Nechako White Sturgeon Predation Risk Review 2022

A Technical Report Prepared for

The Juvenile Survival and Predation Subcommittee, Nechako White Sturgeon Recovery Initiative (NWSRI) Technical Working Group.

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Executive Summary

The Nechako White Sturgeon Recovery Initiative (NWSRI) Technical Working Group (TWG) formed the survival and predation subcommittee in 2020 to address questions related to the predation of Nechako White Sturgeon from the egg to juvenile stage. This predation risk review will inform the subcommittee in formulating a comprehensive predation plan that addresses those predators identified to be a high risk to the survival of both wild and hatchery-reared Nechako White Sturgeon. This document consists of an extensive, systematic review of relevant literature to identify potential and confirmed predators of Nechako White Sturgeon at all sturgeon life stages, including the biology and ecology of predators, descriptions of the interaction between predator and prey (i.e., capture), factors affecting the interaction, including biotic and abiotic variables, assessment of predation risk for hatchery-reared sturgeon, GIS analysis and mapping of predation risk using publicly available species occurrence data, mitigation strategies, and uncertainties.

North American river otter, Bald Eagle, and Osprey were identified as High-risk predators. American mink, Great Blue Heron, and American White Pelican were classified as Moderate-risk, and Common Loon, Belted Kingfisher, Common Merganser, and Red-necked Grebe were considered Low-risk (Table 1). A previous review of fish predators classified Northern Pikeminnow, Prickly Sculpin, Peamouth Chub, Largescale Sucker, and Burbot as High-risk, adult White Sturgeon, Bull Trout, Longnose Sucker, Redside Shiner, Mountain Whitefish, and Slimy Sculpin as Moderate-risk, and Rainbow Trout and juvenile Chinook Salmon as Low-risk (Table 1; EDI 2016).

Mitigation actions that reduce predation rates of vulnerable life stages of sturgeon should be considered an integral part of a comprehensive restoration plan for White Sturgeon in the

Nechako River. Flow, turbidity, cover habitat, and water depth have been shown to influence predation success among most of the predators included in this review. Potential mitigations for consideration, identified from studies in other systems, include flow regulation to decrease vulnerability to predation, habitat enhancements to increase escape cover, and habitat alterations to decrease predation risk. Overall, flows in the Nechako River are much lower under the current management regime compared to natural historic flows (Macdonald et al. 2012).

The limitations and knowledge gaps inherent in this review should be acknowledged prior to consideration of mitigation actions. Risk rankings developed should be considered preliminary and subject to change based on targeted monitoring programs in the Nechako River and upper Fraser River. Studies should investigate predator abundance and distribution in the Nechako River and the interactions between predators and Nechako White Sturgeon. Studies should be conducted to investigate and measure predation-caused mortality of Nechako White Sturgeon on a predator-specific basis.

Introduction

White Sturgeon (*Acipenser transmontanus*) in the Nechako River, British Columbia (BC), Canada have experienced recruitment failure since 1967 (McAdam et al. 2005). In 2000, the recovery planning process was initiated for the Nechako River White Sturgeon population based on the results of age class analyses and apparent lack of recruitment (RL & L Environmental Services 2000). A formal recovery plan was developed in 2004 and this population was listed as endangered under the Species at Risk Act (SARA) in 2006 (Nechako White Sturgeon Recovery Initiative [NWSRI] 2004; Fisheries and Oceans Canada [DFO] 2014). Conservation aquaculture was identified as a temporary recovery tool and pilot aquaculture efforts to release juvenile Nechako White Sturgeon into the Nechako River took place from 2006 to 2009, with an experimental embryo release in 2011. Larger scale releases from the Nechako White Sturgeon Conservation Center (NWSCC), a specially-designed aquaculture facility, began in 2015 (Hildebrand et al. 2016). In addition to investigating the role of predation in the recruitment failure of wild sturgeon as outlined in the recovery plan (NWSRI 2004), it is important to understand how predation of hatchery-reared sturgeon poses a threat to the success of the conservation aquaculture program and to the recruitment of these individuals into the reproducing population.

Prohibitions on harvesting Nechako White Sturgeon reduced human-caused mortality of adult sturgeon; however, the existence of other natural predators poses a potentially high predation risk to early life stages (eggs, yolk-sac larvae, and free-swimming larvae) and juveniles. During the egg, larval, and early juvenile stages, White Sturgeon are vulnerable to several species of fish predators that occur in the Nechako River, including Northern Pikeminnow (*Ptychocheilus oregonensis*), Peamouth Chub (*Mylocheilus caurinus*), Largescale

Sucker (*Catostomus macrocheilus*), Prickly Sculpin (*Cottus asper*), and Burbot (*Lota lota*; Gadomski and Parsley 2005; EDI 2016). Larger hatchery-reared and wild Nechako White Sturgeon between 15–70 cm length are vulnerable to predation by North American river otter (*Lontra canadensis*; Babey et al. 2020). However, there have been no systematic investigations of predation of sturgeon by other mammalian and avian species (although, see Keefer et al. 2012; U.S. Army Corps of Engineers 2016; Hilton and McGrath 2021). There is differential predation risk to hatchery and wild individuals, as sturgeon reared at the NWSCC are released at a size that surpasses their vulnerability to fish predators; however, hatchery individuals are still vulnerable to mammalian and avian predators. Alternatively, wild individuals are present in the river during the vulnerable egg to early juvenile stages, making them susceptible to a much broader collection of predators.

Anti-Predator Behaviour Deficits in Hatchery Fish

The hatchery environment often does not prepare fish with an anti-predator behaviour repertoire appropriate under natural conditions (Brown and Laland 2001; Brown 2003). Lack of previous experience with predators reduces the capacity of fish to recognize predators and accurately perceive threats (Olla et al. 1998; Mitchell et al. 2015). The hatchery environment may suppress important anti-predator behaviours and promote development of maladaptive behaviours that make fish more vulnerable to predation (Berejikian et al. 1996; Solberg et al. 2020). Therefore, hatchery-released juvenile sturgeon in the Nechako River may be at a survival disadvantage compared to naturally reared fish.

The hatchery environment generally promotes behaviours that make fish more vulnerable to predators in the wild. Maladaptive behaviours include increased risk-taking, decreased use of protective habitat, and habituation to potentially threatening stimuli (Ferrari et al. 2010a; Bosiger et al. 2012; Solberg et al. 2020). In a hatchery environment, fish are confined to tanks with limited space and often in high densities (Huntingford 2004; Ashley 2007). Food is plentiful, easy to obtain, and is often a pelleted diet that promotes fast growth but has little resemblance to a natural diet (Brown and Day 2002). Fish do not encounter natural predators in the hatchery environment; thus, the hatchery could be considered a safe, low risk environment (Gro Vea Salvanes and Braithwaite 2006).

Habituation occurs when repeated exposure to certain stimuli suppresses innate responses (Ferrari et al. 2010a). For example, a novel object such as a cleaning brush constantly entering a tank may elicit a reflexive fleeing response at first, but eventually fish will not expend the energy if there are no negative consequences (Kelley and Magurran 2003). Behavioural deficits among hatchery-reared fish increase the probability of predator encounters, and reduce the ability of fish to avoid detection and escape from predators (Kelley and Magurran 2003).

Experience with predator stimuli promotes adaptive anti-predator behaviour and reduces predation risk for hatchery-reared fish (Brown 2003; Kopack et al. 2015). Immobility and hiding are two common actions to avoid detection from predators (Krause et al. 1998; Brown and Dreier 2002). Immobility or 'freezing' is a response to avoid detection by visual predators; however, immobility is most effective when paired with visual crypsis such as countershading (Ruxton et al. 2004; Domenici and Hale 2019). Hiding involves increased use of natural structures as refuge to avoid detection from predators (Krause et al. 1998). However, hatchery tanks are often devoid of structures and may promote behaviors that are maladaptive in a structurally complex environment (Roberts et al. 2011). Particularly, hatchery fish may be less likely to seek cover relative to wild fish, resulting in increased vulnerability to predators among hatchery fish (Yamamoto and Reinhardt 2003). Further, cultured fish may be inherently risk-prone (Swain and

Riddell 1990). Particularly, feeding without risk of predation in hatcheries leads to bold fish that are more likely to expose themselves to high predation risk in nature (Salvanes 2017). Additionally, hatcheries with increased densities of fish competing for food may promote the development of aggressive behaviours (Fenderson and Carpenter 1971; Swain and Riddell 1990). Aggressive fish may be more vulnerable to predation due to decreased predator vigilance and less cryptic behaviours (Landeau and Terborgh 1986; Swain and Riddell 1990). There are no apparent studies indicating the longevity of these hatchery deficits once fish are released into the wild, so it is certainly possible hatchery sturgeon become less vulnerable to predation in the wild over time. However, even a relatively short time of high vulnerability after release could be detrimental to survival.

Objectives

This review presents a preliminary summary of recent predation research to identify mammalian and avian predators of the egg, larvae, and juvenile life stages of wild and hatchery White Sturgeon and their level of risk. It integrates previous and ongoing research on fish predators (EDI 2016), as well as river otter predation of Nechako White Sturgeon (Babey 2021a). Mitigation strategies are also proposed, as well as relative uncertainty. This review investigates the following research questions:

1. What are the effects of predation on White Sturgeon populations?
2. What role might hatchery practices play in increased predation vulnerability?
3. What are the key predators at each life stage and size class of White Sturgeon?
4. What environmental conditions in the Nechako River increase the risk of predation?
5. What are potentially effective mitigations against predation of White Sturgeon?
6. What monitoring is required to improve certainties of predator mitigation?

The effects of predation include behavioral changes, such as shifts in habitat use, physiological stress responses, and demographic changes (Prugh et al. 2019). Understanding size-related vulnerability to predation, as well as environmental conditions that increase predation risk, will inform efforts to increase recruitment of wild and hatchery origin Nechako White Sturgeon (Gadomski and Parsley 2005b). Mitigation actions that reduce predation rates of eggs, larval, and juvenile sturgeon should be considered an integral part of a comprehensive restoration plan for Nechako White Sturgeon in the Nechako River (DFO 2014). Therefore, this risk review will be used to inform the creation of a predation plan to address the high-risk predators that may impact recruitment success.

Study Area

The Nechako River is located in central BC and runs for approximately 280 km until flowing into the Upper Fraser River in Prince George, BC (Fig. 1). It has been regulated upstream by the Kenney Dam since 1952, with White Sturgeon present below the dam. The river experiences variable flow and water levels, with periods of considerably low river levels that may decrease suitable sturgeon habitat and protection from predators. White Sturgeon prefer deep, low velocity habitats during the winter (Hildebrand et al. 2016) and while Nechako White Sturgeon may overwinter in nearby lakes, those that stay in the river have a small number of options for overwintering areas. Between November and April, juvenile White Sturgeon overwinter in deep pools of the Nechako River. There are 3 regularly monitored overwintering pools at river-kms 110.6, 116.8, and 125.3 (Fig. 1). These overwintering pools are within an approximately 30-km river length core area composed of relatively high-quality juvenile sturgeon habitat. Further, these overwintering pools are located in close proximity to known river otter latrine sites with evidence of otter predation of juvenile White Sturgeon (Babey et al. 2020).

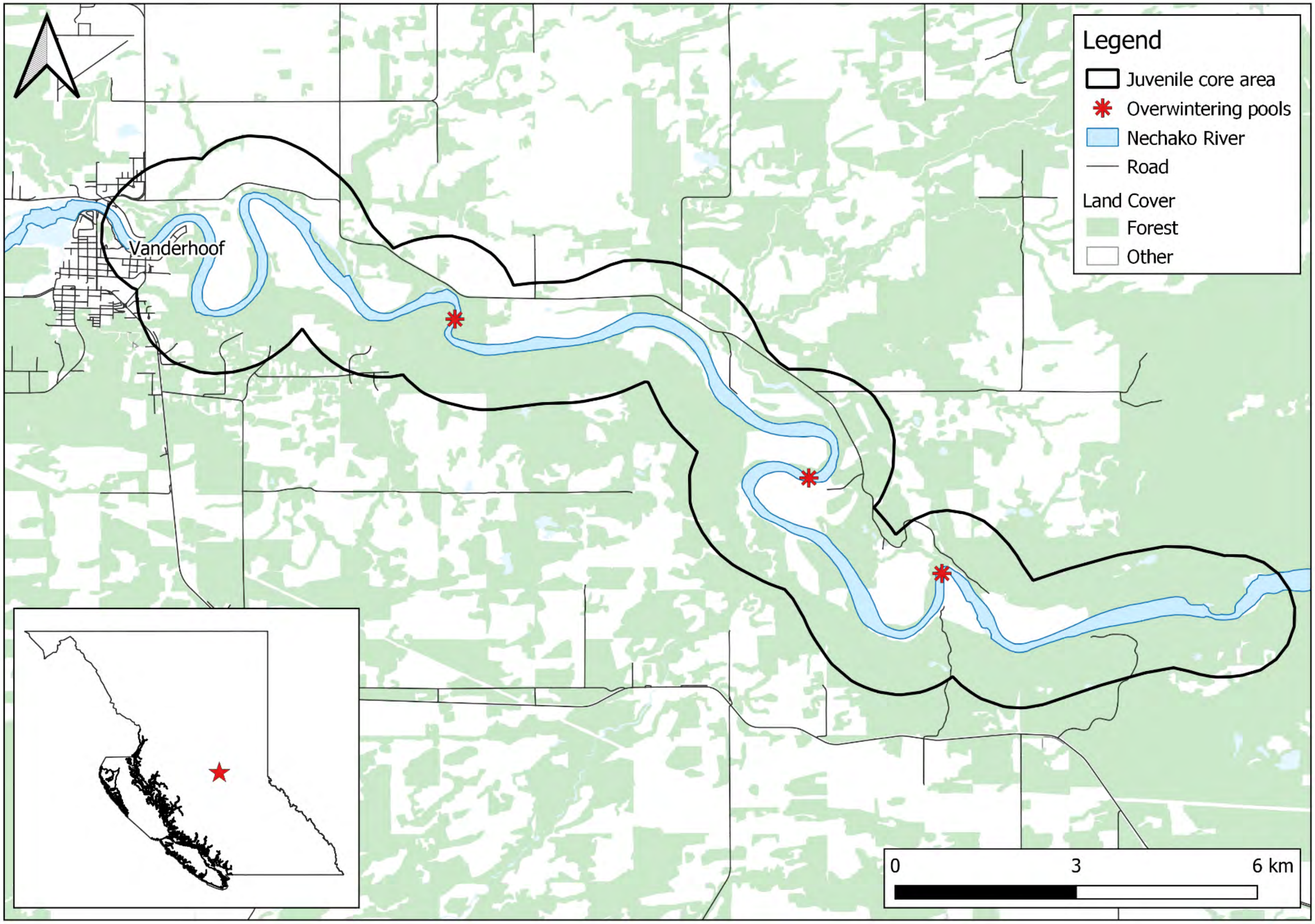

Figure 1. The 30-km core area (1-km buffer) and locations of 3 known overwintering pools for juvenile White Sturgeon in the Nechako River.

Methods

Literature review

A literature review was conducted to identify piscivorous predators in North America which overlap in distribution with the Nechako River and Upper Fraser River. All literature was accessed via web searches through the UNBC Library. Literature found during web searches was often used as a source of further references which were searched for by DOI, URL, or Article/Report Title through Google Scholar. Literature search results were sorted in order of relevance by location (i.e., Nechako River > north-central BC > Canada > North America), and by year of the source study, prioritizing more recent findings. Key words used included: "terrestrial predators sturgeon", "American mink *Mustela vison* diet North America", "muskrat diet", "osprey *Pandion haliaetus* diet North America", "bald eagle *Haliaeetus leucocephalus* diet North America", "great blue heron diet North America", "belted kingfisher diet North America", "common merganser diet North America", "common merganser movement distances", "red-necked grebe diet North America", "red-necked grebe home range movement distances", "grebe movement distances home range North America", "grebe movement distances home range", "common loon diet North America", "American white pelican diet North America", and "white pelican home range movement distances". River otter information was incorporated into the report from a previous literature review (Babey 2021a).

Information from literature was summarized by predator and included ecology in North America generally and in north-central BC specifically, or as close as possible to the Nechako River. Relevant information included the ecology (e.g., benthic or limnetic foraging behaviour) and the range of sizes of fish prey captured by each predator. This information was used to assess size-related vulnerability of White Sturgeon to each predator. Other information synthesized included biotic and abiotic variables known to affect predation risk and capture success (e.g., habitat, cover, season, water velocity, turbidity, temperature, and prey size), home range and daily movement distances, and migratory patterns. Previous literature reviews of Nechako White Sturgeon predation risk were integrated into the project (EDI 2016; Babey 2021a, 2021b). The conservation status (provincial and federal), was listed for each predator species, including fish predators outlined in EDI (2016).

Mammalian and avian predators were rated as High risk if there was physical evidence of Nechako White Sturgeon consumption, or evidence of White Sturgeon consumption elsewhere in North America. Predators with no evidence of sturgeon predation were evaluated and assigned a risk rating based on vulnerability of White Sturgeon to each predator. Risk scores were averaged across the four criteria and combined into a final predation risk rating. The following assumptions and criteria were applied to risk ratings for mammalian and avian predators:

1. Risk increases with the range of size classes of White Sturgeon likely affected. Predators that consumed fish over a range of sizes ≥30 cm were ranked High risk, and those that consumed fish over a range <30 cm were ranked Low risk.
2. Juvenile White Sturgeon prefer deep water; therefore, predators with preferred foraging depths ≥2 m were ranked High risk, and those that preferred depths <2 m were ranked Low risk.
3. Predators with >25% spatial overlap (see next section for details regarding spatial analysis of predator occurrences) with the juvenile White Sturgeon core area were ranked High risk, and those with ≤25% overlap were ranked Low risk.
4. Predation risk increases with greater temporal overlap between predators and Nechako White Sturgeon. Therefore, predators that were year-round residents across

the geographic range of Nechako White Sturgeon were ranked High risk, migratory predators present for 6–11 months of the year were ranked Moderate risk, and predators present for less than 6 months of the year were ranked Low risk.

A list of fish predators of White Sturgeon in the Nechako River was created by EDI (2016), using the Fisheries Inventory Data Queries (FIDQ) tool available on the BC Ministry of Environment website (http://www.env.gov.bc.ca/fish/fidq/index.html). Each fish species was ranked as High, Moderate, or Low risk based on an assessment similar to that outlined for mammalian and avian predators. The probability of predation was based on current research of food habits, habitat preferences, and average body length of each predator, as well as bycatch data collected during juvenile White Sturgeon assessments in the Nechako River between 2007–2009 (NWSRI 2021). Current research from the Nechako River, Fraser River, and Columbia River watersheds was prioritized (EDI 2016). Fish species in the High-risk category were integrated into the project risk rankings and mitigation action plans.

Potential mitigation strategies indicated in the literature were summarized for each predator species. Some species have not been managed specifically to reduce predation risk; in those cases, mitigation strategies were generalized from other species based on taxonomic and ecological similarities. Mitigation actions attempted to account for the conservation status and management policies regarding the predator.

Mapping

Species occurrence data was downloaded from GBIF.org for North American river otter (*Lutra canadensis* Schreber, 1777), American mink (*Mustela vison* Schreber, 1777), muskrat (*Ondatra zibethicus* Linnaeus, 1766), Osprey (*Pandion haliaetus* Linnaeus, 1758), Bald Eagle (*Haliaeetus leucocephalus* Linnaeus, 1766), Great Blue Heron (*Ardea herodias* Linnaeus, 1758), American White Pelican (*Pelecanus erythrorhynchos* Gmelin, 1789), Common Loon (*Gavia immer* Brunnich, 1764), Belted Kingfisher (*Megaceryle alcyon* Linnaeus, 1758), Common Merganser (*Mergus merganser* Linnaeus, 1758), and Red-necked Grebe (*Podiceps grisegena* Boddaert, 1783; GBIF.org 2021). Occurrence data for migratory birds was summarized by month in order to assess seasonal variability of predation risk.

The stream centreline network (WDIC_WATERBODY_STREAM_LINE_SVW) was accessed through the BC Data Catalogue. River-kms for the Nechako juvenile sturgeon core area were acquired from C. Babey, and the core area was represented by a 1-km buffer. The locations of 3 known overwintering pools were also mapped for ease in visually assessing predation risk at those critical sites (C. Babey, pers. comm. 2021).

Mammalian and avian predator occurrence data were merged, and kernel density estimation was used to construct predation risk heat maps in QGIS (QGIS.org 2021). Each species was weighted to reflect relative risk (High risk = 10, Moderate risk = 5, and Low risk = 1) based on the criteria outlined in the previous section. The spatial scale of risk was adjusted to reflect each predator's home range and movement distances.

The radius used to scale kernel density estimation was based on the length of linear home ranges or movement distances. River otter daily movement distances are 5.2 km (Helon et al. 2013), and home ranges are between 8.02–11.0 km^2 (Helon et al. 2004); therefore, the radius used for kernel density estimation was 1,740 m (the radius of a circle with area = 9.5 km^2; Helon et al. 2004). American mink daily movement distances are between 532–732 m, and mean linear home ranges are between 2.7–3.0 km (Haan and Halbrook 2015). Therefore, the radius used for kernel density estimation was 1,500 m. Osprey have mean home ranges of 1.76 km^2 (Bedrosian et al. 2015); therefore, the radius chosen for kernel density estimation was 750 m (Bedrosian et al. 2015). Bald Eagle have linear home ranges between 17–27 km, and mean home ranges in riverine habitats are 5 km^2 (Hunt et al. 2002; Watson 2002). Therefore, the radius used for kernel density estimation was 1,260 m (Watson 2002). Great Blue Heron fly on average 4,800 m distance from nest to foraging habitat (Dowd and Flake 1985); therefore, the radius used for kernel density estimation was 4,800 m. The average territory length of Belted Kingfisher is 800 m (Salyer and Lagler 1949); therefore, the radius used for kernel density estimation was 400 m.

No information was available for within-season home ranges or movement distances of Common Merganser. Therefore, information from Red-breasted Merganser (*Mergus serrator*) were used as a proxy. Red-breasted Merganser move on average 3,500 m from nesting to brood rearing areas (Craik and Titman 2008); therefore, the radius used for kernel density estimation was 3,500 m. Common Loon have been shown to consistently use one area, approximately 10–20 km^2, for the duration of winter (Paruk et al. 2015). Therefore, the radius used for kernel density estimation was 2,200 m. There was no information on within-season movement distances or home ranges of Red-necked Grebe; therefore, the radius used for kernel density estimation was 3 km (3000 m), based on movement and habitat use of Red-breasted Merganser and Common Loon. American White Pelican have large home ranges between 177–4,710 km^2 (King et al. 2016); therefore, the radius used for kernel density estimation was 7,500 m (the radius of a circle with area = 177 km^2). Maps were created at two different spatial scales: the Nechako juvenile sturgeon core area scale, and the Nechako River and upper Fraser River scale.

Results

North American river otter, Bald Eagle, and Osprey were identified as High-risk predators. American mink, Great Blue Heron, and American White Pelican were classified as Moderate-risk, and Common Loon, Belted Kingfisher, Common Merganser, and Red-necked Grebe were considered Low-risk (Table 1; Table 2). A previous review classified Northern Pikeminnow, Prickly Sculpin, Peamouth Chub, Largescale Sucker, and Burbot as High-risk, adult White Sturgeon, Bull Trout (*Salvelinus confluentus* Suckley, 1859), Longnose Sucker (*Catostomus catostomus* Forster, 1773), Redside Shiner (*Richardsonius balteatus* Richardson, 1836), Mountain Whitefish (*Prosopium williamsoni* Girard, 1856), and Slimy Sculpin (*Cottus cognatus* Richardson, 1836) as Moderate-risk, and Rainbow Trout (*Oncorhynchus mykiss* Walbaum, 1792) and juvenile Chinook Salmon (*Oncorhynchus tshawytscha* Walbaum in Artedi, 1792) as Low-risk (EDI 2016).

Kernel density estimation indicated that predation risk is relatively high in sections of river that coincide with areas of relatively high human density (Fig. 2; Fig. 3). High risk of predation within the Nechako juvenile sturgeon core area is of particular concern (Fig. 2), and likely reflects the high density of river otter latrine sites, as well as the large home ranges of American White Pelican. At the Nechako River and upper Fraser River scale, predation risk appears to be greatest in areas surrounding Vanderhoof, Prince George, Quesnel, and Williams Lake (Fig. 3). This likely reflects significant observation bias; however, areas with relatively high densities of predator occurrence should be given priority for predation monitoring and mitigation programs.

Table 1. Confirmed and potential mammalian and avian predators of Nechako White Sturgeon by risk category with rationale/criteria for assignment.

		Criteria (Weight of qualitative risk assessment)				
Risk	**Predator**	**Evidence of sturgeon predation?**	**Consumes fish over size range (>30 cm)?**	**Preferred foraging depth >2 m?**	**High spatial overlap?**	**High temporal overlap?**
High	North American river otter	X	X	X	X	X
	Bald Eagle	X	X		X	X
	Osprey	X	X			X
Moderate	American mink		X			X
	Great Blue Heron		X		X	X
	American White Pelican		X		X	
Low	Common Loon			X		
	Belted Kingfisher					X
	Common Merganser			X		X
	Red-necked Grebe			X		X

Table 2. Values for multiple criteria used to assess risk for confirmed and potential predators of Nechako White Sturgeon.

Predator	Criteria (Weight of qualitative risk assessment)				
	Evidence of sturgeon predation?	Size range of fish prey (cm)	Preferred foraging depth (m)	Spatial overlap with NWS core area (%)	Seasonal overlap with NWS
North American river otter	Yes	15–70	0–3	98	Year-round
American mink	No	1–30	0.45	0	Year-round
Bald Eagle	Yes	12–69	0.58	35	Oct–Jan
Osprey	Yes	10–51	0–1	5	Mar–Aug
Great Blue Heron	No	1–38	0.10–0.17	29	Apr–Oct
American White Pelican	No	1–40	1–2	38	May–Jul
Common Loon	No	2–5	<5	25	May–Sep
Belted Kingfisher	No	3–18	0	2	Mar–Sep
Common Merganser	No	3–21	2–3	23	Mar–Sep
Red-necked Grebe	No	5–14	1–3	22	Apr–Sep

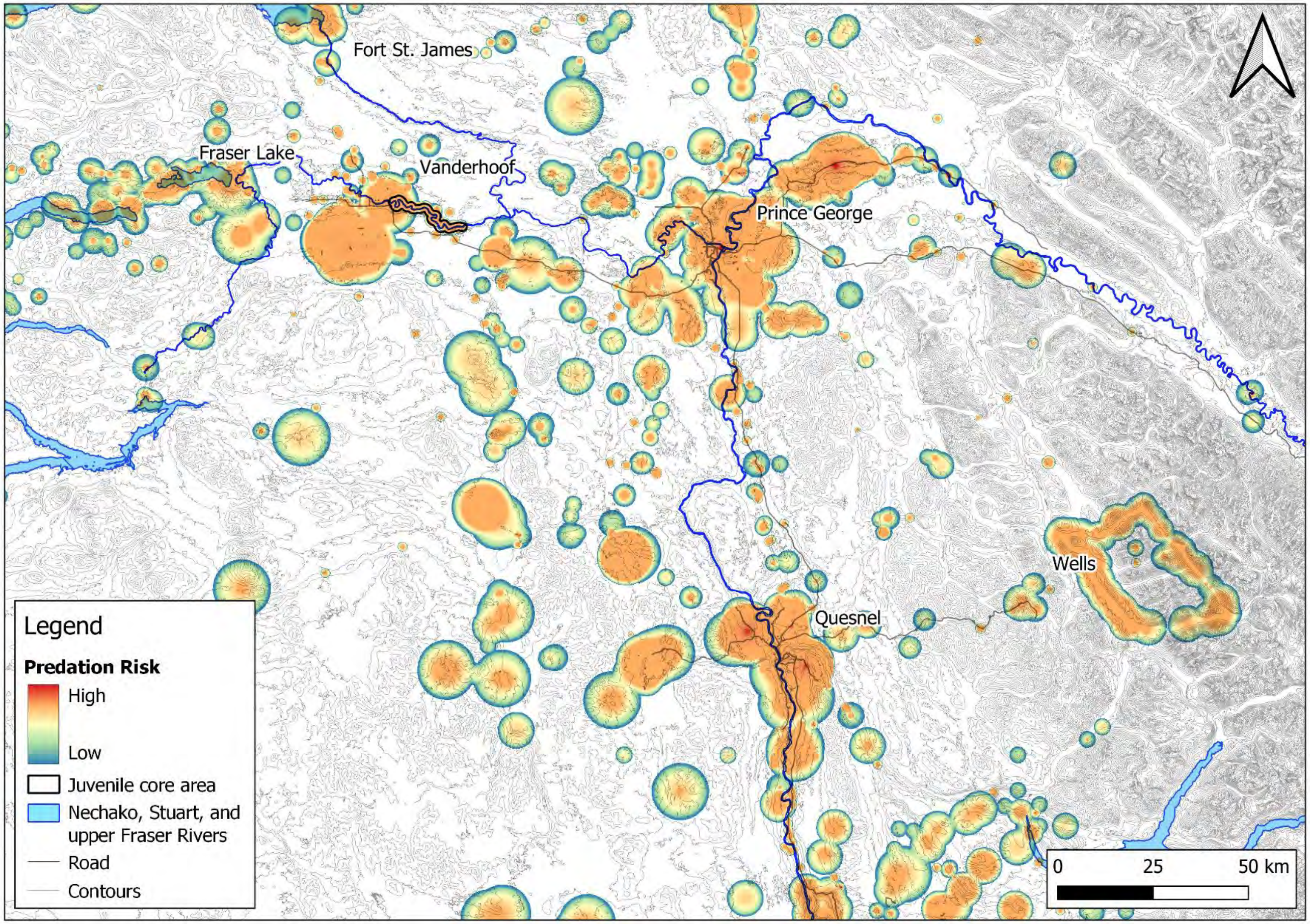

Figure 2. The 30-km core area (1-km buffer) and the Nechako River, Stuart River, as well as mid and upper Fraser River, overlayed with overall predation risk calculated from kernel density estimation for all confirmed and potential predators.

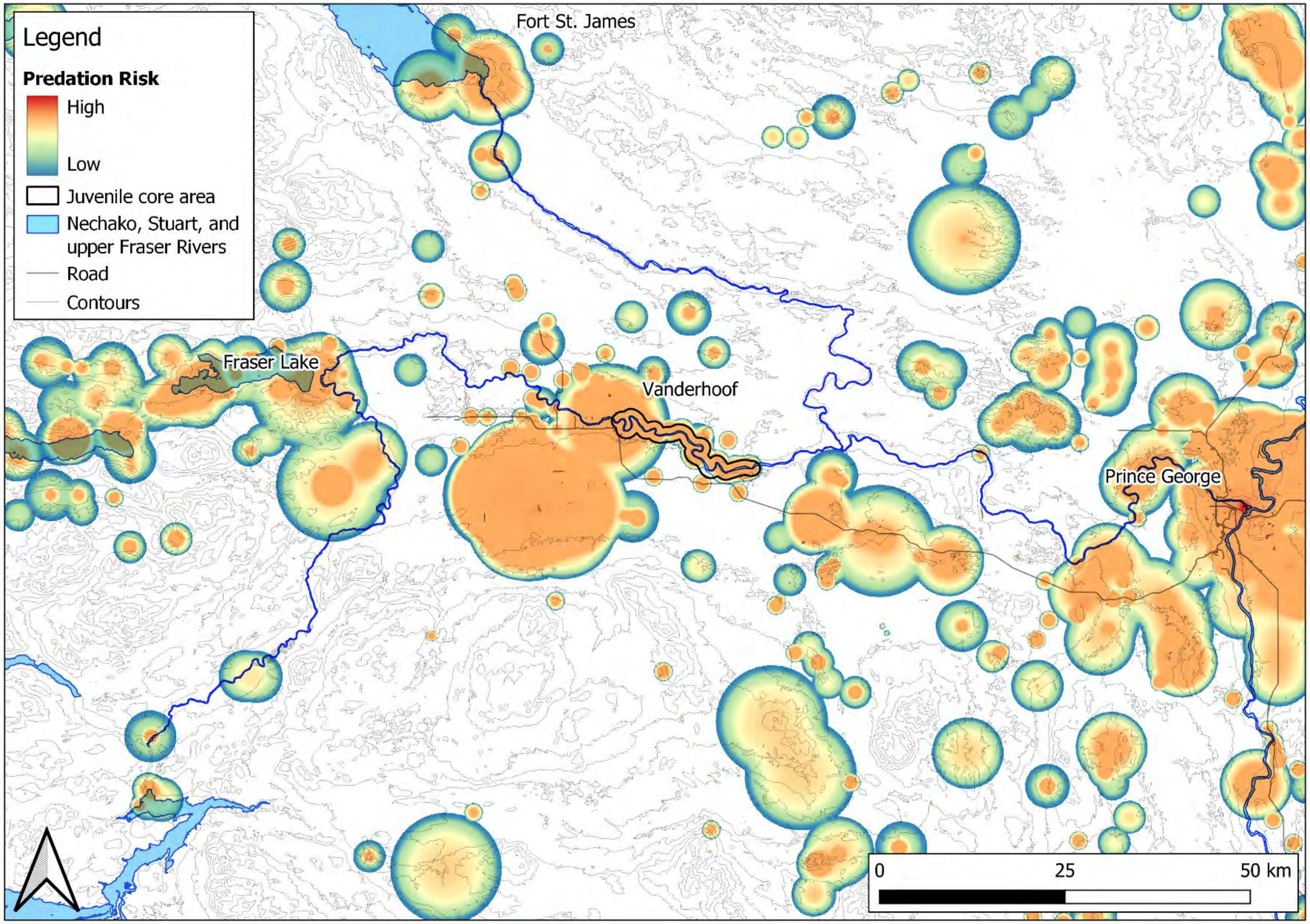

Figure 3. The 30-km core area (1-km buffer), the Nechako River, and the Stuart River, overlayed with overall predation risk calculated from kernel density estimation for all confirmed and potential predators.

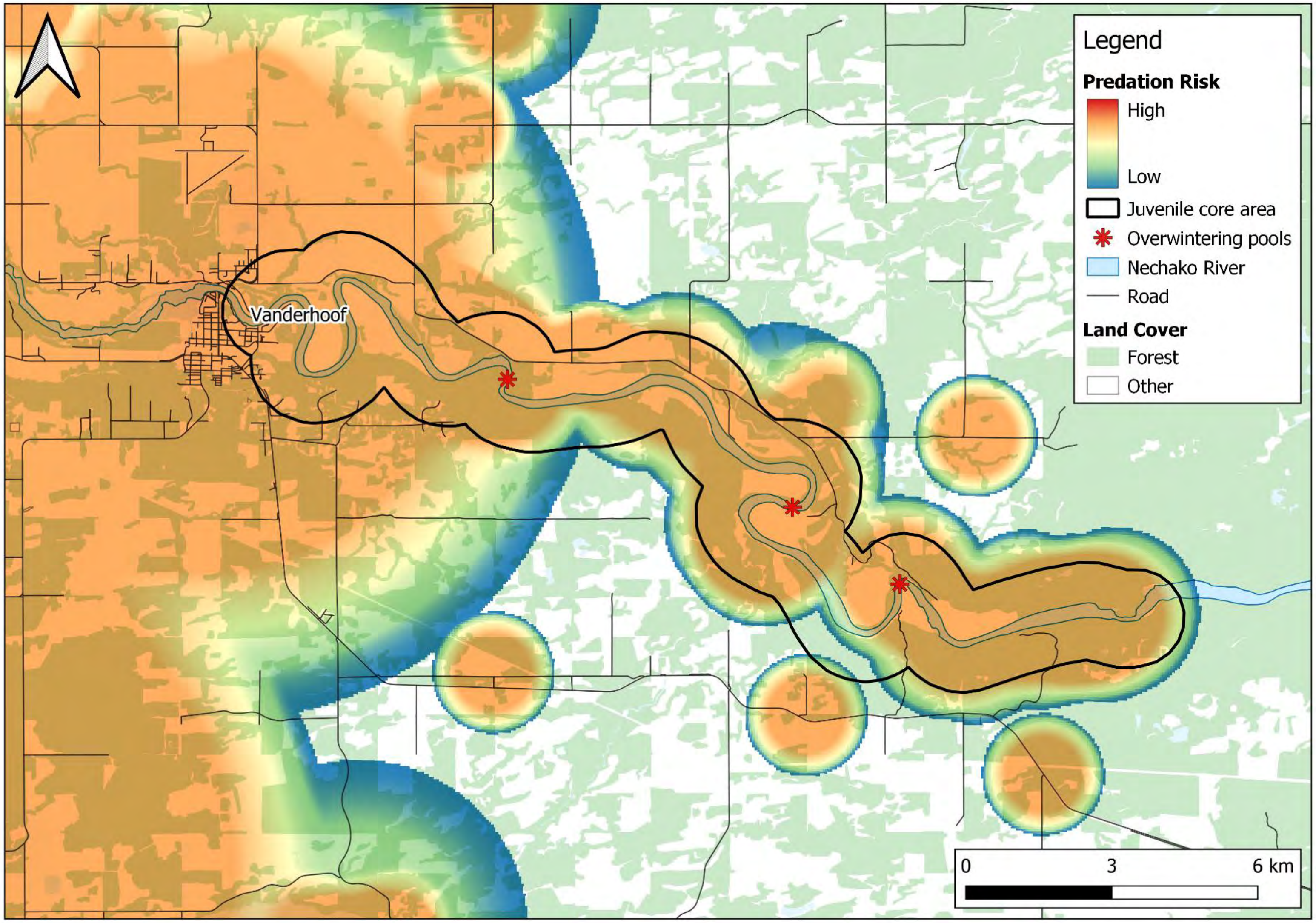

Figure 4. The 30-km core area (1-km buffer) and locations of 3 known overwintering pools for juvenile White Sturgeon in the Nechako River, overlayed with overall predation risk calculated from kernel density estimation for all confirmed and potential predators.

Based on the number of predator species identified from this study, overall predation risk appears to be greatest for wild juvenile sturgeon from 1–10 cm length (Table 3; Fig. 4). A total of 14 species of fish, mammals, and birds were identified as confirmed or possible predators of juvenile sturgeon from 1–10 cm length in the Nechako River and upper Fraser River (Table 3; Fig. 4). Not surprisingly, the number of known predators and correspondingly, predation risk, appears to decrease as the size of White Sturgeon increases (Fig. 4). Also as expected, sturgeon reared at the NWSCC are released at a size that surpasses their vulnerability to fish predators and most mammalian and avian predators (Table 3). There are no known mammal or bird predators of egg and larval stages of White Sturgeon; however, 13 fish species may consume sturgeon eggs and larvae in the Nechako River (Table 3; EDI 2016). Contrastingly, predation risk for larger White Sturgeon (>70 cm length) remains unknown.

Table 3. Confirmed or potential predators of Nechako White Sturgeon by size (cm), age (years), and origin (wild [W] or hatchery [H]), based on published sizes of fish capture by predators.

White sturgeon size (cm)	Age (years)	Origin	Fish Predators (EDI 2016)	Avian and Mammalian Predators
Egg–Larvae	0	W	Northern Pikeminnow, Prickly Sculpin, Peamouth Chub, Largscale Sucker, Burbot, White Sturgeon (adult), Bull Trout, Longnose Sucker, Redside Shiner, Mountain Whitefish, Slimy Sculpin, Rainbow Trout, Chinook Salmon (juvenile)	Unknown
1–10	0–2	W	Northern Pikeminnow, Prickly Sculpin, Burbot, White Sturgeon (adult), Bull Trout, Redside Shiner, Rainbow Trout	American mink, Great Blue Heron, Belted Kingfisher, Common Merganser, Common Loon, American White Pelican, Red-necked Grebe
10–20	1–2	W	Northern Pikeminnow	River otter, American mink, Great Blue Heron, Belted Kingfisher, Common Merganser, Red-necked Grebe, American White Pelican, Osprey, Bald Eagle
20–30	2–5	W-H	Unknown	River otter, American mink, Great Blue Heron, American White Pelican, Osprey, Bald Eagle
30–40	2–5	W-H	Unknown	River otter, Great Blue Heron, American White Pelican, Osprey, Bald Eagle
40–50	2–5	W-H	Unknown	River otter, Osprey, Bald Eagle
50–70	5–10	W-H	Unknown	River otter, Bald eagle
>70	>10	W	Unknown	River otter*

*(sturgeon was <70 cm but >10 years old)

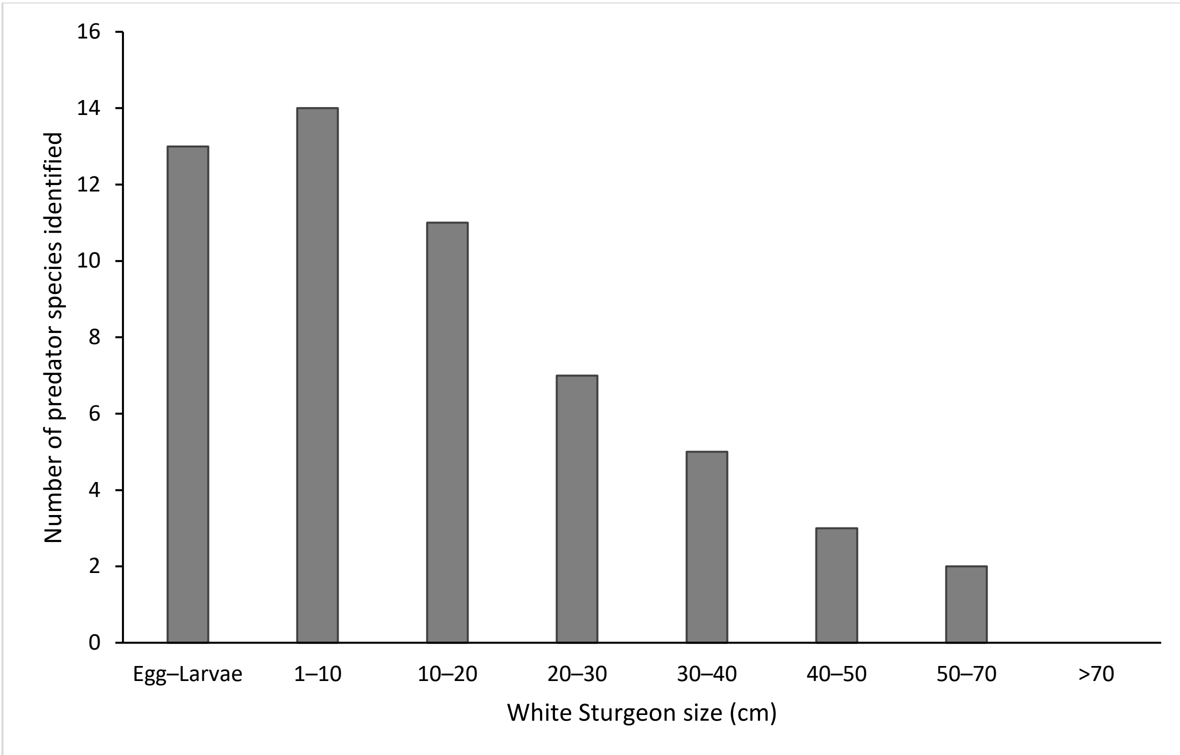

Figure 5. The number of confirmed or possible species of predators of Nechako White Sturgeon by life stage (egg–larvae) and size class (cm). Hatchery-released sturgeon are only represented in the 20–70 cm size classes.

Mammalian Predators

North American River Otter

The North American river otter is among the largest species of Mustelidae in North America, is semiaquatic and mainly piscivorous (Reid et al. 2011; Fretueg et al. 2015). River otters move between 1.8–5.2 km per day and have home ranges between 8.02–11.0 km^2 (Helon et al. 2004, 2013). In all seasons, fish and crustaceans compose the majority (81–97%) of river otter diet and terrestrial vertebrates and invertebrates generally contribute <10% of total diet (Roberts et al. 2008; Reid et al. 2011; Crowley et al. 2013; Day et al. 2015). Predation by river otters was confirmed through the collection of PIT tags from river otter latrine sites and radio tags from suspected river otter feeding sites (Babey et al. 2020). Therefore, North American river otter are a High-risk predator of hatchery-released juvenile Nechako White Sturgeon between 10–70 cm length in the Nechako River (Table 1). Further, kernel density estimation indicated that otter predation risk was high throughout the Nechako juvenile sturgeon core area (Fig. 5; Fig. 6).

Unlike fish predators, river otter can eat larger fish, and are evidently not deterred by the sharp scutes still present on the juvenile sturgeon (Table 3; Babey et al. 2020). River otter have sharp canine teeth and sharp claws on their forepaws allowing them to capture and bring large prey to shore, or to selectively fragment certain prey (Popowics 2003; Kruuk 2006; Reed-Smith 2008). Selective fragmentation of prey is aided by carnassial teeth which act as blades for shearing prey tissue (Toweill and Tabor 1982; Popowics 2003). River otter are known to eat fish with sharp defenses such as yellow perch (*Perca flavescens*) and walleye (*Sander vitreus*; Sheldon and Toll 1964). Related Eurasian otter (*Lutra lutra*) are also known to consume fish with sharp defenses such as long-spined sea scorpion (*Taurulus bubalis*) and butterfish (*Phollus gunnellus*), and carefully bring them to shore for consumption (Kruuk 2006).

It is unclear if otter are careful to avoid ingesting scutes when eating sturgeon; however, the presence of scutes in collected scat samples suggests they have little effect on the otter digestive system (Babey et al. 2020). This is not surprising given that otters continually ingest sharp bone fragments from other fish and defecate them without issue. River otter have a layer of mucous lining their intestinal tract and it is suggested that this serves to prevent damage from these sharp fragments as they pass (Reed-Smith 2008; Oldham and Black 2009; Huang et al. 2018).

River otter may choose prey based on their abundance or swimming ability (Ryder 1955). River otter have a high metabolic rate and spend the majority of their active time hunting and eating prey to meet energy requirements (Davis et al. 1992). River otter may eat up to 1.5 kg of food every day and their diet typically consists primarily of fish (Anderson and Woolf 1987; Serfass et al. 1990; Reid et al. 1994; Roberts et al. 2008). This could be problematic if preferred prey are in low abundance; however, river otter are opportunistic feeders and consume alternative prey when their preferred prey is not available (Stenson et al. 1984).

The opportunistic behaviour of otter in combination with the optimal foraging theory suggest that otter will adjust their feeding habits and take advantage of large congregations of fish that are not a preferred food source (Pyke et al. 1977; Gilbert and Nancekivell 1982; Thompson and Stelle 2014). Therefore, it would be expected to find otter in areas with a high abundance of prey fish (Cote et al. 2008b; Crowley et al. 2012). Examples include evidence of predation of congregated Kokanee (*Oncorhynchus nerka*; Melquist and Hornocker 1983; Crowley et al. 2013) and Cutthroat Trout (*Oncorhynchus clarkia*; Crait and Ben-David 2006) during their respective spawning seasons. Additionally, multiple studies present evidence of otter taking advantage of schooling fish (Sheldon and Toll 1964; Ben-David et al. 2005; Albeke et al. 2015).

River otter may select fish prey in inverse proportion to their swimming ability (Ryder 1955). The swimming ability of juvenile White Sturgeon is generally considered to be quite poor (Peake et al. 1997; Kieffer et al. 2009; Downie and Kieffer 2017). Beamish (1978) classified three categories of fish swimming performance: sustained, prolonged, and burst. Sustained swimming speed is fueled aerobically and maintained for long periods (>200 min). Prolonged swimming speed is also fueled aerobically; however, prolonged swimming is shorter (20 s to 200 min) than sustained swimming and fish may become fatigued. Burst swimming uses anaerobically derived energy and is the maximum capable speed of a fish. Burst swimming occurs over short periods of time (<20 s), and is likely the type of swimming most beneficial during encounters with predators as it allows fish to make quick escapes to refuge (Domenici and Blake 1997).

Juvenile White Sturgeon prefer to inhabit areas with low to moderate water velocities (Parsley et al. 1993; DFO 2014) where a high prolonged (critical) swimming speed may not be necessary. Still, this relatively poor swimming ability may be advantageous to river otter, which are considered to be strong swimmers. Their slim and elongated bodies make them highly hydrodynamic, their flexible spine enhances maneuverability in water, and their dorso-ventral body undulations and long tail provide sub-surface propulsion (Tarasoff et al. 1972; Williams 1989). Together, these characteristics improve swimming performance through speed, acceleration, and maneuverability (Williams 1989). Little research is available for river otter swimming speeds, but they are known to reach speeds of up to 11 km/hr (Lariviere and Walton 1998). This translates to 3.06 m/s, 5.4 times faster than the critical swimming speed of juvenile

White Sturgeon (Counihan and Frost 1999). River otter are more likely to ambush their prey and capture them with a quick lunge, rather than pursue a prolonged chase (Park 1971). Therefore, the speed and swimming ability of an otter easily outmatches that of a juvenile White Sturgeon.

It is likely that juvenile White Sturgeon possess some ability for burst swimming; however, it is unknown if they are fast enough to evade river otter. The average thrust generated by Lake Sturgeon (*Acipenser fulvescens* Rafinesque, 1817) has been shown to be 82% that of similar sized Rainbow Trout and drag per unit area of Lake Sturgeon is about 3.5 times that of trout (Webb 1986). This "drag penalty" is suggested to be a result of scutes (Webb 1986). The heterocercal tail of sturgeon also contributes less to thrust than the homocercal tail seen in salmonids (Webb 1986; Peake et al. 1997). Finally, the metabolism of sturgeon is significantly lower than many teleosts and they may not produce enough energy for the high-speed swimming necessary for evading fast predators for prolonged periods of time (Singer et al. 1990; Peake et al. 1997).

Habitat use of fish has been shown to influence prey selection by river otter (Sheldon and Toll 1964; Day et al. 2015). River otter select fish that feed in shallow areas, likely because they are more accessible for capture (Cote et al. 2008b). In addition to shorter travel time, preference for shallow diving (0–3 m depth) in the closely related Eurasian otter is related to lower thermo-regulatory costs (Nolet et al. 1993). Additionally, river otter may be shallow divers due to partial calcification of their trachea limiting their dive depth (Tarasoff and Kooyman 1973).

Specific information is limited for habitat use of juvenile White Sturgeon in BC; however, they generally prefer deeper areas with low to moderate flow (Parsley et al. 1993; DFO 2014). This is seen in the Nechako River where juvenile sturgeon tend to congregate in relatively deep, slow moving sections (J. Beardsall, personal communication). Facilitated by their sensory barbels, White Sturgeon are adapted to feeding in low-light benthic habitats (Brannon et al. 1986). It might be expected that inhabiting deep, benthic, low-light habitats would reduce predation of juvenile sturgeon by the shallow-diving, river otter which has superior vision. However, habitat use of juvenile Nechako White Sturgeon is clearly not a deterrent to predation by river otter. Otters often feed at night which relies heavily on their whiskers, and it is suggested that this use of tactile stimuli may be more important for foraging than visual stimuli (Kruuk 2006). Therefore, the low-light, turbid environments that Sturgeon prefer may have little advantage in avoiding otters. Additionally, although dive depth is not well-studied in the species, it is reported that river otter are capable of diving to a depth of nearly 20 m (Lariviere and Walton 1998). The better-studied Eurasian otter is reported to dive as deep as 14 m (Kruuk 1995). The deepest pool in the Nechako River within known juvenile sturgeon habitat is approximately 18 m (C. Babey, personal observation). It is therefore possible otters are diving to depths to capture sturgeon that are deeper than preferred; however, it may be more likely otter are targeting sturgeon spending time in shallower habitats. Captures of juvenile sturgeon in the Nechako River using set-lines indicate habitat use and feeding areas. Nechako White Sturgeon are typically captured in relatively deep water (4–7 m), but can be captured in low to moderate depths of 1–4 m (J. Beardsall, personal communication). These depths are more suitable to otter diving preference and capability.

Further, there is evidence that river otter select prey fish based on size (Cote et al. 2008a). River otter in Newfoundland have been shown to select larger, piscivorous fish (Cote et al. 2008b, 2008a). River otter selected cod >10 cm length, cunner and sculpin >15 cm, and flounder >25 cm (Cote et al. 2008a). In Denmark, the closely-related Eurasian otter consumed fish between 9–21 cm in length and have been shown to consume Brown Trout (*Salmo trutta*) up to

40 cm in length (Taastrom and Jacobsen 1999; Jacobsen 2005). River otter appear to select larger prey sizes relative to availability, and avoid smaller prey (Jacobsen 2005).

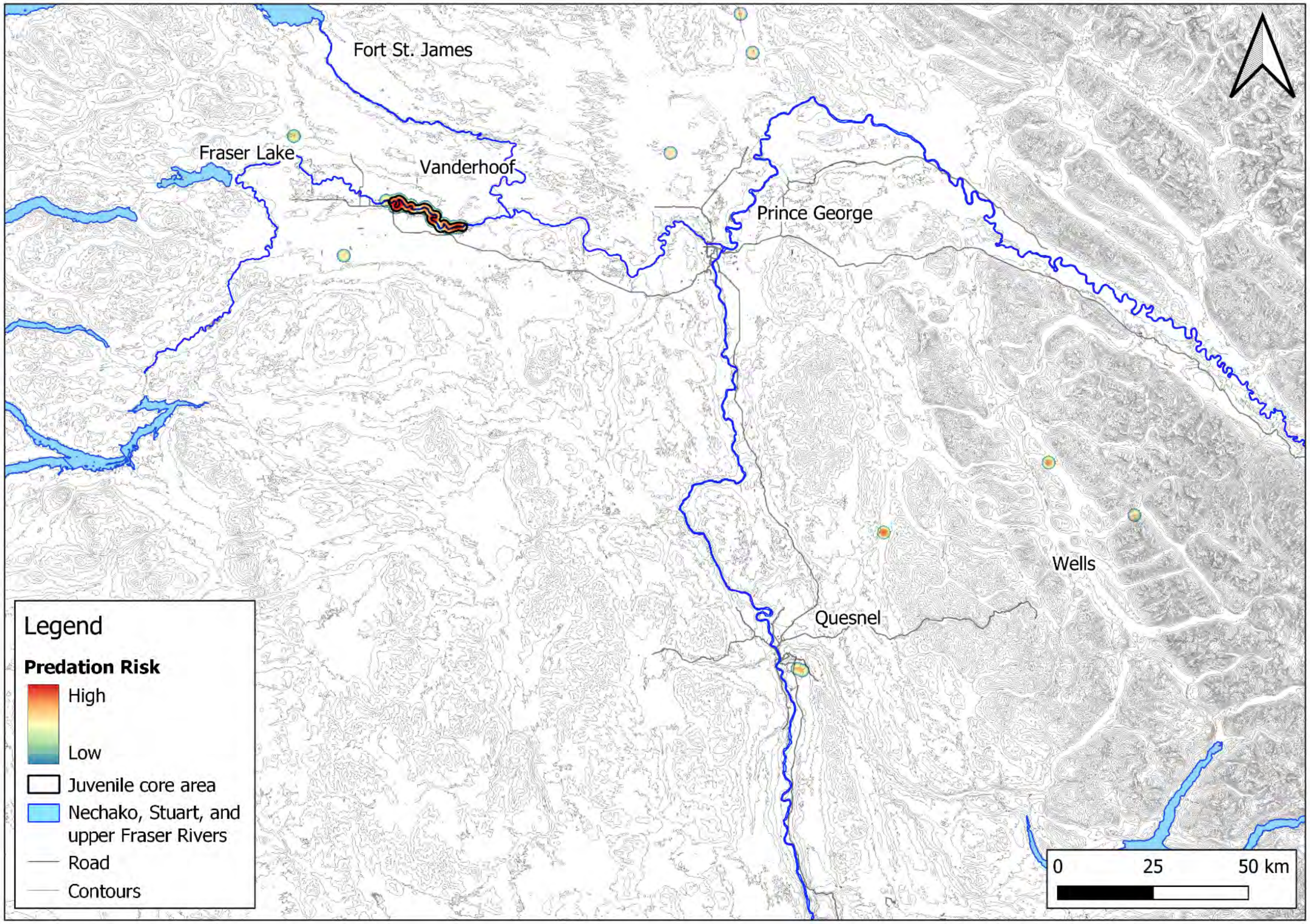

Figure 6. The 30-km core area (1-km buffer), the Nechako River, Stuart River, and mid and upper Fraser River, overlayed with river otter predation risk.

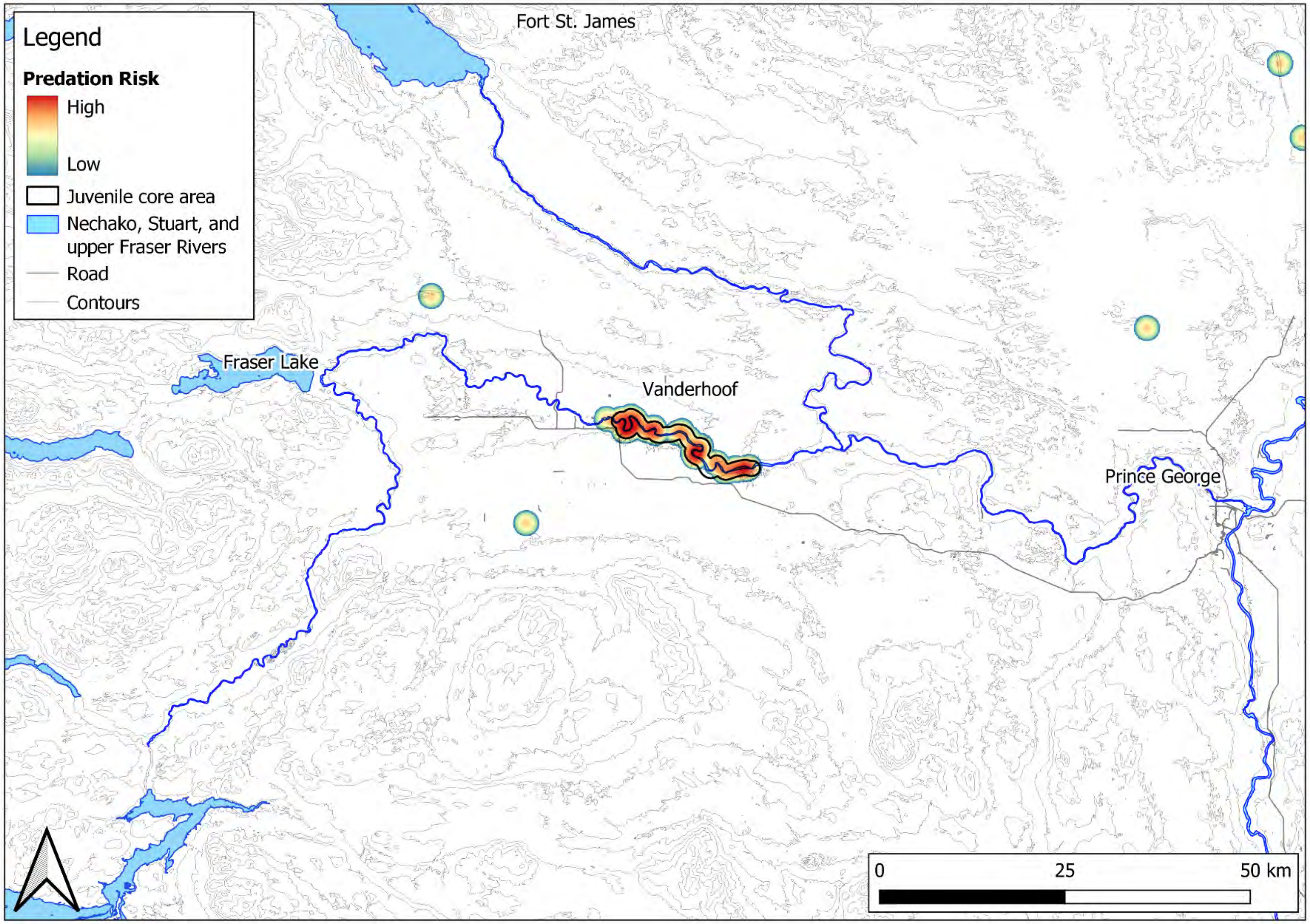

Figure 7. The 30-km core area (1-km buffer), the Nechako River, and Stuart River, overlayed with river otter predation risk.

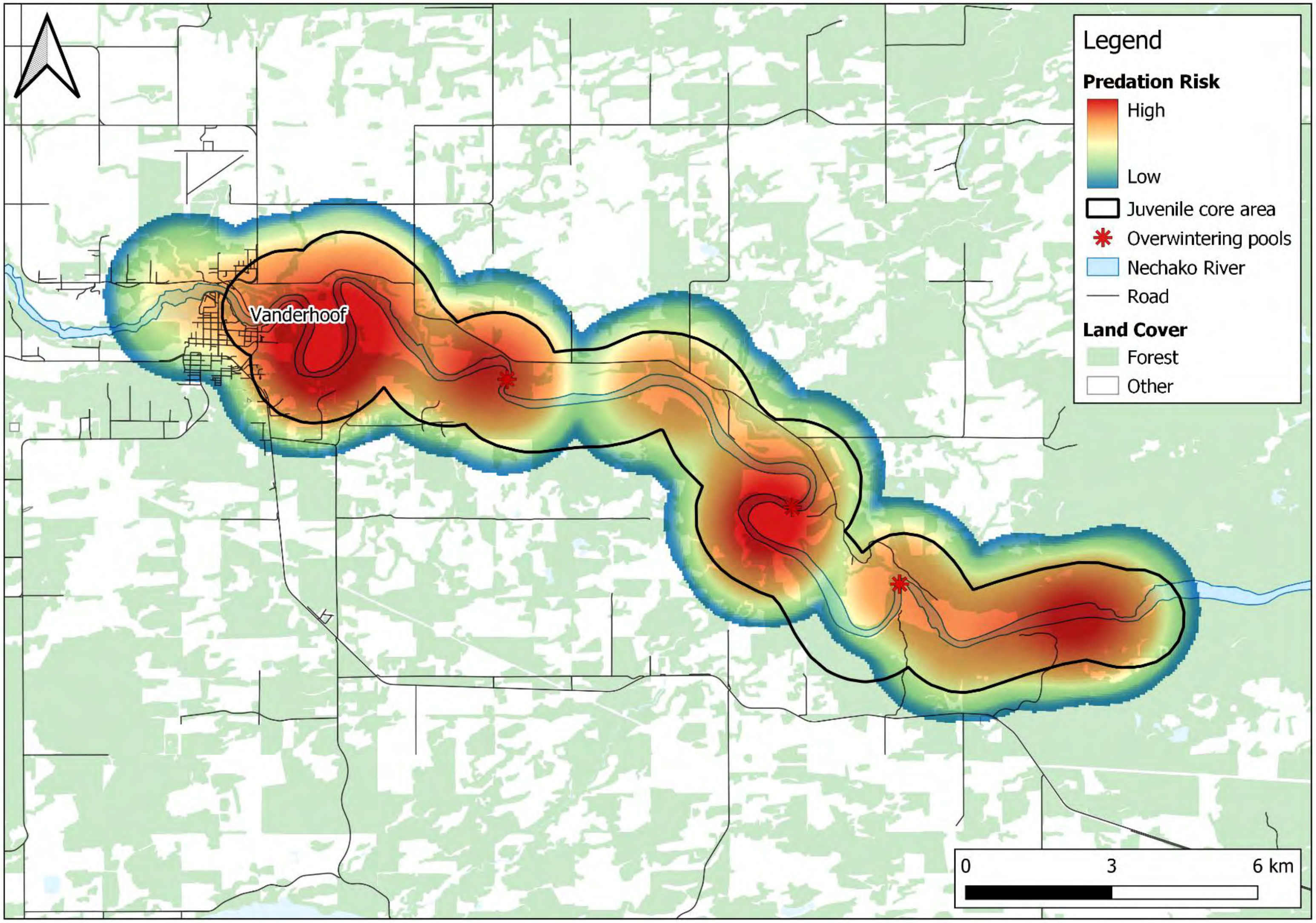

Figure 8. The 30-km core area (1-km buffer) and locations of 3 known overwintering pools for juvenile White Sturgeon in the Nechako River, overlayed with river otter predation risk.

American Mink

American mink are semiaquatic across their native and introduced range, and unlike sympatric river otter, mink are dietary generalists and opportunistic (Hatler 1976; Ben-David et al. 1996, 1997; Hoffman et al. 2009; Schooley et al. 2012). Mink consume a variety of prey from terrestrial and aquatic sources, including fish, mammals, amphibians, birds, and crustaceans (Ferreras and Macdonald 1999; Bonesi et al. 2004; Dunstone and Gorman 2007). In north-central BC, mink have the broadest ecological niche of all sympatric Mustelidae (Breault et al. 2021). Mink overlap considerably in dietary niche with semi-aquatic river otter, as well as terrestrial marten and short-tailed weasel (Breault et al. 2021). Relative to other sympatric mesocarnivores, mink likely experience the greatest competition for resources and thus exhibit several adaptive resource-use strategies, including intersexual niche partitioning, that allow for coexistence with more specialized species (Gilbert and Nancekivell 1982; Lodé 1993; Macdonald and Harrington 2003). Mink were ranked as Moderate-risk due to their generalist diets that include both terrestrial and aquatic prey items, as well as their high degree of temporal overlap with Nechako White Sturgeon (Table 1; Ferreras and Macdonald 1999; Bonesi et al. 2004; Dunstone and Gorman 2007).

Mink are thought to be outcompeted for aquatic resources by river otter, due to the larger body size and greater swimming abilities of river otter (Bonesi et al. 2004). Mink are relatively inefficient swimmers with small surface area of feet, reduced anterior propulsion relative to river otter, and low oxygen storage capacity (Ben-David et al. 1997). Mink lack webbing on their feet that would aid in propulsion underwater (Dunstone and Gorman 2007), and they have lower density of guard hair than otter which limits thermoregulation in cold water (Dunstone and O’Connor 1979). Mink have an average diving depth of 0.45 m, an average dive duration of 10.9

s, and maximum swimming speed of 0.75 m/s (Williams 1983; Bagniewska et al. 2015). Therefore, the maximum swimming speed of mink is 1.3 times faster than the critical swimming speed of juvenile White Sturgeon (Williams 1983; Counihan and Frost 1999). Further, the vision of mink underwater is reduced relative to their vision in air (Poole and Dunstone 1976). Swimming speed is positively correlated with fish size; therefore, mink are more successful at capturing smaller fish that are typically slower than larger fish (Poole and Dunstone 1976). Both mink and river otter have been found to commonly predate species of Salmonidae, mostly in the parr stages (<10 cm length; Table 4; Bonesi et al. 2004).

In riparian habitats where river otter and mink co-occur, river otter target larger fish (30–40 cm) than mink, which subsist on smaller species and juvenile salmonids (Table 4; Erlinge 1972). Both mink and otter appear to target medium-sized fish (10–15 cm); however, otter predate larger fish (>15 cm) and reject smaller fish (<5 cm) while mink do the opposite (Bueno 1996). Both species exploit pike and burbot; however, mink take only smaller pike (<20 cm) while otter can capture larger specimens (>20 cm). Among cyprinids, larger specimens (>15 cm) were captured by otter and no specimens >15 cm were captured by mink (Table 4; Erlinge 1972).

However, mink are capable of capturing larger fish occasionally, namely eels (*Anguilla anguilla*; Bueno 1996), and are able to capture small fish in loose schools, including juvenile salmonids (Table 4; Poole and Dunstone 1976; Ben-David et al. 1997). In coastal areas of British Columbia, mink consume adult Dolly Varden (*Salvelinus malma*) in early summer (<30 cm length; COSEWIC 2010), spawning pink, chum, and coho salmon in summer and autumn, and emerging juvenile salmonids in spring (Ben-David et al. 1997). Juvenile salmonids vary in length but are typically <6 cm fork length at time of emergence (Cogliati et al. 2018). Therefore, mink are most likely to capture White Sturgeon between 1–30 cm length (Table 3).

Mink and otter share several adaptations for capturing and consuming fish with hard body parts or sharp defenses. Mink have sharp carnassial teeth and claws for capturing and fragmenting prey (Banfield 1974; Harris and Yalden 2008; Hatler et al. 2008). Mink capture their prey in their mouth by biting the fish behind the head, on the head or on the tail, occasionally using their paws to manipulate the fish (Poole and Dunstone 1976). Similar to otter, mink remove captured prey from the water and devour fish on land immediately after capture (Poole and Dunstone 1976). In northeastern Alberta, Brook Stickleback (*Culaea inconstans*) were the most common aquatic prey item in diets of mink and otter (Gilbert and Nancekivell 1982). Brook Sticklebacks are usually only a minor diet item for most predators due to their protective spines and hard plates (Winn 1960). Mink are also known to consume prey much larger than themselves, causing declines in several species of terns and gulls in coastal areas where mink are invasive (Macdonald and Harrington 2003). Therefore, mink are likely not deterred by the sharp scutes of juvenile sturgeon <30 cm in length.

Mink can shift back and forth between aquatic and terrestrial diets in response to many factors, including temporal changes in prey abundance and availability, as well as competition (Bonesi et al. 2004). A study of competition between Eurasian river otter and invasive American mink in Britain found that at higher otter densities, the diet of mink included more terrestrial prey and fewer aquatic prey relative to times of lower otter density (Bonesi et al. 2004). Mink shifted diet from eating primarily fish, including eels, when eel abundance was high, to eating mostly small mammals when eel abundance decreased (Bonesi et al. 2004). Therefore, mink appear to capture fish based on the most abundant size without selecting for specific sizes (Bueno 1996).

Available cover for prey is the most important factor affecting predation success of diving mink (Dunstone and O'Connor 1979). Mink spend 18–30% of the duration of foraging activities diving below the water surface (Hatler 1976; Ben-David et al. 1996). Mink spend 5–20 s underwater at one time, locating prey from above the surface prior to entering (Poole and Dunstone 1976). Smaller fish in loose shoals are more vulnerable to capture by mink, compared to larger fish and highly organized shoals (Poole and Dunstone 1976). Mink are more likely to capture slow-moving, less active fish compared to fish that spend more time actively swimming (Poole and Dunstone 1976).

Mink detect fish before entering the water and are able to fatigue prey using long pursuit times (Poole and Dunstone 1976). The distance at which mink are detected by fish is negatively correlated with probability of capture (Poole and Dunstone 1976). Therefore, shorter distances of detection and longer pursuit times increase the probability of capture by mink (Poole and Dunstone 1976). Larger fish swim more rapidly, therefore mink are more successful at capturing smaller fish (Poole and Dunstone 1976).

Mink and otter have been shown to segregate spatially on the landscape, as well as utilize the same areas at different times (Erlinge 1972). Mink are associated with riparian forests (Hodder 2016; Hodder et al. 2017, 2018) and have linear home ranges between 2.7–3.0 river-km. Mink can travel 532–732 m daily, with greatest daily movement distances of 3.1 km (Haan and Halbrook 2015). However, mink are capable of moving longer distances (3–7 km) in search of important food sources (Ben-David et al. 1997). There was no overlap between mink occurrences and the 30-km Nechako core area, and no mink were detected on remote cameras installed at river otter latrine sites (Fig 7; C. Babey, pers. comm. 2021).

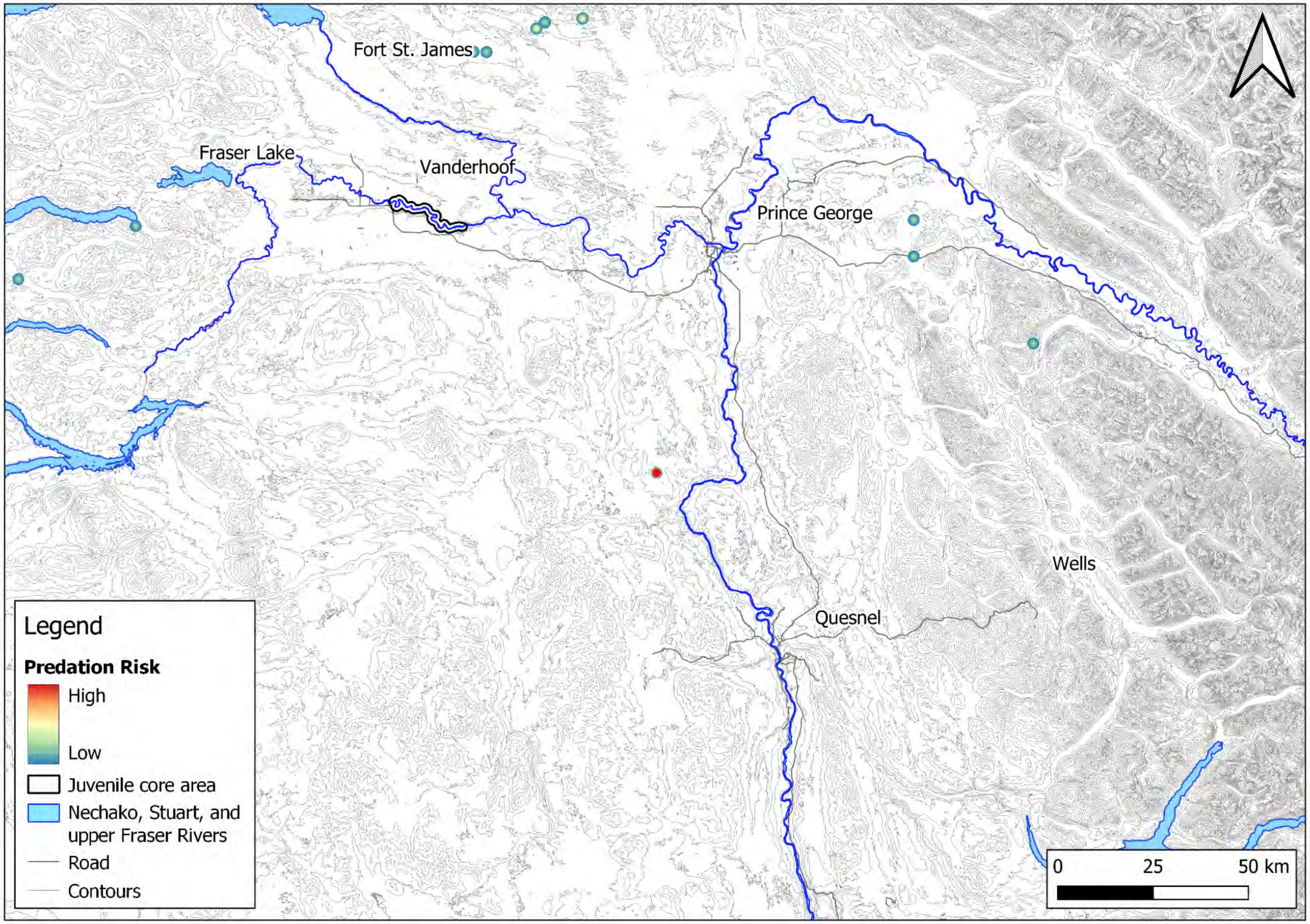

Figure 9. The 30-km core area (1-km buffer), the Nechako River, Stuart River, and mid and upper Fraser River, overlayed with mink predation risk.

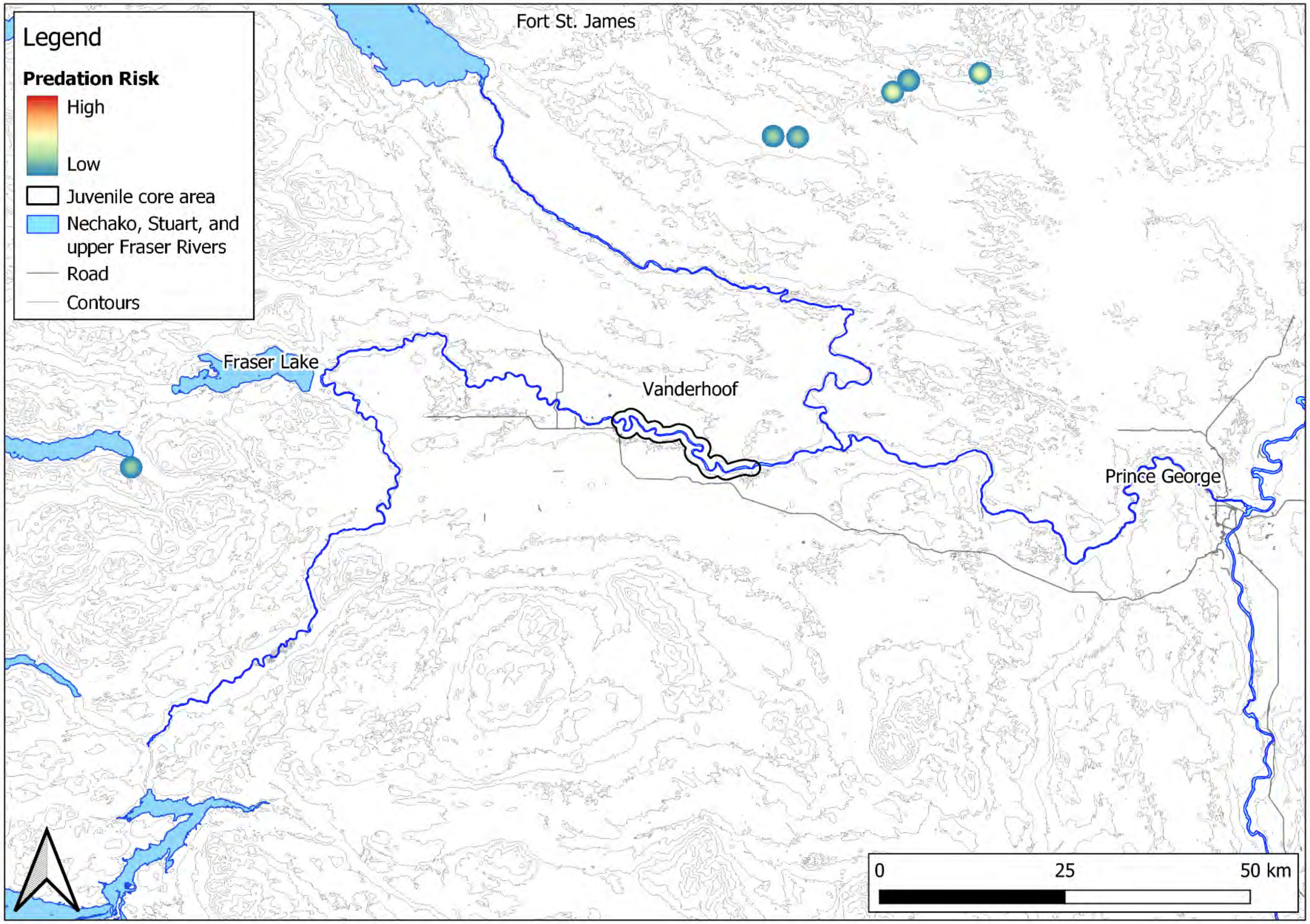

Figure 10. The 30-km core area (1-km buffer), Nechako River, and Stuart River, overlayed with mink predation risk.

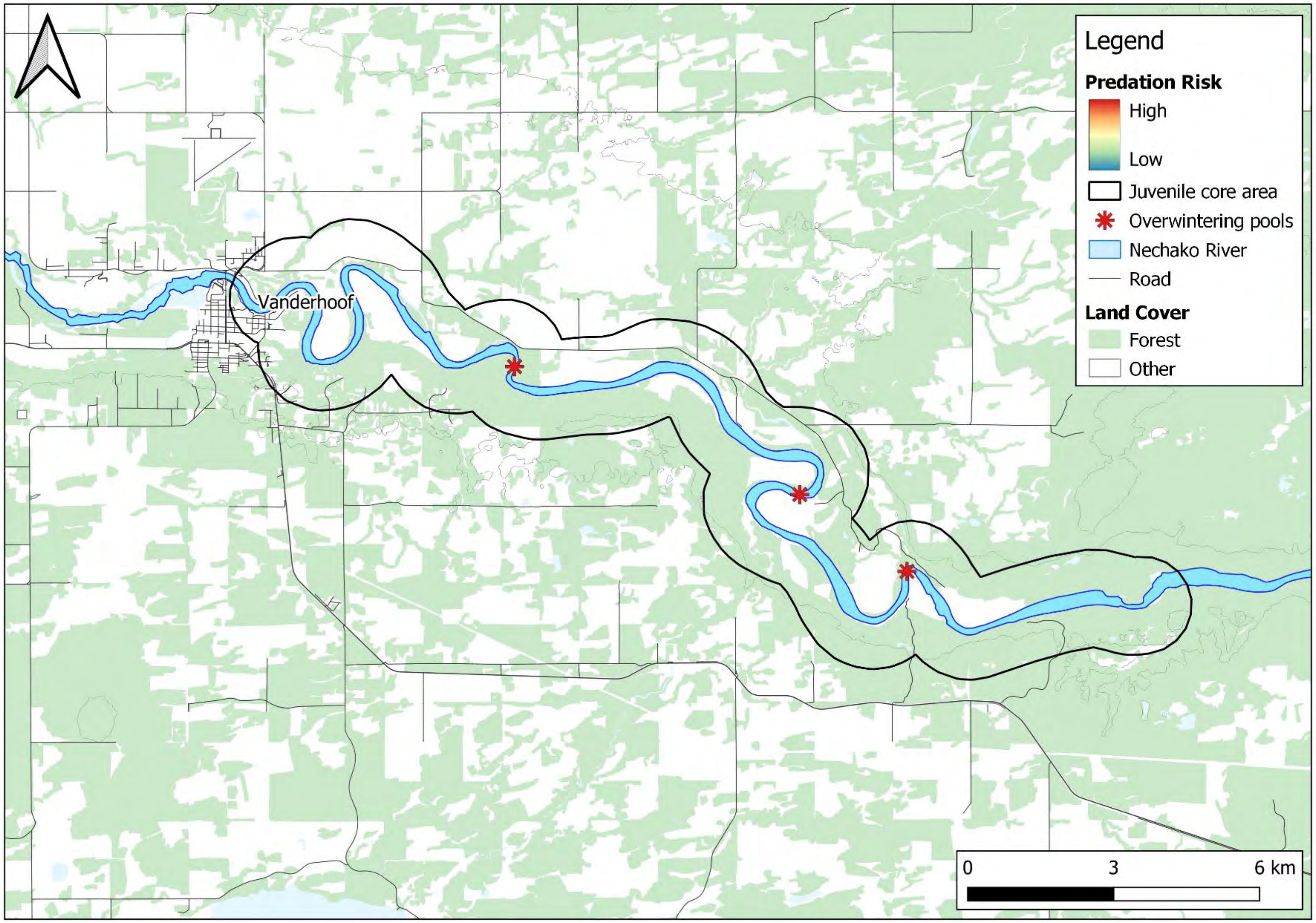

Figure 11. The 30-km core area (1-km buffer) and locations of 3 known overwintering pools for juvenile White Sturgeon in the Nechako River, overlayed with mink predation risk.

Avian Predators

Bald Eagle

In British Columbia, Bald Eagle populations increased dramatically between 1970 and 2000, due to hunting restrictions and regulation of environmental contaminants (Elliott et al. 2011). Populations of eagles now appear to be stable at or near carrying capacity in BC. Bald Eagles in the Pacific northwest of North America migrate during the fall from Alaska through BC south to northern Washington following salmon spawning patterns (Elliott et al. 2011). Thus, populations of eagles are likely most abundant in BC during October–January (Table 5). Bald Eagles are opportunistic, generalist predators, and their diet reflects the local abundance of the most available prey items (Thompson et al. 2005; Hanson and Baldwin 2017; Buehler 2020). Population increases of generalist predators can sometimes negatively impact the abundance of rare prey species (Reid et al. 2000; Roemer et al. 2001; Elliott 2006). In most regions of North America, Bald Eagles consume mostly fish (56–90%), whereas in areas with abundant small mammals, reptiles, or waterfowl, these prey items are consumed in greater proportions (Dunstan and Harper 1975; Stalmaster 1987; Mabie et al. 1995; Hanson and Baldwin 2017). Bald Eagles in BC primarily eat fish throughout the year, and in coastal areas Bald Eagles switch to eating mostly birds (waterfowl and gulls) during winter (Elliott et al. 2011).

Bald Eagles in Texas consume Carp (*Cyprinus carpio*), Crappie (*Pomoxis* spp.), Largemouth Bass (*Micropterus salmoides*), Gar (*Lepisosteus* spp.), Gizzard Shad (*Polydactylus cepedianom*), and Striped Bass (*Morone saxatilis*; Mabie et al. 1995). Bald Eagles in north-central Minnesota eat mostly Bullheads (*Ictalurus nebulosus, I. natalis,* and *I. melas*), Suckers (*Catostomus commersoni, Moxostoma macrolepidotum*), Northern Pike (*Esox Lucius*) under 1,400 g, as well as Largemouth and Rock Bass (Table 4; Dunstan and Harper 1975). Muskrat also comprise a small proportion of eagle diet in Minnesota (Dunstan and Harper 1975). In

Arizona, the minimum length of benthic-feeding fish prey is 12.8 cm, and the maximum length is 47.6. cm, with mean length between 24.2–31.3 cm (Table 4; Haywood and Ohmart 1986). Minimum weight is 29 g and maximum weight is 1,492 g, with mean weight between 263–636 g (Haywood and Ohmart 1986). Of the major prey species, 76% of 245 fish retrieved are between 200–350 mm in standard length (Table 4; Haywood and Ohmart 1986). Further, the carcass of a Nechako White Sturgeon of 69 cm length was located below a suspected Bald Eagle nest (FLNRORD unpublished). Therefore, risk of predation by Bald Eagles is likely greatest for juvenile White Sturgeon between 10–70 cm length (Table 3).

Foraging activity of Bald Eagles peaks between 1–4 hours after sunrise and between 8–10 hours after sunrise (Haywood and Ohmart 1986). Bald eagles nest within 1.6 km of permanent water and spend most of their time foraging in streams close to the nest (Anthony and Isaacs 1989). In Minnesota, suckers were caught alive during spring spawning or dead from lakes during summer and Northern Pike were captured in shallow creeks while spawning in late-April (Dunstan and Harper 1975). On rivers in Arizona, eagles captured fish alive as they spawned or foraged in shallow water, whereas in reservoirs, most fish were obtained as carrion (Hunt et al. 2002). Suckers were the most common prey for nesting Bald Eagles in free-flowing reaches of relatively low temperature downstream from cold-water dam releases (Hunt et al. 2002). Most suckers were alive when captured, mainly in riffles while spawning or foraging, and the majority of strike points of live suckers were in water <30 cm depth. The mean depth at strike points was 16.4 cm (Hunt et al. 2002). Similarly, carp were caught in shallows of runs or riffles, mostly in water <36 cm depth (Hunt et al. 2002). Most catfish were obtained as carrion from reservoirs; however, of the limited number caught alive in rivers, most were caught in pocket water rather than riffles, and the mean depth of capture was 58 cm (Hunt et al. 2002).

Along the lower Hudson River in New York, unvegetated tidal mudflats isolated from intensive human activity were the highest quality foraging habitat for Bald Eagles (Thompson et al. 2005). Kernel density estimation indicated that predation risk from Bald Eagle was high within the Nechako juvenile White Sturgeon core area (Fig. 8) and were most commonly observed surrounding populated areas (Fig. 9).

Bald Eagles in inland areas prey mostly on benthic-feeding fishes, including catfish, suckers, and carp, regardless of differences in habitat types and climatic regions (Dunstan and Harper 1975; Todd et al. 1982; Haywood and Ohmart 1986; Hunt et al. 2002). There appears to be a strong relationship between river-bottom profile and acquisition of benthic-feeding fish by Bald Eagles (Haywood and Ohmart 1986). Hourly fluctuations in river flows have been shown to influence habitat use, prey capture, and foraging success among Bald Eagles (Brown et al. 1998). Foraging in river, shore, and isolated pool habitats decreased to 0% at high flows, whereas foraging in adjacent creek habitat increased to 100% (Brown et al. 1998). As river flows increased, more foraging took place farther from the river in adjacent creek habitat. Rainbow Trout stranded by fluctuating river flows comprised 12–19% of eagle captures. Foraging success rates decreased from 74% to 39% as river flows increased (Brown et al. 1998). High river flows reduce surface visibility and may decrease foraging success of Bald Eagles (Machmer and Ydenberg 1990).

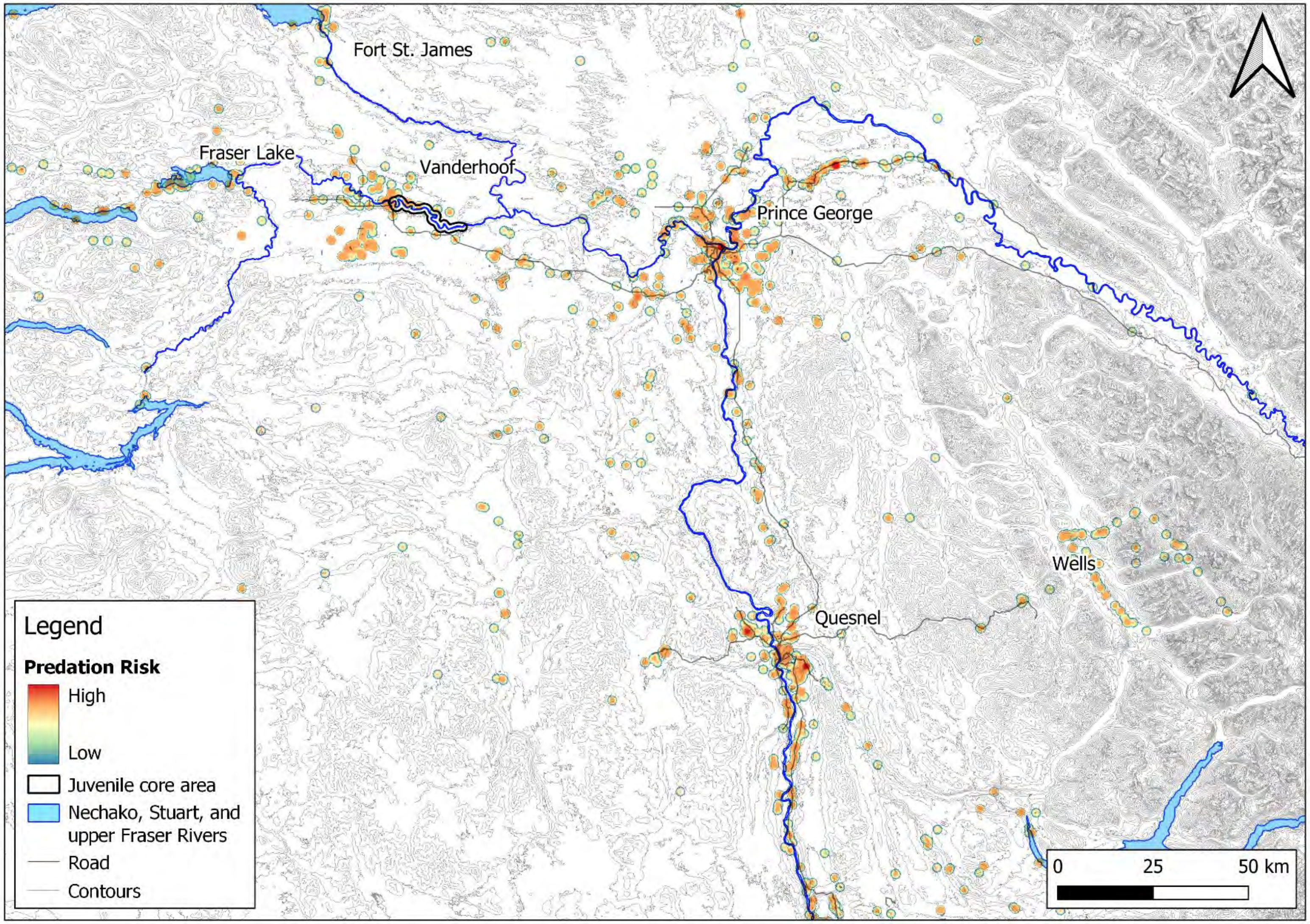

Figure 12. The 30-km core area (1-km buffer), Nechako River, Stuart River, and mid and upper Fraser River, overlayed with Bald Eagle predation risk.

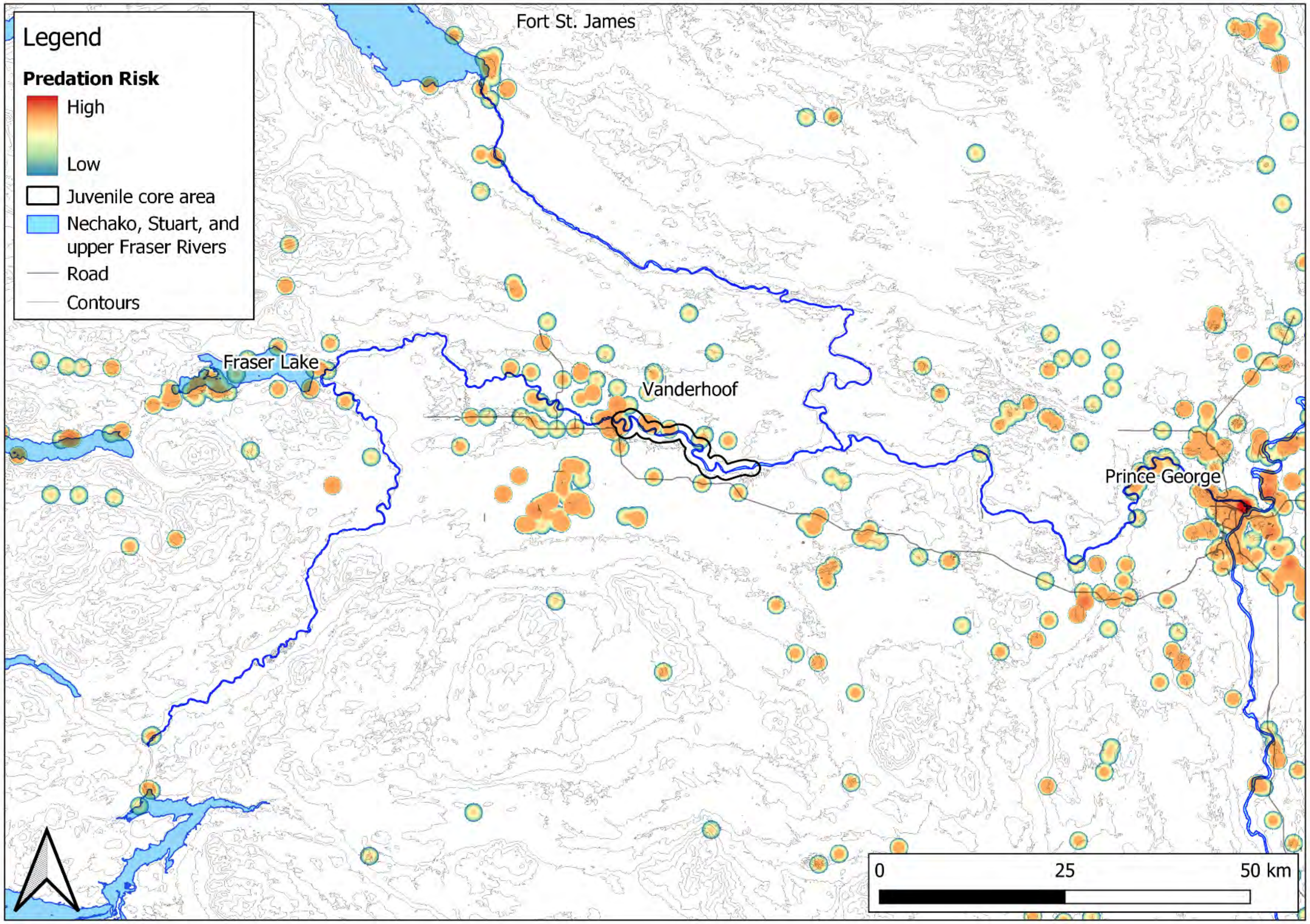

Figure 13. The 30-km core area (1-km buffer), Nechako River, and Stuart River, overlayed with Bald Eagle predation risk.

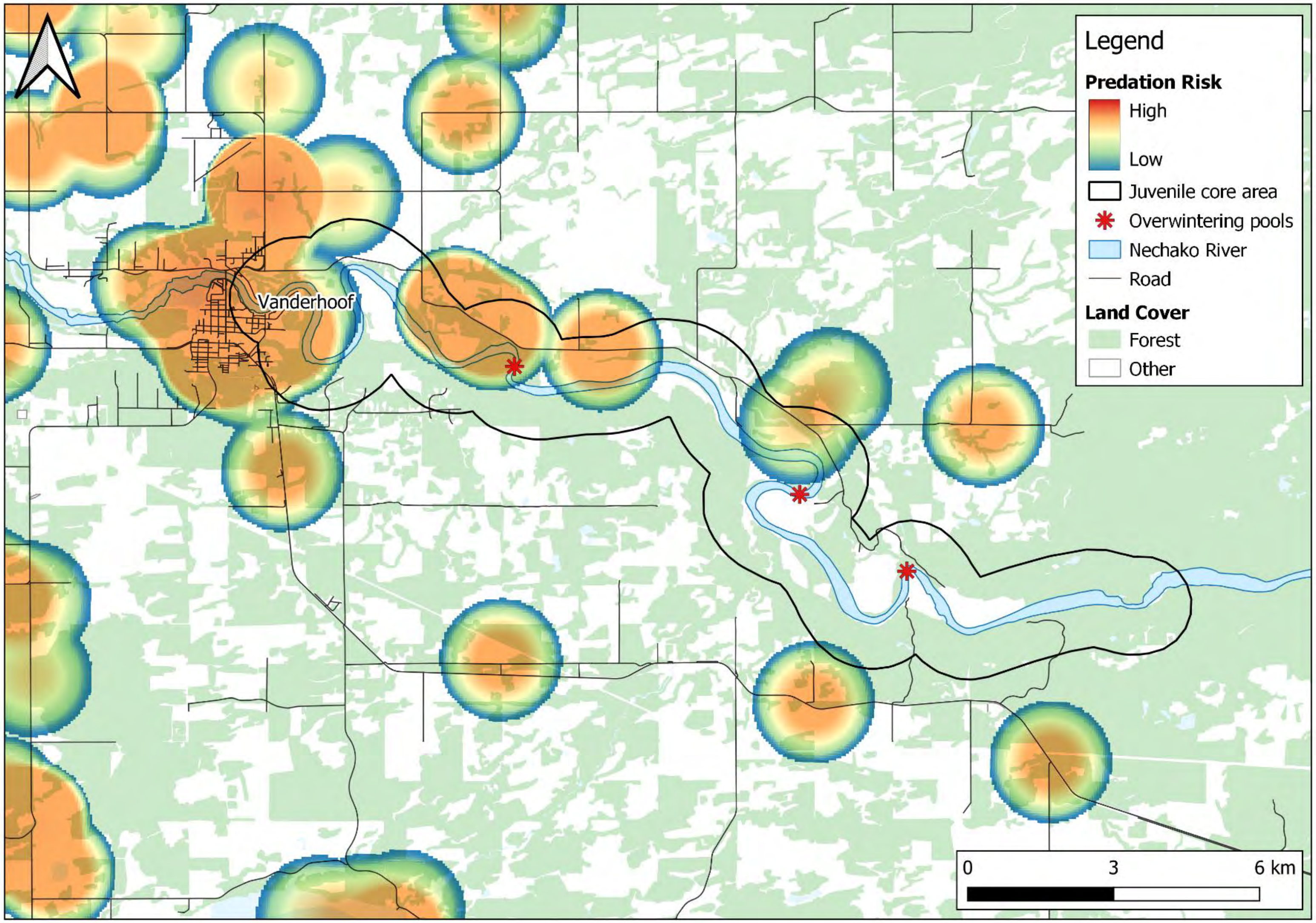

Figure 14. The 30-km core area (1-km buffer) and locations of 3 known overwintering pools for juvenile White Sturgeon in the Nechako River, overlayed with Bald Eagle predation risk.

Osprey

In North America, Osprey breed across Canada, the northwestern United States, and along the Atlantic coast. Osprey in Florida are non-migratory, whereas all other North American populations overwinter in the Caribbean, as well as Central and South America (Henny and Velzen 1972; Henny 1986; Mitchell and Wolters 2000). Osprey arrive at summer breeding locations in northern North America between March and April and depart for overwintering areas between August and September (Table 5; Bedrosian et al. 2015). Eggs are laid in April and incubate for 36–42 days and hatch between June and July (Steeger et al. 1992). Summer home ranges for adult Osprey show considerable variability by sex and year of nesting; however, the mean home range of nesting adults is 1.76 km^2 (Bedrosian et al. 2015). Osprey will fly up to 10 km from their nest to fish (Van Daele and Van Daele 1982).

Inland nesting occurs in riparian areas primarily in the tops of snags or live trees with dead crowns, as well as human-made posts and platforms (Henny 1986). Nesting platforms constructed by humans are immediately occupied by Osprey pairs (Steeger et al. 1992). Osprey in southeastern BC nest on broken tops and dead trunks of tall black cottonwood and Douglas-fir, as well as on human-made structures, including pilings, power poles, and bridges (Steeger et al. 1992). In southwestern Chesapeake Bay, Virginia, Osprey nest between 25–125 m from the shore (McLean and Byrd 1991).

An adult Osprey may consume 200–400 g of fish per day, or 1–4 fish per day depending on the size of the fish (Henny 1986). A pair with 2 young will consume up to 170 kg of fish during a breeding season (Henny 1986). Following capture, male Osprey will deliver prey to the nest for their own consumption or consumption by family (Clancy 2005). During the nesting period (April–July; Steeger et al. 1992; Green and Krebs 1995), males provision all food for females on the nest (Stinson et al. 1987; McLean and Byrd 1991; Green and Krebs 1995). The rate of fish delivery increases with the number of hatchlings as well as with energy demands as the time since incubation increases (Levenson 1976; Van Daele and Van Daele 1982). Across northern California and Idaho, males deliver between 0.20–0.68 fish/hour to nests (Levenson 1976, 1979; Van Daele and Van Daele 1982; McLean and Byrd 1991). Most deliveries occur during the morning (0800–1000) and late-afternoon and early evening (1600–2000; Van Daele and Van Daele 1982).

Osprey in the western Mediterranean consume mostly Mullet with mean length 29.7 cm (range = 22.5–41.0 cm; Table 4; Francour and Thibault 1996). Mean size of Common Carp captured by Osprey in the Canarian archipelago is 25.9 cm length (range = 21.5–32.3 cm), and weigh 223.3 g (range = 147.4–329.3 g; Siverio et al. 2011). Osprey are likely limited to mostly prey <400 g, or 30% of the body weight of adult male osprey; however, 15% of prey recorded weigh >400 g (Francour and Thibault 1996). Osprey in Finland showed preference for hatchery-reared Rainbow Trout (*Salmo gairdneri*). Mean length of prey fish was 24–36 cm and mean weight was 150–350 g. The smallest fishes caught by Osprey were roach and perch 10–15 cm length (Table 4). The largest prey items were pike 57 cm length (1.3 kg) and a bream of 48 cm length (1.2 kg; Hakkinen 1978). Therefore, Osprey appear to efficiently capture prey which weigh 200–400 g (Hakkinen 1978). Osprey in New South Whales captured Mullet between 25.0–45.0 cm in length and most fish were captured alive rather than scavenged (Clancy 2005).

In Virginia, Osprey captured fish that were 10.2–42.9 cm in length (mean = 23.7 cm), and weighed 10.2–850.0 g (mean = 239.8 g; Glass and Watts 2009). Further, there is one report of the probable predation of a 51.2 cm total length Atlantic Sturgeon (*Acipenser oxyrinchus*), by Osprey in Virginia (Table 4; Hilton and McGrath 2021). The sturgeon carcass was probably carried 120 m inland from the shoreline of the river before being dropped. An anecdotal account exists of Osprey drowning following the capture of a fish, such as a sturgeon, too large to lift (Forbush 1927). In Idaho, fishes between 0–10 cm length constitute 3.3% of Osprey diet, fishes between 11–20 cm length constitute 42.1% of diet, fishes between 21–30 cm length constitute 46.7% of diet, fishes between 31–40 cm length constitute 6.6% of diet, and fishes >41 cm length constitute 1.3% of diet (Table 4; Van Daele and Van Daele 1982). Therefore, Osprey are most likely to capture Nechako White Sturgeon between 10–50 cm length (Table 3).

In southeastern BC, Osprey captured Black Bullhead (*Ictalurus melas*), Yellow Perch (*Perca flavescens*), Pumpkinseed (*Lepomis gibbosus*), Mountain Whitefish, Kokanee, Rainbow Trout, Longnose Sucker, and Largescale Sucker (Table 4; Steeger et al. 1992). Mean weight of fish captured varied by location and habitat and was between 274–767 g (Steeger et al. 1992). Osprey consume fish starting at the head, remove the operculum bones, viscera, large and sharp fins, spines, and other bones (Clancy 2005).

Capture rates among fish prey likely result from variation in vulnerability to predation, rather than prey selection by Osprey (Van Daele and Van Daele 1982). It is easier for Osprey to capture benthic-feeding fishes and non-piscivorous limnetic-feeding fishes compared to fishes that are piscivorous and limnetic-feeding, as measured by dive success rates (Swenson 1979). Benthic-feeding fishes may be limited in their ability to perceive attacks from above, and non-piscivorous fishes have slower swimming speeds and tend to be smaller compared to predatory fishes (Swenson 1979).

In a reservoir in Idaho, bullheads are the most frequently captured fish species, likely because they rest near the surface of the reservoir on warm days and show less predator avoidance (Van Daele and Van Daele 1982). Osprey increase capture of Northern Pikeminnow when the reservoir water level is low, likely because Northern Pikeminnow spawn in shallow areas where they are more vulnerable to predators during low water levels (Van Daele and Van Daele 1982). Osprey nest productivity significantly increases with decreased water levels and corresponding increased prey availability (Van Daele and Van Daele 1982). Males spend more time away from nests and catch fewer fish when water levels are high (mean depth = 7.6 m; Van Daele and Van Daele 1982). Generally, osprey are not adapted for catching prey >1 m depth; therefore, it is not surprising that low water levels would increase prey availability. However, caution should be used when making inferences from reservoirs to flowing systems such as the Nechako and Fraser Rivers.

Factors that affect foraging efficiency include reduced prey abundance and increased water turbidity or turbulence (Francour and Thibault 1996; Clancy 2005). Hunting is either by flying or by perching; perching is less energetically costly and results in greater hunting success compared to flight-hunting (Steeger et al. 1992). Wind speed and water surface conditions have the strongest effect on hunting behavior among male Osprey, compared to cloud cover, sun brightness, and precipitation (Machmer and Ydenberg 1990). As wind speed increases and the surface conditions of the water become less favorable, Osprey are less likely to capture fish (Machmer and Ydenberg 1990). Further, the duration of hunting trips may increase with increasingly gusty winds (Stinson et al. 1987). The importance of surface visibility in terms of turbulence has been demonstrated for Osprey and Bald Eagles (Machmer and Ydenberg 1990). Scavenging is more likely following floods which increase turbidity and reduce hunting efficiency (Clancy 2005).

Density of Osprey observations is sparse; however, predation risk is high in Vanderhoof and overlaps with the Nechako juvenile White Sturgeon core area (Fig. 10; Fig. 11). Osprey were ranked as High risk due to evidence of probable Osprey predation of a relatively large (51 cm total length) Atlantic Sturgeon (Hilton and McGrath 2021). Furthermore, Osprey are entirely piscivorous, and adult Osprey may consume 1–4 fish per day depending on the size of the fish (Henny 1986). A pair with 2 young will consume up to 170 kg of fish during a breeding season. Lastly, Osprey mostly consume fish between 20 and 40 cm length; therefore, juvenile Nechako White Sturgeon are vulnerable to Osprey predation for several years (Van Daele and Van Daele 1982; Glass and Watts 2009).

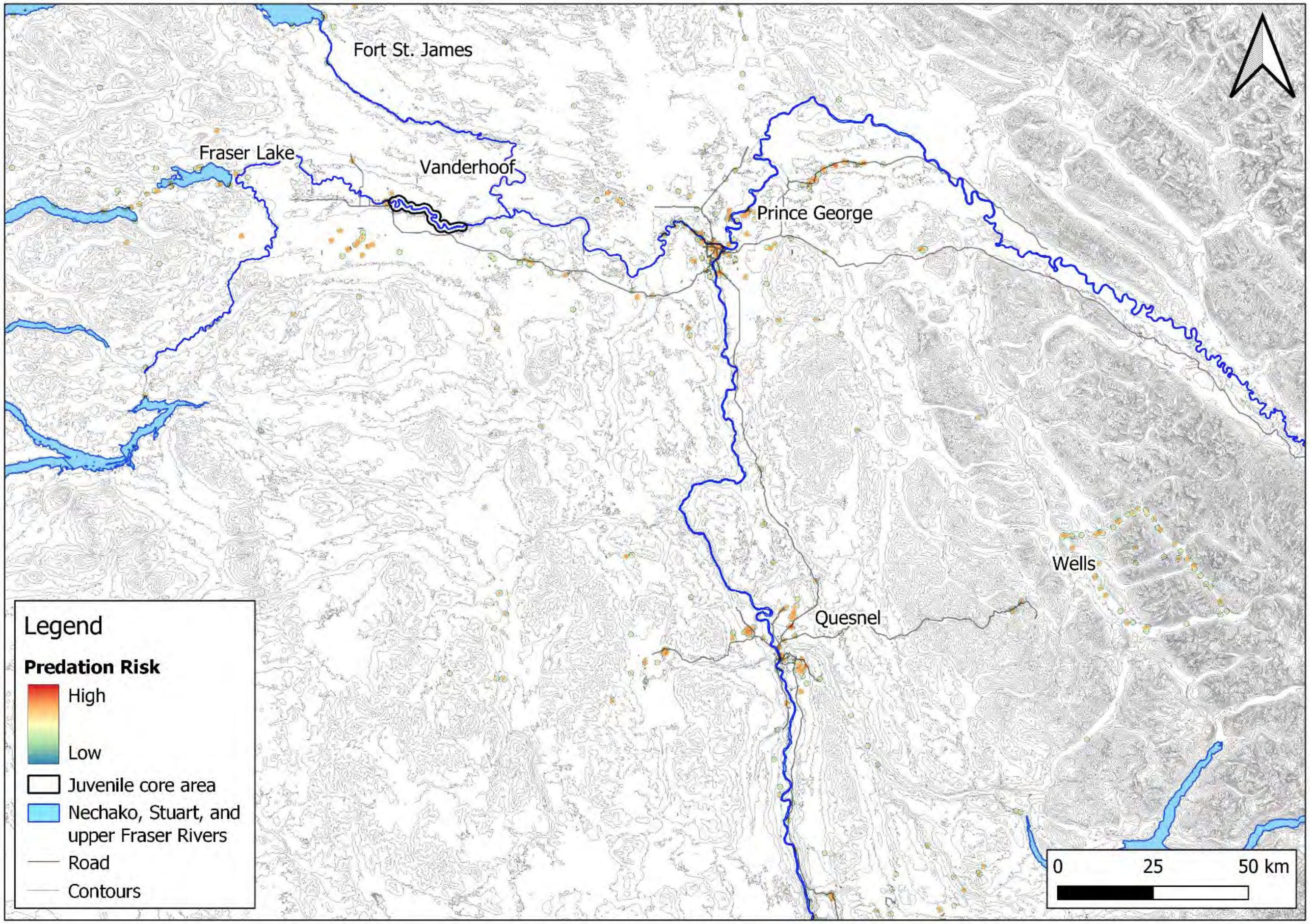

Figure 15. The 30-km core area (1-km buffer), Nechako River, Stuart River, and mid and upper Fraser River, overlayed with Osprey predation risk.

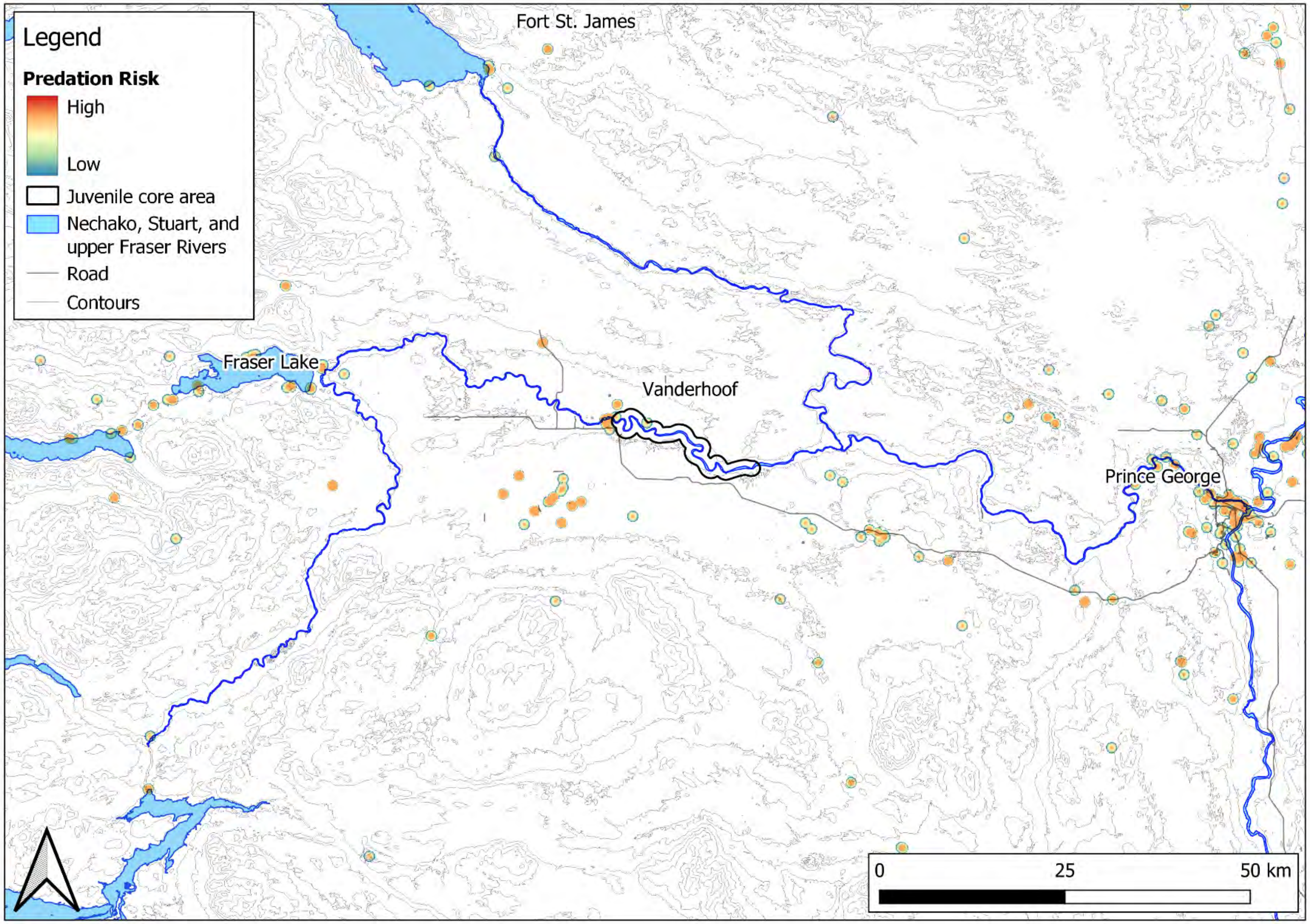

Figure 16. The 30-km core area (1-km buffer), Nechako River, and Stuart River, overlayed with Osprey predation risk.

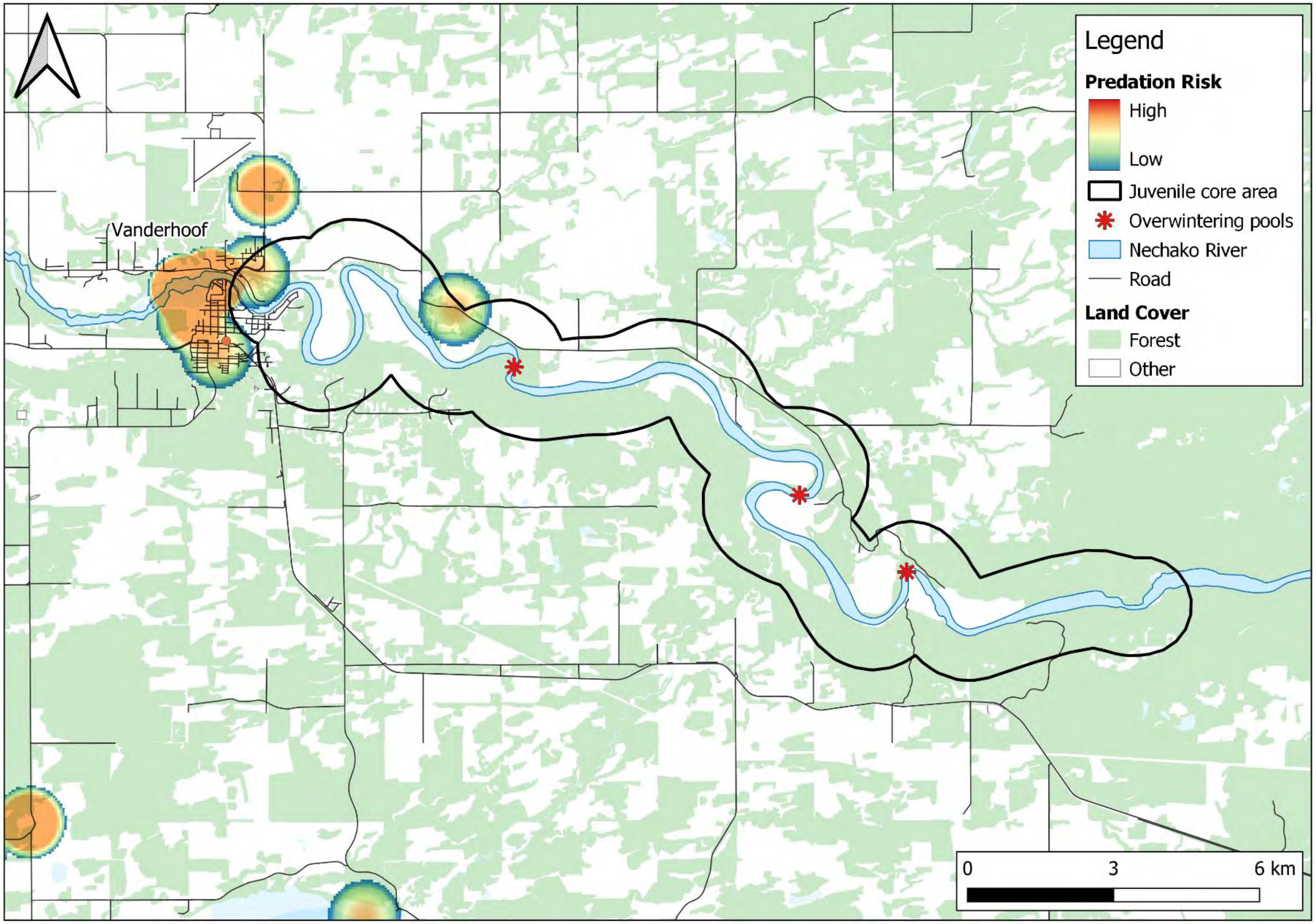

Figure 17. The 30-km core area (1-km buffer) and locations of 3 known overwintering pools for juvenile White Sturgeon in the Nechako River, overlayed with Osprey predation risk.

Great Blue Heron

Great Blue Heron nest in colonies called heronries or rookeries (2–80 nests) located in the crowns of trees (Finley 1906; Cottrille and Cottrille 1958; Gibbs 1991). Great Blue Heron overwinter along the Pacific coast and are most common in the interior of north-central BC between April–October (Table 5). Great Blue Heron forage in streams, rivers and inlets, and intermittent streams in isolated pools where fish become stranded during low flow events (Dowd and Flake 1985). Large heron colonies have greater amounts of foraging habitat within <15 km relative to smaller colonies (Gibbs 1991). The average distance flown from nest sites to foraging habitats is between 3.1–6.5 km, and the greatest distance flown is 24.4 km (Dowd and Flake 1985). In a study of Heron predation on salmon, Great Blue Heron rookeries were all within 35 km of large rivers where salmon spawned annually (Sherker 2020). Due to there large home ranges, there is significant overlap between High-risk Great Blue Heron areas and the Nechako juvenile White Sturgeon core area (Fig. 12), as well as between High-risk heron areas and areas surrounding Prince George and Quesnel (Fig. 13).

Great Blue Heron in Arkansas consume mostly sculpin (*Cottus* spp.), and most prey (including shad, dace, shiners, minnows, darters, sculpin, and trout) are <14 cm length (Table 4; Hodgens et al. 2004). Most stocked Rainbow Trout that are captured by Great Blue Heron are between 10.5–28.0 cm in length (Table 4; Hodgens et al. 2004). Great Blue Heron in the northeastern United States consume farmed Brown Trout that are on average 21.6 cm total length (range = 12–38 cm; Table 4; Glahn et al. 1999). Therefore, Great Blue Heron are most likely to consume Nechako White Sturgeon between 1–38 cm length (Table 3).

Heron are opportunistic predators and are known to cause fish losses at hatcheries. Heron using trout-rearing facilities have diets consisting almost entirely of trout (96% of diet), and cause fish production losses of up to 44.8% (Glahn et al. 1999). In some systems, fish losses to piscivorous birds are greater than 50%, particularly due to Great Blue Heron among trout-rearing facilities (Hodgens et al. 2004). Losses are greater in regulated rivers relative to lakes due to reduced water volume and reduced cover due to scouring effects of water releases from dams (Hodgens et al. 2004).

Great Blue Heron energy demands peak during breeding season (March–May), and predation rates coincidingly increase during the chick-rearing phase (Sherker 2020). Timing of foraging varies with tidal influence and the study system; however, nocturnal foraging rates may be up to 63% of diurnal foraging rates in non-tidal riverine systems (McNeil et al. 1993; Hodgens et al. 2004). Therefore, nocturnal foraging activity is significant. Great Blue Heron forage by wading in shallow (<0.5 m) and slow-moving water; however, they have shown preference for depths between 10–17 cm, and <20 cm (Hodgens et al. 2004). Deeper foraging patches are less profitable than shallower patches with the same density of prey (Gawlik 2002; Hodgens et al. 2004). Small, diseased fish (fingerlings) closer to the surface are more vulnerable to heron predation compared to larger, healthy fish in deeper water (Glahn et al. 2002; Hodgens et al. 2004). Predation rates of salmon smolts are higher during low river-flow years in BC (Sherker 2020).

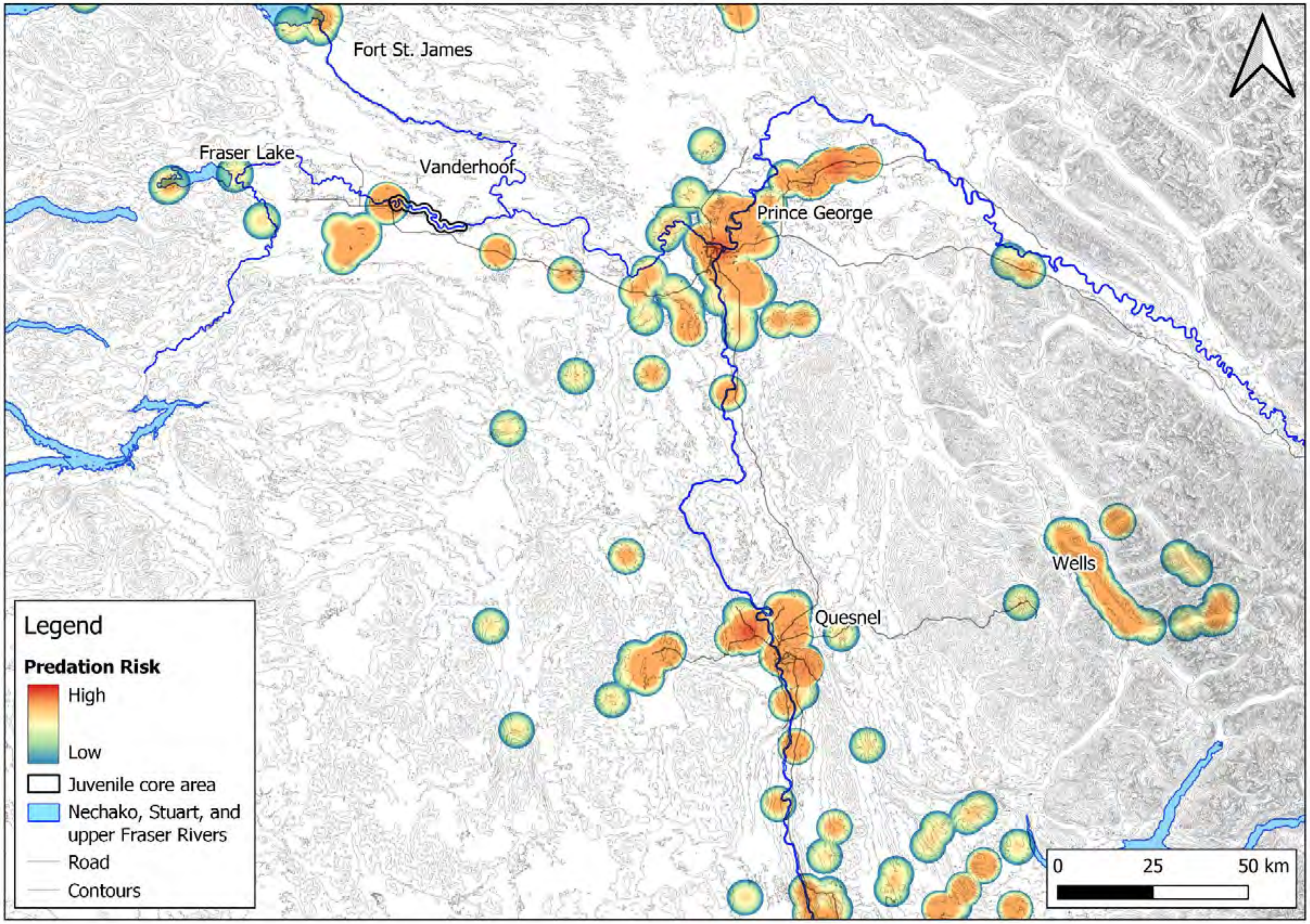

Figure 18. The 30-km core area (1-km buffer), Nechako River, Stuart River, and mid and upper Fraser River, overlayed with Great Blue Heron predation risk.

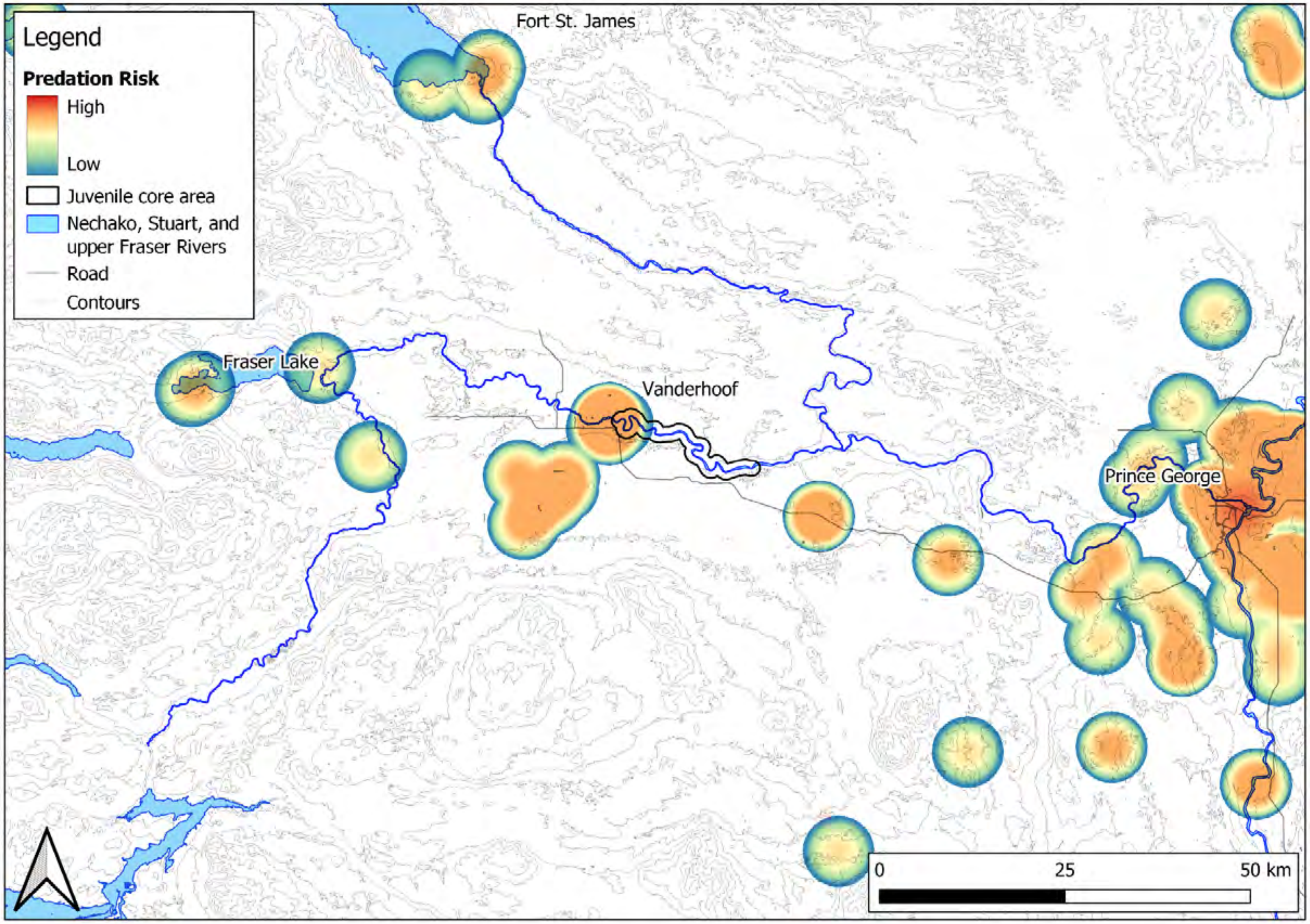

Figure 19. The 30-km core area (1-km buffer), Nechako River, and Stuart River, overlayed with Great Blue Heron predation risk.

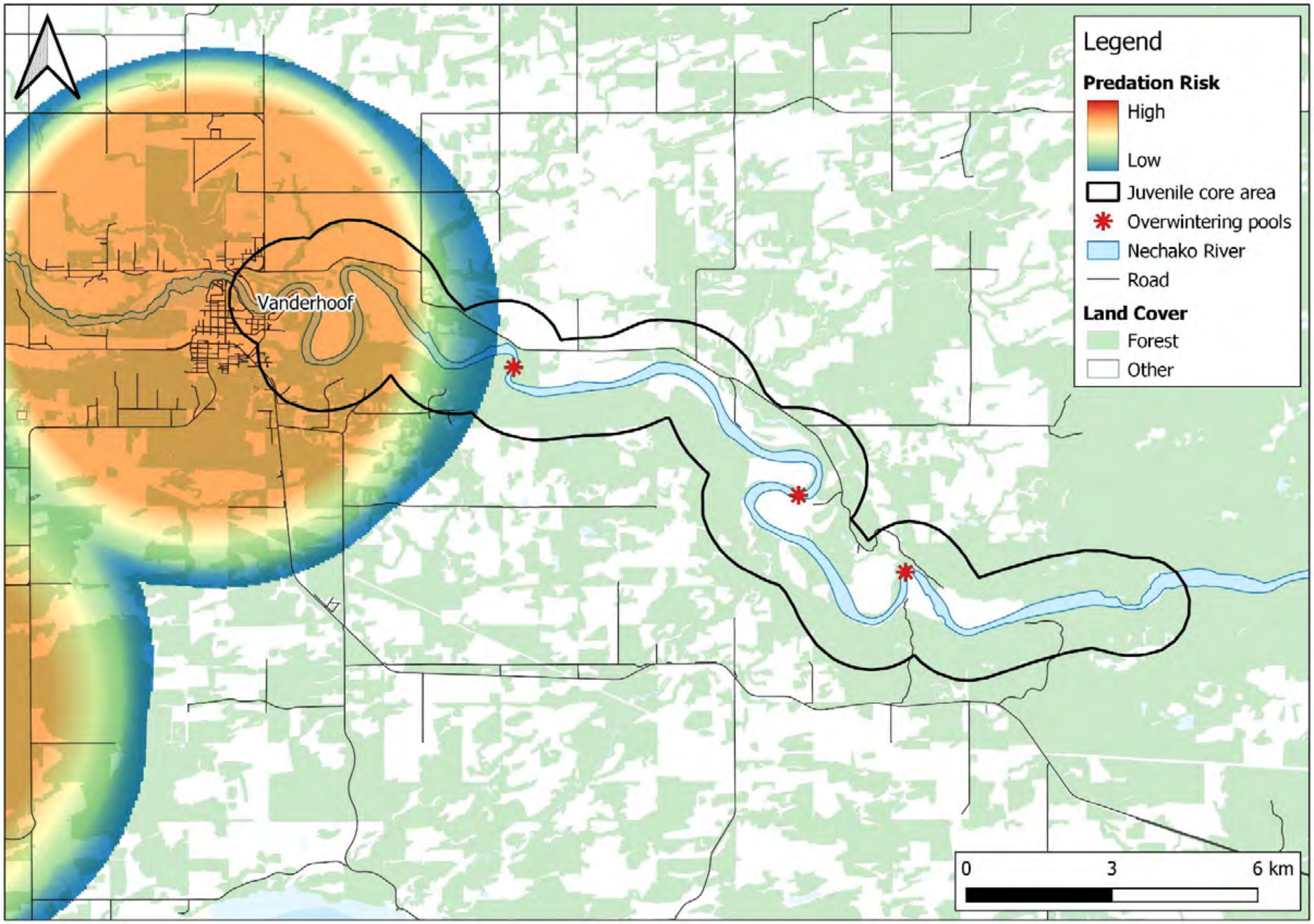

Figure 20. The 30-km core area (1-km buffer) and locations of 3 known overwintering pools for juvenile White Sturgeon in the Nechako River, overlayed with Great Blue Heron predation risk.

American White Pelican

American White Pelicans have been recorded migrating from Louisiana to prairies in southern Canada (Walter et al. 2011). Pelicans nest in BC between May and late July (Table 5), and show very strong fidelity to breeding sites (Harper 2004). American White Pelicans in North America nest on isolated lakes with islands that have relatively stable water levels, and are of sufficient distance from the mainland (>80 m) to detract mammalian predators (Dunbar 1982). A population of American White Pelicans forage at Nulki and Tachick Lake, 15 km southwest of Vanderhoof, and nesting is known to occur at Stum Lake, 70 km northwest of Williams Lake, BC (Harper 2004). Foraging trips can be >100 km from the nesting area (McMahon and Evans 1992; Harper 2004; Stinson 2016). Foraging sites between 3–142 km from nesting locations are observed for the breeding colony at Stum Lake (Dunbar 1982). Therefore, High-risk areas for American White Pelican predation overlap significantly with the Nechako juvenile White Sturgeon core area (Fig. 14). Pelican have been sighted five times on the Nechako River between 2013 and 2020, always during April (Fig. 15).

American White Pelicans are mainly piscivorous and forage in shallow, slow-moving streams, rivers, and lakes (mean depth 1–2 m) with relatively abundant prey (Dunbar 1982; Harper 2004). Feeding occurs during the day and nocturnally (McMahon and Evans 1992), primarily at the surface and in the upper metre of the water column. Foraging at the inlets and outlets of streams occurs in spring and coincides with spawning of coarse fish (Harper 2004). Pelicans spend a significant amount of time preening and resting near foraging sites, in relatively flat areas lacking vegetation that would conceal approaching predators (Dunbar 1982).

Pelicans are one of the largest birds in North America and have been heavily persecuted due to apparent impacts on game fish species (e.g., salmonids; del Hoyo et al. 1996). For example, American White Pelicans have been associated with an annual loss of 80% of stocked trout in Wyoming (Hodgens et al. 2004). However, several studies show that pelicans mostly consume non-game or coarse fish species (e.g., chub, stickleback, bullhead, carp, perch, catfish, suckers, and minnows; Dunbar 1982; Derby and Lovvorn 1997).

A study of nocturnal foraging habits of American White Pelicans found that most prey were very small (<1/4 bill length or <9 cm) or small (1/4–1/2 bill length or 9–17 cm) schooling fish, and some larger fish >1/2 bill length (>17 cm; Table 4; McMahon and Evans 1992; del Hoyo et al. 1996; Stinson 2016). However, American White Pelicans nesting at Stum Lake, BC, captured much larger fish, namely suckers (*Catastomus* spp.) and Northern Pikeminnow (*Ptychocheilus oregonensis*) between 30–40 cm length (Table 4; Dunbar 1982). Other fish prey species include minnows (*Cyprinidae – Cyprinus, Gila, Pimephales, Richardsonius, Rhinichthys, Ptychocheilus*), stickleback (*Gasterosteidae – Pungitius, Culaea*), sunfish (*Centrarchidae – Archoplites, Pomoxis*), bullhead (*Ameiurus* spp.), perch (*Percidae – Perca, Stizostedion, Etheostoma, Micropterus*), salmon, and trout <17 cm length (Table 4; Harper 2004; Stinson 2016). Therefore, pelicans are most likely to consume Nechako White sturgeon between 1–40 cm length (Table 3).

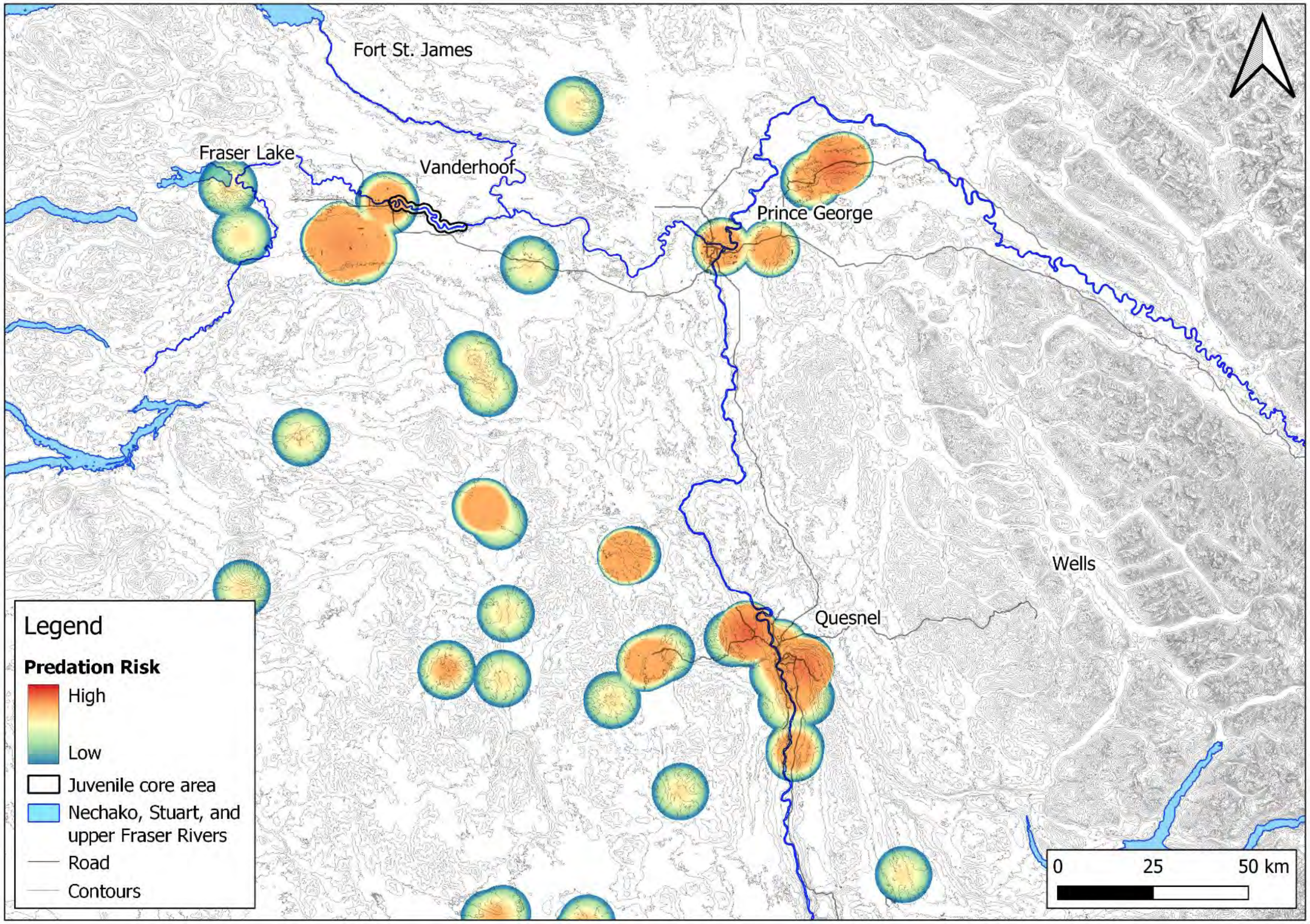

Figure 21. The 30-km core area (1-km buffer), Nechako River, Stuart River, and mid and upper Fraser River, overlayed with American White Pelican predation risk.

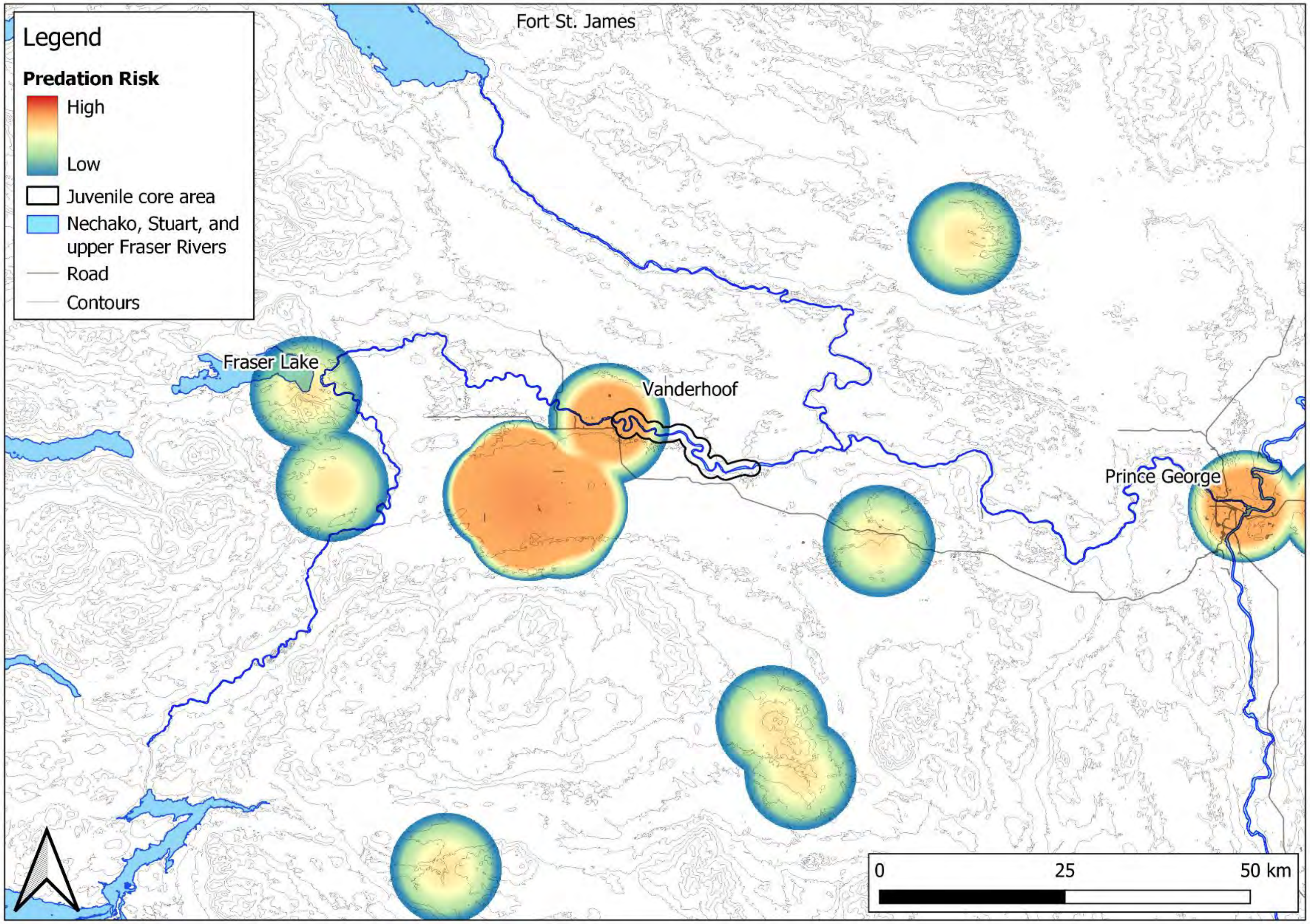

Figure 22. The 30-km core area (1-km buffer), Nechako River, and Stuart River, overlayed with American White Pelican predation risk.

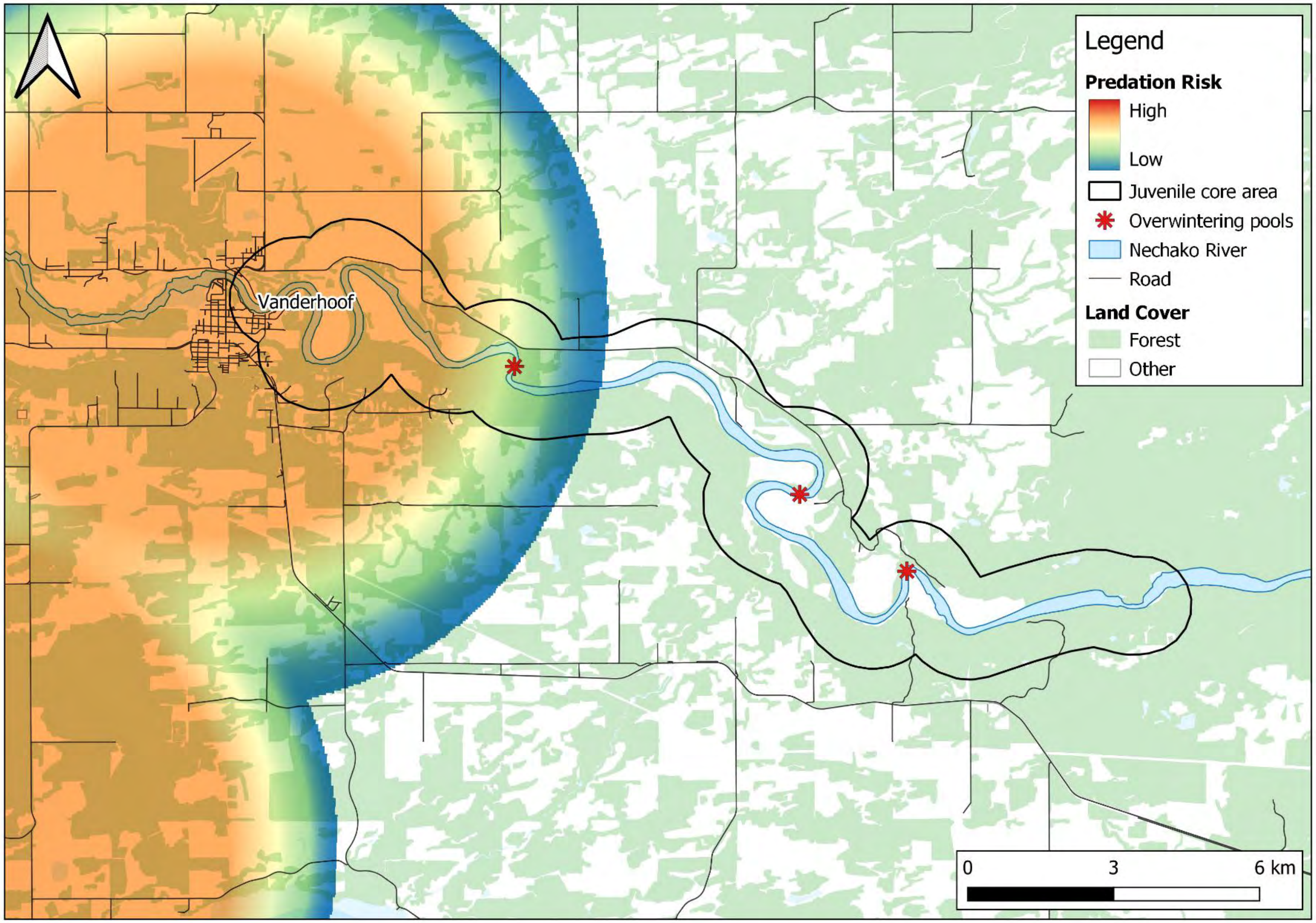

Figure 23. The 30-km core area (1-km buffer) and locations of 3 known overwintering pools for juvenile White Sturgeon in the Nechako River, overlayed with predation risk.

Common Loon

Common Loons in western Canada migrate to the Pacific coast during winter and are found in north-central BC mainly during the breeding season (May–September; Table 5; Barr 1996; Hanson and Kerekes 2006). Loons exhibit strong winter site and breeding site fidelity (0.93) across North America (Paruk et al. 2015).

Common Loons consume prey underwater; therefore, diet studies focus on food provisioning to chicks. Common Loons are piscivorous and primarily consume fish (78–82%) across a range of body sizes (Table 4; Hanson and Kerekes 2006). Selection for fish between 10–70 g has been recorded among Common Loons and Common Mergansers (Barr 1996) and loons rarely consume large fish >300 g (Pierre et al. 2005). In Alberta, Common Loons nesting on shallow lakes feed their chicks Fathead Minnows (*Pimephales promelas*) <2 cm length (Table 4; Hanson and Kerekes 2006). In Algonquin Park, Ontario, Common Loons select smaller fish (5–15 g) of a given species, and select species with smaller heads, long, slender (fusiform) bodies with soft scales and no spines (Barr 1996). Loons have difficulty ingesting Pumpkinseed and Rock Bass >25 g and discard individuals of these species >30 g (Barr 1996). Medium sized chub and suckers (10–70 g) are ingested and larger individuals of these species (80–125 g) are manipulated before being swallowed (Barr 1996). Small Pumpkinseed (4–5 cm) are easily captured by adult common loons (Barr 1996). Therefore, Common Loons are most likely to consume Nechako White Sturgeon between 2–5 cm length (Table 3).

Loons select prey mostly based on availability rather than species (Barr 1996). Loons appear to forage near the surface of lakes and dive duration is positively correlated with prey size. Loons remain underwater up to 75 s, searching and probing the bottom (Barr 1996). Fish prey are most vulnerable in clear and shallow (<5 m) water during the day when visibility is greatest and when loons are most active (Barr 1996). Loons are adept at turning quickly to catch zig-zagging prey, such as perch, which swim erratically (Barr 1996). Suckers are consumed frequently due to high rates of encounter during underwater searches (Barr 1996). There is some overlap between Common Loon High-risk areas and the Nechako juvenile White Sturgeon core area (Fig. 16) and loon occurrences are evenly distributed throughout the Nechako River and upper Fraser River (Fig. 17).

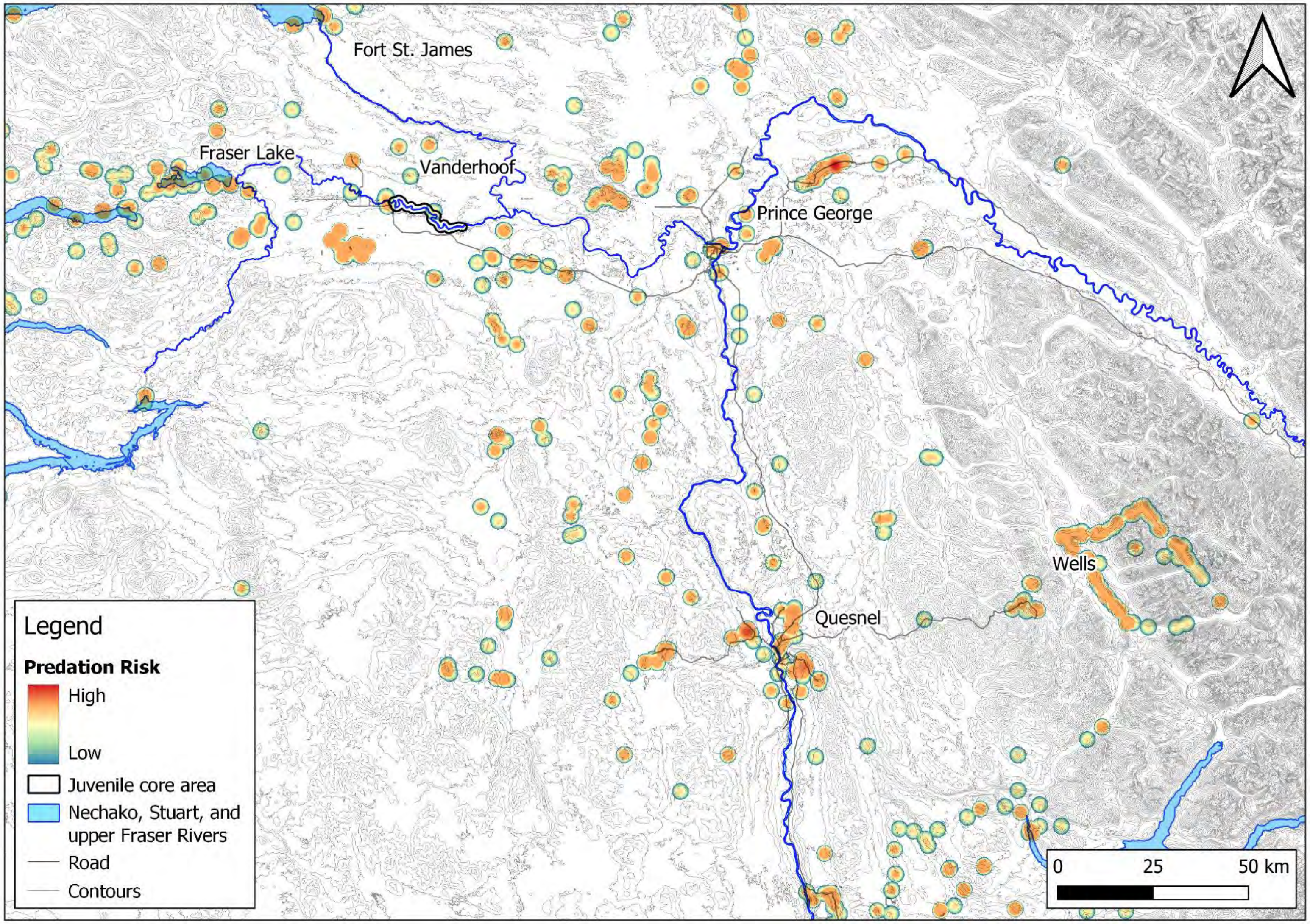

Figure 24. The 30-km core area (1-km buffer), Nechako River, Stuart River, and mid and upper Fraser River, overlayed with Common Loon predation risk.

Belted Kingfisher

Belted Kingfisher are mostly piscivorous (75%), and consume aquatic organisms of suitable size in relation to their abundance and availability (Salyer and Lagler 1949). Average length of all fish caught by kingfishers in Michigan (*n* = 729) is <7.6 cm (range = 2.5–17.8 cm), and most fish caught are <12.7 cm length (Table 4; Salyer and Lagler 1949). Larger fish are presumably difficult to ingest or carry in flight (Salyer and Lagler 1949). Therefore, Belted Kingfisher are most likely to consume Nechako White Sturgeon between 3–18 cm length (Table 3).

Kingfishers are only active diurnally, with peaks in activity in the morning, afternoon, and evening. Kingfisher feeding is limited by vegetative cover, deep and unfishable pools, and fast currents that reduce visibility (Salyer and Lagler 1949). Kingfishers capture fish in a pincer-like action rather than spearing as in the Great Blue Heron; fish are swallowed whole, head first (Salyer and Lagler 1949).

Kingfishers in the northern hemisphere may remain all year long depending on availability of open water throughout the winter; however, most birds migrate to southern latitudes during winter (Salyer and Lagler 1949). In Michigan, the longest length of territory defended by a breeding pair of Belted Kingfisher was 2.4 km of shoreline (average length = 0.8 km; Salyer and Lagler 1949). Belted Kingfisher occur sparsely within the Nechako juvenile White Sturgeon core area (Fig. 18). Due to relatively small home ranges, predation risk of Belted Kingfisher was very low and not easily visualized at the Upper Fraser River scale.

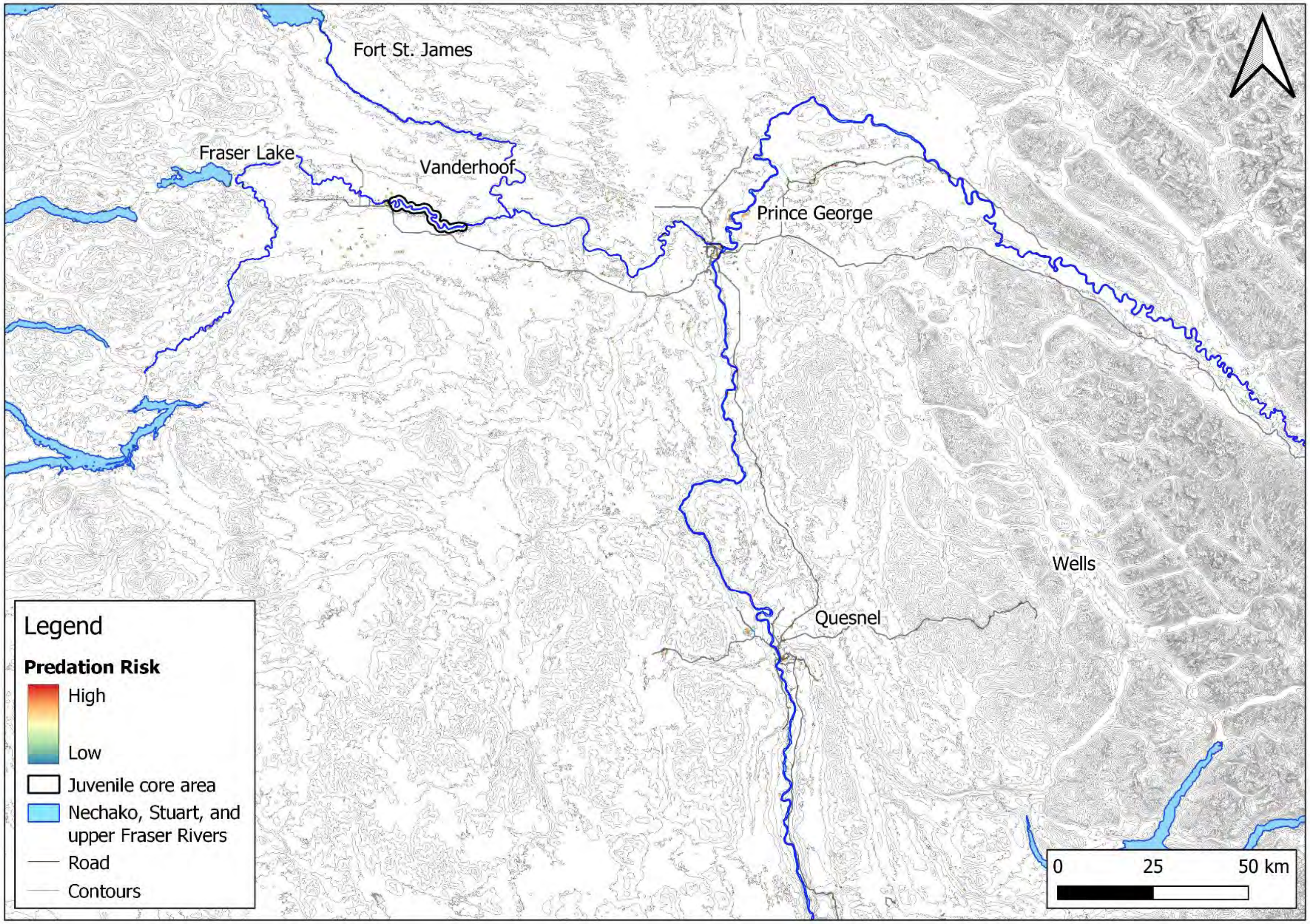

Figure 25. The 30-km core area (1-km buffer), Nechako River, Stuart River, and mid and upper Fraser River, overlayed with Belted Kingfisher predation risk.

Common Merganser

Common Mergansers are considered carnivorous (Barnes and Thomas 1987) and consume approximately 0.4 kg of fresh fish per day (Wood 1987). Mergansers foraging in tidal waters consume intertidal fishes, primarily sculpins (*Cottidae*) and blennies (*Stichaeidae* or *Pholidae*; Wood 1987). Mergansers foraging in freshwater eat almost exclusively salmonids, and some freshwater sculpins (*Cottus* spp.; Wood 1987). Mergansers consume a variety of sizes of salmonid prey, from emergent fry weighing between 0.33–0.9 g and between 3–5 cm in length, to reared Steelhead smolt weighing up to 90 g and 21 cm in length (Table 4; Wood 1987). Common Mergansers have been shown to cause 24–65% of juvenile Coho Salmon mortality in a given stream (Martel and Dill 1995).

Mergansers appear to select disproportionately larger fish compared to sizes available. For example, mergansers select Coho smolt weighing 40 g (~17 cm length) rather than Coho fry weighing 2 g (~6 cm length; Table 4; Wood 1987). However, mergansers and other diving ducks may select fish based on girth rather than length. Three species of piscivorous ducks, including mergansers, select fish with girths that are approximately half the maximum size that can be swallowed (Wood 1987). Therefore, Common Mergansers are most likely to consume Nechako White Sturgeon between 3–21 cm length (Table 3).

Mergansers fish by dipping their head underwater and searching for prey (Martel and Dill 1995). Mergansers typically forage from 2–3 m depth (Mallory and Metz 1998). Detection of fish is a function of visual capabilities of the bird as well as the movement rates of the fish (Martel and Dill 1995). The greater the proportion of time the fish spends moving and the longer the searching time, the greater the probability of detection and capture (Martel and Dill 1995). In other words, stationary fish are less likely to be attacked by mergansers (Martel and Dill 1995).

There is an area around Vanderhoof of significant overlap between Common Merganser High-risk and the Nechako juvenile White Sturgeon core area (Fig. 19). Common Mergansers are relatively evenly distributed throughout the Nechako River and upper Fraser River, with relatively High-risk areas around Prince George and Quesnel (Fig. 20).

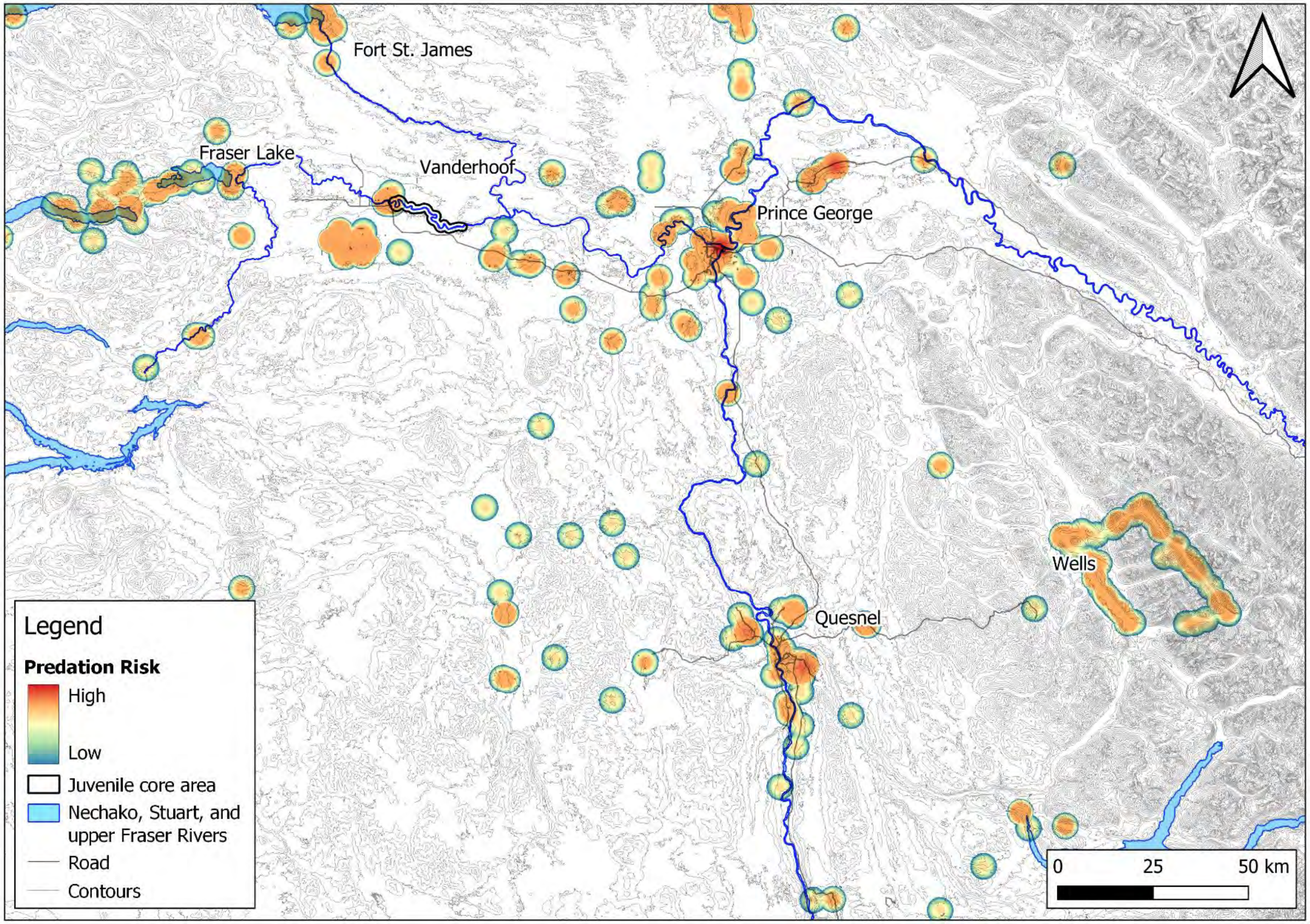

Figure 26. The 30-km core area (1-km buffer), Nechako River, Stuart River, and mid and upper Fraser River, overlayed with Common Merganser predation risk.

Red-necked Grebe

Red-necked Grebe are deep-diving ducks that breed on inland lakes and overwinter along marine coastlines in North America, especially along marine shorelines of the Pacific Northwest (Wagner and Hansson 1998; Humple and Holcomb 2014). Red-necked Grebe can make round-trip migrations up to 3,000 km distance from breeding sites on shallow lakes and ponds to coastal overwintering sites (Wagner and Hansson 1998; Mills et al. 2016). Migrant and wintering Red-necked Grebe use large lakes and major rivers in BC (Cannings et al. 2016). Most grebes that are banded and recaptured within a single winter are recovered within 25 km of the release location; however, some have been recaptured >400 km of the initial banding location (Humple and Holcomb 2014). Red-necked Grebe exhibit colonial and solitary nesting depending on several ecological factors (Klatt 2003). There is overlap between an area of High-risk of predation from Red-necked Grebe and the Nechako juvenile White Sturgeon core area (Fig. 21). Density of Red-necked Grebe is relatively high around Eaglet Lake, northeast of Prince George (Fig. 22).

Juvenile Red-necked Grebe consume mostly small aquatic invertebrates and adults are mainly piscivorous (Wagner and Hansson 1998). The closely-related Western Grebe has been observed feeding mostly at 2 m depth in Clear Lake, California (Lawrence 1950). Stable isotope analysis and gut contents from Red-necked Grebe occupying lakes in the western boreal forest indicate mixed diets of fish (sticklebacks and minnows) between 5.0–14.1 cm in length (Table 4) and macroinvertebrates (Paszkowski et al. 2004). On inland lakes, grebe are at the same trophic level as piscivorous fishes (Paszkowski et al. 2004). Therefore, Red-necked Grebe are most likely to consume Nechako White Sturgeon between 5–14 cm length (Table 3).

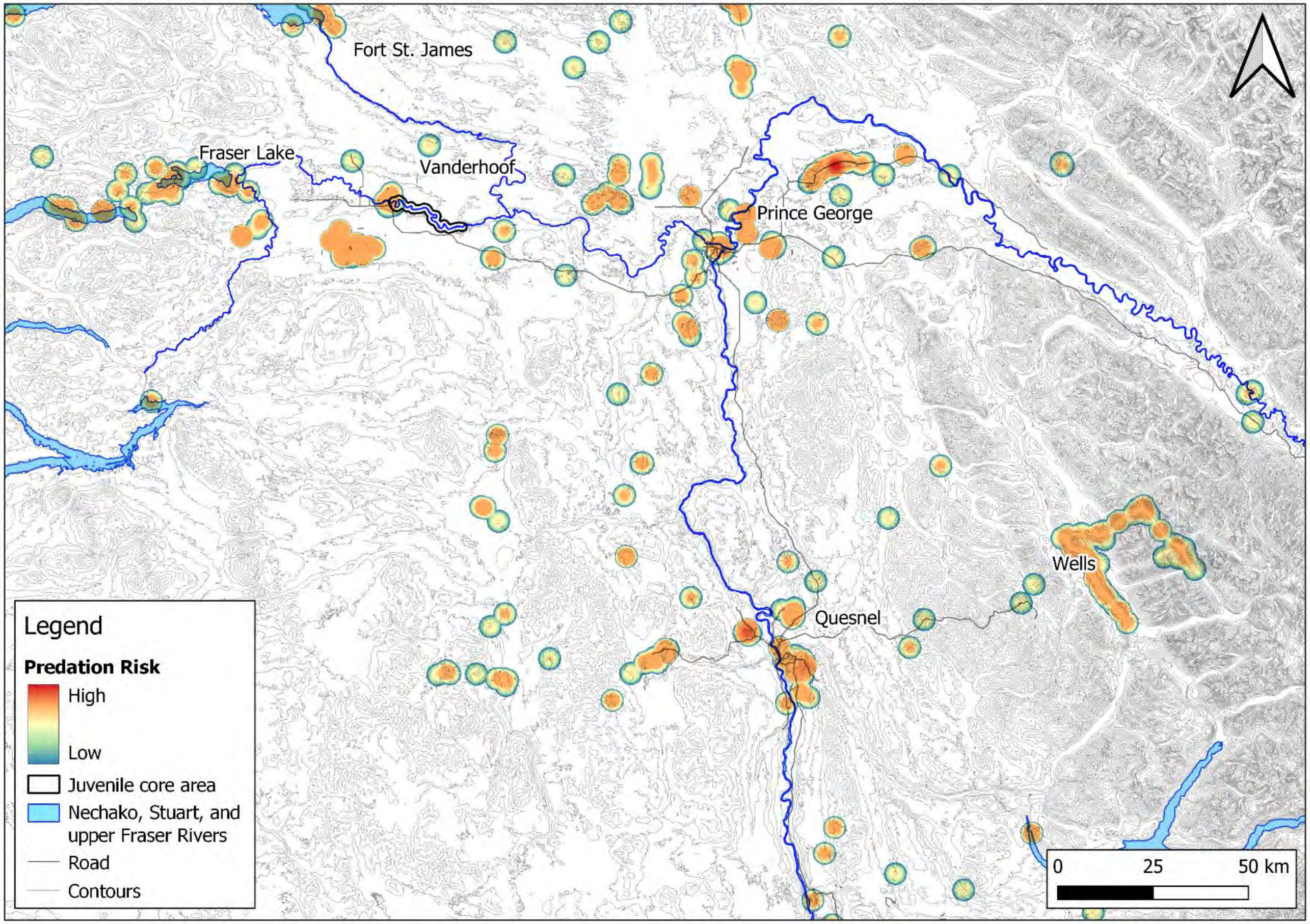

Figure 27. The 30-km core area (1-km buffer), Nechako River, Stuart River, and mid and upper Fraser River, overlayed with Red-necked Grebe predation risk.

Table 4. Prey species and size classes (cm) of confirmed or potential predators of Nechako White Sturgeon.

Predator	Prey scientific name	Prey common name	Prey length (cm)	References
North American river otter	*Acipenser transmontanus*	White Sturgeon	15–70	(Babey et al. 2020)
	Gadus spp.	Cod	>10	(Cote et al. 2008a)
	Cottus spp.	Sculpin	>15	(Cote et al. 2008a)
	Tautogolabrus adspersus	Cunner	>15	(Cote et al. 2008a)
	Pseudopleuronectes americanus	Winter Flounder	>25	(Cote et al. 2008a)
	Esox lucius	Northern Pike	48–60	(Taastrom and Jacobsen 1999)
	Salmo trutta	Brown Trout	9–30	(Jacobsen 2005)
	Cyprinidae	Carp/minnow family	30–40	(Erlinge 1972)
	Esox lucius	Northern Pike	>20	(Erlinge 1972)
	Lota lota	Burbot	>20	(Erlinge 1972)
	Perca fluviatilis	European Perch	>15	(Erlinge 1972)
	Acerina cernua	Eurasian Ruffe	>15	(Erlinge 1972)
American mink	*Cottus gobio*	European Bullhead	6–8*	(Bonesi et al. 2004)
	Anguilla anguilla	American Eel	60–80*	(Bonesi et al. 2004)
	Salmo salar	Atlantic Salmon (parr)	<10*	(Bonesi et al. 2004)
	Salmo trutta	Brown Trout (parr)	<10*	(Bonesi et al. 2004)
	Salvelinus malma	Dolly Varden	<30	(Ben-David et al. 1997)
	Salmonidae	Anadromous salmon (emerging)	<6*	(Ben-David et al. 1997)
	Phoxinus phoxinus	Minnow	8–10	(Poole and Dunstone 1976)
	Cyprinus carpio	Common carp	8–10	(Poole and Dunstone 1976)
	Carassius auratus	Goldfish	8–10	(Poole and Dunstone 1976)
	Esox lucius	Northern Pike	<20	(Erlinge 1972)
	Cyprinidae	Carp/minnow family	<15	(Erlinge 1972)

Predator	Prey scientific name	Prey common name	Prey length (cm)	References
	Lota lota	Burbot	<20	(Erlinge 1972)
	Perca fluviatilis	European Perch	<15	(Erlinge 1972)
	Acerina cernua	Eurasian Ruffe	<15	(Erlinge 1972)
Bald Eagle	*Cyprinus carpio*	Common Carp	16.1–43.8	(Haywood and Ohmart 1986)
	Ictalurus punctatus	Channel Catfish	12.8–47.6	(Haywood and Ohmart 1986)
	Catostomus clarki	Desert Sucker	16.3–31.4	(Haywood and Ohmart 1986)
	Catostomus insignis	Sonora Sucker	16.6–47.3	(Haywood and Ohmart 1986)
	Acipenser transmontanus	White Sturgeon	69	(FLNRORD unpublished)
Osprey	*Acipenser oxyrinchus*	Atlantic Sturgeon	<51	(Hilton and McGrath 2021)
	Mugil liza	Lebranche Mullet	25–45	(Clancy 2005)
	Myxus elongatus	Sand Grey Mullet	25–45	(Clancy 2005)
	Mugil cephalus	Flathead Grey Mullet	22–41	(Francour and Thibault 1996)
	Liza ramada	Thinlipped Mullet	22–41	(Francour and Thibault 1996)
	Liza aurata	Golden Mullet	22–41	(Francour and Thibault 1996)
	Chelon labrosus	Thicklipped Mullet	22–41	(Francour and Thibault 1996)
	Diplodus sargus	White Seabream	30	(Francour and Thibault 1996)
	Diplodus vulgaris	Common Two-banded Seabream	30	(Francour and Thibault 1996)
	Abramis brama	Common Bream	32.4	(Hakkinen 1978)
	Abramis ballerus	Blue Bream	35.1	(Hakkinen 1978)
	Rutilus rutilus	Common Roach	24.2	(Hakkinen 1978)
	Leuciscus idus	Ide	29.5	(Hakkinen 1978)
	Scardinus erythrophthalmus	Rudd	24.5	(Hakkinen 1978)
	Carassius carassius	Crucian Carp	24.6	(Hakkinen 1978)
	Esox lucius	Northern Pike	33.9	(Hakkinen 1978)
	Perca fluviatilis	European Perch	24.4	(Hakkinen 1978)

Predator	Prey scientific name	Prey common name	Prey length (cm)	References
	Lucioperca lucioperca	Zander	36.8	(Hakkinen 1978)
	Oncorhynchus mykiss	Rainbow Trout	30.2	(Hakkinen 1978)
	Coregonus lavaretus	European Whitefish	30	(Hakkinen 1978)
	Ictaluridae	Catfish	10.2–42.9	(Glass and Watts 2009)
	Dorosoma cepedianum	Gizzard Shad	10.2–42.9	(Glass and Watts 2009)
	Cynoscion spp	Seatrout	10.2–42.9	(Glass and Watts 2009)
	Brevoortia tyrannus	Atlantic Menhaden	10.2–42.9	(Glass and Watts 2009)
	Leiostomus xanthurus	Spot	10.2–42.9	(Glass and Watts 2009)
	Micropogonias undulatus	Atlantic Croaker	10.2–42.9	(Glass and Watts 2009)
	Cyprinus carpio	Common Carp	21.5–32.3	(Siverio et al. 2011)
Great Blue Heron	*Oncorhynchus mykiss*	Rainbow Trout	10.5–28.0	(Hodgens et al. 2004)
	Salmo trutta	Brown Trout	21.6 (12–38)	(Glahn et al. 1999)
		All fish (shad, dace, shiners, minnows, darters, sculpin, and trout)	<14.0 cm	(Hodgens et al. 2004)
American White Pelican	*Catastomus spp.*	Sucker	30–40	(Dunbar 1982)
	Ptychocheilus oregonensis	Northern Pikeminnow	30–40	(Dunbar 1982)
	Percidae	Perch	<17*	(Dunbar 1982)
	Cyprinidae	Minnow	<17*	(Dunbar 1982)
	Salmonidae	Trout	<17*	(Dunbar 1982)
	Gasterosteidae	Stickleback	<17*	(Dunbar 1982)
	Centrarchidae	Sunfish	<17*	(Dunbar 1982)
	Ameiurus spp.	Bullhead	<17*	(Dunbar 1982)
Common Loon	*Pimephales promelas*	Fathead Minnow	1.9–7.8*	(Hanson and Kerekes 2006)
	Lepomis gibbosus	Pumpkinseed	4–5	(Barr 1996)
	Percidae	Perch	12–16	(Barr 1996)

Predator	Prey scientific name	Prey common name	Prey length (cm)	References
	Salvelinus fontinalis	Brook Trout	<25*	(Barr 1996)
Belted Kingfisher	*Salmonidae*	Trout	5.8 (2.5–17.8)	(Salyer and Lagler 1949)
	Catostomidae	Sucker	8.6 (6.9–10.2)	(Salyer and Lagler 1949)
	Cyprinidae	Minnow	5.8 (3.8–10.2)	(Salyer and Lagler 1949)
	Ameiurus spp.	Bullhead	8.9 (8.9–8.9)	(Salyer and Lagler 1949)
	Esox lucius	Northern Pike	11.9 (11.9–11.9)	(Salyer and Lagler 1949)
	Fundulidae	Topminnow	4.6 (3.8–5.1)	(Salyer and Lagler 1949)
	Umbridae	Mudminnow	7.6 (3.8–12.7)	(Salyer and Lagler 1949)
	Perca flavescens	Yellow Perch	7.9 (4.6–11.4)	(Salyer and Lagler 1949)
	Micropterus	Black Bass	7.6 (4.6–12.7)	(Salyer and Lagler 1949)
	Centrarchidae	Sunfish	6.6 (4.6–10.2)	(Salyer and Lagler 1949)
	Cottus spp.	Sculpin	6.9 (4.3–10.2)	(Salyer and Lagler 1949)
	Gasterosteidae	Stickleback	4.6 (3.8–5.8)	(Salyer and Lagler 1949)
	Salvelinus fontinalis	Brook Trout	3.8–14.0	(Salyer and Lagler 1949)
Common Merganser	*Oncorhynchus kisutch*	Coho (emergent fry)	3.2*	(Wood 1987)
	Oncorhynchus keta	Chum (emergent fry)	3.2*	(Wood 1987)
	Oncorhynchus keta	Chum (reared fry)	4.5*	(Wood 1987)
	Oncorhynchus tshawytscha	Chinook (reared smolt)	8.4*	(Wood 1987)
	Oncorhynchus kisutch	Coho (reared smolt)	11.9*	(Wood 1987)
	Oncorhynchus mykiss	Steelhead (reared smolt)	16.5–20.8*	(Wood 1987)
Red-necked Grebe	*Perca flavescens*	Yellow Perch	14.1	(Paszkowski et al. 2004)
	Pimephales promelas	Fathead Minnow	5.0–6.5	(Paszkowski et al. 2004)
	Culaea inconstans	Brook Stickleback	5.0–6.5	(Paszkowski et al. 2004)

*not directly stated (e.g. inferred from weight, age class, etc.)

Table 5. Monthly occurrence of mammalian and avian predators across the geographic range of Nechako White Sturgeon based on publicly available species occurrence data (GBIF.org) and regional migratory/breeding patterns. Time periods of low probability of occurrence are light grey and time periods of high probability of occurrence (e.g., breeding and nesting period) are dark grey.

	Month											
Predator	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
North American river otter												
American mink												
Bald Eagle												
Osprey												
Great Blue Heron												
American White Pelican												
Common Loon												
Belted Kingfisher												
Common Merganser												
Red-necked Grebe												

Fish Predators

Northern Pikeminnow

Northern Pikeminnow are often >300 mm fork length, and may reach lengths >400 mm (EDI 2016). Northern Pikeminnow captured as bycatch during juvenile White Sturgeon assessments (*n* = 1,534) on the Nechako River between 2007–2009 were between 10–693 mm fork length (NWSRI 2021). Northern Pikeminnow between 100-125 mm in length begin to prey on other fish (e.g., shiners, sticklebacks) and are primarily piscivorous when >300 mm in length.

Northern Pikeminnow are found in large, slow-moving rivers, and water velocities >1.0 m/s may exclude Northern Pikeminnow. Northern Pikeminnow occur in shallow, near-shore habitats during summer and deeper habitats during winter. Adults are more bottom-orientated during summer, while juveniles are often associated with shallow, quiet water. Based on these habitat preferences, the potential for interaction with juvenile White Sturgeon habitats is assumed to be high.

White Sturgeon eggs and one White Sturgeon larvae have been found in the stomach contents of Northern Pikeminnow on the Columbia River (Miller and Beckman 1996; Rust and Wakkinen 2005). Adult Northern Pikeminnow (mean total length = 472 mm) from the Columbia River have been shown to consume juvenile White Sturgeon up to between 120–134 mm mean length (~5 months old; Kern et al. 2002; Gadomski and Parsley 2005a, 2005b). White Sturgeon size and the availability of cover did not affect the proportions of prey species ingested (Gadomski and Parsley 2005a).

Prickly Sculpin

Prickly Sculpin can reach 225 mm total length and 13 Prickly Sculpin caught as bycatch on the Nechako River during 2007–2009 juvenile sturgeon surveys were between 100–150 mm length (NWSRI 2021). Prickly Sculpin >70 mm in length prey on other fish and fish eggs. White Sturgeon eggs and larvae have been found in the stomach contents of Prickly Sculpin on the Columbia River (Miller and Beckman 1996). Adults >120 mm in length can be significant predators of salmon fry (EDI 2016).

Decreased turbidity levels (i.e., ~20 Nephelometric Turbidity units or NTUs) significantly increase predation by Prickly Sculpin on White Sturgeon larvae (Kern et al. 2002; Gadomski and Parsley 2005a). In contrast, predation decreased when turbidity levels were increased from 30 to 60 NTUs (Gadomski and Parsley 2005a). For comparison, turbidity levels in the Nechako River sampled at Prince George never exceeded 30 NTUs between 1985 and 1995 (Holms et al. 1997). In contrast, Prickly Sculpin predation on very small sturgeon larvae decreased with decreased light levels and increased cover (Kern et al. 2002; Gadomski and Parsley 2005a). Adult Prickly Sculpin prefer shallow, fast water over rocky substrates, while juveniles are typically found in quiet edge water associated with vegetation and woody debris. Prickly Sculpin are bottom-dwelling ambush feeders and White Sturgeon are also benthic (Gadomski and Parsley 2005b). Based on habitat preferences and foraging activity, there is a high risk of predation by Prickly Sculpin on early life stages and very small juvenile White Sturgeon in the Nechako River (EDI 2016).

Peamouth Chub

Peamouth Chub are typically between 102–152 mm length and can be >250 mm length (EDI 2016). During juvenile sturgeon assessments on the Nechako River, 298 Peamouth Chub were sampled as bycatch and were between 110–335 mm fork length (NWSRI 2021). Peamouth Chub are known to prey on White Sturgeon eggs in the Columbia River (Miller and Beckman 1996). During spring, Peamouth Chub are found in large rivers where they are bottom-oriented.

During spring, they move inshore to spawn in small streams. Therefore, Peamouth Chub may be a significant predator of sturgeon eggs and larvae based on relatively high bycatch in the Nechako River.

Largescale Sucker

Largescale Sucker are on average 330–432 mm in length and can reach 600 mm length. During Nechako White Sturgeon assessments, 178 Largescale Sucker captured as bycatch were between 85–490 mm fork length (NWSRI 2021). Adult Largescale Sucker are benthivores, while juveniles prefer relatively shallow, slow-water areas with sand or silt bottoms (EDI 2016). Largescale Sucker occur in warmer water in large, low- to moderate-gradient rivers. They are relatively sedentary except for spawning migrations. Largescale Sucker are known to consume fish eggs and larvae (e.g., Kokanee, salmon) in the spring, as well as White Sturgeon eggs on the Columbia River (Miller and Beckman 1996).

Burbot

Burbot are on average 381 mm in length and 86 Burbot captured during Nechako White Sturgeon assessments were between 140–610 mm fork length (NWSRI 2021). Adults >500 mm in length are primarily piscivorous (e.g., trout, grayling, suckers, minnows, and sculpins) and are known to eat fish eggs (EDI 2016). Smaller adults (150–500 mm) can also be highly predatory on juvenile salmonids (EDI 2016). Burbot are a cool-water species (temperatures <18°C) that prefer turbid water. Adults are benthic, often associated with deep main channels >2 m depth (EDI 2016). Juveniles occupy water <2 m depth and are strongly associated with cover (EDI 2016).

White Sturgeon (adult)

Adult White Sturgeon are primarily piscivorous and are known to consume Eulachon, sculpins, sticklebacks, lampreys, adult salmon, and Kokanee. Smaller White Sturgeon have been found in stomach contents of larger White Sturgeon on the Fraser River (Semakula and Larkin 1968). Further, adult White Sturgeon from the Columbia River were found to consume larval White Sturgeon (Parsley et al. 2002). Adult White Sturgeon occur in river mainstems, large tributaries, reservoirs, and large lakes. Adults overwinter in deep water and move out of deep water into shallow areas in spring and summer (EDI 2016). Interaction with juvenile White Sturgeon is assumed to be low; however, further investigation is required.

Bull Trout

Bull Trout are between 550–850 mm in length on average (EDI 2016) and 28 individuals sampled as bycatch during Nechako sturgeon assessments were between 247–670 mm fork length (NWSRI 2021). Adult Bull Trout are piscivorous and are known to eat salmon eggs, and juveniles >100 mm fork length can eat small fish. Piscivory by Bull Trout and Rainbow Trout is associated with low juvenile survival rates and population collapse of Kokanee in Kootenay Lake, BC (Warnock et al. 2021). Bull Trout are a cold-water species (temperatures <15°C; EDI 2016). In rivers, Bull Trout are commonly associated with tail-outs of pools and overhead cover, and move to deeper water during fall and winter (EDI 2016). Based on their piscivorous diet and habitat preferences, the potential for predation of White Sturgeon is moderate. A forthcoming publication will present Bull Trout telemetry data in the Nechako River and upper Fraser River, including distribution and migration patterns/timing (Chudnow et al. in press).

Mitigations

Reduction in the total population of Nechako White Sturgeon may be due to many possible factors, including predation by mammals, birds, and fish on early life stages (eggs, yolk-sac larvae, and free-swimming larvae) and juvenile sturgeon (NWSRI 2020). Therefore, mitigation actions that reduce predation rates of early life stages and juvenile sturgeon, as well as monitoring strategies which improve understanding of the link between predation and recruitment failure, should be considered integral parts of a comprehensive restoration plan for Nechako White Sturgeon in the Nechako River and upper Fraser River.

In most cases, potential mitigation actions should be preceded by field surveys to evaluate baseline mortality rates of both hatchery-reared and wild Nechako White Sturgeon (Wood 1987). Studies should focus on rates of predation-caused mortality by each predator taxa included in this review, and risk ratings should be adjusted using an adaptive management approach (EDI 2016). Actions must consider the conservation status of predator species (Table 6), the feasibility of maintaining measures long-term, monitoring plans to evaluate efficacy, and adaptive management strategies. Mitigation actions can be broadly categorized by taxa (Table 6) and defined as either population or habitat management strategies. Potential strategies include flow regulation to decrease vulnerability to predation, habitat alterations to decrease predation risk, non-lethal predator removal, and lethal predator control (McAdam 2012; McLaren 2016). Further, the objective of mitigations may be to reduce predation of hatchery-reared sturgeon, wild sturgeon, or both; thus, monitoring plans must be designed for hatchery-reared and wild sturgeon in the Nechako River and upper Fraser River. In the following section, mitigation actions are discussed by predator species and risk rating following the order of Table 1.

River otter

Overall, flows in the Nechako River are much lower under the current regime compared to natural historic flows (Macdonald et al. 2012; Babey 2021a). River velocity (i.e., flow), turbidity, and water depth have been shown to influence predation success among several predators, including river otter (Table 6). From late-summer until spring freshet, low water levels likely leads to more sturgeon in fewer locations during these times of year. Relatively high densities of juvenile sturgeon congregated in a few overwintering pools may increase vulnerability to opportunistic river otter (Babey 2021a). Reduced discharge as a result of flow regulation also increases water clarity, which is more advantageous for visual predators such as river otter than for sturgeon (Babey 2021a). Further, brush piles and woody debris anchored at the bottom of overwintering pools may provide escape cover for juvenile sturgeon and reduce hunting success of river otter (Missouri Department of Conservation 2002).

Where practical, hi-tensile electric fences can be effective at preventing otter predation (Missouri Department of Conservation 2002). Fences must consist of at least 4 strands spaced 10–12 cm apart, which must be kept tight and clear of grass or weeds that could ground the electric charge (Missouri Department of Conservation 2002). The bottom wire should be close to the ground and wire spacing should be such that otters cannot pass between without shock (Missouri Department of Conservation 2002). However, this method is typically used for excluding otters from ponds, and is not realistically feasible for remote river sites (Missouri Department of Conservation 2002).

Table 6. Mammalian, avian, and fish predators by risk category with provincial and federal conservation status and potential impact mechanisms for predation risk.

Risk	Predator	BC Listing	Canada Listing	Potential Impact Mechanisms
High	North American river otter	Yellow	Not at Risk	increased discharge; escape cover; electric fence; beaver and muskrat removal; river otter removal
	Bald Eagle	Yellow	Not at Risk	increased discharge; screening; nest tree removal/topping
	Osprey	Yellow	No Status	increased discharge; screening; artificial nesting platforms removal
	Northern Pikeminnow	Yellow	No Status	increased discharge; sport-reward fishery; increased porous substrate
	Prickly Sculpin	Yellow	No Status	increased discharge; escape cover; increased porous substrate
	Peamouth Chub	Yellow	No Status	increased discharge; escape cover; increased porous substrate
	Largescale Sucker	Yellow	No Status	increased discharge; escape cover; increased porous substrate
	Burbot	Yellow	No Status	increased discharge; escape cover; increased porous substrate
Moderate	American mink	Yellow	No Status	increased discharge; escape cover; beaver and muskrat removal; reduced bank cover
	Great Blue Heron	No Status	No Status	increased discharge; screening
	American White Pelican	Red	Not at Risk	bird excluders
	White Sturgeon (adult)	Red	Endangered	increased discharge; escape cover; increased porous substrate
	Bull Trout	Blue	Special Concern	increased discharge; increased porous substrate
	Longnose Sucker	Yellow	No Status	increased discharge; escape cover; increased porous substrate
	Redside Shiner	Yellow	No Status	increased discharge; escape cover; increased porous substrate
	Mountain Whitefish	Yellow	No Status	increased discharge; escape cover; increased porous substrate
	Slimy Sculpin	Yellow	No Status	increased discharge; ; escape cover, increased porous substrate
Low	Common Loon	Yellow	Not at Risk	increased discharge
	Belted Kingfisher	Yellow	No Status	screening; bird excluders; remove posts >1.2 m height
	Common Merganser	Yellow	No Status	increased discharge
	Red-necked Grebe	Yellow	Not at Risk	increased discharge
	Rainbow Trout	Yellow	No Status	increased discharge; escape cover; increased porous substrate
	Chinook Salmon (juvenile)	No Status	Endangered	increased discharge; escape cover; increased porous substrate

River otter use beaver and muskrat bank-dens as natal and resting dens (Lariviere and Walton 1998; Missouri Department of Conservation 2002; Gorman et al. 2006). Removing beaver and muskrat within 5 km of critical overwintering pools may discourage river otter from using these areas (Lariviere and Walton 1998; Missouri Department of Conservation 2002). Beaver and muskrat are Class 1 Species and are managed on individual traplines (Province of BC 2020). Lethal and non-lethal trapping of beaver and muskrat in Regions 6 and 7 is allowed between October 1–May 31 (Province of BC 2020). Approved methods for trapping and killing beaver and muskrat include killing neck snares, killing traps, and live box traps (Province of BC 2020). Non-lethal traps must be checked at least once every 72 hours and killing traps must be checked every 14 days (Province of BC 2020).

Following removal of beaver and muskrat, beaver dams and beaver/muskrat dens should be destroyed to discourage denning by river otter (Fisheries and Oceans Canada 2020). Bank alterations and den removals should take place outside of the natal denning season for river otter (March–May). Removal of beaver dams must minimize disturbance to critical sturgeon habitat (Fisheries and Oceans Canada 2020). Removal should take place downstream to upstream and should be carried out with hand tools to avoid disturbance to sturgeon habitat (Fisheries and Oceans Canada 2020).

Native predators are generally indicators of healthy ecosystem function and predator removals often result in outcomes that are the opposite of what was intended (Courchamp et al. 2003; Johnson et al. 2019). For example, removal of one predator may cause the abundance of competing predators to increase, resulting in increased predation on the species intended for recovery (Courchamp et al. 2003). River otter primarily consume trout, minnow, sculpin, and suckers, many of which are High-risk predators of early life stages of Nechako White Sturgeon

(Table 5; Erlinge 1972; Crait and Ben-David 2006). Therefore, removal of river otter may cause fish predators to become overabundant, resulting in increased predation by coarse fish on sturgeon eggs and larvae, as well as juveniles between 1–10 cm length. Further, river otter outcompete mink for aquatic resources, namely larger size classes of fish (Bonesi et al. 2004). Therefore, a decrease in the density of river otter may result in increased predation by mink on juvenile sturgeon, including larger size classes from which mink are normally outcompeted by otter (Bonesi et al. 2004). Studies of predator-prey dynamics are required to investigate the ecological consequences of culling or otherwise removing river otter on the Nechako River and upper Fraser River (Table 6).

Bald Eagle & Osprey

Several characteristics of stream morphology correspond with greater prey vulnerability and availability for Bald Eagles (Haywood and Ohmart 1986). Bald Eagles are more likely to strike prey in water that is clear to the bottom and during prolonged periods of high turbidity from snowmelt eagles forage in clear tributaries rather than mainstems (Hunt et al. 2002). Therefore, decreased turbidity is associated with increased Bald Eagle predation (Hunt et al. 2002).

Bald Eagle nests are commonly located directly adjacent to foraging sites, and nests are the most frequently used foraging perches (Haywood and Ohmart 1986). Foraging is constant throughout the day; therefore, proximity of nests to foraging sites allows simultaneous foraging and monitoring of the nest (Haywood and Ohmart 1986). Foraging sites adjacent to nests are often characterized by deep pools (>3 m depth) bounded by riffles or sandbars. Where practicable, removal of the largest trees within 1.6 km distance of overwintering pools may reduce predation by Bald Eagles (Table 6; Haywood and Ohmart 1986; Anthony and Isaacs

1989). Alternatively, nest trees that meet the above criteria may be topped and turned into wildlife trees to encourage cavity nesters and provide a source of debris input to the river (Table 6).

Osprey foraging efficiency may also be reduced by increased water turbidity or turbulence (Clancy 2005). Riparian habitat modifications may reduce the nest productivity and associated predation rates of birds during the breeding season. For example, nest productivity of Osprey is higher among artificial sites (e.g., power poles, nesting platforms) compared to natural snags or live trees (Van Daele and Van Daele 1982). Osprey will fly up to 10 km from their nest to fish (Van Daele and Van Daele 1982); therefore, removal of artificial nesting sites within 10 km of critical juvenile sturgeon habitat may reduce the risk of Osprey predation (Table 6).

Northern Pikeminnow

Based on habitat preferences, high abundance in the Nechako River, and dietary preferences, Northern Pikeminnow are likely the most significant predator of juvenile sturgeon <13 cm length (C. Babey, pers. comm. 2021). A sport-reward fishery program may reduce predation by piscivorous fish on juvenile White Sturgeon (Washington Department of and Fish and Wildlife 2021). A program developed in Washington, US, offers financial incentives to anglers who catch Northern Pikeminnow >228 mm length. Removal of the largest Northern Pikeminnow from the native population in the Columbia and Snake Rivers appears to reduce predation rates on juvenile salmonids (The Chronicle Staff 2021; Washington Department of and Fish and Wildlife 2021). Northern Pikeminnow are primarily piscivorous when >300 mm in length. Therefore, a sport-reward fishery program that offers a nominal cash reward to anglers who register and check-in Northern Pikeminnow >300 mm length may be an effective mitigation strategy in the Nechako River and upper Fraser River. However, a baseline understanding of the level of Northern Pikeminnow predation would be required to assess the efficacy of such a program. Furthermore, other sturgeon predators, such as river otter, American White Pelican, Great Blue Heron, and Belted Kingfisher, consume primarily coarse fish, including native Northern Pikeminnow (Table 4). Therefore, removal of large Northern Pikeminnow or other piscivorous fish may result in increased predation rates on White Sturgeon by mammalian and avian predators.

Prickly Sculpin

Fish predators such as Prickly Sculpin may be attracted to sturgeon spawning areas due to high density and availability of eggs and larvae (Parsley et al. 2002). Cover, substrate composition, and availability of interstitial spaces in rearing habitats may influence predation risk in early life stages of Nechako White Sturgeon (Rust and Wakkinen 2005). For example, predation by sculpins on larval sturgeon decreases with increased availability of interstitial hiding places in porous substrates (McAdam 2011). During the initial hiding phase (0–6 days post-hatch), suitable cover reduces vulnerability of sturgeon larvae to all predators (Brannon et al. 1986). The positive effects of cover may be greater for smaller sturgeon larvae (<17 mm total length) relative to larger larvae (>20 mm total length) that have lost their yolk sacs and must search for food (Gadomski and Parsley 2005a). Indeed, newly hatched White Sturgeon larvae settle predominantly on cobble, while older larvae and juveniles prefer sand. Therefore, larval rearing habitat for White Sturgeon on the Nechako River should include porous substrates (e.g., pea gravel, larger gravel, and cobble) to enable rapid interstitial hiding (McAdam 2011).

Nechako White Sturgeon spawn during spring freshet. This trait is adaptive since floods provide increased food resources and may decrease predation via dispersal and increased turbidity. Turbidity is important in reducing vulnerability of larval White Sturgeon to visual predators (Poole and Dunstone 1976; Gadomski and Parsley 2005a). Food-detecting barbels allow sturgeon to feed in turbid waters undetected by piscivorous fish (Gadomski and Parsley 2005a). Higher turbidity levels lower predation rates of Prickly Sculpin on White Sturgeon larvae (Kern et al. 2002). However, increased turbidity may only decrease predation at levels greater than ambient or historical conditions (McAdam 2012). Turbidity levels associated with successful sturgeon spawning and recruitment are between 6–92 NTU in the lower Fraser River (Perrin et al. 2003; Hatfield et al. 2004).

Dams reduce velocity and turbulence, and increase light penetration due to reduced silt, which make early life stages of White Sturgeon more vulnerable to fish predation (Brannon et al. 1986). Impoundment and dam operations reduce water velocity and may increase predation by Northern Pikeminnow, Prickly Sculpin, and Largescale Sucker on sturgeon eggs (Parsley et al. 2002). Higher velocity currents in spawning areas could limit predation on eggs by excluding predators (Parsley et al. 2002). Increased water velocity at the time of hatchery releases and spawning may increase dispersal rates and reduce encounters with potential predators (Ben-David et al. 1997; Parsley et al. 2002). However, this method has been attempted in the Columbia River without success (S. McAdam, pers. comm. 2021). Furthermore, increased drift by White Sturgeon larvae may also increase exposure to predation (DFO 2014).

American mink

Sturgeon activity becomes limited in water temperatures <7 °C (COSEWIC 2012); this may increase vulnerability of juvenile sturgeon to mink predation during fall and winter. Mink are more likely to capture slow-moving, less active fish compared to fish that spend more time actively swimming (Poole and Dunstone 1976). Reduced flows increases water clarity, which is more advantageous for visual predators than for sturgeon (Babey 2021a). Mink locate prey from above the surface prior to entering; thus, predation by mink is limited by water clarity (Poole and Dunstone 1976). Therefore, flow regulation which increases flow and reduces clarity may also limit predation by mink.

Modifications to riparian habitat and in-stream characteristics may reduce vulnerability and availability of juvenile sturgeon to predation by mink (Table 6; Salyer and Lagler 1949; Dunstone and O'Connor 1979; Van Daele and Van Daele 1982; Haywood and Ohmart 1986; Ben-David et al. 1996). Mink select shallow pools with greater cover from overstory and understory vegetation (Ben-David et al. 1996). Therefore, selective thinning and brush clearing within 500 m of critical juvenile sturgeon areas may reduce predation by mink (Table 6; Haan and Halbrook 2015). This may also reduce denning opportunities for river otter, which frequently use brush piles as natal dens during the denning season (Gorman et al. 2006).

Further, beaver facilitate the existence of muskrat, which in turn sustain inland mink populations (Holmengen et al. 2009; Crego et al. 2016; Breault et al. 2021). Mink and river otter consume muskrat during fall and winter (Wilson 1954) and mink and muskrat populations have been shown to be coupled through predator-prey interactions (Holmengen et al. 2009). Mink have linear home ranges in riparian forests between 2.7–3.0 river-km (Haan and Halbrook 2015). Therefore, removal of beaver dams and muskrat dens within 3.0 river-km of important sturgeon habitat may reduce risk of mink predation for juvenile sturgeon (Table 6). As previously described for river otter mitigation, removal of beaver dams and beaver/muskrat dens should be preceded by removal of beaver and muskrat from the area by lethal or non-lethal methods (Province of BC 2020; Fisheries and Oceans Canada 2020).

Successful evasion of mink may require in-stream structures that function as refugia for juvenile sturgeon. Indeed, available cover for prey is the most important factor affecting predation success of diving mink (Dunstone and O'Connor 1979). Therefore, brush piles or woody debris anchored at the bottom of overwintering pools may provide cover from mink. However, mink target known hides where there is a greater probability of encountering prey relative to open water (Dunstone and O'Connor 1979). Woody debris may also provide cover for ambush predators, such as Prickly Sculpin, which may prey on small (1–10 cm length) juvenile sturgeon (EDI 2016).

Great Blue Heron

Low water levels can greatly increase the vulnerability of fish to predation from wading birds such as Great Blue Heron (Hodgens et al. 2004). Sturgeon are released in large groups at a limited number of locations and although it is unclear how long these fish stay congregated in release areas, this high density and availability of sturgeon may attract wading birds and other predators (Ben-David et al. 1997; Parsley et al. 2002). Even some time after release, it is common to find White Sturgeon in large groups of varying age and size (Hildebrand et al. 2016). These congregations may be more available to predators at certain times of year. High minimum flows may reduce predation by herons by creating deep water refugia (Table 6; Hodgens et al. 2004). The number of nests in heron rookeries and their distance to the Nechako River core area may be a good indicator of the impact of heron predation on survival of juvenile sturgeon, as it is for juvenile salmon in coastal BC (Sherker 2020).

American White Pelican

Bird excluders made of wire spike strips have been used as an effective measure of preventing pelicans and other piscivorous birds from perching and roosting on vertical pilings and pile dikes in the Columbia River estuary (Table 6; Collis et al. 2001). Excluders may also be effective at reducing foraging around piles and prevent piscivorous birds from predating migrating juvenile salmonids (Collis et al. 2001). However, pelicans that perch on pilings following installation of excluders may suffer foot injuries and there is no evidence that excluders reduce predation on juvenile salmonids (Collis et al. 2001). Use of foraging areas by pelicans likely increases during the nesting period, between early May and late July (Table 5; Harper 2004). This coincides with the spawning period of Nechako White Sturgeon (May–June); thus, young juvenile sturgeon may be vulnerable to predation by American White Pelican. However, there is very low temporal overlap between American White Pelican and juvenile White Sturgeon in the Nechako River. Excluders should be installed on all pilings and repaired annually prior to the arrival of nesting birds to ensure effective deterrence of pelican and other perching birds (Collis et al. 2001). Therefore, the effort required to effectively mitigate pelican predation risk using bird excluders may not be an efficient use of resources.

Low-risk birds

Poles or other supports >1.2 m height function as observation perches and facilitate hunting success for Belted Kingfisher (Salyer and Lagler 1949). Predation by Belted Kingfisher on hatchery-released sturgeon is likely greatest during May–June when breeding pairs establish territories and begin nesting (Table 5; Salyer and Lagler 1949). The average length of territory defended by a breeding pair of Belted Kingfisher is 0.8 river km; therefore, removal of perching structures >1.2 m height within 0.8 river-km of hatchery-release sites may reduce kingfisher predation rates (Table 6; Salyer and Lagler 1949). Alternatively, simply netting rearing and overwintering pools can effectively protect fish from predation by herons and kingfisher at low cost (Glahn et al. 1999). Lastly, turbidity reduces hunting success and increases dive durations among Common Loons and likely other diving ducks including Common Merganser, and Red-necked Grebe (Pierre et al. 2005).

Hatchery Mitigations

Hatchery practices may be modified to increase predator wariness among hatchery-reared fish (Collis et al. 2002). Promoting experience with natural predators is key to prepare hatchery fish for predators once released (Van Daele and Van Daele 1982). Presenting fish with natural stimuli (e.g., natural food, cover, interspecific competition, environmental cues, and predators), prior to release may increase post-release survival.

Early detection of predators by fish decreases the probability of capture (Poole and Dunstone 1976). Predator detection involves the sensory ability of fish to detect the predator and the ability to recognize it as a threat. Predator recognition may be innate or a result of experience and learning (Kieffer and Colgan 1992; Berejikian et al. 2003). However, familiarizing hatchery fish with live predators comes with many logistical and ethical constraints. Predator models are an alternative method; however, results may be ambiguous (Vilhunen 2006).

Instead, a large and growing body of research has shown the benefits of conditioning using fish olfactory senses (Brown 2003). Two predation-related chemical stimuli are predator kairomones and conspecific alarm cues. A kairomone is a chemical signal given off by an individual of one species and received by individuals of a different species (Brönmark and Hansson 2000). For example, odours given off by a predator may make prey aware of their presence. Chemical alarm cues are released from damaged epidermal cells of fish, often due to predator attacks, and received by nearby conspecifics resulting in anti-predator behaviour (Smith 1992). Fish have an innate anti-predator response when exposed to alarm cues; however, there may not be an innate response to predator kairomones (Wisenden 2008).

In species with innate anti-predator responses, simply subjecting hatchery fish to predator kairomones prior to release may increase post-release survival (Kopack et al. 2015). Among fish species that do not have innate abilities of predator recognition and anti-predator response, associative conditioning with a negative stimulus in the hatchery environment may be necessary. Targeting fish olfactory systems by pairing a novel predator odour with a conspecific chemical alarm cue conditions fish to associate a novel predator as a threat (Ferrari et al. 2010b). Success of chemical-based conditioning varies by species and depends on innate learning abilities, as well as the innate response to predator stimuli and conspecific alarm cues.

Fish have genetically fixed activity patterns that are adapted to temporal patterns of predator activity (Daan 1981; López-Olmeda et al. 2012). Feeding without risk of predation in hatcheries leads to bold fish that are more likely to expose themselves to high predation risk in natural systems (Salvanes 2017). Fish in the hatchery should therefore be fed during time periods when their wild counterparts would be active (López-Olmeda et al. 2012). Some fish species may show behavioural flexibility in their daily and seasonal feeding activity, which is important in environments with variable predator activity (Madrid et al. 2001). In some cases, scheduled feeding times in the hatchery may reduce feeding flexibility and it may be beneficial to use self-feeding systems (López-Olmeda et al. 2012). Fish can be conditioned to associate certain time periods with predation risk by exposing fish to a novel predator stimulus paired with a negative stimulus on a set schedule (Bosiger et al. 2012).

Measures that reduce surface orientation of juvenile sturgeon may reduce their vulnerability to predation by surface-feeding birds, including American White Pelican, Great Blue Herons, and Belted Kingfishers (Salyer and Lagler 1949; McMahon and Evans 1992; Hodgens et al. 2004). This could involve pairing a negative stimulus, such as a conspecific alarm cue, with a novel predator stimulus at the surface (Chivers and Smith 1995). Exposing hatchery fish to appropriate predator cues prior to release could decrease post-release mortality (Brown 2003).

Additionally, hatcheries may promote aggressive behaviours as a result of unnaturally high densities of fish competing for food (Fenderson and Carpenter 1971; Swain and Riddell 1990). Aggressive fish may be more vulnerable to predation due to decreased predator vigilance and behaviours that make them more conspicuous to predators (Landeau and Terborgh 1986; Swain and Riddell 1990). Reducing rearing densities and ensuring fish are satiated could reduce competition and the development of hyperaggressive phenotypes in the hatchery.

Hiding and immobility are two common ways fish can avoid detection by predators (Krause et al. 1998; Brown and Dreier 2002), and the hatchery environment can influence these behaviors in the wild. For example, enriching holding tanks with structures to match the structural complexity of the natural environment may promote refuge-seeking and predator avoidance in hatchery fish (Olla et al. 1998; Huntingford 2004). Further, providing fish with a refuge opportunity during predator recognition training may decrease the risk of stimulus habituation (Vilhunen 2006).

Study Limitations

The limitations and knowledge gaps inherent in this review should be acknowledged prior to implementation of mitigation actions. Namely, many of the results were generalized from studies which occurred outside the range of Nechako White Sturgeon, and distribution maps were created using publicly available data (GBIF.org 2021). Bycatch numbers obtained during juvenile White Sturgeon assessments are biased towards fish predators that utilize the same habitat as juvenile White Sturgeon, predators that are of similar size to juvenile White Sturgeon, and predators that are effectively captured in the fishing gear used to capture juvenile

White Sturgeon (EDI 2016). Species that do not fit the above listed criteria are likely not well represented in the bycatch data (e.g., Prickly Sculpin, juvenile Chinook Salmon, and Redside Shiner).

Little is known about the abundance and distribution of predators in the Nechako River system and the specific predator-prey interactions between these predators and the early life stages of White Sturgeon (Hatfield et al. 2004). Relative abundance and distribution of potential predators before and after Nechako flow regulation is not known, and the functional relationship between predation and successful sturgeon recruitment is unknown (Hatfield et al. 2004). Therefore, the effect of predators on Nechako White Sturgeon survival remains unknown (Hatfield et al. 2004).

Thus, risk rankings developed should be considered preliminary and subject to change based on targeted monitoring programs in the Nechako River and upper Fraser River. Studies of predator-prey dynamics should investigate predator abundance and distribution in the Nechako River and the interactions between predators and juvenile Nechako White Sturgeon. Studies should be conducted to measure predation-caused mortality rates of Nechako White Sturgeon on a predator-specific basis. Mitigations should only be implemented in conjunction with monitoring to evaluate efficacy of a given strategy. For example, perching and roosting structures (e.g., pilings, posts, and platforms) should be monitored before and after installation of bird excluders to determine if predation on sturgeon was reduced. Empirical data from targeted monitoring are crucial for defining predation risk and outlining effective mitigation plans with any certainty.

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References

Albeke, S.E., Nibbelink, N.P., and Ben-David, M. 2015. Modeling Behavior by Coastal River Otter (*Lontra canadensis*) in Response to Prey Availability in Prince William Sound, Alaska: A Spatially-Explicit Individual-Based Approach. PLOS ONE **10**(6): e0126208. doi:10.1371/journal.pone.0126208.

Anderson, E.A., and Woolf, A. 1987. River Otter Food Habits in Northwestern Illinois. Trans. Ill. Acad. Sci. **80**: 115–118.

Anthony, R.G., and Isaacs, F.B. 1989. Characteristics of Bald Eagle Nest Sites in Oregon. J. Wildl. Manag. **53**(1): 148. doi:10.2307/3801322.

Ashley, P.J. 2007. Fish welfare: Current issues in aquaculture. Appl. Anim. Behav. Sci. **104**(3–4): 199–235. doi:10.1016/j.applanim.2006.09.001.

Babey, C.N. 2021a. Investigating Potential Explanations for Predation of Juvenile Nechako White Sturgeon (*Acipenser transmontanus*) by North American River Otter (*Lontra canadensis*). Unpublished.

Babey, C.N. 2021b. Anti-Predator Behavior Deficits in Hatchery Fish. Unpublished.

Babey, C.N., Gantner, N., Williamson, C.J., Spendlow, I.E., and Shrimpton, J.M. 2020. Evidence of predation of juvenile white sturgeon (*Acipenser transmontanus*) by North American river otter (*Lontra canadensis*) in the Nechako River, British Columbia, Canada. J. Appl. Ichthyol. **36**(6): 780–784. doi:10.1111/jai.14114.

Bagniewska, J.M., Harrington, L.A., Hart, T., Harrington, A.L., Fasola, L., and Macdonald, D.W. 2015. Persistence in diving American mink. Anim. Biotelemetry **3**(1): 18. doi:10.1186/s40317-015-0057-4.

Banfield, A.W.F. 1974. The mammals of Canada. University of Toronto Press for the National Museum of Natural Sciences, Toronto, Ontario, Canada.

Barnes, G.G., and Thomas, V.G. 1987. Digestive organ morphology, diet, and guild structure of North American Anatidae. Can. J. Zool. **65**(7): 1812–1817. doi:10.1139/z87-274.

Barr, J.F. 1996. Aspects of Common Loon (*Gavia immer*) feeding biology on its breeding ground. Hydrobiologia **321**(2): 119–144. doi:10.1007/BF00023169.

Bedrosian, B.E., Cain, S.L., Wolff, S., and Craighead, D.J. 2015. Migratory Pathways, Timing, and Home Ranges of Southern Greater Yellowstone Osprey. J. Raptor Res. **49**(3): 325. doi:10.3356/JRR-14-42.1.

Ben-David, M., Blundell, G.M., Kern, J.W., Maier, J.A.K., Brown, E.D., and Jewett, S.C. 2005. Communication in river otters: Creation of variable resource sheds for terrestrial communities. Ecology **86**(5): 1331–1345. doi:10.1890/04-0783.

Ben-David, M., Bowyer, R.T., and Faro, J.B. 1996. Niche Separation by Mink and River Otters: Coexistence in a Marine Environment. Oikos **75**(1): 41–48. doi:10.2307/3546319.

Ben-David, M., Hanley, T.A., Klein, D.R., and Schell, D.M. 1997. Seasonal changes in diets of coastal and riverine mink: the role of spawning Pacific salmon. Can. J. Zool. **75**(5): 803–811. doi:10.1139/z97-102.

Berejikian, B.A., Mathews, S.B., and Quinn, T.P. 1996. Effects of hatchery and wild ancestry and rearing environments on the development of agonistic behavior in steelhead trout (<I>Oncorhynchus mykiss</I>) fry. Can. J. Fish. Aquat. Sci. **53**(9): 2004–2014. doi:10.1139/cjfas-53-9-2004.

Berejikian, B.A., Tezak, E.P., and LaRae, A.L. 2003. Innate and enhanced predator recognition in hatchery-reared chinook salmon. Environ. Biol. Fishes **67**(3): 241–251. doi:10.1023/A:1025887015436.

Bonesi, L., Chanin, P., and Macdonald, D.W. 2004. Competition between Eurasian otter *Lutra lutra* and American mink *Mustela vison* probed by niche shift. Oikos **106**(1): 19–26. doi:10.1111/j.0030-1299.2004.12763.x.

Bosiger, Y.J., Lonnstedt, O.M., McCormick, M.I., and Ferrari, M.C.O. 2012. Learning Temporal Patterns of Risk in a Predator-Diverse Environment. PLoS ONE **7**(4): e34535. doi:10.1371/journal.pone.0034535.

Brannon, E., Winans, G., Carperter, L., Brewer, S., Utter, F., Hershberger, W., Setter, A., and Miller, M. 1986. Columbia River White Sturgeon (*Acipenser transmontanus*). Final Report, Bonneville Power Administration, Portland, OR.

Breault, D.N., Hodder, D.P., Crowley, S.M., and Johnson, C.J. 2021. Ecological niche breadth and overlap shape the trophic structure of a Mustelidae community in the subboreal forests of Canada. Press: 33.

Brönmark, C., and Hansson, L.-A. 2000. Chemical communication in aquatic systems: an introduction. Oikos **88**(1): 103–109. doi:10.1034/j.1600-0706.2000.880112.x.

Brown, B.T., Stevens, L.E., and Yates, T.A. 1998. Influences of Fluctuating River Flows on Bald Eagle Foraging Behavior. The Condor **100**(4): 745–748. doi:10.2307/1369759.

Brown, C., and Day, R.L. 2002. The future of stock enhancements: lessons for hatchery practice from conservation biology. Fish Fish. **3**(2): 79–94. doi:10.1046/j.1467-2979.2002.00077.x.

Brown, C., and Laland, K. 2001. Social learning and life skills training for hatchery reared fish. J. Fish Biol. **59**(3): 471–493. doi:10.1111/j.1095-8649.2001.tb02354.x.

Brown, G.E. 2003. Learning about danger: chemical alarm cues and local risk assessment in prey fishes. Fish Fish. **4**(3): 227–234. doi:10.1046/j.1467-2979.2003.00132.x.

Brown, G.E., and Dreier, V.M. 2002. Predator inspection behaviour and attack cone avoidance in a characin fish: the effects of predator diet and prey experience. Anim. Behav. **63**(6): 1175–1181. doi:10.1006/anbe.2002.3024.

Buehler, D.A. 2020, March 4. Bald Eagle (*Haliaeetus leucocephalus*), version 1.0. Available from https://birdsoftheworld.org/bow/species/baleag/cur/introduction [accessed 23 June 2021].

Bueno, F. 1996. Competition between American mink *Mustela vison* and otter *Lutra lutra* during winter. **41**(2): 149–154.

Cannings, R., Aversa, T., and Opperman, H. 2016. Birds of British Columbia and the Pacific Northwest: A Complete Guide. Heritage House Publishing Co. Ltd.

Chivers, D.P., and Smith, R.J.F. 1995. Fathead minnows (*Pimephales promelas*) learn to recognize chemical stimuli from high-risk habitats by the presence of alarm substance. Behav. Ecol. **6**(2): 155–158. doi:10.1093/beheco/6.2.155.

Clancy, G.P. 2005. Feeding Behaviour of the Osprey *Pandion haliaetus* on the North Coast of New South Whales. Corella **29**(4): 91–96.

Cogliati, K.M., Unrein, J.R., Stewart, H.A., Schreck, C.B., and Noakes, D.L.G. 2018. Egg size and emergence timing affect morphology and behavior in juvenile Chinook Salmon, *Oncorhynchus tshawytscha*. Ecol. Evol. **8**(1): 778–789. doi:10.1002/ece3.3670.

Collis, K., Hawbecker, M., Roby, D.D., Thompson, M., Faustino, C., Cardoni, C., Anderson, C.D., and Lyons, D.E. 2001. Cormorant and Brown Pelican Use of Excluder-fitted Pile Dikes in the Columbia River Estuary. Oregon State University, Corvallis, OR. Available from http://www.birdresearchnw.org/2001_Pile_Dike_Report.pdf [accessed 16 July 2021].

Collis, K., Roby, D.D., Craig, D.P., Adamany, S., Adkins, J.Y., and Lyons, D.E. 2002. Colony Size and Diet Composition of Piscivorous Waterbirds on the Lower Columbia River: Implications for Losses of Juvenile Salmonids to Avian Predation. Trans. Am. Fish. Soc. **131**: 537–550.

COSEWIC. 2010. COSEWIC assessment and status report on the Dolly Varden, *Salvelinus malma malma*, western Arctic populations in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa. Available from https://wildlife-species.canada.ca/species-risk-registry/virtual_sara/files/cosewic/sr_dolly_varden_0911_eng.pdf [accessed 20 May 2021].

COSEWIC. 2012. White sturgeon (*Acipenser transmontanus*) COSEWIC assessment and status report 2012. assessments;research. Available from https://www.canada.ca/en/environment-climate-change/services/species-risk-public-registry/cosewic-assessments-status-reports/white-sturgeon-2012.html [accessed 22 July 2021].

Cote, D., Gregory, R.S., and Stewart, H.M.J. 2008a. Size-selective predation by river otter (*Lontra canadensis*) improves refuge properties of shallow coastal marine nursery habitats. Can. J. Zool. **86**(11): 1324–1328. doi:10.1139/Z08-120.

Cote, D., Stewart, H.M.J., Gregory, R.S., Gosse, J., Reynolds, J.J., Stenson, G.B., and Miller, E.H. 2008b. Prey Selection by Marine-Coastal River Otters (*Lontra canadensis*) in Newfoundland, Canada. J. Mammal. **89**(4): 1001–1011. doi:10.1644/07-MAMM-A-192.1.

Cottrille, W.P., and Cottrille, B.D. 1958. Great Blue Heron: Behavior at the Nest. Mus. Zool. Univ. Mich. **102**: 24.

Counihan, T.D., and Frost, C.N. 1999. Influence of Externally Attached Transmitters on the Swimming Performance of Juvenile White Sturgeon. Trans. Am. Fish. Soc. **128**: 965–970.

Courchamp, F., Woodroffe, R., and Roemer, G.W. 2003. Removing Protected Populations to Save Endangered Species. Science **302**: 1532.

Craik, S.R., and Titman, R.D. 2008. Movements and habitat use by Red-breasted Merganser broods in eastern New Brunswick. Wilson J. Ornithol. **120**(4): 743–754. doi:10.1676/07-100.1.

Crait, J.R., and Ben-David, M. 2006. River Otters in Yellowstone Lake Depend on a Declining Cutthroat Trout Population. J. Mammal. **87**(3): 485–494. doi:10.1644/05-MAMM-A-205R1.1.

Crego, R.D., Jiménez, J.E., and Rozzi, R. 2016. A synergistic trio of invasive mammals? Facilitative interactions among beavers, muskrats, and mink at the southern end of the Americas. Biol. Invasions **18**(7): 1923–1938. doi:10.1007/s10530-016-1135-0.

Crowley, S., Johnson, C.J., and Hodder, D. 2012. Spatial and behavioral scales of habitat selection and activity by river otters at latrine sites. J. Mammal. **93**(1): 170–182. doi:10.1644/10-MAMM-A-362.1.

Crowley, S., Johnson, C.J., and Hodder, D.P. 2013. Spatio-temporal variation in river otter (*Lontra canadensis*) diet and latrine site activity. Écoscience **20**(1): 28–39. doi:10.2980/20-1-3509.

Daan, S. 1981. Adaptive Daily Strategies in Behavior. *In* Biological Rhythms. *Edited by* J. Aschoff. Springer US, Boston, MA. pp. 275–298. doi:10.1007/978-1-4615-6552-9_15.

Davis, H.G., Aulerich, R.J., Bursian, S.J., Sikarskie, J.G., and Stuht, J.N. 1992. Feed Consumption and Food Transit Time in Northern River Otters (*Lutra canadensis*). J. Zoo Wildl. Med. **23**(2): 241–244.

Day, C., Westover, M., and Mcmillan, B. 2015. Seasonal diet of the northern river otter (*Lontra canadensis*): What drives prey selection? Can. J. Zool. **93**: 197–205. doi:10.1139/cjz-2014-0218.

Derby, C.E., and Lovvorn, J.R. 1997. Predation on fish by cormorants and pelicans in a cold-water river: a field and modeling study. **54**: 14.

DFO. 2014. Recovery Strategy for White Sturgeon (*Acipenser transmontanus*) in Canada [Final]. Fisheries and Oceans Canada, Ottawa. Available from https://wildlife-species.canada.ca/species-risk-registry/virtual_sara/files/plans/rs_esturgeon_blc_wh_sturgeon_0314a_e.pdf [accessed 17 July 2021].

Domenici, P., and Blake, R.W. 1997. The kinematics and performance of fish fast-start swimming. J. Exp. Biol. **200**: 1165–1178.

Domenici, P., and Hale, M.E. 2019. Escape responses of fish: a review of the diversity in motor control, kinematics and behaviour. J. Exp. Biol. **222**(18): jeb166009. doi:10.1242/jeb.166009.

Dowd, E.M., and Flake, L.D. 1985. Foraging Habitats and Movements of Nesting Great Blue Herons in a Prairie River Ecosystem, South Dakota. J. Field Ornithol. **56**(4): 379–387.

Downie, A.T., and Kieffer, J.D. 2017. Swimming performance in juvenile shortnose sturgeon (*Acipenser brevirostrum*): the influence of time interval and velocity increments on critical swimming tests. Conserv. Physiol. **5**(1). doi:10.1093/conphys/cox038.

Dunbar, D.L. 1982. The breeding ecology and management of White Pelicans at Stum Lake, British Columbia. Master of Science Thesis, University of British Columbia, Vancouver, BC.

Dunstan, T.C., and Harper, J.F. 1975. Food Habits of Bald Eagles in North-Central Minnesota. J. Wildl. Manag. **39**(1): 140. doi:10.2307/3800476.

Dunstone, N., and Gorman, M.L. 2007. Behaviour and Ecology of Riparian Mammals. Cambridge University Press.

Dunstone, N., and O'Connor, R.J. 1979. Optimal foraging in an amphibious mammal. I. The aqualung effect. Anim. Behav. **27**: 1182–1194. doi:10.1016/0003-3472(79)90065-4.

EDI. 2016. Literature Review on Juvenile Nechako White Sturgeon Predation. Environmental Dynamics Inc., Prince George, BC V2L 1R4.

Elliott, K. 2006. Declining numbers of Western Screech-Owl in the Lower Mainland of British Columbia. Br. Columbia Birds **14**: 10.

Elliott, K.H., Elliott, J.E., Wilson, L.K., Jones, I., and Stenerson, K. 2011. Density-dependence in the survival and reproduction of Bald Eagles: Linkages to Chum Salmon. J. Wildl. Manag. **75**(8): 1688–1699. doi:10.1002/jwmg.233.

Erlinge, S. 1972. Interspecific Relations between Otter *Lutra Lutra* and Mink *Mustella Vison* in Sweden. Oikos **23**(3): 327–335. [Nordic Society Oikos, Wiley]. doi:10.2307/3543171.

Fenderson, O.C., and Carpenter, M.R. 1971. Effects of crowding on the behaviour of juvenile hatchery and wild landlocked Atlantic salmon (*Salmo salar* L.). Anim. Behav. **19**(3): 439–447. doi:10.1016/S0003-3472(71)80096-9.

Ferrari, M.C.O., Elvidge, C.K., Jackson, C.D., Chivers, D.P., and Brown, G.E. 2010a. The responses of prey fish to temporal variation in predation risk: sensory habituation or risk assessment? Behav. Ecol. **21**(3): 532–536. doi:10.1093/beheco/arq023.

Ferrari, M.C.O., Wisenden, B.D., and Chivers, D.P. 2010b. Chemical ecology of predator–prey interactions in aquatic ecosystems: a review and prospectus. Can. J. Zool. **88**(7): 698–724. doi:10.1139/Z10-029.

Ferreras, P., and Macdonald, D.W. 1999. The impact of American mink *Mustela vison* on water birds in the upper Thames. J. Appl. Ecol. **36**(5): 701–708. doi:10.1046/j.1365-2664.1999.00431.x.

Finley, W.L. 1906. Herons at Home. The Condor **8**(2): 35–40. doi:10.2307/1361084.

Fisheries and Oceans Canada. 2014. Recovery Strategy for White Sturgeon (*Acipenser transmontanus*) in Canada. Fisheries and Oceans Canada, Ottawa, Ont.

Fisheries and Oceans Canada. 2020, July 8. Interim code of practice: beaver dam removal. Available from https://www.dfo-mpo.gc.ca/pnw-ppe/codes/beaver-dam-barrage-castor-eng.html [accessed 3 August 2021].

Forbush, E.H. 1927. Birds of Massachusetts And Other New England States - Part II. Land Birds From Bob-Whites To Grackles. *In* 1st edition. Norwood Press.

Francour, P., and Thibault, J.-C. 1996. The diet of breeding Osprey *Pandion haliaetus* on Corsica: exploitation of a coastal marine environment. Bird Study **43**(2): 129–133. doi:10.1080/00063659609461004.

Fretueg, G.R., Martin, T.J., Widga, C., and Ruez, D.R. 2015. Summer Diet Characteristics of North American River Otters (*Lontra canadensis*) in Central Illinois. Am. Midl. Nat. **173**(2): 294–304. doi:10.1674/amid-173-02-294-304.1.

Gadomski, D.M., and Parsley, M.J. 2005a. Effects of Turbidity, Light Level, and Cover on Predation of White Sturgeon Larvae by Prickly Sculpins. Trans. Am. Fish. Soc. **134**(2): 369–374. doi:10.1577/T03-213.1.

Gadomski, D.M., and Parsley, M.J. 2005b. Laboratory Studies on the Vulnerability of Young White Sturgeon to Predation. North Am. J. Fish. Manag. **25**(2): 667–674. doi:10.1577/M03-220.1.

Gawlik, D.E. 2002. THE EFFECTS OF PREY AVAILABILITY ON THE NUMERICAL RESPONSE OF WADING BIRDS. Ecol. Monogr. **72**(3): 18.

GBIF.org. 2021, June 22. GBIF Occurrence Download. Available from https://doi.org/10.15468/dl.yv94ee [accessed 22 June 2021].

Gibbs, J. 1991. Spatial Relationships between Nesting Colonies and Foraging Areas of Great Blue Herons. The Auk **108**: 764–770. doi:10.1093/AUK/108.4.764.

Gilbert, F.F., and Nancekivell, E.G. 1982. Food habits of mink (*Mustela vison*) and otter (*Lutra canadensis*) in northeastern Alberta. Can. J. Zool. **60**(6): 1282–1288. doi:10.1139/z82-172.

Glahn, J.F., Dorr, B., Harrel, J.B., and Khoo, L. 2002. Foraging Ecology and Depredation Management of Great Blue Herons at Mississippi Catfish Farms. J. Wildl. Manag. **66**(1): 194. doi:10.2307/3802885.

Glahn, J.F., Tomsa, T., and Preusser, K.J. 1999. Impact of Great Blue Heron Predation at Trout-Rearing Facilities in the Northeastern United States. North Am. J. Aquac. **61**(4): 349–354. doi:https://doi.org/10.1577/1548-8454(1999)061<0349:IOGBHP>2.0.CO;2.

Glass, K.A., and Watts, B.D. 2009. Osprey Diet Composition and Quality in High- and Low-Salinity Areas of Lower Chesapeake Bay. J. Raptor Res. **43**(1): 27–36. doi:10.3356/JRR-08-22.1.

Gorman, T.A., Erb, J.D., McMillan, B.R., Martin, D.J., and Homyack, J.A. 2006. Site Characteristics of River Otter (*Lontra canadensis*) Natal Dens in Minnesota. Am. Midl. Nat. **156**(1): 109–117. doi:10.1674/0003-0031(2006)156[109:SCOROL]2.0.CO;2.

Green, D.J., and Krebs, E.A. 1995. Courtship feeding in Ospreys *Pandion haliaetus*: a criterion for mate assessment? Ibis **137**(1): 35–43. doi:10.1111/j.1474-919X.1995.tb03217.x.

Gro Vea Salvanes, A., and Braithwaite, V. 2006. The need to understand the behaviour of fish reared for mariculture or restocking. ICES J. Mar. Sci. **63**(2): 345–354. doi:10.1016/j.icesjms.2005.11.010.

Haan, D.M., and Halbrook, R.S. 2015. Home Ranges and Movement Characteristics of Minks in East-central New York. Am. Midl. Nat. **174**(2): 302–309. doi:10.1674/0003-0031-174.2.302.

Hakkinen, I. 1978. Diet of the Osprey *Pandion haliaetus* in Finland. Ornis Scand. **9**(1): 111. doi:10.2307/3676145.

Hanson, A.R., and Kerekes, J.J. (*Editors*). 2006. Limnology and aquatic birds: proceedings of the Fourth Conference, Working Group on Aquatic Birds of Societas Internationalis Limnologiae (SIL), Sackville, New Brunswick, Canada, August 3-7, 2003. Springer, Dordrecht.

Hanson, M.R., and Baldwin, J.D. 2017. Adjusted Diets of Bald Eagles (*Haliaeetus leucocephalus*) Breeding In An Altered Estuary. J. Raptor Res. **51**(1): 1–14. doi:10.3356/JRR-16-00005.1.

Harper, W.L. 2004. American White Pelican *Pelecanus erythrorhynchos*. Province of British Columbia, Victoria, B.C. Available from https://www2.gov.bc.ca/assets/gov/environment/natural-resource-policy-legislation/accounts-measures-for-managing-identified-wildlife/birds_american_white_pelican.pdf.

Harris, S., and Yalden, D.W. 2008. Mammals of the British Isles: Handbook. Mammal Society.

Hatfield, T., McAdam, S.O., and Nelson, T. 2004. Impacts to Abundance and Distribution of Fraser River White Sturgeon: A Summary of Existing Information and Presentation of Impact Hypotheses. Fraser River Sturgeon Conservation Society Fraser River White Sturgeon Working Group, British Columbia. Available from http://frasersturgeon.com/wp-content/uploads/2019/01/Fraser-Impact-hypothesis-2004.pdf [accessed 17 July 2021].

Hatler, D.F. 1976. The coastal mink on Vancouver Island, British Columbia. University of British Columbia. doi:10.14288/1.0093865.

Hatler, D.F., Nagorsen, D.W., and Beal, A.M. 2008. Royal BC Museum Handbook: Carnivores of British Columbia. Royal BC Museum, Victoria, B.C. Available from https://publications.royalbcmuseum.bc.ca/product/carnivores-of-british-columbia/ [accessed 9 August 2019].

Haywood, D.D., and Ohmart, R.D. 1986. Utilization of Benthic-Feeding Fish by Inland Breeding Bald Eagles. The Condor **88**(1): 35. doi:10.2307/1367750.

Helon, D.A., Anderson, J.T., Dwyer, C., Harbor, O., and Edwards, J. 2004. Summer home range size and habitat use by river otters in Ohio. undefined. Available from https://www.semanticscholar.org/paper/SUMMER-HOME-RANGE-SIZE-AND-HABITAT-USE-BY-RIVER-IN-Helon-Anderson/12b1345ae40194817e829392fd2945fa729b4b3f [accessed 28 June 2021].

Helon, D.A., Dwyer, C.P., Witt, M.D., Edwards, J.W., and Anderson, J.T. 2013. Summer movements and activity patterns of river otters in Northeastern Ohio, USA. : 10.

Henny, C.J. 1986. Osprey (*Pandion haliaetus*): Section 4.3.1. Technical Report, U.S. Army Corps of Engineers, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Henny, C.J., and Velzen, W.T.V. 1972. Migration Patterns and Wintering Localities of American Ospreys. J. Wildl. Manag. **36**(4): 1133. doi:10.2307/3799242.

Hildebrand, L.R., Drauch Schreier, A., Lepla, K., McAdam, S.O., McLellan, J., Parsley, M.J., Paragamian, V.L., and Young, S.P. 2016. Status of White Sturgeon (*Acipenser transmontanus* Richardson, 1863) throughout the species range, threats to survival, and prognosis for the future. J. Appl. Ichthyol. **32**: 261–312. doi:10.1111/jai.13243.

Hilton, E.J., and McGrath, P.E. 2021. It's raining sturgeons: a likely occurrence of avian predation or scavenging of Atlantic Sturgeon (*Acipenser oxyrinchus* Mitchell, 1815). Banisteria **55**: N7-12.

Hodder, D.P. 2016. Habitat selection and occupancy patterns of American mink (*Neovison vison*) during winter in North-Central British Columbia, Canada. Master of Science, Thompson Rivers University, British Columbia.

Hodder, D.P., Larsen, K.W., and Crowley, S.M. 2017. The role of environmental variables and sympatric meso-carnivores on the detection and occupancy of American mink during winter. Hystrix Ital. J. Mammal. **28**(1): 16–20.

Hodder, D.P., Larsen, K.W., and Crowley, S.M. 2018. Effects of Scale and Gender on Winter Habitat Selection by American Mink. Am. Midl. Nat. **179**(2): 261–274. doi:10.1674/0003-0031-179.2.261.

Hodgens, L.S., Blumenshine, S.C., and Bednarz, J.C. 2004. Great Blue Heron Predation on Stocked Rainbow Trout in an Arkansas Tailwater Fishery. North Am. J. Fish. Manag. **24**(1): 63–75. doi:10.1577/M02-130.

Hoffman, J.D., Genoways, H.H., and Wilson, S. 2009. Historical Winter Diets of Mink (Mustela vison) in Nebraska. Trans. Kans. Acad. Sci. **112**(1/2): 119–122. doi:10.1660/062.112.0216.

Holmengen, N., Seip, K.L., Boyce, M., and Stenseth, N.C. 2009. Predator–prey coupling: interaction between mink Mustela vison and muskrat Ondatra zibethicus across Canada. Oikos **118**(3): 440–448. doi:10.1111/j.1600-0706.2008.16613.x.

Holms, G.B., Canada, Environment Canada, Pacific and Yukon Region, Aquatic Science Section, British Columbia, Water Quality Section, and Canada-British Columbia Water Quality Monitoring Agreement. 1997. State of water quality of Nechako River at Prince George, 1985-1995. Water Quality Section, Ministry of Environment, Lands and Parks, Victoria, B.C. Available from http://www.llbc.leg.bc.ca/public/PubDocs/bcdocs/349941/index.pdf [accessed 15 December 2021].

del Hoyo, J., Elliot, A., and Sargatal, J. (*Editors*). 1996. Handbook of the Birds of the World: Hoatzin to Auks. Lynx Edicions. Available from https://www.lynxeds.com/product/handbook-of-the-birds-of-the-world-volume-3/ [accessed 8 July 2021].

Huang, A.C., Nelson, C., Elliott, J.E., Guertin, D.A., Ritland, C., Drouillard, K., Cheng, K.M., and Schwantje, H.M. 2018. River otters (*Lontra canadensis*) “trapped” in a coastal environment contaminated with persistent organic pollutants: Demographic and physiological consequences. Environ. Pollut. **238**: 306–316. doi:10.1016/j.envpol.2018.03.035.

Humple, D.L., and Holcomb, J.B. 2014. Winter Movements of Western Grebes and Clark’s Grebes: Insights from Band Recoveries. North Am. Bird Bander **39**(1): 8.

Hunt, W.G., Jackman, R.E., and Driscoll, D.E. 2002. Foraging ecology of nesting Bald Eagles in Arizona. J. Raptor Res. **36**(4): 245–255.

Huntingford, F.A. 2004. Implications of domestication and rearing conditions for the behaviour of cultivated fishes. J. Fish Biol. **65**(s1): 122–142. doi:10.1111/j.0022-1112.2004.00562.x.

Jacobsen, L. 2005. Otter (*Lutra lutra*) predation on stocked brown trout (*Salmo trutta*) in two Danish lowland rivers. Ecol. Freshw. Fish **14**(1): 59–68. doi:10.1111/j.1600-0633.2004.00076.x.

Johnson, C.J., Mumma, M.A., and St-Laurent, M. 2019. Modeling multispecies predator–prey dynamics: predicting the outcomes of conservation actions for woodland caribou. Ecosphere **10**(3): e02622. doi:10.1002/ecs2.2622.

Kelley, J.L., and Magurran, A.E. 2003. Learned predator recognition and antipredator responses in fishes. Fish Fish. **4**(3): 216–226. doi:10.1046/j.1467-2979.2003.00126.x.

Kern, J.C., Farr, R.A., Rien, T.A., James, B.W., Gilliland, D.R., Cady, B.J., DeVore, J.D., Gadomski, D.M., Parsley, M.J., Kofoot, P., Kappenman, K., Parker, B.L., Holmes, J.A.S., Webb, M.A.H., and Schreck, C.B. 2002. White sturgeon mitigation and restoration in the Columbia and Snake Rivers upstream from Bonneville Dam. Annual Progress Report, U.S. Department of Energy Bonneville Power Administration Environment, Fish and Wildlife, Portland, OR. Available from https://www.dfw.state.or.us/fish/oscrp/cri/docs/AllRpt00.pdf [accessed 17 July 2021].

Kieffer, J.D., Arsenault, L.M., and Litvak, M.K. 2009. Behaviour and performance of juvenile shortnose sturgeon *Acipenser brevirostrum* at different water velocities. J. Fish Biol. **74**(3): 674–682. doi:10.1111/j.1095-8649.2008.02139.x.

Kieffer, J.D., and Colgan, P.W. 1992. The role of learning in fish behaviour. Rev. Fish Biol. Fish. **2**(2): 125–143. doi:10.1007/BF00042881.

King, D.T. 2005. Interactions Between the American White Pelican and Aquaculture in the Southeastern United States: an Overview. Waterbirds **28**(sp1): 83–86. doi:10.1675/1524-4695(2005)28[83:IBTAWP]2.0.CO;2.

King, D.T., Fischer, J., Strickland, B., Walter, W.D., Cunningham, F.L., and Wang, G. 2016. Winter and Summer Home Ranges of American White Pelicans (*Pelecanus* *erythrorhynchos*) Captured at Loafing Sites in the Southeastern United States. Waterbirds **39**(3): 287–294. doi:10.1675/063.039.0308.

Klatt, P.H. 2003. Territorial Behavior and Nesting Dispersion in Red-Necked Grebes. Waterbirds Int. J. Waterbird Biol. **26**(1): 94–99.

Kopack, C.J., Dale Broder, E., Lepak, J.M., Fetherman, E.R., and Angeloni, L.M. 2015. Behavioral responses of a highly domesticated, predator naïve rainbow trout to chemical cues of predation. Fish. Res. **169**: 1–7. doi:10.1016/j.fishres.2015.04.005.

Krause, J., Loader, S.P., McDermott, J., and Ruxton, G.D. 1998. Refuge use by fish as a function of body length–related metabolic expenditure and predation risks. Proc. R. Soc. Lond. B Biol. Sci. **265**(1413): 2373–2379. doi:10.1098/rspb.1998.0586.

Kruuk, H. 1995. Wild otters: predation and populations. Oxford University Press, New York.

Kruuk, H. 2006. Otters: Ecology, Behaviour and Conservation. Oxford University Press, New York.

Landeau, L., and Terborgh, J. 1986. Oddity and the ‘confusion effect’ in predation. Anim. Behav. **34**(5): 1372–1380. doi:10.1016/S0003-3472(86)80208-1.

Lariviere, S., and Walton, L.R. 1998. *Lontra canadensis*. Mamm. Species (587): 1–8. doi:10.2307/3504417.

Lawrence, G.E. 1950. The Diving and Feeding Activity of the Western Grebe on the Breeding Grounds. The Condor **52**(1): 3–16. doi:10.2307/1364743.

Levenson, H. 1976. Behavior and energetics of ospreys nesting in northern California. Master of Science, Humboldt State University, California.

Levenson, H. 1979. Time and Activity Budget of Ospreys Nesting in Northern California. The Condor **81**(4): 364. doi:10.2307/1366960.

Lodé, T. 1993. Diet composition and habitat use of sympatric polecat and American mink in western France. Acta Theriol. (Warsz.) **38**: 161–166. doi:10.4098/AT.arch.93-14.

López-Olmeda, J.F., Noble, C., and Sánchez-Vázquez, F.J. 2012. Does feeding time affect fish welfare? Fish Physiol. Biochem. **38**(1): 143–152. doi:10.1007/s10695-011-9523-y.

Mabie, D.W., Merendino, M.T., and Reid, D.H. 1995. Prey of Nesting Bald Eagles in Texas. J. Raptor Res. **29**(1): 10–14.

Macdonald, D.W., and Harrington, L.A. 2003. The American mink: The triumph and tragedy of adaptation out of context. N. Z. J. Zool. **30**(4): 421–441. doi:10.1080/03014223.2003.9518350.

Macdonald, J.S., Morrison, J., and Patterson, D.A. 2012. The Efficacy of Reservoir Flow Regulation for Cooling Migration Temperature for Sockeye Salmon in the Nechako River Watershed of British Columbia. North Am. J. Fish. Manag. **32**(3): 415–427. doi:10.1080/02755947.2012.675946.

Machmer, M.M., and Ydenberg, R.C. 1990. Weather and Osprey foraging energetics. Can. J. Zool. **68**(1): 40–43. doi:10.1139/z90-007.

Madrid, J.A., Boujard, T., and Sánchez-Vázquez, F.J. 2001. Feeding Rhythms. *In* Food Intake in Fish. John Wiley & Sons, Ltd. pp. 189–215. doi:10.1002/9780470999516.ch8.

Mallory, M., and Metz, K. 1998. Common Merganser. *In* The Birds of North America, First. *Edited by* A. Poole and F. Gill. The Birds of North American, Inc., Philadelphia, PA. pp. 1–28.

Martel, G., and Dill, L.M. 1995. Influence of Movement by Coho Salmon (*Oncorhynchus kisutch*) Parr on Their Detection by Common Mergansers (*Mergus merganser*). Ethology **99**: 139–149. doi:10.1111/j.1439-0310.1995.tb01095.x.

McAdam, S.O. 2011. Effects of substrate condition on habitat use and survival by white sturgeon (*Acipenser transmontanus*) larvae and potential implications for recruitment. Can. J. Fish. Aquat. Sci. **68**(5): 812–822. doi:10.1139/f2011-021.

McAdam, S.O. 2012. Diagnosing causes of white sturgeon (*Acipenser transmontanus*) recruitment failure and the importance of substrate condition to yolksac larvae survival. Doctor of Philosophy in the Faculty of Graduate Studies (Zoology), University of British Columbia, Vancouver, BC.

McAdam, S.O., Walters, C.J., and Nistor, C. 2005. Linkages between White Sturgeon Recruitment and Altered Bed Substrates in the Nechako River, Canada. Trans. Am. Fish. Soc. **134**(6): 1448–1456. doi:10.1577/T04-199.1.

McLaren, A. 2016. Wolf Management Programs in Northwest Territories, Alaska, Yukon, British Columbia, and Alberta: A Review of Options for Management on the Bathurst Caribou Herd Range in the Northwest Territories. Government of Northwest Territories, NWT.

McLean, P.K., and Byrd, M.A. 1991. Feeding Ecology of Chesapeake Bay Ospreys and Growth and Behavior of Their Young. Wilson Bull. **103**(1): 105–111.

McMahon, B.F., and Evans, R.M. 1992. Nocturnal Foraging in the American White Pelican. The Condor **94**(1): 101–109. doi:10.2307/1368800.

McNeil, R., Benoît, R., and Desgranges, J.-L. 1993. Daytime and nighttime activity at a breeding colony of Great Blue Herons in a nontidal environment. Can. J. Zool. **71**(6): 1075–1078. doi:10.1139/z93-145.

Melquist, W.E., and Hornocker, M.G. 1983. Ecology of River Otters in West Central Idaho. Wildl. Monogr. **83**: 3–60.

Miller, A.I., and Beckman, L.G. 1996. First Record of Predation on White Sturgeon Eggs by Sympatric Fishes. Trans. Am. Fish. Soc. **125**(2): 338–340. doi:10.1577/1548-8659(1996)125<0338:fropow>2.3.co;2.

Mills, K.L., Gaydos, J.K., Fiorello, C.V., Whitmer, E.R., Cruz, S.D.L., Mulcahy, D.M., Vilchis, L.I., and Ziccardi, M.H. 2016. Post-Release Survival and Movement of Western Grebes (*Aechmophorus occidentalis*) Implanted with Intracoelomic Satellite Transmitters. Waterbirds **39**(2): 175–186. doi:10.1675/063.039.0208.

Missouri Department of Conservation. 2002. Missouri's River Otter: A Guide to Management and Damage Control. Conservation Commission of the State of Missouri. Available from http://fisheries.tamu.edu/files/2013/10/Missouri%E2%80%99s-River-Otter-A-Guide-to-Management-and-Damage-Control.pdf [accessed 17 July 2021].

Mitchell, M.D., Chivers, D.P., McCormick, M.I., and Ferrari, M.C.O. 2015. Learning to distinguish between predators and non-predators: understanding the critical role of diet cues and predator odours in generalisation. Sci. Rep. **5**(1): 13918. doi:10.1038/srep13918.

Mitchell, W.A., and Wolters, M.S. 2000. Riparian Raptors on USACE Projects: Osprey (*Pandion haliaetus*). U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS. Available from www.wes.army.mil/el/emrrp.

Nolet, B.A., Wansink, D.E.H., and Kruuk, H. 1993. Diving of Otters (*Lutra lutra*) in a Marine Habitat: Use of Depths by a Single-Prey Loader. J. Anim. Ecol. **62**(1): 22–32. doi:10.2307/5479.

NWSRI. 2020. Nechako White Sturgeon Recovery Initiative 2019-2020 Annual Report. The Nechako White Sturgeon Conservation Centre, Vanderhoof, BC. Available from nechakowhitesturgeon.org.

NWSRI. 2021. Annual Reports. Available from https://www.nechakowhitesturgeon.org/publications/annual-reports [accessed 20 July 2021].

Oldham, A.R., and Black, J.M. 2009. Experimental Tests of Latrine Use and Communication by River Otters. Northwest. Nat. **90**(3): 207–211. doi:10.1898/NWN08-20.1.

Olla, B.L., Davis, M.W., and Ryer, C.H. 1998. Understanding how the Hatchery Environment Represses or Promotes the Development of Behavioral Survival Skills. Bull. Mar. Sci. **62**(2): 26.

Park, E. 1971. The world of the otter. J.B. Lippincott and Company, New York.

Parsley, M.J., Anders, P.J., Miller, A.I., Beckman, L.G., and McCabe, G.T. 2002. Recovery of white sturgeon populations through natural production: understanding the influence of abiotic and biotic factors on spawning and subsequent recruitment. Am. Fish. Soc. Symp. **28**: 55–66.

Parsley, M.J., Beckman, L.G., and Mccabe, G.T. 1993. Spawning and Rearing Habitat Use by White Sturgeons in the Columbia River Downstream from McNary Dam. Trans. Am. Fish. Soc. **122**: 217–227.

Paruk, J.D., Chickering, M.D., Long, D., Uher-Koch, H., East, A., Poleschook, D., Gumm, V., Hanson, W., Adams, E.M., Kovach, K.A., and Evers, D.C. 2015. Winter site fidelity and winter movements in Common Loons (*Gavia immer*) across North America. The Condor **117**(4): 485–493. doi:10.1650/CONDOR-15-6.1.

Paszkowski, C.A., Gingras, B.A., Wilcox, K., Klatt, P.H., and Tonn, W.M. 2004. Trophic Relations of the Red-Necked Grebe on Lakes in the Western Boreal Forest: A Stable-Isotope Analysis. The Condor **106**(3): 638–651. doi:10.1093/condor/106.3.638.

Peake, S., Beamish, F.W., McKinley, R.S., Scruton, D.A., and Katopodis, C. 1997. Relating swimming performance of lake sturgeon, *Acipenser fulvescens*, to fishway design. Can. J. Fish. Aquat. Sci. **54**(6): 1361–1366. doi:10.1139/f97-039.

Perrin, C.J., Rempel, L.L., and Rosenau, M.L. 2003. White Sturgeon Spawning Habitat in an Unregulated River: Fraser River, Canada. Trans. Am. Fish. Soc. **132**(1): 154–165. doi:10.1577/1548-8659(2003)132<0154:wsshia>2.0.co;2.

Pierre, J.P., Boss, S.M., and Paszkowski, C.A. 2005. Effects of forest harvesting on Bufflehead and Common Loon foraging behavior. Ornithol. Sci. **4**(2): 161–168. doi:10.2326/osj.4.161.

Poole, T.B., and Dunstone, N. 1976. Underwater predatory behaviour of the American mink (*Mustela vison*). J. Zool. **178**(3): 395–412. doi:10.1111/j.1469-7998.1976.tb02277.x.

Popowics, T.E. 2003. Postcanine dental form in the mustelidae and viverridae (Carnivora: Mammalia). J. Morphol. **256**(3): 322–341. doi:10.1002/jmor.10091.

Province of BC. 2020. Trapping Regulations 2020–2022. Ministry of Forests, Lands, Natural Resource Operations and Rural Development. Available from https://www2.gov.bc.ca/assets/gov/sports-recreation-arts-and-culture/outdoor-recreation/fishing-and-hunting/hunting/regulations/2020-2022/trapping-synopsis-2020-2022.pdf [accessed 3 August 2021].

Prugh, L.R., Sivy, K.J., Mahoney, P.J., Ganz, T.R., Ditmer, M.A., van de Kerk, M., Gilbert, S.L., and Montgomery, R.A. 2019. Designing studies of predation risk for improved inference in carnivore-ungulate systems. Biol. Conserv. **232**: 194–207. doi:10.1016/j.biocon.2019.02.011.

Pyke, G.H., Pulliam, H.R., and Charnov, E.L. 1977. Optimal Foraging: A Selective Review of Theory and Tests. Q. Rev. Biol. **52**(2): 137–154. doi:10.1086/409852.

QGIS.org. 2021. QGIS Geographic Information System. QGIS Association. Available from http://www.qgis.org [accessed 18 June 2021].

Reed-Smith, J. (*Editor*). 2008. North American river otter (*Lontra canadensis*) husbandry notebook. *In* 3rd edition. John Ball Zoo, Grand Rapids, Michigan.

Reid, D., Code, T., Reid, A., and Herrero, S. 2011. Food habits of the river otter in a boreal ecosystem. Can. J. Zool. **72**: 1306–1313. doi:10.1139/z94-174.

Reid, D.G., Code, T.E., Reid, A.C.H., and Herrero, S.M. 1994. Food habits of the river otter in a boreal ecosystem. Can. J. Zool. **72**(7): 1306–1313. doi:10.1139/z94-174.

Reid, D.G., Waterhouse, L., Buck, P.E., Derocher, A.E., Bettner, R., and French, C.D. 2000. Inventory of the Queen Charlotte Islands ermine. *In* Proceedings of a Conference on the Biology and Management of Species and Habitats at Risk. *Edited by* L.M. Darling. B.C. Ministry of Environment, Lands and Parks, and University College of the Cariboo, Kamloops, BC. pp. 393–406.

Roberts, L.J., Taylor, J., and Garcia de Leaniz, C. 2011. Environmental enrichment reduces maladaptive risk-taking behavior in salmon reared for conservation. Biol. Conserv. **144**(7): 1972–1979. doi:10.1016/j.biocon.2011.04.017.

Roberts, N.M., Rabeni, C.F., Stanovick, J.S., and Hamilton, D.A. 2008. River Otter, *Lontra canadensis*, Food Habits in the Missouri Ozarks. Can. Field-Nat. **122**(4): 303. doi:10.22621/cfn.v122i4.636.

Roemer, G.W., Coonan, T.J., Garcelon, D.K., Bascompte, J., and Laughrin, L. 2001. Feral pigs facilitate hyperpredation by golden eagles and indirectly cause the decline of the island fox. Anim. Conserv. **4**(4): 307–318. doi:10.1017/S1367943001001366.

Rust, P., and Wakkinen, V. 2005. Kootenai River White Sturgeon Investigations: White Sturgeon Spawning and Recruitment Evaluation, 2004-2005 Annual Report. Bonneville Power Administration, Portland, OR.

Ruxton, G.D., Speed, M.P., and Kelly, D.J. 2004. What, if anything, is the adaptive function of countershading? Anim. Behav. **68**(3): 445–451. doi:10.1016/j.anbehav.2003.12.009.

Ryder, R.A. 1955. Fish Predation by the Otter in Michigan. J. Wildl. Manag. **19**(4): 497. doi:10.2307/3797475.

Salvanes, A.G.V. 2017. Are antipredator behaviours of hatchery *Salmo salar* juveniles similar to wild juveniles?: antipredator behaviour in juvenile *salmo salar*. J. Fish Biol. **90**(5): 1785–1796. doi:10.1111/jfb.13268.

Salyer, J.C., and Lagler, K.F. 1949. The Eastern Belted Kingfisher, Megaceryle Alcyon Alcyon (Linnaeus), in Relation to Fish Management. Trans. Am. Fish. Soc. **76**(1): 97–117. doi:10.1577/1548-8659(1946)76[97:TEBKMA]2.0.CO;2.

Schooley, R.L., Cotner, L.A., Ahlers, A.A., Heske, E.J., and Levengood, J.M. 2012. Monitoring site occupancy for American mink in its native range: Occupancy Surveys for Mink. J. Wildl. Manag. **76**(4): 824–831. doi:10.1002/jwmg.294.

Semakula, S.N., and Larkin, P.A. 1968. Age, Growth, Food, and Yield of the White Sturgeon (*Acipenser transmontanus*) of the Fraser River, British Columbia. J. Fish. Res. Board Can. **25**(12): 2589–2602. doi:10.1139/f68-229.

Serfass, T., Rymon, L.M., and Brooks, R. 1990. Feeding relationships of river otters in northeastern Pennsylvania. Trans. Northeast Sect. Wildl. Soc. **47**: 43–53.

Sheldon, W.G., and Toll, W.G. 1964. Feeding Habits of the River Otter in a Reservoir in Central Massachusetts. J. Mammal. **45**(3): 449–455. doi:10.2307/1377419.

Sherker, Z.T. 2020. Predation by Pacific great blue herons on juvenile salmon. University of British Columbia. doi:10.14288/1.0390460.

Singer, T.D., Mahadevappa, V.G., and Ballantyne, J.S. 1990. Aspects of the Energy Metabolism of Lake Sturgeon, *Acipenser fulvescens* , with Special Emphasis on Lipid and Ketone Body Metabolism. Can. J. Fish. Aquat. Sci. **47**(5): 873–881. doi:10.1139/f90-100.

Siverio, M., Rodríguez, B., Rodríguez, A., and Siverio, F. 2011. Inter-insular variation of the diet of osprey *Pandion haliaetus* in the Canarian archipelago. Wildl. Biol. **17**(3): 240–247. doi:10.2981/10-004.

Smith, R.J.F. 1992. Alarm signals in fishes. Rev. Fish Biol. Fish. **2**(1): 33–63. doi:10.1007/BF00042916.

Solberg, M.F., Robertsen, G., Sundt-Hansen, L.E., Hindar, K., and Glover, K.A. 2020. Domestication leads to increased predation susceptibility. Sci. Rep. **10**(1): 1929. doi:10.1038/s41598-020-58661-9.

Stalmaster, M.V. 1987. The bald eagle. Universe Books, New York.

Steeger, C., Esselink, H., and Ydenberg, R.C. 1992. Comparative feeding ecology and reproductive performance of ospreys in different habitats of southeastern British Columbia. Can. J. Zool. **70**(3): 470–475. doi:10.1139/z92-071.

Stenson, G.B., Badgero, G.A., and Fisher, H.D. 1984. Food habits of the river otter *Lutra canadensis* in the marine environment of British Columbia. Can. J. Zool. **62**(1): 88–91. doi:10.1139/z84-015.

Stinson, C.H., Lauthner, J., and Ray, R.T. 1987. The effect of weather conditions on the behavior of ospreys in northwestern Washington. Can. J. Zool. **65**(8): 2116–2118. doi:10.1139/z87-325.

Stinson, D.W. 2016. Periodic Status Review for the American White Pelican in Washington. Technical Report, Washington Department of Fish and Wildlife, Olympia, Washington.

Swain, D.P., and Riddell, B.E. 1990. Variation in Agonistic Behavior between Newly Emerged Juveniles from Hatchery and Wild Populations of Coho Salmon, *Oncorhynchus kisutch*. Can. J. Fish. Aquat. Sci. **47**(3): 566–571. doi:10.1139/f90-065.

Swenson, J.E. 1979. The Relationship between Prey Species Ecology and Dive Success in Ospreys. The Auk **96**(2): 408–412.

Taastrom, H.-M., and Jacobsen, L. 1999. The diet of otters (*Lutra lutra* L.) in Danish freshwater habitats: comparisons of prey fish populations. J. Zool. **248**(1): 1–13. doi:10.1111/j.1469-7998.1999.tb01017.x.

Tarasoff, F.J., Bisaillon, A., Piérard, J., and Whitt, A.P. 1972. Locomotory patterns and external morphology of the river otter, sea otter, and harp seal (Mammalia). Can. J. Zool. **50**(7): 915–929. doi:10.1139/z72-124.

Tarasoff, F.J., and Kooyman, G.L. 1973. Observations on the anatomy of the respiratory system of the river otter, sea otter, and harp seal. II. The trachea and bronchial tree. Can. J. Zool. **51**(2): 171–177. doi:10.1139/z73-025.

The Chronicle Staff. 2021. Anglers Remove More Than 100,000 Pikeminnow From Rivers During Pandemic. News. Available from https://www.chronline.com/stories/anglers-remove-more-than-100000-pikeminnow-from-rivers-during-pandemic,260138 [accessed 30 July 2021].

Thompson, C.M., Nye, P.E., Schmidt, G.A., and Garcelon, D.K. 2005. Foraging ecology of bald eagles in a freshwater tidal system. J. Wildl. Manag. **69**(2): 609–617. doi:10.2193/0022-541X(2005)069[0609:FEOBEI]2.0.CO;2.

Thompson, L., and Stelle, L.L. 2014. Prey preference of the North American river otter (*Lontra canadensis*) evaluated based on optimal foraging theory. IUCN Otter Spec. Group Bull. **31**: 15–29.

Todd, C.S., Young, L.S., Owen, R.B., and Gramlich, F.J. 1982. Food Habits of Bald Eagles in Maine. J. Wildl. Manag. **46**(3): 636–645. doi:10.2307/3808554.

Toweill, D.E., and Tabor, J.E. 1982. River otter: *Lutra canadensis*. *In* Wild mammals of North America: Biology, management, and economics. *Edited by* J.A. Chapman. Johns Hopkins University Press, Baltimore. pp. 688–703.

U.S. Army Corps of Engineers. 2016. 2015 Field Report: Evaluation of Pinniped Predation on Adult Salmonids and Other Fish in the Bonneville Dam Tailrace, 2015. NMFS (National Marine Fisheries Service), Portland District Cascade Locks, OR 97014. Available from https://repository.library.noaa.gov/view/noaa/23909 [accessed 21 June 2021].

Van Daele, L.J., and Van Daele, H.A. 1982. Factors Affecting the Productivity of Ospreys Nesting in West-Central Idaho. The Condor **84**(3): 292–299. doi:10.2307/1367371.

Vilhunen, S. 2006. Repeated antipredator conditioning: a pathway to habituation or to better avoidance? J. Fish Biol. **68**(1): 25–43. doi:10.1111/j.0022-1112.2006.00873.x.

Wagner, B.M.A., and Hansson, L.-A. 1998. Food competition and niche separation between fish and the Red-necked Grebe *Podiceps grisegena* (Boddaert, 1783). Hydrobiologia **368**(1): 75–81. doi:10.1023/A:1003213224327.

Walter, W.D., Fischer, J.W., Baruch-Mordo, S., and Vercauteren, K.C. 2011. What Is the Proper Method to Delineate Home Range of an Animal Using Today's Advanced GPS Telemetry Systems: The Initial Step. USDA Natl. Wildl. Res. Cent. - Staff Publ.: 1375. doi:10.5772/24660.

Warnock, W.G., Thorley, J.L., Arndt, S.K., Weir, T.J., Neufeld, M.D., Burrows, J.A., and Andrusak, G.F. 2021. Kootenay Lake kokanee (*Oncorhynchus nerka*) collapse into a predator pit. Can. J. Fish. Aquat. Sci.: 49. doi:10.1139/cjfas-2020-0410.

Washington Department of and Fish and Wildlife. 2021. Pikeminnow Sport-Reward Fishery Program. Available from https://wdfw.wa.gov/fishing/reports/creel/pikeminnow [accessed 30 July 2021].

Watson, J.W. 2002. Comparative Home Ranges and Food Habits of Bald Eagles Nesting in Four Aquatic Habitats in Western Washington. Northwest. Nat. **83**(3): 101. doi:10.2307/3536608.

Webb, P.W. 1986. Kinematics of lake sturgeon, *Acipenser fulvescens* , at cruising speeds. Can. J. Zool. **64**(10): 2137–2141. doi:10.1139/z86-328.

Williams, T.M. 1983. Locomotion in the North American mink, a semi-aquatic mammal. J. Exp. Biol. **103**: 155–168.

Williams, T.M. 1989. Swimming by sea otters: adaptations for low energetic cost locomotion. J. Comp. Physiol. A **164**(6): 815–824. doi:10.1007/BF00616753.

Wilson, K.A. 1954. The Role of Mink and Otter as Muskrat Predators in Northeastern North Carolina. J. Wildl. Manag. **18**(2): 199. doi:10.2307/3797715.

Winn, H.E. 1960. Biology of the Brook Stickleback Eucalia inconstans (Kirtland). Am. Midl. Nat. **63**(2): 424. doi:10.2307/2422804.

Wisenden, B. 2008. Active space of chemical alarm cue in natural fish populations. Behaviour **145**(3): 391–407. doi:10.1163/156853908783402920.

Wood, C.C. 1987. Predation of Juvenile Pacific Salmon by the Common Merganser (*Mergus merganser*) on Eastern Vancouver Island. I: Predation during the Seaward Migration. Can. J. Fish. Aquat. Sci. **44**(5): 941–949. doi:10.1139/f87-112.

Yamamoto, T., and Reinhardt, U.G. 2003. Dominance and predator avoidance in domesticated and wild masu salmon Oncorhynchus masou. Fish. Sci. **69**(1): 88–94. doi:10.1046/j.1444-2906.2003.00591.x.