IMPACTS TO ABUNDANCE AND DISTRIBUTION OF FRASER RIVER WHITE STURGEON

A SUMMARY OF EXISTING INFORMATION AND PRESENTATION OF IMPACT HYPOTHESES

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1. INTRODUCTION

The white sturgeon, *Acipenser transmontanus*, is the largest freshwater fish in North America, and one of five sturgeon species in Canada. White sturgeon occur in three large river systems on the west coast: the Fraser, Columbia and Sacramento drainages. In British Columbia they occur in the Fraser River system from the estuary upstream past the Morkill River, northwest of McBride; in the upper Columbia system in Arrow and Slocan lakes and in the mainstem downstream of Hugh L. Keenleyside Dam; and in the Kootenay River from Kootenay Lake upstream to the U.S. border.

The most distinguishing features of white sturgeon are a long scale-less body, with rows of large bony plates, called scutes, along the back and sides (Figure 1). Also conspicuous are the shark-like tail, and long snout. Sturgeon have no teeth but can extend their mouth to engulf food, detection of which is aided by four barbels in front of the mouth. Young white sturgeon feed on a variety of foods, including benthic invertebrates and small fish; larger fish (e.g., salmon and eulachon) can be important in the diets of older white sturgeon, although this may vary among populations.

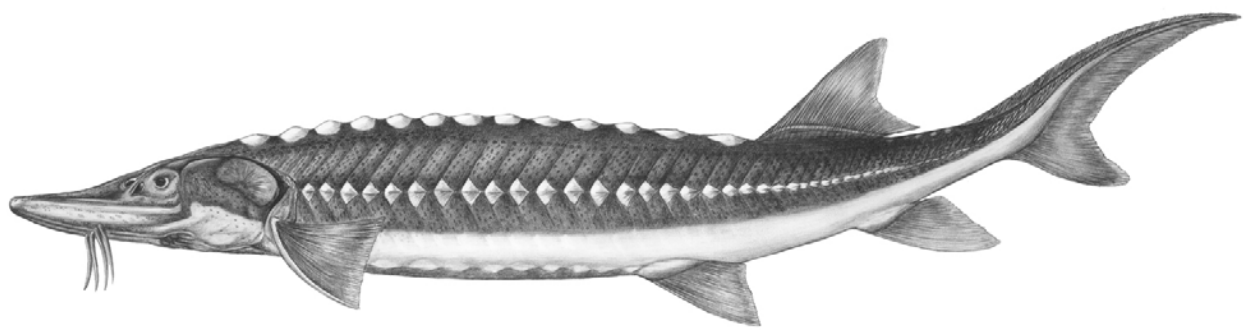

Figure 1. The white sturgeon, *Acipenser transmontanus.* (Drawing by Loucas Raptis of a specimen from the Nechako River.)

White sturgeon are slow-growing, take a long time to reach sexual maturity, and live a long time. In the Fraser River, some individuals have been aged at more than 100 years. Age of reproductive maturity for females may be 26 years or more, although it can be half this for males. Spawning occurs at intervals of up to 10 years. The record white sturgeon was caught in the Columbia River, at Astoria, and weighed approximately 1900 pounds. Specimens exceeding 1300 pounds and 6 m have been caught in the Fraser River.

White sturgeon are one of the few fish species in British Columbia that spawn during the peak freshet period in the spring, typically May and June. The number of eggs released by a female during spawning may vary from about 700,000 in a medium-sized female to more than four million in a very large one. The eggs are sticky and attach to the rocky bottom or vegetation. Embryos hatch into larvae with an attached yolk sac, then metamorphose to look like miniature adults within 30 days.

In British Columbia, white sturgeon habitat has declined in both quality and quantity. The regulation of river flows has had a large influence, particularly on the Columbia, Kootenay and Nechako systems. The effects of dams are numerous, including changes to water quality, streamflow patterns, water temperature, physically suitable habitat, and potentially changes in species composition. Dredging, gravel extraction, dyking and channelization have also been common practices throughout the province, and may be especially important on the lower Fraser River.

Population declines have occurred in many parts of the Canadian range, particularly in the lower Fraser, Nechako, Columbia and Kootenay rivers. The abundance of sturgeon in the Fraser River mainstem upstream of Hell's Gate may be naturally low but stable. Conservation planning efforts have been initiated and are mostly complete for the Columbia, Kootenay, and Nechako Rivers. White sturgeon were uplisted by COSEWIC in November 2003, from a "species of management concern" to "endangered," although legal listing under SARA has not yet occurred.

The Conservation Plan.— Development of a Fraser River White Sturgeon Conservation Plan (referred to henceforth as the "Plan") has recently been initiated, and a Working Group has been assembled to oversee development of a draft Plan. The Plan will be a high-level planning document that provides information on white sturgeon biology and conservation, identifies information gaps, and sets priorities for action by government and non-government organizations. Development of the Plan requires an understanding of the threats to long-term persistence of white sturgeon in the Fraser River. This document attempts to summarize the issues facing conservation of Fraser River white sturgeon stocks. The document is meant as a discussion paper rather than a final conclusion; the intent is for the Working Group, technical experts, and stakeholders to review the contents so that a set of priorities for action can emerge as part of the Plan. A separate document will be prepared to capture the input received from the Working Group and others.

Fraser River white sturgeon are divided into four distinct stock groups (**Figure 2**); the challenges facing the species vary among these different stock groups (Ptolemy and Vannesland 2003). For the most part, the various threats can be described but not quantified. Despite difficulties with quantification, in many cases there may be considerable evidence that a specific threat is real. The threats are presented and discussed here as "impact hypotheses," hypothesized mechanisms that influence abundance, distribution and health of white sturgeon. The intent is to focus attention first on the underlying mechanisms influencing white sturgeon (e.g., water temperature) before assessing the causal agents controlling the mechanism (e.g., river regulation). Our aim in doing this is to focus attention on available data and uncertainties as a first step, rather than foster immediate arguments about which cause is most important.

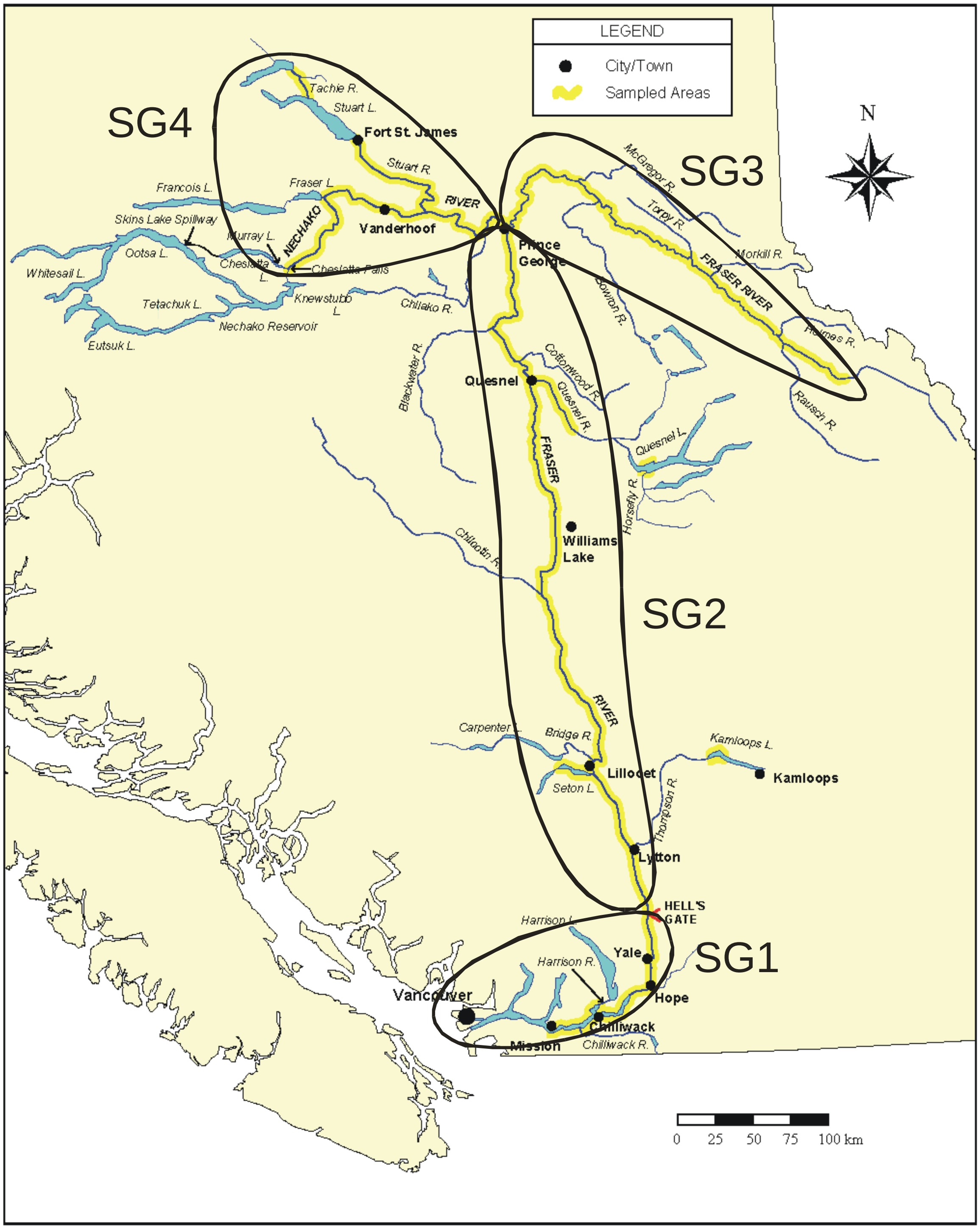

Figure 2. Distribution and stock group (SG) designations of Fraser River white sturgeon (adapted from Nechako White Sturgeon Recovery Team 2003). Note that "Sampled Areas" (indicated in yellow) refers to the sampling extent of studies conducted from 1995-99. Subsequent sampling conducted since 1999 by the Fraser River Sturgeon Conservation Society has included the tidal and estuarine areas of the lower Fraser River downstream of Mission, the Pitt River, and the nearshore areas of Sturgeon Bank and Roberts Bank in the Strait of Georgia; white sturgeon have been observed and sampled from all of these areas.

There are five general categories of impact mechanism for white sturgeon:

1. water quantity,
2. water quality,
3. instream habitat alterations,
4. harvest, and
5. other.

Each of these impact mechanisms can affect Fraser River white sturgeon in both direct and indirect ways. For example, river regulation can directly influence the abundance and distribution of physical habitat in a river, but it may also act in subtle ways that are more difficult to test such as the alteration of behavioural cues. The threats are summarized in an influence diagram (**Figure 3**), which shows possible pathways linking human activities to consequences for white sturgeon.

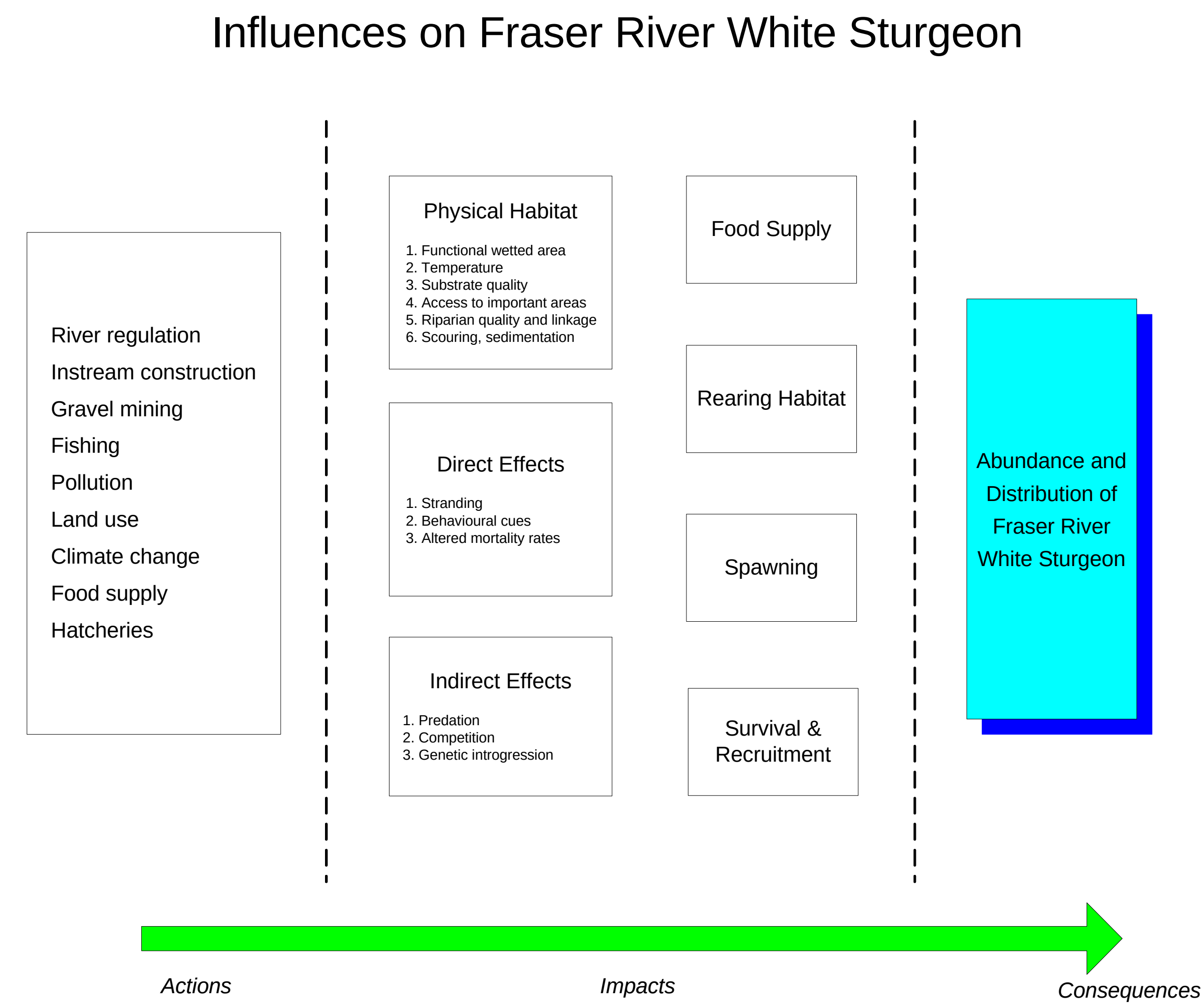

Figure 3. Influence diagram of hypothesized pathways linking human activities to consequences for Fraser River white sturgeon. Changes in abundance and distribution of sturgeon may arise in a wide variety of ways. For example, river regulation can directly alter the available habitat, and it may also influence the behavioural cues for spawning. Since there are many possible pathways between actions and consequences, all hypothesized pathways are not indicated.

Assessing risks to Fraser River white sturgeon is not straightforward because risk is a product of two quantities: probability of impact and consequences of the impact. If one of these quantities is large it does not necessarily follow that the risk is high; likewise if one of the quantities is low the overall risk may still be quite high. For example, the probability of river regulation on the mainstem Fraser River may be low, however, the consequences may be very high. Taken together these may create a high risk and present a high priority target for consideration in the Plan. In contrast, the probability of additional dyking may be low. If the consequences are merely moderate, this topic may be deemed a lower priority target, because the risk to sturgeon is deemed to be low.

Assessing risks to Fraser River white sturgeon is difficult to do except in a very qualitative manner. Since prioritization is nevertheless required for development of the Plan, we attempt to summarize the greatest threats to sturgeon. The results will be used to decide which threats should be the primary focus of recovery planning efforts. The strategies to address these threats will be developed elsewhere.

The purpose of this document is to:

- provide an overview of factors that are impacting Fraser River white sturgeon,
- identify information gaps that lead to uncertainty in assessment of impacts, and
- provide background for conclusions and recommendations in the Plan.

The various impact hypotheses for Fraser River white sturgeon are summarized in Error! Reference source not found. and then presented individually (in alphabetical order) in the main body of the document. Not all impact hypotheses are equally valid for each stock group, and there are differing degrees of support for each impact and its ability to strongly influence the abundance, distribution and health of white sturgeon in the Fraser River. This document will be used as supporting documentation for a technical workshop with sturgeon experts from British Columbia.

Impact Hypothesis	**Present relevance**			
	Lower Fraser SG1	**Mid Fraser SG2**	**Upper Fraser SG3**	**Nechako SG4**
Change in ecological community	?	?	?	?
Disease	?	?	?	?
Effects of small population size	?	?	?	✓
Fishing effects	✓	✓	✓	✓
Food supply	✓	✓	✓	✓
Habitat — In-channel rearing habitat	✓			✓
Habitat — Off-channel rearing habitat	✓			✓
Habitat — Spawning habitat	✓			✓
Hatchery effects	✓	✓	✓	✓
Hydrograph components				✓
Macrophyte development				✓
Pollution	✓	✓		
Sequential years of adequate flows				✓
Thermal regime	✓			✓
Turbidity				✓

Table 1. Summary of impact hypotheses considered for Fraser River White Sturgeon. Impacts are listed by type, and the affected stock groups are indicated.

2. IMPACT HYPOTHESES

2.1 Change in ecological community

Hypothesis.— Changes in the broader aquatic community lead to altered predation and competition with concomitant effects on white sturgeon survival and recruitment.

Potential Influences: Flow regulation
Species introductions / movements
Climate change

Description.— River regulation can affect a wide variety of species, altering relative abundance and distribution as a result of changes to flow patterns, temperature, and other factors. Increased abundance of predators or competitors of white sturgeon, for example an increase in some cyprinids is hypothesized in the case of the Nechako River. Predation on juvenile sturgeon may therefore have increased in comparison to historic levels.

Assessment.— This hypothesis was given a "high" plausibility rating at the Nechako River White Sturgeon Recovery Planning Workshop in October 2000 (Korman and Walters 2001) in part due to the observed time lag between dam construction and white sturgeon recruitment decline, which conformed with a time lag that would be expected for an increase in predators. The NRWSRP focussed on the predation aspect of this hypothesis and rated it as a moderate priority. This hypothesis does not explain any of the recruitment variation prior to the major changes in the 1960's. Predation risk would presumably increase with other factors affected by flow, such as increased fine sediment on the bed and reduced turbidity, and therefore may be one of several causes of declines in survival.

Uncertainties and Data Gaps.— The relative abundance and distribution of potential predators before and after Nechako flow regulation is not known. Studies that have been conducted have focussed on salmon, which are not anticipated to have an interaction with white sturgeon (except possibly as a reduction in sturgeon food supply) . We do not know the functional relationship between predation and successful sturgeon recruitment, or whether predators are capable of (or responsible for) a large reduction in sturgeon survival.

2.2 Disease

Hypothesis.— Disease poses a significant risk to Fraser River white sturgeon.

Potential Influences: Conservation aquaculture
Production aquaculture
Thermal regime changes (e.g., climate change, river regulation)
Introduction of pathogens

Description.— Several parasites and diseases of white sturgeon are known to be present in British Columbia. We do not know the risks associated with other diseases and their vectors or mechanisms of spread. However, we do know that the risks of disease outbreak increase under conditions where fish are stressed (e.g., high temperature). The movement of large numbers of fish between watersheds (e.g., release from hatcheries) is probably the greatest threat, and is amenable to control.

Assessment.— This risk is not well-defined at this point. Work on wild white sturgeon has shown that manifestations (epizootics) are generally not a threat to wild fish (Sherry Guest personal communication). Artificial culture does increase the chance of disease, and some US hatchery programs have encountered disease problems, apparently due to culture conditions. Operations at provincial culture facilities near Cranbrook have not detected any sturgeon viruses during the course of an extensive screening program. It seems reasonable to assume that disease poses a potentially greater risk to small populations than to large ones. The continued persistence of upper mainstem populations indicates the ability of these populations to persist in conjunction with diseases and parasites.

Uncertainties and Data Gaps.— Relative to fish such as salmon, little is known about parasites and diseases of Fraser River white sturgeon. The risks posed to long-term persistence of each stock group are therefore unclear.

2.3 *Effects of small population size*

Hypothesis.— Some stock groups of Fraser River white sturgeon are sufficiently small as to be limited by one or more "population size effects."

Potential Influences: historic forces leading to small population size (e.g., food supply, habitat availability, water quality, disease, etc.)
anthropogenic factors causing recruitment failure

Description.— When populations become sufficiently small there are a number of ecological effects that may prevent the population from increasing, even if resources are not limiting. For example, the Allee effect occurs when population levels decline to the point that individuals have difficulty locating a suitable mate. In this case suitable mates may exist in the population but the probability of finding one may be low enough that a significant proportion of the population goes unmated. Other effects of small population size include genetic effects such as founder effects, inbreeding depression, or loss of genetic variance due to small effective population size. The genetic effects of small population size are similar to the problems faced by some captive breeding programs.

Assessment.— The effects of small population size have been well-studied in the fields of theoretical and empirical population genetics. The effects are well-known, but there seems little that one can do to offset them in wild populations, except to ensure that natural abundance remains well above levels where these effects might be encountered. It is perhaps better to understand and communicate these effects as a cautionary tale to provide motivation for maintaining reasonable abundance of Fraser River white sturgeon.

Uncertainties and Data Gaps.— The general effects of small population size are well known. Factors such as longevity, iteroparity, and the potential for genetic mixing between many year classes may act to diminish the potential effects of small population sizes for white sturgeon. However, the precise mating patterns of each stock group of Fraser River white sturgeon is not sufficiently well-known to develop stock-specific relationships for different components of the effect of small population size. For example, we do not know at what abundance level the Allee effect becomes relevant for each stock group, nor do we know the rate at which genetic variance is lost in relation to population size.

2.4 *Fishing effects*

Hypothesis.— Fraser River white sturgeon abundance is limited by injury or mortality induced by activities associated with specific fisheries: recreational angling, aboriginal net fisheries (drift gill net, set gill net, and seine net), commercial gill net fisheries, and illegal harvest (poaching).

Potential Influences:
Recreational catch and release of sturgeon
Aboriginal and commercial net fishery interception and release of sturgeon
Aboriginal and illegal retention of sturgeon

Description.— Fraser River white sturgeon are caught both intentionally and incidentally by distinct fisheries that use a range of capture methods and gear. It is important to differentiate between the fisheries and gear types because their effects on white sturgeon abundance and distribution likely range from low to high.

Recreational Fishery - The recreational fishery for white sturgeon is a non-retention fishery; by regulation, all sturgeon must be released following capture. The levels of serious injury and latent mortality (fish that die subsequent to release as a direct result of angling-related injuries or stress) directly associated with the catch-and-release recreational fishery have not been thoroughly studied.

Aboriginal Fisheries – Aboriginal food, social, and ceremonial net fisheries in the Fraser River use drift gill nets (mostly downstream of Mission), set gill nets (mostly upstream of Mission) and seine nets. The high majority of in-river aboriginal fisheries target migrating schools of Pacific salmon, with very little direct targeting of sturgeon. The majority of sturgeon intercepted in aboriginal net fisheries are released, but some are retained. Limited studies suggest that injury, mortality, and latent mortality levels vary significantly between the two major gear types (drift gill net and set gill net).

Commercial Fisheries – Commercial net fisheries that target specific runs of Pacific salmon are periodically allowed (by order of Fisheries and Oceans Canada) to occur in the Fraser River. Although these fisheries are typically short in duration, they can be high in intensity. Most in-river commercial net fisheries occur downstream of Mission and utilize drift gill nets. White sturgeon interceptions are reported during these fishery openings; by regulation, all sturgeon must be released. The number of sturgeon captured by commercial net fisheries on an annual basis varies with the number of commercial fishery openings, and the timing and duration of these openings. There have been no quantitative assessments of the levels of sturgeon injury, mortality, and latent mortality associated with in-river commercial net fisheries.

Illegal Harvest (Poaching) - White sturgeon are harvested illegally (poached) for both personal consumption and for sale on the black market. White sturgeon are valued both for their meat and their roe (caviar). Capture methods used by poachers include set line, rod and reel (with legal or illegal terminal gear), and gill net. Because the intent of this fishery is retention, mortality rates for captured sturgeon are very high. The numbers of sturgeon illegally harvested from the Fraser River on an annual basis is unknown, although estimates produced by enforcement personnel in the lower Fraser indicate that the minimum number may be several hundred animals. There have been no estimates of the injury rate for sturgeon that escape illegal capture gear such as set lines and gill nets.

Assessment.— There have been no direct studies of injury or latent mortality levels for Fraser River white sturgeon released from recreational and commercial fisheries, and only limited studies regarding injury, initial mortality, and latent mortality levels associated with release from Aboriginal gill net fisheries. There appears to be good compliance to the request to release white sturgeon from aboriginal fisheries (voluntary agreement) and commercial fisheries (regulation). The extent of poaching (i.e., number of sturgeon killed illegally on an annual basis) is not known.

Uncertainties and Data Gaps.— There are no specific data sets available that can be used to reliably assess white sturgeon injury and mortality levels associated with Fraser River recreational, aboriginal, and commercial fisheries, and no reliable estimates of annual harvest and injury associated with the illegal retention (poaching) fishery. Reliable information regarding injury and mortality levels is required for all fisheries and gear types that capture sturgeon in the Fraser River, especially in light of restrictions that may come into effect if the species is listed as "endangered" under SARA.

Inference can be drawn from a number of sources that injury and latent mortality rates for sturgeon released from the non-retention recreational fishery are low, but this has not been specifically investigated. There is evidence of measurable mortality and injury levels associated with aboriginal net fisheries, but the extent of this information is limited, and there has been limited effort to investigate temporal and spatial variations in mortality rates. Although sturgeon interceptions are reported during most commercial net fishery openings in the Fraser, there is no information available regarding the respective levels of mortality and injury associated with these openings. Reliable assessment programs need to be developed to address and quantify the levels of mortality and injury associated with all in-river fisheries. Assessments should determine whether there is a seasonal component associated with injury/mortality levels. For example, observed mortality levels in the 2001-03 aboriginal set-net fisheries in the lower Fraser steadily increased from May through August with increasing water temperatures (Troy Nelson, personal communication). In addition, observations at Malaspina University College suggest that wounds may heal slowly for cultured sturgeon at water temperatures < 10 ˚C (Dave Lane, personal communication).

2.5 Food supply

Hypothesis.— Abundance of Fraser River white sturgeon is proportional to the available food supply.

Potential Influences: Commercial, Aboriginal, and recreational fishing
Land use (e.g., dyking)

Description.— Diets are not fully understood for all age classes of Fraser River white sturgeon, and effects of food supply on population abundance may occur via a number of pathways. Humans exploit a number of anadromous and resident fish species in the Fraser River. Many of these same species form part of the food base for Fraser River white sturgeon. For example, eulachon and salmon are known to be an important food source for white sturgeon, yet are also harvested in considerable numbers. Activities other than direct exploitation in a fishery may also lead to decreased food supplies. Loss of floodplain habitat in the lower Fraser River may have contributed to decreased salmon production. The operation of the Kenney Dam has also been suggested as a cause of salmon declines in the Nechako River (Jaramovic and Rowland 1988).

Assessment.— This impact hypothesis could be explored by comparing trends in sturgeon abundance with catch statistics of fish species utilized by both sturgeon and humans. Unfortunately, there are no such long-term records. As a surrogate, one could examine sturgeon growth as indicated in otoliths, fin rays, or similar structures, in relation to catch records for salmon. Growth comparison between different stock groups is being pursued to examine this sort of hypothesis for white sturgeon in the Columbia and Nechako Rivers. However, at present assessment of this hypothesis must rest on professional judgement.

Uncertainties and Data Gaps.— We do not know whether abundance of sturgeon is limited by its food supply, and if it is, the functional relationship between the two is also unknown. There have been concerns raised by some sturgeon experts in BC with respect to the effects of the commercial fishery on food supply for sturgeon throughout the Fraser watershed, but the magnitude of this effect is not known.

2.6 Habitat — In-channel rearing habitat

Hypothesis.— Changes have occurred to key in-channel rearing habitats with concomitant effects on Fraser River white sturgeon abundance and distribution.

Potential Influences: Flow regulation
Gravel and sand extraction
Instream construction

Description. - Rearing habitat for sturgeon can be directly impacted by river regulation in two important ways: changes in abundance and distribution of hydraulically suitable habitat, and geomorphic changes to instream habitats. Flows directly affect the hydraulic conditions in a river, determining the abundance and distribution of areas with suitable velocities and depths.

If the regulated regime is sufficiently different from the natural flow regime then there is a potential for loss of key rearing areas. Alternatively, when flows become regulated there are often geomorphologic responses, such as changes in the river form and the substrate composition of the bed. If the responses to river regulation include physical alterations to key rearing areas then sturgeon survival may decline. For example, in the Nechako River elevated levels of sand and finer material on the bed is directly related to the lack of high flows. The resulting embeddedness and loss of interstitial spaces has the potential to reduce juvenile survival.

Gravel and sand extraction from the lower Fraser River has been occurring for many years. The extraction process (by suction dredging in the wetted perimeter or surface mining in the floodplain) may kill sturgeon directly via entrainment, and may disrupt or alter habitats of importance to sturgeon.

There are varieties of developments that require instream construction or ongoing use of instream habitats. For example, footings for bridges, instream log storage, and river marinas displace or alter benthic habitat. These habitats are either permanently removed from the supply of available habitat, or the suitability of the remaining habitat is reduced. It is assumed that reductions in habitat translate into a lower carrying capacity for Fraser River white sturgeon.

Assessment.— Shifts toward a sand substrate have been identified for the Nechako River (nhc 2003; nhc and McAdam 2003) and the Kootenai/y River (USFWS 1999, Paragamian et al. in prep.). While increased sand in the substrate clearly limits the availability of interstitial spaces, the mechanism by which this may affect white sturgeon has not been demonstrated. Interstitial spaces may be used as refuges from predators, or may provide important for food sources. Overall, however, current assessment of the plausibility of this hypothesis is based on professional judgement and was deemed to be of moderate priority in the NRWSRP.

There has been little direct study of the biological effects of suction dredging (Harvey and Lisle 1998) on the Fraser River or elsewhere. One study in the lower Fraser River identified apparent young of the year white sturgeon in an area with potential for sand extraction (Perrin et al. 2003).

A tally of habitat losses due to construction and industry has not been conducted for the Fraser River. The effects from construction and industry are expected to be additive to other effects.

Uncertainties and Data Gaps.— There remains significant uncertainty about the early life history of white sturgeon and especially the habitats that they use. While changes in physical habitat have been noted for the Nechako and Kootenai/y Rivers, the linkages to white sturgeon juvenile habitat utilization must still be examined. This sort of effect would seem unlikely elsewhere in the Fraser River.

The direct effects of entrainment into suction dredges may affect sturgeon of various size classes; the extent of this effect is not known. The extent of habitat loss in the Fraser River due to gravel and sand extraction is also not known, but the key areas of present and historic extraction are well known. The importance of these areas to white sturgeon is similarly unknown.

The functional relationship between habitat and white sturgeon abundance and distribution is not known, but it is generally assumed that abundance is proportional to habitat availability.

2.7 Habitat — Off-channel rearing habitat

Hypothesis.— Lost access to floodplain habitat for rearing juvenile sturgeon causes declines in juvenile survival and recruitment.

Potential Influences: Flow regulation
Gravel and sand extraction
Land use (especially dyking)

Description.— The use of side-channels and other floodplain components during early life history is a common feature of species that spawn during high flow periods. While limited information is available about white sturgeon habitat use during their first year, there are indications that floodplain habitats are used and may be important (Lane and Rosenau 1995, Coutant submitted). The loss of these habitats can occur due to dyking, flow regulation, and modifications to the available floodplain.

Assessment.— Dyking in the lower Fraser led to a considerable loss of wetland habitat by the 1930's (Boyle et al. 1997) with relatively minor losses since that time. For the Nechako River an 85% loss of type 1 side channels occurred in the 1960's (Rood and Neil 1987), with reasonable correspondence between white sturgeon recruitment failure and the timing of these habitat changes (nhc and McAdam 2003). Similar patterns are also apparent for the Kootenay River (Ireland personal communication, McAdam unpublished), lending support to the hypothesis that off-channel habitats are important.

Uncertainties and Data Gaps.— Coutant (submitted) investigated factors affecting white sturgeon recruitment, and results indicated support for the importance of both in-channel and off-channel habitats. Although we do not know the functional relationship between amount of shallow water habitat and sturgeon abundance, it is reasonable to assume that habitat losses translate into lower sturgeon abundance. To some extent off-channel and in channel impacts are associated, particularly in the lower Fraser, where dredging has coincided with dyking.

2.8 Habitat — Spawning habitat

Hypothesis. — Alterations to key spawning habitats have had negative influences on Fraser River white sturgeon abundance and distribution.

Potential Influences: Flow regulation
Land use (including dyking)
Gravel mining

Description. — River regulation can affect spawning areas for sturgeon in two important ways: changes in abundance and distribution of hydraulically suitable habitat, and alterations to geomorphologic processes that create and maintain spawning habitat. Flows directly affect the hydraulic conditions in a river, determining the abundance and distribution of areas with suitable velocities and depths. If the regulated regime is sufficiently different from the natural flow regime then there is a potential for loss of key spawning areas. Alternatively, when flows become regulated there are often geomorphologic responses; for example, sand deposition has been noted in the Nechako River. If the responses to river regulation include physical alterations to key spawning areas then spawning success may decline. This sort of effect has been suggested for the Kootenay River as well.

Evidence from the lower Fraser River also indicates that white sturgeon spawn in large side channel habitat (Perrin et al. 2000). This type of habitat could be affected by channel modifications such as dyking or other river engineering, which could affect both the quantity and quality of spawning habitat.

Assessment.— The hypothesis has not been tested directly in the Fraser watershed. There is evidence of sand accumulation in the Nechako River (nhc and McAdam 2003) in areas with attributes similar to spawning habitats, but the linkages to potential white sturgeon spawning areas needs further investigation. The NRWSRP rates this impact as a moderate priority. Similarly, this hypothesis has not been directly examined for the lower Fraser River.

Uncertainties and Data Gaps. — There are several knowledge gaps, including the abundance and distribution of pre-regulation spawning habitats in the Nechako River.

2.9 *Hatchery effects*

Hypothesis.— Hatchery fish will have negative influences on the genetic integrity of Fraser River white sturgeon stocks, if conservation or commercial aquaculture programs are initiated.

Potential Influences: Conservation aquaculture
Commercial aquaculture

Description.— Hatchery effects are well-known in salmon, and for some other species. These effects include population effects, genetic effects, and disease transfer. Population effects occur when hatcheries release fish in sufficient numbers to displace fish of wild (i.e., non-hatchery) origin. In this case the hatcheries do not supplement wild populations, they merely replace them. This effect is well-described in the scientific literature (e.g., Hilborn 1999; Hilborn and Eggers 2000). Genetic effects occur due to a variety of processes common to many captive breeding programs (e.g., small effective population size, unintentional character selection, founder effects, inbreeding depression, etc.), and ultimately lead to less genetic variation than is observed in wild populations.

There is concern that hatchery effects will occur for Fraser River white sturgeon if conservation or commercial aquaculture programs are initiated. An additional concern is that hatchery effects will be exported throughout the watershed via downstream migration of fish to adjacent populations. Escapes from aquaculture operations are known to occur; escapes of a large number of closely related individuals could have a negative impact on the genetic integrity of the wild population. In addition, there is concern that the establishment of a local market for white sturgeon meat and caviar will encourage poaching by stimulating demand and making it easier to disguise illegally-harvested fish as cultured fish.

Wild Fraser River white sturgeon may also be exposed to risks of disease from commercial aquaculture facilities. Disease outbreaks appear to be much more prevalent under culture conditions. The accidental release of such fish, or the discharge of effluent, could lead to disease transmission to wild fish.

Applications to capture wild broodstock for use in commercial aquaculture have been viewed negatively due to the perceived risks that could result from the removal of adults from the wild population

Assessment.— There is a significant distinction between commercial aquaculture and conservation aquaculture. Conservation aquaculture is intended to be a hatchery breeding program established for the express purpose of maintaining and enhancing the genetic integrity of a population. A conservation aquaculture program would be initiated as a step to avoid extinction, and would usually have a defined lifetime as part of a study program and would typically include the intentional release of cultured sturgeon into the watershed to mix with the wild population. Commercial aquaculture, on the other hand, is a commercial venture aimed at producing white sturgeon either as a source of fish for human consumption or as a source of eggs for caviar. Commercial aquaculture does not necessarily include the intended release of cultured sturgeon into the environment.

The proposed Nechako conservation fish culture program has been designed around a breeding plan (Pollard 2003) that would create a founder population of specific size. In so doing it also aims to maximize genetic diversity being contributed to subsequent generations. Mating would follow a structure with checks to minimize problems such as inbreeding. The breeding plan follows a format similar to plans developed for the Columbia River (Pollard 2002) and the Kootenai/Kootenay River (Kincaid 1994 – now substantially modified).

A further consideration for the Nechako River is the potential for mixing among the four stock groups within the Fraser River, as cultured sturgeon released in the Nechako watershed can enter the mainstem Fraser River. Genetic risks have been evaluated (Williamson et al. 2003), and are considered to be low. However, in the event that cultured sturgeon are released into the Nechako River, monitoring has been recommended to provide ongoing evaluation of this risk. NRWSRP has deemed the risk of extinction to be greatly in excess of risks associated with conservation fish culture.

To date there has been little direct assessment of the threats posed by commercial aquaculture to wild white sturgeon populations in the Fraser River (or elsewhere). These threats have been supported largely based on information from the experiences with salmonid aquaculture.

Uncertainties and Data Gaps.— Uncertainty regarding white sturgeon movement patterns affects the risk of genetic transfer to other stock groups, and monitoring is needed to evaluate this risk. With respect to genetic effects, the scale of the conservation fish culture program will influence its ability to avoid such affects. For example, difficulties with the capture of sufficient broodstock may limit the ability to form a sufficiently large founder population, and the effectiveness of and commitment to a long-term monitoring program are uncertain. Delays and uncertainty regarding funding act to increase the risks.

Specific quantification of the risks posed by commercial aquaculture will be difficult, but the assessment of risks from conservation aquaculture can guide a qualitative assessment. Population genetics modeling may help quantify some of the genetic risks associated with the proposed Nechako conservation program.

2.10 Hydrograph components

Hypothesis.— Specific features of the natural hydrograph (e.g., a spring freshet) are biologically significant for Fraser River white sturgeon.

Potential Influences: Flow regulation
Land use

Description.— In British Columbia, white sturgeon are severely threatened in the Columbia River, the Kootenay River, and the Nechako River. Flows in each system are heavily regulated. The precise mechanisms responsible for population decline are hotly debated, but there is little doubt that river regulation is heavily implicated.

Sturgeon are obviously adapted to the natural hydrograph, having persisted successfully in large rivers for millennia. This impact hypothesis is built around the idea that sturgeon *require* a natural hydrograph, with seasonal fluctuations in river flow, particularly a pronounced spring freshet. The importance of winter flows has been considered by the Nechako River White Sturgeon Recovery Team (NRWSRT), but received less attention. The hypothesis focuses on sturgeon behavioural and physiological responses to river flows. Flow alteration also affects habitat quality and quantity; however, secondary effects such as changes to physical habitats and geomorphic responses are addressed in subsequent hypotheses.

Assessment.— This hypothesis has been the focus of considerable discussion, and the Nechako River White Sturgeon Recovery Plan (NRWSRP) rates it as a high priority. Most attention to date has focussed on the absence of high spring flows. In response to a similar hypothesis, large scale flow tests have been implemented at Libby Dam for the Kootenay River since 1995 (Paragamian et al. 2001) Reproduction appears to occur annually in that system, but flow tests do not appear to have stimulated recruitment with increased spring flow. In addition, high flows in the Nechako River in 1976 and 1997 provided a "natural test" of this hypothesis, and there is no evidence of recruitment in either year. McAdam and Lu (2002) examined the relationship between high flows and historic Nechako recruitment. Correlations were weak for a variety of reasons; however, the best correlations were obtained for the August-September period of 1957-66 for the upper section of the river. Results also indicate a possible winter influence in recent years (McAdam and Lu 2002). The contrast between results for the Nechako and Kootenay rivers, and the generally accepted relationship between high flows and white sturgeon recruitment, most likely indicate that increased flow of the magnitudes tested may not be the only manipulation required under present conditions.

Uncertainties and Data Gaps.— There are a number of knowledge gaps that preclude further testing of this hypothesis at this stage. We do not know whether white sturgeon physiologically respond to flows to stimulate oogenesis or require specific flows to stimulate spawning behaviours. If they do respond to flows we do not know the magnitude, duration, or frequency of flows that are required to generate successful spawning.

2.11 Macrophyte development

Hypothesis.— Macrophyte development affects juvenile sturgeon survival due to increased oxygen demand in the river.

Potential Influences: Flow regulation
Land use

Description.— Reductions in peak flows and land use changes have resulted in significant macrophyte development in some sections of the Nechako River (French and Chambers 1997). These changes have a number of effects on the physical conditions within the macrophyte beds, which may be detrimental to juvenile white sturgeon. Of particular interest are potential changes to water quality, and especially the biological oxygen demand (BOD). Although plants produce oxygen during the day when photosynthesizing, they consume oxygen during the dark, and may create substantial BOD when the plant material decays. Decomposition-related oxygen deficits have been observed in other lake and stream systems, and fish production has been negatively affected. It is possible that white sturgeon recruitment is affected through lower juvenile survival.

Assessment.— The hypothesis has not been tested directly. Current assessment of the plausibility of this hypothesis is based on professional judgement. The NRWSRP rates this as a moderate priority. While some further water quality testing has been undertaken it has not yet been fully reported.

Uncertainties and Data Gaps.— Mapping of the macrophyte areas of the Nechako River has been well executed, but the functional relationship between macrophyte abundance and distribution versus sturgeon survival and recruitment is not known. Dissolved oxygen concentrations within the macrophyte beds are not known, nor are the sensitivities of juvenile white sturgeon to low oxygen conditions. Heavy macrophyte growth may preclude use of some side channels in the lower Fraser River (D. Lane, personal communication).

2.12 Pollution

Hypothesis. — Survival and recruitment of Fraser River white sturgeon is influenced by toxic pollutants in the Fraser River.

Potential Influences: Industrial effluents
Municipal discharges (e.g., sewage)
Agricultural runoff

Description.— The Fraser River acts as the receiving waters for a wide variety point and non-point source pollutants. These pollutants are introduced over a very broad geographic scale. In the upper reaches of the river the main point sources are pulp mill effluent in Prince George and Quesnel. In the lower river there is a wide variety of sources downstream of Mission.

Assessment.— Despite the broad variety of pollutants present in the lower Fraser River, analysis of carcasses from the 1993/94 mortalities indicated relatively low levels of pollutants (McAdam 1995). This may be due to an adult diet that consists largely of salmon and eulachon, which are predominantly marine, indicating that adult white sturgeon may be less prone to local pollutant effects, at least in the lower Fraser. Since juvenile white sturgeon depend on locally-derived food supplies (e.g., benthic invertebrates, young fish, etc.) they may be more susceptible to pollutants. Bennett and Farrell (1994) indicated that the toxicant anti-sapstain was about 1,000 times more toxic to white sturgeon fry as compared to rainbow trout, indicating the potential for a pollutant effect. Susceptibility of white sturgeon to a broader variety of other toxicants has not been tested, although Nener (1992) found that heavy metals associated with slag proved toxic to juvenile white sturgeon.

Uncertainties and Data Gaps.— Susceptibility of white sturgeon, and particularly juveniles, to a wide variety of pollutants remains untested. Further information on juvenile white sturgeon diets, with investigation of the pollutant levels in these food sources might be one route of analysis. It is worth noting that environmental toxins may have lethal or sublethal effects; the latter would likely be more difficult to assess.

2.13 Sequential years of adequate flows

Hypothesis.— A single year of suitably high flows is insufficient to stimulate successful white sturgeon spawning.

Potential Influences: Flow regulation

Description. — This hypothesis grew in part out of the failure of Nechako River sturgeon to respond to high flows during the 1976 freshet. It has been hypothesized that consecutive years of high flow may be required to generate a recruitment event. A period of high flow may be required to initiate physiological changes during the winter prior to spawning, and a second event may be required to stimulate spawning and enhance juvenile survival.

Assessment.— This hypothesis has not been specifically tested since consecutive high flow years last occurred in the Nechako River in 1963/64, or perhaps 1967/68. The NRWSRP rates this as a high priority hypothesis. The persistence of recruitment during the low flow years during the reservoir fill period as well as apparent correlation between white sturgeon recruitment and single year freshets in other systems (e.g., Kootenai 1961, mid-Columbia 1997) do not appear to support this hypothesis.

Uncertainties and Data Gaps. — The functional relationship between duration of adequate habitat conditions and successful sturgeon survival and recruitment is not known. For example, there are few data on year class strength to correlate with flow data.

2.14 Thermal regime

Hypothesis.— Successful spawning and rearing of Fraser River white sturgeon requires a specific range of water temperatures during critical time periods.

Potential Influences: Flow regulation
Climate change

Description.— River temperatures are dictated by the interaction of river flow and climate, so changes in climate or flow have the potential to alter water temperatures. Scientific evidence clearly indicates that climate is changing and animal and plant distributions are responding to these changes (Parmesan and Yohe 2003). Since climate affects water flow and temperature in many ways, it may also affect white sturgeon abundance and distribution. Global climate change may affect temperature in the whole Fraser River, but the effect would likely be greatest in the lower Fraser due to the greater distance from the cooling sources.

Dams can also alter the temporal pattern and range of water temperatures observed in a river. A dam's influence is generally dependent on the storage characteristics of the reservoir and the depth from which water is withdrawn.

One of the principle effects of altered temperatures on white sturgeon is a decline in egg viability at temperatures in excess of 20 ˚C (Wang et al. 1985). Elevated winter and summer temperatures may also alter bioengergetic requirements, and thereby affect reproductive condition. Elevated temperatures may also affect susceptibility to disease.

Assessment.— For the Nechako Reservoir the similarity between the surface withdrawal at Skins Lake Spillway and a natural lake outlet would likely lead to a similar discharge temperature regime, however, this assumption has not been tested. Lower river volume during the summer is known to affect downstream summer temperatures in the Nechako (Triton 2001). Implementation of Summer Temperature Management flows (STMP) limits elevated temperatures during July and August, but temperatures during June could be 2 to 3 ˚C higher than natural in warm and hot years (Triton 2001). Flows in May were not tested, but may not have changed markedly from natural due to the later onset of spring in this northern area.

Long-term trends indicate that the summer temperature of the Fraser River has increased from 1941-98 (MWLAP 2002). This might create a long term threat, but the rate of change is about 0.01 ˚C/year, though extreme conditions may become more common. In this respect it is important to note that higher than normal temperatures in 1993 and 1994 were implicated as one of the multiple causes responsible for adult mortalities in the Lower Fraser River (McAdam 1995).

The extent to which climate change poses a risk to Fraser River white sturgeon is difficult to determine. Factors that influence white sturgeon reproduction and productivity (e.g., food supply, river temperatures) will likely be affected by climate change, and the net effect may be negative. The response of white sturgeon to climate change is of concern, however, the issue is outside the scope of this conservation planning effort.

Uncertainties and Data Gaps.— Despite previous and ongoing research there is uncertainty in temperature modeling of the Nechako and Fraser. Some changes to historic river temperatures have been noted, but they don't appear to have been large. The biological effects of these changes is uncertain, and still require further investigation. In particular, there is uncertainty regarding direct effects of thermal regime on adult fish, and for all life stages, additive effects of temperature and other stressors.

There is strong scientific evidence that climate is changing and that species distributions are changing in response. However, there remains considerable uncertainty in predicting how specific areas of the globe will be affected and how individual species will respond to the changes. This holds true for Fraser River white sturgeon.

2.14.1 Notes

Experience at Malaspina indicates strong temperature effects on spawning and rearing success, and general health of sturgeon (D. Lane, personal communication). Embryos and larvae from a single female spawned at 7-10 ˚C had very high mortality in comparison to females spawned at 15 – 17 ˚C. Fry and fingerlings reared in captivity showed increased growth with temperature up to 25 ˚C. Optimal temperature for rearing and survival appears to be 15 – 18 ˚C. Recovery from surgery also appears to be temperature dependent. Wounds on cultured sturgeon in captivity heal more rapidly at 12 – 20 ˚C than at 10 – 12 ˚C. In addition, mortality rates for sturgeon intercepted in set gill nets increases with increasing water temperatures (T. Nelson, personal communication). These observations that both healing and mortality levels change with water temperature may be relevant for management of recreational, aboriginal, and commercial fisheries.

2.15 Turbidity

Hypothesis.— Successful recruitment of white sturgeon requires concentrations of suspended sediments in excess of a threshold level during a critical time window.

Potential Influences:	Flow regulation
	Land use
	Sewage discharge

Description.— White sturgeon are one of the few fish species in British Columbia that spawn during the peak freshet period in the spring. This trait is adaptive since floods provide increased food resources and allows decreased predation through mechanisms such as dispersal onto the floodplain (Welcomme 1976). White sturgeon are planktonic during their very early life stage, and may escape predation when water is more turbid, which typically occurs during the freshet period. Regulated systems tend to be considerably clearer than unregulated streams, due to sediment settlement in reservoirs and the diminished erosive potential of lower peak flows. Since predators of sturgeon larvae are primarily visual hunters, recruitment failure may occur in regulated systems because water clarity allows a high predation rate.

Assessment.— Laboratory tests indicate that predation rate decreased when turbidities increased from 30 to 60 NTU (Gadomski and Parsley 2001). Turbidities associated with successful sturgeon spawning and recruitment were 6 to 92 NTU in the lower Fraser River (Perrin et al. 2000). Values exceeding 50 NTU are regularly recorded for the Fraser River at Hope (http://wlapwww.gov.bc.ca/wat/wq/quality/hope/hope-58.htm), indicating this may not be a concern in the lower Fraser River. The NRWSRP rates this as moderate priority for the Nechako River, and recommends further assessment.

Uncertainties and Data Gaps. — Like many of the other impact hypotheses there are a number of knowledge gaps. In particular, although laboratory tests indicate a possible effect we do not know the functional relationship between turbidity and recruitment within a riverine environment. There is also very little information about the turbidity regime prior to the construction of the Kenney Dam and the effects that flow regulation may have caused on the Nechako, or further downstream. As a result, we also do not know the magnitude, duration, or frequency of changes to the present turbidity regime that would be required to generate successful recruitment. Tests of this hypothesis have been proposed as part of recovery planning for the Columbia River white sturgeon.

3. CONCLUSIONS

Clearly there are a number of potential impacts to abundance and distribution of Fraser River white sturgeon. The purpose of this document is simply to present a summary of existing information relevant to conservation of Fraser River white sturgeon. Not all of the potential impacts are relevant for each stock group of white sturgeon, and several potential impacts will likely need to be assessed further before specific management actions are formulated. This document is part of supporting information that will be presented to British Columbia white sturgeon experts during a technical workshop to develop priorities for management action. The details and outcomes of the technical workshop are presented in a separate document (Hatfield and Long 2004).

4. REFERENCES

Bennett, B. and T. Farrell. 1994. Reproductive toxicity in white sturgeon. Paper presented at the Fraser River Action Plan, Research Program Workshop. Nov. 29-30, 1994.

Boyle, C. A., L. Lavkulich, H. Schreier, and E. Kiss. 1997. Changes in land cover and subsequent effects on Fraser Basin Ecosystems from 1823 to 1900. Environmental Management, 21(2):185-196.

Coutant, C. C. 2003. A riparian habitat hypothesis for successful reproduction of white sturgeon. Submitted for publication.

French, T. D. and P. A. Chambers. 1997. Reducing flows in the Nechako River (British Columbia, Canada): Potential response of the macrophyte community. Canadian Journal of Fisheries and Aquatic Sciences 54: 2247-2254

Gadomski, D. M. and M. J. Parsley, 2001. Vulnerability of age-0 white sturgeon *Acipenser transmontanus* to predation. Abstract for oral presentation. U.S. Geol. Surv. Western Fisheries Res. Center, Col. R. Research Lab.

Harvey, B. C. and T. E. Lisle. 1998. Effects of suction dredging on streams: a review and an evaluation strategy. Fisheries 23 (8): 8-17.

Hatfield, T. and G. Long. 2004. Impacts to abundance and distribution of Fraser River white sturgeon: Results of expert elicitation survey and technical workshop. Report prepared for the Fraser River Sturgeon Conservation Society and the Fraser River White Sturgeon Working Group.

Hilborn, R. and D. Eggers. 2000. A review of the hatchery programs for pink salmon in Prince William Sound and Kodiak Island, Alaska. Transactions of the American Fisheries Society 129: 333-350.

Hilborn, R. 1999. Confessions of a reformed hatchery basher. Fisheries 24: 30-31.

Jaremovic, L. and D. Rowland. 1988 Review of chinook salmon escapements in the Nechako River, British Columbia. Can. MS. Rep. Fish. Aquat. Sci. 1963, 135 pp.

Kincaid, H. 1993. Breeding Plan to Preserve the Genetic Variability of the Kootenai River White Sturgeon. Final Report to Bonneville Power Administration, U.S. Fish and Wildlife Service. Project 93-27. Contract Number DE-AI79-93B002886. Portland, Oregon.

Korman, J. and Walters, C. 2001. Nechako River White Sturgeon Recovery Planning: Summary of Stock Assessment and Oct. 2-3 2000 Workshop. Prepared for Ministry of Water, Land and Air Protection, Victoria, BC. 26 pp.

Kukulka, T. and D. A. Jay. 2003. Impacts of Columbia River discharge on salmonid habitat II. Changes in shallow-water habitat. manuscript Submitted to Journal of Geophysical Research – Oceans. (currently available at: http://www.ese.ogi.edu/~jaylab/public/kukulka%26jay_jgr03b.pdf)

Lane, E. D. and M. Rosenau. 1995. The conservation of sturgeon in the Lower Fraser River watershed. A baseline investigation of habitat, distribution, and age and population of juvenile white sturgeon (*Acipenser transmontanus*) in the Lower Fraser River, downstream of Hope, B.C. Conservation Fund Project-Final Report, Surrey, B.C. 172 p

McAdam, S. 1995. Report on the mortalities of Fraser River white sturgeon (*Acipenser transmontanus*) during the summer-fall period of 1993-94. Ministry of Env. Unpubl. Report.

McAdam S. and M. Lu 2002. Investigation of relationships between flow, temperature, and white sturgeon (*Acipenser transmontanus*) recruitment in the Nechako River. Unpubl. Report.

Ministry of Water, Land and Air Protection. 2002. Indicators of climate change for BC. Available at http://wlapwww.gov.bc.ca/air/climate/indicat/pdf/indcc.pdf. 50 pp.

Nechako White Sturgeon Recovery Team. 2003. Draft Recovery Plan for Nechako White Sturgeon. 73 pp

Nener, J. C., 1992, Survival and water quality of bioassays on five species of aquatic organisms exposed to slag from Cominco's T rail operations, Department of Fisheries and Oceans, Vancouver, B.C.

Northwest Hydraulic Consultants. 2003. Nechako River Geomorphic Assessment Phase I: Historical analysis of the lower Nechako River. Prep. For BC Min. Water, Land and Air Protection. 31 pp. + app.

Northwest Hydraulic Consultants and S. McAdam. 2003. Nechako River Geomorphic Assessment Phase II: Detailed analysis of potential white sturgeon habitat sites. Prep. For BC Min. Water, Land and Air Protection. 17 pp. +app.

Paragamian, V. L., V. D. Wakkinen, and G. Kruse. 2002. Spawning locations and movement of Kootenai River white sturgeon. J. Appl. Ichthyol. 18:608-616.

Parmesan, C. and G. Yohe. 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421: 37-42.

Perrin, C. J., J. L. Taylor, and T. B. Stables. 2003. Effects of dredging operations on the aquatic community in the lower Fraser River near Barnston Island. Draft Report. Report prepared by Limnotek Research and Development Inc. for Fraser River Port Authority. 112p plus appendices.

Perrin, C. J., A. Heaton and M. A. Laynes, 2000. White sturgeon (Acipenser transmontanus) spawning habitat in the lower Fraser River, 1999. Report prepared by Limnotek Research and Development Inc. for BC Ministry of Fisheries. 65 p.

Pollard, S. 2002. Upper Columbia white sturgeon conservation fish culture breeding plan. Prepared for Ministry of Water, Land and Air Protection, Victoria, BC. 21 p.

Ptolemy, J. and R. Vannesland. 2003. Update COSEWIC status report on white sturgeon *Acipenser transmontanus*. Prepared for Committee On the Status of Endangered Wildlife In Canada.

Rood, K and C. R. Neill. 1987. A study of some aspects of the geomorphology of the Nechako River. Reid Crowther and Partners Ltd. And Northwest Hydraulic Consultants Ltd. Prepared for Fisheries and Oceans Canada, Vancouver, B.C. DSS File #FP501-6-0142/01-SB. 84 pp. + app.

Triton Environmental Consultants. 2001. Estimation of natural water temperatures in the Nechako River. Prepared for Nechako Environmental Enhancement Fund. Draft report.

U.S. Fish and Wildlife Service. 1999. Recovery plan for the Kootenai River population of the white sturgeon (Acipenser transmontanus). Region 1, USFWS, Portland, OR.

Whitfield, P. H. 2001. Linked hydrologic and climate variations in British Columbia and Yukon. Environmental Monitoring and Assessment 67: 217-238.

Whitfield, P. H. 2003. Hydrologic considerations and instream flow setting. DFO Instream Flow Workshop. Richmond, BC, February 2003.

Whitfield, P. H., K. Bodtker, and A. J. Cannon. 2002. Recent variations in seasonality of temperature and precipitation in Canada, 1976-95. International Journal of Climatology 22: 1617-1644.

Welcomme, R. L. 1976. Some general and theoretical considerations on the fish yield of African rivers. Journal of Fish Biology. 8:351-364.

Williamson, C., D. Cadden, and S. McAdam. 2003. Genetic hazards and risks associated with the recovery of Nechako white sturgeon. Prepared for the Nechako River white sturgeon recovery team. 15 pp.