U.S. Fish & Wildlife Service

Seasonal Migrations and Essential Habitats of Broad Whitefish, Humpback Whitefish, and Least Cisco in the Selawik River Delta, as Inferred from Radiotelemetry Data, 2004–2006

Alaska Fisheries Data Series Number 2013-3

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Cover: Satellite image of the Selawik River delta courtesy of Google Earth. The eastern part of Selawik Lake is along the left side of the image. The delta region included in this image is approximately 45 km by 45 km.

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Randy J. Brown

Abstract

Thousands of whitefish of three primary species in the subfamily Coregoninae are harvested each year in the Selawik River delta in northwest Alaska, yet little is known about contributing populations, their migrations in the region, or the habitats they use. Radio transmitters were deployed in 64 broad whitefish *Coregonus nasus*, 64 humpback whitefish *C. pidschian*, and 32 least cisco *C. sardinella* during 2004 and 2005 to identify their seasonal migrations and essential habitats. Few fish tagged in the northern region of the delta migrated to the southern region, and few fish tagged in the southern region migrated to the northern region, indicating significant habitat fidelity at that spatial scale. No radio-tagged fish of any species were harvested during the three years of this project indicating that annual harvest rates of whitefish species were very low. Spawning areas were located for broad whitefish in the Kobuk River and for humpback whitefish in the upper Selawik River and in two smaller drainages in the Selawik River delta region. No least cisco spawning areas were identified. Because only a small fraction of radio-tagged fish migrated to upstream spawning habitats, it was hypothesized that some individuals of all three species spawned over suitable gravel or sand substrate in Selawik Lake. Future research designed to test this hypothesis would add significantly to our knowledge of this productive fishery.

Introduction

Residents of Selawik, in the Selawik River drainage in northwest Alaska (Figure 1), are dependent on several whitefish species (Family: Salmonidae, Subfamily: Coregoninae), northern pike *Esox lucius*, and burbot *Lota lota* to meet their subsistence fish needs because Pacific salmon *Oncorhynchus* spp. are rarely encountered in the area (Georgette and Shiedt 2005; Menard et al. 2012). Fishing takes place during all seasons (Georgette and Shiedt 2005) and the harvest of whitefish species far exceeds that of all other fishes (Braem et al. draft report). In 2010, Braem et al. (draft report) conducted a comprehensive subsistence harvest survey in Selawik and reported that approximately 33% of the total wild food harvest by weight was broad whitefish *Coregonus nasus*. They estimated that over the course of the year, Selawik residents harvested approximately 47,000 broad whitefish, 13,000 humpback whitefish *C. pidschian*, and 6,000 least cisco *C. sardinella*, for a total of about 66,000 whitefish. The Selawik River delta is clearly an extraordinarily productive environment for whitefish species.

Five whitefish species have been reported in the Selawik River drainage (Alt 1980; USFWS 1993; Brown 2004). Inconnu *Stenodus leucichthys* (sheefish), broad whitefish, and humpback whitefish are relatively large fish and are actively targeted in subsistence fisheries in the area (Georgette and Shiedt 2005; Braem et al. draft report). Least cisco and round whitefish

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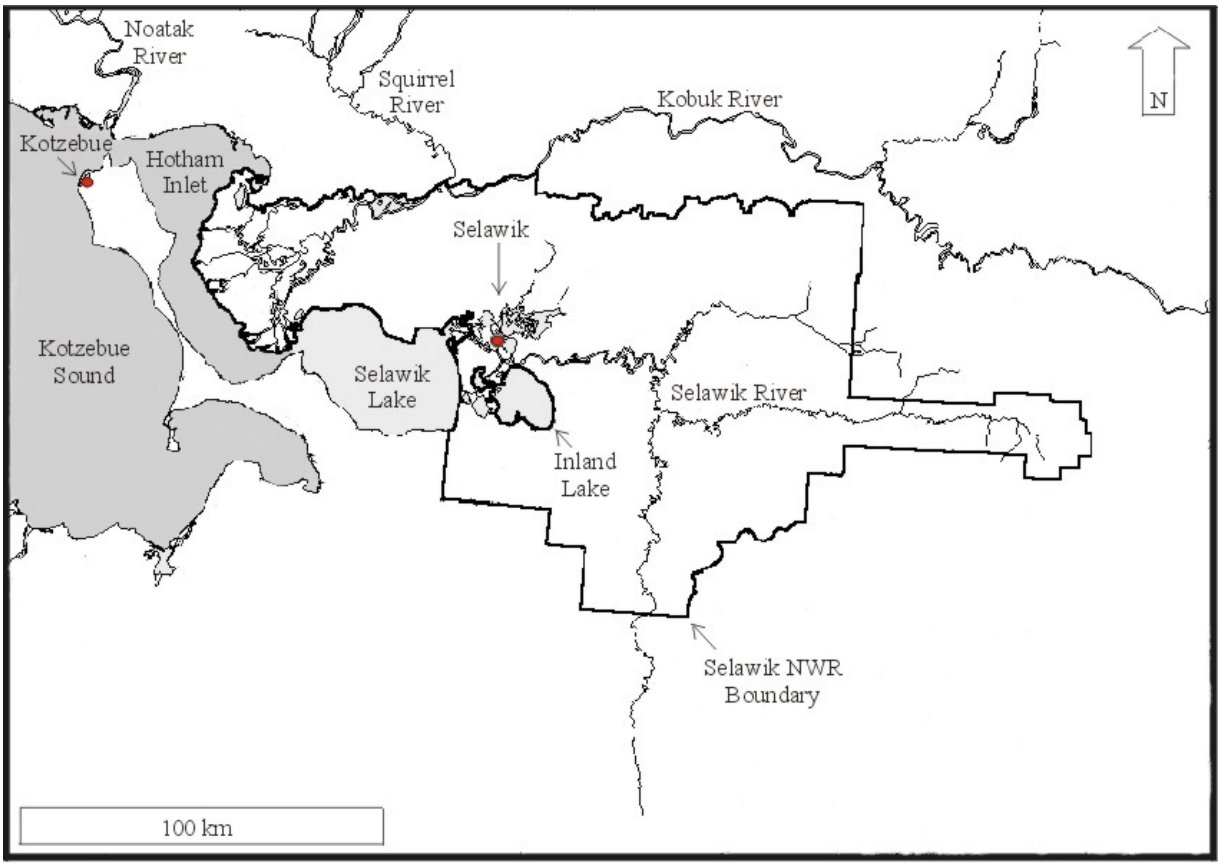

Figure 1. The Selawik River drainage and surrounding area in northwest Alaska.

Prosopium cylindraceum are relatively small fish. Some least cisco are taken in the fishery, but most pass unhindered through the large mesh gillnets that are commonly used (Brown 2004). Round whitefish are present in the upper reaches of the Selawik River drainage, but are not common in the fishery, which takes place in the lower reaches of the drainage (USFWS 1993).

Spawning, rearing, feeding, and overwintering habitats are all essential to sustain whitefish populations. Spawning habitats, however, are considered to be the most critical because they are more vulnerable to disturbance than other essential habitats. Spawning habitats in riverine environments can be singular geographic regions, often occupying a stream reach only a few km long, where a large fraction of a population congregates during the fall spawning season each year (Alt 1979, 1980; Underwood 2000; Brown 2006). The discrete nature of whitefish spawning areas suggests that specific habitat qualities are required for successful reproduction. By contrast, there are a wide variety of habitats used for rearing, feeding, and overwintering that are distributed over the entire geographic range of a population indicating much less specificity for those habitats (Reist and Bond 1988; Chang-Kue and Jessop 1992; Brown et al. 2007). Understanding where these essential habitats are located allows us to identify migrations, assess distribution, direct sampling efforts effectively, and evaluate potential risks faced by whitefish populations.

Our knowledge of spawning, rearing, feeding, and overwintering habitats of broad whitefish, humpback whitefish, and least cisco in the Selawik River delta is limited. These species are all highly migratory in other northern drainages (Reist and Bond 1988; Brown et al. 2007; Harper et al. 2009) and similar life history characteristics were expected in the Selawik River. Apparent

spawning migrations of all three species take place up the Kobuk River (Georgette and Shiedt 2005) and a substantial run of humpback whitefish migrate up the Noatak River (Fleischman et al. 1990). Broad whitefish and least cisco are apparently present in the Noatak River drainage also but no migrations have been identified and neither species is captured there in large numbers (Alt 1979; Georgette and Shiedt 2005). Demographic data have not been collected on whitefish species in either the Kobuk or Noatak rivers, but the descriptions of large egg masses of harvested females in Kobuk River communities, as presented in Georgette and Shiedt (2005), indicate that spawning migrations are taking place in that drainage.

All three whitefish species are captured in subsistence fisheries in the Selawik River delta region during all seasons (Johnson 1986; Georgette and Shiedt 2005). Brown (2004) found that mature-size individuals were common during spring and fall seasons but that immature-size individuals were rarely encountered. Otolith chemistry data revealed that most broad whitefish and humpback whitefish reared during their early years in salt water but a majority of least cisco remained in fresh water throughout life. Salinity measurements taken in surface water and at depth from points along a transect across Selawik Lake, up the length of Hotham Inlet, and out into Kotzebue Sound (Appendix Table 1; Appendix Figure 1) during summer 2004 and late winter 2005 suggest that Selawik Lake is a freshwater environment and Hotham Inlet and beyond are brackish or marine environments. However, a data logging salinity meter fixed to the lake bottom in 2010 found evidence of saline intrusions in the western part of Selawik Lake during winter, just south of the outlet channel (N. Smith, UAF, pers. comm.), indicating that Selawik Lake is not entirely or not always a freshwater lake. Despite what may be irregular or seasonal saline intrusions in Selawik Lake, fish exposed to salt water, as determined through otolith chemistry analysis, are thought to have migrated into Hotham Inlet or Kotzebue Sound where saline conditions are more prevalent. This saline gradient may explain the scarcity of juvenile broad whitefish and humpback whitefish in the Selawik River delta. Because there was little otolith chemistry evidence that juvenile least cisco went to salt water (Brown 2004), their scarcity in the Selawik River delta might indicate that they were rearing in the pelagic habitat of Selawik Lake.

Monitoring whitefish populations in the Selawik River delta or managing their harvests requires a greater understanding of their seasonal migrations and important habitats. Radiotelemetry has been an effective method for tracking fish migrations and locating important habitats used by fish. Eiler et al. (1992), for example, identified many previously known and new sockeye salmon *O. nerka* spawning areas in the turbid waters of the Taku River in southeast Alaska and British Columbia by tracking radio-tagged fish to their spawning destinations. Using similar methods, Chang-Kue and Jessop (1983) and Underwood (2000) successfully identified the timing of spawning migrations and located spawning habitats used by broad whitefish in the Mackenzie River in northern Canada and inconnu in the Selawik River drainage, respectively. Johnson (1987) attempted to locate spawning and overwintering habitats of broad whitefish and humpback whitefish in the Selawik River using radiotelemetry techniques but the project was not successful because of technical difficulties locating fish following tagging. The primary goals of this study were to identify spawning, overwintering, and feeding habitats used by mature broad whitefish, humpback whitefish, and least cisco based on the seasonal migrations of radio-tagged fish captured in the Selawik River delta. Secondary goals were to evaluate feeding habitat fidelity in north and south regions of the Selawik River delta, estimate harvest rates, and document sequential year spawning if it occurred.

Study Area

The Selawik River is a 6th order stream (Horton-Strahler method with 1:63,360 scale topographic map; Wetzel and Likens 1991) lying almost entirely within the Selawik National Wildlife Refuge in northwest Alaska (Figure 1). The river flows approximately 300 km from east to west through a wide tundra valley bisected by the Arctic Circle at north latitude 66.5622°. The lower 150 km of the Selawik River meanders through an extensive lowland region rich in large and small lakes drained by numerous streams. The river flows through two major distributaries into Selawik Lake, which is the third largest freshwater lake in Alaska with a surface area of about 1,050 km^2 (National Atlas of the United States 2013) and dimensions of approximately 32 km north to south and 42 km east to west. The region has the qualities of a northern maritime climate, particularly during the ice-free periods of the year (late May to early October), and becomes more similar to a continental climate during the winter months (Shulski and Wendler 2007). Annual precipitation ranges between 25 and 50 cm. Seasonal temperature extremes range from about 30°C in the summer to -50°C in the winter (USFWS 1993).

Methods

Sampling and fish selection criteria

Broad whitefish, humpback whitefish, and least cisco were captured for tagging during early summer in the Selawik River delta in areas where Selawik residents commonly fish (Johnson 1986; Georgette and Shiedt 2005). The delta was arbitrarily classified into northern and southern regions to evaluate distribution patterns within the delta (Figure 2). The regions were defined as being north or south of an east-west line separating the large Inland and Tuklomarak lake systems in the south from the smaller interconnected lake systems in the north. Monofilament gillnets with 5 cm stretch-mesh webbing were utilized for fish capture because mature individuals were more likely to get tangled by their maxilla and fins in the small-mesh nets than actually gilled, which reduced the likelihood of injury. Gillnets were set and constantly monitored until fish became entangled, at which time they were removed, placed into a tub of water, and evaluated for tagging.

Mature fish were sought for tagging because the primary objective was to identify spawning areas. Maturity was inferred based on fish length. Brown (2004) evaluated the maturity of female fish of all three species in the Selawik River delta using a gonadosomatic index (GSI) and for male humpback whitefish based on the presence of pearl tubercles, which are only present on pre-spawning fish during spawning season (Vladykov 1970). Brown (2004) determined that the minimum fork length (FL) at maturity for broad whitefish was approximately 44.5 cm, for humpback whitefish 38.0 cm, and for least cisco 27.5 cm. Tallman et al. (2002) reported that the smallest mature broad whitefish in a Mackenzie River population was about 39 cm FL, which was also the smallest mature female in a main-stem Yukon River population (Brown et al. 2012). Fleming (1996) reported that the smallest mature humpback whitefish and least cisco in the Chatanika River were 33.4 cm and 26.4 cm FL, respectively. Brown (2006) similarly identified the smallest mature humpback whitefish in an upper Tanana River population to be 33 cm FL. The smallest mature humpback whitefish and least cisco in main-stem Yukon River samples were 37 cm and 23 cm FL, respectively (Brown et al. 2012). These data indicate some variability among populations. In this study an effort was made to tag fish with fork lengths similar to or greater than those reported as mature by Brown (2004) for broad whitefish (44.5 cm), humpback whitefish (38.0 cm), and least cisco (27.5 cm).

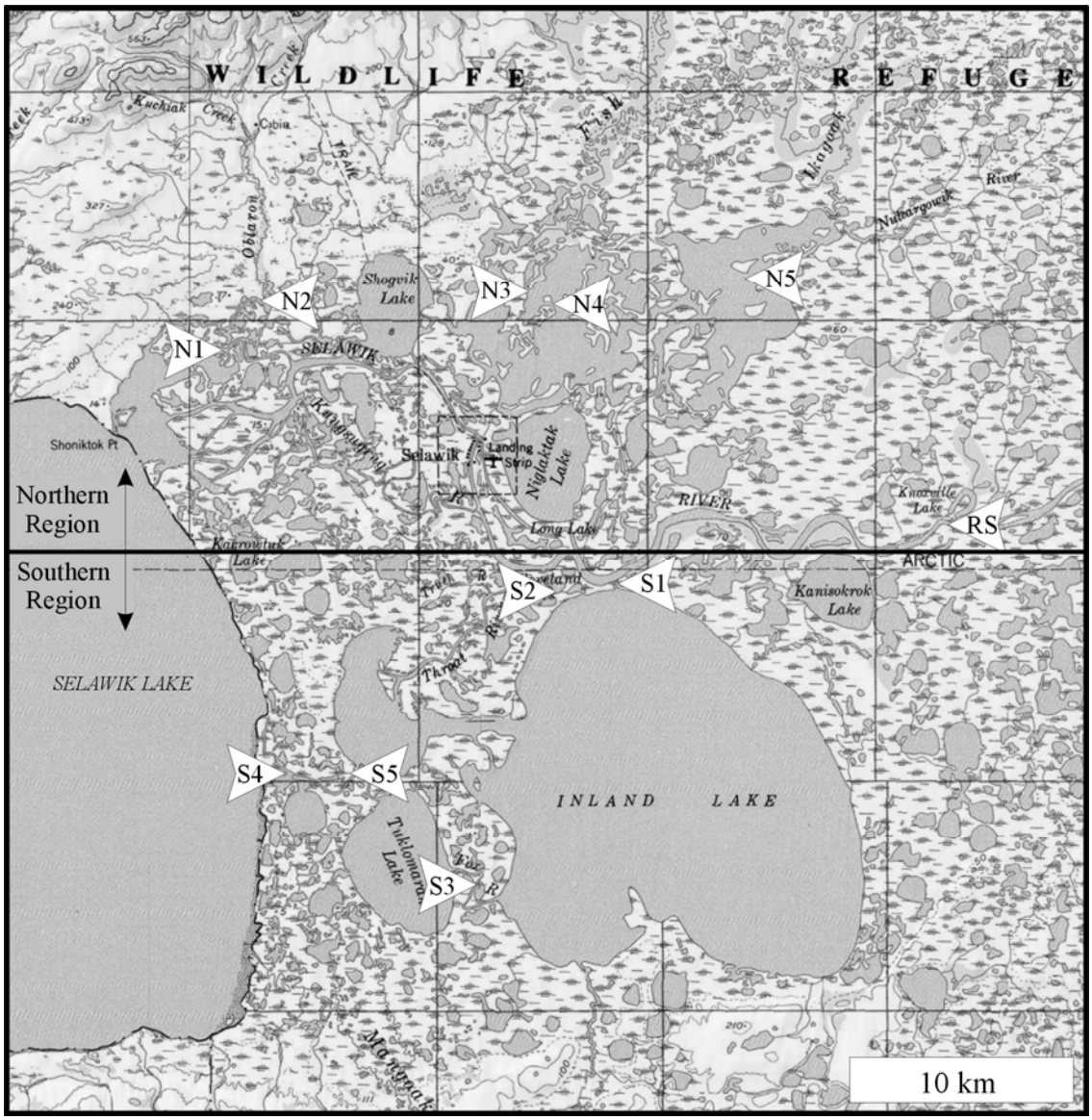

Figure 2. Tagging sites in the north (N#) and south (S#) Selawik River delta during 2004 and 2005. The location of the remote radio receiving station is indicated by the icon labeled "RS".

Radio transmitters and tagging procedures

Radio transmitters used in this study operated on four frequencies in the 162 MHz band. Individual transmitters were digitally coded for unique identification. The radio tags for broad whitefish, humpback whitefish, and least cisco weighed 10.0 g, 8.9 g, and 7.7 g, respectively. They were 11 mm in diameter and 59 mm, 49 mm, and 43 mm long, respectively. They each had a whip antenna about 42 cm long. The 2004 transmitters (n = 96, 32 for each species) were turned on in spring prior to surgery and programmed to transmit every 3 s for 6 months, go dormant for 4 months during winter, and begin transmitting again the following spring until their batteries expired in mid-summer. They functioned for approximately 13 months and provided a year-long record of fish locations excluding the mid-winter period. The 2005 transmitters (n = 64, 32 each for broad whitefish and humpback whitefish) were programmed to transmit every 3 s for 2 months during each of three important life history periods: 1) spawning (mid-September through early November); 2) overwintering (mid-January through early March); and 3) feeding

(mid-May through mid-July). They functioned for 2 years and were designed to provide additional information on seasonal habitat use and specific information on spawning site fidelity and spawning frequency of tagged fish. Because transmitters for least cisco were necessarily limited in size and therefore functional time, least cisco were not included in the 2005 tagging program.

Radio transmitters were surgically implanted into 160 fish during 2004 and 2005 using methods that are appropriate and effective for salmonid fishes (Winter 1996; Wagner et al. 2000; Jepsen et al. 2002). Following capture, fish were placed in an anesthetic solution composed of 40 $mg \cdot L^{-1}$ clove oil for most fish and 20 $mg \cdot L^{-1}$ clove oil for a small sample that were tagged when water temperature warmed to 15°C or greater. In the absence of an FDA approved immediate release anesthetic for fish, clove oil was selected because it is an effective anesthetic for salmonid fishes (Anderson et al. 1997; Woody et al. 2002), has been identified by the Alaska Department of Fish and Game as the preferred anesthetic when fish must be sedated (as stipulated in annual Fish Resource Permits), and is an approved food product for humans. Anesthetized fish were placed in a V-shaped cradle and water was delivered to their gills during surgery. An incision approximately 2 cm in length was made through the body wall into the peritoneum anterior to the pelvic girdle and to the left of center to avoid centrally located blood vessels and nerve channels, as suggested by Winter (1996). The antenna was routed posterior to the pelvic girdle with a long hypodermic needle and a grooved director in a modified, shielded-needle procedure (Ross and Kleiner 1982). The transmitter was placed into the incision and the incision was closed with three monofilament sutures using a simple interrupted suture pattern (Wagner et al. 2000). Following surgery, fish were held in a recovery tub of fresh water and released when they were able to swim away vigorously. Time from capture to release averaged 14 minutes and ranged from 8 to 22 minutes.

Aerial surveys and receiving station relocations

Radio-tagged fish were located during a series of aerial survey flights and by a remote radio receiving station located approximately 50 km up the Selawik River (Figure 2). There were 30 aerial survey flights conducted during the course of this project (Table 1). Because of transmitter programming differences between 2004 and 2005, aerial surveys for fish tagged in 2004 were conducted at approximately 2-3 week intervals throughout the summer and fall of 2004 and summer 2005, while aerial surveys for fish tagged in 2005 were conducted less frequently and were more directed to identifying spawning migrations with less focus on summer movements within the delta. The survey flights covered the Selawik River delta and numerous small streams flowing into the delta region; the Selawik River and its major tributaries, the Kobuk River delta, the Kobuk River, the Squirrel River, which is a tributary of the lower Kobuk River, the Noatak River, Selawik Lake, and Hotham Inlet. Data from the receiving station were downloaded opportunistically during summer and in September prior to spawning season so all fish that had migrated upstream would be known prior to fall aerial surveys. Migration patterns were inferred based on the series of relocations for each fish.

Spawning habitats

Spawning destinations, as characterized by Alt (1979), McPhail and Lindsey (1970), and Brown (2006), were indicated by late fall aggregations of fish in upstream, gravel-substrate, flowing water habitats. Humpback whitefish and least cisco spawn in late September or early October (Kepler 1973; Mann and McCart 1981; Alt 1979; Brown 2006) and the spawning time for broad whitefish is thought to be late October or November for most populations (Chang-Kue and Jessop 1983; VanGerwen-Toyne et al. 2008; Carter 2010). These seasonal spawning times, as

Table 1. Aerial survey dates and geographic coverage. Major regions and rivers that were surveyed (see Figure 1) include the Selawik River delta (Sel D.), Selawik Lake (Sel L.), Selawik River (Sel R.), small tributary streams flowing into the Selawik River delta (Sel ST, which includes the Ikagoak River [I], Fish River [F], Obleron Creek [O], Singauruk River [S], and the Mangoak River [M]), Tagagawik River (Tag R.), Hotham Inlet (Hot I.), Kobuk River delta (Kob D.), Kobuk River (Kob R.), and the Noatak River (Noa R.). At times only the north (N), south (S), east (E), or west (W) parts of a major region were successfully surveyed and these are indicated in the corresponding cells to provide a qualitative concept of coverage. Often a survey was relatively comprehensive within an entire region (All). The approximate downstream to upstream range are indicated in river kilometers (rkm) for river surveys.

	Major regions and rivers								
Aerial survey dates	Sel D.	Sel L.	Sel R.	Sel ST	Tag R.	Hot I.	Kob D.	Kob R.	Noa R.
June 30, 2004	All	N							
July 16, 2004	All	N,E							
July 29, 2004	All	All		F					
August 22, 2004		N							
August 23, 2004	E,N	N	0-150	I,F		S,E	E	0-190	0-140
September 1, 2004	All	N,E	0-240						
September 9, 2004	All	All		F		S,E			
September 22, 2004	All	All	0-290	F,O,M	0-20		W		
September 24, 2004	S	N,E	0-240			S,E	W,S		
October 12, 2004	All	All	0-240	F,S	0-80				
October 25, 2004	All	S,E	0-140	F,S				0-100	
November 4, 2004							N,S	0-190	
November 5, 2004	All	All		F		S			0-110
March 31, 2005	All	All		F		S			
May 9, 2005		All				E,N			
May 24, 2005	All	All		F		S,E			
June 9, 2005	S	S	0-240		0-12		W		
June 13, 2005	N	N				S,E			
August 8, 2005		E	0-240						
September 28, 2005			0-290	F					
September 29, 2005	NW,S	N,E		S,M			W		
October 31, 2005	S	All	200-240	S		S,W			
November 1, 2005						N		0-440	0-110
February 23, 2006	All	S,E	0-110			N	W,S	0-240	
February 27, 2006	All	N					W,S		
June 15, 2006	All	All		F			W,S		
August 8, 2006			110-250						
September 28, 2006			200-240		55-180				
October 12, 2006	N	N	0-110	F		S,E			
October 24, 2006								100-440	

documented in other locations, are consistent with observations of residents in the upper Kobuk River, who favor the large egg masses of female whitefish in late fall (Georgette and Shiedt 2005). Fall migrations from the Selawik River delta upstream to gravel substrate reaches were interpreted as spawning migrations. The upstream locations of humpback whitefish and least cisco during early October, and broad whitefish during late October or early November, were classified as spawning destinations. Sequential year spawning would be indicated if broad whitefish or humpback whitefish tagged in spring 2005 made repeat migrations to spawning habitats during fall 2005 and 2006.

Habitat fidelity and geographic distribution

Feeding and overwintering habitats were identified based on locations of radio-tagged fish during early summer and winter aerial surveys, respectively. Whitefish species feed heavily during spring and early summer (Alt 1979; Brown 2004; Harper et al. 2007) and minimally during winter (Schmidt et al. 1989). Brown (2004) considered the Selawik River delta optimal feeding habitat for all three species based on a high percentage of fish with food in their stomachs in early summer. In upstream riverine environments fish migrate in spring from the larger rivers where they overwinter to shallow, off-channel, floodplain lakes where zooplankton and aquatic insects are abundant. These species generally feed in lakes until mid- to late summer when they return to riverine environments to spawn and overwinter. Both Brown (2006) and Harper et al. (2009) observed a tendency for tagged fish to return to the same feeding lakes on sequential years indicating high levels of feeding habitat fidelity. Because the tagging region in the Selawik River was a relatively uniform environment with little distinction among lakes or between river and lake environments, it was hypothesized that broad whitefish, humpback whitefish, and least cisco would move randomly throughout the delta rather than exhibit fidelity to any one lake or region. A Chi-squared test of equal probability was used to test the null hypothesis ($\alpha = 0.05$) that all radio-tagged fish, regardless of tagging location, would have an equal probability of being relocated in the north and south regions of the delta. Data used in this analysis were species-specific records of fish relocated in the northern or southern regions of the delta during the summer feeding season with no statistical weight attached to the number of times relocated. As an example, if a fish was relocated once or 10 times in the southern part of the delta, it would receive a single record of being relocated in the south. Similarly, if a fish was relocated three times in the north and once in the south, it would simply be recorded as having been relocated in both regions. Relocation data from fall or winter, or from areas outside the delta environment, were not considered for this analysis. A significant outcome would indicate a tendency towards feeding site fidelity rather than random feeding throughout the delta.

Annual harvest rates

Annual harvest rates of broad whitefish, humpback whitefish, and least cisco populations within the Selawik River delta were estimated for the 2004 sample of radio-tagged fish as:

$$\widehat{H}_i = \frac{n_{ih}}{\left(n_{is} + n_{ih}\right)}$$

where, $\widehat{H}_i$ = estimated annual harvest rate of species *i*,

n_{ih} = number of tagged fish of species *i* that were harvested within a year of tagging,

n_{is} = number of tagged fish of species *i* that were known to be alive a year after tagging.

The 95% confidence intervals of the species-specific harvest rate estimates were calculated based on the binomial probability distribution as described by Conover (1999). The analysis was based on the assumption of equal probability of capture among tagged and untagged fish. This assumption required that tagged fish were not “trap-happy” or “trap-shy” (Seber 2002) and that tagged and untagged fish would be equally likely to migrate to and from the Selawik River delta region where fishing was taking place. Harvested fish were identified if they were reported (radio tags included contact information) or if extraordinarily strong radio signals emanated from the village of Selawik or from fish camps in the delta during aerial surveys, which would

indicate a radio tag out of the water. Water greatly attenuates radio transmission (Kuechle and Kuechle 2012) so radio tags in air can be detected at more than 10 times the distance of transmitters in water, making harvested fish very distinctive. Radio-tagged fish implanted in 2004 and located during summer 2005 that migrated 2 km or more from a winter or spring location were considered to be alive based on location precision criterion presented by Fleming (1996) and Brown (2006). In both of these radiotelemetry studies mortalities had been verified by boat. Multiple aerial surveys had subsequently been flown collecting position data that included the stationary transmitters for the duration of each project. Both Fleming (1996) and Brown (2006) reported that all stationary transmitter locations were within approximately 1 km of each other and conservatively concluded that position error using their survey methods, which were very similar to those used in this study, was less than 2 km. Fish that were located but not harvested and not considered to be alive were assumed to have succumbed to natural mortality, although this fate could not be assigned with certainty. Therefore, the number of radio-tagged fish considered to be alive in summer 2005 was potentially biased low, which would result in a biased high estimate of annual harvest rate. This harvest rate analysis was not conducted for radio tags deployed in 2005 because the frequency of flights in 2006 was substantially reduced so our confidence in classifying fish as alive or not was reduced.

Results

Overview of the project

Broad whitefish (n = 64), humpback whitefish (n = 64), and least cisco (n = 32) were tagged at five sites in the northern region of the Selawik River delta and five sites in the southern region during 2004 and 2005 (Figure 2). Most broad whitefish and humpback whitefish, and all least cisco, were equal to or larger than the minimum size at maturity (Figure 3). Aerial surveys were effective in the Selawik River delta and along all the surveyed river systems and the probability of missing fish that were present was thought to be very low. Radio signals were routinely detected in these environments at distances of 5 km or more, signal strength was uniformly high on close approach, and all detected transmitters were decoded, which is required to identify specific tagged fish. In contrast, aerial surveys of the large lake and estuary environments of Selawik Lake and Hotham Inlet were not particularly effective and the probability of missing fish that were present was thought to be relatively high. According to the coastal survey chart of the region by the National Oceanic and Atmospheric Administration (NOAA 1998), which provides soundings within these water bodies, neither is greater than 6 m deep except in the northern region of Hotham Inlet. Radio signals should transmit sufficiently strong through 6 m of fresh (i.e., low conductivity) water for aerial survey reception (Winter 1996; Kuechle and Kuechle 2012). Hotham Inlet was brackish but apparently highly stratified under ice through most of its expanse so reception was thought to be possible, particularly along the Kobuk River delta front. Because radio signals appeared to be strong in the Selawik River delta, where lake depths are generally less than 3 m, it was assumed that Selawik Lake would have similarly good radio signal propagation characteristics. The primary issue impacting survey efficiency in these lake and estuary environments was their large surface areas, which allowed the detection of faint signals at the periphery of reception range, but frequently required time consuming aerial searches to receive signals strong enough to decode. Lake surveys within about 1 km of shore were much more effective than offshore surveys.

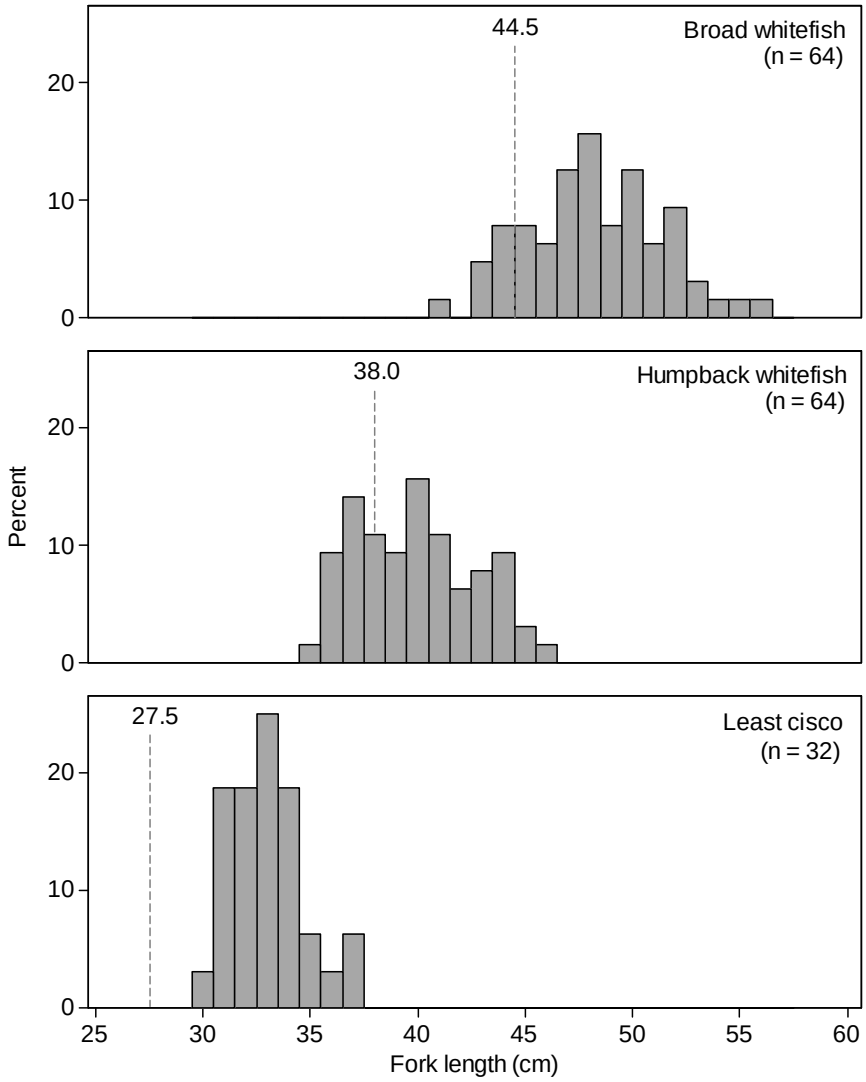

Figure 3. Length distributions of radio-tagged samples of broad whitefish, humpback whitefish, and least cisco in the Selawik River delta during 2004 and 2005. The vertical dashed lines indicate the minimum lengths of maturity for the three species as determined with gonadosomatic indices and the presence of pearl tubercles (Brown 2004). Most radio-tagged broad whitefish and humpback whitefish and all least cisco were larger than these target values.

Spawning habitats

During the spawning season 38 radio-tagged broad whitefish, 43 humpback whitefish, and 19 least cisco were relocated. There were 8 broad whitefish and 23 humpback whitefish relocated in flowing water, gravel-substrate habitats characteristic of known spawning habitats. All other radio-tagged fish, including all least cisco, remained in the Selawik River delta or in Selawik Lake, which would not generally be characterized as spawning habitats for whitefish species. All eight broad whitefish in characteristic spawning habitats were located in the Kobuk River. The farthest upstream group of broad whitefish (n = 5) was located between Ambler and Shungnak, approximately 280 river kilometers (rkm) from Hotham Inlet. Humpback whitefish in characteristic spawning habitats were located as far as 35 rkm up the Fish River (n = 16),

about 230 rkm up the Selawik River (n = 5), and about 20 rkm up the Singauruk River (n = 2; Figure 4). All five humpback whitefish located in the upper Selawik River during spawning season had previously been recorded migrating upstream past the receiving station on the lower Selawik River (Figure 2). Seven additional humpback whitefish and two broad whitefish were recorded migrating upstream past the receiving station during summer and then back downstream again a few days later, suggesting that a small fraction of fish feed upstream in the Selawik River. No least cisco were recorded migrating past the station. Several broad whitefish and humpback whitefish tagged in 2005 migrated to spawning habitats in 2005 or 2006, but none migrated to spawning habitats during both years.

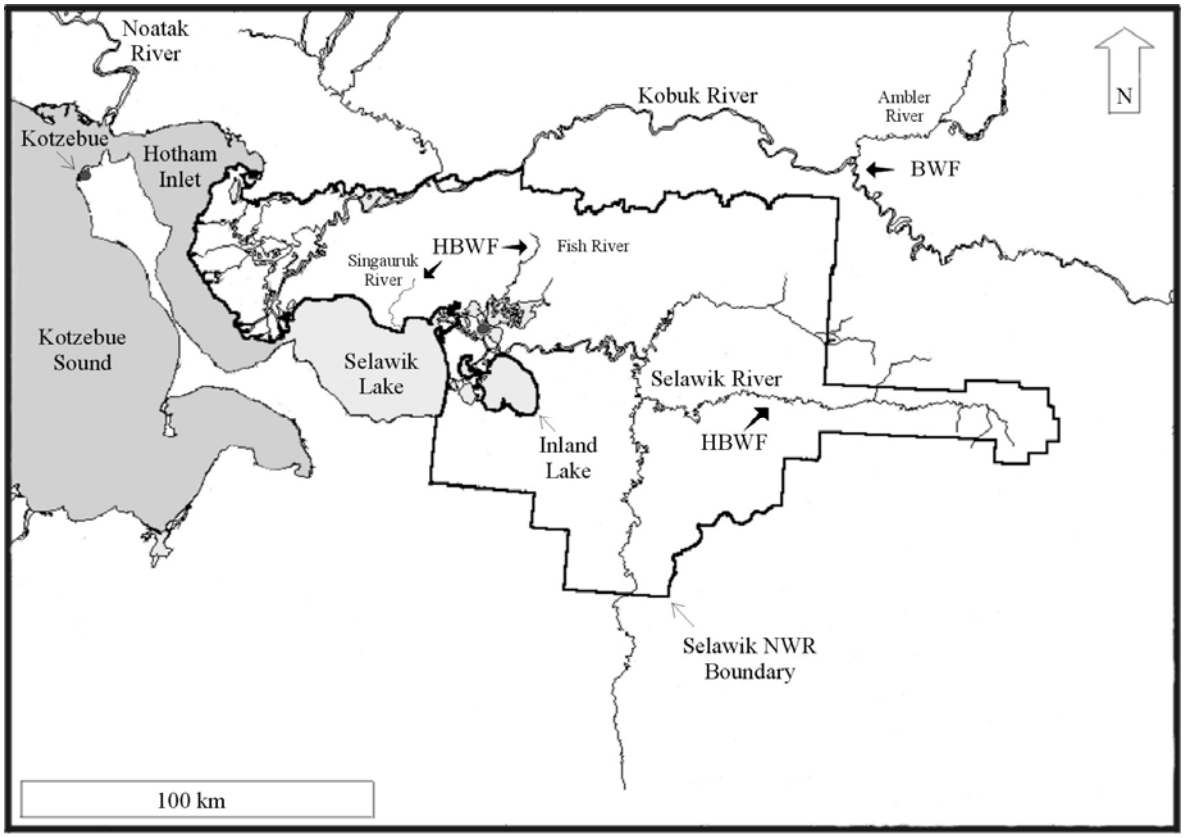

Figure 4. Spawning regions of humpback whitefish (HBWF) in the Selawik River drainage and broad whitefish (BWF) in the Kobuk River based on spawning season aggregations in gravel-substrate, flowing water habitats.

Habitat fidelity and geographic distribution

Fish relocated in the Selawik River delta were predominantly located within the region where they were tagged. Few fish tagged in the north region were relocated in the south region, and few fish tagged in the south region were relocated in the north region (Table 2). The null hypothesis that all fish, regardless of tagging region, had an equal probability of being located in the north and the south delta regions during summer was rejected for all three species (broad whitefish: $P < 0.001$; humpback whitefish: $P < 0.001$; least cisco: $P = 0.023$), indicating significant feeding habitat fidelity at that spatial scale. Additionally, all but 1 of the 14 fish recorded at the receiving station had been tagged in the south region of the delta. Some fish of all three species were relocated in Selawik Lake. Twenty-six fish were never relocated following tagging.

Table 2. Tagging and relocation history of radio-tagged broad whitefish (BWF), humpback whitefish (HBWF), and least cisco (LCIS) by major regions of the Selawik River delta. Note that an individual fish may have been relocated in more than one geographic region.

Tagging region	Species	Number tagged	Relocated in north region	Relocated in south region	Relocated in Selawik Lake	Not relocated
North	BWF	36	28	3	4	3
North	HBWF	40	23	1	9	10
North	LCIS	16	10	4	4	3
South	BWF	28	2	21	4	3
South	HBWF	24	3	9	10	3
South	LCIS	16	4	10	2	4
Total		160	70	48	33	26

There were 13 of 64 broad whitefish (20%), 10 of 64 humpback whitefish (16%), and 16 of 32 least cisco (50%) relocated in the Selawik River delta and in coastal regions of Selawik Lake during winter. The relative scarcity of tagged broad whitefish and humpback whitefish in the winter suggests they may have dispersed into Hotham Inlet, which would be consistent with otolith chemistry analyses indicating exposure to salt water, as discussed by Brown (2004). By contrast, otolith chemistry data for least cisco indicated that few individuals ever migrated to brackish water. Also, least cisco were relocated in freshwater habitats of the Selawik River delta region during the winter at a greater apparent rate than the other species. Pelagic regions of Selawik Lake were the most likely habitat occupied by least cisco that were not relocated during the winter.

Harvest rates

Residents of the village of Selawik pursued their subsistence fishing traditions in the Selawik River delta during 2004 and 2005, as evidenced by aerial survey observations of many nets in the water and large numbers of fish hanging on racks. Most of the fishing effort appeared to be in the northern part of the delta, consistent with data presented by Johnson (1986) and Georgette and Shiedt (2005). Despite the obviously successful fishing efforts by local residents and the many radio-tagged fish present in the area, there were no reported harvests of tagged fish. Additionally, no radio tags were identified as being out of the water in Selawik or fish camps in the delta, which would have been expected if tagged fish were captured but not reported. Fish tagged in summer 2004 that were alive in summer 2005 included 30 broad whitefish, 26 humpback whitefish, and 24 least cisco. Because the error around a binomial proportion estimate is directly influenced by sample size and 0 is a possible result, annual harvest rate estimates in the Selawik River delta during 2004 and 2005, expressed as 95% confidence intervals, were 0.0 to 0.116 for broad whitefish, 0.0 to 0.132 for humpback whitefish, and 0.0 to 0.142 for least cisco. Even though no formal analyses were conducted with fish tagged in summer 2005, none were reported harvested and none were identified out of the water during aerial surveys, providing additional support for estimates of low annual harvest rates for whitefish species in the Selawik River delta.

Discussion

There were 26 of 160 tagged fish (16%) that were never relocated following tagging (Table 2), while others were relocated on nearly every survey. It is possible to miss a radio signal during an aerial survey, but the probability of missing a signal repeatedly when a transmitter is

operating properly is extremely low, particularly in a shallow, freshwater environment such as the Selawik River delta. To ensure proper function, all transmitters were tested prior to being deployed and there were no malfunctions. Evidence of post-deployment malfunctions of modern fish transmitters is extraordinarily rare and tag failure is not thought to explain relocation failures in this investigation. While we cannot know the position of a radio-tagged fish without relocation information, the repeated absence of signals from the 26 undetected fish suggests they migrated away from the Selawik River delta following tagging.

Spawning habitats

Georgette and Shiedt (2005) documented the presence of several whitefish species in both the Kobuk and Noatak rivers based on the harvests and accounts of residents of those rivers. Some tagged inconnu that spawn in the Kobuk River have been captured in the Selawik River delta demonstrating that inconnu populations in the region share common estuarine feeding environments (Alt 1977; Miller et al. 1998; Underwood 2000). It was thought that some broad whitefish, humpback whitefish, and least cisco might follow a similar distribution pattern with spawning origins in other rivers while using the Selawik River delta for feeding. Aerial surveys during the spawning seasons of 2004 through 2006 located broad whitefish in the Kobuk River but no radio-tagged fish of any species were located in the Noatak River. Eight broad whitefish were ultimately relocated in the Kobuk River, five upstream and three downstream from the mouth of the Ambler River, about 280 rkm up the Kobuk River (Figure 4). The Kobuk River was the only drainage where broad whitefish were located in gravel-substrate, flowing water habitat, and it is thought that their farthest upstream positions represented spawning locations.

Broad whitefish

Spawning areas for broad whitefish are less clearly defined than for other whitefish species, primarily because they spawn later than the others, during or shortly after freeze-up (Reist and Bond 1988; Shestakov 2001). Cheng-Kue and Jessop (1983) identified broad whitefish spawning areas approximately 240 rkm and 630 rkm upstream from the river delta in the main-stem Mackenzie River based on migration patterns of radio-tagged fish. The substrate over which spawning occurred was not known, but the upstream site was at the foot of a large rapid, and it was assumed that the substrate was composed of rocky material suitable for spawning. Carter (2010) conducted a similar radio-tagging project with pre-spawning broad whitefish in the Yukon River and identified a key spawning area dominated by gravel substrate in the central Yukon Flats, approximately 1,500 km from the Bering Sea. Residents of the upper Kobuk River reported late fall harvests of broad whitefish in which the females were heavy with eggs (Georgette and Shiedt 2005), indicating a late spawning migration in the drainage. Radiotelemetry data presented here confirm broad whitefish migrations from the Selawik River delta up the Kobuk River during a season that is consistent with spawning activity. Brown (2004), however, found that approximately half of mature broad whitefish present in the Selawik River delta during September were preparing to spawn, which led to the expectation that half of the radio-tagged fish would migrate to spawning areas in the fall. Yet, only 13% (n = 8) of the radio-tagged fish (n = 64) were present in recognizable spawning habitats, which was significantly less than half (95% CI = 0.06 to 0.23; based on the binomial probability distribution). These relocation data suggest that broad whitefish in the Selawik River delta region spawn less frequently than the biological sampling data indicated (Brown 2004), or alternatively, that some spawned over suitable substrate in Selawik Lake. Documenting spawning in a large lake environment would require an intensive sampling program, similar to that described by Bidgood (1974) for lake whitefish *C. clupeaformis*. Bidgood's (1974) study

was designed to capture and identify pre-spawning and post-spawning lake whitefish concurrently in an environment similar to Selawik Lake.

Humpback whitefish

Known whitefish spawning areas for humpback whitefish (and the closely related lake whitefish) have always been characterized as having rock, gravel, or sand substrate, and never as a substrate of mud or other soft material (McPhail and Lindsey 1970; Scott and Crossman 1973; Morrow 1980). Spawning areas have been documented in flowing water (Alt 1979; Brown 2006; Harper et al. 2012) and in lakes (Hart 1930; Bidgood 1974; Anras et al. 1999). Distinct migrations from summer feeding areas to fall spawning areas have been documented (Brown 2006; Dupuis 2010; Harper et al. 2012) and are assumed to occur for most riverine populations. The migrations of radio-tagged humpback whitefish into gravel substrate reaches of the Fish, Singauruk, and Selawik rivers in late September and early October are consistent with our understanding of riverine spawning migrations. Georgette and Shiedt (2005) reported that Selawik elders identified the same three areas as humpback whitefish spawning locations and provided additional support for the Fish River as a spawning destination with their description of a traditional weir site used to harvest large numbers of humpback whitefish as they migrated out of the river in late fall, presumably after spawning. Hander et al. (2008) conducted a mark-recapture project with inconnu in the upper Selawik River in which fish capture was done in part with large beach seines. While the formal report does not discuss the capture of other species, R. Hander (U.S. Fish and Wildlife Service, pers. comm.) indicated that large numbers of pre-spawning humpback whitefish with breeding tubercles present were captured in beach seines along with inconnu, verifying the upper Selawik River as a spawning destination. In the current study, an additional 10 humpback whitefish were located in Selawik Lake during the spawning season, however, because they were not in gravel-substrate, flowing water habitats, they were not thought to be spawning. Additionally, fall aerial survey flights into the Kobuk and Noatak rivers found no radio-tagged humpback whitefish, suggesting that few fish from those spawning populations feed in the Selawik River delta during spring and summer. Humpback whitefish present in recognizable spawning habitats (n = 23) represented only 36% of radio-tagged fish (n = 64), which was significantly less than half (95% CI = 0.24 to 0.49; based on the binomial probability distribution).

There has been a perception among many fisheries scientists that mature humpback whitefish and other closely related whitefish species spawn once every two or three years (Morin et al. 1982; Reist and Bond 1988; Lambert and Dodson 1990). This perception is based primarily on observations that some fraction of mature fish remain in non-spawning condition during the fall spawning period. Lambert and Dodson (1990) conducted a physiological study on anadromous lake whitefish in Hudson Bay and concluded that the energetic demands of reproduction did not allow those fish to spawn two years in a row. If the mature members of a population were to spawn once every two years, approximately half of the mature population would prepare to spawn each fall. Brown (2004) did not capture sufficient numbers of humpback whitefish in the Selawik River delta during fall sampling to estimate the spawning fraction of the population using biological sampling data, but other studies suggest that half or more of the mature component of humpback whitefish populations should be preparing to spawn in any given year. For example, in similar radiotelemetry studies with humpback whitefish in the upper Tanana and Koyukuk River drainages, Brown (2006, 2009) estimated that more than 70% of the mature populations migrated to spawn each year indicating that some fraction of those populations spawned two or more years in a row. In a more similar environment to the Selawik River delta,

Moulton et al. (1997) sampled humpback whitefish in Dease Inlet along the western Beaufort Sea coast of Alaska and estimated that approximately half of the mature population was preparing to spawn, consistent with the concept of spawning once every two years. Spawning data from this study suggest that humpback whitefish either spawn less frequently than once every two years, or that some spawn in Selawik Lake, presumably in locations with rock, gravel, or sand substrates as reported in other lake systems by Hart (1930), Bidgood (1974), and Anras et al. (1999). Documenting spawning in a large lake environment would require an intensive sampling program as discussed above for broad whitefish.

Least cisco

Spawning areas for least cisco have been documented in flowing water over gravel substrate (Alt 1983; Fleming 1996), and their presence in isolated lakes indicates their capacity to spawn in lake habitats as well (Doxey 1991; Glesne et al. 2011). Additionally, Mann and McCart (1981) determined that spawning occurred in Trout Lake, a lake in northwest Canada with a small outlet stream but no inlet stream, by documenting the presence of both pre-spawning and post-spawning least cisco. Distinct migrations from summer feeding areas to fall spawning areas have been documented or inferred (Berg 1962; Fleming 1996; Brown et al. 2007), and were assumed to occur for most riverine populations. However, Berg (1962) contended that while some least cisco found in the deltas of large Asian rivers migrated to upstream spawning areas, others simply spawned in the delta environment. Residents of the upper Kobuk River harvest least cisco that apparently make upstream spawning migrations, although their presence in the upper river during spring, as reported by Georgette and Shiedt (2005), suggests that at least some may be residents of the upper river. Maturity sampling in Trout Lake (Mann and McCart 1981) and the Selawik River delta (Brown 2004) suggest that once least cisco became mature in these environments, they spawned every year. Moulton et al. (1997), however, reported that only about half of the mature least cisco sampled in Dease Inlet were preparing to spawn, indicating that in some environments spawning may occur once every two years. Biological data from the Selawik River delta (Brown 2004) led to the expectation that all radio-tagged least cisco would migrate to upstream spawning habitats during the fall. Yet all fish located in the fall (21 of 32), were in the delta or in Selawik Lake and none were in upstream, gravel-substrate habitats. These data strongly suggest that least cisco spawn over suitable substrate in Selawik Lake, which could be confirmed with an intensive sampling program as discussed above.

Habitat fidelity

The finding that few fish migrated from the northern region of the Selawik River delta to the southern region or from the southern region to the northern region (Table 2), indicates that most individuals exhibited some level of habitat fidelity within the delta. Further, the localized area selected during summer by humpback whitefish appeared to be related to the locations of their spawning areas. For example, of the 16 humpback whitefish that migrated into the Fish River during spawning season (Figure 4), 15 were tagged in the northern region and only 1 was tagged in the southern region. Also, all 5 of the humpback whitefish that migrated up the Selawik River during spawning season were tagged in the southern region. Additionally, most fish of all species relocated in northeast Selawik Lake were tagged in the northern region and most of those relocated in southeast Selawik Lake were tagged in the southern region. These findings suggest that fish tagged and relocated in the northern region were accessing the delta primarily through the northern mouth of the Selawik River and those tagged and relocated in the southern region were accessing the delta primarily through the southern mouth of the river. Presumably, populations in the northern region could vary in abundance independently from those in the

southern region. These data could be used to direct fishing effort to different populations of fish if harvest management is ever required.

Harvest rates

The uniformly low harvest rates observed in this study suggest the fishery is sustainable at current levels. While data used to estimate harvest rates in this study did not provide sufficient accuracy or precision to monitor minor changes in harvest rates, they did provide a measure of confidence that the fishery was not significantly impacting whitefish populations. Healy (1980) and Mills et al. (1995) found that annual exploitation rates as high as 30% to 40% for lake whitefish populations resulted in significant increases in recruitment and growth, indicating a density dependency within those populations. They argued that production, as measured in biomass of young, rapidly growing fish, increased short term with increased exploitation. Mills et al. (1995) further suggested that annual exploitation rates as high as 26% of the adult population would be sustainable without major changes in size and age structure, but contended that annual exploitation rates of 40% or greater could potentially reduce a population's capacity to return to an unexploited condition. The Selawik River environment is more complex than the lake environments studied by Healy (1980) and Mills et al. (1995). Therefore, their findings may not be directly applicable, but they do provide useful guidelines. Major changes in Selawik area harvest patterns that could arise from significant commercial exploitation, which was explored briefly during the mid-1980s (Lean et al. 1992), would warrant a monitoring program in the future.

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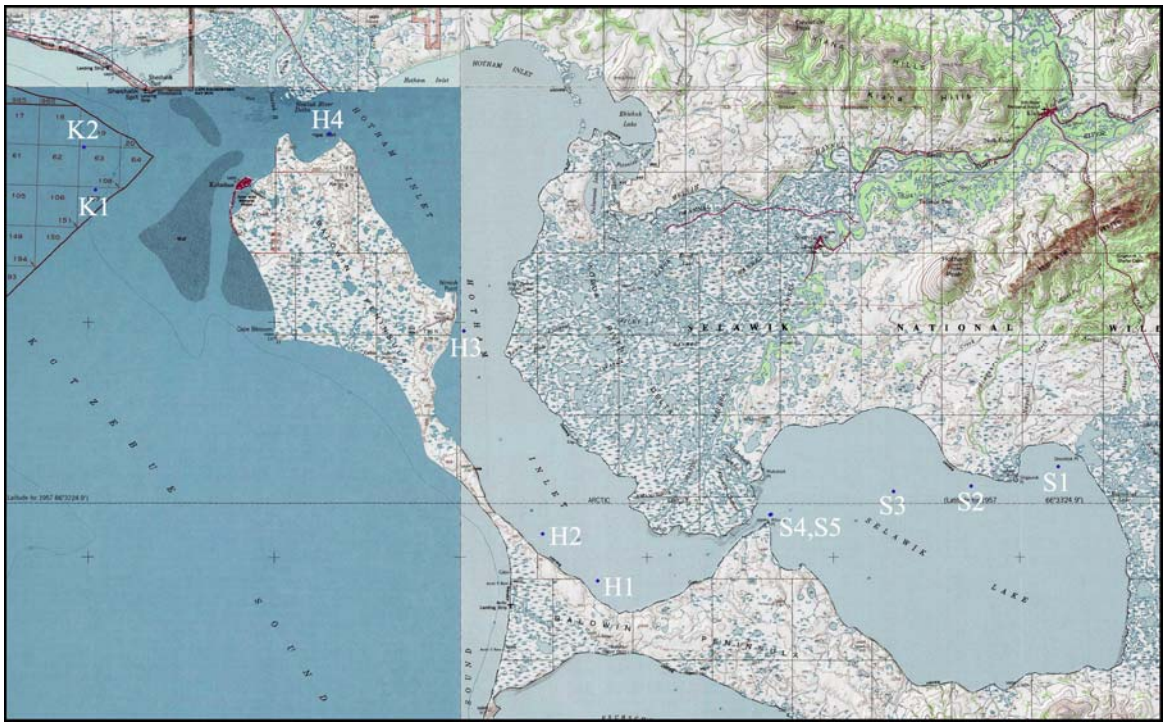
Appendices

Appendix Table 1. Salinity (Sal; practical salinity units, psu), temperature (Temp; °C), and dissolved oxygen (DO; mg•L^{-1}) measurements collected during summer 2004 and late winter 2005 from locations in Selawik Lake, Hotham Inlet, and Kotzebue Sound (see Appendix Figure 1 for a location map). Data were collected approximately 0.5 m below the surface (or below the bottom of the ice for winter measurements) and approximately 0.5 m above the bottom for all collection locations and at mid-depth for some collection locations. All data were collected with a calibrated YSI model 85 water quality meter.

Location	Date	N Lat	W Long	Depth (m)	Sal (psu)	Temp (°C)	DO (mg•L^{-1})
Selawik 1	6/18/04	66.5954	160.4003				
Surface				0.5	0.0	18.4	*
Bottom				2.1	0.0	18.0	*
Selawik 2	6/18/04	66.5746	160.6342				
Surface				0.5	0.1	13.7	*
Bottom				3.0	0.1	13.0	*
Selawik 3	6/18/04	66.5688	160.8422				
Surface				0.5	0.1	13.6	*
Bottom				4.5	0.1	10.7	*
Selawik 4	6/18/04	66.5441	161.1728				
Surface				0.5	0.1	11.6	*
Bottom				2.0	0.1	11.0	*
Selawik 5**	4/6/05	66.5447	161.1703				
Surface				1.0	0.0	0.0	9.6
Bottom				2.0	0.0	0.2	5.3
Hotham 1	3/29/05	66.4679	161.6491				
Surface				1.0	0.2	0.2	15.8
Midwater				2.3	0.2	0.2	15.2
Bottom				3.5	23.3	2.1	2.5
Hotham 2	3/29/05	66.5238	161.7831				
Surface				1.0	0.2	0.2	16.1
Midwater				2.5	0.2	0.3	15.0
Bottom				4.5	24.4	1.8	2.9
Hotham 3	3/29/05	66.7403	161.9952				
Surface				1.0	0.3	0.0	14.9
Midwater				2.5	11.1	0.2	12.2
Bottom				4.5	23.0	0.8	7.4
Hotham 4	3/29/05	66.9502	162.3546				
Surface				1.0	6.8	-0.5	9.5
Midwater				3.5	7.2	-0.5	9.5
Bottom				6.5	7.2	-0.5	9.5
Kotzebue 1	3/30/05	66.8906	162.9833				
Surface				1.0	13.4	-0.8	12.7
Midwater				3.5	26.7	-1.4	14.5
Bottom				6.6	30.1	-1.6	15.1
Kotzebue 2	3/30/05	66.9354	163.0145				
Surface				1.0	10.3	-0.6	11.3
Midwater				4.0	25.0	-1.4	10.1
Bottom				7.3	25.1	-1.5	12.0

*Dissolved oxygen was assumed to be saturated during these open water measurements.
**These winter data from Selawik Lake are courtesy of C. Lean, Nome, Alaska.



Appendix Figure 1. Salinity, temperature, and dissolved oxygen measurement locations across Selawik Lake (blue points labeled as S1 through S5 correspond with sites Selawik 1 through Selawik 5 in Appendix Table 1, etc.), Hotham Inlet, and Kotzebue Sound. Map figure is from a USGS 1:250,000 scale topographic map.