Summary of Ecological Information Relevant to Great Slave Lake Fisheries

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SUMMARY OF ECOLOGICAL INFORMATION RELEVANT TO GREAT SLAVE LAKE FISHERIES

by

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To support development of an Integrated Fisheries Management Plan (IFMP) for Great Slave Lake, Fisheries and Oceans Canada (DFO) requested a synthesis of over 300 periodic research and monitoring studies on fish species and ecosystem dynamics. This literature review provides a summary of results provided by topic area, rather than a re-analysis of previously collected data and includes a focused synthesis of 122 documents on species-specific content. Focus was placed on the commercial fishery species of Lake Whitefish (*Coregonus clupeaformis*) and Lake Trout (*Salvelinus namaycush*). Since the collapse of Lake Trout stocks in the 1960s, other species such as Cisco (*Coregonus artedi*), Northern Pike (*Esox lucius*), and Inconnu (*Stenodus leucichthys*) have become more prominent in the commercial harvest. Also reviewed in this report are products of DFO's long-term monitoring program; recent fisheries research containing integrated data on limnological and lake-river interactions, which recognize the influence of the unique physio-geographic features of the lake; and a five year (2011–2016) fishery-independent systematic grid survey, which sampled environmental variables and the food web throughout the Main Basin. The report concludes with identification of information gaps in support of finalizing the IFMP for Great Slave Lake.

RÉSUMÉ

MacKenzie, C.J.A., Fortin, B.L., and Stevens C.E. 2022. Summary of Ecological Information Relevant to Great Slave Lake Fisheries. Can. Manuscr. Rep. Fish. Aquat. Sci. 3214: vii + 63 p.

Afin d'appuyer l'élaboration d'un Plan de gestion intégrée des pêches (PGIP) pour le Grand lac des Esclaves, Pêches et Océans Canada (MPO) a demandé une synthèse de plus de 300 études périodiques de recherche et de surveillance sur les espèces de poissons et la dynamique des écosystèmes. Cette revue de littérature fournit un résumé des résultats par thème, plutôt qu'une nouvelle analyse des données recueillies précédemment et comprend une synthèse ciblée de 122 documents sur le contenu spécifique aux espèces. L'accent a été mis sur les espèces de pêche commerciale du grand corégone (*Coregonus clupeaformis*) et du touladi (*Salvelinus namaycush*). Depuis l'effondrement des stocks de touladi dans les années 1960, d'autres espèces telles que le cisco (*Coregonus artedi*), le grand brochet (*Esox lucius*) et l'inconnu (*Stenodus leucichthys*) sont devenues plus importantes dans la récolte commerciale. Des produits du programme de surveillance à long terme du MPO sont également examinés dans le présent rapport ; des recherches halieutiques récentes contenant des données intégrées sur les interactions limnologiques et les interactions entre le lac et les rivières, qui reconnaisse l'influence des caractéristiques physiogéographiques uniques du lac et un relevé systématique par quadrillage indépendant de la pêche de cinq ans (2011 à 2016), qui a échantillonné les variables environnementales et le réseau trophique dans l'ensemble du bassin principal. Le rapport conclut avec l'identification des lacunes en matière de renseignements en vue de soutenir la finalisation du PGIP pour le Grand lac des Esclaves.

1. INTRODUCTION

Fisheries and Oceans Canada (DFO), Arctic Region, is working on the development of an Integrated Fisheries Management Plan (IFMP) for Great Slave Lake (GSL), Northwest Territories (NWT). The lake is home to commercial, subsistence Indigenous, and sport fisheries and sustains one of the largest freshwater fisheries in North America. There has been considerable scientific research undertaken on the lake since the inception of commercial fisheries in the 1940s; however, only periodic attempts have been made to organize and quantify all of the periodic research data into a single usable document. The creation of a summary report articulating existing ecological information for the GSL will better support DFO Science to organize a Canadian Science Advisory Secretariat (CSAS) framework and determine the best stock assessment methodologies to apply to GSL. The summary report will also support DFO Resource Management in its IFMP consultation process and help identify conservation priorities and fisheries management objectives for GSL.

This summary report was completed as a desktop assessment based on a review of existing information in the literature (published and unpublished reports), methods of which are described in Section 1.1. The remainder of the report has been organized as follows:

Environmental and Ecological Information – This section describes the biological and ecological attributes and identifies special features within the GSL ecosystem. This section represents the bulk of information presented in the report providing detailed information on regional context and ecosystem structure and function.

Fisheries Management – This section describes historical and active fisheries in GSL, including the Indigenous subsistence, recreational, and commercial fisheries. Threats posed to the fishery by current and future human-related stressors, including climate change, are discussed.

Gap Analysis and Perspectives – This section attempts to identify areas that are lacking in scientific knowledge and where more work is needed to understand this ecosystem. Key findings from the review of GSL ecosystem and fisheries management are also provided.

1.1. LITERATURE REVIEW APPROACH

Research on GSL fisheries and aquatic ecology has been ongoing since the 1940s and a long history of research has occurred. The vast extent of the available research and data related to the fish community necessitated a structured approach to the literature review. The objective of the search was to compile as many documents as possible and sort them based on relevance to GSL. Relevance was determined based on a substantive discussion about GSL, or collection, use and synthesis of GSL data. From initial sorting, a database of documents with data or discussions relevant to GSL was developed. As the review progressed, more documents were added to the database as they were discovered. No limit was placed on the type of document (e.g., consultant reports, government documents, or primary sources) or the publication year; however, peer- reviewed and contemporary documents were given precedence over historical documents in cases where information conflicted. In total, documents and webpage sources (primarily repositories for government statistics) were identified. The inclusion of available Indigenous Traditional Knowledge, which could also be used to support the IFMP, was outside the scope of the literature review for this summary report.

One of the defined objectives was to summarize the spatial scope of research effort represented in the historical record for GSL. For each record, publications were codified by management area and two of the principle tributaries (i.e., Slave River and Hay River), if reported. If the location was not defined to a management area the publication was omitted from the analysis. The research effort summary provides a proportional representation of the spatial distribution of research effort contained in the database developed for this study.

To review species-specific fish biology, references in the database were subset by searching species names in the titles and abstracts and sorting the available documents by species. A list of research topics and search terms designed to summarize the desired species information was developed. Research topics of interest were structured in consultation with DFO through a series of scoping meetings, which included requests to scientists attending those meetings for any new documents related to, and relevant to GSL fisheries. There is a large amount of fish data and information available in DFO data reports and annual reports (e.g., Falk and Dahlke 1975, Moshenko and Gillman 1978); however, as the objective was to provide a summary of available information (rather than a detailed analysis of each research topic), reviews were limited to documents that provided substantive discussions or data summaries of the topic (i.e., not all literature is summarized in this report, DFO Resource Management Arctic Region holds the database for literature review). The focus of the review was on documents that provided synthesis or summarized known information in a topic area (e.g., Slave River fisheries; Tallman et al. 1996a). This approach is designed to provide a summary of the key findings from the majority of the studies on GSL rather than a synthesis and analysis (or re- analysis) of the results collected from all publications. Wherever possible, major documents on a research topic are highlighted for further research.

2. ENVIRONMENTAL AND ECOLOGICAL INFORMATION

2.1. REGIONAL CONTEXT

2.1.1. Fish and Fisheries

At least 34 fish species have been identified in the GSL system, including large-bodied species important for commercial, subsistence Indigenous, and sport fisheries and a broader diversity of small-bodied forage fishes (Table 1). Table 1 was compiled from the most recent summary of fish in GSL (Reist et al. 2016) and also includes a few species listed in other sources (Zhu et al. 2017a). A description of the fish community is provided in Section 2.2.4.

Prominent among the large-bodied species are several species of Salmonidae, Catostomidae (Longnose Sucker *Catostomus catostomus* and White Sucker *Catostomus commersonii*), Gadidae (Burbot *Lota lota*), Percidae (Walleye *Sander vitreus*, Yellow Perch *Perca flavescens*, and Sauger *Sander canadensis*), and Esocidae (Northern Pike *Esox lucius*). Of the Salmonidae, Lake Trout (*Salvelinus namaycush*) and Lake Whitefish (*Coregonus clupeaformis*) are the most sought after for commercial, recreational and Indigenous fisheries; however, Arctic Grayling (*Thymallus arcticus*), Cisco (*Coregonus artedi*), and Inconnu (*Stenodus leucichthys*) are also commonly fished as by-catch species. Chum Salmon (*Oncorhynchus keta*) and Sockeye Salmon (*Oncorhynchus nerka*) are extremely rare in the fishing catch records and Rainbow Trout (*Oncorhynchus mykiss*) have not been documented in the lake but have been introduced and established in a sub-basin of GSL.

Great Slave Lake provides a unique example of a large commercial fishery being conducted since its inception under guidelines formulated by biologists (Rawson 1949, Keleher 1972). In early 1944, the Fisheries Research Board of Canada engaged Dr. Donald Rawson (University of Saskatchewan) to survey GSL and initial surveys were completed that summer (Rawson 1947,1949). Based on the recommendations of the survey, commercial fishing began late in the summer of 1945 (Rawson 1947). During the early years of the fishery, over 90% of the landed catch was Lake Trout and Lake Whitefish combined. By 1964, however, the Lake Trout in the Main Basin (i.e., western shallow zone of GSL including the North Arm and West Arm/Basin of GSL) were considered collapsed from exploitation by the commercial fishery (Keleher 1972), and since then, Lake Whitefish have been the primary target species for commercial harvest. A trophy Lake Trout fishery persists in the East Arm of the lake due to, in part, closures for commercial fishing following the collapse in the Main Basin. The current management regime (described in Section 3.0) has remained roughly unchanged since 1972 and has largely focused on managing the commercial fisheries harvests; however, recent work has tried to move toward an ecosystem management approach that integrates all sectors of the biological production and incorporates knowledge of the entire GSL aquatic ecosystem into a comprehensive assessment of GSL fisheries and aquatic ecology (Janjua and Tallman 2015, Zhu et al. 2017a).

Table 1. List of fish species documented in Great Slave Lake.

Family	Common Name	Scientific Name
Catostomidae	Longnose Sucker	*Catostomus catostomus*
	White Sucker	*Catostomus commersonii*
Cottidae	Arctic Sculpin	*Myoxocephalus scorpioides*
	Deepwater Sculpin	*Myoxocephalus thompsonii*
	Shorthorn Sculpin	*Myoxocephalus scorpius*
	Slimy Sculpin	*Cottus cognatus*
	Spoonhead Sculpin	*Cottus ricei*
Cyprinidae	Emerald Shiner	*Notropis atherinoides*
	Fathead Minnow	*Pimephales promelas*
	Finescale Dace	*Chrosomus neogaeus*
	Flathead Chub	*Platygobio gracilis*
	Lake Chub	*Couesius plumbeus*
	Longnose Dace	*Rhinichthys cataractae*
	Peamouth	*Mylocheilus caurinus*
	Northern Pearl Dace	*Margariscus nachtriebi*
	Spottail Shiner	*Notropis hudsonius*
Esocidae	Northern Pike	*Esox lucius*
Gadidae	Burbot	*Lota lota*
Gasterosteidae	Brook Stickleback	*Culaea inconstans*
	Ninespine Stickleback	*Pungitius pungitius*
Hiodontidae	Goldeye	*Hiodon tergisus*
Percidae(	Sauger	*Sander canadensis*
	Walleye	*Sander vitreus*
	Yellow Perch	*Perca flavescens*
Percopsidae	Trout-perch	*Percopsis omiscomaycus*
Petromyzontidae	Arctic Lamprey	*Lethenteron camtschaticum*
Salmonidae	Arctic Grayling	*Thymallus arcticus*
	Chum Salmon	*Oncorhynchus keta*
	Cisco	*Coregonus artedi*
	Inconnu	*Stenodus leucichthys*
	Lake Trout	*Salvelinus namaycush*
	Lake Whitefish	*Coregonus clupeaformis*
	Least Cisco	*Coregonus sardinella*
	Rainbow Trout	*Oncorhynchus mykiss*
	Round Whitefish	*Prosopium cylindraceum*
	Sockeye Salmon	*Oncorhynchus nerka*
	Shortjaw Cisco	*Coregonus zenithicus*

Data sources: Reist et al. 2016; Arctic Sculpin, Shorthorn Sculpin, and Sauger also reported in the catch in Zhu et al. (2017a)

2.1.2. Geographic Characteristics

Great Slave Lake is centrally located within the Mackenzie River Basin (Figure 1), receiving flows from headwaters in the Rocky Mountains and Boreal Plains heading North to a delta outlet on the Beaufort Sea through the Mackenzie River. The lake functions as a hydrologic, biogeochemical, and sedimentary regulator by stabilizing the flow, water temperature, and water levels of the entire upper Mackenzie River (Mudroch et al. 1992). Roughly 50% of annual basin runoff to the Beaufort Sea originates from GSL, conveying water from headwater sources 1,500 km upstream (MRBB 2004, Gibson et al. 2006a, Yi et al. 2010).

The Main Basin of the lake is defined in this report as all waters outside of the East Arm (Management Area VI) and includes the Western Basin (Management Areas IW and IE) (Zhu et al. 2017a; Figure 2) and is bounded by the Interior Plains, the Taiga Plains and Boreal Plains terrestrial ecozones (Kokelj 2003; Figure 2). The inflow of the Slave River into the Main Basin, together with local geology and water depth, contribute to regional differences in the limnological features of the lake, including fisheries productivity and standing stock biomass (Rawson 1947, 1953a, 1956a, Fee et al. 1985, Evans 2000). The East Arm (i.e., eastern deep zone of GSL) lies over the Precambrian Canadian Shield and is bounded by the Taiga Shield ecozone (Evans 2000, Kokelj 2003). The East Arm is deep, with a maximum measured depth of 614 m (Rawson 1950), making GSL the deepest lake in North America. As is typical of Precambrian Shield lakes, the East Arm has minimal post-glaciation sediment deposits (Sharpe et al. 2017) and has much less riverine inflow than the Main Basin. By contrast, the Main Basin is much shallower with a mean depth of 32 m (Schertzer et al. 2003), substrate is composed of paleozoic deposits, and waters are much more productive than the East Arm (Evans 2000).

Another important characteristic of GSL contributing to differences between the East Arm and Main Basin is the source of inflow water and strong influences of river-lake interactions. Greater than 80% of inflow waters enter and exit the lake in the Main Basin, with 74% of total inflow sourced from relatively productive southern watersheds (Rouse et al. 2008). Gibson et al. (2006b) calculated the water balance for the Main Basin and estimated a regionally high throughflow rate with a mean residence time of 14.2 years (1964 – 1998 period). It has been noted that the Main Basin of GSL is expected to flush about twice as rapidly than the East Arm owing to shallower mean depth and the bypass of Slave River water directly to the outlet of the Mackenzie River (Evans 2000, Gibson et al. 2006b). By contrast, direct inflow into the East Arm comes from sources on the Precambrian Shield (Evans 2000). Thus, differences in the volume of inflow, the circulation pattern, and the chemical and physical composition of the source waters all contribute to observed differences in productivity, trophic structure, and limnological properties between the East Arm and Main Basin. These differences are also discussed in Section 2.2.2.

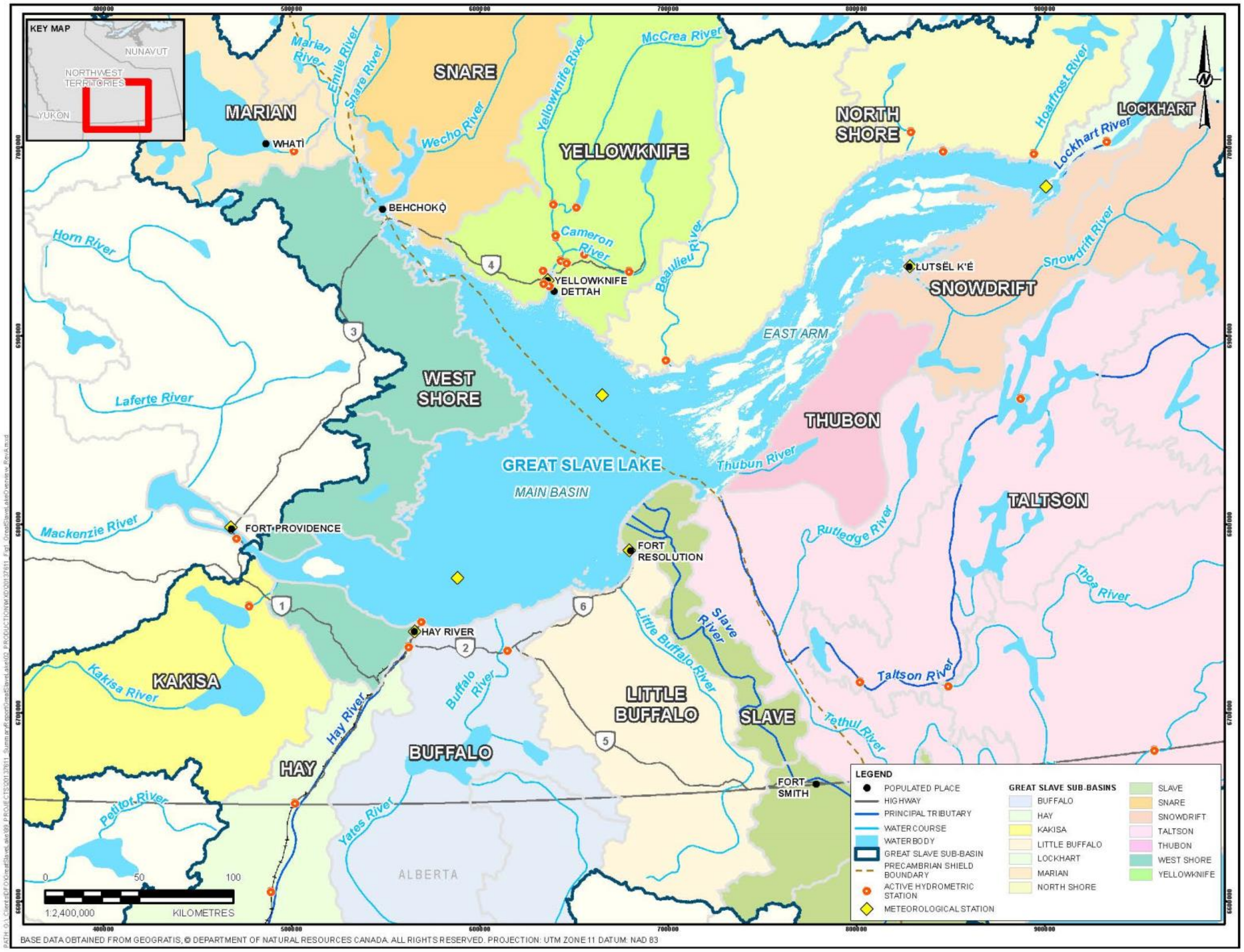

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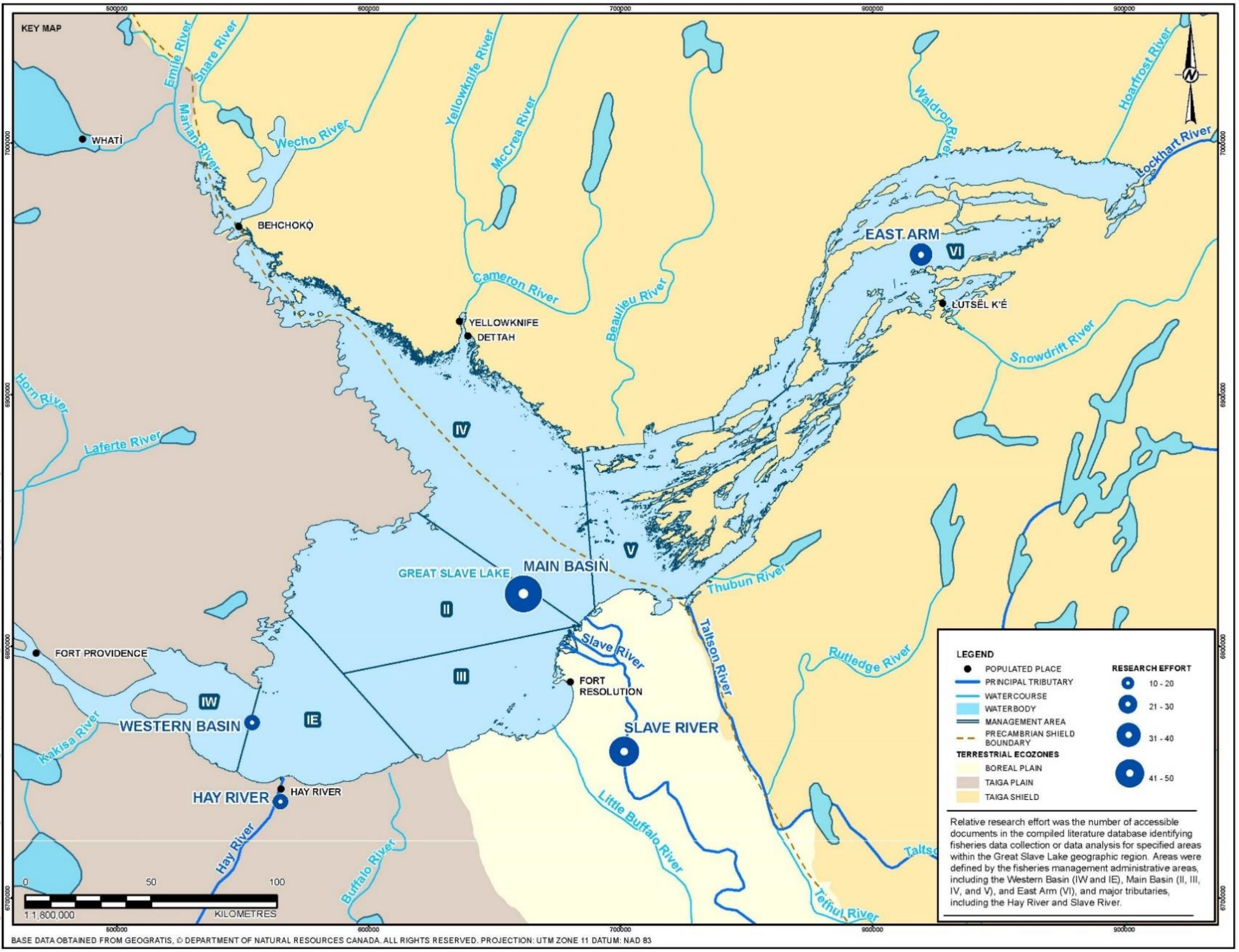
Figure 1. Hydrological setting of Great Slave Lake in the Mackenzie River Basin, with tributaries, sub-basins (as summarized in MRBB 2004) and land use features indicated. Location of active hydrometric and meteorological monitoring stations are also indicated.



Relative research effort was the number of accessible documents in the compiled literature database identifying fisheries data collection or data analysis for specified areas within the Great Slave Lake geographic region. Areas were defined by the fisheries management administrative areas, including the Western Basin (IW and IE), Main Basin (II, III, IV, and V), and East Arm (VI), and major tributaries, including the Hay River and Slave River.

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Figure 2. Terrestrial, and physiographic setting of Great Slave Lake in the Mackenzie River Basin, with fisheries management area boundaries defined and the spatial distribution of research effort indicated. Relative research effort is grouped by basin (as defined in Zhu et al. 2017a) and tributaries.

Lake size and morphometry is another key characteristic defining the GSL ecosystem. The lake is the fifth largest lake in North America, with a surface area of 27,200 km^2. Volume calculations for the lake show considerable variation in the reported values. Some reports give total volume as high as 2,088 km^3 (e.g., Gibson et al. 2006b and Gardner et al. 2006 citing Kalff 2002). Others report total lake volume as low as 1,070 km^3 (e.g., Schertzer et al. 2003 and 2008 citing Van der Leeden et al. 1990). Rouse et al. (2008) and Kheyrollah Pour et al. (2012) report a value of 1,580 km^3, which is the mean value of the two estimates. A bathymetric survey estimated water volume in the Main Basin at 596 km^3 (Schertzer et al. 2003), which is either 29% or 56% of total lake volume depending on the estimate for the East Arm. Water residency could consequently be half of the reported value (14.2 years; Gibson et al. 2006b) which has important implications for estimating ecological processes such as nutrient input and availability for cycling, sedimentation of particles, and residency of contaminants (Kalff 2002). The discrepancy is assumed to be from uncertainty in the bathymetry of the East Arm, relying on the seminal soundings taken by Dr. Donald Rawson and others in the 1940s with steel cable and meter-wheel methods (Rawson 1953b).

Great Slave Lake lies within the continental sub-Arctic climate region with cool summers, cold winters, low annual rainfall, and pronounced seasonality in day length (Evans 2000). Large-scale atmospheric patterns influenced by sea surface temperatures in the Pacific have controlled continental-scale precipitation patterns in the Yellowknife region for over the past three centuries (Pisaric et al. 2009). The prevailing wind direction on the lake is northwesterly (Rawson 1950, Gardner et al. 2006). Mean annual unadjusted precipitation is roughly 280 mm, with just under half falling as snow (Spence and Rausch 2005). Seasonal Yellowknife air temperatures range from between a mean of 17ºC in July to -27ºC in January (Figure 3). Mean monthly temperatures in the winter (November to March) and in the summer (May to September) tend to be spatially and temporally uniform throughout the Mackenzie River Valley from Inuvik to GSL (Dyke 2001, Blanken et al. 2003), and this atmospheric stability helps suppress cloud cover and increase solar radiation in the area (Rouse et al. 2005).

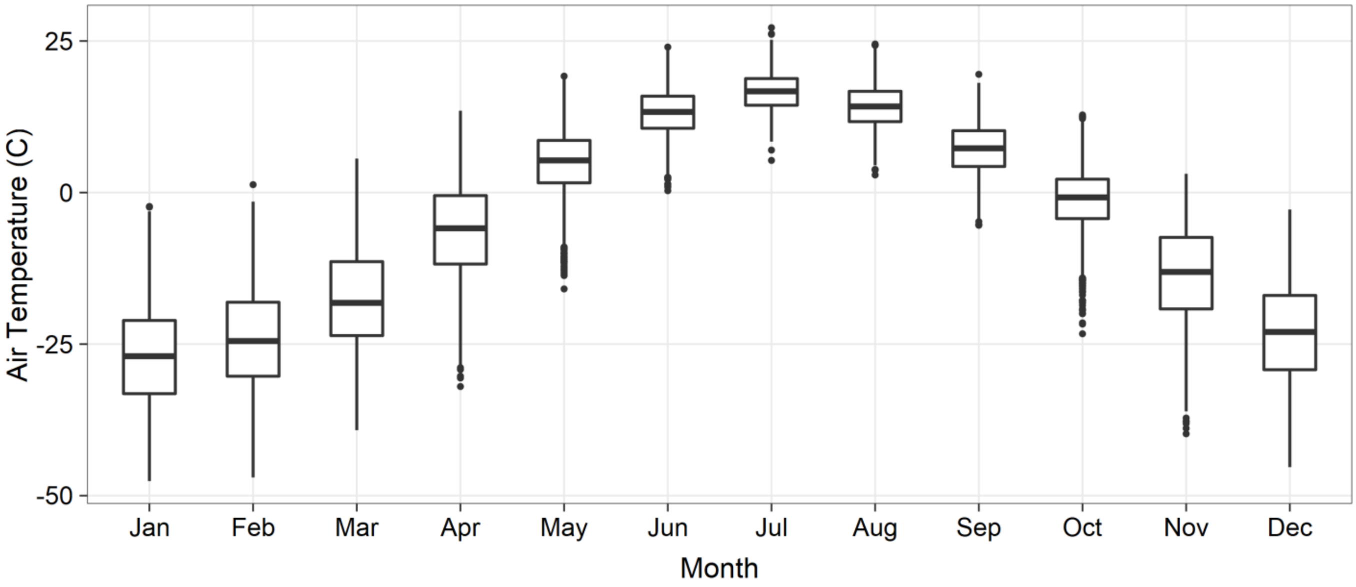

Figure 3. Monthly air temperatures in Yellowknife, NWT, 1943 to 2020. Source: GOC (2020) Station 2204100.

2.2. GREAT SLAVE LAKE ECOSYSTEM

2.2.1. Tributary River Inflow

A description of historical hydrometric monitoring of inflow waters for GSL is provided in Kokelj (2003). The principal seasonal flow pattern exhibited by most inflow tributaries is the Sub-Arctic Nival regime, in which snowmelt, often accompanied by river ice breakup, generates high spring flows (Woo and Thorne 2003). The water balance of GSL is dominated by riverine inflow from the Slave, Taltson, Lockhart, and Hay rivers, representing 77%, 4%, 3%, and 2% of the total water inputs into the lake, respectively (Gibson et al. 2006b). Other minor contributions to GSL are provided by numerous other drainages (9%) and precipitation (5%) (Gibson et al. 2006b). Seasonal flow regimes from the four principal tributaries are provided in Figure 4 . The Slave River and Hay River are discussed in detail because of their importance to ecological function and the presence of developed fisheries typical to the GSL ecosystem (Zhu et al. 2015a). More details on the hydrology of GSL can be found in Woo and Thorne (2003), Gibson et al. (2006b), and Kokelj (2003).

2.2.1.1. Slave River

The Slave River has been the focus of the most intense research and monitoring efforts of the tributaries because of its influence on physical, chemical, and biological functions of GSL. The source waters of the Slave River are fed from the Peace and Athabasca Rivers in the Peace-Athabasca delta, and receive waters from a large transboundary 660,000 km^2 catchment (Tallman et al. 2005) extending into Alberta, British Columbia, and Saskatchewan. There are two communities located in the watershed in NWT: Fort Smith (Population [2016]: 2,542; Statistics Canada 2016) located close to the border with Alberta, and Fort Resolution (Population [2016]: 470; Statistics Canada 2016). The Slave River empties into GSL through a broad delta covering approximately 640 km^2 (Kokelj 2003) and supports a diversity of habitat types and a relatively high diversity of fish species (Tallman et al. 2005). Slave River is the largest contributor to GSL water balance and a major driver for seasonal discharge in the Mackenzie River Basin (Sanderson et al. 2012). Only 1% of the Slave River catchment is located in NWT and about 66% of the inflow is sourced from the Peace River, which has been regulated by hydroelectric power since 1968 (English et al. 1997).

Flow regulation from the upstream operation of hydroelectric facilities is a key attribute of the Slave River and combines the regulated flow effect of the Williston Reservoir at W.A.C Bennett Dam with the Sub-Arctic Nival regime runoff of tributaries downstream of the dam (Woo and Thorne 2003). Regulation has not affected total annual flow but seasonality of peak flows has been altered by increasing winter flows by approximately 75% and reducing the spring freshet flows by approximately 20% from pre-dam flows (Sanderson et al. 2012; Figure 5). Impacts of flow regulation on the GSL ecosystem, particularly the Main Basin, may include altered water levels (Gardner et al. 2006), reductions in flood frequency (Gardner et al. 2006, Sokal et al. 2010) and riparian zone inundations, reductions in Slave River delta deposition and erosion (Prowse et al. 2006, Sokal et al. 2010), and higher winter inflows (Woo and Thorne 2014); however, overall water levels are the net product of discharge, evaporation, and precipitation dynamics in GSL and contributing watersheds with climate variability expected to obscure the effects further away from the dam (Prowse et al. 2006, Zhu et al. 2015a).

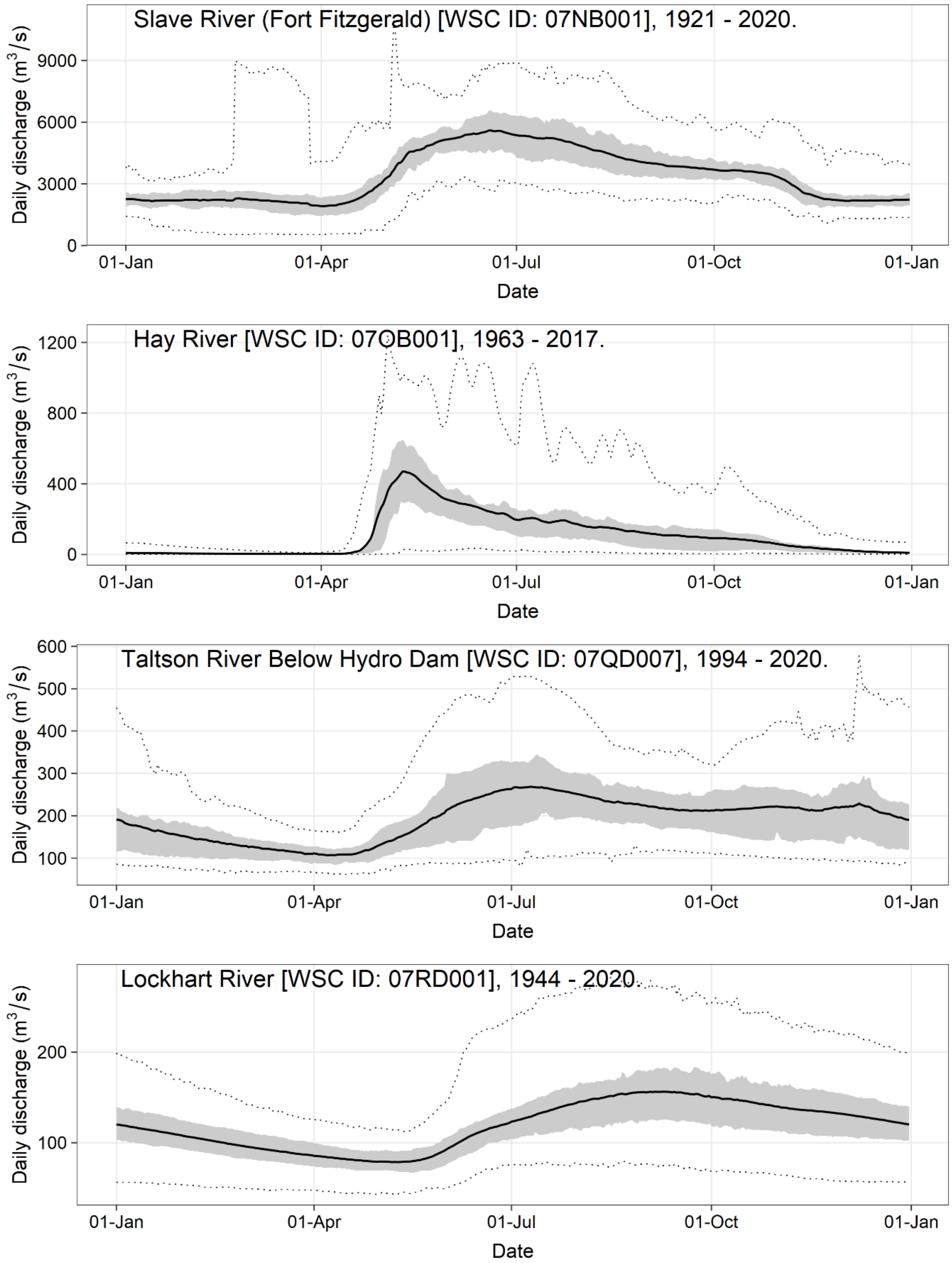

Figure 4. Mean streamflow regime (solid line) of the principal inflow tributaries of GSL. The shaded area and dotted lines indicate the interquartile range, and minimum and maximum values of the unmodified data. Source: WSC (2020).

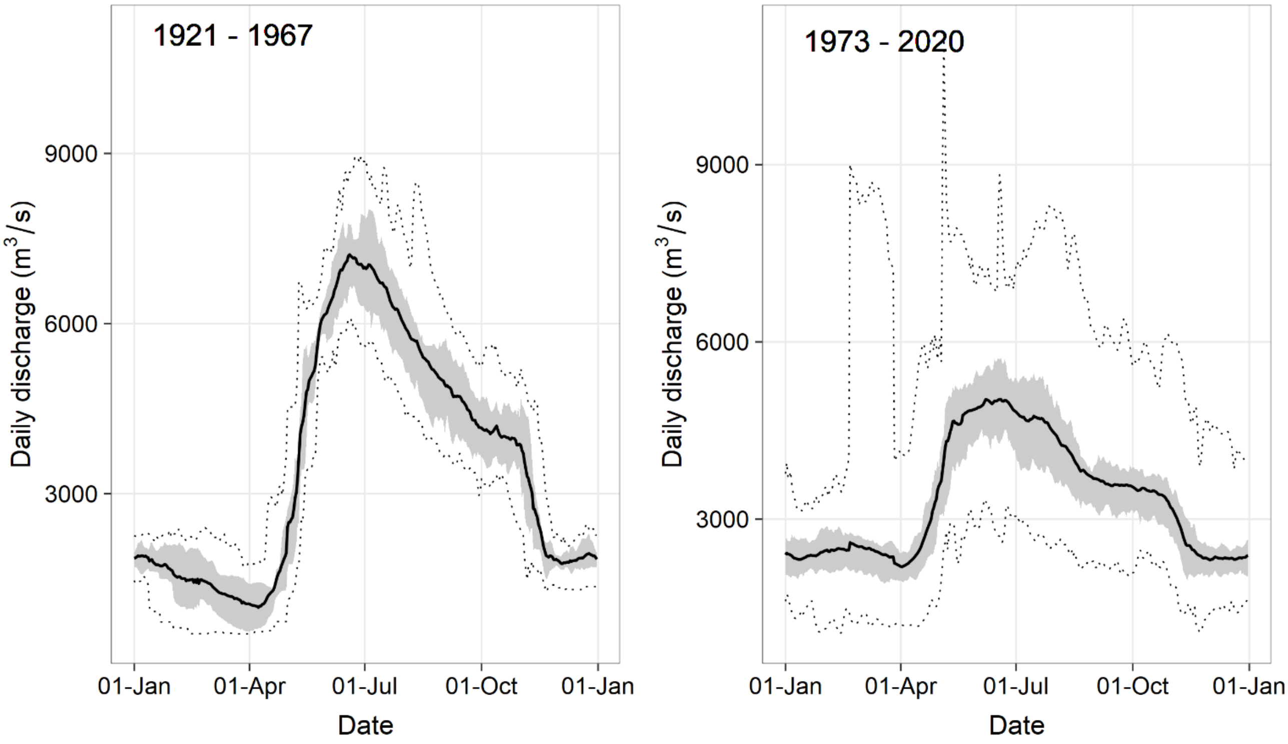

Figure 5. Mean pre-dam and post-dam streamflow regimes (solid line) of the Slave River, NWT. The shaded area and dotted lines indicate the interquartile range, and minimum and maximum values of the unmodified data. Source: WSC (2020) station 07NB001.

The fish community of the Slave River is diverse with over 31 different species (Tallman et al. 2005 and references therein) supporting a subsistence fishery, centered mainly on the Slave River delta and Resolution Bay, and some commercial fishing effort in Resolution Bay (Stewart 1999). The Slave River environment has remained reasonably constant without significant degradation of the habitat; similarly, fish health in populations in most reaches throughout the catchment have been shown to be only mildly affected by any potential environmental contamination from upstream natural resource development (Cash et al. 2000). Inconnu and Walleye are important to local fisheries and both species have been highlighted as species of special concern in the Slave River delta that may require more detailed assessments and management measures in the near future (Baldwin et al. 2018).

Overall, the Slave River is a relatively pristine environment with low levels of contaminants and water quality suitable for aquatic life (McCarthy et al. 1997a, 1997b, 1997c, Williams et al. 1997). Sanderson et al. (2012) provides a general overview of the current and historical state of water quality, suspended sediment levels, and flows of the Slave River. Major findings include: a decreasing trend in summer and fall flow discharge and an increase in winter flow discharge; an increase in winter and spring total dissolved phosphorus over time (ranging from < 0.002 to 0.343 mg/L; n = 215; 1978 to 2010); and changes in seasonal water quality correlated with changes in flow discharge. The decrease in summer flow discharge has also been observed by local fish harvesters in the Slave River delta (Baldwin et al. 2018). Lower water levels mean that fish may spawn less in the smaller channels and may travel less broadly in the delta than in the past. Fish harvesters are often now finding fish opportunistically instead of based on distribution patterns from the past and knowledge shared by their ancestors. The cause and impacts of these observed trends are not fully known at present; however, several hypotheses were put forward for future analysis in Sanderson et al. (2012). Potential causes may be a combination of anthropogenic and natural factors leading to cumulative impacts on downstream flow conditions (e.g., hydroelectric dam regulation, land use practices, and climate change).

2.2.1.2. Hay River

The Hay River originates in the Northern Rocky Mountains of British Columbia and Alberta and flows into GSL at the town of Hay River (Zhao et al. 2015), receiving water from a 51,700 km^2 catchment area (Woo and Thorne 2014). Breakup produces an annual spring ice jam that frequently results in flooding events at the town site (Zhao et al. 2015). Annual flow follows a Sub-Arctic Nival regime with the spring freshet coinciding with the peak flow for the season. Recent reviews of hydrometric data found no annual trends in surface water flow into GSL (St. Jacques and Sauchyn 2009, Stantec 2016); however, significant increases in winter flow have been observed over time (Woo and Thorne 2003, St. Jacques and Sauchyn 2009). On average, freeze up occurs earlier in the fall than other principal rivers in the Mackenzie River Basin because of its relatively small size and low gradient (Woo and Thorne 2014, Zhu et al. 2015b).

The oil and gas and forestry sectors are the main development pressures in the basin, with most of the activity occurring upstream in Alberta and British Columbia. Local natural resource activities in NWT are relatively light in intensity and the watershed is lightly populated with a low density. The largest community (town of Hay River) in the watershed had 3,528 residents in 2016 (Statistics Canada 2016). Hay River fisheries are summarized in Stewart and Low (2000) where the focus is on tributaries to Hay River. Two impassible waterfall barriers (the Louise and Alexandra falls) restrict fish movements to 32 km upstream of GSL. Fishing effort in the Hay River at GSL is primarily a subsistence fishery gill netting Lake Whitefish and a recreational fishery targeting Walleye, but also Burbot, Inconnu, and Northern Pike, mostly near the town.

2.2.2. Limnology

2.2.2.1. Geophysical Setting

Large lakes are effective sentinels and integrators of changes in their watersheds, particularly in the Arctic (Reist et al. 2016). Wherever large, deep lakes are present, they are also major components of the hydrologic system because of their large heat storage capacities, acting as energy sinks in the early summer and energy sources in the fall (Schertzer et al. 2000, Long et al. 2007) and the larger the fetch of the lake, the greater the effect the lake will have on local climate (Rouse et al. 2005, Kheyrollah Pour et al. 2012). Rouse et al. (2005) demonstrated that the size of GSL is important to the magnitude of regional energy balances. During the open water season, GSL heats to substantial depths (July thermocline depth = 18 m; Rouse et al. 2005), despite relatively turbid water and shallow penetration of solar radiation (approximately 2.5 m; Rouse et al. 2005). Heating proceeds slowly and the deep heating is derived from wind-driven mechanical mixing due to large upwind fetches and large wind shear. This heat budget contributes to a dimictic stratification regime, with vertical mixing throughout the water column occurring twice a year in spring (June) and fall (October). In a five- year systematic survey of lake temperatures (2011 to 2016), aggregated mean temperatures were 22.3ºC at the surface and 3.5ºC at the bottom over the summer (Zhu et al. 2017a). These water column temperatures are uniform across the Main Basin, and indicate the strong mixing predicted by other studies (Figure 6).

One consequence of the large latent heat capacity on GSL is a longer ice-free period into fall and early winter than smaller lakes in the area, typically occurring from late November to the end of December (Rouse et al. 2005). Freeze onset over GSL occurs first within the East Arm, closely followed by the North and West arms, and then finally in the centre of the Main Basin (Howell et al. 2009). Ice thickness gradually increases until the spring and generally ranges between 0.3 m to 1.6 m between January and April (Kheyrollah Pour 2011, Duguay et al. 2015). Lake size does not have a similar lag effect on break-up, which typically happens within a two-week period at the beginning of June, although the seasonality of ice conditions varies significantly from year to year (Kang et al. 2014). Melt onset begins first in the Main Basin and progresses to the North and East arms later in the season. The Main Basin of GSL clears earlier than the periphery of the basin due to the discharge from Slave River (Howell et al. 2009).

Seasonal variability in lake water levels on GSL is largely a product of seasonality in the riverine inflows from the Slave River, to which the Peace is the dominant headwater river further upstream (Gibson et al. 2006a, Prowse et al. 2006). More recently, lake height data from satellite altimetry have been used to define the circulation patterns and distinct water level regions in the Main Basin of GSL and corroborate previously identified trends from individual gauging stations to the whole lake (León et al. 2006, Sarmiento and Khan 2010). The strong circulation in the lake patterns creates relatively large spatial gradients in surface temperatures and plays an important role in heat transport throughout the lake.

Three major interannual cycles of wetting and drying have been identified in GSL water levels since construction of the W.A.C Bennett Dam (1964 to 1998), strongly linked to cyclical trends in riverine inflow from the Slave River (Gibson et al. 2006b). The frequency of seiche events (i.e., sharp water level fluctuations forced by a sustained wind or barometric forcing) also decreased concurrently with dry periods and resumed to typical frequency when the lake experienced wetter periods (Gardner et al. 2006, Gibson et al. 2006b). Impacts of the human and climate drivers have generally offset each other and mediated effects on amplitude and magnitude of water levels but have cumulatively contributed to a seasonal shift toward earlier peak water levels in the lake (Prowse et al. 2006a).

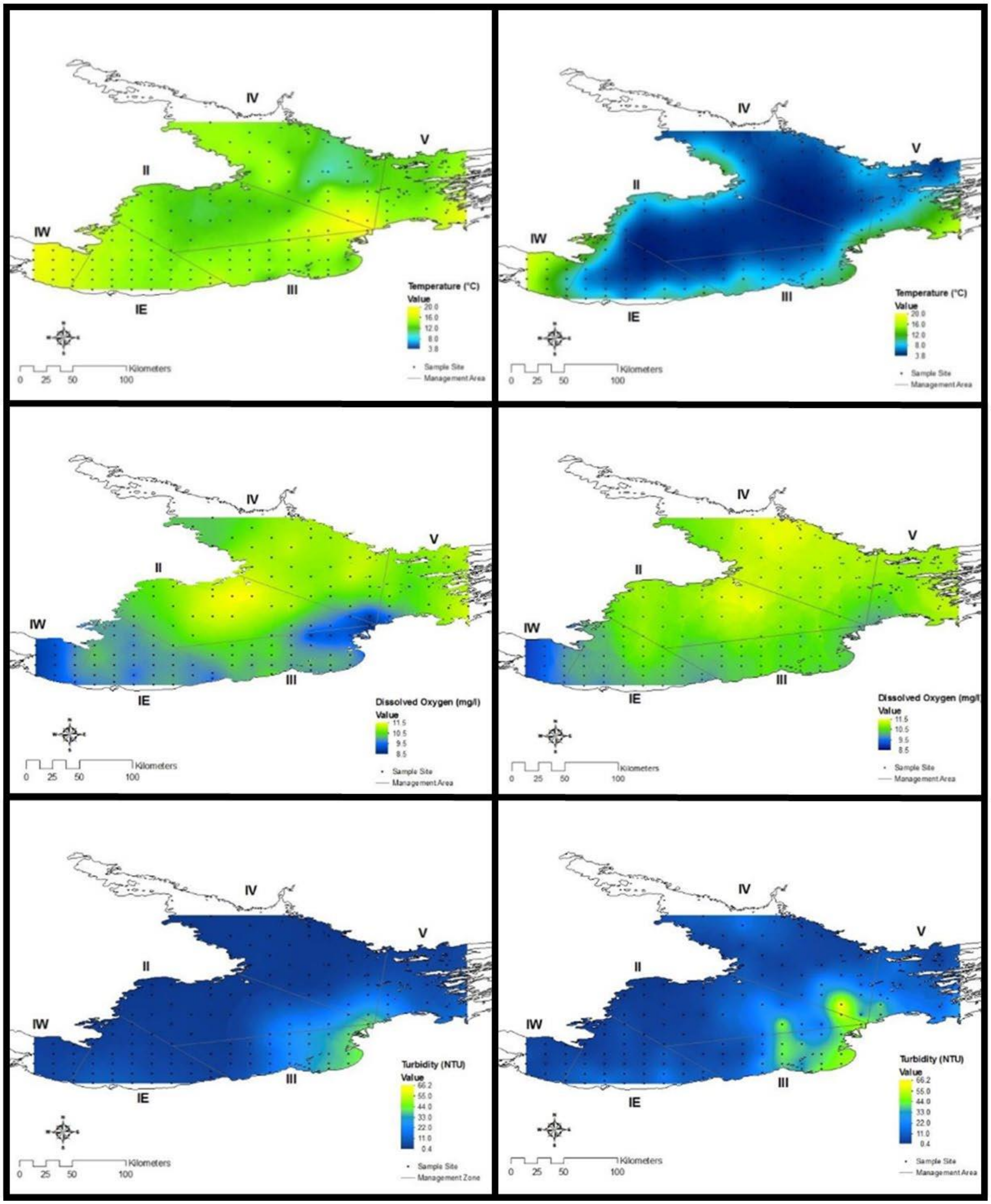

Figure 6. Spatial distribution of water temperature, dissolved oxygen, and turbidity in the Main Basin of GSL for surface waters (left panels) and bottom environments (right panels), observed June through August, 2011 to 2016. Adapted from Zhu et al. (2017a).

2.2.2.2. Chemical Conditions

The physical and chemical composition of inflow water from contributing watersheds influences the spatial distribution of water chemistry in the lake. The East Arm is on the Precambrian Shield and the Main Basin is on Paleozoic deposits. Therefore, waters in the East Arm are less productive, have greater water clarity, and lower total dissolved sediments (Evans 2000 and references therein; Table 2). The Main Basin water quality is strongly influenced by the Slave River inflow and the shallower lake morphology. Epilimnion temperatures are higher and deeper from mixing associated with large upwind fetches and wind shear, resulting in high phosphorus and high chlorophyll concentrations relative to the East Arm (Table 2; Evans 2000) and deep uniformly mixed dissolved oxygen concentrations have been observed throughout the Main Basin in the summer months (Zhu et al. 2017a; Figure 6). The Main Basin also acts as a sink for suspended sediments in the Mackenzie River Basin derived from southern watersheds (Mudroch et al. 1992). In a review of Slave River water quality data from 1993 to 2010, a decreasing annual trend was found in total dissolved solids and none of the physical parameters exceeded existing standards (Sanderson et al. 2012). Concentrations of total dissolved phosphorous can reach 0.35 mg/L and total dissolved nitrogen can reach 1.02 mg/L in the Slave River (Evans 2000). Nutrient levels are relatively high in the Main Basin for a lake at this latitude (Rühland and Smol 1998); however, the lake may be still considered oligotrophic (Rawson 1950, Moore 1981). Inflow from the river creates a highly clustered distribution of high turbidity values around the mouth of the Slave River, that appears to attenuate rapidly into the Main Basin (Zhu et al. 2017a; Figure 6).

Table 2. Limnological features of GSL. Adapted from reported values in Evans (2000). Maximum and mean depth for the Main Basin were updated by Schertzer et al. 2000.

Lake Feature	Main Basin	East Arm	Relative% Difference
Area (m^2)	19,400	9,168	-52.7
Maximum depth (m)	187(a)	614	228.3
Mean depth (m)	32(a)	185	478.1
Total dissolved solids (mg/L)	160	50	-68.8
Secchi depth (m)	2.5	9	260.0
Epilimnion temperature (°C)	10.0	4.0	-60.0
Total phosphorus (µg/l)	12.5	8.8	-29.6
Nitrile-Nitrate (µg/l)	144	190	31.9
Silicone (mg/l)	1.3	1.0	-23.1
Chlorophyll (µg/l)	2.7	1.7	-37.0

(a) Schertzer et al. 2000

2.2.2.3. Contaminants

The role of contaminants is a key topic of interest for the GSL aquatic ecosystem based on the number of previously published reports and studies on the subject. GSL has a legacy of localized impacts from mining operations that have resulted in environmental contamination of arsenic, among other contaminants, particularly in the North Arm (Chételat et al. 2019). Con Mine (operating 1938 to 2003) and Giant Mine (operating 1948 to 2004) are located in Yellowknife Bay on the North Arm; Yellowknife Bay has received loadings of arsenic, antimony, and metals through tailings dumps and mine effluent from the Giant Mine, as well as atmospheric deposition from ore roasting emissions at Giant and Con mines (Chételat et al. 2019). At the peak influence of those mining activities, researchers concluded that levels represented acute toxicity to the aquatic ecosystem (Falk et al. 1973a).

Remediation and research have been underway since the 1970s, include recent assessments on the current status of fish health in Yellowknife Bay (e.g., Cott et al. 2016, Rohonczy et al. 2019) and an examination of processes affecting arsenic bioaccumulation and food web transfer (Chételat et al.

2019). Overall, based on these studies, elevated arsenic concentrations in the aquatic food web persist although no bioaccumulation is apparent in the higher trophic levels of the fish community. The effect is species-specific and thought to be related to exposure during use of nearshore habitats with elevated arsenic concentrations.

Mercury contamination in GSL is another topic under on-going study in the region where there are records of anthropogenic mercury deposition from air masses originating in industrialized regions outside of Canada (reviewed in Kalff 2002). The Canadian Government's Northern Contaminants Program (NCP) has collected extensive information on mercury in Arctic freshwaters since the early 1990s (reviewed in Chételat et al. 2015). Beginning in 1999, a long-term monitoring program of contaminants in fish was initiated for GSL as part of the NCP, focusing on three top predator species: Lake Trout, Burbot, and Northern Pike (Evans et al. 2013). Since the 1990s, mercury concentrations have increased approximately two-fold in piscivorous fish species, with mercury concentrations of Lake Trout and Burbot from both the West Basin and East Arm increasing significantly at a rate of 2 to 5% per year (Evans et al. 2013). This increasing trend raises concerns about bioaccumulation in these slow-growing fish, and biomagnification through the food web, and whether concentrations can remain below consumption guidelines for the top piscivores in the lake (Evans et al. 2013).

A recent study conducted from 2013 to 2015 in the North Arm provides a comprehensive examination of mercury contamination within the GSL aquatic trophic structure (Rohonczy et al. 2019). This study concluded that body size and trophic position explained most of the variation in fish muscle mercury concentrations and that secondary producers (i.e., zooplankton) had relatively low methylmercury uptake in tissues, providing evidence for bioaccumulation. Habitat-specific feeding did not influence mercury bioaccumulation in fish and no point source for the contamination was identified in the North Arm. Furthermore, sampling of mercury tissue in GSL fish (North Arm) showed low concentrations, with the majority of muscle samples below the current allowable Health Canada limit of 0.5 mg/g (wet weight) for commercial fish (Rohonczy et al. 2019). In a similar study of Burbot and Lake Whitefish captured during 2010 to 2012 from the North Arm and Main Basin near Hay River, tissue concentrations remained below Health Canada consumption guidelines (Cott et al. 2016). Species that are not considered top piscivores in GSL, such as Lake Whitefish, consistently show that total mercury concentrations are quite low, rarely exceeding guideline limits (Lockhart et al. 2005, Cott et al. 2016, Rohonczy et al. 2019).

Exceedances of the Health Canada consumption limit for commercial fish have, however, been recorded for top piscivores in GSL. The highest recorded concentrations in the study by Rohonczy et al. (2019) were in Northern Pike, three of which had mercury concentrations at or above the allowable maximum level for mercury. The sampled Northern Pike had low levels of mercury compared to those reported for other Northern Canadian lakes (Lockhart et al. 2005). Several Walleye and Northern Pike samples from the Slave River delta exceeded the consumption guideline for mercury, whereas adult Inconnu, also considered a top predator in GSL (Carr et al. 2017), consistently had lower mercury concentrations than both Northern Pike and Walleye, a pattern observed elsewhere (Lockhart et al. 2005). According to Kidd et al. (2012), three possible mechanisms can account for differences in mercury concentrations of top predators across systems: 1) higher baseline mercury concentrations (inputs at the base of the food web), 2) longer food chains, and 3) steeper trophic magnification slopes.

2.2.3. Lower Trophic Levels

2.2.3.1. Primary Production

The GSL ecosystem spans three terrestrial ecozones: Boreal Plains to the south where the Slave River enters GSL, Taiga Shield surrounding the East Arm, and Taiga Plain overlapping with most of the Main Basin (Kokelj 2003; Figure 2). This setting has a large impact on spatial trends in primary productivity across the lake such that primary production is almost twice as high in the Main Basin compared to the East Arm (Fee et al. 1985, also reviewed in Evans 2000). Also, photosynthetic rates are higher in waters influenced by the Slave River than waters received only from the Taiga Shield (Evans 2000). The implications for a fishery are potentially large where the Main Basin has been observed to produce high fish yields for its primary production rate, depth, and latitude (Fee et al. 1985, Evans 2000 and references therein).

In summer, nutrient concentrations attenuate rapidly in the lake as the Slave River plume is diluted away from the delta and as the phytoplankton take up the nutrients (Evans 2000). Although chlorophyll concentrations are higher in the Main Basin versus the East Arm, concentrations in both the Main Basin and East Arm of the lake are indicative of oligotrophic conditions (Rawson 1950). Latitude can also influence primary productivity, where the East Arm is naturally more productive than Great Bear Lake, a similar sized area of water but more Northern lake receiving runoff from the Canadian Shield (Reist et al. 2016).

Rawson (1956a) summarized extensive baseline surveys of the benthic and planktonic algal community at up to 57 stations throughout the lake (1944 to 1947) and annual collection at a single station from 1947 to 1954. Since Rawson, there have been very few studies on the algal communities in GSL, however one study (Moore 1980) contrasted the nearshore benthic algal community densities and species composition in the North Arm and East Arm of GSL. Nearshore benthic algae densities in the North Arm experienced peaks in the spring with estimated maximum densities for epiphyton at 5 to 6 x 10^8 $\mu m^3/cm^2$ in June and for epipelon at 4.2 x 10^8 $\mu m^3/cm^2$ in June. Algal densities in the East Arm were less than North Arm samples, which was attributed to nutrient availability in the two regions. Within the North Arm, species diversity varied across sites depending on total phosphorus and alkalinity. It is important to note that benthic primary production (i.e., macrophytes and periphyton) is not expected to compose a substantial part of whole lake primary production or contribute to higher trophic level function like phytoplankton (Janjua and Tallman 2015).

2.2.3.2. Secondary Production

Rawson (1956a) provides a detailed analysis of the zooplankton community in the open water, including species composition and spatiotemporal distributions across the lake. The observed trends in open-water zooplankton community dynamics and structure were corroborated and expanded to near shore environments in a recent synoptic survey of the Main Basin (2011 – 2016) (Zhu et al. 2017a). Mean density was negatively correlated with depth where shallow sites (less than 20 m depths) contained 78% of the total density of the samples.

The amphipod *Monoporeia affinis* (formerly *Pontoporeia*), the mysid *Mysis diluviana (*a benthopelagic crustacean previously identified as *Mysis relicta),* and several species of ostracods are the most abundant benthic-dwelling organisms in the lake although chironomids, oligochaetes, and sphaerid clams are relatively abundant in shallow waters (Rawson 1953b, Tressler 1957). At the extreme depths encountered in the East Arm (200 to 600 m), the bottom fauna is made up of single species of amphipod, ostracod, nematode, oligochaete, sphaerid clam, and chironomid (Rawson 1953b). In other words, species diversity at extreme depths was limited to one species per taxonomic group and the most diversity among taxa was found at the inflow of the Slave River (Rawson 1953b, Tressler 1957). Zhu et al. (2017a) similarly found that ostracods and amphipods were the most abundant component of the benthic community in the Main Basin, with mean densities of 599 individuals/m² and 551 individuals/m², respectively. No temporal variation (2012 – 2016) was observed across seasons at the sampled locations; however, densities varied throughout the Main Basin with the highest densities generally found along the boundary to the East Arm and in the North Arm (Figure 7), corresponding to the prevailing water circulation pattern from the mouth of the Slave River.

Dry weight biomass density (i.e., kg/ha; commonly called standing stock) of combined algal plankton and zooplankton has been shown to vary regionally across the lake because of: variability in depth and morphometry; edaphic differences in the lake (turbidity, total dissolved solids; Rawson 1956a,1956b); and water temperature (Rawson 1956a,1956b, Moore 1981). Fee et al. (1985) reported phytoplankton biomass as low as 135 mg/m^3 in McLeod Bay in the East Arm to 656 mg/m^3 at inshore locations of the

Main Basin, where the phytoplankton samples represented three main groups in the lake: chrysophytes, cryptophytes, and diatoms. The baseline surveys by Rawson (1956a) estimated that the standing stocks of combined phytoplankton and zooplankton in the Main Basin (i.e., calculated by excluding Christie Bay and McLeod Bay) was 21.8 kg/ha, with greater standing stocks in warmer water than colder water. Standing stocks in the East Arm were estimated to be 14.3 kg/ha and 9.0 kg/ha for Christie Bay and McLeod Bay, respectively. Overall, 70 – 80% of the combined plankton biomass was found in the upper 25 m of the water column. Diatoms dominate the phytoplankton and Copepods represent the largest grouping of zooplankton.

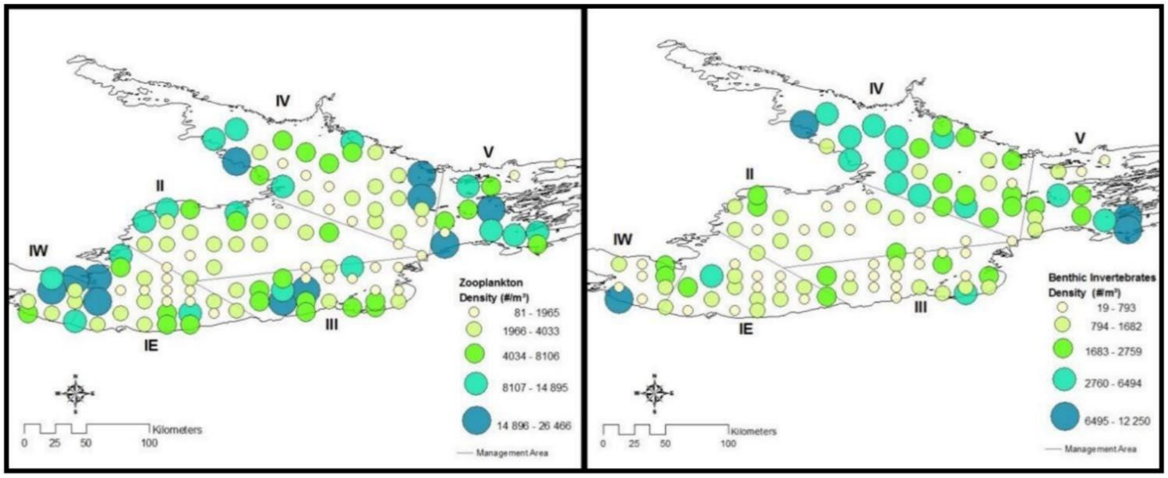

Figure 7. Density distribution of zooplankton (left) and benthic invertebrates (right) in the Main Basin of GSL, June to August, 2012 to 2016. Source: Zhu et al. 2017a.

2.2.4. Fish Community

In total, 122 documents were identified for the species-specific review of the GSL fish community, however not all were summarized in this report (Table 3). Species that have been important to the commercial fishery (e.g., Lake Whitefish, Lake Trout, Inconnu) are emphasized in the literature. Most research has taken place since 1985; however, Lake Whitefish and Lake Trout received more research effort earlier in the record, relative to Inconnu and Cisco species. Collection of basic biological data was a common focus of many documents, but secondary research topics tended to vary by species. For example, Inconnu is a highly migratory species and has experienced dramatic recruitment failures due to overfishing on spawning migrations (Van Gerwen-Toyne et al. 2013); therefore, the recent research for Inconnu has focused on identification of spawning habitat, movement patterns, and genetics (e.g., reviewed in Tallman and Howland 2017, Wiens 2018).

Table 3. Number of documents for the Great Slave Lake fish community identified by research topic and species.

Research topic[(a)]	**Fish Species**								
	Lake Whitefish	**Lake Trout**	**Inconnu**	**cisco spp.**	**Northern Pike**	**Burbot**	**Arctic Grayling**	**sucker spp.**	**Walleye**
Biological data[(b)]	18	12	11	15	8	9	5	8	3
Food webs	7	9	6	5	2	-	-	3	1
Spawning habitat	1	2	14	2	-	2	2	2	1
Movement	1	1	11	4	2	-	3	1	1
Recruitment	1	2	-	-	-	-	-	-	-
Mortality/Survival	4	6	1	5	2[(e)]	1	-	1	-
Abundance	3	2	3	4	-	-	-	3	-

Research topic(a)	Fish Species								
	Lake Whitefish	**Lake Trout**	**Inconnu**	**cisco spp.**	**Northern Pike**	**Burbot**	**Arctic Grayling**	**sucker spp.**	**Walleye**
Genetics	-	3	5	5	-	-	3	-	-
PY ≥1985(c)	23	19	21	19	14	4	10	7	9
Total Documents(d)	35	36	27	26	19	9	12	15	11

(a) Search terms included length, weight, mass, age, maturity, or growth for biological data; diet or food or isotope for food webs; spawn for spawning habitat; movement or 'migrant' for movement; recruit or fecundity for recruitment; mortality or survival for mortality; abundance or density or biomass for abundance; and genetic for genetics

(b) Summaries of fish length, weight, age, sex, maturity, growth

(c) Number of documents published since 1985

(d) Total number of documents with the species name in the title and/or abstract

(e) Hooking mortality

2.2.4.1. Focal Species for Commercial, Subsistence Indigenous, and Sport Fisheries

Whitefish Species

Whitefish populations in GSL consist of Lake Whitefish and Round Whitefish (*Prosopium cylindraceum*), with Lake Whitefish being far more prominent in the fish assemblage (Richardson et al. 2001, Evans et al. 2002). Lake Whitefish is also the dominant fish species in the GSL fish community based on biomass and population abundance (Rawson 1951, Zhu et al. 2017a) and one of the most valuable species for commercial and Indigenous subsistence fisheries in Canada (Keleher 1972, Scott and Crossman 1998). Early studies described the relative importance of Lake Whitefish in the fishery as approximately 27% of total catch numbers and 28% of total catch biomass (Rawson 1951). Over a 20-year period of historical commercial fishing from 1945 to 1964, which overlaps with the Lake Trout fishery collapse in the early 1950s, the Lake Whitefish harvest comprised 65% of total catch by weight (Keleher 1972). Lake Whitefish now may make up 93% of the commercial catch (Tallman and Friesen 2007, DFO 2015a). Recent systematic sampling of the fish community in the Main Basin (2011 to 2016) demonstrated that Lake Whitefish make up 20% of the fish community by numbers and 37% by weight (Zhu et al. 2017a).

The life history of northern populations of Lake Whitefish include alternate year spawning and spawning every two or possibly three years depending on environmental conditions (Scott and Crossman 1998). An alternate year spawning strategy by Whitefish is assumed to save energy, lead to increased survival, and increase the probability of spawning in subsequent years. Earliest sexual maturity may occur at age 5 in GSL and approximately half of Lake Whitefish mature by age 8 years (Richardson et al. 2001). Tallman and Friesen (2007) identified the first age of maturity for GSL Lake Whitefish at approximately 7 years. Round Whitefish have been documented to reach sexual maturity at age 6 years, although the earliest they typically mature is age 8 (Richardson et al. 2001). Spawning may occur from late summer to December; however, spawning usually occurs from mid-September to mid-October in northern regions (Richardson et al. 2001). Optimal spawning temperatures are expected to be between approximately 1°C and 8°C (Morrow 1979).

Fecundity (total number of eggs in ovaries) of Lake Whitefish in GSL was previously described by Healey and Nicol (1975):

$$Fecundity = 0.0043 \cdot FL^{4.06}$$

where fork length (FL) is measured in centimeters. Both species of Whitefish can spawn in lakes and rivers and are nocturnal broadcast spawners (Richardson et al. 2001). Preferred substrates range from small boulders to gravel, and occasionally sand (Richardson et al. 2001). Both species prefer to release their eggs over a hard or stony substrate (Scott and Crossman 1998) where the eggs can settle into crevices to incubate for several months before hatching in approximately March to May (Richardson et al. 2001). Spawning usually takes place in shallow water areas at depths less than 8 m, but deeper spawning has been reported for both species (Scott and Crossman 1998, Evans et al. 2002). Preferred depths are assumed to be those that extend beyond the maximum thickness of ice development in GSL (expected to be in the range of a maximum thickness of 1 to 1.5 m; Golder Associates Ltd., unpublished data). Adfluvial populations of Whitefish are also present in GSL, including those that utilize spawning areas below the Rapids of the Drowned on the lower Slave River (McLeod et al. 1985) and at Tartan Rapids and Bluefish Rapids on the Yellowknife River (e.g., Golder 2016, 2018ab, 2019a).

Adults often leave the spawning grounds shortly after spawning for deep-water locations to overwinter (Ford et al. 1995). A fish tracking study of adult Lake Whitefish completed in GSL from 1946 to 1955 suggested that tagged individuals displayed movement behavior that was similar to a sedentary life history (i.e., most movements were limited to an 8-km radius) (Keleher 1963). Adults of both Whitefish species are typically found at deeper depths than juveniles. Juvenile Whitefish are commonly found near the surface in shallow water close to spawning areas and coarse substrates where there is cover (Richardson et al. 2001).

Lake Whitefish typically inhabit depths ranging from 10 to 100 m (McPhail and Lindsey 1970) and are generally found in the benthic zone but are also found in the pelagic zone of lakes (Ford et al. 1995). Adult Round Whitefish are typically in depths ranging from 7 to 22 m with boulders present, where they feed primarily on small benthic invertebrates (Richardson et al. 2001). The diet of Lake Whitefish includes snails, clams, terrestrial insects, aquatic insects, plankton, and small fish (Scott and Crossman 1998). Lake Whitefish are preyed upon by Lake Trout and Burbot in both the juvenile and adult life-stages (Scott and Crossman 1998).

Densities of Lake Whitefish are higher in the more productive Main Basin versus East Arm (Keleher 1972). Within the Main Basin, Zhu et al. (2017a) found that Lake Whitefish biomass was distributed uniformly across the Main Basin with biomass 4.5 times greater in deeper sets than near the surface (Figure 8). Biomass was highest between 20 to 40 m and declined gradually to a depth of 80 m, below which biomass dropped off quickly. Similarly, Rawson (1951) noted that Lake Whitefish are common down to a depth of 75 m. Lake Whitefish are known to move into shallow water habitats at night to feed (McPhail and Lindsey 1970). Between 2011 and 2016, biomass was significantly different between years, with the highest biomass in 2012 (Zhu et al. 2017a). Tallman and Friesen (2007) reviewed population trends in length and age of Lake Whitefish harvested from GSL between 1972 and 1995. Over this period, average length of fish caught increased from 377 mm to 425 mm, and average age of fish caught increased from 7.7 to 10.6 years.

Growth rates of Lake Whitefish are variable across lakes, affected by temperature, primary production, and population density (McPhail 2007). Northern populations of Lake Whitefish typically grow slower and live longer than southern populations. However, the dataset of commercial fish captured between 1972 and 1995 would suggest the Lake Whitefish were fast growing through this period (Tallman and Friesen 2007). A data summary of length and weight at age using a total of 4,472 Lake Whitefish captured from the GSL commercial fishery in 1979 (Moshenko and Low 1980) would also suggest that Lake Whitefish can be fast-growing, but additional analyses are warranted. Maximum lifespans exceeding 25 years have been recorded in GSL (Zhu et al. 2017a).

Growth model parameters for Lake Whitefish have been estimated using a commercial fishery dataset from 1972 to 2009 (summarized in Table 4 and Table 5; Zhu et al. 2016). Parameters L_∞ (asymptotic length) and K (Brody growth coefficient) varied from 438 to 607 mm and 0.078 to 0.281 per year, respectively. Compared to the growth parameters of southern populations of Lake Whitefish in the Laurentian Great Lakes, the average values of L_∞ and K for the GSL fish were smaller by 16% and 50%, respectively (reviewed in Zhu et al. 2016). Within GSL, parameter L_∞ varied between 492 and 515 mm across the GSL administrative areas, except area V where L_∞ was smaller (467 mm). Spatial variations in the model parameter K, averaging 0.166 per year, were 30% greater for fish in

Management Area IW, IE and III than those in areas II and IV, while model parameter L_∞ was 1% smaller than that in deep-water areas. Growth in length-at-age for Lake Whitefish tends to be faster in southern shallow areas (Management Area IW, IE and III) than those in deep water areas (areas II and IV). Fish in area V were also different from fish in the other areas, characterized by the smallest L_∞ (467 ± 4.6 mm), greatest K (0.202 ± 0.010 per year) and largest coefficient of variation (CV = 29%).

Limited biological data for Round Whitefish populations in GSL and for Whitefish species in the East Arm are available, with some information provided in Rawson (1951) and Falk and Gillman (1975). Lake Whitefish is the best studied fish species in GSL because of its enduring importance to the commercial fishery, with extensive reviews of their ecology, life history, and management. Species presence in tributaries of the North Slave region of GSL has been summarized in Stewart (1997). Biological and life history data for Lake Whitefish populations in GSL are available from various sources (e.g., Rawson 1951, Kennedy 1953, Scott and Wheaton 1954, Falk and Gillman 1975, Keleher 1972, Moshenko and Low 1980, Tallman and Friesen 2007, DFO 2015a; Zhu et al. 2015a, 2016, 2017a, 2017b; also see total number of studies in Table 3), including summaries of length-weight relationships, length and age distributions, length at age, growth, age at maturity, and mortality. There are no long-terms studies on survival rates for Lake Whitefish to the knowledge of the authors of this report.

Table 4. Summary for fork length and round weight of Lake Whitefish sampled from commercial fisheries per administrative area in GSL during 1972 to 2004.

Body Measurement	Statistic	DFO Fisheries Management Area					
		IW	IE	III	II	IV	V
Fork length (mm)	Min	302	286	301	294	298	318
	Max	599	580	581	607	648	589
	Mean	425.9	417.1	418.9	411.6	408.8	421.9
	SD	36.87	31.03	30.96	32.85	30.29	26.77
	CV (%)	8.66	7.44	7.39	7.98	7.41	6.34
	n	11,302	17,026	6,547	15,702	19,122	14,139
Round weight (g)	Min	350	250	411	300	300	350
	Max	3,367	3,226	4,457	4,692	4,516	3,343
	Mean	1,164	1,131	1,166	1,059	1,041	1,101
	SD	335.5	270.8	323.0	300.2	259.9	245.0
	CV (%)	28.82	23.95	27.69	28.34	24.98	22.24
Dressed weight (g)	Min	298	213	350	256	256	298
	Max	2,870	2,750	3,800	4,000	3,850	2,850
	Mean	992	964	994	903	887	939
	SD	286.0	230.8	275.3	255.9	221.5	208.8
	CV (%)	28.82	23.95	27.69	28.34	24.97	22.24

SD = standard deviation; n = sample size; CV = coefficient of variation; source = Zhu et al. (2015a)

Table 5. Fork length-round weight relationships for Lake Whitefish by GSL administrative areas during 1972 to 2004.

Weight (g) Equation (= $a \cdot FL^{b}$)	DFO Fisheries Management Area					
	IW	IE	III	II	IV	V
a	2 x 10^{-05}	6 x 10^{-05}	9 x 10^{-06}	2 x 10^{-05}	4 x 10^{-05}	4 x 10^{-05}
b	2.96	2.7668	3.0883	2.996	2.8369	2.8354
R^2	0.861	0.779	0.812	0.816	0.791	0.718
n	11,303	17,026	6,547	15,702	19,122	14,139

FL = fork length in mm; R^2 = coefficient of determination; n = sample size; Source = Zhu et al. (2015a)

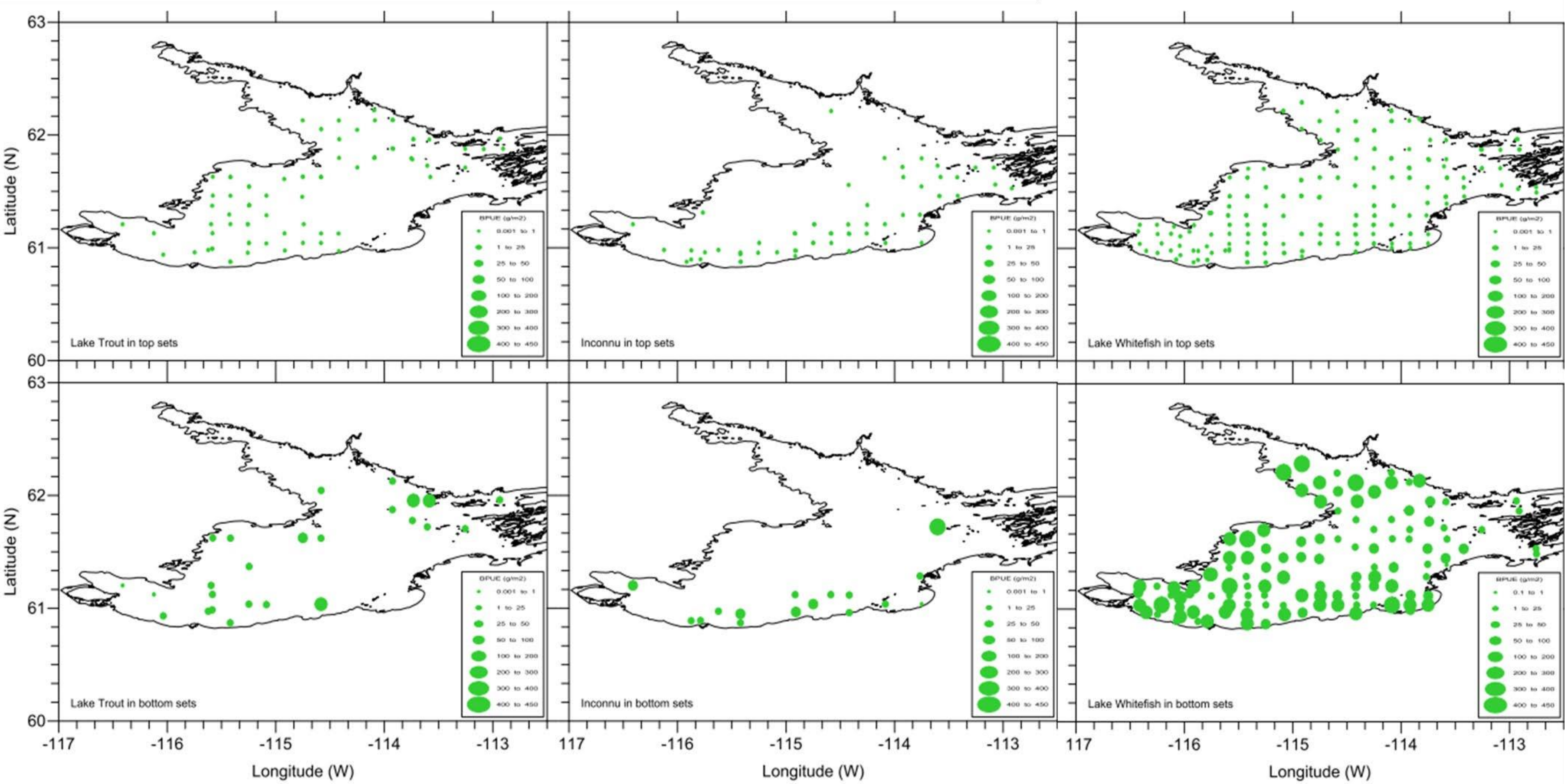

Figure 8. Spatial distribution of biomass per unit effort (BPUE; g/m²) for Lake Trout (left), Inconnu (centre), and Lake Whitefish (right) in topset pelagic (upper panels) and bottom benthic (lower panels) gillnet sets during a fishery independent survey in GSL, 2011 to 2016. Source: Zhu et al. 2017a.

Lake Trout

Lake Trout primarily use lake habitats and remain in freshwater systems throughout their lifecycle (reviewed in Scott and Crossman 1998, Evans et al. 2002, Richardson et al. 2001, McPhail 2007). Lake Trout are found in most lakes throughout Northern Canada where there are sufficient depths for overwintering fish. In GSL and throughout most of NWT, Lake Trout is also an important species for commercial, subsistence Indigenous, and recreational sport fisheries. Rawson (1949) described fish community composition in GSL with Lake Trout making up 10% of the community by numbers and 46% by weight based on 145 standard gill-net sets in GSL from 1944 to 1946. Lake Trout was the third most numerically abundant species, behind Lake Whitefish and Cisco, and was the largest biomass of all 21 species sampled, with an estimated yield similar to the upper Laurentian Great Lakes and Lake Nipigon (Rawson 1949, 1951). Historical records from the commercial fishery in GSL include individual fish weighing up to 25 kg (Rawson 1951). But with declines starting in the Main Basin in the 1950s and then the East Arm, the commercial fishery began to target other species with the closure of the East Arm to commercial fishing in 1974 (Yaremchuk 1986). Recent monitoring efforts in the Main Basin have described stable populations from 2011 through 2016 (Zhu et al. 2017a). Over this period, the Lake Trout was 0.6% of the fish community by numbers and 6.6% by weight based on catch data from a grid-based monitoring system using three different sets of gillnets deployed across the Main Basin of GSL (Zhu et al. 2017a).

In northern populations, Lake Trout are especially long-lived and fish older than 20 years are common (Power 1978), including in GSL, where the density of Lake Trout older than twenty years is estimated at 0.49 fish per utilized ha (i.e., hectares of GSL fished by Sport fishing lodges; Yaremchuk 1986). Given the size of GSL, it is possible that ages approaching 50 years are relatively common (Shuter et al. 1998). Furthermore, the instantaneous natural mortality rate for adult Lake Trout was previously estimated to be 9% per year, based on a nine-year study of sport fish exploitation (Yaremchuk 1986). This is consistent with observations made by previous authors on the longevity of northern populations (Power 1978).

Lake Trout spawning occurs in the fall when water temperatures fall below approximately 10°C (Scott and Crossman 1998, Richardson et al. 2001, McPhail 2007), and GSL populations appear to spawn every second year, a common reproductive strategy for salmonids in Northern waters (Kennedy 1954, Moshenko and Gillman 1978). Lake Trout typically start to mature as early as age 6 to 7 years (Scott and Crossman 1998), with the onset of maturity in GSL higher than other populations in North America (Hansen et al. 2016). Age at 50% maturity was calculated as age 16 years based on Lake Trout sampled using gill-net sets in the East Arm from 2002 to 2010 (Hansen et al. 2016). During early years of exploitation (1948–1952), maturity was at a much younger age (50% maturity by age 9) (Kennedy 1954). Lake trout in GSL can also attain sexual maturity 4 to 5 years earlier and at a smaller size than Lake Trout on Great Bear Lake (Moshenko and Gillman 1983). Sex ratios of the Lake Trout population vary little from the 1:1 relationship (Falk et al. 1973b).

Suitable spawning substrate (e.g., rocky shoals) seems to be highly abundant throughout the East and North arms, and areas of the Main Basin where suspended sediment levels are relatively low, and therefore, spawning habitat does not appear to be a limiting resource for Lake Trout (Muir et al. 2012). In the Main Basin, Lake Trout distributions are often constrained to areas of clear water, away from high turbidity areas near the mouth of the Slave River (Figure 8). Spawning occurs at night, and females broadcast eggs over shoals of large boulder or rubble typically at depths up to 12 m (Richardson et al. 2001). The fertilized eggs settle into the interstitial spaces within the substrate to incubate. Fecundity is low compared to Coregonid species in GSL (McPhail 2007). However, fecundities for Lake Trout from GSL are higher than those from other lakes in North America, averaging 1,700 eggs per kg of body weight (Healey 1978). Eggs remain in the substrate over winter, and hatch four to five months later in March or April. Young Lake Trout feed in shallows for several months before they are large enough to venture into deeper water. There is evidence that adults in some populations return to their natal spawning sites.

A fish tracking study of adult Lake Trout completed from 1946 to 1955 suggested that tagged individuals displayed movement behavior that was more similar to a sedentary life history (i.e., most movements were limited to a 8-km radius) (Keleher 1963). However, adfluvial populations of Lake Trout have also been identified in GSL, spawning in rivers such as the Yellowknife River (Stewart 1997, Golder 2018a, 2019a), and these adfluvial fish may make sizeable movements between spawning locations and GSL compared to those described in Keleher (1963). Moshenko and Gillman (1983) also report long distance movements of Lake Trout that can extend almost 270 km between capture and recapture locations within GSL.

Zhu et al. (2017a) found that Lake Trout biomass, unlike Lake Whitefish, was distributed in areas of clear water in the Main Basin (Figure 8) and was evenly distributed across different depth strata. Peak abundance may occur at 25 m depths with distributions that can extend to depths of 75 m. The densities of Lake Trout may also be higher in the East Arm versus the Main Basin (Rawson 1951). Yaremchuk (1986) suggested that only a fraction of the shallow, sedimentary Main Basin is suitable habitat for Lake Trout.

Young Lake Trout primarily feed on plankton and aquatic insect larvae until they reach adequate size to prey on other fish, such as cisco spp., juvenile Lake Whitefish, and juvenile Round Whitefish (Scott and Crossman 1998, Richardson et al. 2001, McPhail 2007). Cisco is a common food item found in Lake Trout stomachs (Moshenko and Gillman 1983). Seasonal changes in diet are also common, reflecting changes in surface water temperatures. For example, in the spring, adults may feed on forage fish and terrestrial insects in shallow water. When the lake continues to warm, and then stratifies in summer, Lake Trout can be separated from these littoral sources by a thermal barrier (i.e., temperatures above 15°C in the upper layer of the lake). Under these conditions, Lake Trout can switch back to planktivory in the open water. Large adult Lake Trout in GSL also exhibit phenotypic variation associated with water depths, with differences in colour, body shape, buoyancy, and pectoral fin length observed in fish that typically inhabit water deeper than 50 m (Zimmerman et al. 2006, Hansen et al. 2016).

Sympatric morphs of Lake Trout in GSL include a fat morph that occupies mostly deep waters, eating mostly invertebrates, especially opossum shrimp, having a narrow caudal peduncle, light body color, greater buoyancy, and deep anterior body, versus the sympatric lean morph that occupies mostly shallow water, eats mostly fish, having a streamlined shape, dark colour and less buoyancy (Zimmerman et al. 2006, 2009). Based on Lake Trout sampled using gill-net sets in the East Arm from 2002 to 2010, Hansen et al. (2016) described the life history measurements of the two morphs (Table 6). The fat morph was 26% heavier at length than the lean morph in GSL. The fat morph also grew at a slower early growth rate to a shorter average asymptotic length than the lean morph in GSL (Table 6). Age at 50% maturity was similar between the two morphs: 16.0 years for the fat morph and 16.2 years for the lean morph.

Biological life history data for Lake Trout populations in GSL are available from various sources (e.g., Rawson 1951, Scott and Wheaton 1954, Falk et al. 1973b, Falk et al. 1982, Healy 1978, Moshenko and Gillman 1983, Yaremchuk 1986, Zimmerman et al. 2006, Hansen et al. 2016), including summaries of length-weight relationships, length and age distributions, length at age, growth, and length and age at maturity. Keleher (1963) provides limited information on Lake Trout movements and Lake Trout presence in tributaries of the North Slave region of GSL has been summarized in Stewart (1997). Genetic analysis is increasingly being considered to investigate phenotypic morphs in GSL (Zimmerman et al. 2006, Hansen et al. 2016) and to answer questions about spawning behaviour (Muir et al. 2012).

Table 6. Life history characteristics for fat and lean morphs for Lake Trout sampled in the East Arm, 2002–2010.

Morph Type	n	Mean FL (mm) (SE)	Mean Weight (g) (SE)	L-W Equation 'a'	L-W Equation 'b'	L-W Equation R^2	Early Growth Rate (ω) [mm/year])	Asymptotic Length (L_∞ [mm])
Fat	122	583 (12.1)	2319 (119)	4.02×10^{-07}	3.5081	0.96	54.1	730
Lean	114	568 (12.5)	1838 (123)	3.18×10^{-06}	3.1452	0.98	58.4	760

SE = standard error; FL = fork length; R^2 = coefficient of determination; n = sample size; L-W equation, where weight (g) = a · FL^b; Source = Hansen et al. (2016)

Inconnu

Inconnu are found throughout the Mackenzie River basin, including populations found in GSL and several of its major tributaries. In the GSL ecosystem, Inconnu are the largest member of the Coregonid subfamily (which includes Whitefish and Cisco species), with spawning adults often exceeding 600 mm in length (Howland et al. 2001). Early studies of the GSL fish community (1945 to 1947) described Inconnu as a minor component of the GSL fish community, estimated at 1.3% of the total catch by numbers and 5% by weight (Rawson 1949, 1951), but Inconnu would become more important to commercial fisheries, with several harvests targeting the species in the 1970s. With sustained decades of overfishing several Inconnu populations in GSL, numerous fishing closures were implemented and have remained in place such that Inconnu are now primarily captured only for Indigenous and recreational fisheries (VanGerwen-Toyne et al. 2013). Inconnu remains a dominant by-catch species (Zhu et al. 2017a). A historical review of Inconnu presence throughout GSL strongly suggested that this species is vulnerable to recruitment overfishing (Day et al. 2013). Recent monitoring efforts in the Main Basin have described stable populations from 2011 through 2016 (Zhu et al. 2017a). Over this period, Inconnu was 0.8% of the fish community by numbers and 10.4% by weight based on catch data for a grid-based monitoring program in the Main Basin (Zhu et al. 2017a).

The life history of Inconnu in the GSL region is adfluvial, with mature adults overwintering in GSL and then making upstream spawning migrations into the major tributaries of the lake over several months in the summer (Richardson et al. 2001). Currently, seven Inconnu stocks are recognized within GSL that correspond to major tributaries. Unfortunately, fall spawning runs of Inconnu in the tributaries have declined, including the Buffalo, Slave, and Mackenzie rivers (VanGerwen-Toyne et al. 2013). For example, excessive fishing pressure targeting spawning stocks of Inconnu in Buffalo River over two seasons (1978–1979) contributed to a year class failure and lower catches of mature individuals into the early 1980s (VanGerwen-Toyne et al. 2013). Spawning stocks on Yellowknife, Taltson, Little Buffalo, and Hay rivers were likely extirpated by the 1960s (reviewed in MRBB 2004). Inconnu may be particularly vulnerable to recruitment overfishing because juveniles grow rapidly to a large size and can become vulnerable to the fishery several years before they mature (Tallman and Howland 2017). They also undergo concerted migrations, through restricted corridors or pinchpoints at predictable times, making them susceptible to harvesting along their migration routes.

Because Inconnu are characterized by high spawning site fidelity (Alt 1969), the likelihood of the recovery of the extirpated stocks may be very low without assisted relocation from nearby self-sustaining populations. The river supporting the largest self-sustaining run of spawning Inconnu may be the Slave River where large spawning congregations extend below the Rapids of the Drowned (Fuller 1955, McLeod et al. 1985, Tallman and Howland 2017). For populations that have persisted despite historical exploitation, unpublished data from recent monitoring and anecdotal reports of recovery by various researchers working in Yellowknife Bay and Marian River, including DFO and Golder, suggest that some Inconnu stocks are increasing in size (Golder 2019c). To aid with conservation and management of existing stocks in the GSL ecosystem, a recent study by Wiens (2018) was completed to assess the population genetics of Inconnu. If Inconnu are philopatric to specific river systems for spawning, then each river system is predicted to support a distinct genetic population. Four genetic groups of Inconnu were identified, one in the lower and upper Mackenzie and three within GSL (Wiens 2018). Additional sub-structuring among locations in GSL corresponded to three major river systems: Slave River, Buffalo River and Marion River, suggesting that each river supports a genetically distinct Inconnu population (Wiens 2018).

Inconnu have lifespans often exceeding 20 years and rapid growth rates during early years of juvenile development (Table 7) (Fuller 1995, Howland et al. 2004, Tallman and Howland 2017). Maximum lengths of the Slave River stock are approximately 1,100 mm for female Inconnu and 890 mm for male Inconnu (Howland 2005). See Table 8 for calculations of asymptotic lengths for the Slave River and Buffalo River stocks.

Length-weight relationships were estimated for adult Inconnu in the Slave River stock (McLeod et al. 1985):

$$weight = a \cdot FL^{b}$$

where weight is measured in grams and length is measured in millimeters. Parameter ‘a’ was 0.203 x 10^{-4} for 1983 data and 0.549 x 10^{-4} for 1984 data, and parameter ‘b’ was 2.921 for 1983 data and 2.762 for 1984 data.

Inconnu are sexually mature between 6 and 10 years of age and are thought to spawn every 2 to 4 years (Richardson et al. 2001, Howland 2005). Inconnu are nocturnal broadcast spawners and share similar reproductive life histories with adfluvial Lake Whitefish (Brown 2009). The relationship between fecundity (total egg dry biomass; milligrams) and fork length (millimeters) has been estimated for year-round residents of GSL ($Fecundity_{GSL}$) and anadromous populations in the lower Mackenzie River ($Fecundity_{MR}$), described by the following equations (Howland 2005):

$$Fecundity_{GSL} = e^{(1.482 \cdot 10^{-3}) \cdot FL + 3.842}$$

$$Fecundity_{MR} = e^{(1.807 \cdot 10^{-3}) \cdot FL + 3.463}$$

Optimal spawning temperatures range from 1°C to 5°C for Inconnu (Morrow 1979). Although exact locations and characteristics of spawning are not well understood for GSL Inconnu populations, Alaskan populations are known to spawn over gravel-dominant substrate in water approximately 1 to 2 m in depth (Richardson et al. 2001), and in the Slave River, spawning areas are characterized by run habitat types (maximum depths exceeding 1.5 m with moderate to high water column velocities near 1.0 m/s) and gravel dominated substrate types (Mcleod et al. 1985).

Inconnu are highly migratory and widely distributed in the Mackenzie River Basin from the lower reaches of GSL tributaries to the Mackenzie Delta, and the Beaufort Sea coast (Howland et al. 2009). Within the lake, recent studies of Inconnu (2011 to 2016) found that Inconnu biomass is aggregated in the south and east areas of the Main Basin (Figure 8) (Zhu et al. 2017a). Fuller (1955) identified maximum abundance of Inconnu in the shallow, heavily silted water off the south shore from the Slave River delta to the source of the Mackenzie. On average, Inconnu biomass near the surface was more than double the biomass in deeper areas but Inconnu were observed to range up to depths of 40 m. They are seldom found in deeper portions of the lake (Fuller 1955). No inter-annual variation in biomass was observed from 2011 to 2016, indicating stable population dynamics. Unlike Inconnu in the lower Mackenzie River, GSL Inconnu exhibit an entirely freshwater life history (Howland et al. 2001, 2005, 2009).

Inconnu typically return from spawning tributaries to GSL in late-October (Richardson et al. 2001). Life history details of Inconnu development by stages are currently not well known, and juvenile Inconnu may rear in spawning tributaries for up to two years before migrating into GSL (Richardson et al. 2001). Young Inconnu found in tributaries eat primarily invertebrates, whereas larger Inconnu in GSL have a primarily piscivorous diet, which include juvenile whitefish spp., cisco spp. and even juvenile Inconnu (Fuller 1955, Day and Low 1993). Inconnu presence in tributaries of the North Slave region of GSL has been summarized in Stewart (1997). Additional statistics on life history parameters for Inconnu in GSL can be obtained from various sources (e.g., Fuller 1955, McLeod et al. 1985, Howland 2005, Tallman and Howland 2017, Wiens 2018).

Table 7. Estimated Inconnu weights at age for Great Slave Lake.

Inconnu Age / Stage	Weight (kg)	Key Sources for Weight
1	0.073	Fuller (1955), McLeod et al. (1985)
2	0.324	Fuller (1955), McLeod et al. (1985)
3	0.628	Fuller (1955), McLeod et al. (1985)
4	2.052	DFO (2018)
5	2.646	DFO (2018)
6	3.053	DFO (2018)
7	3.741	DFO (2018)
8	4.533	DFO (2018)

Note: weights for ages 1 to 4 derived using length-weight equations in McLeod et al. (1985) and lengths reported in Fuller (1955).

kg = kilogram.

Table 8. The Von Bertalanffy growth rate (K), asymptotic length (L_∞), instantaneous total mortality (Z), instantaneous natural mortality (M), estimated harvestable biomass, and fishing mortality (F) for select Inconnu stocks.

Stock	Growth Rate (K)	Asymptotic Length (L_∞; cm)	Z Mortality	M Mortality	F Mortality	Harvestable Biomass (tonnes)
Slave	0.20	97.8	0.85	0.196	0.65	4.29
Buffalo	0.30	82.6	1.00	0.268	0.73	0.90
Buffalo (Historical Unexploited)	0.15	123.1	0.50	0.152	0.35	4.75

Source: Tallman and Howland (2017)

2.2.4.2. Other Species for Commercial, Subsistence Indigenous, and Sport Fisheries

Northern Pike

Northern Pike have a circumpolar distribution and have the broadest range of any member of the Esocidae family, occurring in freshwaters across the Northern hemisphere (Scott and Crossman 1998). Northern Pike are also found throughout freshwater systems of the mainland NWT (with the exception of the northern tundra), and within the GSL ecosystem, they typically inhabit shallow bays in lakes and slow-moving sections of stream and rivers (Richardson et al. 2001). Northern Pike are known to exhibit lacustrine, adfluvial, and riverine life histories. Most populations are relatively sedentary but will make migrations to reach spawning grounds (Evans et al. 2002, Cott 2004). Riverine pike seek out low-gradient pools, marshy areas connected to rivers, gradual sloping banks, and floodplains as spawning habitat (Cott 2004). Northern Pike are a small component of the GSL commercial fisheries harvest but are an important species for Indigenous and recreational fisheries (Richardson et al. 2001). In a recent fishery-independent survey in the Main Basin, Northern Pike was 1% of all catch across all depths (Zhu et al. 2017a). The survey did not provide information on the relative density or biomass of Northern Pike in the Main Basin, possibly due to biases in sampling locations that targeted open water areas away from shorelines where Northern Pike are less numerous.

Northern Pike in GSL begin spawning in the spring after ice breakup, typically between May and June, using shallow water (less than 1 m deep) in lakes, ponds, and backwaters of rivers (Richardson et al.

2001). Northern Pike deposit their eggs in areas with fine substrates, such as silt, and adhere their eggs to vegetation with fine leaves, such as emergent grasses and sedges (Richardson et al. 2001). The eggs incubate for 10 to 21 days before hatching, and the young remain attached to the vegetation for an additional 6 to 10 days (Richardson et al. 2001). Juvenile Northern Pike typically remain in the sheltered, vegetated spawning areas for weeks after hatching, which act as shelter from predators as well as shelter for their prey.

Northern populations of Northern Pike reach sexual maturity between 5 and 6 years of age, and the lifespan of Northern Pike in GSL can exceed 25 years (Evans et al. 2002). Adult Northern Pike prefer to occupy depths of less than 5 m during the open water season but move to deeper water to overwinter. Northern Pike in GSL are rarely captured at depths greater than 10 m (Richardson et al. 2001). Adult Northern Pike are primarily piscivorous but are also known to opportunistically feed on small waterfowl and mammals. Recent modelling studies of trophic networks in GSL suggest that Northern Pike is a keystone species in the ecosystem (Janjua et al. 2014).

Biological life history data for Northern Pike populations in GSL are available from various sources (Miller and Kennedy 1948, Rawson 1951, Bond and Turnbull 1973, Tallman et al. 1996a, Stewart et al. 1999), including summaries of length-weight relationships, length and age distributions, length at age, growth, and length and age at maturity. Keleher (1963) provides the limited available information on Northern Pike movements. Cott (2004) provides a detailed discussion of Northern Pike spawning habitat in a GSL tributary.

Cisco

Cisco species are found throughout much of Canada, including the central Canadian Arctic (reviewed in Scott and Crossman 1998, Evans et al. 2002, Richardson et al. 2001). Cisco (locally called Lake Herring), Least Cisco (*Coregonus sardinella*), and Shortjaw Cisco (*Coregonus zenithicus*) are present in GSL (Turgeon et al. 2016). Numerically, Cisco and Least Cisco may represent the most abundant species in GSL (Rawson 1951, Zhu et al. 2017a). Speciation and phenotypic variation of cisco spp. have been a keen research topic in GSL in recent years (described in Turgeon et al. 2016), because cisco spp. have been identified as an important trophic nutrient for energy transfer in the fish community. Cisco spp. are important links in the food web as a prey species for larger predatory fish, specifically Lake Trout, Inconnu, and Burbot in GSL, and for the biotic transfer of nutrients and energy from offshore pelagic water to nearshore littoral habitats during fall spawning migrations.

The Cisco of GSL have been defined by three distinct phenotypic morphologies (Muir et al. 2011, 2014): Lacustrine *C. artedi* that are similar to those from other populations throughout North America; an adfluvial *C. artedi* morph that is distinct from its lacustrine conspecific (Blackie et al. 2012, Turgeon et al. 2016); and a Big-eye *C. artedi* morph that remains taxonomically uncertain (Turgeon et al. 2016). Shortjaw Cisco is morphologically like lacustrine *C. artedi* but distinguished by low numbers of short gillrakers and a slightly shorter lower jaw than upper jaw (Turgeon et al. 2016). The species also has a faster growth rate and a shorter asymptotic average length compared to lacustrine *C. artedi*.

Cisco species primarily inhabit the pelagic zone of lakes but move below the thermocline in the summer and into shallow waters as the water temperature cools in fall (Scott and Crossman 1998). Cisco species are also zooplanktivores (Rawson 1951, Muir et al. 2013). Rawson (1951) examined the stomach contents of 378 cisco spp. and determined that collectively their diets across the lake are composed primarily of copepods (59%), *Mysis* (29%), and aquatic insect larvae (10%). Variability in diet composition in different regions of the lake was observed; however, speciation in Cisco was not known at the time. The diet composition among phenotypes of Cisco is currently unknown and has been highlighted as a key research area for determining the feeding behaviour, habitat use, and trophic structure of Cisco phenotypes (Blackie et al. 2012) and determining how ontogenetic shifts in diet and body form drive phenotypic divergence (Vecsei et al. 2012). Recent isotopic analysis indicates an ontogenetic shift in resource use for lacustrine *C. artedi*, where large *C. artedi* had a greater reliance on pelagic prey resources compared to small *C. artedi,* which relied slightly more on nearshore benthic prey (Muir et al. 2013).

Cisco spp. spawn in the fall (September/October) at water temperatures between approximately 3°C and 5°C. During the spawn, large numbers of fish gather in shallow water (1 to 3 m deep) to deposit their eggs over gravel or stony substrates (Scott and Crossman 1998). The adfluvial phenotype of Cisco also enter rivers during the fall to spawn (Muir et al. 2013), where in the Yellowknife River the abundance and timing of river-spawning Cisco are monitored annually by the Northwest Territories Power Corporation since 2013 (Golder 2018a, 2019a). Cisco eggs incubate over the winter and hatch in the spring. Cisco in GSL typically reach sexual maturity between the ages of 3 and 5 years, although Shortjaw Cisco mature at age 2 years. Cisco spp. are important prey species for larger predatory fish, specifically Lake Trout, Inconnu, and Burbot in GSL, and play a role in trophic dynamics in the fish community through biotic transfer of nutrients and energy from offshore pelagic water to nearshore littoral habitats during fall spawning migrations. All cisco spp. have lifespans that can exceed 20 years, although significant variation in maximum ages exist between phenotypes of Cisco. The Cisco lacustrine phenotype can exceed 30 years of age, whereas the adfluvial phenotype has a maximum recorded age of 9 years (Muir et al. 2011).

Shortjaw Cisco has been assessed by COSEWIC as Threatened (2003) although not listed under Schedule 1 of the Species at Risk Act (SARA), due to overall population declines in North America. The species has been extirpated from lakes Huron and Erie and is also in decline in Lake Superior and possibly GSL. Threats in GSL have included overfishing and elsewhere have included the introduction of exotic species and climate change.

Biological and life history data for populations of cisco spp. in GSL are available from various sources (e.g., Rawson 1951, Kennedy 1956, Bond 1974, Stewart et al. 1999, Muir et al. 2011, Muir et al. 2014, Vecsei et al. 2012, Zhu et al. 2017a) including summaries of length-weight relationships, length and age distributions, length at age, growth, and length and age at maturity. Cisco (*C. artedi*) presence in tributaries of the North Slave region of GSL has been summarized in Stewart (1997). Genetic information on cisco spp. is provided by Turgeon and Bernatchez (2001), Turgeon and Bourret (2013), and Turgeon et al. (2016).

Arctic Grayling

Arctic Grayling are found in freshwater systems throughout the central Canadian Arctic and typically rely on a variety of habitats including lakes, rivers, and streams to complete their life cycle (reviewed in Scott and Crossman 1998, Evans et al. 2002, Richardson et al. 2001). Arctic Grayling in GSL are typically found in water less than 3 m deep during the open water periods, often over silt, sand, and gravel substrates as well as along rocky shorelines (Richardson et al. 2001). Adult and juvenile fish spend the winter sheltered in lakes, or in deeper pools of rivers. Arctic Grayling are an important fish for both Indigenous and recreational fisheries in GSL.

During spring break up, adult Arctic Grayling populations will begin their migration from GSL and larger rivers to smaller streams and tributaries with areas of small gravel or rocky substrates to spawn (Bishop 1971; Scott and Crossman 1998). Although spawning has been documented in shallow lacustrine habitat elsewhere in the Arctic, no lacustrine spawning has been documented in GSL populations (Richardson et al. 2001). Spawning can occur over several weeks, typically between April and mid-June. Identified spawning locations for GSL include Slave River, Hay River, Baker Creek, and tributaries of the Mackenzie River. Females broadcast eggs over small gravel and cobble to be fertilized, and then adults return to larger rivers or GSL. Eggs incubate for 13 to 18 days before hatching, at which point the newly hatched fish spend the next 3 to 4 days sheltered in the substrate while absorbing their yolk sac and starting to feed (Stewart et al. 2007). Male and female Arctic Grayling in GSL have been noted to reach maturity at 3 to 6 years of age, but most spawners are between 6 and 9 years of age (Bishop 1971, Scott and Crossman 1998). Maximum lifespan of Arctic Grayling in GSL is at least age 12 (Stewart et al. 2007).

Young Arctic Grayling feed primarily on zooplankton in streams and shallow water of lakes, shifting to immature insects as they grow (Stewart et al. 2007). In general, adults are opportunistic in their feeding habits and their diet is extremely variable compared to other species (Bishop 1967, De Bruyn and McCart 1974). Rawson (1951) analyzed the stomach contents of 28 Arctic Grayling and the estimated diet was composed primarily of amphipods, aquatic insects (chiefly caddis fly), and terrestrial insects in the lake. Insects were also found to be the predominant food resource in the Mackenzie River (Stein et al. 1973).

Biological and life history data for Arctic Grayling populations in GSL are available from Falk and Gillman (1975), including summaries of length-weight relationships, length and age distributions, length at age, growth, sex and maturity ratios. Limited information on spatial distribution by depth and diet is available in Rawson (1951). Stein et al. (1973) provides a summary of biological data for the Arctic Grayling populations downstream of GSL in the Mackenzie River. Spawning locations in tributaries are identified in Bishop (1971), Moshenko and Low (1983), and Arctic Grayling presence has been summarized for tributaries of the North Slave region of GSL in Stewart (1997).

Walleye

Walleye are native to freshwater lakes and rivers in Northern latitudes of North America and their current distribution is a result of repeated glacial events, river migration movements, and colonization (Scott and Crossman 1998). Walleye are also widely distributed across the NWT and are present in the Mackenzie River watershed as far north as the Mackenzie River delta, and in the tributary streams and rivers of GSL. Across their range, Walleye have adapted lacustrine and riverine habitats, with lakes representing most of their aquatic habitat (Richardson et al. 2001). They are also relatively abundant year-round in the Slave and Hay rivers (Stewart and Low 2000, Tallman et al. 2005), and there is report of strong harvest pressure on the Hay River population, however that population is thought to be stable because of low angling catchability related to high water and turbidity during summer flows when angling activity is highest. The area closure to commercial fishing at the mouth of the Hay River is also thought to help sustain the productivity of the Hay River Walleye population (Stewart and Low 2000).

Walleye are primarily a cool water species (occupying waters between 19ºC to 25ºC in summer). They spawn between spring and early summer over gravel, boulder, and rubble substrates, primarily at depths less than 2 m, and eggs incubate for 12 to 18 days before hatching. Major aggregations of spawning Walleye in the GSL area have been recorded below the Rapids of the Drowned on the Slave River (Tallman et al. 2005), and at the mouth of Dore Creek on Marian Lake (WRRB 2014). Juvenile and adult Walleye are photonegative and seek cover from the sun under banks, sunken trees, logs, boulder shoals, weed beds, as well as in deep water and turbid water. This behaviour also means increased feeding at night when Walleye move from deep water, or from underneath overhead cover to feed in shallow water (Richardson et al. 2001). Walleye of all ages seek deeper water in the summer, possibly to avoid warming lake temperatures or as a response to shifts in the distribution of prey such as cisco spp. and juvenile Whitefish (Richardson et al. 2001). Walleye in the GSL region are primarily piscivorous; however, Walleye can exhibit a generalist feeding strategy consuming both fish and aquatic invertebrates (Little et al. 1998). Walleye in GSL do not inhabit depths greater than 10 m and are most frequently captured at depths of less than 5 m (Richardson et al. 2001).

Walleye in northern lakes are slow growing and long living, and fish 16 years of age may be common in lakes such as GSL (Richardson et al. 2001, Evans et al. 2002). Biological and life history data for Walleye populations in GSL are generally lacking in the literature; however, some information is reported in Stewart et al. (1999), including length, weight, and condition factor. Tallman et al. (1996a) provides information on Walleye biology in the Slave River and Stein et al. (1973) provides a summary of biological data for the Walleye populations downstream of GSL in the Mackenzie River. Walleye presence in tributaries of the North Slave region of GSL has been summarized in Stewart (1997). The two reports by Falk et al. (1980) and Falk (1980) provide detailed information on the Walleye population that spawns in Mosquito Creek, a tributary of the North Arm of GSL. The spawning population of Walleye was studied from 1973 to 1978 through a creel census and biological sampling program which included weir, gillnet, hoop net, and fyke net operations, and tagging. Detailed biological data on length, length-weight relationships, age, mortality, fecundity, spawning migration, and movement of Walleye are provided and summarized in the reports (Falk 1980, Falk et al. 1980).

Burbot

Burbot are the only freshwater species from the cod family and are found throughout the continental NWT, typically occurring in deep lakes but also exhibiting riverine life histories (Richardson et al. 2001, Van Houdt et al. 2003). Burbot in GSL can be divided into lacustrine populations that spend their entire life history in lakes, and adfluvial populations that spawn in watercourses but complete most of their rearing and feeding in lakes (Richardson et al. 2001). Burbot make up a proportion of commercial fishery bycatch but are targeted by Indigenous and recreational fisheries.

Burbot genetics have been the focus of several studies in GSL and the region because two subspecies (i.e., the Eurasian subpecies *Lota lota lota* and the North American subspecies *Lota lota maculosa*) are known to inhabit the Mackenzie River Basin. The suture zone (i.e., area of postglacial parapatry for subspecies) was recently determined to be in the Mackenzie River delta (Elmer et al. 2012).

In the NWT, Burbot sexually mature between the ages of 3 to 5 years, with males often maturing one to two years before females. Burbot typically spawn under the ice between January and March when water temperatures are between 0ºC and 2°C. They are known to vocalize during the spawning period (Cott et al. 2014) and are broadcast spawners, typically releasing their eggs over sand, gravel, or rubble substrates less than 3 m deep (Richardson et al. 2001). Burbot are said to perform the act of spawning by moving across the substrate in an intertwined, writhing ball of up to 12 fish (Evans et al. 2002, Elmer et al. 2012). Eggs drift and often settle in coarse substrate, where they incubate for 3 to 12 weeks, depending on water temperature. There is some evidence that in sub-Arctic lakes Burbot undergo diel bank migration, occupying deeper water during the day, at the transition of soft, low complexity substrates and ascend to shallower water habitats at night (Elmer et al. 2012).

Upon hatching, young Burbot are typically found in the pelagic zone, congregating over sand and rubble substrates. Once young Burbot reach fingerling size, they change from crepuscular to nocturnal feeders and seek shelter under physical structures such as rocks and logs during the day (Richardson et al. 2001). Like the juveniles, adult Burbot are sensitive to light and seek shelter during the day. Adult Burbot are primarily piscivorous, with populations in GSL typically feeding on juvenile whitefish spp., cisco spp., and forage fish species. Recent modelling studies on trophic networks in GSL suggest that Burbot is a keystone species in the ecosystem (Janjua et al. 2014).

Northern populations of Burbot are slower growing and can reach greater size than southern populations, with maximum ages exceeding 20 years and weights exceeding 8 kg (Richardson et al. 2001, Evans et al. 2002). Additional data on the life history of Burbot populations in GSL are available from various sources (e.g., Rawson 1951, Bond 1974, Tallman et al. 1996b, Elmer et al. 2012, Cott et al. 2016), including summaries of length and weight data relationships, length and age distributions, and length at age. Burbot presence in tributaries of the North Slave region of GSL has been summarized in Stewart (1997). Keleher (1963) provides the limited information that is available on Burbot movements. Genetics in the GSL population have been studied by Elmer et al. (2012).

Sucker Species

Suckers in the GSL region are comprised of two species: Longnose Sucker and White Sucker. Both species are common throughout the region, although White Suckers are less common throughout the NWT, typically only found below the treeline (Richardson et al. 2001). Suckers can exhibit lacustrine, riverine, and adfluvial life histories, but typically spawn in rivers (Richardson et al. 2001). Suckers are not a significant component of commercial or recreational sport fisheries, although historically they have been important to subsistence fisheries in the GSL region where they were traditionally harvested for dog food (Harris 1962). Paulette Creek, on the south shore of the Main Basin, supports an active fishery of Longnose Sucker that is important to the nearby community of Fort Resolution (Falk and Dahlke 1975, Golder 2019b).

Suckers spawn following ice melting on lakes, typically between May and June, with Longnose Sucker starting spawning migrations earlier than White Sucker. Suckers prefer to spawn in rivers over coarse substrate between 10 and 50 cm in diameter, with flow rates between 0.2 and 1.0 m/s, and depths up 0.5 m for Longnose Sucker and 1.0 m for White Sucker (Evans et al. 2002). Where Suckers are known to spawn in lake habitat, they prefer substrates consisting of gravel and sand in shallow areas (< 0.3 m) along rocky, wave-swept shorelines (Richardson et al. 2001). Sucker eggs are adhesive and incubate within coarse substrate for 5 to 15 days, depending on temperature. Hatched fish then remain in the coarse substrate for 1 to 2 weeks before emerging (Richardson et al. 2001, Evans et al. 2002).

After young Suckers leave the coarse substrate, they prefer to occupy protected, shallow water with vegetative cover until later in the summer when they move out into deeper water (Richardson et al. 2001, Evans et al. 2002). Adult Suckers tend to occupy shallow water habitat less than 17 m in depth, with White Suckers preferring water shallower than 13 m. Suckers in the GSL region feed mostly on invertebrates, including small crustaceans, bivalves, and insect larvae (Richardson et al. 2001). Adult White Sucker typically mature between age 5 years and 8 years, and Longnose Sucker mature at age 7 years, although they may not undergo spawning migrations until at least age 9 years (Evans et al. 2002). White Sucker is shorter-lived than Longnose Sucker in the GSL region, with maximum recorded age of 12 years for White Suckers and 28 years for Longnose Suckers (Evans et al. 2002). Presence of Longnose and White Suckers in tributaries of the North Slave region of GSL has been summarized in Stewart (1997). Additional details on results from creel surveys and biological sampling of the Longnose Sucker fishery at Paulette Creek are in Falk and Dahlke (1975).

Small-bodied Forage Fishes

Forage fish are an important component of the diet of predatory fish species in GSL which include Lake Trout, Northern Pike, Inconnu, Walleye, and Burbot (Janjua et al. 2014). The availability of forage fish species as a food source in lakes and rivers of the GSL region is essential when assessing the overall state or health of a fishery.

Forage fish species native to GSL consist of several groupings, with nine species in the Cyprinidae family, five species in the Cottidae (Sculpin) family, two species in the Gasterosteidae (Stickleback) family, and a single species in the Percopsidae family (Trout-Perch *Percopsis omiscomaycus*) (Table 1; Reist et al. 2016). The most abundant and widely distributed forage fish species in GSL may be the Ninespine Stickleback (*Pungitius pungitius*), which is a small, euryhaline fish (typically 4 to 6 cm standard length) (Rawson 1951; Scott and Crossman 1998). Although Ninespine Stickleback can be a dominant fish species in Arctic and sub-Arctic lakes (Laske et al. 2017), the ecological role of Ninespine Stickleback in large lakes such as GSL is not well understood. Rawson (1951) noted that the Ninespine Stickleback is a common prey for Northern Pike, Burbot, and Inconnu in GSL. The species spawns in the summer, with young of the year leaving the nest at about 2 weeks of age; the lifespan is approximately 3.5 years. Ninespine Stickleback, like the majority of forage fish species, feed on a diet of zooplankton, algae, and small crustaceans and insects, although Ninespine Stickleback and Sculpin species are more predatory and can obtain part of their diet from small fish and fish eggs (Richardson et al. 2001).

Rawson (1951) noted the lack of small-bodied fish on or near exposed shoal habitat in GSL, with larger concentrations of young fish and small-bodied species in protected ‘weedy’ bays, which are uncommon in GSL. A recent study in the Main Basin (2011 to 2016) also showed that shallow warm waters contained most prey species such as Spottail Shiner (*Notropis hudsonius*), Finescale Dace (*Chrosomus neogaeus*), Northern Pearl Dace (*Margariscus nachtriebi*), and Ninespine Stickleback (Zhu et al. 2017a), although several species may make diel migrations to deeper water to feed or use deeper water for overwintering (Richardson et al. 2001). Sculpins inhabit a wider range of depths from 0.5 m to greater than 200 m, although Slimy Sculpin (*Cottus cognatus*) prefer water depths less than 10 m and Spoonhead Sculpin (*Cottus ricei*) and Deepwater Sculpin (*Myoxocephalus thompsonii*) are most abundant at depths greater than 50 m and 70 m, respectively (Richardson et al. 2001, Zhu et al. 2017a). Most forage fish species have lifespans with maximum ages between 2 and 5 years, although Deepwater Sculpin can reach age 7 (Richardson et al. 2001). Forage fish species in GSL can exhibit lacustrine and riverine life histories, though Flathead Chub (*Platygobio gracilis*) are almost entirely riverine and are only occasionally found in lakes (Little et al. 1998, Richardson et al. 2001).

Detailed summaries of species life history data for Slimy Sculpin and Ninespine Stickleback populations in Yellowknife Bay (e.g., length, weight, and age information) are available in the appendices of environmental effects monitoring (EEM) reports submitted for the Giant Mine Remediation Project (e.g., Golder 2008, Golder 2011, Golder 2018c). Both species are focal sentinel species studied under the on-going EEM program for detecting changes in fish health in Yellowknife Bay.

2.2.5. Trophic Structure

The large surface area and depth of GSL alone provides potential for a high diversity of species (and individual stocks and morphological forms within populations), habitat (e.g., profundal zone), and basal resources to consumers compared to small lakes. The size of GSL may also mean that the lake is subject to biophysical phenomena (e.g., currents, depths) more similar to marine ecosystems than small lakes (Sterner et al. 2017). In terms of trophic structure in a large lake, an ecosystem may be best characterized as processes occurring within and among three habitat compartments or zones: nearshore, offshore pelagic (offshore photic waters), and offshore profundal (offshore aphotic waters) (Ives et al. 2018). For GSL, previous descriptions generally distinguish at least two habitat zones, namely Main Basin which is relatively shallow and the East Arm which is substantially deeper.

Rawson (1951) first summarized the trophic links in the GSL ecosystem through an extensive four-year study (1944 to 1947) of the diet of 21 fish species sampled throughout the lake. The sampling results demonstrated the rather sharp distinction between inshore and offshore associations of fish species in GSL. This was evident in the waters of the East Arm and along the Precambrian shore toward Yellowknife where great depths are encountered not far from shore, limiting the availability of inshore habitat.

Rawson (1951) proposed that the most important trophic chains for fish in GSL are the following:

- plankton → cisco spp. → Lake Trout, and
- plankton → detritus → bottom organisms (especially amphipods) → Lake Whitefish.

Mysids*, Pontoporeia spp.* and Sculpins were identified as important food items for fish in deep water. A key trophic linkage from Rawson (1951), included *Mysis* as an intermediate form using plankton and being itself available as food for cisco spp. Although not illustrated by Rawson's original figure, Lake Trout and Burbot were also identified as direct consumers of *Mysis* (Rawson 1951). The bottom organism of outstanding importance was identified as the amphipod *Monoporeia affinis* (formerly *Pontoporeia* spp.). The five main piscivores were those that feed on several other groups of fish. The Lake Trout, for instance, was found to eat mostly cisco spp. with moderate consumption of Sculpins, Burbot, Lake Whitefish, and Longnose Sucker. Lake Trout were unique in that they were found to eat all the species found in the open deep water of GSL. The conceptual food wed provided by Rawson (1951) (Figure 9) was later advanced using results from a trophic modelling exercise by Janjua et al. (2014).

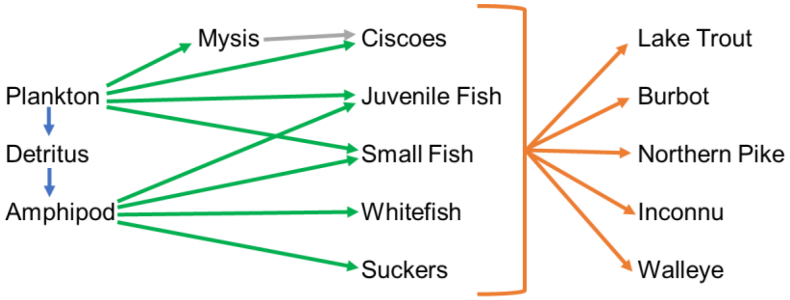

Figure 9. The principal food chains among the fish in Great Slave Lake described by Rawson (1951).

Since Rawson (1951), most field investigations on the trophic structure of GSL have been spatially restricted to specific regions of the lake, either in the North Arm closer to the city of Yellowknife (Rohonczy et al. 2019) or within the Slave River delta near the hamlet of Fort Resolution (Evans et al. 2013, Carr et al. 2017). The study by Evans et al. (2013) collected fish from the East Arm, near the community of Lutsel K’e, and the Main Basin, near the town of Hay River. All recent investigations on trophic ecology were carried out as part of a larger study assessing trends in concentrations of contaminants in fish (e.g., mercury contamination). Specifically, the researchers described food web linkages of common fish species in their study area using carbon isotope ratios ($\delta^{13}C$) to determine habitat-specific feeding and nitrogen isotopes ratios ($\delta^{15}N$) to determine fish trophic position within the food web (Post 2002). Nearshore dietary carbon sources have higher $\delta^{13}C$ values than offshore sources while $\delta^{15}N$ values are enriched approximately 3.4‰ between trophic levels (Post 2002).

Rohonczy et al. (2019) characterized the trophic web in the North Arm near the City of Yellowknife using a dataset of stable isotope values representing 13 species of fish, plankton and benthic invertebrates (Figure 13). Resource partitioning was observed among fish species in the GSL study area. Northern Pike and Lake Whitefish fed predominantly nearshore, cisco spp. and Longnose Sucker fed predominantly offshore, and Burbot fed roughly equally in both habitats. Ontogenetic shifts in feeding were also observed for Burbot, Lake Whitefish, and Northern Pike. As described in Rawson (1951), fish community composition was observed to vary significantly across GSL however, and in the deep waters of the East Arm, Lake Trout are the dominant piscivorous species, whereas Northern Pike dominate shallower regions of the North Arm of the Main Basin. The Evans et al. (2013) dataset of stable isotope values for captured fish also showed differences between the East Arm and Main Basin, likely reflecting the greater productivity and richer food supply for the Main Basin. For example, Lake Trout were significantly heavier, younger, more pelagic and predaceous than East Arm fish. Main Basin Burbot were also significantly longer, heavier, older, more predaceous and relied more on pelagic food sources than East Arm Burbot.

In the GSL-Slave River delta, the food web position (and trophic relations) across large-bodied species were weakly connected, reflecting, in part, highly mobile behaviors and differences in the timing of movements and the type of habitat required for each species life history; for example, some species from GSL may rely on prey provided by the delta during their juvenile developmental stages, whereas others may rely exclusively on the lake year-round for prey (Little et al. 1998, Carr et al. 2017). A study of the diet of nine species (four piscivores and five invertebrate feeders) during summer and winter (1994 to 1995) also showed that there is minimal diet overlap within the fish communities throughout all seasons in the lower Slave River, including the delta (Little et al. 1998). The study proposed that the trophic relations of top fish predators in the Slave River delta may reflect not only differential use of habitat, but also differences in the mouth morphology, which may lead to differential feeding styles and size limitations (Little et al. 1998). For example, among the piscivores, Walleye may be more limited by the size of the prey that can be consumed compared with Northern Pike; thus, larger prey, such as Flathead Chub and sucker spp., may be consumed by Northern Pike, but not necessarily by Walleye. Furthermore, trophic relations between Northern Pike and Inconnu were predicted to be minimal given that Inconnu are limited to small fish prey, generally less than 100 mm in length (e.g., Fuller 1955). Among the invertebrate feeders captured in the lower Slave River, Goldeye (*Hiodon tergisus*) is the only species with a supra-terminal mouth, designed for effective feeding on surface prey, such as adult winged insects. Conversely, Lake Whitefish and sucker spp. have subterminal mouths adapted for feeding on benthic-dwelling organisms.

Although there remains limited knowledge of the current role of organisms at lower trophic levels (aquatic invertebrates and smaller species of fish) in the GSL ecosystem, recent information collected during a study conducted throughout the Main Basin between 2011 and 2016 (Zhu et al. 2017a) may be used to better understand the current trophic web structure and vulnerabilities to environmental changes. Benthic invertebrate density, dominated by ostracods and amphipods, was variable across the Main Basin. Lake Whitefish, a benthivore that largely resides in the bottom environment consuming benthic resources, exhibited size-dependent distribution, with small Lake Whitefish being most abundant in shallow turbid habitats and large Lake Whitefish collected in deep, cold habitats. Findings from Zhu et al. (2017a) supported those from historical studies (e.g., Rawson 1951 and others) that describe significant variation in turbidity from strong river- lake interactions, potentially impacting bottom-up biological primary, and secondary production in GSL. Their research concluded that the ecological characteristics of the fish community in the Main Basin of GSL is controlled by moderate-sized (Lake Whitefish) Coregonids and small-sized (Least Cisco and Cisco) Coregonids, which interact with large-sized predacious fishes (Burbot, Inconnu, Lake Trout, Northern Pike) as top-down regulators.

Janjua et al. (2014) provide additional insight into foodweb organization, trophic structure, function, and stability of the GSL ecosystem (Figure 10). Recognizing that primary production and detritus flows from lower trophic levels are potentially key components of sustaining fisheries, the trophic modelling showed that the GSL fisheries for Lake Whitefish require only a small proportion of the primary production capacity of the ecosystem to remain sustainable. The simulations also showed that the Lake Whitefish fishery was relatively sustainable under moderate catch levels. In contrast to Lake Whitefish, the maximum primary production of the ecosystem was required for the commercial harvest of Walleye and Lake Trout in GSL. Simulations showed that Lake Trout and Inconnu were most likely to show a rapid decline with an increase in fishing effort and pressure. Average fish biomass density obtained from the GSL ecosystem model was estimated at 1.86 tonnes per km^2.

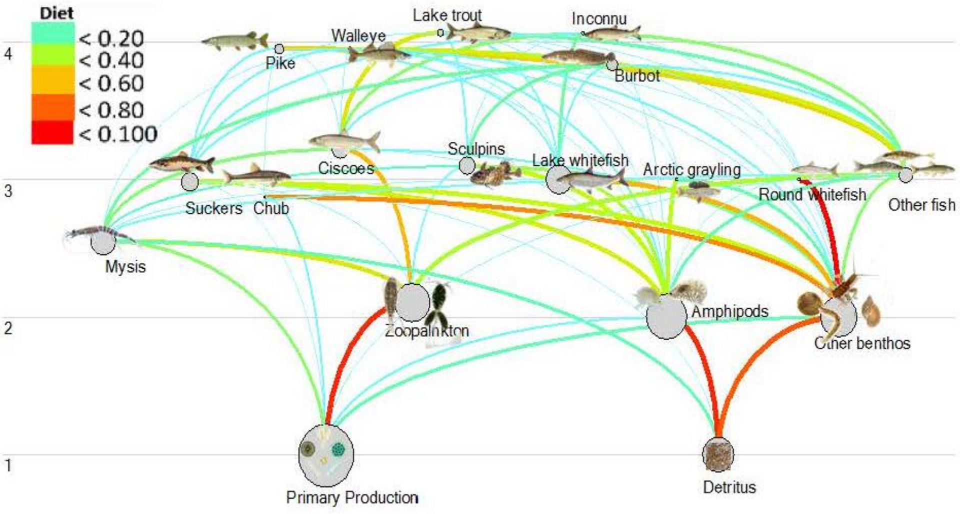

Figure 10. Updated Great Slave Lake food web conceptualization from an Ecopath modelling output.

Notes: Each functional group is shown as a circle and its size is approximately proportional to its biomass; colour of the lines illustrate the magnitude of the flow; the vertical line demonstrates the trophic levels of each functional group. Source: Janjua and Tallman (2015)

3. FISHERIES MANAGEMENT

Fisheries and Oceans Canada (previously the Fisheries and Marine Service) began a long-term program in 1971 designed to collect information deemed essential to the efficient management of the GSL commercial fishery (Bond 1974) that culminated in the management regime that is currently used. The commercial fishery is harvested with area quotas for seven management areas throughout the lake. Commercial quotas are administered by DFO. The Freshwater Fish Marketing Corporation (FFMC) is the primary buyer, processor, and marketer of commercially harvested fish from the NWT (Tonn et al. 2016) and sole exporter. Harvesters can also sell commercially caught fish locally. The fishery quota is managed based primarily on purchase slip information from the processing plants (Tallman and Friesen 2007). Sport fishing licenses are regulated by the GNWT with oversight on gear restrictions, effort restrictions, and area closures provided by DFO. Tonn et al. (2016) provides a detailed summary of fisheries management in GSL.

Fisheries management in the NWT is a co-management process with regional advisory boards appointed by stakeholders in the fishery (Tonn et al. 2016). The Great Slave Lake Advisory Committee is composed of representatives from the commercial, recreational, and sport-fishing lodge industries and Indigenous governments, meeting semi-annually to review management issues and applications, update regulations, and recommend changes to commercial area quotas. DFO takes these recommendations into account when making its management decisions. DFO also works with local Indigenous harvesters through the Northern Integrated Commercial Fisheries Initiative, which funds and supports Indigenous commercial fishing enterprise and aquaculture development, business development planning, and targeted training (DFO 2019).

In GSL, fishery types are defined and tracked by the type of license required to fish. The available licenses for GSL include:

- Commercial Licenses
    - Commercial Fishery: Allows fishers to sell catch to market
    - Domestic Commercial Fishery: Open to NWT residents for personal use (no sales allowed)
- Indigenous Licenses
    - Subsistence Fishery: Open to NWT resident Indigenous community for personal and family use (no sales allowed)
    - Indigenous Domestic Fishery: Open to NWT non-resident Indigenous community for subsistence fishing (no sales allowed)
    - Indigenous Commercial Fishery: Open to NWT Indigenous community that wish to sell their fish
- Sport Fishing Licenses: Open to all for personal use (no sales allowed).

Definitions of these fisheries can be found in the Northwest Territories Fishing Regulations (GNWT 2019) and the Northwest Territories Fishery Regulations of Canada’s Fisheries Act (Fisheries Act. R.S.C. 1985). Additional details are provided in the subsections below.

Over the 75-year history of fisheries management in GSL, substantial changes to fish species composition and productivity have been observed in response to a variety of stressors (Zhu et al. 2017a). Observed impacts have generally been addressed with a series of focused academic studies but they have tended to be limited in spatial and temporal scale and have not generally contributed scientific knowledge to the management of fisheries (Tallman and Friesen 2007). Recent work by researchers and managers at DFO have tried to address these shortcomings in fisheries management by applying active adaptive management principles (Hilborn and Walters 1992) and by considering new biological data collection and fishery-independent surveys toward an ecosystem management approach (Walters and Martell 2004). For example, data on limnological and lake-river interactions are now being integrated into a more comprehensive assessment of cumulative impacts on GSL fisheries

(Janjua and Tallman 2015, Zhu et al. 2017a). Between 2011 and 2016, a fishery-independent systematic grid survey was also undertaken, sampling environmental variables, and the food web throughout the main basin, representing the first comprehensive assessment of the aquatic ecosystem since the opening of the fishery in the 1940s. Results from the effort are being used to develop an Integrated Fisheries Management Plan (IFMP) for GSL.

3.1. SUBSISTENCE FISHERY

A subsistence fishery is described as a local, non-commercial fishery, oriented not primarily for recreation but for the procurement of fish for consumption of the fishers, their families, and community (Berkes 1990). Rawson (1947) first described the non-commercial fishery within GSL which included studies of fish use by Indigenous peoples, trappers, fur-farmers, missions, trading posts, park wardens, and the Royal Canadian Mounted Police in a variety of communities surrounding the lake. In more recent years, when describing subsistence fisheries, the use of domestic fishery appears less frequently and has been replaced with Indigenous food fishery to describe subsistence harvest (Stewart 1997, Stewart 1999, Stewart and Low 2000). Fish harvested for subsistence were predominantly used for human consumption, to feed sled dogs, as bait in traps (trappers), and traditional medicines (Rawson 1947, Berkes 1990, Stewart 1999, WLEC 2002). WLEC (2002) summarizes contemporary fishing practices and views on the integral role fisheries play in community life through a series of interviews in the Lutsel K’e community of the East Arm.

The NWT Bureau of Statistics (2019a) identify four areas or zones in the GSL region including the Dehcho, South Slave, Tłı̨chǫ, and Yellowknife areas. Participation in subsistence harvest activities between 1998 and 2018 has remained consistent across areas and over time, with an average of 43% of persons over the age of 15 in the GSL region participating in hunting and fishing within a given year (Table 9). Consumption of meat or fish obtained from subsistence harvest (defined as country foods by the GNWT) shows a general decline over time with consumption in the GSL region declining from an average of 28% in 1998 to 20% annually in 2018. Consumption of country foods also varies spatially within the GSL region, with the highest annual average consumption estimated for the Tłı̨chǫ community at 41%. By contrast, consumption in the city of Yellowknife averaged 5% annually. This decreasing trend in consumption of country foods can likely be attributed to increased accessibility to commercially produced food sources outside of urban centres. However, 23% of households still consume most of their meat from the land and subsistence harvest remains of importance to the communities in the GSL region.

Table 9. Percentage of persons who hunted or fished and households where most (> 75%) meat consumed was obtained through subsistence harvest within communities in the GSL Region Between 1998 and 2018.

Persons 15 & Over Who Hunted or Fished in the year (%)[a]						
Area	**1998**	**2003**	**2008**	**2013**	**2018**	**1998 to 2018**
Decho	42	47	47	58	52	49
South Slave	40	34	39	48	41	41
Tłįchǫ	37	39	40	46	39	40
Yellowknife Area	49	43	38	37	38	41
GSL Region Average	42	41	41	47	42	43
Households Where 75% or More of the Meat or Fish Eaten was Obtained through Hunting or Fishing (%)[b]						
Area	**1998**	**2003**	**2008**	**2013**	**2018**	**1998 to 2018**
Decho	27	33	30	25	34	30
South Slave	19	16	17	12	10	15
Tłįchǫ	58	42	37	36	31	41
Yellowknife Area	9	5	5	4	3	5
GSL Region Average	28	24	22	19	20	23

(a) Source: NWT Bureau of Statistics 2019b.

(b) Source: NWT Bureau of Statistics 2019c.

The first descriptions of the domestic harvests in GSL were completed by Rawson (1947) who quantified a lake wide harvest of 700 tonnes/year and a per capita consumption of 75 kg. Further information for historical estimates of total fish harvested by subsistence and domestic fisheries and intermittent catch data in the GSL region can be found in Rawson (1947), Keleher and Haight (1959, 1962, and 1964), Stewart (1997), Stewart (1999), Stewart and Low (2000) and DFO annual harvest reports (DFO 1995, 1996, 1997, and 1999). Keleher and Haight (1964) also describe detailed accounts of the domestic community fish stockpiles within the North Arm of GSL in 1959 and 1962.

Table 10 summarizes available historical harvest statistics by species based on available reports for the subsistence fisheries of select communities of the GSL region. Although annual harvest by species tends to vary between the communities of the GSL region, Lake Whitefish consistently makes up the largest quantity of harvested fish species in all communities.

Table 10. Summary of mean annual harvest data for the subsistence fisheries (Indigenous and domestic) of the GSL Area.

Community	Location	Species	Fishing Seasons (yr)	Mean Annual Harvest (#)	Mean Annual Harvest (kg)	Source
Fort Resolution	Great Slake Lake	Burbot	1993 to 1997(a)	2137	4274	DFO 1995, Stewart et al. 1999
		Lake Whitefish		3685	3685	
		Northern Pike		1549	3155	
		Walleye		242	242	
		Inconnu		310	999	
		Sucker Spp(b)		2251	2832	
		Lake Trout(c)		18	54	
		Lake Cisco(d)		705	518	
	Little Buffalo River	Burbot(e)	1993 to 1998(a)	37	73	DFO 1995, Stewart 1999, Stewart et al. 1999
		Lake Whitefish		11858	11351	
		Northern Pike		2702	5454	
		Walleye		78	78	
		Inconnu(c)		3	9	
		Sucker Spp(e)		41	51	
		Lake Whitefish	1975 to 1981, 1983(f)	7953	6872	Stewart 1999
	Slave River Delta	Burbot	1976 to 1977(f)	-	7585	Stewart 1999
		Lake Whitefish		-	2280	
		Northern Pike		-	1979	
		Inconnu		-	1676	
		sucker spp.		-	1593	
Fort Smith	Slave River	Lake Whitefish	1983 to 1984(f)	13485	13494	Stewart 1999
		Northern Pike		963	1537	
		Walleye		845	871	
		Inconnu		2807	11395	
		sucker spp.		1653	1622	
		Goldeye		1642	714	
		Lake Whitefish	1994 to 1998(g)	2959	2959	DFO 1996, DFO 1997, DFO 1999 Stewart 1999
		Northern Pike		239	478	
		Walleye		641	641	
		Inconnu		977	3200	
		sucker spp.		730	824	
		Goldeye		667	205	
Hay River	Hay River and Great Slave Lake confluence	Lake Whitefish	1958(f)	8278	9514	Keleher and Haight 1959
		Lake Trout		26	80	
		Burbot		169	415	
		Northern Pike		306	863	
		sucker Spp.		725	1246	
		Inconnu		1654	6410	

Community	Location	Species	Fishing Seasons (yr)	Mean Annual Harvest (#)	Mean Annual Harvest (kg)	Source
		cisco Spp.		2	1	
		Walleye		28	38	
Hay River	Hay River	Lake Whitefish	1996(h)	3420	3420	DFO 1999
		Lake Trout		1	3	
		Burbot		19	38	
		Northern Pike		30	60	
		sucker Spp.		84	168	
		Inconnu		3	12	
		Walleye		19	19	
Rae Edzo	Marrion, Russel and Great Slave lakes	Lake Whitefish	1994 to 1995(h)	2526	2526	DFO 1996, DFO 1997
		Northern Pike		424	570	
		Burbot		57	113	
		Inconnu		133	490	
		sucker Spp.		211	321	
		Walleye		373	373	
Lutsel K'e	Snowdrift and Stark Rivers, Stark and Great Slave lakes	Lake Whitefish	1962(f)	6579	9724	Keleher and Haight 1962
		Lake Trout		956	2809	
		Northern Pike		169	-	
		sucker Spp.		103	-	
		Burbot		100	-	
		Grayling		1	-	
		Round Whitefish		89	-	
Cunningham Landing	Slave River Delta	Goldeye	1984(f)	94	44	Stewart 1999
		Inconnu		179	921	
		Lake Whitefish		1067	992	
		Northern Pike		101	187	
		sucker Spp.		217	282	
		Walleye		515	603	

(a) These data represent an estimated 90% of total annual harvest.

(b) Includes both Longnose and White Suckers.

(c) Mean harvest only represents one season of reported data.

(d) Mean harvest only represents three seasons of reported data.

(e) Mean harvest only represents four seasons of reported data.

(f) Estimated annual harvest.

(g) These data represent an estimated ±20% of total annual harvest for 1994 to 1995 and 90%of total annual harvest for 1996 to 1998.

(h) These data represent an unknown percentage of total annual harvest.

A mechanism employed for the management of subsistence fisheries in the GSL region includes the closure of certain areas to the commercial fishing sector by DFO. Keleher and Haight (1964) concluded that most fish harvested for subsistence in the North Arm of GSL were taken from within closed commercial zones including Yellowknife Bay, Tartan Rapids, New Trout Rock, Frank Channel, and Marian and Russel lakes. In support of sustaining harvests, the management of commercial fishing area boundaries remains an important strategy for the domestic fishery in GSL. Stewart (1999) discusses the 1996 extension of the Fort Resolution domestic fishery boundary westward (and similarly moving the commercial fishing boundary away from the mouth of the Little Buffalo River). Commercial fishing closures are also described for inshore zones along the south shore and within the Slave River delta to protect the Slave River and Buffalo River Inconnu stocks. To protect the Indigenous food fishery at Fort Resolution, some areas of Resolution Bay have been closed to commercial fishing (Stewart 1999). Additional management techniques have included the cancellation of non-Indigenous domestic fishing licenses. According to Stewart (1999), the Slave River was closed to fishing by holders of non-Indigenous domestic fishing licenses during the 1995 to 1998 fishing seasons to reduce fishing pressure on the Inconnu. Furthermore, DFO does not issue non-Indigenous domestic fishing licenses for management area VI (the East Arm; Low et al. 1999).

Berkes (1990) discusses the co-management strategy as a vital tool when managing subsistence fisheries. The strategy recommends the sharing of decision-making powers among government, Indigenous people and other stakeholders, and provides for the recognition of cultural as well as economic benefits through the sustainable use and development of renewable resources. The challenge, however, is managing activities over a large geographic area which is poorly monitored relative to the commercial fisheries (Berkes 1990).

3.2. RECREATIONAL FISHERY

Recreational sport fishing on GSL came into prominence in the 1960s with construction of a series of fishing lodges in the East Arm, motivated by angling the large Lake Trout in the area. Commercial gill-net fishing was uneconomical at the time, so the resource was largely reserved for the use of this sport lodge industry (Yaremchuk 1986, GNWT 2017). The fishery has since developed throughout GSL to a highly regarded recreational fishery with both guided sport fishing by lodges and outfitters, and unguided fishing by “itinerant” anglers (Low et al. 1999, Low 2006), of whom an average of 70% of anglers surveyed between 1986 and 2005 were Yellowknife residents. Most non-Yellowknife anglers that returned voluntary surveys were from outside of the NWT (Low 2006). Recreational sportfishing is regarded as a major recreational activity in the NWT and is an important component of the renewable resource economy (DFO 1985). Between 2007 and 2011, 16% of leisure visitors to the Territory consisted of anglers, spending an average of 15.4 million dollars annually, accounting for one of the highest sectors of visitor spending. In 2008, 55% of anglers visiting the NWT participated in guided fishing tours during their trip (GNWT 2009).

Beginning in 1972, a variety of creel census and biological sampling programs were carried out to estimate catch and effort in the recreational fishery (Table 11). Yaremchuk (1986) summarized these early creel efforts to determine the level of exploitation of Lake Trout stocks by the sport lodge industry, to determine the effects of this exploitation on the stocks, and to produce preliminary predictions on the responses of the stocks to different levels of exploitation. Although it was recommended that creel surveys were a poor method for monitoring population sizes due to the sampling bias, creel surveys remained a common method into the 2000s, providing data on historical fishing pressure. Catch, harvest, and retention data from available creel surveys are summarized in Table 11.

In general, recreationally captured Lake Trout are caught in the East Arm with a consistent catch per unit effort over time for both guided and unguided fishing, ranging between annual averages of 0.66 and 0.86 fish per angler hour (Table 11). Total annual harvest is estimated to be highest for the lodges and lowest for the unguided trips and retention is highly variable. Between 1986 and 2005, survey data indicates that catch and release is increasingly a feature of recreational angling on the East Arm with 87% of Lake Trout, 95% of Northern Pike, and 77% of Arctic Grayling being released (Table 11). Outside of the East Arm, the best available information is provided by smaller scale fisheries on the Hay River, Kakisa River, Mosquito Creek, and Brabant Island Lodge (Main Basin confluence with Mackenzie River) (Table 11). These fisheries primarily target Northern Pike, Arctic Grayling, and Walleye. Mean annual catch per unit effort is highly variable for these fisheries, as is harvest, and retention rates were generally higher in these fisheries than in the East Arm. Intermittent catch and effort data for Mountain Whitefish, Lake Whitefish, Lake Trout, Northern Pike, Longnose Sucker, Burbot, and Inconnu are available in Falk and Dahlke (1975), Falk et al. (1980), and Falk and Gillman (1975).

Table 11. Summary of recreational fisheries catch and harvest data in GSL and tributaries.

Location	**Species**	**Fishing Type**	**Fishing Seasons (yr)**	**Mean Annual Catch**	**Mean Annual Harvest**	**Mean Annual Retention (%)**	**Mean CPUE (fish/hr)**	**Source**
East Arm	Lake Trout	Guided(a)	1972	2,367	-	-	-	Falk et al. 1973b
			1972 to 1974	-	1,907(c)	-	-	Moshenko and Low 1983
			1975 to1978	3,496(d)	1,268	39	0.66	Moshenko and Gillman 1978, Moshenko and Low 1983
			1979	397 (d)	102	26	0.85	Falk et al. 1982
			1983 to 1996	-	258	-	0.86	DFO 1991, DFO 1999
		Itinerant(b)	1986, 1994, 1999 to 2005	1,324(e)	-	13	0.83	Low et al. 1999, Low 2006
	Northern Pike	Guided	1975, 1977 to 1978	1,069 (d)	91	11	-	Moshenko and Gillman 1978, Moshenko and Low 1983
			1983 to 1996	150	-	-	1.62	DFO 1991, DFO 1999
		Itinerant	1986,1994, 1999 to 2005	163(e)	-	4	0.08	Low et al. 1999, Low 2006
	Arctic Grayling	Guided	1975 to 1978	493(d)	106	24	-	Moshenko and Gillman 1978, Moshenko and Low 1983
			1979	61(d)	26	43	-	Falk et al. 1982
		Itinerant	1986, 1994 1999 to 2005	142(e)	-	20	0.09	Low et al. 1999, Low 2006

Location	Species	Fishing Type	Fishing Seasons (yr)	Mean Annual Catch	Mean Annual Harvest	Mean Annual Retention (%)	Mean CPUE (fish/hr)	Source
Kakisa River	Arctic Grayling	Itinerant	1974 to 1984	-	521	-	0.53	Stewart and Low 2000
		Itinerant	1971,1974	129	106	82	1.01	Falk and Dahlke 1975
	Northern Pike	Itinerant	1971,1974	53	33	62	0.21	Falk and Dahlke 1975
	Walleye	Itinerant	1971,1974	6	5	83	0.04	Falk and Dahlke 1975
Brabant Island	Arctic Grayling	Guided	1972, 1973, 1978, 1991 to 1992	-	692	-	1.68	Stewart and Low 2000
Kakisa River	Northern Pike	Guided	1972, 1973, 1978, 1991 to 1992	-	1,253	-	3.45	Stewart and Low 2000
	Walleye	Guided	1991 to 1992	-	265	-	1.1	Stewart and Low 2000
Hay River	Walleye	Itinerant	1975, 1978, 1986	-	2,586	-	1.08	Stewart and Low 2000
	-	Itinerant	1972, 1974	262	224	88	0.64	Falk and Dahlke 1975
	Northern Pike	Itinerant	1972, 1974	25	21	82	0.41	Falk and Dahlke 1975
Mosquito Creek	Walleye	Itinerant	1973 to 1977, 1983, 1986 to 1987	886	747	84	-	Stewart 1997, Falk et al. 1980, Falk 1980

(a) Guided fishing is defined as recreational fishing trips guided by Sport fishing lodges or outfitters (Low 2006)

(b) Itinerant fishing is defined as unguided recreational fishing (Low 2006)

(c) Data includes catch and effort within Beaver Lake

(d) Calculated as mean value of catch across all lodges and years

(e) Calculated as mean value of reported questionnaire survey catches across all years

Total effort in the recreational fishery is provided by two primary sources: total fishing licenses for all recreational anglers, and lodge visits. Angling license sales provide an index of total recreational angling effort on GSL. First introduced in 1950 in the NWT, 7,603 total licenses were sold between 1950 and 1962, with 40% of those licenses being obtained within the GSL area (Keleher 1964). DFO found that in the years 1989 to 1997, an average of 81% of all resident sports fishing licenses and 80% of all non-resident license sales were obtained in the GSL area (see annual reports DFO 1991 to DFO 1999). Table 12 provides license sales on a five-year interval between 1980 and 2015. Annual contemporary angling license sales in the NWT are, on average, approximately 13,000 per year from 1980 to 2015. Between 1980 and 2000, overall license sales showed a relatively consistent trend, with resident license sales showing a steady decline and non-resident license sales remaining relatively stable. A notable drop in license sales was observed in 2005; however, by 2010, license sales began showing an increasing trend but remained lower than sales observed prior to 2000 (Table 12). The general decline over time in license sales was attributed to continued aging of return fishers, the lack of returning younger fishers, and minimal recruitment of younger first-time fishers (Zimmermann 2014).

Table 12. Number of all licensed anglers in the Northwest Territories by category, 1980 to 2015.

Year	NWT Resident	Non-resident Canada	Non-resident Other	Total
1980[(a)]	10,656	4,468*		15,124
1985[(b)]	8,952	4,329	3,626	16,907
1990[(c)]	6,937	4,805	2,368	14,130
1995[(d)]	7,523	4,404	3,137	15,054
2000[(d)]	4,720	4,247	3,902	12,870
2005[(e)]	2,403	2,630	2,348	7,381
2010[(f)]	5,008	4,436	1,302	10,746
2015[(g)]	5,043	5,815	1,456	12,314

Data Sources:

(a) DFO 1991;

(b) DFO 1985;

(c) Economic and Policy Analysis Directorate 2003;

(d) DFO 2016;

(e) DFO 2007;

(f) DFO 2012;

(g) DFO 2015b

* No distinction between non-resident licenses available

Recreational fisheries management has changed over the years to better manage fish stocks in the GSL area. Primary methods that have been utilized to regulate the fisheries include daily catch and possession limits, size restrictions, special management areas, seasonal closures, and use of barbless hooks to reduce mortality of released fish (Low et al. 1999, Low 2006, Stewart and Low 2000). In 1974, the East Arm of GSL was designated as administrative area VI to allow for trophy management of the Lake Trout fishery (Low et al. 1999). The outflow of GSL to the Mackenzie River (including Kakisa River) was designated as the Mackenzie River Management Area and restricts limits on Arctic Grayling and Northern Pike. Daily catch and possession limits have been altered significantly over the years to promote sustainable fish stocks. In GSL area VI, Lake Trout limits have changed from 5 daily and 10 possession in 1973, to 1 daily and 2 possession in 2003, with only one allowed greater than 700 mm (Low 2006). In the Mackenzie River Management Area, Arctic Grayling limits have changed from 10 daily and 10 possession in 1973, to 0 daily and 0 possession in 1991, and back to 1 daily and 1 possession in 2000 (Stewart and Low 2000). At present, daily limits and possession limits remain the same as 2000 limits; however, barbless hooks are also mandatory in the NWT and a size restriction on Arctic Grayling (> 360 mm) has been added (GNWT 2019). Seasonal closures to recreational fishing are also employed in GSL. For example, Mosquito Creek and waters of GSL within 1 km of the creek are closed to sport fishing from 1 May to 30 June to protect spawning Walleye populations (Stewart 1997).

3.3. COMMERCIAL FISHERY

The commercial fishery on GSL and its tributaries has been in operation since 1945, and since that time, has accounted for more than 90% of the NWT annual commercial fisheries harvest (Tallman et al. 2005). Gill netting is the only method of capture used for commercial fishing in GSL, with stretched mesh sizes of either 133 mm or 140 mm the only netting currently permitted, and all fishing vessels are under 13 m in length (Tallman and Friesen 2007).

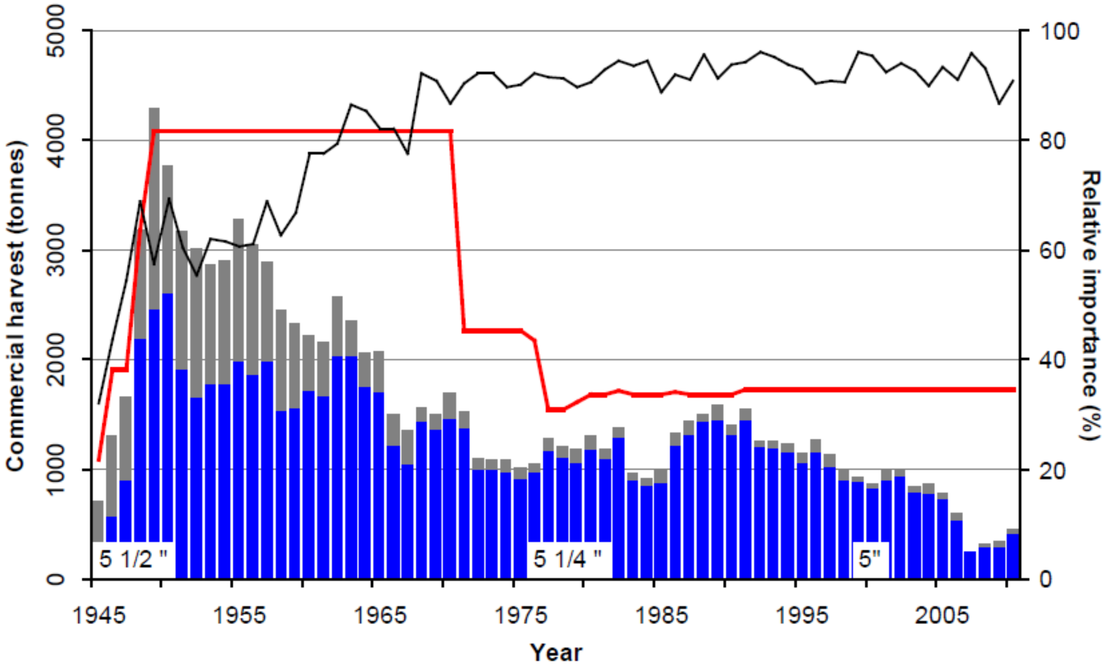

Figure 11. Temporal changes in commercial harvests and total commercial harvest quota (red line) for Lake Whitefish (dark blue) and Lake Trout (grey) in GSL from 1944 through 2010. The trend in percentage of Lake Whitefish harvest relative to total harvest of both species (i.e., Relative Importance) is indicated by the black line. Timing of regulated reductions in gillnet mesh size limits (5 ½", 5 ¼", and 5") is indicated. Source: Zhu et al. 2015a.

The establishment of the GSL commercial fishery offered a unique opportunity for freshwater scientists to study and observe effects of the fishery from its inception. Baseline information combined with annual monitoring of harvest and biological parameters of the commercially important species allowed for the tracking of population trends, size variations, and community structures over the past 75 years (Kennedy 1956, Tallman and Friesen 2007, Janjua and Tallman 2015). Results from this data collection has been essential in the ongoing management of the commercial fishery.

At inception, the fishery focused on the catch of Lake Whitefish and Lake Trout, with all other species considered bycatch (Figure 11). For the first two years of commercial fishing, Lake Trout comprised most of the harvested mass, although total harvested mass since 1947 has been dominated by Lake Whitefish (Kennedy 1956, Yaremchuk et al. 1989, Zhu et al. 2015a, GNWT 2017; Figure 11). During the first ten years of commercial fishing, Lake Trout comprised more than 40% by mass of the average yearly harvests (Kennedy 1956); however, the proportion of Lake Trout harvest in the Main Basin declined steadily to the point where it was considered collapsed by the mid-1960s. Since the collapse, other species such as Cisco, Northern Pike, and Inconnu have become more prominent in the commercial harvest (Yaremchuk et al. 1989, Zhu et al. 2017a). Lake Trout populations have persisted in the East

Arm and administrative area VI in the East Arm of GSL remains closed to commercial fishing since 1974 to protect further degradation of stocks (Janjua and Tallman 2015).

Overall, total harvest by the GSL commercial fishery has declined dramatically since its start in 1945. Initially, the commercial fishery was run as a private brokers market, with as many as 14 private buyers working with individual fishers to obtain, process, and transport fish (GNWT 2017). Since 1971, the commercial fishery has been run by the FFMC, which took over to alleviate price concerns, reduce wastage, and apply uniform quality control standards. The FFMC also built a processing plant in Hay River to act as a central hub to the GSL commercial fishery operations (GNWT 2017). The takeover led to increased harvest for more than three decades before harvest started declining towards the current period of historic low. The decline is attributed to a decrease in fishing effort rather than changes in the fish community (Tallman and Friesen 2007). Factors such as a less favourable United States/Canadian dollar exchange rate, closures of several receiving stations on more remote areas of the lake, market competition from other freshwater fisheries, changing government subsidies to fishers, deteriorating boats and equipment, and fish prices not increasing in line with the increasing costs of operations have all been contributing to decreased commercial harvests (GNWT 2017).

In 2013, an economic advisory panel created by the GNWT identified the GSL commercial fishery as a priority to meet short and long-term economic objectives and developed a strategy to revitalize the fishery (GNWT 2017). Part of the strategy was to transfer management of the commercial fishery from the FFMC to a fisher-owned cooperative that would partner with the FFMC to facilitate sales outside of the NWT. Other areas of focus outlined in the strategy are to expand the market within the NWT to 40% of the total lake harvest, provide incentives to increase remote and winter fisheries as well as increase the number of fishers, and empower the fishers to help make decisions on infrastructure investments and setting harvest targets (GNWT 2017).

3.4. HUMAN-RELATED STRESSORS

Despite the remote location of GSL, a wide range of stressors ranging from localized land-use and fisheries practice impacts to pervasive and global-driven impacts (e.g., atmospheric transport of pollutants) are likely affecting the lake and its associated fish faunas (reviewed in Reist et al. 2016). Some of the existing local stressors may be more a result of the legacy of historical land-use or fisheries activities. A commonly identified local stressor as indicated by the number of previously completed studies on the environmental issue would be the residual effects from historical mining on the Yellowknife Bay ecosystem in the vicinity of the city of Yellowknife. For example, sediment levels of arsenic in Yellowknife Bay have increased from approximately 100 ppm in the 1900 to 1925 time period to 400–500 ppm from about 1970 to 1990 (MRRB 2004) and levels are elevated in fish collected near the mine site (Cott et al. 2016). However, the environmental legacy of historical mining near Yellowknife Bay is currently being addressed by the federal and territorial governments, for example, through the Giant Mine Remediation Project in Yellowknife (Cott et al. 2016, Golder 2018c). Remediation efforts will address the long-term containment and management of the arsenic trioxide waste and will include the remediation of surface areas and the tailings ponds at the former Giant Mine site. It also includes water management and treatment options.

Although the large size of GSL will continue to provide some resiliency to many of the effects of human-caused stressors, including climate change, risks related to the cascading effects from climate change may remain (Reist et al. 2016). General predictions under climate change scenarios include direct effects such as shifts in nature and timing of key events in the hydrological cycle (e.g., rain versus snow, seasonality of ice-on/ice- off periods, warming and deepening of the epilimnion, increased anoxia at depths). A wide range of indirect effects are also forecasted, ranging from increased nutrient loadings and associated productivity shifts to altered biodiversity at all levels of the ecosystem. Guzzo et al. (2017) contend that climate-mediated interactions in northern lakes can influence the dominant energy pathways of top predators, such as Lake Trout, with implications ranging from individual fitness to food web stability. However, the cumulative impacts of potential stressors on the GSL ecosystem cannot be addressed or forecasted without a comprehensive understanding of the underlying processes governing present-day fish community structure and functions in GSL. The recent integrated monitoring work completed by Zhu et al. (2017a) and future studies like it are anticipated to fill that gap and complement historical synoptic surveys for GSL that date from the 1940s (e.g., Rawson 1949, 1950, 1951).

Recognizing that physical-chemical properties of the GSL ecosystem are primarily determined by its main source of water (flows from the Slave River) the greatest threats would be those with the potential to interact with the water-balance and biogeochemical processes in the Slave River and its headwaters. The GSL ecosystem offers an interesting example of a northern ecosystem that may be less influenced by changes in northern hydrologic processes (e.g., changes in lake evaporation and precipitation) relative to southern processes that have a greater potential to affect change in the system (Gibson et al. 2006a, Prowse et al. 2006). Previous research has described the effects of flow regulation and climatic variability in the Peace River, approximately 2,000 km upstream in the Rocky Mountain headwaters, on the seasonality of water levels in GSL. GSL is also a high throughflow water system (i.e., low water residency time) such that the continuity of lake hydrology and water chemistry into the future may depend less on local anthropogenic stressors and more on the effects of changing climate conditions and on the voracity of water abstraction in the contributing basins, particularly in the primary source regions such as the Peace-Athabasca basin (Gibson et al. 2006a). There are also several pulp mills, coal mines, agriculture, urban centres, and oil sands developments in Southern tributaries where there is the potential to change the chemistry of water. Without consideration of land-use planning and watershed-based management practices led by provincial and territorial governments, the general expansion of infrastructure and resource development within the Slave River watershed has the potential to affect downstream water quality, and in turn, the GSL fish fauna.

In addition to risks related to habitat loss and degradation, other potential threats to the GSL fish community may include those from invasive species. However, potential threats related to any recent colonizations and introductions of non-native fishes or other biota are low, with impacts localized to a tributary waterbody or having no obvious impacts to the native fish fauna of GSL. With exception of Rainbow Trout in small lakes draining into GSL (Sawatzky et al. 2007), there are no known intentional introductions of non-native fishes or other biota into the lake (reviewed in Reist et al. 2016). There is also no evidence that stocked populations of Rainbow Trout have expanded beyond their introduction area since the initial stocking of those fish by DFO. Natural colonizations of GSL or lakes associated with the GSL ecosystem by non-native fishes have not occurred. There is only the occasional record of a vagrant non-native species, i.e., migratory individuals that occur outside of their normal geographic distribution, such as Sockeye Salmon (reviewed in Reist et al. 2016) and Chum Salmon (Irvine et al. 2009).

Of particular concern are potential risks to the GSL fish community from a future invasion of mollusc species, specifically the Zebra Mussel (*Dreissena polymorpha*) and Quagga Mussel (*D. rostriformis bugensis*) (Therriault et al. 2013). Although the probability of arrival to GSL is very low, the potential risk for the GSL ecosystem has been ranked as low for the East Arm and as moderate to high for the Main Basin (Therriault et al. 2013). The southern region of the Main Basin being most at risk of an invasion because of suitable calcium concentrations and water temperatures for mollusc survival. The largest ecological impacts associated with Zebra Mussel and Quagga Mussel would be negative impacts on biota that inhabit the pelagic (offshore) zones (e.g., losses in productivity for phytoplankton, zooplankton, and planktivorous fishes), and to unionid mussels (major declines in abundance and biodiversity) (Therriault et al. 2013).

4. SUMMARY

The overall goal of this summary report was to provide details characterizing available ecological information for the GSL ecosystem that can support DFO through the CSAS framework and determine the best stock assessment methodologies to apply to GSL into the future. The summary report was also intended to support DFO Resource Management in its Integrated Fisheries Management Plan consultation process and help identify conservation priorities and fisheries management objectives for GSL. Recognizing that there has been considerable scientific research undertaken on the lake over the last 75 years, the task of organizing and quantifying all of the historical research data into a single usable document required the review of over 300 published and unpublished reports. Because of the vast extent of the available research and data related to the fish community, a structured approach to the literature review was undertaken.

Defining physical features of GSL included lake size and morphometry: the lake is the fifth largest lake in North America, with a surface area of 27,200 km^2; volume calculations for the lake show considerable variation in the reported values, but may be as high as 2,088 km^3. The East Arm (i.e., east zone of the lake) is deep, with a maximum measured depth of 614 m, making it the deepest lake in North America. The size and depth of the lake combined with the Slave River inflow as a major source of nutrients for primary production in the Main Basin (i.e., shallow, west zone of the lake) were identified as contributing factors for relatively high fisheries yields for a northern lake. Furthermore, the main source of water to GSL is the Slave River, which represents 77% of the total riverine inflow to GSL and most of the flow in the Slave River originates 2,000 km upstream in the Rocky Mountain headwaters of the Peace River. In other words, the status of the GSL ecosystem depends principally on hydrology and geochemical processes operating south of the sub-Arctic region where the lake is situated.

The lake sustains one of the largest freshwater fisheries in North America, supported by at least 34 fish species. Prominent among the large-bodied species are Lake Trout and Lake Whitefish as the most sought after for recreational and commercial fisheries; however, Arctic Grayling, Cisco, and Inconnu are also commonly fished. Of these fishes, Lake Whitefish are the dominant fish species in GSL based on biomass and population size. Recent research on the GSL ecosystem concluded that the ecological characteristics of the fish community in the Main Basin of GSL is controlled primarily by Lake Whitefish and cisco spp., which interact with large-sized predacious fishes (Burbot, Inconnu, Lake Trout, Northern Pike) as top-down regulators.

Great Slave Lake provides a unique example of a large commercial fishery being conducted, since its inception in 1945, under guidelines formulated by biologists. During the early years of the fishery, over 90% of the landed catch was Lake Trout and Lake Whitefish. However, by 1964, the Lake Trout fishery in the Main Basin was considered collapsed from exploitation by the commercial fishery and Lake Whitefish have since been the primary target species for harvest as the most valuable species for commercial, Indigenous subsistence, and recreational sport fisheries in NWT. A trophy Lake Trout fishery persists in the eastern parts of the lake where closures for commercial fishing remain in place following the collapse in the Main Basin. The current management regime has remained roughly unchanged since 1972 and has largely focused on managing the commercial fisheries harvests within seven management areas.

Over the 75-year history of fisheries management on GSL, substantial changes to fish species composition and productivity have been observed in response to a variety of stressors.

Observed impacts have generally been addressed with a series of focused academic studies but they have tended to be limited in spatial and temporal scale and have not generally contributed scientific knowledge to the management of fisheries (Tallman and Friesen 2007). Recognizing that environmental conditions of GSL have changed since the 1960s, an integrated approach using the principles of active adaptive management (Hilborn and Walters 1992) and ecosystem management (Walters and Martell 2004) has been initiated. The following section includes information gaps in support of finalizing the Integrated Fisheries Management Plan (IFMP).

4.1. INFORMATION GAPS

From the outset of commercial fishing on GSL in 1945, research was undertaken to study the effects of the commercial fishery on the fish community (Rawson 1951, Kennedy 1953, 1954, Fuller 1955). Subsequent to these seminal publications, seven decades of research have been undertaken with the same general fisheries management objectives of monitoring impacts from anthropogenic stressors, including harvests, on the fish community of GSL. Most research and monitoring for the lake has, therefore, been necessarily focused on monitoring the commercially important species for tracking the overall health or state of the fishery. Recent management efforts have been motivated by a move toward an Integrated Fisheries Management Plan that is based on ecosystem processes to better identify and monitor emerging trends in the GSL aquatic ecosystem.

Indeed, recent studies have been undertaken by DFO with objectives designed to gain a better understanding of ecosystem structure and function that will help develop the IFMP. Information gaps identified in the literature of GSL that will aid in this process include:

- Detailed bathymetric surveys in East Arm for a complete understanding of physical and chemical conditions in the lake and the role of the East Arm in whole lake metabolism, the water balance, and changes in nutrient and energy fluxes; current understanding of the bathymetry is based on only one study conducted in the later 1940s (Rawson 1950).
- Systematic monitoring of commercial fish population dynamics using proven technologies adopted for monitoring in the Great Lakes and marine environments such as mobile hydroacoustic surveys; hydroacoustic methods combined with trawl netting or purse seining would be particularly effective in quantifying the abundance, biomass, and distribution of pelagic fishes (e.g., Cisco) (Parker-Stetter 2009).
- Long-term monitoring of water chemistry and hydrology of the Slave River and its major tributaries as a suitable indicator of the state or health of the GSL ecosystem.
- Location and vulnerability of tributary spawning locations to habitat degradation and exploitation for highly migratory and seasonal fish use of tributary streams of GSL; environmental studies of key tributaries that support spawning migrations (other than the Slave River) will help to better understand changing conditions for adfluvial populations and to better protect those habitats from degradation; emerging technologies like environmental DNA may be of use in evaluating current use of tributaries for spawning habitat.
- The state of lower trophic levels and food web interactions, supported by paleolimnological studies to address knowledge gaps in temporal changes in primary and secondary production over time; integration of this information with the current understanding of GSL trophic webs will help better forecast changes in ecosystem food web dynamics.
- Similar to the above point, there is limited information on the ecology of small-bodied forage fish species in GSL and their contributing roles in supporting fisheries productivity.

- Recognizing the potential importance of Burbot and Northern Pike in structuring the fish community as keystone species in GSL (Janjua et al. 2014), the population dynamics of Burbot and Northern Pike are not well understood to track their top-down roles underlying fisheries productivity over time and across the lake.
- Continued genetic analyses of population (stock) units will help identify species stock structure and phenotypic polymorphism in commercially harvested species such as Lake Whitefish and Lake Trout.
- Development of a comprehensive database of previously collected life history data for species as a resource to help refine fisheries productivity models, and ultimately catch quotas.
- The identification and development of fisheries management practices for sustainable ecosystem management (Walters and Martell 2004), including for example, development of clear exploitation targets and limit reference points for management areas, and development of incentives for fishers to participate in data collection, fisheries regulation, and innovative fishing practices.

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