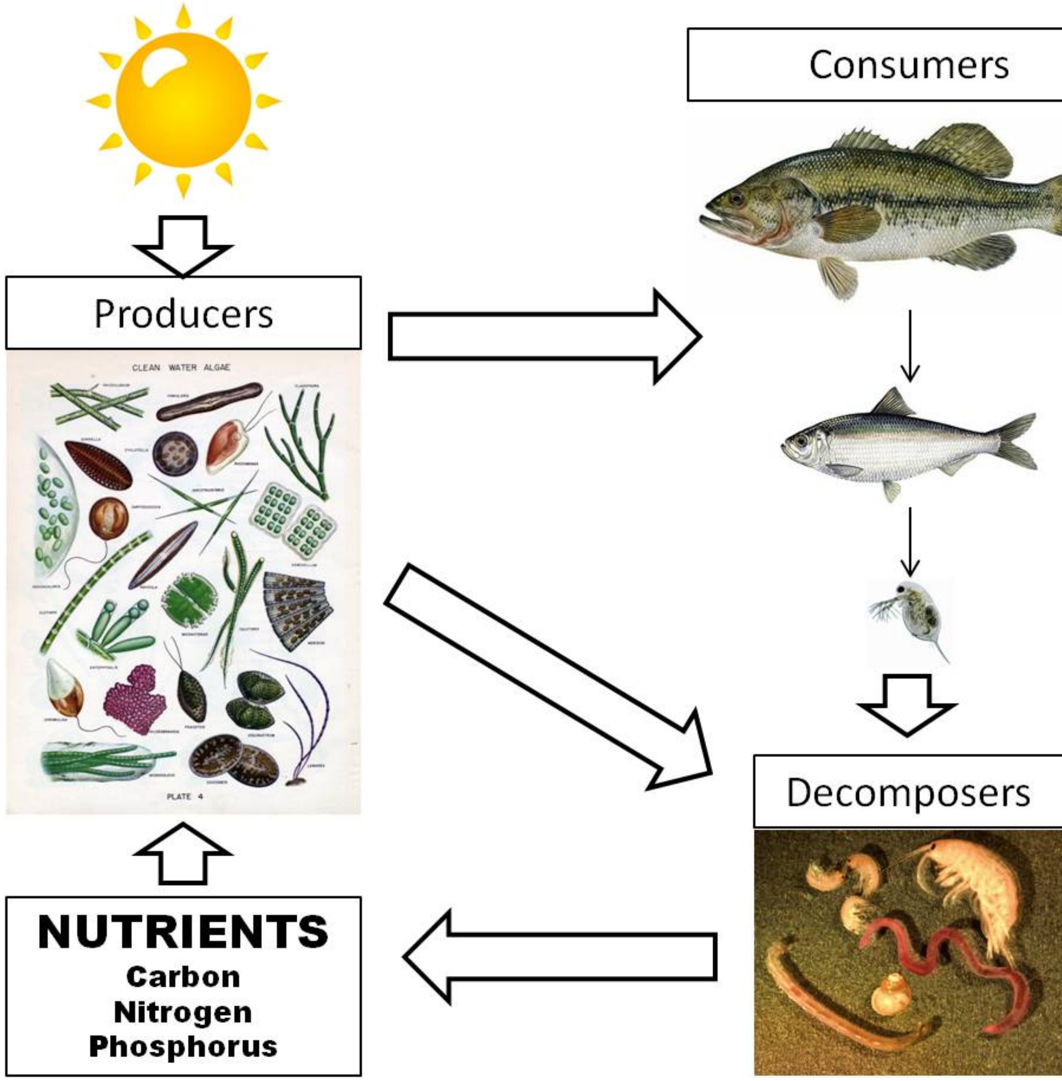

FIGURE 2 SIMPLIFIED AQUATIC FOOD WEB

The size-selective predation of zooplankton by alewife has been well documented since the seminal paper by Brooks and Dodson (1965) describing the demise of large-bodied cladocerans (zooplankton) in Connecticut lakes with the introduction of alewife populations. In the subsequent decades, numerous studies have postulated and reinforced the concept of trophic cascade (Carpenter and Kitchell 1996; Vanni, 2002; Schmitz et al. 2010). Trophic cascades can occur when predators control the population or behavior of their prey to the benefit of a lower trophic level. For example, alewives consume large-bodied zooplankton which, in turn, can no longer graze on phytoplankton (e.g., green algae) in the water column. Large-bodied cladocerans are more effective at grazing phytoplankton than small-bodied cladocerans, such as *Bosmina*

(Carpenter et al. 1987); therefore, it is postulated that the presence of alewife will contribute to the proliferation of algal blooms in ponds. Unfortunately, this paradigm has been used as justification for choosing not to restore alewife to its historic spawning grounds with little to no evidence that their presence actually promotes algal blooms (Strus and Hurley 1992).

The alewife became a maligned species after well-intentioned, but misguided, fisheries biologists introduced it as a non-native prey species for game fish such as lake trout and other salmonids in landlocked waterbodies such as the Great Lakes, the Finger Lakes in New York, and mountainous lakes in New England (Lackey 1969). As with many introductions of non-native species, unintended consequences arose over time, and the intended objective to provide a nutritious forage fish was also unsuccessful because consuming landlocked alewife produced thiamine deficiency in game fish (Fisher et al. 1996). For the next few decades, most alewife research involved documenting the negative effects of the species as it related to eutrophication, oxygen depletion, and food web dynamics in lakes in which nature never intended the alewife to be present (Bartell 1981; O’Gorman and Schneider 1986; Eck and Wells 1987; Kraft 1993; Harman et al. 2002; Babeu et al. 2010). Until recently, the native, the anadromous alewife of coastal waters has been defamed by the invasive, landlocked alewife. Landlocked populations of alewife must be clearly distinguished from anadromous populations because the potential effects on water quality and food web dynamics of these phenotypically divergent organisms are not the same (Palkovacs and Post 2008).

3.0 REGIONAL ANALYSIS

Over the last few decades, DMR along and other government agencies and restoration advocates have implemented a successful campaign to restore the alewife to its historical habitat in Maine (e.g., Lake George, Unity Pond, Webber Pond, Threemile Pond, Sebasticook Lake). The results of these restoration efforts offer some evidence upon which to base a prediction of the potential effects of restoring alewife in China Lake. Except for the Lake George, however, these cases provide mostly anecdotal information because field research on the effects of restoring alewife in Maine lakes is limited, especially for eutrophic[3] lakes.

To investigate the potential effects of reintroducing alewife into the unstudied lakes, water quality data including total phosphorus concentration, Secchi depth measurements, and chlorophyll *a* concentration[4] were downloaded from the Lakes of Maine Web site[5]. These data were analyzed to identify any changes in water quality parameters that may be related to alewife restoration. The publically available data include sampling years up to 2012. In addition, the fish community of each lake was identified (Table 1). Prior to the reintroduction of alewife, landlocked Atlantic salmon had been extirpated from Lake George, Webber Pond, and Unity Pond. Likewise, some trout species had been extirpated from Unity Pond, Webber Pond, and Sebasticook Lake. Rainbow smelt had been extirpated from Sebasticook Lake. These extirpations probably were the result of the construction of dams, poor water quality, species introductions, or a combination of those influences.

TABLE 1 FISH COMMUNITIES OF REGIONAL LAKES

FISH SPECIES	LAKE GEORGE	UNITY POND	THREEMILE POND	WEBBER POND	SEBASTICOOK LAKE
Alewife	X	X	X	X	X
Brown bullhead	X	X	X	X	X
American eel	X	X	X	X	X
Fourspine stickleback			X		
White sucker	X	X	X	X	X
Chain pickerel	X	X	X	X	X
Banded killifish		X	X	X	
Threespine stickleback					X

[3] highly productive
[4] a direct measurement of phytoplankton pigment that is used to estimate biomass
[5] www.lakesofmaine.org

FISH SPECIES	LAKE GEORGE	UNITY POND	THREEMILE POND	WEBBER POND	SEBASTICOOK LAKE
Redbreast sunfish	X	X	X	X	X
Pumpkinseed	X	X	X	X	X
Cusk	X	X			X
Common shiner		X	X		X
Smallmouth bass	X	X	X	X	X
Largemouth bass	X	X	X	X	X
White perch	X	X	X	X	X
Golden shiner	X	X	X	X	X
Rainbow trout	X				
Rainbow smelt	X	X	X		
Yellow perch	X	X	X	X	X
Sea lamprey			X	X	
Black crappie		X	X		X
Brown trout	X	X	X	X	
Brook trout	X	X	X	X	
Splake	X				
Fallfish	X	X	X	X	X

3.1 LAKE GEORGE

Lake George in southern Somerset County, Maine, occupies 318 acres, draining into Carrabassett Stream and eventually to the Kennebec River. Numerous downstream dams that lack fish passage facilities have long denied alewives volitional access to the lake. Lake George, however, was within the historical range of alewife and other sea run species before those dams were constructed. Water quality in Lake George is above average, and there is little development surrounding the lake that may lead to future water quality problems. As a result of the planned DMR restoration efforts in the Kennebec watershed (DMR 1986), state agencies including DMR, the Maine Department of Environmental Protection, and Inland Fisheries and Wildlife planned a decade-long study to investigate the potential effects on water quality of reintroducing alewife to Lake George (Kircheis et al. 2004). The study included three phases:

- Phase I – background sampling for 3 years before alewives were stocked.
- Phase II – sampling during 3 years while alewives were stocked.
- Phase III – sampling during the 3 years after stocking had ceased.

The sampling included collecting data on water quality, zooplankton community structure, and fish community structure. This comprehensive study showed a significant decrease in total phosphorus concentrations in the water column during the 3 years when alewives were stocked in the pond. The most likely explanation for this phenomenon is the emigration of adult and juvenile alewives after sequestering nutrients in the lake. Other water quality parameters showed significant changes during Phase III that are most likely explained by hydrologic drivers. Shifts in zooplankton community structure suggest size-selective predation by alewives. The fish community of Lake George showed no significant changes other than an increase in the growth rate of young-of-year rainbow smelt and decreased population densities.

3.2 UNITY POND

Unity Pond is located in Waldo County, Maine, occupies 2,523 acres, draining into Twenty-five Mile Stream and eventually to the Kennebec River. The water quality of Unity Pond has been in decline for many decades. A TMDL study showed that the total input of phosphorus into the pond is approximately 2,358 kg/yr, and that roughly 75 percent of that comes from watershed inputs and the remainder from internal recycling (DEP 2004). Alewife stocking in Unity Pond began in 1989 and continued until removing the Fort Halifax dam established free passage. Alewife productivity in Unity Pond is high because there are no barriers between the pond and the ocean. Water quality in Unity Pond has continued to decline since alewives were stocked there; Secchi[6] readings have declined (Figure 3) and chlorophyll *a* measurements have risen (Figure 4).

[6] a measure of turbidity

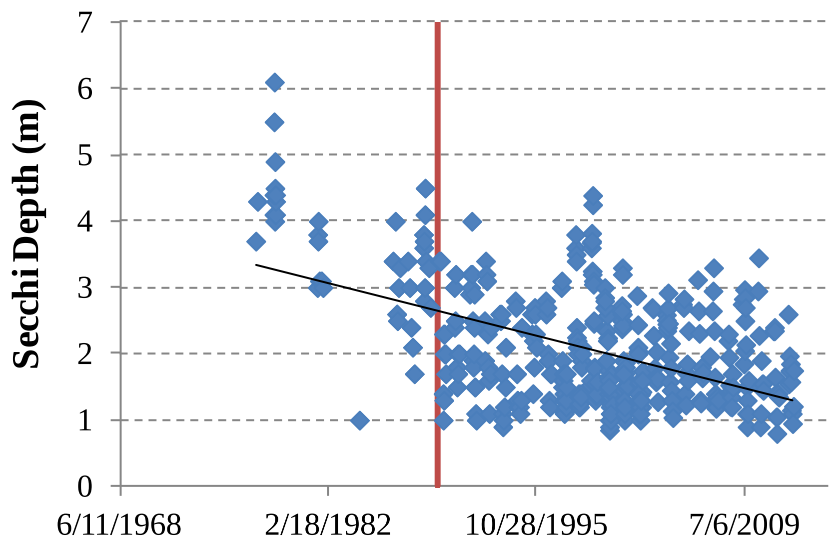

FIGURE 3 SECCHI DEPTH READINGS IN UNITY POND

The red and black lines represent the date of initial alewife stocking and the trendline, respectively.

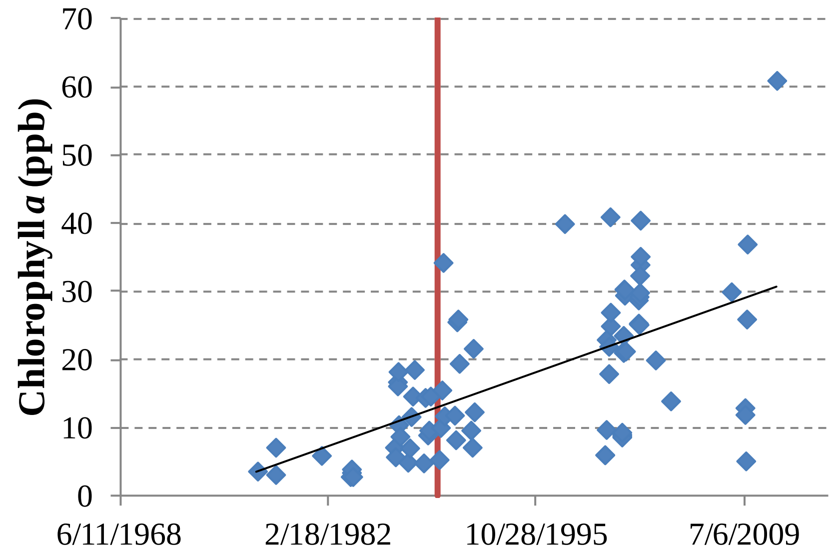

FIGURE 4 CHLOROPHYLL *A* MEASUREMENTS IN UNITY POND

The red and black lines represent the date of initial alewife stocking and the trendline, respectively.

The alewife restoration in Unity Pond has not led to any water quality improvements as evidenced by the continuation of nuisance algal blooms; however, the declining trend in water quality started well before the first stocking of alewife. Whether the presence of alewives in the pond has exacerbated the situation is unclear. Local stakeholders have stated that during some years, the lack of flow out of the pond has inhibited juvenile alewife emigration (Rick Kersbergen, personal communication). Inhibited emigration of juvenile alewives could have a two-fold effect: (1) decreased nutrient export, and (2) sustained predation pressure on zooplankton. A more likely explanation for the continued decline in water quality, however, is that the external, watershed-derived nutrient loads that caused the algal blooms in the first place have accumulated in the sediments of the pond and are now contributing a much larger percentage of bioavailable nutrients to the water column through internal recycling processes. The sediment in Unity Pond has shown an increasing trend in phosphorus concentration, and the recycling of phosphorus through sediment dynamics is likely to be driving the continued water quality problems (Killarney 2015).

3.3 WEBBER AND THREEMILE PONDS

Webber and Threemile Ponds are located in Kennebec County, Maine. Threemile Pond occupies 1,132 acres and drains into the 1,201-acre Webber Pond and eventually to the Kennebec River through Seven Mile Brook. Both ponds have documented poor water quality and TMDL studies describing the potential causes of eutrophication (DEP 2003a, 2003b). Webber and Threemile Ponds have prescribed phosphorus reductions of 532 and 398 kg/yr, respectively. Alewife stocking in Webber Pond began in 1997 and continued until the construction of the Webber Pond fishway in 2009 permitted a natural migration. Stocking of alewives in Threemile Pond began in 2001. Today, a robust natural migration of alewives reaches both ponds since the construction of the fishway and stream modifications at the outlet of Threemile Pond. Approximately, 275,175 adults passed the Webber Pond fishway in 2012 (DMR 2012). Water quality in both ponds has improved noticeably over the last few years, leading many local stakeholders to attribute the improvements to alewife restoration. Figure 5 through Figure 7 shows the historical water quality data for both ponds.

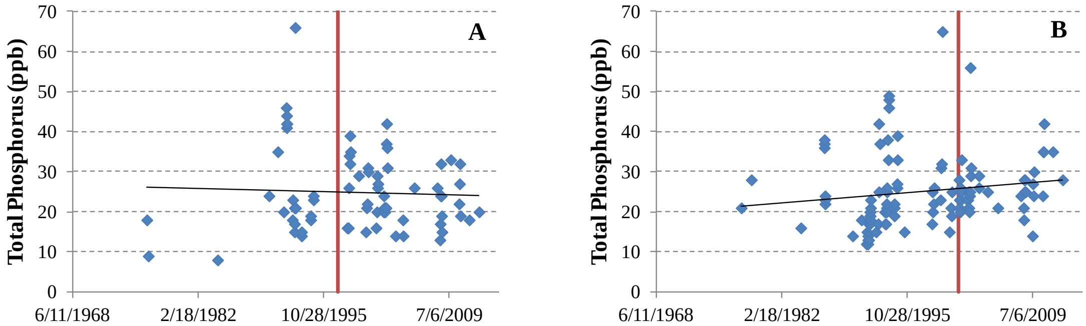

FIGURE 5 TOTAL PHOSPHORUS MEASUREMENTS IN WEBBER POND (A) AND THREEMILE POND (B)

The red and black lines represent the date of initial alewife stocking and the trendline, respectively.

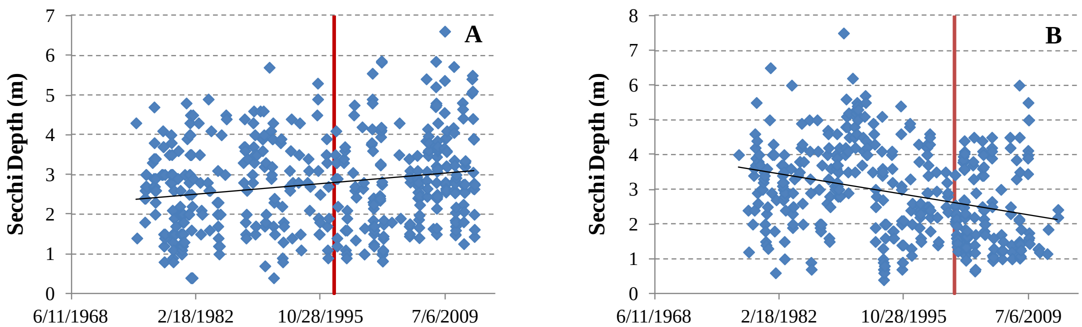

FIGURE 6 SECCHI DEPTH READINGS IN WEBBER POND (A) AND THREEMILE POND (B)

The red and black lines represent the date of initial alewife stocking and the trendline, respectively.

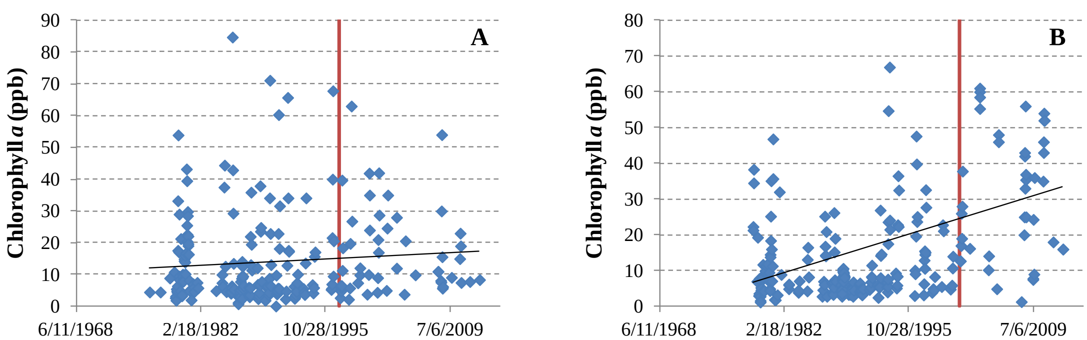

FIGURE 7 CHLOROPHYLL *A* MEASUREMENTS IN WEBBER POND (A) AND THREEMILE POND (B)

The red and black lines represent the date of initial alewife stocking and the trendline, respectively.

The historical water quality data from Webber and Threemile Ponds are inconclusive regarding the effect of alewife stocking on water quality. Secchi readings in Webber Pond have increased steadily, indicating improvement in water clarity; whereas, water clarity in Threemile Pond has continued to decrease. The improved water clarity in Webber Pond probably is the result of the fall drawdown program, which exports many kilograms of phosphorus and other nutrients each year. Total phosphorus concentrations in the epilimnion[7] show a similar response to water clarity, although the decreasing trend in concentration in Webber Pond is minor. The yearly maxima for both total phosphorus and chlorophyll *a* are decreasing, suggesting that the magnitude of the algal bloom is decreasing in both ponds. The yearly minima for water clarity are increasing in both ponds since alewife restoration.

3.4 SEBASTICOOK LAKE

Sebasticook Lake in Penobscot County, Maine, occupies 4,537 acres and is an integral part of the East Branch of the Sebasticook River. The lake is listed as an impaired waterbody, and a TMDL study was completed in 2001 (DEP 2001b). The outlet dam is in downtown Newport and has a fishway that was installed in 2003. Although still recovering, water quality in Sebasticook Lake has improved dramatically over the last few decades. Figure 8 through Figure 10 shows this improvement for all water quality parameters analyzed in this study.

[7] Upper layer in the water column

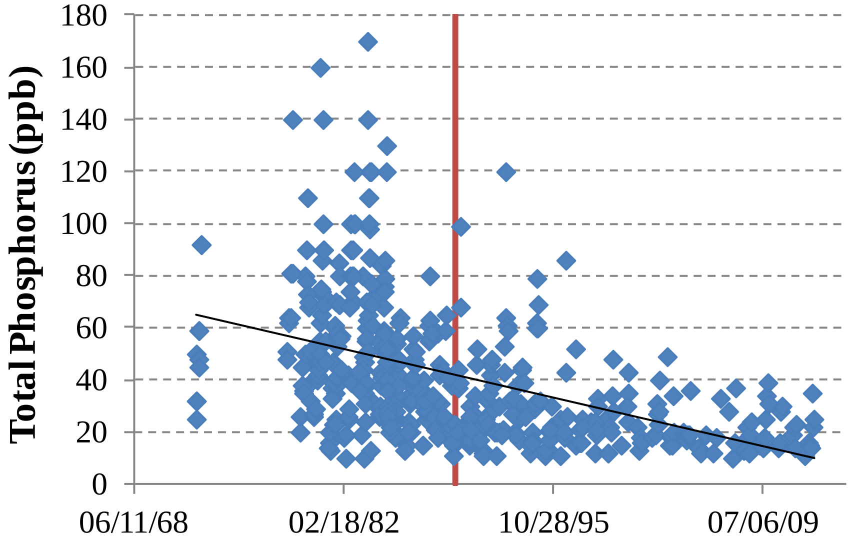

FIGURE 8 TOTAL PHOSPHORUS IN GRAB SAMPLES FROM THE EPILIMNION OF SEBASTICOOK LAKE

The red and black lines represent the date of initial alewife stocking and the trendline, respectively.

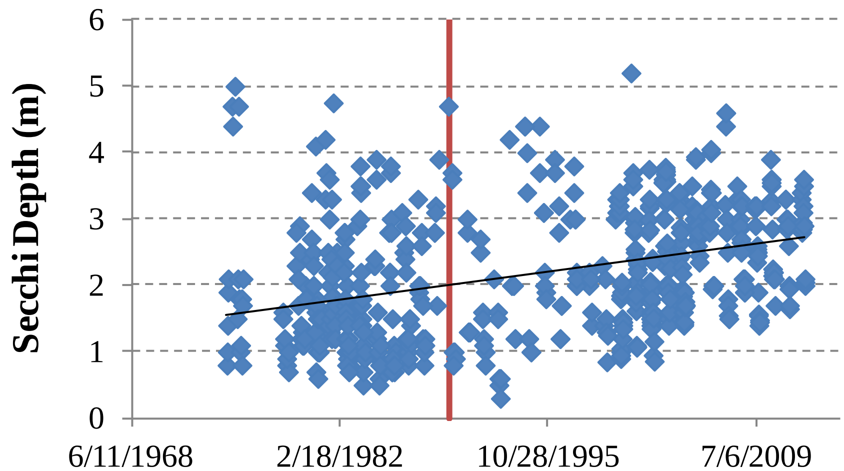

FIGURE 9 SECCHI DEPTH MEASUREMENTS IN SEBASTICOOK LAKE

The red and black lines represent the date of initial alewife stocking and the trendline, respectively.

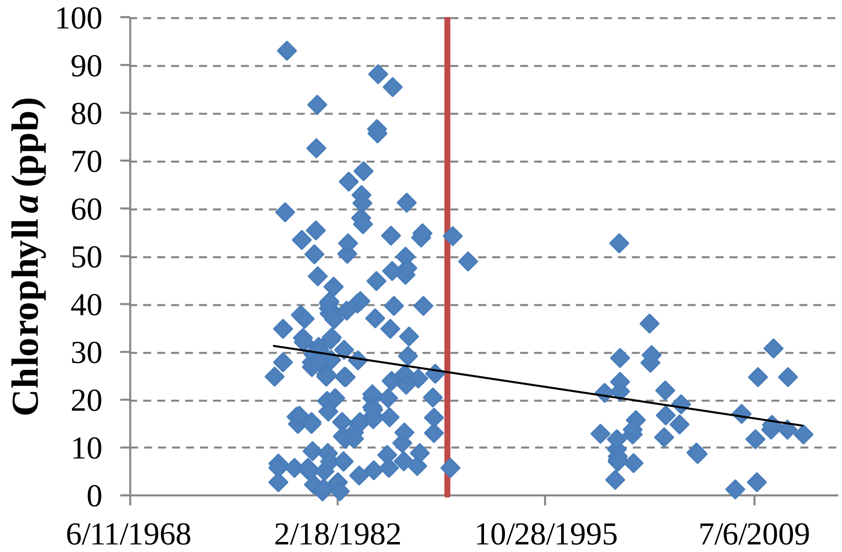

FIGURE 10 CHLOROPHYLL *A* MEASUREMENTS IN SEBASTICOOK LAKE

The red and black lines represent the date of initial alewife stocking and the trendline, respectively.

Water quality in Sebasticook Lake has improved for the following reasons: regulatory action on point-source pollution and mitigation of non-point-source pollution; a fast flushing rate; and initiation of a yearly drawdown program. Since the passage of the Clean Water Act, waterbodies have benefited from the elimination of point-source pollution and mitigation of non-point-source pollution. This legislation slowed the steady flow of excess nutrients into Sebasticook Lake, but the innate ability of the lake to flush nutrients downstream and the implementation of a drawdown program accelerated the improvement of water quality. The yearly drawdown is conducted after fall turnover, when the nutrient concentrations are typically highest, thereby maximizing the flush of nutrients out of the system. The yearly drawdown started in 1982, and the positive results are clearly apparent in the figures.

Alewife stocking began in Sebasticook Lake during the 1980s at the onset of water quality improvements. Today, alewives have access to the lake through fishways, resulting in a natural migration of anadromous alewives and a steady population in the lake. Whether the addition of anadromous alewives into the lake was a significant factor in the recovery of Sebasticook Lake is debatable, but what can be stated unequivocally is that water quality improvements can be realized in a lake system that has large anadromous alewife migrations.

4.0 SITE-SPECIFIC ANALYSIS

China Lake occupies 3,963 acres and has a slow flushing rate of approximately once every 3 years. Water quality problems started during the 1980s and continue to the present. The DEP, academic institutions, and the KWD have studied China Lake's water quality problems extensively (DEP 2001a; Colby College 2006; Lake et al. 2007; Kleinschmidt 2012). China Lake is deep with a slow flushing rate; therefore, internal recycling of nutrients is a large contributor to the yearly nuisance algal blooms, which has slowed the recovery of the system. In 2008, the Kennebec Soil and Water Conservation District, the KWD, and the China Region Lakes Alliance drafted a watershed management plan. Many of the non-point-source prevention strategies recommended in that plan have been implemented across the watershed over the last decade. In 2013, a yearly drawdown program was initiated that has resulted in an increased export of nutrients during fall turnover.

We estimated the net input of marine-derived nutrients to China Lake that would result from restoring alewife using the methods of West et al (2010), except that we estimated the measurements of adult mass and length using data collected at Benton Falls (DMR 2012). West and colleagues (2010) used a density-dependent function with a maximum fish biomass density of 5.42 grams per square meter (g/m^2) to determine the potential export of phosphorus via emigrating juveniles based on mesocosm studies completed in Bride Lake, Connecticut. We used the same maximum fish biomass density and slope relationship to calculate the potential export of phosphorus via juvenile anadromous alewives based on the surface area of China Lake and adult immigration numbers (Figure 11). Bride Lake is more than 50 times smaller than China Lake; therefore, the phosphorus export from juvenile emigration may be underestimated using the relationship developed by West and colleagues (2010), but other estimation methods (e.g. Durbin 1979) were infeasible due to the lack of information on the biomass of emigrating juveniles. We ran the model for two scenarios: one with a high in-lake adult mortality rate of 57 percent and the other with a low in-lake adult mortality of 39 percent (Cooper 1961; Havey 1961; Kissil 1969).

The restoration of anadromous alewives in China Lake is likely to provide a net increase in marine-derived nutrients based on projected escapement numbers (i.e., the number of adult anadromous alewives immigrating into the lake). We estimate that up to a 900,000 adult alewives may return each year once the migration is fully restored. If all the alewives have access to China Lake, a net increase of 320 to 407 kg/yr of phosphorus will be added to the existing phosphorus load. This amount is less than 10 percent of the total phosphorus load for the lake based on the TMDL study (DEP 2001a). At lower escapement into China Lake (e.g., density of 35 fish per acre), the phosphorus load becomes insignificant. At an even lower escapement into China Lake (e.g., density of 6 fish per acre), anadromous alewife migrations become a net export of phosphorus, though at insignificant levels.

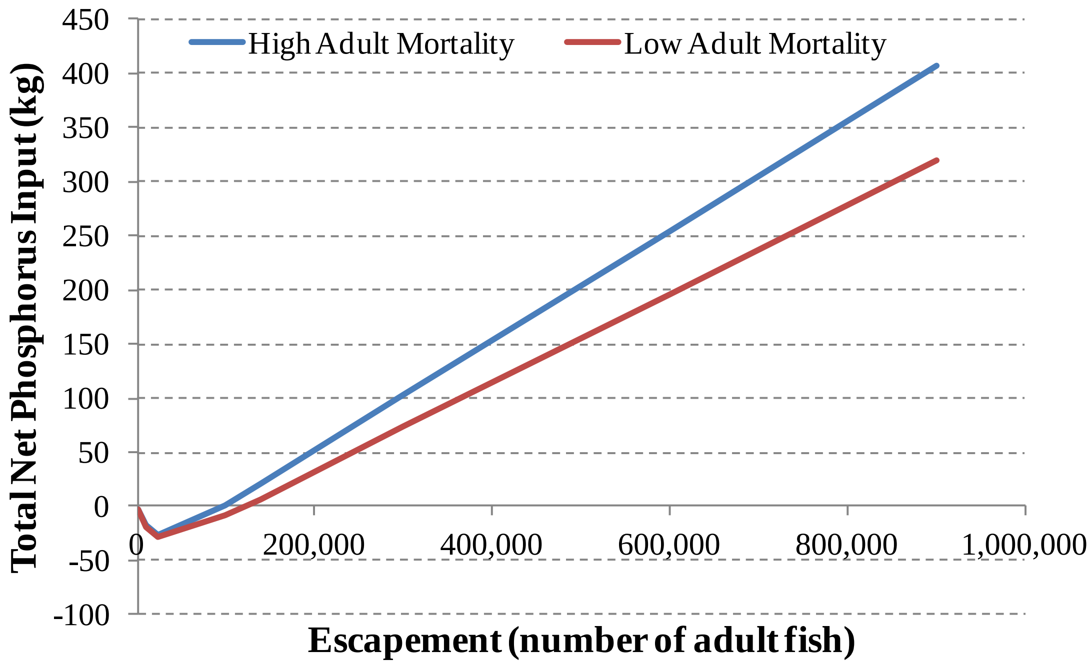

FIGURE 11 POTENTIAL NET PHOSPHORUS INPUT BASED ON ESCAPEMENT NUMBERS IN CHINA LAKE

The fisheries community in China Lake is robust and is managed as a mixed warmwater and coldwater fishery (Table 2). The coldwater habitat is minimized each summer during periods of oxygen depletion in deeper, cooler waters of the lake; consequently, the obligate coldwater species are struggling to survive, and populations have plummeted. Species that are tolerant of warm water are thriving in the lake, and trophy bass is a regular catch for anglers. As noted in Table 2, fish species that feed on zooplankton are numerous, so restoring alewife will increase predation on zooplankton without filling a vacant niche in the food web niche (i.e., juvenile white perch are voracious, size-selective predators of zooplankton). Competition between fish that feed on zooplankton, therefore, will increase. Predation pressure on zooplankton is likely to affect community dynamics, although the diverse structure of the existing food web may mitigate the effect. China Lake's bevy of predators will benefit from the additional prey that adult and juvenile anadromous alewives will supply.

TABLE 2 FISH SPECIES, DIETS, AND HABITAT PREFERENCES WITHIN CHINA LAKE

FISH SPECIES	**DIET**	**HABITAT**
Alewife	Zooplankton	Pelagic
Brown bullhead	Omnivorous	Benthic
American eel	Omnivorous	Benthic
Fourspine stickleback	Zooplankton, phytoplankton	Littoral, benthic
White sucker	Invertebrates, plants	Benthic
Northern pike	Fish, crayfish, amphibians	Littoral
Chain pickerel	Fish, crayfish, amphibians	Littoral
Banded killifish	Zooplankton, microscopic insects	Littoral
Threespine stickleback	Zooplankton, microscopic insects	Littoral, benthic
Redbreast sunfish	Insects, worms	Littoral
Pumpkinseed	Insects, worms	Littoral
Common shiner	Zooplankton, insects, plants, algae	Littoral
Smallmouth bass	Insects, crayfish, amphibians, fish	Offshore
Largemouth bass	Insects, crayfish, amphibians, fish	Littoral
White perch	Zooplankton, eggs, small fish	Pelagic
Golden shiner	Zooplankton, insects, plants, algae	Littoral
Rainbow smelt	Zooplankton, small fish	Pelagic
Yellow perch	Zooplankton, eggs, insects, small fish	Littoral
Ninespine stickleback	Zooplankton, microscopic insects	Littoral, benthic
Blacknose dace	Aquatic invertebrates, plants	Littoral
Landlocked salmon	Aquatic invertebrates, small fish	Pelagic
Brown trout	Aquatic invertebrates, small fish	Pelagic
Brook trout	Aquatic invertebrates, small fish	Pelagic
Lake trout	Zooplankton, small fish	Pelagic
Creek chub	Omnivorous	Littoral

5.0 CONCLUSIONS

China Lake is a large, eutrophic waterbody that provides thousands of acres of suitable spawning habitat for anadromous alewives. Based on our review of the literature, a regional analysis, and a site-specific analysis, we conclude that anadromous alewife does not cause water quality problems in lakes and ponds in Maine. Conversely, there is little evidence that restoring alewife is a panacea for accelerating the recovery of eutrophic lakes.

Although the risk that restoring anadromous alewife in China Lake will affect water quality negatively is minimal, controlling the escapement of adult immigrating alewives is prudent because our nutrient model shows a minor influx of nutrients at large escapement levels. The proposed alewife restoration project on Outlet Stream involves constructing two technical fishways: one at Ladd dam, and the other at the China Lake outlet dam. Both of these fishways will provide opportunities to manage the escapement numbers into China Lake. Technical fishways allow the fisheries manager to shut off access to upstream habitat when escapement targets are met; therefore, the yearly migration can be managed to the benefit of China Lake.

In addition to controlling escapement, the fisheries managers should design downstream fish passage at the China Lake outlet dam to ensure that juvenile emigration is feasible. Currently, the dam has an overflow spillway and two sluice gates that are used to manage the water levels of the lake throughout the year. The overflow spillway will be adequate for downstream passage at high water levels (6 inches or greater above spillway crest), but the sluice gates are not optimal for lower water levels because juvenile emigrates may respond adversely to the turbulent hydraulics caused by the pressurized release of water from the sluice gates. The design for the fishway should provide an alternate downstream pathway to mitigate any risk that juvenile alewives will become landlocked in China Lake.

The movement to restore anadromous alewife will offer, researchers plenty of opportunities to improve our understanding of the effects of alewife on lake ecosystems. Recommendations for further research include:

- The nutrient export by juvenile anadromous alewives is poorly understood, and the density-dependent function describing the relationship between the biomass of emigrating juveniles and the number of adult spawners in large, eutrophic lakes is nonexistent. Studies conducted at Unity Pond, Sebasticook Lake, or China Lake may improve the understanding of how juvenile anadromous alewives provide a sink for and eventually export phosphorus.

- In-lake mortality of spawning adults is poorly understood. Mortality estimates are decades old and may not reflect a euthrophic lake with robust populations of piscivorous fish. In addition, translocation of adult carcasses to terrestrial environments needs to be estimated because avian or mammalian predation account for some percentage of in-lake mortality.
- Nutrient excretion rates from anadromous juvenile alewives should be measured and compared to nutrient excretion rates of zooplankton normalized for biomass. A better understanding of the potential for juvenile alewives to sequester nutrients in non-bioavailable forms is important to understand the potential benefits of consumption at higher trophic levels on water quality.
- Seasonal effects of anadromous alewife should be better characterized. Would timing of flushing events to coincide with anadromous alewife migration be beneficial to water quality? How does the zooplankton community structure adapt to increased size-selective predation, and is that really a potential cause of water quality problems?
- Rate-limiting nutrients in lakes supporting anadromous alewife should be investigated further. Do large populations of alewife shift the rate-limiting nutrient from phosphorus to nitrogen or vice versa?
- Does competition for zooplankton affect the population dynamics of resident fishes? If so, does zooplankton predation decrease when transient adult and juvenile anadromous alewives are not present in the lake?

Restoring anadromous alewife to its historical habitat is important for numerous reasons, including providing a source of prey for higher trophic levels and influencing zooplankton dynamics in freshwater ecosystems. In addition, restoring access to historical spawning habitat will benefit the ground fishery stocks in the Gulf of Maine (Ames and Lichter 2013) and other endangered diadromous species (Saunders et al. 2006). Finally, harvesting migrating adult alewives provides an economic benefit to communities. For many years, anadromous alewives have been associated with landlocked alewives and the potential negative effects of non-native stocking or invasiveness. There are distinct differences, both behaviorally and phenotypically, between these members of the same species. In conclusion, the KWD should not consider the restoration of anadromous alewife to be a threat to its mission to provide clean, safe water to its customers.

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