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Recovery potential assessment for white sturgeon populations listed under the *Species at Risk Act*

Évaluation du potentiel de rétablissement des populations d'esturgeon blanc inscrites en vertu de la *Loi sur les espèces en péril*

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Abstract

We assessed recovery potential for each of four populations of white sturgeon now listed as Endangered under the *Species at Risk Act* by considering current status, potential direct sources of human-induced mortality, and various strategies to mitigate harm and promote recovery. We used a simulation model to evaluate scenarios that span the range of plausible human activities that cause mortality or change the quantity or quality of important habitat.

Best estimates of the abundance of mature fish in each population in 2006 are 185 in the Upper Fraser River, 305 in the Nechako River, 455 in the Kootenay River and 1000 in the Canadian portion of the Columbia River. Habitat is believed to limit current abundance in all populations. The Nechako, Kootenay, and Columbia populations are declining following decades of recruitment failure related to extensive habitat changes, primarily associated with dams and river regulation. Potential critical habitats (but not residences) have been identifed for all populations and include key areas for spawning, larval and juvenile rearing, adult feeding and staging prior to spawning migration. Threats to habitat include river regulation; instream activities such as dredging for gravel or sand; linear development; alterations or development of riparian, foreshore, or floodplain areas; upstream use of land and water; and effluent discharge from both point and non-point sources. Specific sources of harm or mortality to individual white sturgeon include targeted or incidental capture in recreational fisheries, bycatch in salmon gillnet fisheries, passage through dams, and sampling for research and hatchery broodstock. Best estimates for total annual mortality directly induced by humans range from 0.01% in the Upper Fraser to 0.07% in the Columbia population for small sturgeon (ages 2 to 10); and from 0.02% in the Upper Fraser to 0.3% in the Nechako population for large sturgeon (ages >10).

The recovery goal specified in the draft national recovery strategy for white sturgeon is to ensure the long-term viability of naturally-reproducing populations throughout the species' natural range, and restore opportunities for beneficial use, if and when feasible. Specified quantitative recovery objectives that could be assessed in simulation scenarios include (1) to ensure no net loss of reproductive potential, (2) to achieve within 50 years (a) 1000 mature individuals, (d) ongoing natural recruitment, and (e) population growth when below the abundance target.

For the Upper Fraser population, simulation model projections suggest that all recovery objectives except 2a can be achieved if total human-induced mortality does not exceed twice the estimated status quo level. Simulation results based on our assumptions about historic abundance lead us to question the necessity of achieving 1000 mature fish (recovery objective 2a) and continued population growth (recovery objective 2e). An alternative approach is to recognize that the naturally small size of the Upper Fraser population makes it inherently vulnerable to extinction, and to seek to maintain its current viability by preventing further deleterious impacts. Concerns about the potential loss of genetic diversity over the longer term that motivate recovery objective 2a might be addressed by intervention to manage gene flow with other populations.

For the Nechako, Kootenay, and Columbia populations, simulation model projections indicate that unless human intervention can restore natural recruitment, extinction in the wild is inevitable, even in the absence of further human-induced mortality. Our simulation results indicate first, that close to full restoration of the historic rates of natural recruitment will be necessary to achieve recovery objectives, and second, that restoration of historic rates of natural recruitment would be sufficient to achieve abundance objectives within 100 years, but not within 50 years. Hatchery supplementation will also be necessary to achieve abundance objectives, but would not be sufficient by itself. Hatchery supplementation should be viewed as experimental, but supported as a calculated risk to reduce the serious risk of genetic bottlenecks in natural spawning expected over the next 30 years. Given that the very feasibility of recovery depends upon successful human interventions to increase natural recruitment, it might be reasonable to allow some continuing incidental harm contingent on a commitment to engage in habitat restoration that is deemed sufficient to increase natural recruitment to historic levels, and to hatchery

supplementation that is deemed sufficient to avoid future genetic bottlenecks. Simulated scenarios with habitat restoration to fully restore historic rates of natural recruitment combined with low level, short-term hatchery releases, indicate that recovery objectives could likely be achieved in the face of continuing incidental mortality not exceeding twice the current estimated level in each of the three non-recruiting populations. Sensitivity analyses suggest that this conclusion is robust over plausible ranges of parameter values and levels of annual variability. Our analyses were designed to demonstrate the necessary and sufficient conditions for achieving recovery objectives, not to determine the best options for recovery. We acknowledge that other scenarios involving different trade-offs might achieve recovery objectives with better socio-economic outcomes.

Résumé

Nous avons évalué le potentiel de rétablissement de quatre populations d'esturgeon blanc dorénavant désignées, en vertu de la Loi sur les espèces en péril, comme étant « en voie de disparition » d'après leur situation actuelle et les éventuelles sources directes de mortalité d'origine anthropique et en fonction des diverses stratégies d'atténuation des dommages et de promotion du rétablissement. Nous avons utilisé un modèle de simulation pour évaluer des scénarios qui couvrent l'éventail des activités humaines pour lesquelles il est réaliste de penser qu'elles constituent des causes de mortalité ou qu'elles modifient l'étendue ou la qualité de l'habitat important.

En 2006, les meilleures estimations de l'abondance des poissons adultes dans chaque population s'établissaient à 185 individus dans le haut Fraser, à 305 individus dans la rivière Nechako, à 455 individus dans la rivière Kootenay et à 1 000 individus dans la partie canadienne du fleuve Columbia. L'habitat limiterait l'abondance actuelle de toutes les populations. Dans les rivières Nechako et Kootenay et dans le fleuve Columbia, les populations déclinent après des décennies marquées par l'échec du recrutement, lequel échec est imputable à des changements profonds dans l'habitat principalement provoqués par la construction de barrages et la régularisation des cours d'eau. Des habitats essentiels potentiels (mais non des résidences) ont été relevés pour toutes les populations et incluent des zones clés pour le frai, la croissance des larves et des juvéniles, l'alimentation des adultes et le rassemblement préalable à la migration de reproduction. Parmi les menaces pesant sur l'habitat, citons la régularisation des cours d'eau; la réalisation d'activités dans les cours d'eau, comme le dragage du gravier ou du sable; les projets linéaires; la modification ou l'aménagement des rives, de l'estran ou des plaines inondables; l'utilisation en amont des terres et de l'eau; les rejets d'effluents de sources ponctuelles et diffuses. Parmi les sources particulières de dommages ou de mortalité pour l'esturgeon blanc figurent les prises dirigées ou fortuites dans la pêche sportive, les prises accessoires dans la pêche au saumon au filet maillant, le franchissement des barrages, l'échantillonnage à des fins scientifiques et d'élevage. Les meilleures estimations de la mortalité annuelle totale directement induite par l'homme varient de 0,01 % dans le haut Fraser à 0,07 % dans le fleuve Columbia pour la population de petits esturgeons (âges 2 à 10), et de 0,02 % dans le haut Fraser à 0,3 % dans la rivière Nechako pour la population de grands esturgeons (âges > 10).

L'objectif de rétablissement précisé dans l'ébauche du programme national de rétablissement pour l'esturgeon blanc est d'assurer la viabilité à long terme des populations qui se reproduisent naturellement dans toute l'aire de répartition naturelle de l'espèce et de rétablir des occasions d'utilisation bénéfique, lorsque c'est possible. Les objectifs de rétablissement quantitatifs précisés, évaluables dans des simulations, incluent les suivants : 1) prévenir toute perte nette du potentiel de reproduction; 2) atteindre dans un délai de 50 ans a) une population de 1 000 individus adultes, d) un recrutement naturel continu et e) l'accroissement de la population lorsqu'elle est inférieure à la cible relative à l'abondance.

Dans le cas de la population du haut Fraser, les projections obtenues au moyen du modèle de simulation semblent indiquer que tous les objectifs de rétablissement, sauf l'objectif 2a, peuvent être atteints si la mortalité d'origine anthropique n'excède pas du double le taux estimé pour le maintien du statu quo. Au vu des résultats issus de la simulation et fondés sur nos hypothèses relatives à l'abondance historique, nous nous interrogeons sur la nécessité d'atteindre une population de 1 000 poissons adultes (objectif de rétablissement 2a) et un accroissement continu de la population (objectif de rétablissement 2e). Comme autre approche, nous pouvons reconnaître que la taille naturellement faible de la population du haut Fraser rend cette dernière intrinsèquement vulnérable à l'extinction et tenter de maintenir sa viabilité actuelle en prévenant tout impact futur nuisible. De même, pour répondre aux préoccupations sous-jacentes à la perte potentielle de diversité génétique à plus long terme, lesquelles motivent l'objectif de rétablissement 2a, nous pourrions intervenir afin de gérer le flux génétique avec d'autres populations.

Pour ce qui est des populations de Nechako, de Kootenay et de Columbia, les projections modélisées indiquent que, sauf si une intervention humaine permet de rétablir le recrutement naturel, l'extinction des populations sauvages est inévitable, même si la mortalité d'origine anthropique demeure stable. D'après les résultats issus de nos simulations, il faut d'abord rétablir le taux de recrutement naturel près des valeurs historiques pour permettre l'atteinte des objectifs de rétablissement et, ensuite, que ces nouveaux taux de recrutement suffisent pour permettre l'atteinte les objectifs d'abondance dans un délai de 100 ans et non de 50 ans. L'ajout de poissons de pisciculture sera également nécessaire à l'atteinte les objectifs d'abondance, mais ne suffira pas. Cet ajout sera aussi considéré comme expérimental, mais sera soutenu en tant que risque calculé destiné à réduire le risque grave que représente l'érosion de la diversité génétique dans le frai naturel attendue dans les 30 prochaines années. Étant donné que la faisabilité même du rétablissement repose sur des interventions humaines qui augmenteront le recrutement naturel, il pourrait être raisonnable de continuer, d'une part, à autoriser certains dommages fortuits éventuels, tout en s'engageant, d'autre part, à participer à la restauration de l'habitat jugé suffisant à l'accroissement du recrutement naturel à des taux historiques et à procéder à l'ajout de poissons de pisciculture à un taux jugé suffisant pour prévenir toute érosion future de la diversité génétique. D'après les scénarios simulés de la restauration de l'habitat, où sont pleinement restaurés les taux historiques du recrutement naturel combinés à l'ajout de poissons de pisciculture à de faibles quantités et à court terme, les objectifs de rétablissement pourraient probablement être atteints malgré une mortalité fortuite n'excédant pas du double le taux estimé pour chacune des trois populations qui ne connaissent aucun recrutement. Les analyses de sensibilité laissent sous-entendre que cette conclusion résiste à des gammes plausibles de valeurs paramétriques et de taux de variabilité annuelle. Nous avons conçu nos analyses pour démontrer les conditions nécessaires et suffisantes à l'atteinte des objectifs de rétablissement et non pour déterminer les meilleures options pour le rétablissement. Nous reconnaissons que d'autres scénarios supposant différents compromis pourraient permettre l'atteinte des objectifs de rétablissement, avec de meilleurs résultats sur le plan socio-économique.

Introduction

This document provides a comprehensive Recovery Potential Assessment (RPA) for each of four populations of white sturgeon now listed as Endangered under the *Species at Risk Act* (referred to as the upper Fraser, Nechako, Kootenay, and Columbia populations). An RPA is a scientific evaluation of the likelihood that specified recovery goals can be achieved in biologically reasonable time frames. Feasibility of recovery is assessed under various scenarios that span the range of plausible human activities that cause mortality or change the quantity or quality of important habitat. Background information on the biology, distribution, and population structure of white sturgeon in Canada is presented in Appendix 1.

Our assessment comprises three phases. In phase 1, we summarize what is known about current population status and recent trends in abundance for each population, describe potential residences and habitats that are likely critical to population persistence or recovery, and formulate recovery targets. This information is available in more detail in Appendix 1 and the draft national recovery strategy for white sturgeon, cited as the National Recovery Team for White Sturgeon (NRTWS 2006). We also present results from simulation modeling to estimate the likelihood that recovery targets will be achieved under the “natural scenario” of no further human intervention implying no human-induced mortality and no further changes to existing habitat, either positive or negative. Details of the simulation modeling are presented in Appendix 2.

In phase 2, we compile an inventory of human threats that could jeopardize recovery, considering both human activities that directly threaten individual animals, and other human activities that affect critical habitat or residences, and thus, indirectly threaten the viability of the white sturgeon populations. Detailed information about threats is presented in NRTWS (2006). We present results from simulation modeling to illustrate the likely impact of existing human threats and estimate the maximum level of harm from all potential sources that could be sustained without unduly jeopardizing recovery.

In phase 3, we present population projections and evaluate performance measures for recovery under a variety of simulated scenarios that span the range of plausible interventions to restore damaged habitat, to supplement natural recruitment with hatchery-reared juveniles, and to restrict incidental mortality from fisheries, passage through dams, and sampling for research. These scenarios reveal the kind of interventions that are necessary and sufficient for recovery, and allow comparison of possible trade-offs between the type, magnitude, and time frame for intervention.

Phase 1: Current status

1. Abundance and past trends

Best estimates of the abundance of mature fish in each population are presented in Table 1. Trends in abundance are discussed in the following subsections. Long-term trend data on fluctuations in population size or density are generally lacking for all white sturgeon populations because most studies are relatively recent (Ptolemy and Vennesland 2003).

Table 1. Number of mature white sturgeon in SARA-listed populations in 2006 (details of estimation in Appendix 1).

Population	Number of mature fish in 2006	Reference for uncorrected abundance estimate
Upper Fraser	185	Yarmish and Toth 2002
Nechako	305	RL&L 2000
Kootenay	455	Paragamian et al. 2005
Columbia above HLK	52	Golder 2006
Columbia between HLK and Canada-US border	948	Golder 2005
Columbia below border to FDR	2003	Golder 2005

1.1 Upper Fraser population

No trend data are available for white sturgeon populations in the upper Fraser, but abundance is believed to be naturally low in this region and to be within the historic range (Ptolemy and Vennesland 2003). This conclusion is based on the apparent absence of significant threats both historically and currently (see Phase 2) and evidence that age composition is as expected for a population at equilibrium (see Appendix 2). The population in 2001 was estimated to be 815 fish of 50 cm or larger based on a mark-recapture study (Yarmish and Toth 2002).

1.2 Nechako population

Monitoring of the Nechako population began in 1982 and became more intensive in 1995 (RL&L 2000). Estimates are based on information from radio telemetry, recreational catch statistics, mark-recapture estimates and life history studies. Age composition is dominated by older individuals indicating that little or no juvenile recruitment has occurred since 1967 (McAdam et al. 2005). RL&L (2000) estimated that the Nechako population in 1999 comprised only 571 fish. Korman and Walters (2001) indicated that about 300 of these might be mature, and projected that this number would decline to 25 by 2025. Similarly, we projected their estimate for 1999 forwards to 2006 by applying an annual survival rate of 92.3% (or M=0.08), resulting in a total population estimate of only 318 fish of which 286 are likely mature (Table 1).

1.3 Kootenay population

Monitoring of the Kootenay River began in 1977 and became more intensive after 1990. Estimates are again based on radio telemetry, recreational catch statistics, mark-recapture estimates and life history studies (Duke et al. 1999; Paragamian et al. 2005). Age composition indicates that recruitment began to decline in the mid-1960s (Partridge 1983 cited in Duke et al. 1999). Natural recruitment has been negligible since 1974 and the population now consists of an ageing cohort of large, mature fish (Paragamian et al. 2005). Total abundance throughout the transboundary reach from Libby Dam to Bonnington Falls was estimated to be 760 in 2000, and this was projected to be fewer than 500 fish in 2005 assuming an annual survival rate of 91% (Paragamian et al. 2005). Continuing this projection, the total population in 2006 would be <450 fish (all mature).

1.4 Columbia population

The Columbia population has been monitored since 1990 (Hildebrand et al. 1999; UCRRP 2002). Age composition indicates that natural recruitment began to decline in 1969, and has failed almost entirely since 1985 (RL&L 1994; Hildebrand et al. 1999). Thus, the remaining natural population is at least 90% mature fish. Abundance has been estimated by separate mark-recapture studies above and below Keenleyside Dam. Total abundance was estimated at 52 (95% CI was 37-92) above Keenleyside Dam in 2006 (Golder 2006), 1157 (95% CI was 414-1899) from Keenleyside Dam to the border in 2003 (Golder 2005), and 2295 (95% CI was 1528-3574) downstream of the Canada-US border to the Grand Coulee Dam (including the Roosevelt Reservoir) (Golder 2005). These estimates were projected forwards to estimate mature abundance in 2006 at 52, 948, and 200, respectively (Table 1), assuming an annual survival rate of 97% and that 90% of the surviving fish are mature (details in Appendix 1).

Anecdotal reports that white sturgeon occur upstream of Revelstoke Dam have not yet been confirmed by surveys but survey effort has not been intensive (RL&L 1996; Hildebrand et al. 1999). The only confirmed spawning locations for white sturgeon in the Canadian portion of the upper Columbia are Waneta Eddy below Keenleyside Dam, and a small reach below Revelstoke Dam. A third spawning location has been identified at Northport Washington, although evidence points to this site being used primarily by fish residing in Roosevelt Reservoir (Howell and McLellan 2006).

2. Critical habitat

Habitat likely limits current abundance in each of the four populations. Populations in the Nechako, Kootenay, and Columbia rivers are declining as a result of recruitment failure related to extensive changes in habitat, many of which are associated with dams and river regulation. Some restoration and protection of these habitats is therefore considered essential to restoration of historic rates of recruitment, and recovery of these populations. In the upper Fraser River, natural carrying capacity for white sturgeon appears to be limited by the small extent and low productivity of suitable habitat, so preservation of existing habitat features will be critical to the viability of this population.

Critical habitat for white sturgeon has not yet been formally designated, but the NRTWS has reviewed existing information on habitats likely to be necessary for survival and recovery of each population. The NRTWS recommendations are summarized here and described in detail in Appendix 1.

2.1 Upper Fraser population

Some important habitats have been identified for juvenile rearing and feeding, adult holding and feeding, and adult overwintering in the upper Fraser River. Spawning locations have not been identified at this time. Locations that have been identified as important for juveniles and adults include the Nechako River confluence, Bowron River confluence, and the mainstem Fraser River downstream of Longworth Canyon. Additional research is required to identify other potentially critical habitats in the Upper Fraser River.

2.2 Nechako population

Spawning and incubation habitat - The only known location for spawning in the Nechako River system is the braided section of river near Vanderhoof. The precise location of this spawning area might change from year to year depending on flow conditions. This area will likely be deemed as critical habitat for spawning and incubation on an annual basis during May and June.
Larval habitat - Larval development includes the period from hatch to exogenous feeding (0 to 21 days). Critical habitat during this period will likely include the braided section of the Nechako River near Vanderhoof, extending downstream beyond the boundaries of the spawning and incubation area to an extent that cannot be defined at this time. This habitat will likely be deemed critical on an annual basis during May, June and July.

Early juvenile habitat - Critical habitat during the early juvenile stage (21 days to 2 years) likely includes the Sinkut River confluence (115 – 117 km), Leduc Creek confluence (122 – 127 km), Nechako River at 67 – 79 km, and Nechako River at 89 – 95 km. These areas will likely be deemed critical year-round.

Late juvenile and adult habitat - For late juvenile and adult feeding, overwintering and pre-spawning staging, critical habitats likely include the Sinkut River confluence (115 – 117 km), Leduc Creek confluence (122 – 127 km), Nechako River at 67 – 79 km, and Nechako River at 89 – 95 km. These habitats will likely be deemed critical year-round. Other overwintering sites, proposed as critical on an annual basis from November to May, include a deep area at 110 – 111 km, Isle Pierre (65-79 km), Tachie River confluence, Pinchi Bay, and Middle River confluence with Trembleur Lake.

Additional critical habitat factors - Additional habitat features that could be included in a definition of critical habitat for the Nechako River population include connectivity among habitats and water quality. Tolerance limits for specific attributes of water quality that affect white sturgeon have yet to be determined.

2.3 Kootenay population

Spawning and incubation habitat - All spawning and incubation habitat for the Kootenay River population of white sturgeon is located within the United States. Water level in Kootenay Lake, situated in Canada downstream of spawning sites, influences the suitability of the spawning habitat through a backwatering effect. The lake level is regulated by Canada and might be considered a component of critical habitat.

Larval habitat - Given uncertainties as to whether larval white sturgeon occur in the Kootenay system in Canada, critical habitat has not been proposed for this life stage.

Early juvenile habitat - Critical habitat for the early juvenile phase (21 days to 2 years) likely includes portions of the lower Kootenay River and the Kootenay River delta. This habitat will likely be considered critical year-round.

Late juvenile and adult habitat - Portions of the lower Kootenay River and the Kootenay River delta, the Crawford Creek delta, and the Duncan River delta are proposed as critical habitat for rearing and feeding of late juvenile and adult white sturgeon. This habitat will likely be deemed critical year-round. Some areas of Kootenay Lake and its tributaries (particularly where kokanee spawn) have been identified as important sturgeon feeding areas, but existing information is insufficient to identify them as critical at this time.

Additional critical habitat factors - Passage and water quality may also be important habitat components for Kootenay River white sturgeon. Information available at present is insufficient to deem these requirements as critical.

Remnant populations - Critical habitat has not yet been proposed for remnant subpopulations in the Kootenay system in Canada, including those in Duncan Reservoir and Slocan Lake.

2.4 Columbia population

Spawning and incubation habitat - The known spawning and incubation habitat for the Arrow Reservoir subpopulation is located in the Columbia River adjacent to the Revelstoke golf course, immediately downstream from Revelstoke Dam. This habitat will likely be deemed critical on an annual basis from June to August.

Spawning and incubation of the Columbia transboundary subpopulation occurs the Waneta area, including the Pend d'Oreille River from the Highway 22A bridge to the confluence with the Columbia, and the Columbia River from the Pend d'Oreille confluence to the international border. This spawning site will likely be deemed critical on an annual basis during June, July and the first week of August, based on known timing of spawning and incubation.

Larval habitat - For the Arrow Reservoir subpopulation, critical habitat for larval development likely includes the spawning and incubation site below Revelstoke Dam, as well as additional areas downstream that cannot be defined at this time. This habitat will likely be deemed critical on an annual basis during July through September.

Critical habitat for the larval phase in the transboundary subpopulation likely includes the areas used for spawning and incubation, and additional habitat extending downstream at least as far as the U.S. border.

Early juvenile habitat - For the Arrow Reservoir subpopulation, critical habitat for the early juvenile phase (21 days to 2 years) is expected to include a range of mainstem and off-channel habitats, as well as deltaic habitats at the northern end of Arrow Reservoir. Detailed locations of these habitats have not yet been identified.

For the transboundary subpopulation, critical habitat for the early juvenile phase likely includes Waneta Eddy, Fort Shepherd Eddy, Robson flats, Kootenay Eddy and Keenleyside Eddy.

Late juvenile and adult habitat - For late juveniles and adults in the Arrow Reservoir subpopulation, critical habitat might include the Beaton Flats area for feeding and overwintering, as well as Big Eddy for staging. These habitats will likely be deemed critical on a year-round basis. Other feeding areas such as the outlets of streams where kokanee spawn are considered important but have not yet been identified as critical.

For the transboundary subpopulation, critical habitats for feeding and overwintering of late juveniles and adults likely include Waneta Eddy, Fort Shepherd Eddy, Kootenay Eddy, the Brilliant Dam tailrace, and the Keenleyside Reach. The Waneta and Fort Shepherd eddies might also be identified as critical habitats for staging. All of these habitats will likely be deemed critical year-round.

Additional critical habitat factors - Other habitat features that are potentially critical for recovery of white sturgeon in the Columbia River include connectivity and both water quality and quantity. For the Arrow Reservoir subpopulation, connectivity is required upstream from the highway bridge to Big Eddy, and from Big Eddy to the spawning site at the golf course. For the transboundary subpopulation, connectivity is identified as a critical habitat feature at Keenleyside Dam, which is believed to divide a formerly contiguous population. Water quality thresholds to define critical habitat have not been proposed at this time. Water quantity has the potential to affect white sturgeon survival, as for example, when fluctuating water flow causes stranding of eggs and larvae. However, understanding of such effects is currently insufficient to propose specific flow criteria.

Remnant populations - Some anecdotal evidence suggests that white sturgeon are still present in the Kinbasket Reservoir in the upper Columbia system. At present, critical habitat designations cannot be made for this portion of the watershed.

3. Residences

Policy for designation and protection of residences under SARA is still being developed (Government of Canada 2004), and explicit direction on whether the concept of residence applies to white sturgeon has not yet been provided. Given this uncertainty, the NRTWS has considered, but not yet documented, descriptions of potential residences for the species. These conceptual definitions of residence are based on current understanding of white sturgeon life history and behaviour (NRTWS 2006), which includes egg incubation and larval hiding within the interstices of stream substrates, as well as aggregations of juveniles, subadults, and adults within discrete overwintering and staging habitats. Whether these habitats should be considered residences is unresolved at this time. If the residence concept is deemed to apply to white sturgeon, additional information on how white sturgeon use particular habitat features would likely be required to support a definition of residence.

4. Recovery targets

4.1 Recovery goal

The recovery goal for white sturgeon is *to ensure the long-term viability of naturally-reproducing populations throughout the species' natural range, and restore opportunities for beneficial use, if and when feasible* (NRTWS 2006).

4.2 Recovery objectives

The NRTWS (2006) also lists three measurable objectives:

1) *Prevent extirpation of white sturgeon in each of the four identified populations by ensuring no net loss of reproductive potential in SARA-listed populations.*
2) *Reach or exceed the following population and distribution targets for conservation within 50 years:*
   a) *1000 mature individuals,*
   b) *approximately 1:1 sex ratio at maturity,*
   c) *distribution over the natural range,*
   d) *ongoing natural recruitment,*
   e) *increasing trend in abundance when below the abundance target.*
3) *Reach or exceed population and distribution targets for beneficial use within specified timeframes. As success is achieved in meeting the biological recovery targets, the beneficial use targets and timelines will be established and adjusted. Such targets may vary among populations.*

The rationale for these objectives is reviewed in Appendix 1; more detailed explanation is provided in the NRTWS (2006).

4.3 Performance measures

We developed performance measures for use in simulations by re-expressing the recovery objectives as numerical or probabilistic targets (see details in Appendix 2). Feasibility of achieving recovery objective 1 by year T (no loss of reproductive potential) was evaluated by keeping track of both the number of mature fish (M_T, defined as the number age 25 or older in year T) and the total potential egg deposition (E_T). The latter index takes into account that older fish are larger and can produce more eggs. Thus, the probability of achieving recovery objective 1 is the probability that $M_T/M_1 > 1$, or alternatively, that $E_T/E_1 > 1$. We estimated the probabilities that this objective was satisfied [$P(M_T \geq M_1)$ or $P(E_T \geq E_1)$] by determining the proportion of the 500 Monte Carlo simulation trials where $M_T \geq M_1$ or $E_T \geq E_1$, respectively.

Recovery objective 2a specifies that in simulation year 50 (T = 50), the number of mature fish (M_T) should exceed the recovery target (M_{targ}) of 1000; The recovery probability $P(M_T \geq M_{targ})$ was estimated as the proportion of simulation trials where $M_T \geq M_{targ}$. We also kept track of the *minimum* number of spawners over the course of the simulation period to compute the expected minimum number (M_{min}); this index indicates the risk of genetic bottlenecks and the expected availability of broodstock for hatchery supplementation.

Recovery objectives 2b (equal sex ratio) and 2c (distribution over the natural range) were not modeled. Instead, demographic stochasticity was introduced explicitly in computing the number of fish older than age 1 that survived each year (equal sex ratio assumed). For scenarios that allowed natural recruitment, recovery objective 2d (continuing natural recruitment) was typically achieved when mature fish remained in the simulated population because natural recruitment to age 1 in each year (t) was computed with a stock-recruitment function based on potential egg deposition (E_t), subject to environmental stochasticity. However, status quo scenarios for some populations were simulated by choosing values for the natural recruitment scaling parameter (Hab_t, reflecting habitat suitability) that prevented natural recruitment.

Feasibility of achieving recovery objective 2e was evaluated as average relative growth rate (r_T) defined as $(M_T - M_1)/M_1$. The probability that this objective is achieved [$P(r_T > 0)$] was estimated by determining the proportion of simulation trials where $r_T > 0$.

For hatchery supplementation scenarios, we computed the proportion of mature fish that were of natural origin (pW_T). Natural age structure has sometimes been suggested as another possible objective for white sturgeon recovery. Accordingly, we computed deviations from equilibrium age structure in year T (ASD_T) assuming that natural age structure would be close to that at equilibrium (ASD < 0.2). Again, we estimated the probabilities that $pW_T > 0.5$ and $ASD_T < 0.2$ by determining the proportion of simulation trials where these outcomes occurred.

Feasibility of achieving recovery objective 3 was not evaluated because targets for beneficial use have not been discussed by the NRTWS. However, we did calculate our performance statistics over a time frame of 100 years. For most populations, recovery objective 2a could be achieved only within this longer time frame.

We remind the reader to interpret simulation outcomes in tables 2 to 6 with appropriate caution, keeping in mind that specific outcomes depend on our choice of parameter values. However, performance statistics typically varied by less than ± 30% over the range of plausible values for parameters (see Sensitivity analyses in Appendix 2).

5. Prognosis with no further human impacts (natural scenario)

In this section we summarize results from population projections in simulated scenarios with only natural reproduction and mortality, that is, in the absence of any human-induced mortality or interventions to promote recovery.
Habitat quality and quantity and population parameters are assumed to remain at current values.

5.1 Upper Fraser population

In the natural scenario, the Upper Fraser population consistently remained near equilibrium abundance with an expected mature population of 175 fish (Fig. 3 in Appendix 2). Recovery objectives 1, 2d and 2e were achieved consistently (probabilities all >0.53), but objective 2a was not (probability <1%) (scenario A1 in Table 2). The expected number of mature fish was only 170 in year 50, and 182 in year 100 (Table 6 in Appendix 2). The expected *minimum* number of mature fish during the 100-yr simulation was 139 and occurred on average in year 59. These results raise questions (addressed in the Conclusions section) about the applicability of recovery objective 2a for the Upper Fraser population given that current abundance is assumed to be near historic levels.

5.2 Nechako population

In the natural scenario, the Nechako population typically declined to <50 mature fish within 22 years and to <20 mature fish within 50 years. The expected number of mature fish was 4 in year 50 and 0 in year 100 (Table 6 in Appendix 2). Extinction consistently occurred within 70 to 80 years. Thus, none of the recovery objectives were achieved (scenario A2 in Table 2).

Table 2. Probabilities for achieving recovery objectives under "natural" scenarios (current recruitment status, no hatchery supplementation, and no human-induced mortality. Shading indicates that an outcome was achieved in at least 50% of trials; M_{min} is the expected minimum value; a full summary is provided in Appendix 2.

Population	**Scenario**				**Recovery objective**				**Other performance measures**		
	ID	extent of restoration	annual release	mortality scalar[1]	1 $E_{50}>E_1$	1 $M_{50}>M_1$	2a $M_{50}>1000$	2e $r_{50}>0$	$pW_{50}>0.5$	$ASD_{50}<0.2$	M_{min}
Upper Fraser	A1	current	0	0	0.58	0.53	0	0.56	1	0.01	139
Nechako	A2	current	0	0	0	0	0	0	0.97	0	0
Kootenay	A3	current	0	0	0	0	0	0	1	0	0
Columbia	A4	current	0	0	0	0	0	0	1	0	0

Notes: [1] HM parameter multiplies estimate of "status quo mortality" (see Table 4 in Appendix 2)

5.3 Kootenay population

Similarly, in the natural scenario, the Kootenay population typically declined to <50 mature fish within 30 years and to <20 mature fish within 50 years. The expected number of mature fish was 7 in year 50 and 0 in year 100 (Table 6 in Appendix 2). Extinction consistently occurred within 70 to 80 years. None of the recovery objectives were achieved (scenario A3 in Table 2).

5.4 Columbia population

Again, in the natural scenario, the Columbia population typically declines to <50 mature fish within 38 years and to <20 mature fish within 50 years; extinction consistently occurs within 70 to 80 years (Fig. 3 in Appendix 2). The expected number of mature fish was 15 in year 50 and 0 in year 100 (Table 6 in Appendix 2). None of the recovery objectives are achieved (scenario A4 in Table 2).

Phase 2 – Scope for human-induced mortality

6. Threats to white sturgeon (as individuals)

Known threats to white sturgeon populations in Canada are summarized in the SARA recovery strategy (NRTWS 2006). Specific sources of harm or mortality to individual white sturgeon within each of the four SARA-listed populations, and associated mortality and vulnerability estimates, are described below.

6.1 Upper Fraser population

Research activities – Relatively few studies have been conducted on white sturgeon in the upper Fraser River. The most recent of these programs employed established sampling techniques including set lines, angling, gill nets, boat electrofishing, radio telemetry, and life history sampling. Harm or mortality were not reported from these studies, and would be expected to be negligible based on extensive use of these methods elsewhere. Additional research to address biological data gaps and identify critical habitats has been recommended for the upper Fraser population (NRTWS 2006).

Recreational fishery - A non-retention sport fishery exists in the upper Fraser River for white sturgeon, which are also captured in recreational fisheries for other species. Information on these fisheries is very limited, but it is thought that targeted angling for white sturgeon is rare to non-existent at present. Any larger fish caught and released would be expected to have high survival based on inferences from other sources, including a study on the lower Fraser white sturgeon recreational fishery which found low rates of direct mortality (0.012%) associated with angling catch and release (Robichaud et al. 2006). Bycatch in other sport fisheries is unknown but expected to be low and predominated by smaller fish. For the purposes of analysis, mortality rate following capture was assumed to be the same as identified for Columbia juveniles (4%), and encounter rates were thought to be only 10% of those on the Columbia. This corresponds to an annual juvenile mortality of 0.01% (Table 4 in Appendix 2).

Food, social and ceremonial fisheries – White sturgeon are no longer directly targeted by aboriginal set or drift net fisheries in the upper Fraser River, but may be caught incidentally during food, social and ceremonial (FSC) fisheries for salmon. Most intercepted sturgeon are released unharmed if in good condition, but dead or moribund individuals may be retained. Injury and mortality to white sturgeon tend to be much greater in set nets than in drift nets due to longer soak times. Robichaud et al. (2006) found that set nets had higher direct (6.2%) and latent (46.9%) mortality rates than did drift nets (4.8% and 0%, respectively) in the lower Fraser River. It is thought that set nets tend to be more widely used than drift nets in the upper Fraser River (Fraser River White Sturgeon Working Group 2005).

The upper Fraser FSC gillnet fisheries primarily occur from Shelley downstream to Woodpecker Rapids. A large proportion of the effort occurs in the vicinity of the Stone Creek confluence and in the Fort George canyon area. Yarmish and Toth (2002) observed limited use of this section of the river by white sturgeon, and very few are apparently captured in this fishery, with only one reported mortality over the last 10 years. Our present analysis of this fishery is based on a bycatch rate of 2 adults per year, with one mortality every ten years, for a mortality rate following capture of 5% and a total annual mortality of 0.02% (Table 4 in Appendix 2).

6.2 Nechako population

Research and recovery activities – Assessments of the Nechako white sturgeon population began in the early 1980s and continue to the present in support of an recent recovery initiative (NRTWS 2006). These studies have involved sampling of adults, eggs, and juveniles using a variety of proven techniques including set lines, angling, gill nets, boat electrofishing, telemetry, egg mats, and drift nets. Incidental mortality of juvenile and adult white sturgeon is not known to have occurred in these investigations to date. Additional study needs, to fill data gaps and characterize critical habitats for the Nechako population, have been identified in the national recovery strategy (NRTWS 2006).

As part of the recovery initiative for Nechako white sturgeon, a conservation aquaculture program has been established. This involves collection of wild broodstock, which are spawned in a hatchery facility and subsequently returned to the river. Progeny are raised in the facility until their release. Potential risks to the health and survival of these individuals during these operations have not been quantified.

Recreational fishery – The Nechako River has been closed to directed fishing for white sturgeon since 2000. Further, a bait ban was imposed on the Nechako recreational fishery in 2006, to reduce catch of bull trout as well as future encounters of juvenile white sturgeon as they enter the system from the recently established conservation culture program. Current hatchery progeny have not yet reached the vulnerable age classes (i.e., 2-10 years), so incidental catch of juveniles in the sport fishery is probably negligible at this time. To estimate overall juvenile mortality, we assumed that juvenile mortality following capture was 4% (as in the Columbia) but that encounter rate was only 5% of the Columbia rate, which implies a current annual mortality of 0.003% (Table 4 in Appendix 2). This catch rate and resulting mortality in the Nechako could increase substantially as hatchery juveniles become vulnerable to the fishery.

Food, social, and ceremonial fisheries – White sturgeon are occasionally encountered during aboriginal gill net fisheries for salmon that occur throughout the Nechako watershed. FSC fishing occurs in various locations in the lower Nechako River downstream of Isle Pierre, but sturgeon bycatch has not been reported in this area over the past 10 years. In the mainstem Nechako upstream of Isle Pierre, gillnetting is concentrated above the Stuart River confluence at Finmore and below the Nautley River confluence. In Fraser Lake, incidental captures of white sturgeon appear to be most frequent at its outlet to the Nautley River, and a few other areas within the lake. In the Stuart system, gillnetting occurs primarily at the outlet and southern end of Stuart Lake, with reports of one to two white sturgeon captured per year, as well as in the Tachie River, Trembleur Lake, and Middle River. White sturgeon have also been captured historically in Takla Lake, but bycatch has not been reported there in recent years. In addition, FSC fisheries in the Fraser River immediately downstream of Prince George could potentially encounter Nechako white sturgeon.

The Carrier Sekani Tribal Council (CSTC) has recently undertaken projects to assess bycatch and promote harm reduction for white sturgeon in FSC fisheries, including the adoption of selective techniques (Toth et al. 2005, CSTC Fisheries Program 2006). These studies found that gillnets primarily captured sturgeon in the 1.0-2.5 m range, thereby potentially harming the most reproductively viable portion of the population. Reported encounters of white sturgeon were highly variable, including about five to ten per year in 2002-2003, about half of which died or were harvested; one mortality in 2004 that was retained for food; and 21 captures in 2005, of which four were dead and the remainder released (Toth et al. 2005, CSTC Fisheries Program 2006). Estimates used in our analysis were one adult mortality out of five caught in FSC fisheries each year, resulting in an overall annual mortality of 0.3% (Table 4 in Appendix 2).

6.3 Kootenay population

Research and Recovery Activities – The Kootenay River population of white sturgeon has been studied since the 1970s, and a transboundary recovery effort was initiated in the 1990s in response to a US Endangered Species Act listing (NRTWS 2006). Research and recovery activities for the population have generally focused on key life history phases that occur in the US portion of its range. Studies in Canada have included telemetry of adults in Kootenay Lake and standard sampling methods to monitor juveniles in the lake and the Canadian portion of the Kootenay River. Further research requirements have been proposed as part of SARA recovery planning for the Kootenay white sturgeon population in Canada (NRTWS 2006).

The international recovery initiative for Kootenay white sturgeon has also established a conservation culture program in the US and Canada. Broodstock collection and primary hatchery operations occur in Idaho, and a portion of the embryos are transported to and reared at a second culture facility in British Columbia. There are likely some risks to the health and survival of these individuals during these operations.

Passage Through Dams – Small numbers of white sturgeon apparently move through the lower Kootenay River downstream of the lake, a section which is impounded by five dams. Some entrainment of white sturgeon has been observed at Brilliant Dam, the furthest downstream of these facilities. There is an anecdotal report from the late 1990s of a dead adult sturgeon impinged on a trash rack of the dam, and in 2001 a juvenile entrained into a draft tube was recovered alive and released downstream into Kootenay Eddy.

Overall, we estimated that one adult was killed every two years as a result of entrainment and research/recovery activities, which corresponds to an annual mortality of 0.1% (Table 4 in Appendix 2).

6.4 Columbia population

Research and Recovery Activities – Directed research on Columbia white sturgeon began in 1990, and continues as part of a recovery initiative established in 2000 (NRTWS 2006). Numerous studies have been undertaken on this population throughout its range, including assessments of abundance, distribution, habitat use, movement, spawning, and life history. Sampling of all life stages has been conducted using set lines, angling, gill nets, boat electrofishing, telemetry, egg mats, and drift nets. The national recovery strategy (NRTWS 2006) calls for additional research, in part to support the identification of critical habitat for the Columbia population.

A conservation aquaculture program has also been operating annually for Columbia white sturgeon since 2002. As in other such programs, each year several wild broodstock are temporarily transported to a hatchery for spawning, and juveniles are subsequently released at various locations in the river. Annual gill net sampling of these juveniles has been conducted for monitoring and research purposes.

Incidental mortalities had not been documented in the preceding years of sampling this population; however, more intervention as part of the recovery initiative has resulted in some impacts. During the first four years of the culture program, one brood female died as a result of spawning hormone treatment in the hatchery. In addition, a total of seven incidental mortalities by gill netting have occurred during juvenile monitoring since 2002, including one wild and five cultured juveniles as well as a single adult. This is the only known adult mortality during white sturgeon collection in the Columbia to date.

The juvenile monitoring program has also involved lethal sampling of some hatchery fish for detailed health and dietary assessments. A total of 51 cultured juveniles captured during field sampling were sacrificed for this purpose between 2002 and 2004. Additional sacrifices are not currently planned for future juvenile monitoring of the Columbia population.

Recreational Fishery – The sport fishery for white sturgeon in the Canadian portion of the Columbia system was closed in 1996. Incidental captures have not recently been reported in fisheries upstream of Keenleyside Dam, but have probably increased in the intensive fishery between Keenleyside Dam and the US border, where angling effort has reportedly doubled since the early 1990s (CCRITFC 2006). This fishery primarily targets rainbow trout and walleye, both of which occur in habitats also used by white sturgeon over age 1. Bait use in this fishery also increases susceptibility of white sturgeon to capture.

Large white sturgeon (> age 10) would rarely be landed and bycatch mortalities are expected to be very low. Smaller fish (ages 2 to 10) are vulnerable to angling and more likely to receive fatal hooking injuries, whereas white sturgeon < age 2 are too small to be caught. As such, the older cohorts of cultured juveniles are now vulnerable to incidental capture in the recreational fishery.

There have been considerable anecdotal reports of both adult and juvenile white sturgeon encounters in the Columbia sport fishery, but evidence of angling-related mortality is limited. One cultured juvenile was reported dead from angling in 2005, and the remains of an illegally harvested adult were recovered in 2006. The extent of poaching of Columbia white sturgeon is not known.

Overall, we estimated that 150 adults were hooked in the recreational fishery each year, with an average of one mortality every three years, for a total annual mortality of 0.2%. We estimated that 20 juveniles were killed out of 500 caught in the sport fishery each year, for a mortality rate following capture of 4% and an overall mortality of 0.07% per year (Table 4 in Appendix 2)

Passage Through Dams - Dead white sturgeon are occasionally found in the downstream vicinity of Keenleyside Dam, with injuries consistent with some interaction with the facility, such as downstream or attempted upstream passage. Some of these may be fish from Arrow Reservoir entrained through the dam, which would be a particular concern given the very low abundance of that subpopulation.

Since formal reporting began in 1999, five such mortalities of white sturgeon have been documented. All of these were adults or subadults that exhibited severe external and internal injuries consistent with blunt force trauma. Further research is required to confirm the cause of these mortalities. For the purposes of modeling we assume that one fish is killed at Keenleyside Dam every two years, which corresponds to an overall adult mortality of 0.05% (Table 4 in Appendix 2).

Other Threats - An incidental white sturgeon mortality at the Celgar mill in Castlegar was reported in 2004. An adult female was fatally injured when it was apparently caught in a floating log bundle and transferred into a sorting facility. The extent of this risk and how it might be prevented is not known.

Unexplained mortalities of white sturgeon have also been observed at various locations along the Columbia River. A total of six of these have been documented since formal reporting began in 1999. These fish were of various sizes and had unexplained or no apparent injuries. Further research would be required to assess the causes of these mortalities.

7. Threats to critical habitat and residences

Threats to critical habitats have been identified by the NRTWS and are summarized in the following sections (details are provided in Appendix 1). Most threats to critical habitat could also be considered threats to residences.

7.1 Upper Fraser population

Given that potential critical habitats have not been specifically identified for white sturgeon in the upper Fraser River, it is not possible at present to characterize specific threats. Activities that might impact critical habitat include: river regulation; instream activities such as dredging for gravel or sand; linear development; alterations or development of riparian, foreshore, or floodplain areas; upstream use of land and water; and effluent discharge from both point and non-point sources.

7.2 Nechako population

Spawning and incubation habitat – It is widely believed that regulation of the Nechako River has had a significant influence on habitat quality at the single known spawning and incubation site, in particular by reducing peak flows in the hydrograph. As a result, gravel bars are flooded less frequently, the vegetation on bars and islands has increased, and the movement of stream substrates has been reduced. Other potential threats include: dredging for gravel or sand; linear development; alterations or development of riparian, foreshore, or floodplain areas; upstream use of land and water; and effluent discharge from both point and non-point sources.

Larval, juvenile, and adult habitat - Activities that could impact critical habitat for these life stages include: river regulation; dredging for gravel or sand; linear development; alterations or development of riparian, foreshore, or floodplain areas; upstream use of land and water; and effluent discharge from both point and non-point sources. Specific threats would depend upon the nature of these activities.

Additional critical habitat factors - Potential threats to water quality for white sturgeon include contamination of benthic sediments (e.g., metals, organochlorine compounds), point source discharges from pulp mills, treated and untreated municipal and private sewage, and non-point sources of pollution from agriculture and forestry.

7.3 Kootenay population

Spawning and incubation habitat - Inflows and outflows to Kootenay Lake are regulated, and resulting lake levels might influence the suitability of critical spawning and incubation habitat in the Kootenay River through a backwatering effect. As such, particular operations of the hydrosystem, such as those that result in lower than natural lake elevations in the spring, could be considered a threat to these habitats.

Larval, juvenile, and adult habitat - Suitability of the lower Kootenay River, various tributary deltas, and Kootenay Lake itself for feeding and rearing of white sturgeon is also likely affected by lake levels. As a result, lake operations represent a potential threat to the critical habitats of these life stages too.

Additional critical habitat factors – Water quality for Kootenay white sturgeon could be threatened by contamination of benthic sediments (e.g., metals, organochlorine compounds), point source discharges from pulp mills, treated and untreated municipal and private sewage, and non-point sources of pollution from agriculture and forestry.

7.4 Columbia population

Spawning and incubation habitat - Spawning and incubation habitat for the Arrow Reservoir subpopulation is located immediately downstream from Revelstoke Dam, which is currently operated as a load-following facility. Although spawning appears to occur naturally, hypolimnetic releases (i.e., from deep, cold water) from Revelstoke Dam have altered water temperatures and are believed to influence the timing of spawning and duration of embryo development. Operations of Revelstoke Dam are also thought to impact the suitability of incubation habitat through occasional stranding of eggs and embryos. In addition, the elevation of Arrow Reservoir can alter flow conditions below Revelstoke Dam and the resulting backwatering effect might influence suitability of spawning and incubation habitats.

The transboundary population spawning area at Waneta is impacted by load-following and water storage associated with a series of dams on Pend d'Oreille River, including Seven Mile and Waneta dams within Canada and additional facilities upstream in the US. Spawning at this site occurs primarily beyond the Pend d'Oreille channel, just upstream from its confluence with the Columbia mainstem and downstream a short distance. Thus, Columbia and Pend d'Oreille river dams further impact spawning and incubation habitats, also as a result of both load-following and storage. In addition, slag and other contaminant effluents from smelting have impacted substrate conditions and water quality in the Columbia River downstream.

Larval, juvenile, and adult habitat - Activities that could impact critical habitat for these life stages in the Columbia River include: river regulation; dredging for gravel or sand; linear development; alterations or development of riparian, foreshore, or floodplain areas; upstream use of land and water; and effluent discharge from both point and non-point sources. Actual impacts would depend on the particular aspects of these activities.

Additional critical habitat factors – The Arrow Reservoir subpopulation might be affected by water regulation at the Revelstoke Dam that limits connectivity among habitats from Arrow Reservoir to the spawning site at the Revelstoke golf course. The historic range of the transboundary population is thought to be fragmented by the presence of Keenleyside Dam, rather than by its continuing operations or related activities.

Water and substrate quality for white sturgeon in the Columbia River could be impacted by contamination of benthic sediments (e.g., metals, organochlorine compounds), point source discharges from pulp mills and smelters, industrial plants, treated and untreated municipal and private sewage, and various other industrial and urban discharges, and non-point sources of pollution from agriculture, forestry, and urban areas.

8. Scope for total allowable harm

8.1 Upper Fraser population

Population projections for the Upper Fraser population indicate that some but not all recovery objectives can be achieved under the natural scenario of no human-induced mortality. At first sight, this suggests that there is no scope for allowable harm. However, the simulation results for this population, which are based on our assumptions about historic abundance, lead us to question the necessity for achieving 1000 mature fish (recovery objective 2a) and continued population growth (recovery objective 2e) (see Conclusions).

The population projections suggest that most other recovery objectives (excluding 2a) can be achieved provided total human-induced mortality does not exceed twice the estimated status quo level (scenario E4 in Table 3).

8.2 Nechako, Kootenay, and Columbia populations

Population projections for all three population affected by dams indicate that recovery is infeasible under the natural scenario. In fact, extinction appears inevitable in these populations even in the absence of direct human-induced mortality, unless human intervention can restore natural recruitment. Without such intervention, there appears to be no scope for allowable harm. Even so, it might

Table 3. Probabilities for achieving recovery objectives under "status quo" scenarios with current recruitment status, current hatchery supplementation (for 20 years), and human-induced mortality. Shading indicates that an outcome was achieved in at least 50% of trials; M_{min} is the expected minimum value; a full summary is provided in Appendix 2.

Population	Scenario				Recovery objective				Other performance measures		
	ID	extent of restoration	annual release	mortality scalar[1]	1 $E_{50}>E_1$	1 $M_{50}>M_1$	2a $M_{50}>1000$	2e $r_{50}>0$	$pW_{50}>0.5$	$ASD_{50}<0.2$	M_{min}
Upper Fraser	E2	current	0	1	0.57	0.52	0	0.56	1	0	139
	E1	current	0	0.5	0.55	0.52	0	0.56	1	0	138
	E3	current	0	1.5	0.52	0.49	0	0.54	1	0.01	138
	E4	current	0	2	0.5	0.49	0	0.52	1	0	137
Nechako	E11	current	5000	1	1	1	0.02	1	0.01	0	14
Kootenay	E18	current	15000	1	1	1	1	1	0.01	0	50
Columbia	E25	current	15000	1	1	1	1	1	0.02	0	51

Notes: [1] HM parameter multiplies estimate of "status quo mortality" (see Table 4 in Appendix 2) be reasonable to allow some harm contingent on successful interventions to increase natural recruitment, given that the very feasibility of recovery depends upon such interventions. Plausible scenarios with interventions to promote recovery are considered in the next section.

Phase 3 – Scenarios to promote recovery

9. Habitat restoration

We simulated scenarios of habitat restoration to promote natural recruitment by adjusting a recruitment scaling parameter (Hab_t, see details in Appendix 2). Although these scenarios are labeled "habitat restoration", we do not mean to imply that any particular habitat restoration activity is necessary, merely that action is taken to increase natural recruitment by the amount specified. For the Upper Fraser population, Hab_1 was set to 1 reflecting that habitat conditions for natural recruitment remain similar to historic conditions; in one scenario (B1), this value was increased to 2. For non-recruiting Nechako, Kootenay, and Columbia populations, Hab_t was set to 0 before restoration, then increased to 0.25, 0.5, or 1.0 in various scenarios. In all but one case (Figure 4 in Appendix 2), restoration began in year 5 such that the Hab_t value increased lineally until the specified level was achieved by year 10 and thereafter.

Doubling the natural recruitment rate for the Upper Fraser population ($Hab_t = 2$) increased the average abundance of mature fish to 321 by year 50 but this was still well below M_{targ} (scenario B1 in Table 4 and Table 6 of Appendix 2). Similarly, increasing Hab_t to 0.5 for the Nechako, Kootenay, and Columbia populations increased the average abundance of mature fish in year 50 to between 274 and 416, but did not consistently achieve any of the recovery objectives (scenarios B3 to B10 in Table 4).

On the other hand, fully restoring levels of natural recruitment for Nechako, Kootenay, and Columbia populations resulted in reasonable probabilities (0.39 to 0.70) of achieving 1000 mature fish by year 100, although

Table 4. Probabilities for achieving recovery objectives under habitat restoration scenarios (restoration as specified, no hatchery supplementation, and no human-induced mortality). Shading indicates that an outcome was achieved in at least 50% of trials; M_{min} is the expected minimum value; a full summary is provided in Appendix 2.

Population	Scenario				Recovery objective				Other performance measures		
	ID	restoration scalar[1]	annual release	mortality scalar[2]	1 $E_{50}>E_1$	1 $M_{50}>M_1$	2a $M_{50}>1000$	2e $r_{50}>0$	$pW_{50}>0.5$	$ASD_{50}<0.2$	M_{min}
Upper Fraser	B1	2	0	0	1	1	0	0.56	1	0.01	158
Nechako	B3	0.5	0	0	0	0.24	0	0.36	1	0	28
	B4	1	0	0	0	1	0	1	1	0.01	29
Kootenay	B6	0.5	0	0	0	0.02	0	0.07	1	0	44
	B7	1	0	0	0	0.99	0	1	1	0	45
Columbia	B9	0.5	0	0	0	0	0	0	1	0	90
	B10	1	0	0	0	0.22	0.07	0.4	1	0.02	91

Notes: [1] Hab parameter sets natural recruitment as specified proportion of historic rate in original habitat.
[2] HM parameter multiplies estimate of "status quo mortality" (see Table 4 in Appendix 2)

expected abundance still remained well below target in year 50 (range 558 to 820 across populations) (Table 6, scenarios B4, B7, B10). The recovery probability was greatest for the Columbia population (B10) because it has the largest initial population size. Recovery objectives 1 and 2e were met in most cases (not all) with restoration of historic rates of natural recruitment (Table 4).

10. Hatchery supplementation

We explored the effects of immediate hatchery supplementation by simulating low (3000 age-1 fish), and high (15000) levels of annual stocking for a short duration (t = 1 to 20 years) or over the entire simulation (t = 1 to 100 years). At equilibrium, an annual natural recruitment of 630 age-1 fish would maintain 1000 mature fish in a population with total abundance (No) of 8200 (Appendix 2). After accounting for the reduced survival of hatchery fish in their first year after release ($S_H = 0.2$), annual stocking of 3000 age-1 hatchery fish would be required to maintain the same population size in the absence of any natural recruitment. Most of the hatchery supplementation scenarios involved immediate supplementation to boost to natural recruitment until some level of natural recruitment was restored.

Long-term, low level hatchery supplementation was sufficient to meet all recovery objectives (except wildness) by year 50 in all cases (all scenarios in Table 5 excluding C5). We also simulated one short-term, high supplementation scenario where 15000 fish were stocked each year but only for the first 20 years. In that scenario (C5, Nechako), the mature population grew to 3049 fish in year 50 ($r_{50} = 9.76$) as hatchery fish continued to mature, but later declined as the hatchery fish eventually died ($r_{100} = -0.97$, $M_{100} = 56$) (Table 6 in Appendix 2). Consequently, there was no long-term benefit from this approach used by itself.

The proportion of wild fish under both stocking scenarios was very low (<8%) for the non-recruiting populations. Interestingly, nearly equilibrium age structure (with low ASD_T) was restored under both hatchery scenarios; in fact, the age

Table 5. Probabilities for achieving recovery objectives under hatchery supplementation scenarios (current habitat status, hatchery supplementation as specified, and no human-induced mortality). Shading indicates that an outcome was achieved in at least 50% of trials; M_{min} is the expected minimum value; a full summary is provided in Appendix 2.

Population	Scenario				Recovery objective				Other performance measures		
	ID	stocking duration	first year	annual release	1 $E_{50}>E_1$	1 $M_{50}>M_1$	2a $M_{50}>1000$	2e $r_{50}>0$	$pW_{50}>0.5$	$ASD_{50}<0.2$	M_{min}
Upper Fraser	C1	100	1	3000	1	1	1	1	0	1	162
Nechako	C3	100	1	3000	1	1	0.99	1	0	1	44
	C5	20	1	15000	1	1	1 [1]	1	0	0	43
Kootenay	C6	100	1	3000	1	1	1	1	0	1	67
Columbia	C8	100	1	3000	0	1	1	1	0	1	137

Notes: [1] expected abundance of mature fish declined to only 56 fish by year 100.

structure for the Upper Fraser population under stocking (C1 and C2) became more "natural" than without stocking (A1) because stochastic variation in natural recruitment increased the ASD index.

11. Restrictions on human-induced mortality

Several additional scenarios were designed to assess the implications of different levels and types of incidental mortality under conditions of habitat restoration and hatchery supplementation that otherwise favoured recovery. In each case, separate vulnerability parameters were used to simulate incidental mortality for small (ages 2 to 10) and large (age >11) size classes; incidental mortality was not applied to fish < age 2. "Status quo" rates of incidental mortality were estimated for sockeye gillnet fisheries in the Nechako River, hook and line sampling for broodstock or research and dam passage in the Kootenay population, and hook and line sport fishing for walleye and dam passage in the Columbia population (Table 4 in Appendix 2). Incidental mortality was increased or decreased by scaling the size-class specific status quo estimates with a scalar multiplier.

Because the Upper Fraser population is near equilibrium and self-sustaining, the (very low) estimated status quo level of human-induced mortality has little effect on population viability (Table 6). Comparison of results for the natural scenario (A1) with those for the status quo scenario (E2) suggests that if human mortality were eliminated, then by year 50, the average abundance of mature fish would increase only slightly from 177 to 180 (still far below M_{targ}), and the average rate of population growth would increase only slightly from 0.02 to 0.04. Doubling status quo mortality over the same period would decrease the average abundance of mature fish very slightly from 178 to 177, but would not change average population growth rate (because of the compensation ratio used). Long-term hatchery stocking of 3000 age-1 fish per year would be sufficient to meet all recovery targets (except wildness) even at twice the estimated status quo mortality; however, the proportion wild would decline to 5% or less. Short-term stocking of 15000 fish for 20 years with status quo mortality would achieve M_{targ} in year 50, but the average abundance of mature fish would decline to 267 by year 100.

Preliminary simulations revealed that even modest levels of human-induced mortality could eliminate any chance of recovery for the Nechako, Kootenay, and Columbia populations. Fortunately estimates of status quo mortality appear to be sufficiently low that recovery of wild populations should be feasible with a judicious and timely combination of habitat restoration and hatchery supplementation. In simulations with current incidental mortality and current stocking rates (continued for 20 years) *but no restoration of natural recruitment* (scenarios E11, E18 and E25), the abundance of mature fish exceeded target levels in year 50, but by year 100, had declined to low levels (14, 51, and 51 for Nechako, Kootenay, and Columbia, respectively). Moreover, the proportion wild in year 50 did not exceed 5%.

Outcomes were improved somewhat with less aggressive short-term stocking (3000 per year for 20 years) coupled with 50% restoration of natural recruitment and status quo mortality (scenarios E12, E19, and E26). In these scenarios, the proportion wild in year 50 ranged from 24 to 34% across populations, and the abundance of mature fish almost reached the target in year 50 (range 818 to 997 across populations), then declined (although less severely than before) by year 100 (range 497 to 546 across populations). Longer-term stocking of 3000 fish per year under the same conditions (scenarios E14, E21, and E28) achieved the target in both year 50 and year 100, but the proportion remaining wild in year 50 declined slightly (range 20 to 29%).

Outcomes were improved significantly only with full restoration of natural recruitment and modest short-term stocking (3000 fish per year for 20 years); under these conditions, even with twice the estimated status quo level of human-

Table 6. Probabilities for achieving recovery objectives under scenarios exploring trade-offs with different levels of human-induced mortality, habitat restoration (except Upper Fraser), and hatchery supplementation (both short-term and long-term). Shading indicates that an outcome was achieved in at least 50% of trials; M_{min} is the expected minimum value; a full summary is provided in Appendix 2.

Population	Scenario					Recovery objective				Other performance measures		
	ID	restoration scalar[1]	annual release	stocking duration	mortality scalar[2]	1 $E_{50}>E_1$	1 $M_{50}>M_1$	2a $M_{50}>1000$	2e $r_{50}>0$	$pW_{50}>0.5$	$ASD_{50}<0.2$	M_{min}
Upper Fraser	A1	current	0	n/a	0	0.58	0.53	0	0.56	1	0.01	139
	E2	current	0	n/a	1	0.57	0.52	0	0.56	1	0	139
	E4	current	0	n/a	2	0.5	0.49	0	0.52	1	0	137
	E5	current	3000	20	1	1	1	0	1	0	0	161
	E7	current	3000	100	1	1	1	1	1	0	1	162
Nechako	E11	current	5000	20	0	1	1	0.02	1	0	0	14
	E12	0.5	3000	20	1	1	1	0	1	0	0	40
	E14	0.5	3000	100	1	1	1	1	1	0	1	40
	E15	1	3000	20	2	1	1	0.31	1	0	0.01	37
Kootenay	E18	current	15000	20	0	1	1	1	1	0	0	50
	E19	0.5	3000	20	1	1	1	0.05	1	0	0	66
	E21	0.5	3000	100	1	1	1	1	1	0	0.99	65
	E22	1	3000	20	2	1	1	0.99	1	0.01	0	64
Columbia	E25	current	15000	20	0	1	1	1	1	0	0	51
	E26	0.5	3000	20	1	0	0.92	0.46	0.99	0	0	135
	E28	0.5	3000	100	1	0.01	1	1	1	0	1	134
	E29	1	3000	20	2	0.32	1	1	1	0.27	0	132

induced mortality (scenarios E15, E23, and E29), all recovery objectives could be achieved, and the proportions wild in year 50 ranged from 37 to 48%.

Conclusions

Upper Fraser population – Population projections for the Upper Fraser population suggest that most recovery objectives (excluding 2a) can be achieved if total human-induced mortality does not exceed twice the estimated status quo level. The simulation results, which are based on our assumptions about historic abundance, lead us to question the necessity of achieving 1000 mature fish (recovery objective 2a) and continued population growth (recovery objective 2e). It is worth emphasizing that, from a genetic perspective, the target of 1000 mature individuals is intended to preserve indefinitely the population's reproductive fitness and genetic adaptability, and hence, its *long-term* viability. Thus, it might seem inappropriate to insist on a standard of care for genetic security that this population has never known. Also, concerns about the potential loss of genetic diversity over the longer term that motivate recovery objective 2a might be addressed in other ways. For example, genetic diversity comparable to that in a population of 1000 mature sturgeon could be maintained in a smaller population if human intervention provided just enough gene flow from other white sturgeon populations to offset the loss of diversity expected from random genetic drift, but not so much that the population would experience outbreeding depression. This strategy was developed and applied to conserve the viability of the Florida panther population (Hedrick 1995).

Similarly, one might question whether recovery objective 2e (continuing population growth) is appropriate for a population that is considered to be near its historic carrying capacity. Continuing population growth could only be achieved by creating new or better habitat for white sturgeon in the upper Fraser River, or by increasing abundance artificially through hatchery supplementation. However, the potentially deleterious genetic consequences of supplementation would likely compromise any gain in population viability that could be achieved by increasing population size. A more sensible approach, in our opinion, is to recognize that the naturally small size of the Upper Fraser population makes it inherently vulnerable to extinction, and to seek to maintain its current viability by preventing further deleterious impacts.

Nechako, Kootenay, and Columbia populations – Population projections for all three populations affected by dams indicate that extinction in the wild is inevitable, even in the absence of further human-induced mortality, *unless human intervention can restore natural recruitment*. This task will be formidable given that the specific causes of recruitment failure remain poorly understood, and that technical solutions to reverse the failure have not yet been proven. Nevertheless, we have assumed in our habitat restoration scenarios that these untested solutions are feasible and can be implemented within 5 to 10 years. Our simulation results indicate first, that close to full restoration of the historic rates of natural recruitment will be necessary to achieve recovery objectives, and second, that restoration of historic rates of natural recruitment would be sufficient to achieve abundance objectives within 100 years, but not within 50 years. A corollary of these conclusions is that the recovery potential for each population will be limited by any factor (e.g., degradation of critical habitat) that prevents restoration of natural recruitment to historic levels.

If the 50-year time frame is important, hatchery supplementation will likely be necessary. In the simulation scenarios, long-term hatchery supplementation by itself was sufficient to meet all recovery objectives except 2d (continuing natural recruitment). Long-term hatchery supplementation achieves population abundance and growth targets, but at the cost of dramatically reducing the proportion of wild fish in the population (to <10% in year 50 absent restoration of natural recruitment). In our opinion, such an approach would defeat the recovery goal, which is "to ensure the long-term viability of *naturally-reproducing* populations throughout the species' natural range, and restore opportunities for beneficial use, if and when feasible" (our emphasis). We conclude that the strategy of hatchery supplementation is necessary but not sufficient by itself.

If the 50-year criterion is waived, then it might seem that habitat restoration to fully achieve historic rates of natural recruitment would meet all remaining recovery objectives. However, it is worth emphasizing that the age structure of these populations has been severely distorted by many years of recruitment failure such that even if historic rates of natural recruitment were achieved within 5 to 10 years, the expected number of mature fish will decline to extremely low numbers around year 2035: to 20 fish in the Nechako, 45 fish in the Kootenay, and 91 fish in the Columbia populations. Such low numbers represent “genetic bottlenecks” that threaten genetic diversity and raise additional concerns about extinction from chance events (demographic and environmental stochasticity). In principle, hatchery supplementation could play a useful role in reducing the severity of these bottlenecks. For example, stocking 3000 age-1 hatchery fish each year for the next 20 years, while restoring historic rates of natural recruitment within 5 to 10 years, and restricting incidental mortality to less than twice the estimated current level (scenarios E15, E22, and E29) could achieve all recovery objectives by year 50, and decrease the risk of genetic bottlenecks by increasing the expected *minimum* abundance of mature fish from 29 to 37 in the Nechako, from 45 to 64 in the Kootenay, and from 91 to 137 in the Columbia populations. Despite intensive hatchery supplementation, the proportion of fish from natural spawning in year 50 is expected to range from 37% in the Nechako population to 48% in the Columbia population.

Experience to date with hatchery supplementation of white sturgeon indicates that hatchery fish released at age 1 survive and grow well after their first year in the wild. However, it remains to be seen whether these fish will contribute to natural recruitment in the future as much as has been assumed in our simulations. Aside from fish culture issues, hatchery breeding programs face the difficult challenge of maintaining an adequate genetically effective population size given the small number of broodstock available. In our opinion, hatchery supplementation should be viewed as experimental, but supported as a calculated risk to offset the perhaps more serious risk of genetic bottlenecks in natural spawning expected over the next 30 years.

At first sight, there appears to be no biological case to justify “allowable harm exemptions” for the Nechako, Kootenay, or Columbia populations. Yet given that the very feasibility of recovery depends upon successful human interventions to increase natural recruitment, perhaps it is reasonable to allow some continuing incidental harm contingent on a commitment to engage in habitat restoration that is deemed sufficient to increase natural recruitment to historic levels, and to hatchery supplementation that is deemed sufficient to avoid future genetic bottlenecks. Simulated scenarios (E15, E22, and E29) with habitat restoration to fully restore historic rates of natural recruitment combined with low level, short-term hatchery releases, indicate that recovery objectives could likely be achieved in the face of continuing incidental mortality not exceeding twice the current estimated level in each of the three non-recruiting populations. Sensitivity analyses (see Appendix 2) suggest that this conclusion is robust over a plausible range of parameter values and levels of annual variability. Finally, we emphasize that we chose our scenarios to demonstrate the necessary and sufficient conditions for achieving recovery objectives, not to determine the best options for recovery. We acknowledge that other scenarios involving different trade-offs might achieve recovery objectives with better socio-economic outcomes.

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Appendix 1*

POTENTIAL CRITICAL HABITATS FOR WHITE STURGEON POPULATIONS IN BRITISH COLUMBIA, CANADA

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* *Erratum*: Appendix 1 and 2 were missing from the original version.

Table of Contents

ACKNOWLEDGEMENTS

Much of the background material for this report has been taken from the Recovery Strategy for White Sturgeon, which was written by the White Sturgeon Recovery Team. The Recovery Team is made up of a number of regional technical and community working groups, and a National Technical Coordinating Committee:

Bill Green (Canadian Columbia River Intertribal Fisheries Commission)
Todd Hatfield (Solander Ecological Research)
Steve McAdam (Ministry of Environment, chair)
John Morgan (Malaspina University-College)
Troy Nelson (Fraser River Sturgeon Conservation Society)
Matt Neufeld (Ministry of Environment)
Mike Ramsay (Ministry of Environment)
Dan Sneep (Fisheries and Oceans Canada)
Colin Spence (Ministry of Environment)
Erin Stoddard (Ministry of Environment)
Brian Toth (Lheidli T'enneh First Nation and the Carrier Sekani Tribal Council)
Cory Williamson (Ministry of Environment)
Chris Wood (Fisheries and Oceans Canada)

During development of the recovery strategy, members of the Technical Coordinating Committee were tasked with leading the regional groups through a process to collate and evaluate relevant existing information on critical habitat. Matt Neufeld (Ministry of Environment) led the process for the Kootenay River; Colin Spence (Ministry of Environment) led the process for the Columbia River; and Cory Williamson (Ministry of Environment) led the process for the Nechako and Upper Fraser Rivers. They were supported in this role by other Committee members, in particular Steve McAdam (Ministry of Environment), and reported results back to the Technical Coordinating Committee. This work provided the primary inputs for sections of this document pertaining to recommendations for white sturgeon critical habitats.

An earlier draft of this document was reviewed by the Technical Coordinating Committee, in particular Cory Williamson, Colin Spence, Matt Neufeld, and Steve McAdam.

1. INTRODUCTION

1.1 Purpose of Document

Fisheries and Oceans Canada (DFO) must undertake a Recovery Potential Assessment (RPA) for each of four populations of white sturgeon (the upper Fraser River, Nechako River, Columbia River, and Kootenay River populations) now listed as Endangered under the Species At Risk Act. The RPA should include a scientific evaluation of the likelihood that recovery goals will be achieved in a biologically reasonable time frame. To undertake this evaluation, DFO requires a summary of current knowledge about the freshwater habitat that is potentially critical to the survival and recovery of each population. Critical habitat has yet to be defined by the White Sturgeon Recovery Team, but DFO needs to anticipate likely decisions by the recovery team in order to proceed with the RPA.

The purpose of this document is to review existing information relevant to the determination of critical habitat for white sturgeon in each of the four SARA-listed populations. The report introduces the concept of critical habitat (as distinguished from other important habitat) and summarizes existing information about the location, extent, current status, and potential threats to freshwater habitat that is likely critical to survival and recovery of white sturgeon in Canada. The report documents sources of information, methods by which information was collected, reliability of the information, and provides a brief discussion of data gaps. The report also includes maps to indicate the geographic location of important and potentially critical habitat features. Much of the background information on white sturgeon that is included in this report comes directly from the White Sturgeon Recovery Strategy (National Recovery Team for White Sturgeon 2006).

1.2 The Species

White sturgeon, *Acipenser transmontanus*, is the largest, longest-lived freshwater fish species in North America (Scott and Crossman 1973). Fish of over 6 m in length and over 100 years of age have been reported in the Fraser River (Scott and Crossman 1973). Growth rates and maturity vary significantly throughout the white sturgeon's range, but in general white sturgeon are slow-growing with a delayed onset of sexual maturity.

Females and males may spawn for the first time as young as 26 and 11 years, respectively (Semakula and Larkin 1968), but often it is later. White sturgeon may spawn multiple times throughout their life, with intervals between spawning for females of 4 to 11 years (Semakula and Larkin 1968; Scott and Crossman 1973). Estimated survival is very low during the first year (0.000396 % [Gross et al. 2002]), but is substantially higher in subsequent years (91% for ages $\geq$ 1 [Gross et al. 2002]; 92% [Walters et al. 2005]; >95% for older age classes in the upper Columbia River [Golder 2005a]).

White sturgeon are broadcast spawners, releasing large numbers of eggs and sperm into the water column of turbulent river habitats. Spawning occurs in the late spring and early summer, typically following the highest water levels of freshet, as water temperatures are rising, in fast water velocities, over coarse substrates (Parsley et al. 1993; Parsley and Kappenman 2000; Paragamian et al. 2002; Parsley et al. 2002; Perrin et al. 2003; RL&L 1994a; Liebe et al. 2004), though there are deviations from this general pattern.

Fecundity is directly proportional to female body size, ranging from about 0.7 million eggs in a medium-size female to 3 or 4 million in a large female (Scott and Crossman 1973). Eggs are fairly large (3.5 mm, Deng et al. 2002 cited in Coutant 2004), adhesive, and negatively buoyant. Suspended sediment sticks to the egg surface, possibly preventing clumping while eggs remain in the turbulent water, and eggs sink to the bottom substrate (Perrin et al. 2003).

After white sturgeon larvae exhaust their yolk sac, they begin exogenous feeding. The highest daily mortality rate of young sturgeon occurs in the days of first and early feeding (Gisbert and Williot 2002). First feeding varies from 8–16 days post-hatch, depending on water temperature (Doroshov et al. 1983; Buddington and Christofferson 1985; Gawlicka et al. 1995). Larval drift may occur post-hatch and during the initiation of first feeding, when larvae can become entrained in river currents (Kynard and Parker 2006).

Movement and migrations for later life stages of white sturgeon are linked to feeding, overwintering, and spawning activities. Different movement patterns appear primarily related to food type and availability, and differences in habitat availability and distribution. In general, most individuals seem to remain on summer feeding grounds and exhibit relatively localized movements (RL&L 2000a). They then migrate in fall or winter, followed by a period of relatively low activity during the winter, with the timing and length of inactivity variable among populations (RL&L 2000a; Nelson et al. 2004). Migrations to spawning areas occur in spring and sometimes in fall; spawning migrations are often more extensive than feeding and overwintering movements (RL&L 2000a).

1.3 Populations and Status

White sturgeon occur and are self-sustaining in three major drainages on the Pacific coast of North America: the Fraser, Columbia and Sacramento River systems. They are found in the mainstem of these rivers, as well as several larger tributaries. White sturgeon can exhibit facultative anadromy and have been observed in several coastal inlets and estuaries, typically near creek and river mouths. Some migration occurs via the ocean between the three major drainages and to other coastal watersheds, but the extent of exchange is small.

Within Canada, white sturgeon occur only in British Columbia (Figure 1 and Figure 2). Based on geography and genetics they and are divided into six populations: the lower, mid and upper Fraser River, Nechako River, Columbia River, and Kootenay River. Smith et al. (2002) showed that the six populations are separated genetically. There is genetic evidence of sub-structure within the Columbia population (Nelson and McAdam 2004). The extent of substructure within other populations has not been studied.

All six populations in British Columbia were listed as endangered by COSEWIC in November 2003. However, only four populations were legally listed under SARA (upper Fraser River, Nechako River, Columbia River and Kootenay River). Socioeconomic concerns were cited as the primary motivation for not listing the lower and mid-Fraser River populations. This document addresses critical habitat information for the four SARA-listed populations only.

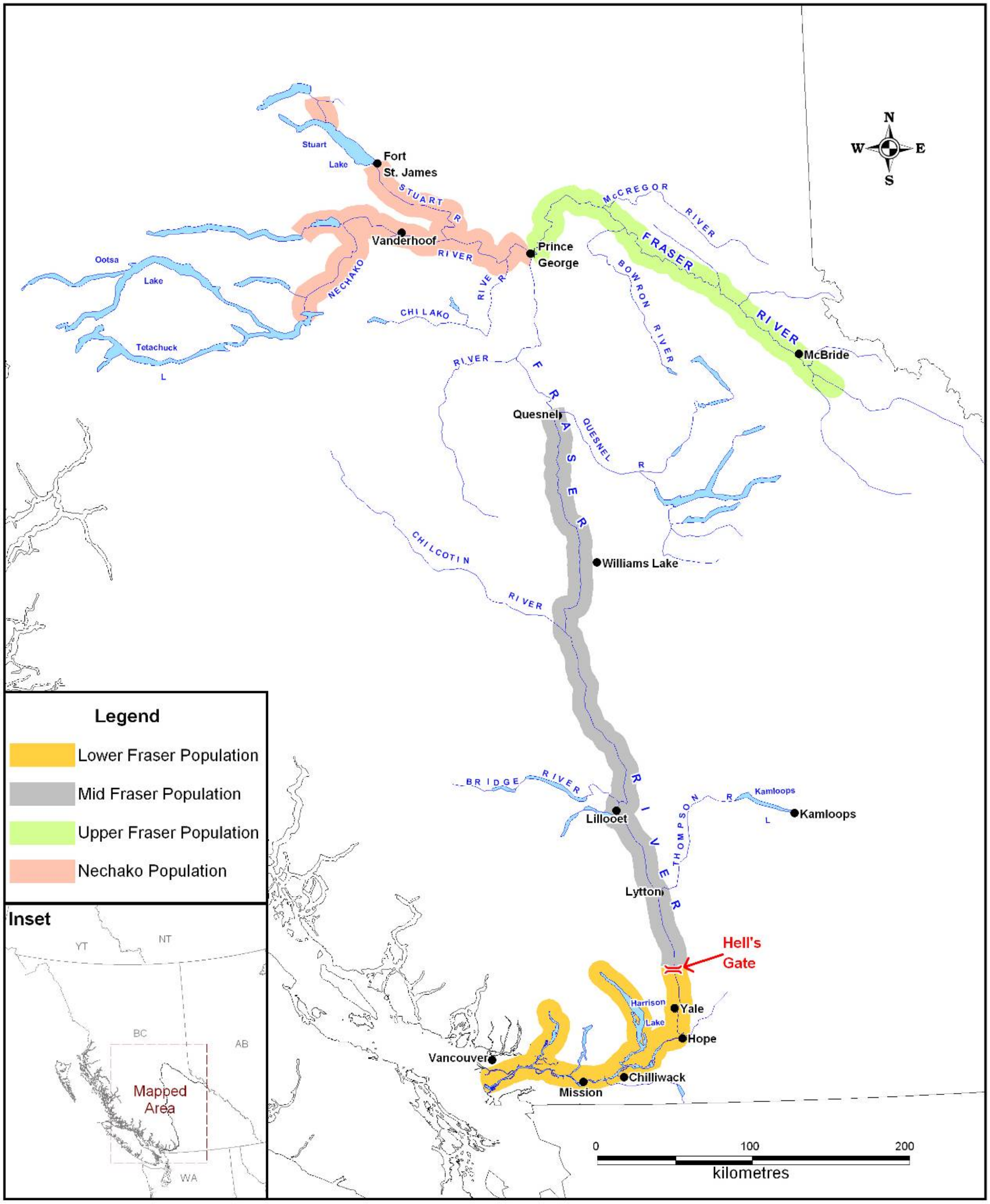

Figure 1. Map of the Fraser River basin showing the approximate ranges for four of the white sturgeon populations in British Columbia. The species is principally found in the mainstem habitats of the Fraser and Nechako Rivers, although in some systems they make extensive use of tributaries and large lakes (such as in the Harrison or Stuart watersheds). Anecdotal records indicate sturgeon presence in several watersheds beyond the described boundaries.

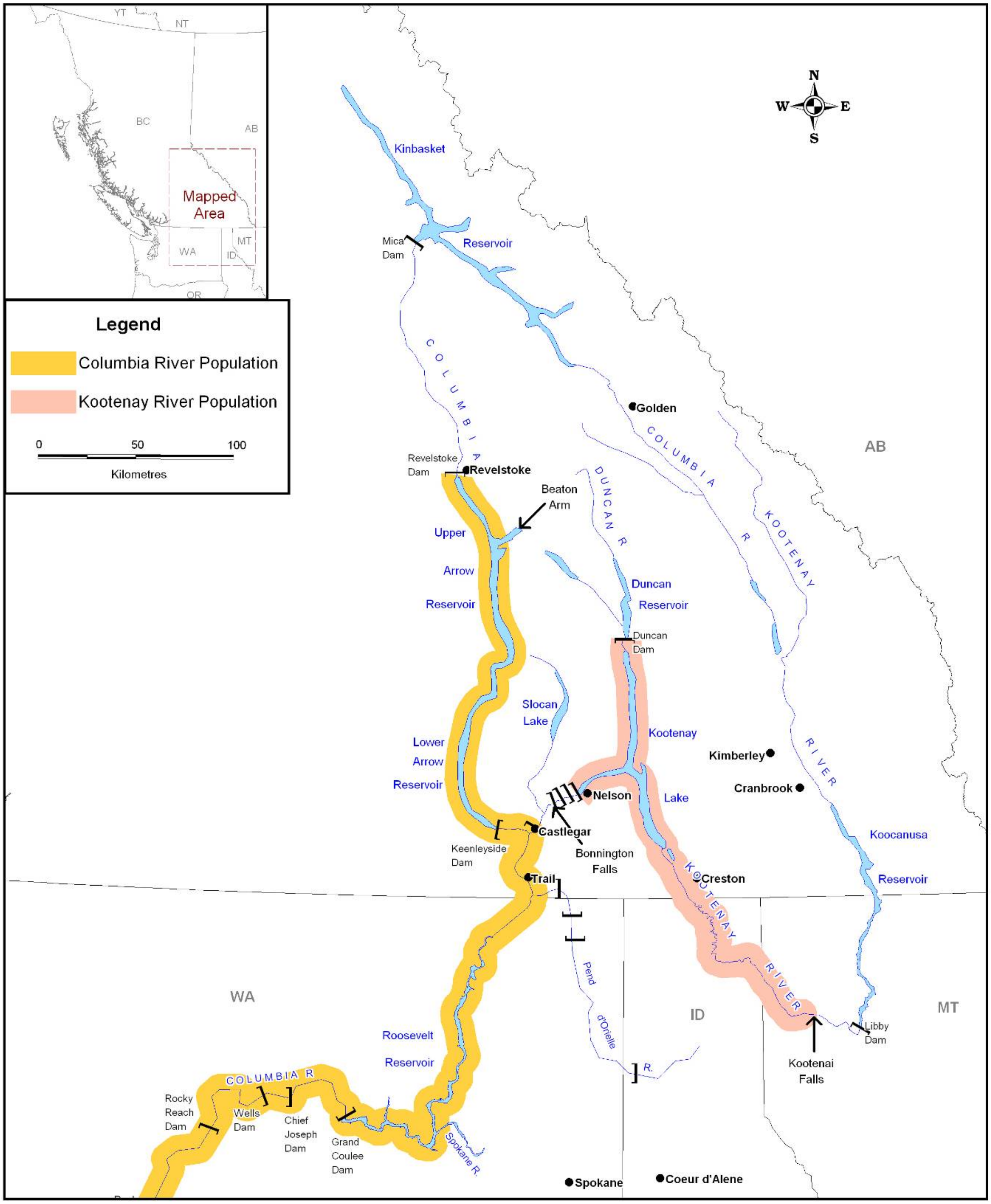

Figure 2. Map of the Columbia and Kootenay basins showing the approximate ranges for two of the white sturgeon populations in British Columbia. Records indicate sturgeon presence in several watersheds beyond the described boundaries (e.g., Duncan River and Slocan Lake), but in all cases abundance is very low (see text for details). White sturgeon are present in the Columbia to its confluence with the Pacific Ocean.

1.4 Key Life Stages and Habitat Needs

1.4.1 Physical Habitat

White sturgeon inhabit large rivers where they are associated with particular habitat features: slow, deep mainstem channels interspersed with a zone of swift and turbulent water, extensive floodplains with sloughs and side channels, and a snowmelt-driven hydrograph with prolonged spring floods (Coutant 2004). Most habitat use studies are recent and have come from regulated rivers, particularly the upper Columbia and Kootenay Rivers. The few studies completed on the Fraser River, which is the only unregulated system in the species' range, indicate that habitat use there may be quite different. Care must therefore be exercised when extrapolating observations and conclusions regarding sturgeon habitat and related behaviours from regulated systems. A considerable amount of work is still required to properly describe habitat requirements for white sturgeon.

Like many fish species, habitat use by white sturgeon varies with life stage and season. The following sections summarize what is currently known about habitat use by white sturgeon.

Spawning and Incubation Habitat.— White sturgeon naturally spawn during the spring freshet. There has been a considerable amount of work done to characterize white sturgeon spawning habitats, but much of the information has come from regulated rivers (e.g., Parsley and Beckman 1994; Parsley et al. 1993; Paragamian et al. 2001; Golder 2005b). These studies indicate strict requirements for deep, swift water and coarse substrates. Parsley et al. (1993) characterized spawning habitat in the Columbia River below McNary Dam as having a 0.8 to 2.8 m sec^{-1} mean water column velocity, and boulder and bedrock substrates. Mean water column velocities typically range from 0.5 to 2.5 m sec^{-1} at most sites studied. Spawning habitat has recently been identified south of the US border at Northport, Washington, with conditions such as high turbulent flows, and coarse substrates (Howell and McLellan 2006).

Spawning has occurred in the Kootenai River[1] in an area characterized by large mobile sand deposits, but this area is believed to have extremely poor egg survival, since eggs collected from here have been coated in sand (Duke et al. 1999; Kock et al. 2006) and only one wild sturgeon larvae has ever been collected (hatched on a egg collection mat; Paragamian personal communication) despite significant collection effort. Spawning was observed in 2004 in the Nechako River over substrates dominated by gravel and fines, but these conditions appear to be one of the causes of ongoing recruitment failure (McAdam et al. 2005).

Evidence from the lower Fraser River indicates that white sturgeon use large side channels for spawning (Perrin et al. 2003) as well as more turbulent areas downstream of the Fraser canyon (RL&L 2000a). Physical characteristics of the side channels included gravel, cobble and sand substrates, and mostly laminar flows with near-bed velocities averaging 1.7 m s^{-1}. Boulder and cobble predominated in the mainstem study site. All sites were within a portion of the lower Fraser that is unconfined and largely unaffected by floodplain development. Coutant (2004) noted that successful spawning is most often associated with turbulent or turbid river sections areas upstream of floodplains.

[1] Portions of the Kootenay River that occur within the US are referred to as the "Kootenai." We use the American spelling to refer to American portions of the river, and to the "Recovery Plan for the Kootenai River Population of the White Sturgeon (*Acipenser transmontanus*)." The plan was developed by the US Fish and Wildlife Service, with input from Canadian agencies, and refers to white sturgeon recovery in both Canadian and American portions of the river.

Incubation success is thought to be greatest when discharges are high and steady (UCWSRI 2002). High velocities in egg deposition areas may exclude some predators and provide high turbidity, which may limit predator efficiency (Gadomski et al. 2001). Substrate condition may also influence larval survival (Gessner et al. 2005). Recent research has indicated a preference by 48 hour-old white sturgeon larvae for gravel sizes between 12 and 22 mm (W. Bennett, Malaspina University-College, personal communication; S. McAdam, BC Ministry of Environment, personal communication).

Juvenile Habitat.— Juvenile (< 2 years) habitat for white sturgeon varies considerably with stage of development. In general, little is known about natural juvenile habitat use for white sturgeon populations in BC, with most information coming from laboratory studies or studies in other river systems. Parsley et al. (1993) defined physical habitat for juvenile white sturgeon in the lower Columbia River as 2 to 58 m depth, 0.1 to 1.2 m s^{-1} mean column velocity, and near-substrate velocity of 0.1 to 0.8 m s^{-1}. Note that the study was conducted downstream of McNary Dam, and the upper end of this depth range rarely exists in natural rivers. Nevertheless, their observations suggest that juvenile white sturgeon may be found at a range of depths, but that they prefer slow to moderate water velocities. Observations and traditional ecological knowledge in a number of locations within the Canadian range (e.g., Bennett et al. 2005; Failing and Gregory 2003), show that juveniles are often associated with the lower reaches or confluences of tributaries, large backwaters, side channels and sloughs. Sampling of side channel and slough habitat on the Kootenay has, however, shown little use of such habitats in comparison to the mainstem (Neufeld and Spence 2002). Extensive use of deep, low velocity mainstem habitats also occurs (RL&L 2000a; Golder 2003a; Neufeld and Spence 2004), especially as fish grow larger. Substrates at collection sites have varied from finer particles through to boulder and hard clay (Parsley et al. 1993; Young and Scarnecchia 2005). Feeding juveniles showed a slight preference for sand substrates, but occupied other substrates if food was present (Brannon et al. 1985). In the Kootenay system, and perhaps in other systems, there is use of lake habitat by juveniles.

Immature and Mature Adult Habitat.— Immature (over 2 years) and mature adult habitat use is variable, depending on time of year and life history-related activities, such as spawning, feeding, overwintering, and movements to and from these key habitats (RL&L 2000a; Neufeld 2005). In general, white sturgeon adults are found in deep near-shore areas, adjacent to heavy flows, defined by deposits of sand and fine gravels with backwater and eddy flow characteristics (RL&L 1994a, 2000a). Adults in the less productive upper Fraser may be widely dispersed including use of tributaries, and may require long migrations to reach feeding and spawning habitats (Yarmish and Toth 2002). Most studies of adult habitat use have focussed on the physical features of spawning habitat. Considerably less attention has been given to other adult habitat requirements including overwintering, feeding, holding habitats, or migration habitats. Large lakes and rivers, where available, are extensively used at all times of the year (e.g. RL&L 1999a; Golder 2006a).

Summer residency. — During this period, which is typically July to September, the movements of white sturgeon in most populations tend to be more localized than in the spring to early summer or fall. In systems like the lower Columbia (RL&L 1994a; Brannon and Setter 1992) and Kootenay Rivers (Apperson and Anders 1991), white sturgeon were reported to use shallower depths during the spring to summer period and exhibited frequent, short distance forays between shallow and deep-water areas to feed. Information on summer residency of Fraser River white sturgeon is sparse, but movements appear to be localized (RL&L 1998a, 1999b) and associated with summer feeding activity.

High-use areas in the upper Columbia River are all depositional areas where food items settle out. These areas also support higher densities of other fish species that likely provide an additional food source (UCWSRI 2002). In Kootenay Lake, adults undertake an annual migration from the south end of the lake to the outlet of the Duncan River at the north end, where large numbers of spawning kokanee provide an excellent food source (RL&L 1999a). Summer residency in other populations is not as well understood, but is likely linked to food availability. In the upper Fraser, the beginning of summer residency is linked to sturgeon spawning, but potentially also cyprinid spawning, and the end is clearly linked to the upstream migration of spawning salmon, especially sockeye.

Overwintering — Reduced activity is generally observed during winter months (e.g., RL&L 2000a; Nelson et al. 2004). Telemetry data for mature adults in the Fraser (RL&L 2000a) indicated that few individuals move more than 5 km during the winter. Individuals in all populations tend to utilize deeper, lower-velocity areas during this period. Large lakes and rivers are extensively used, where available (e.g. RL&L 1999a; Golder 2006a).

Migration Movements — Migration is defined in RL&L (2000a) as sustained, unidirectional movements, either upstream or downstream but not both, likely for feeding, spawning or overwintering. Migration patterns are being studied in many populations, but are not well understood for all BC populations. Migrations in the spring are associated with staging, spawning, and feeding activities associated with spring invertebrate hatches and spawning of other fish species. Fall movements are also associated with feeding opportunities (e.g., kokanee spawning near creek confluences). Since mature white sturgeon do not usually reproduce annually, movements may vary among years. The extent of movements is related to proximity between overwintering areas and spawning and feeding areas. Movements in the upper Columbia are severely restricted by dams.

1.4.2 Diets

Feeding behaviour of white sturgeon is specialized for dark, benthic habitats where prey are often located through direct contact, which is facilitated by highly sensitive taste receptors on barbels near the mouth (Brannon et al. 1985). Juvenile white sturgeon are primarily benthic feeders, feeding on a range of invertebrate and fish species. Diet varies throughout the year and with location depending on availability. Juveniles reportedly eat a variety of aquatic insects, isopods, mysids, clams, snails, small fish, and fish eggs (Scott and Crossman 1973; McCabe et al. 1993). In the Upper Columbia River, *Mysis relicta*, a non-native pelagic crustacean, is the most common prey item of 1 – 2 year old juveniles (Golder 2006b). Adults feed predominantly on fish, particularly migratory salmonids where available, although crayfish and chironomids are also consumed (Scott and Crossman 1973; Partridge 1980).

Natural changes and human activities that affect any of these prey species will directly affect the prey abundance for adult white sturgeon. This could include climate change, or human activities such as habitat elimination or alteration, or the harvest of resident and anadromous fish stocks.

2. CRITICAL HABITAT

Identification and protection of critical habitat is vital for management of species at risk, and is one of the most challenging aspects of species management. Despite its complexity, the core issue is the same for all species: to determine the role of habitat in population limitation, and to answer the question, "How much habitat, and of what type, is required to maintain viable populations of the species?"

The term "critical habitat" has a specific and legal meaning for SARA-listed species. It is:

> *"…the habitat that is necessary for the survival or recovery of a listed wildlife species and that is identified as the species' critical habitat in a recovery strategy or in an action plan for the species."* [s. 2(1)]

The issue of *defining* critical habitat is separate from its *designation*. Definition of critical habitat is a requisite first step: it is a scientific and technical process that determines how much habitat is required and where it is located. This document is concerned solely with the definition of critical habitat, or habitat that is likely to be critical. Designation of critical habitat is the second step: it occurs after a quasi-political process that considers scientific recommendations as well as socioeconomic benefits and costs before creating a legally-binding definition of critical habitat. The designation process — who makes the decision, on what basis, and the transparency of the process — is not clear at present.

To complement the legal definition of critical habitat, Rosenfeld and Hatfield (2006) suggest several practical working definitions that provide general guidance and screening criteria for evaluating candidate critical habitats.

1. **Habitat that is disproportionately important.** The litmus test is whether loss of a particular habitat unit will result in significant population level effects for a population at the abundance level of the recovery target. This emphasizes prioritization of habitat protection based on the population consequences of habitat loss or gain, with the understanding that if a particular habitat unit can be lost without population level effects, it is unlikely to be critical.
2. **The minimum subset of habitats required for a species or population to persist.** This emphasizes that the default objective may not be to protect the entire range of a species, and that for some species different configurations or subsets of habitat of varying quality may ensure species persistence.
3. **Habitats that are necessary to maintain ecosystem integrity and function.** This emphasizes that discrete habitat patches must function "properly," and processes that influence habitat quality must be maintained (e.g., river flooding, riparian buffer, etc.). This may result in expanding the suite of candidate critical habitats to include habitats that are essential for *maintaining* core critical habitat. For example, riparian areas affect instream habitat qualities (e.g., shading, erosion, LWD recruitment); even though fish do not directly inhabit these areas, portions or aspects of riparian area should be considered within the definition of critical habitat.

Rosenfeld and Hatfield also note that the definition of critical habitat under the Species at Risk Act appears to permit the designation of geographic areas as well as habitat features (e.g., water quality, LWD associations, spawning habitat sediment qualities) that may change through space or time. It is therefore important to identify both the location as well as the general properties of critical habitat wherever possible.

3. APPROACH TO IDENTIFYING LIKELY CRITICAL HABITAT

With current information it is possible to delineate many habitats that are important to white sturgeon, and for some populations it is possible to provide a defensible demarcation of some portions of critical habitat. Yet, it is not possible at this time to identify all critical habitat for white sturgeon across its full range. The White Sturgeon Recovery Team anticipates defining critical habitat for each population, to the extent possible, and presenting this information in a single comprehensive document that forms the scientific recommendations for designating critical habitat. The Recovery Team anticipates completing such a document during the Action Planning phase of the recovery process. In the meantime, and in anticipation of DFO's need to undertake an RPA, the Recovery Team has provided input to this document to support the RPA.

Rosenfeld and Hatfield (2006) present a framework for defining critical habitat. They suggest that, for those species where habitat plays a key role in population limitation, the logical steps involved in identifying critical habitat are to:

1. identify a population recovery target,
2. define a quantitative relationship between habitat and population size, and
3. define sufficient habitat to meet the recovery target based on the habitat-population relationship.

For species with multiple life stages that use different habitats, this process needs to be repeated for each life stage. In this document we adhere to this three-step procedure to define likely critical habitats for white sturgeon, to the extent that present information will allow. Additional data that would allow fuller definitions of critical habitat are identified separately.

During development of the Recovery Strategy the Recovery Team noted that the main problem facing white sturgeon in many parts of its range has been recruitment failure. That is, natural spawning events occur regularly, but there has been effectively no recruitment to the population from these spawning events. There are a variety of hypotheses related to the recruitment failure. The critical life stage is believed to be the first year, and especially the first couple months of life. Most attention is focussed on the diverse but correlated changes associated with river regulation that affect the very early life history of this species. Critical habitat determinations are therefore believed to be most important for spawning, incubation and very early life stages. There are of course numerous juvenile and adult habitats that are important, and some of these will likely be identified as critical habitat as additional information is collected.

4. POPULATION TARGETS

The first step in defining critical habitat is to assign a population target for the species of interest (Rosenfeld and Hatfield 2006). Recovery targets and the rationale supporting these are presented and discussed in detail in the Recovery Strategy. The Recovery Strategy follows McElhany et al. (2000) in defining a viable population as one "that has a negligible risk of extinction due to threats from demographic variation (random or directional), local environmental variation, and genetic diversity changes (random or directional) over a 100-year time frame." In assessing viability under the above definition McElhany et al. suggest that it is necessary to consider abundance, population growth rate, population structure, and population diversity, and note that the values of these four parameters would be lower or less functional in an endangered population than in a viable population. In developing population recovery targets, the Recovery Strategy focuses on the first two of these parameters, abundance and population growth rate.

An interim abundance target of 1000 mature individuals is proposed for each of the four SARA-listed populations of white sturgeon, where mature is defined as 25 years of age and older. Based on the available scientific literature (reviewed in the Recovery Strategy) this target is believed sufficient to meet abundance criteria to offset threats from demographic, environmental and genetic stochasticity over the next 100 years provided abundance is rebuilding. This abundance target is coupled with the following growth rate targets: 1) ongoing natural recruitment, and 2) increasing trend in abundance for all populations that are below the abundance target. The long term objective is to have all populations self-supporting, but conservation aquaculture is required in some instances as an interim measure. At present there is insufficient information to conduct a full-blown PVA for any of the white sturgeon populations in Canada; these targets are therefore deemed interim over the next 10 years. The targets are above current abundance and growth rates in the SARA-listed populations. Current population abundance is presented in Table 1 and Table 2 as context for the recovery targets; population trends are discussed in the Recovery Strategy and in Ptolemy and Vennesland (2003).

Table 1. Abundance estimates for naturally produced white sturgeon > 40 cm in British Columbia. Estimates are current for the year of publication, unless noted otherwise in footnotes. Estimates for the lower and mid Fraser are included here to provide context.

Population	Number of fish	95% C.I.	Reference
Lower Fraser	48,995 [1]	46,718 – 51,272 [2]	Nelson et al. 2006
Mid Fraser	3,745	3,064 – 4,813	RL&L 2000a
Upper Fraser	815	677 – 953	Yarmish and Toth 2002
Nechako	571 [3]	421 – 890	RL&L 2000a
Kootenay	500 [4]	NA	Paragamian et al. 2005
Columbia above HLK	52	37 – 92	Golder 2006a
Columbia between HLK and Canada-US border	1157	414 – 1899	Golder 2005a [5]
Columbia below border to FDR	2295	1528 – 3574	Golder 2005a
total in Canada	55,835		

[1] 2005 estimate for fish > 40 cm and < 260 cm. The white sturgeon population in most stocks also includes individuals bigger or smaller, but population estimates cannot be generated due to the inability to capture these fish or the small number of tagged individuals in these size groups (Nelson et al. 2004).
[2] Values for the lower Fraser describe the 95% highest density rather than a parametric confidence interval (see Nelson et al. 2004).
[3] Estimates are for fish > 50 cm fork length.
[4] As noted in the reference, this is an estimate for 2005, based on a direct estimate of 760 fish in 2000, and an assumed annual survival of 91%. This estimate is for wild (i.e., naturally produced) white sturgeon — there are many juvenile hatchery releases that are now >40 cm.
[5] These values are for the year 2003 and combine separate estimates for two river sections from HLK to the US border.

Table 2. Abundance estimates for mature white sturgeon in British Columbia. Estimates for populations with recruitment failure (Nechako, Kootenay, and Columbia) have been updated to 2006 levels using assumed annual survival rates. Fraser River populations are assumed to be in approximate equilibrium, and estimates are assumed to be approximately accurate for 2006. Estimates for the lower and mid Fraser are included here to provide context.

Population	Number of mature fish in 2006	Reference for uncorrected abundance estimate
Lower Fraser	8928	Nelson et al. 2006
Mid Fraser	749	RL&L 2000a
Upper Fraser	185	Yarmish and Toth 2002
Nechako	305 [1]	RL&L 2000a
Kootenay	455 [2]	Paragamian et al. 2005
Columbia above HLK	52	Golder 2006a
Columbia between HLK and Canada-US border	948 [3]	Golder 2005a
Columbia below border to FDR	2003 [4]	Golder 2005a
total in Canada	11,622	

[1] Assumes 95% of uncorrected estimate are mature, with 91% annual survival to 2006. There are no adult survival estimates specific to the Nechako River population; this assumed survival value is taken from Paragamian et al. (2005).
[2] Assumes 91% annual survival to 2006.
[3] The uncorrected abundance estimate is for the year 2003 and combines separate estimates for two river sections from HLK to the US border. The 2006 estimate assumes 90% are mature, with 97% annual survival to 2006. The survival estimate is from Golder (2005a). Abundance estimates are for wild (i.e., naturally produced) fish.
[4] Assumes 90% of the uncorrected abundance estimate are mature, with 97% annual survival to 2006. The survival estimate is from Golder (2005a).

5. ABUNDANCE VS. HABITAT RELATIONSHIPS

The second step in identifying critical habitat is to define a quantitative relationship between habitat and population size (Rosenfeld and Hatfield 2006). This can be done empirically by contrasting habitat availability and abundance across several populations or by manipulating habitat and assessing the response in population abundance. An abundance-habitat relationship can also be assumed, based on expert judgement or theory.

There is little information available to compare habitat availability and abundance across white sturgeon populations, and there are no data on specific habitat features that are related to habitat quality. It is anticipated that steps required to obtain this information will be developed by the Recovery Team during development of the Action Plan.

To some extent this step can be deferred because the focus of attention is clearly and logically focussed on making habitats for early life stages maximally functional. The amount of habitat required for other life stages is considered of secondary importance to ensuring functional habitat for very early life stages.

6. IMPORTANT AND POTENTIAL CRITICAL HABITATS

The final step in identifying critical habitat is to define sufficient habitat to meet the recovery target based on the habitat-population relationship (Rosenfeld and Hatfield 2006). For limiting life stages with scarce habitat, all available habitat may be required to meet the recovery target. For other life stages, various combinations of habitat may support the target population. In essence, different areas may be *substitutable* in contributing to a recovery target. Which combinations are selected may depend on biological features (e.g., determinants of habitat quality) or socioeconomic considerations (e.g., designating some habitat units may accrue higher economic costs). In the following sections, the important habitats of each life stage are discussed and the likely critical habitats are identified, where possible. Threats to important habitats, data gaps and data sources are also presented.

Providing information on critical habitat was a separate and discrete task during development of the Recovery Strategy. The White Sturgeon Recovery Team is made up of a number of regional technical and community working groups, with representation on the National Technical Coordinating Committee. Members of the Committee were tasked with leading the regional groups through a process to collate and evaluate relevant existing information on critical habitat. Matt Neufeld (Ministry of Environment) led the process for the Kootenay River; Colin Spence (Ministry of Environment) led the process for the Columbia River; and Cory Williamson (Ministry of Environment) led the process for the Nechako and Upper Fraser Rivers. They were supported in this role by other Committee members. The basin-specific groups were tasked with determining candidate critical habitats and providing a recommendation for critical habitats. They were asked to document sources of information, methods by which information was collected, reliability of the information, descriptions of data gaps. The results of these basin-specific discussions are provided in the following sections. All background information in this document was assembled during development of a SARA-compliant Recovery Strategy for white sturgeon, or basin-specific recovery or conservation plans.

6.1 Upper Fraser River

No telemetry work has been conducted on white sturgeon in the Upper Fraser River, and no spawning sites have been identified at this time. Some important habitats have been identified for juvenile rearing and feeding, adult holding and feeding, and adult overwintering life stages. As additional information is collected, it will become possible to identify other important habitats and to make additional recommendation for designating critical habitat.

The following locations have been identified as important juvenile and adult habitats:

- Nechako River confluence
- Bowron River confluence
- Fraser River mainstem downstream of Longworth Canyon

Likely Critical Habitat.— Until additional studies are undertaken it is difficult to provide defensible recommendations for critical habitat in the Upper Fraser River.

Activities Likely to Impact Critical Habitat.— Until likely critical habitats are defined it is not possible to provide specific guidance on activities that would impact critical habitats, other than in general terms. Activities that could impact critical habitat include river regulation, instream activities such as gravel or sand dredging, linear developments, riparian, foreshore, floodplain or estuarine alterations or developments, upstream land and water uses, and point and non-point source effluent discharges. General threats to some of the important habitat types for white sturgeon are discussed in Section 3 of the Recovery Strategy.

Data Gaps.— There are substantial data gaps for this population in relation to determining critical habitats. Virtually no information exists on which habitats are used for spawning and incubation. Although three locations have been identified as important habitats for adults and older juveniles, the numbers of fish using these sites, the seasonality of habitat use, and the relative importance of other habitats remains poorly known.

6.2 Nechako River

In the Nechako system, white sturgeon occur from the confluence with the Fraser River, upstream to Cheslatta Falls, and through much of the Stuart River watershed, a major tributary. Data indicate limited movement of Nechako sturgeon into the Fraser, however, feeding at the Fraser River confluence has been observed. There is some uncertainty regarding the role of the Stuart River system for this population, but this uncertainty stems in part from the depressed abundance of this population. Current distribution in the Nechako may be limited by population declines and the alteration of flows (and related effects) below Kenney Dam (NWSRI 2004).

6.2.1 Spawning and Incubation Habitat

Observations to date suggest that there is only one spawning site in the Nechako River, which encompasses the braided section of river near Vanderhoof. The precise spawning location may change from year to year depending on flow conditions. Some believe there may also be other spawning locations either at present or historically (prior to river regulation). It is possible that additional spawning and incubation sites could be identified in the future. Data indicate that white sturgeon eggs do not drift far, so incubation habitats are assumed to be coincident with spawning habitats.

Likely Critical Habitat.— The Vanderhoof braided section of the Nechako River (Figure 3) is likely critical habitat, with the primary supporting rationale being that this is the only known location for spawning in the Nechako River system. Although this location is functioning as spawning habitat, it is believed to be non-functional as habitat for incubation and very early life stages. Various measures are being proposed to restore the functionality of this habitat (Steve McAdam, personal communication).

This habitat would deemed critical on an annual basis during May and June, based on known timing of spawning and incubation. This period is sufficient to encompass known annual variability in onset of spawning.

The degree of certainty in this critical habitat determination is rated as high, based on repeated observations of spawning at this site.

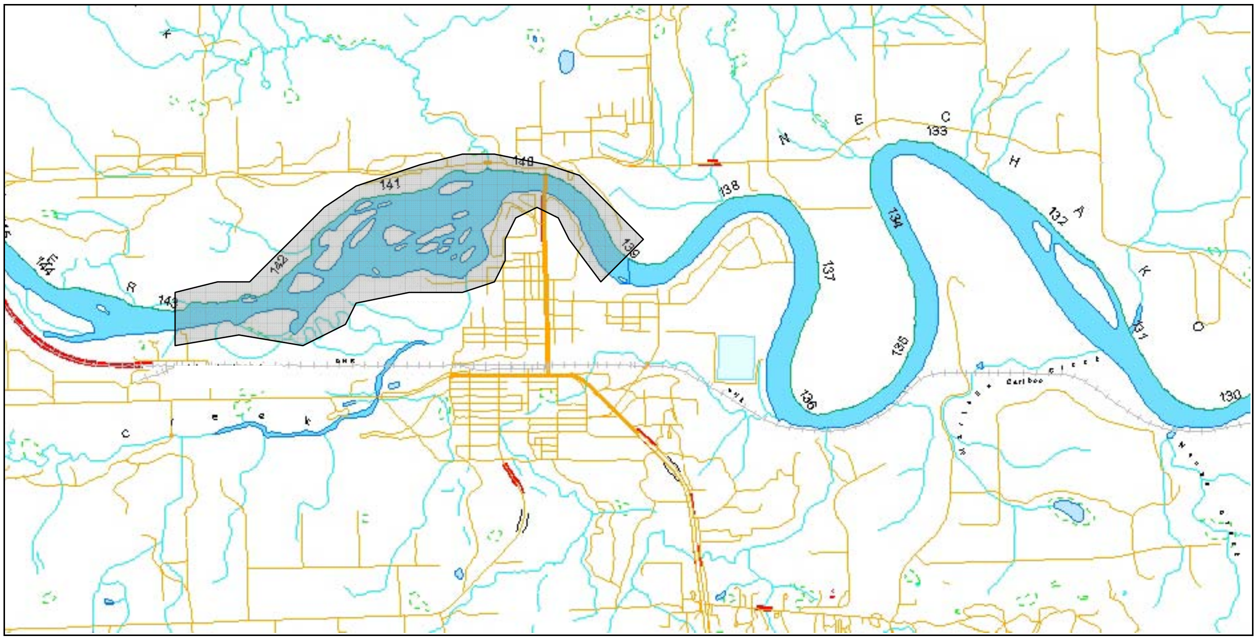

Figure 3. Candidate critical habitat for Nechako River white sturgeon. The shaded polygon is in the vicinity of the town of Vanderhoof. This is the only known spawning habitat for this population and is identified as likely critical habitat for spawning, incubation and early juvenile (0 – 21 days) life stages.

Activities Likely to Impact Critical Habitat.— There are several activities that would impact this habitat. River regulation is believed to have had a significant influence on habitat quality at this site, in particular by removing peak flows from the system. This has led to less frequent flooding of gravel bars, increased vegetation on bars and islands, and generally less movement of stream substrates (with concomitant decrease in substrate suitability for white sturgeon). Other activities such as gravel or sand dredging, linear developments, riparian, foreshore, floodplain alterations or developments, upstream land and water uses, and point and non-point source effluent discharges are possible concerns depending on details of the activities. General threats to some of the important habitat types for white sturgeon are discussed in Section 3 of the Recovery Strategy.

Data Gaps.— There are minor data gaps for determining the geographic boundaries of this critical habitat. Given the relatively small area of this habitat unit, the precision of boundaries is considered inconsequential at this time. There are significant uncertainties with respect to the qualities of habitat that are required to make this habitat unit functional for incubation and early life stages. Work is underway to assess these habitat variables (Steve McAdam, personal communication).

6.2.2 Early Juvenile Habitat

The early juvenile stage is defined as occurring from hatch to 2 years, and may be broken into two stages. The 0 - 21 days stage is the period from hatch to successful initiation of exogenous feeding. It includes phases of hiding in interstitial spaces, drift and swim-up, and the initiation of exogenous feeding. The 21 days to 2 years stage is one in which young fish are less susceptible to predation and are often observed holding in habitats that are similar to adult habitat types. In general it is believed that once white sturgeon are six months old they tend to occupy habitat that is similar to that preferred by adults.

0 - 21 days.— Little is known about this phase in the wild, but it is suspected to be a critically important phase in the recruitment failures observed in regulated systems. Only a single spawning site has been identified in the Nechako River system, and this coupled with ongoing recruitment failure makes it difficult to identify the key components of viable habitat for this life stage. Important habitat for this life stage is assumed to be encompassed within known spawning and incubation habitat near Vanderhoof, and some distance downstream. At present there is insufficient information to estimate the downstream limit of this habitat type.

21 days to 2 years.— Habitat needs within this 2 year period may be considerably different than in the life stage immediately preceding it. In the Columbia and Kootenay Rivers fish younger than 2 years have been observed holding in habitats that are similar to adult habitat types, and in general it is believed that once white sturgeon are six months old they tend to occupy habitat that is similar to that preferred by adults. Very little is known about this life stage in the Nechako River, yet this is also considered to be a recruitment bottleneck. It is one of the highest priorities for study.

No fish within this age class have been captured during the Recovery Teams' course of studies on the Nechako River, so any estimations of this habitat component would necessarily be based on knowledge from other systems. Four likely high use areas for this life stage have been identified (RL&L 2000a):

- Nechako River (65 – 79 km)
- Nechako River (89 – 95 km)
- Sinkut River confluence (115 – 117 km)
- Leduc Creek confluence (122 – 127 km)

Additional holding and feeding areas include Sturgeon Point in the Stuart River (based on captures and historical information, (Toth and Yarmish 2003; Carrier Sekani Tribal Council 2005), confluence of Tachie and Middle rivers, and Pinchi Bay in Stuart Lake. Despite extensive sampling and telemetry, the area from Vanderhoof to Engen and Nadleh has been little used from 1995 to 1999, yet this continues to be an area where fish are observed in FSC fisheries and during helicopter flights. Other sites likely include the confluences of streams where sockeye concentrate.

Likely Critical Habitat.— The likely critical habitat for the 0 - 21 days stage is the Vanderhoof braided section (Figure 3), the same habitat area noted as critical for spawning and incubation. This habitat would be deemed critical on an annual basis during May, June and July, based on known timing of spawning and incubation. This period is sufficient to encompass known annual variability in onset of spawning. Likely critical habitat would extend downstream beyond the boundaries of spawning and incubation habitat, but the downstream limit cannot be described at this time. The degree of certainty in this critical habitat determination is rated as high, based on repeated observations of spawning at this site, although there is insufficient certainty to define the downstream limit of this habitat beyond that already defined for spawning and incubation.

The likely critical habitat for the 21 days to 2 years stage includes the four areas identified as high use areas for multiple life stages:

- Nechako River (65 – 79 km),
- Nechako River (89 – 95 km),
- Sinkut River confluence (115 – 117 km), and
- Leduc Creek confluence (122 – 127 km).

The areas are shown in Figure 4. This habitat would be deemed critical year-round, based on knowledge of continuous occupation of these sites. The degree of certainty in this critical habitat determination is rated as moderate, based on repeated observations of spawning at these sites. Although other candidate sites have been identified there is insufficient certainty to define these as likely critical habitat at this time.

Activities Likely to Impact Critical Habitat.— Activities that would impact likely critical habitat for this life stage include river regulation, gravel or sand dredging, linear developments, riparian, foreshore, floodplain alterations or developments, upstream land and water uses, and point and non-point source effluent discharges. The exact concerns would vary depending on details of the activities. General threats to some of the important habitat types for white sturgeon are discussed in Section 3 of the Recovery Strategy.

Data Gaps.— There are moderate data gaps for determining the geographic boundaries of this critical habitat; river kilometres discussed here are approximate. These areas defined as likely critical habitat are fairly broad, and are based on existing information of white sturgeon habitat use. Additional studies may increase the confidence in these boundaries and may permit greater precision in defining the geographic areas of interest.

6.2.3 Late Juvenile and Adult Habitat

The late juvenile and adult stage is defined as occurring from 2 years onward. Diets of younger fish may be considerably different than those of large adult fish, but in general, all individuals in this class occupy the same habitats for the purposes of feeding, and presumably for overwintering.

Juvenile and adult feeding habitat.
In the Nechako River, feeding habitats are generally similar to overwintering habitat, as there appears to be an affinity for fish to hold in the same areas where they feed. Four high use areas have been identified for this life stage based on information in RL&L (2000a):

- Nechako River (65 – 79 km),
- Nechako River (89 – 95 km),
- Sinkut River confluence (115 – 117 km), and
- Leduc Creek confluence (122 – 127 km).

Additional holding and feeding areas include Sturgeon Point in the Stuart River (based on captures and historical information,(Toth and Yarmish 2003; Carrier Sekani Tribal Council 2005), confluence of Tachie and Middle rivers, and Pinchi Bay in Stuart Lake. Despite extensive sampling and telemetry, the area from Vanderhoof to Engen and Nadleh has had little use from 1995 to 1999, yet this continues to be an area where fish are observed in FSC fisheries and during helicopter flights. Other sites include the confluences of streams where sockeye concentrate.

Adult winter habitat.
Overwintering habitat of white sturgeon is generally characterized as habitat where fish can maintain their position with minimal energy use. The deepest holes in the river are known to be used for overwintering. The specific locations noted as important overwintering areas include:

- Nechako River (65-79 km),
- a deep area of the Nechako River at 110 – 111 km,
- Sinkut River confluence area (115 – 117 km),

- Pinchi Bay (Stuart Lake),
- Tachie River confluence (Stuart Lake), and
- Middle River confluence (Trembleur Lake).

The recovery team has indicated confidence that the overwintering habitats identified are sufficient to support the population's needs at abundance levels up to the recovery target.

Adult Staging.
Nechako River white sturgeon are known to "stage" in specific areas in April and May prior to spawning. Recent work observed mature fish staging in several areas from kilometre 115 to the lower limit of the Vanderhoof spawning site at kilometre 135 (Cory Williamson, Ministry of Environment, personal communication). There are at least six deep holes in this river section used for staging and fish were observed to move frequently throughout the entire section (i.e., 115 – 135 km). Three of these areas were earlier identified as high use areas (RL & L 2000a):

- Nechako River (89 – 95 km),
- Sinkut River confluence (115 – 117 km), and
- Leduc Creek confluence (122 – 127 km).

Fish were observed to move from these locations to the spawning site at or prior to the spawning period (RL & L 2000a; Golder 2003b).

Critical habitat features for staging are likely at least partly redundant to adult holding and overwintering critical habitats identified, as staging fish commonly occupy adult habitats that are used for other purposes.

Likely Critical Habitat.— Based on known habitat use, several areas are proposed as likely critical habitats for feeding, overwintering and staging (Figure 4). These areas are:

- Nechako River (65 – 79 km),
- Nechako River (89 – 95 km),
- Sinkut River confluence (115 – 117 km), and
- Leduc Creek confluence (122 – 127 km).

These habitats would be deemed critical year-round. The degree of certainty in this critical habitat determination is rated as moderate, based on repeated observations of white sturgeon at these sites.

The following additional areas are proposed as likely critical habitats for overwintering:

- Nechako River (65-79 km),
- a deep area of the Nechako River at 110 – 111 km,
- Pinchi Bay (Stuart Lake),
- Tachie River confluence (Stuart Lake), and
- Middle River confluence (Trembleur Lake).

These habitats, which are shown in Figure 4 and Figure 5, would be deemed critical on an annual basis from November to May, based on known overwintering periods. The degree of certainty in this critical habitat determination is rated as moderate, based on repeated observations of high use areas for overwintering. Other areas within kilometre 115 – 135 are deemed important habitats for staging; however, additional work is required to support recommendations as critical habitat.

Activities Likely to Impact Critical Habitat.— Activities that would impact likely critical habitat for this life stage include river regulation, gravel or sand dredging, linear developments, riparian, foreshore, floodplain alterations or developments, upstream land and water uses, and point and non-point source effluent discharges. The exact concerns would vary depending on details of the activities. General threats to some of the important habitat types for white sturgeon are discussed in Section 3 of the Recovery Strategy.

Data Gaps.— There are moderate data gaps for determining the geographic boundaries of this critical habitat component; river kilometres discussed here are approximate. These areas defined as likely critical habitat are fairly broad, and are based on existing information of white sturgeon habitat use. Additional studies may increase the confidence in these boundaries and may permit greater precision in defining the geographic areas of interest.

6.2.4 Additional Critical Habitat Factors

As noted earlier, the definition of critical habitat under the Species at Risk Act appears to permit the designation of habitat features (e.g., water quality, LWD associations, spawning habitat sediment qualities) as well as geographic areas. In this section, additional habitat features are proposed as components of critical habitat.

Migration.— Connectivity among habitats is considered a key habitat variable for white sturgeon in the Nechako River, since fish must be able to move freely between feeding, holding and spawning areas. At present, connectivity is maintained throughout the river, but the variable is acknowledged as key for conservation planning of this species.

Water Quality.— All aquatic organisms require water of sufficient quality to complete their life cycle. Aquatic species may be at risk when water quality degrades beyond specific thresholds for oxygen, temperature, pH, or pollutants. White sturgeon need cool, clean water. The current provincial water quality guidelines provide general direction for the protection of aquatic life (see http://www.env.gov.bc.ca/wat/wq/wq_guidelines.html#approved for details) and are likely sufficient for describing the general boundaries of required water quality for white sturgeon. Additional research is needed to determine tolerance limits for other water quality factors affecting various white sturgeon life stages. Specific concerns at present include contamination of benthic sediments (e.g., metals, organochlorine compounds), point source discharges from pulp mills, treated and untreated municipal and private sewage, and various other industrial and urban discharges, and non-point sources of pollution from agriculture, forestry, and urban areas.

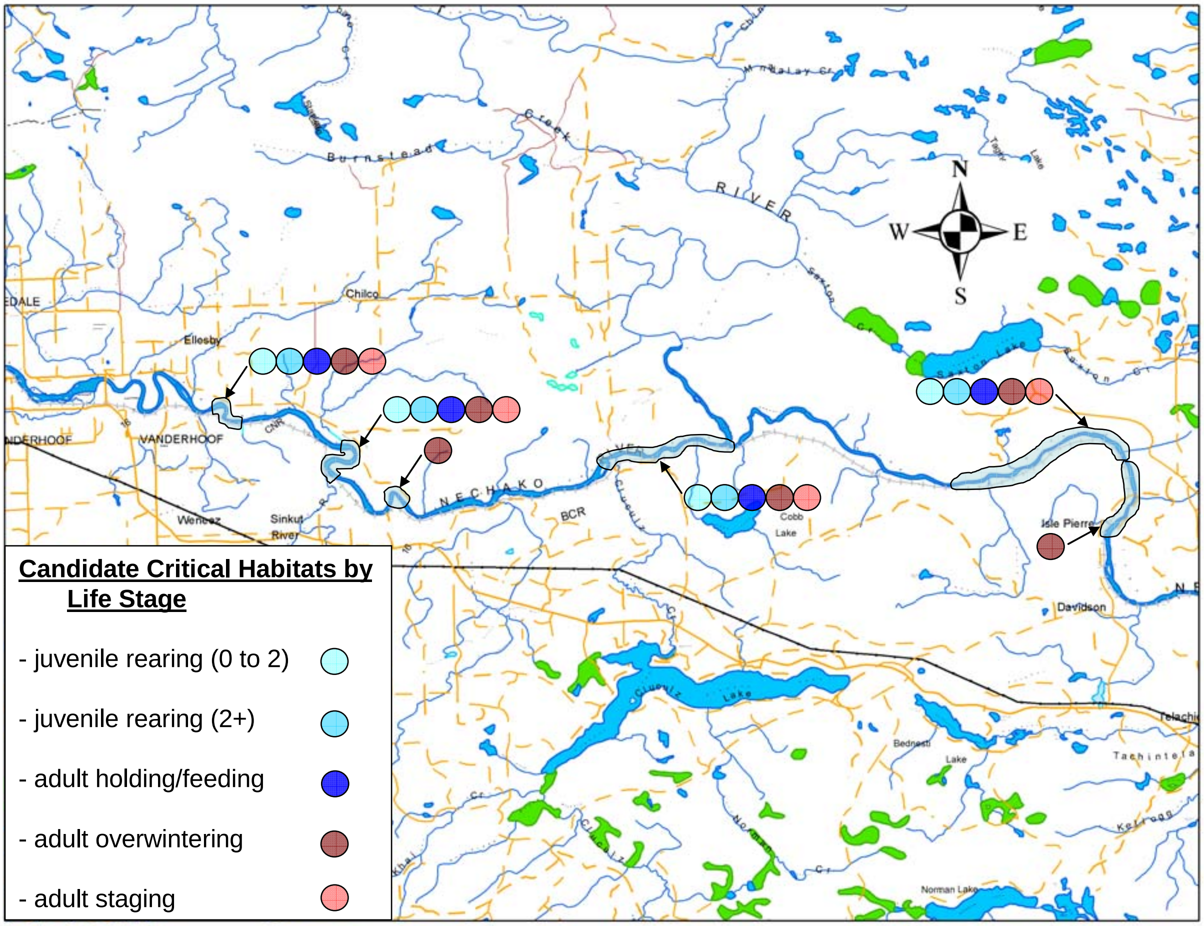

Figure 4. Candidate critical habitats for Nechako white sturgeon. Polygons identify areas known to be important habitats in the Nechako River system for several life stages as indicated, and are recommended for inclusion as critical habitat. In the text these are identified by river kilometre — for reference Prince George is km 0, the Stuart-Nechako confluence is km ~90, and Vanderhoof is km ~137.

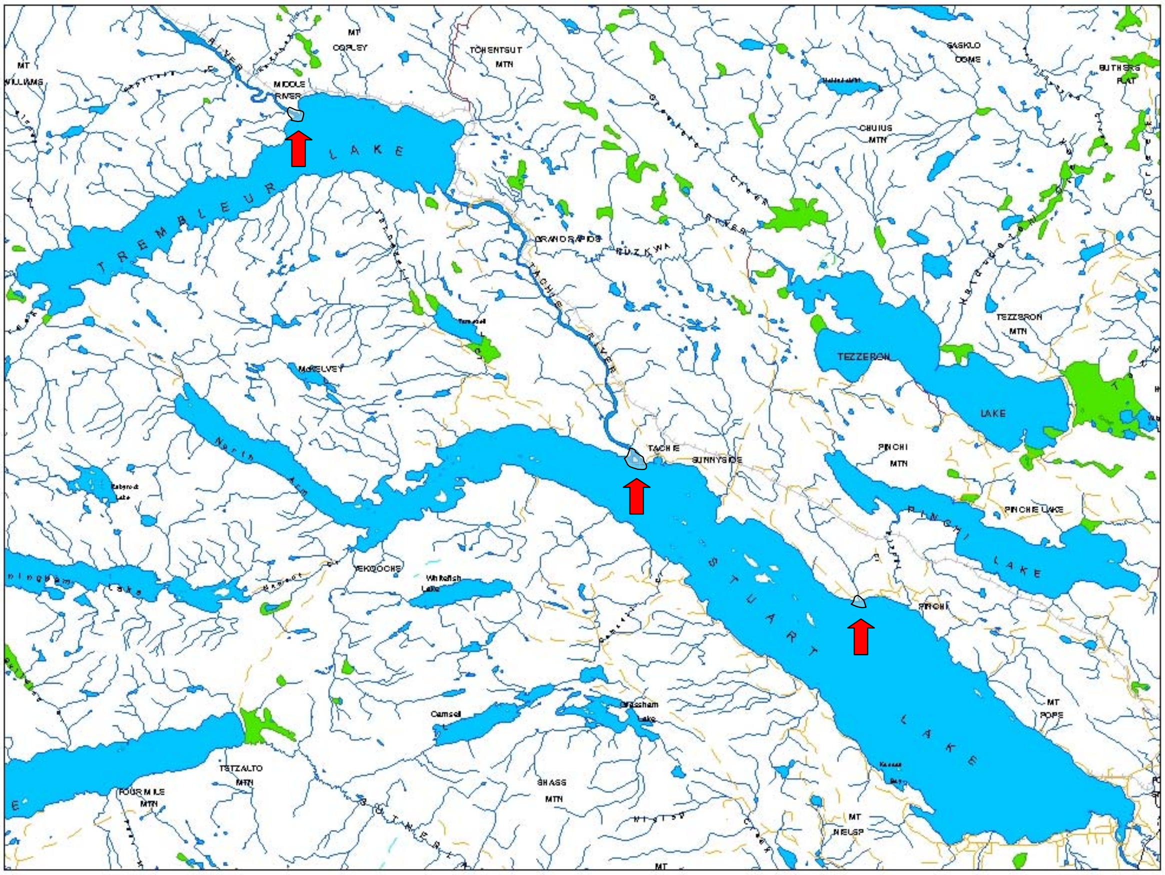

Figure 5. Candidate critical habitats for Nechako white sturgeon. The polygons identified by red arrows show three areas known to be important overwintering habitats in the Stuart River system, and are recommended for inclusion as critical habitat.

6.3 Columbia River

White sturgeon historically had access from the ocean all the way to Columbia Lake in the upper Columbia and Shoshone Falls in the upper Snake River. Populations in the upper reaches of the basin were most likely resident but benefited from the seasonal availability of anadromous salmon. White sturgeon inhabited the upper Columbia mainstem, lower Spokane River, lower Pend d'Oreille River, and lower Kootenay River to Bonnington Falls, and probably also used portions of smaller tributaries including the Sanpoil, Kettle, Slocan, and Salmo Rivers (Hildebrand and Birch 1996; Prince 2001). Distribution was probably patchy with fish concentrated in areas of favourable habitat. Significant concentrations of white sturgeon were reported during the early 1900s in the mainstem downstream from Castlegar, the lower Kootenay River, Arrow Lakes, Big Eddy near Revelstoke, and the present site of Mica Dam (Prince 2001).

At least two significant populations remain in the upper Columbia River, and other remnant populations consisting of a few individuals occur, or are suspected. The largest population resides in the free-flowing transboundary reach between Hugh L. Keenleyside Dam (HLK) and

Roosevelt Reservoir (FDR). In the 56 km section of the Columbia River between HLK and the international boundary, white sturgeon are concentrated throughout the year in four deep, low velocity areas: the area downstream from HLK, Kootenay Eddy at the Kootenay River confluence, Fort Shepherd Eddy, and Waneta Eddy at the Pend d'Oreille River confluence (Hildebrand and English 1991; RL&L 1993, 1994a, 1994b, 1995, 1996a). In the 40 km section of river downstream of the border to FDR, white sturgeon distribution and density are less well understood. They spawn at Northport, show clear recruitment failure, and appear somewhat distinct from white sturgeon residing in the Arrow Lakes and HLK area, based on mtDNA and demographic analyses (S. McAdam, BC Ministry of Environment, personal communication). The population is estimated at around 2000 individuals; most adult sturgeon occur in the transition zone of the reservoir, with smaller numbers in other areas upstream to the border. Density appears to be much lower in FDR main pool, though assessments are limited. Based on recapture data, 26% of tagged fish made forays into Canada within a 2 year study period, indicating some movement and mixing of sturgeon throughout the transboundary reach (Brannon and Setter 1992; Howell and McLellan 2006).

A second, smaller subpopulation of white sturgeon currently inhabits Arrow Lakes Reservoir (ALR). mtDNA analysis suggests this subpopulation may simply reflect splitting of a larger population by the construction of HLK (Nelson and McAdam 2004). Abundance in this subpopulation is substantially lower than in the reach from HLK to FDR. A significant sturgeon concentration was identified in the Beaton Flats area of ALR. Sonic tagged fish were observed to remain in this area throughout the winter but several fish moved during spring and summer upstream to Revelstoke or into Beaton Arm near the confluence with the Incomappleux River. A total of 32 unique fish were captured during a variety of assessment programs (Golder 2006a). Most assessment effort has concentrated on the upper reservoir and almost all fish have been captured there (Golder 2006a). More recently considerable effort was expended on assessments in Lower Arrow Reservoir, which resulted in 10 unique captures (Prince 2002, 2003, 2004).

Adult sturgeon have not been collected during investigations in Kinbasket Reservoir, Revelstoke Reservoir, or Trout Lake (RL&L 1996b, 1996c, 2000b). Given the large size of these reservoirs and limited sampling effort, the failure to catch a white sturgeon does not necessarily preclude their existence, but would suggest that population densities are low (RL&L 2000b). Prince (2001) also reported First Nations and anecdotal sightings of white sturgeon in upper portions of the mainstem Columbia.

The transboundary nature of this population requires that recovery efforts be coordinated across multiple jurisdictions. Designation of critical habitat will be complicated by different jurisdictions and legal requirements. To recover this population will require critical habitats to be designated and managed in both countries in a coordinated manner.

In each of the following sections, the subpopulations in Arrow and the transboundary reach are discussed separately.

6.3.1 Spawning and Incubation Habitat

Arrow Reservoir subpopulation.— The Arrow Reservoir subpopulation of white sturgeon is estimated at 52 fish, based on data collected from 1997 to 2003 (see Table 1). These fish are genetically similar to white sturgeon immediately downstream of HLK, but are prevented from mixing due to lack of passage at HLK. The subpopulation is therefore treated separately for management purposes.

Spawning presently occurs at a site located near Revelstoke in the vicinity of the golf course. Although spawning occurs naturally, extensive sampling over several years (Golder 2006a) has confirmed that there has been no recruitment from these spawning events. This suggests that some component(s) within spawning and incubation habitats are not functional at present, although the majority of mortality could also occur during a later life stage (e.g., juveniles). There are a variety of competing hypotheses to explain the lack of recruitment at this site (National Recovery Team for White Sturgeon 2006).

Transboundary subpopulation.— The area downstream of Waneta dam in the Pend d'Oreille plume is the only known spawning site in the Canadian section of the Columbia River downstream of HLK. The Waneta spawning site is located less then 1 km upstream of the Canada-USA border. One additional spawning site for the transboundary subpopulation occurs in the US at Northport. Management of critical habitat for this subpopulation will require a coordinated approach with US jurisdictions.

Likely Critical Habitat.— All spawning and incubation habitat for the Arrow Reservoir subpopulation is located in the Columbia River adjacent to the Revelstoke golf course (Figure 6). This is a single location and there is therefore no substitutability for this component of critical habitat. The spawning site is immediately downstream from the Revelstoke Dam (REV), and it is unclear whether conditions at this site can be made viable for recruitment given the current hydro development infrastructure, and several studies have been proposed to assess the long term viability of this spawning site. The trade-offs with socioeconomic concerns have not been assessed.

This habitat would be deemed critical on an annual basis during July and August based on known timing of spawning and incubation (Golder 2006a). However, with appropriate flows from REV it may be possible for this activity to occur earlier. Thus, the entire period encompassing June-August must be considered, encompassing known annual variability in onset and completion of spawning in this part of the Columbia basin. The degree of certainty in this critical habitat determination is rated as high, based on repeated observations of spawning at this site and absence of other spawning habitat for this subpopulation.

Likely critical spawning and incubation habitat for the transboundary subpopulation is the Waneta spawning site, which includes the Pend d'Oreille River from the Highway 22A bridge to the confluence with the Columbia, and the Columbia River from the Pend d'Oreille confluence to the international border (Figure 7). This is the only spawning site in Canada for the transboundary subpopulation, and there is no substitutability for this component of critical habitat. There is some potential redundancy with the Northport site, but since recruitment failure is occurring for spawning at the Northport site, there is a need to include all of the Waneta spawning site in the recommendation for critical habitat for the transboundary subpopulation.

The Waneta spawning site would be deemed critical on an annual basis during June, July and the first week of August, based on known timing of spawning and incubation. This period is sufficient to encompass known annual variability in onset of spawning. The degree of certainty in this critical habitat determination is rated as high, based on repeated observations of spawning at this site and absence of other spawning habitat in Canada for this subpopulation.

Activities Likely to Impact Critical Habitat.— The spawning site for the Arrow Reservoir subpopulation is immediately downstream from REV, which is currently operated as a load-following facility. Although spawning appears to occur naturally, operations of REV are believed to influence the viability of incubation habitat by stranding eggs and embryos. Hypolimnetic releases (i.e., from deep, cold water) from REV have altered water temperatures and are believed to influence timing of spawning and duration of embryo development. Elevation of ALR is believed to alter flows below REV due to a backwatering effect, which may influence suitability of spawning and incubation habitats.

The Waneta spawning area is impacted by load-following and water storage associated with a series of dams on Pend d'Oreille River, including Seven Mile and Waneta Dams within Canada and additional facilities upstream in the U.S. Spawning occurs primarily beyond the Pend d'Oreille channel, into the confluence with the Columbia mainstem and downstream a short distance. Thus, Columbia and Kootenay River dams further impact spawning and incubation habitats, again as a result of both load-following and storage. Slag and other contaminant impacts are also of concern.

Data Gaps.— Minor data gaps exist for determining the geographic boundaries of critical spawning and incubation habitat for both subpopulations. However, these habitat units are relatively small and reasonably well-defined, so any increase in the precision of the habitat boundaries is considered inconsequential at this time. For example, the effects of hydro operations are likely to be similar even if these boundaries shift slightly following increased data quality. There remain significant uncertainties with respect to the qualities of habitat that are required to make these habitat units functional for incubation and early life stages. Work is underway to assess these habitat variables (Steve McAdam, BC Ministry of Environment, personal communication).

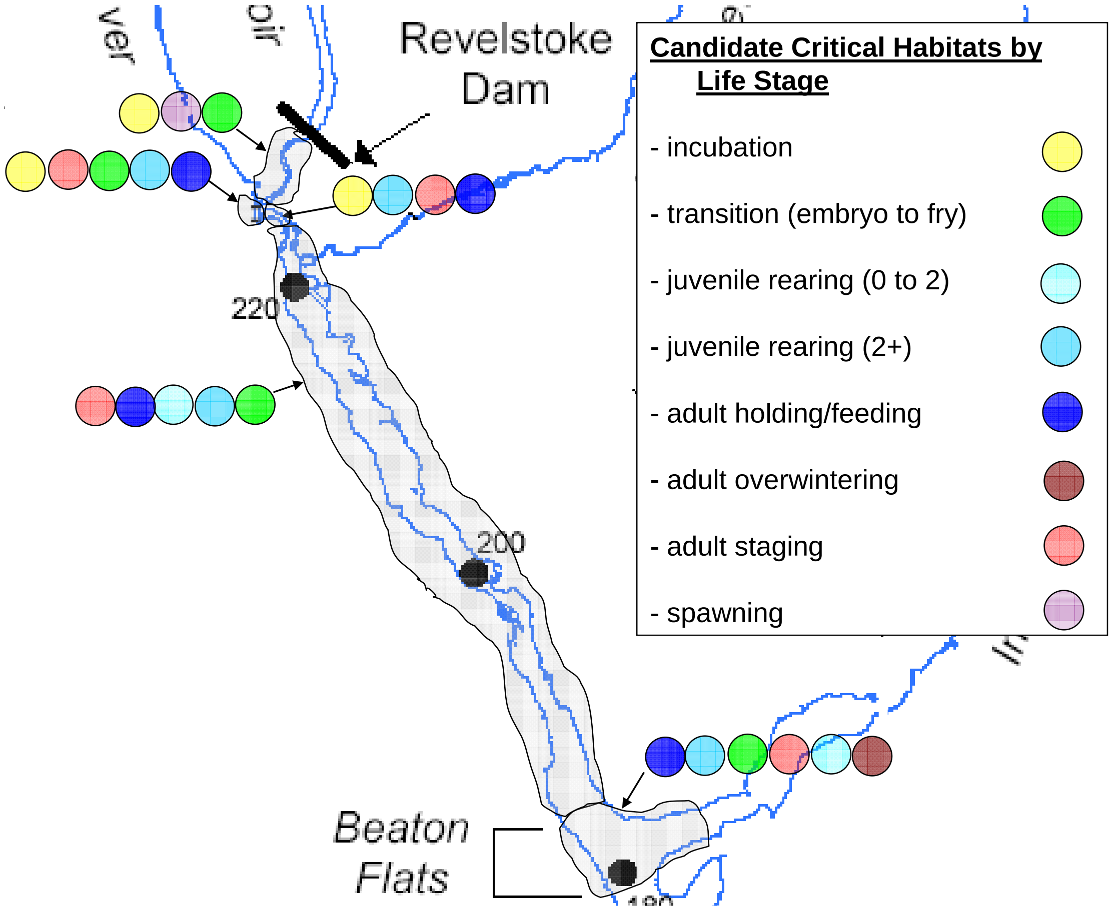

Figure 6. Candidate critical habitats for white sturgeon in the Revelstoke Reach of the Columbia River. These habitats are relevant to the Arrow Reservoir subpopulation. Habitat information is plotted on top of a base map taken from Golder 2006a.

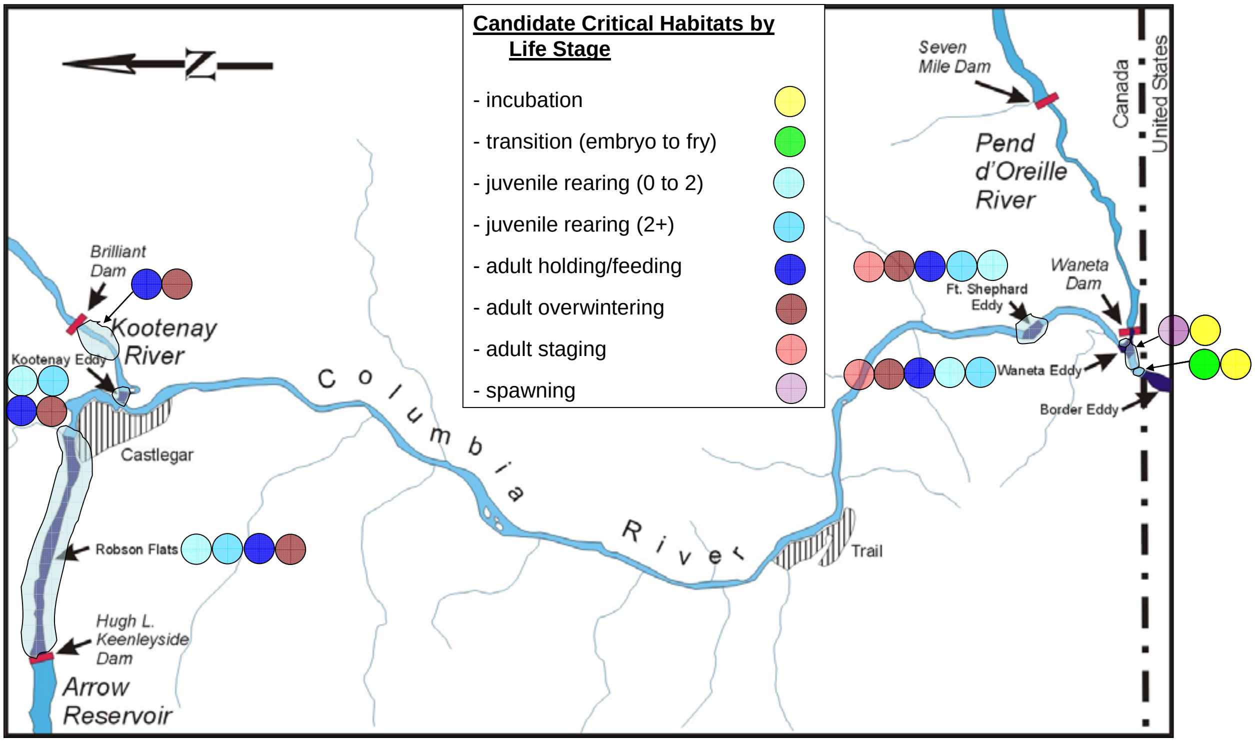

Figure 7. Candidate critical habitats for white sturgeon in the transboundary reach of the Columbia River.

6.3.2 Early Juvenile Habitat

0 - 21 days.— This life stage is considered a key recruitment bottleneck and is therefore a high priority for conservation.

For the Arrow Reservoir subpopulation this stage may last somewhat longer than in other populations due to the low water temperatures found at the spawning site during spawning and early rearing (Tiley 2004). Adhesive eggs are normally retained within the spawning site, but after hatching larvae are mobile and may move downstream. The location of larvae at this stage is not known for the Arrow Reservoir subpopulation. It is assumed that habitat for this stage would include the spawning site, as well as habitat downstream, though the extent of the downstream boundary is not known.

For the transboundary subpopulation the habitat for this stage would be similar to habitats used for spawning. However, the extent of habitat would extend downstream further south of the international border, and may exist primarily in the U.S. The distribution of spawning and incubation habitats is understood fairly well for this location, but the distribution of post-hatch larvae is unknown.

21 days to 2 years.— For the Arrow Reservoir subpopulation this stage has not been observed in the wild due to ongoing recruitment failure. The location of habitat suitable for this life stage is therefore uncertain. During the early part of this phase it is expected that juvenile white sturgeon would use a range of mainstem and off-channel habitats, as well as the deltaic habitats at the northern end of Arrow Reservoir. However, the precise locations of this use and its downstream extent are not clear at this time.

For the transboundary subpopulation, habitat occupied during the early portion of this life stage is unknown. This is partly due to the absence of recruitment, as well as the difficulty in sampling within the large river environment. Habitat use by yearling sturgeon released from conservation aquaculture work in this area suggests that all the main habitats (Waneta Eddy, Fort Shepherd Eddy, Kootenay Eddy and the Keenleyside Reach) would be occupied by later portions of this life stage (e.g., Golder 2006b). Additional sites where juveniles have been detected occur at a number of sites along the river margin, and these should be considered for designation as critical.

Likely Critical Habitat.— For the Arrow Reservoir subpopulation the precise location of habitat for 0 – 21 day life stage is not known, due in large part to ongoing recruitment failure. Likely critical habitat would include the spawning site below REV and extend downstream some distance (Figure 6), though the downstream boundary cannot be defined at this time. This habitat would be deemed critical on an annual basis during July through September, based on known timing of spawning and incubation. This period is sufficient to encompass known annual variability in onset of spawning. The degree of certainty in this critical habitat determination is rated as high, based on repeated observations of spawning at this site, although there is insufficient certainty to define the downstream limit of this habitat beyond that already defined for spawning and incubation. Several studies have been devised to assess suitable habitat for this life stage.

For the Arrow Reservoir subpopulation likely critical habitat for the 21 days to 2 years stage is expected to include a range of mainstem and off-channel habitats, as well as deltaic habitats at the northern end of Arrow Reservoir. Uncertainty regarding the boundaries of this habitat unit are sufficiently high that critical habitat is not being proposed at this time.

Likely critical habitat for the transboundary subpopulation 0 – 21 days stage is defined as the same habitat unit as that used for spawning (Figure 7). The habitat would extend downstream at least as far as the U.S. border. Thus, the recommendation for critical habitat for this life stage is the same as the spawning and incubation habitat.

Likely critical habitat for the transboundary subpopulation 21 days to 2 years stage includes the following habitats: Waneta Eddy, Fort Shepherd Eddy, Kootenay Eddy and the Keenleyside Reach. Additional rearing sites for the early juveniles life stage may be defined in the future with additional data.

Activities Likely to Impact Critical Habitat.— General activities that would impact likely critical habitat for this life stage include several aspects of river regulation, fish community changes, gravel or sand dredging, linear developments, riparian, foreshore, floodplain alterations or developments, upstream land and water uses, and point and non-point source effluent discharges. The exact concerns would vary depending on details of the activities. General threats to some of the important habitat types for white sturgeon are discussed in Section 3 of the Recovery Strategy.

Data Gaps.— There are moderate data gaps for determining the geographic boundaries of this critical habitat. The areas defined as likely critical habitat are fairly broad, and are based on existing information of white sturgeon habitat use. Additional studies may increase the confidence in these boundaries and may permit greater precision in defining the geographic areas of interest. There are significant data gaps with respect to specific qualities of habitat that would allow some of these sites to become fully functional.

6.3.3 Late Juvenile and Adult Habitat

***General*. —** For the Arrow Reservoir subpopulation, there is uncertainty about habitat use during portions of this life stage. However, good evidence has been gathered to show that adult white sturgeon reside in the Revelstoke Reach as well as the Beaton Flats area of Upper Arrow Reservoir, as well as at key feeding sites at the mouths of important kokanee spawning streams (Golder 2006b). It is expected that older juveniles would occupy similar habitats. Further study is needed to increase confidence in these assessments.

For the transboundary subpopulation, there is also uncertainty regarding habitat use by late juveniles and adults, due principally to rarity of young white sturgeon in this portion of the river. It is anticipated that critical habitat for this life stage is the same as for juveniles of 1 - 2 years age. The latter portions of this life stage reside primarily in the four large main river eddies, however, the timing of this transition is unclear. It is also unclear whether this would still be true if abundance was greater than it is at present. There is a high level of confidence in the location of most adults within this reach, based on years of telemetry and sampling.

***Adult Feeding Habitat.* —** Adults have been found more often in the upper basin of Arrow Reservoir. Within that basin they are generally concentrated near the north end, and most consistently in the Beaton Flats area. The Revelstoke Reach is also used as feeding and staging habitat, but further work is needed to clarify the importance of this location.

An important function of the reservoir is to provide feeding habitat to white sturgeon. Kokanee are the predominant food resource of adult white sturgeon, and therefore creek mouths where kokanee congregate are important habitats. Beaton Flats and Beaton Arm are identified as especially important. Creek mouths and lower reaches of the following streams are also identified as important, based on mean annual escapements of more than 5000 kokanee (MoE, data on file):

- Bridge Creek
- Hill Creek
- Cranberry
- Drimmie
- Halfway
- Kuskanax
- MacDonald
- Tonkawatla
- Burton
- Caribou
- Deer
- Mosquito
- Taite

In the transboundary subpopulation, the Waterloo site and Norns Creek are considered important feeding sites for white sturgeon. As well, habitats immediately below HLK and Brilliant Dam likely provide excellent feeding opportunities, specifically feeding on fish entrained through those facilities. Fort Shepherd and Waneta Eddies are used year round by large numbers of adults, and are assumed to provide a consistent food supply based on the ability of these areas to slow and trap organic material in the drift.

***Adult Winter Habitat.* —** Winter habitat of white sturgeon can be characterized as habitat where fish can maintain their position with minimal energy use. Within the Arrow Reservoir overwintering habitats are identified based on past fish capture, and are generally located in the northern end of Arrow Reservoir, at or near Beaton Flats.

For the transboundary subpopulation, there are four main locations of high importance as overwintering habitat: Waneta Eddy, Fort Shepherd Eddy, Kootenay Eddy, and the Keenleyside Reach.

***Adult Staging.* —** Prior to spawning, white sturgeon often "stage" in areas directly adjacent to a spawning area. Given the limited information available about spawning for the Arrow Reservoir subpopulation, precise description of staging areas is challenging. The most likely areas occur upstream of the Highway #1 bridge, extending upstream to the spawning site by the Revelstoke golf course. Of particular importance within this area is the large eddy referred to locally as Big Eddy.

For the transboundary subpopulation, the main staging areas are Fort Shepherd Eddy and Waneta Eddy, and this is well-documented.

***Likely Critical Habitat.*—** For the Arrow Reservoir subpopulation likely critical habitat for this life stage is as follows. For feeding, it is the Beaton Flats area, based on year round use and consistently high densities of adults (Figure 6). Other areas (e.g., kokanee spawning stream outlets) are identified as important, but additional work is required to clarify whether they should be classified as critical. For overwintering Beaton Flats area is also identified, based on past fish captures. For staging, Big Eddy is identified as critical habitat, although additional area is identified as important. Big Eddy and the Beaton Flats area would be deemed critical on a year-round basis, based on known timing of feeding, staging and overwintering. The degree of certainty in this critical habitat determination is rated as high, based on repeated observations of white sturgeon activities at this site, although there is some uncertainty regarding the geographic boundaries of this habitat. Several studies have been devised to improve confidence in the assessment of these boundaries.

Likely critical habitat for the transboundary subpopulation during this life stage is defined as follows. As in the case of the Arrow Reservoir subpopulation, areas have been identified as critical feeding habitat based on year round use and consistently high densities of adults. These are Waneta Eddy, Fort Shepherd Eddy, Kootenay Eddy, Brilliant tailrace and the Keenleyside Reach (Figure 7). The same five locations have also been identified as critical overwintering habitat. Waneta and Fort Shepherd Eddies have been further identified as critical habitats for staging. These habitats are deemed critical on an annual basis because of their combined value as feeding, overwintering and staging habitat. The degree of certainty in this critical habitat determination is rated as high, based on repeated observations of white sturgeon activities in this river reach.

***Activities Likely to Impact Critical Habitat.*—** Activities that would impact likely critical habitat for this life stage include the various effects of river regulation, gravel or sand dredging, linear developments, riparian, foreshore, floodplain alterations or developments, upstream land and water uses, and point and non-point source effluent discharges. The exact concerns would vary depending on details of the activities. General threats to some of the important habitat types for white sturgeon are discussed in Section 3 of the Recovery Strategy.

Data Gaps.— There are moderate data gaps for determining the geographic boundaries for these critical habitats. The eddies are fairly small, and it is unlikely that additional confidence is required to better define these boundaries. The Beaton Flats area is considerably broader, and there may be benefits in trying to better define the geographic boundaries of this site. Additional studies are required for this purpose.

6.3.4 Additional Critical Habitat Factors

Migration.— Connectivity among habitats is considered a key habitat variable for white sturgeon in the Columbia River. The locations of historic spawning sites are unknown, and movement to those sites likely required movement beyond areas currently confined by hydroelectric dams. Currently fish of similar genetic composition are found upstream and downstream of HLK, and it is believed that the dam divided a contiguous population. Upstream movement past HLK is possible through shipping locks but is presumed to be minimal. It is possible that historic spawning sites were upstream of present dam locations and part of the reason for recruitment failure is a shift in spawning location. Thus, a key habitat concern with respect to these dams is connectivity, and the ability to pass freely both upstream and downstream. The limited ability to alter present levels of connectivity is acknowledged, however, consideration must be given to whether such connectivity was critical prior to dam construction. HLK Dam is a particularly important issue in this regard, and so passage at this site is noted as a critical habitat feature.

Flows in some river sections may also present connectivity problems, due primarily to the load-following operations at REV, which reduce flows to near zero on a daily basis. In the Revelstoke reach, the segment upstream from the Highway 1 Bridge to Big Eddy provides important connectivity to Big Eddy and areas upstream for feeding as well as spawning. The proposed minimum flow from REV may provide such connectivity; however, this must be evaluated once the flow is implemented.

Water Quality.— All aquatic organisms require water of sufficient quality to complete their life cycle. Aquatic species may be at risk when water quality degrades beyond specific thresholds for oxygen, temperature, pH, or pollutants. White sturgeon need cool, uncontaminated water. The current provincial water quality guidelines provide general direction for the protection of aquatic life (see http://www.env.gov.bc.ca/wat/wq/wq_guidelines.html#approved for details) and are likely sufficient for describing the general boundaries of required water quality for white sturgeon. Additional research is needed to determine tolerance limits for other water quality factors affecting various white sturgeon life stages. Specific concerns include contamination of benthic sediments (e.g., metals, organochlorine compounds), point source discharges from pulp mills and smelters, treated and untreated municipal and private sewage, and various other industrial and urban discharges, and non-point sources of pollution from agriculture, forestry, and urban areas.

Likely Critical Habitat.— Connectivity is identified as a critical habitat feature for white sturgeon in the Columbia River. For the Arrow Reservoir subpopulation, connectivity is required for the segment upstream from Hwy Bridge to Big Eddy, and from Big Eddy to the spawning site at the golf course. For the transboundary subpopulation connectivity is identified as a critical habitat feature at HLK Dam. It is believed that this dam currently divides a formerly contiguous population. No critical habitat features are defined for water quality at this time.

Activities Likely to Impact Critical Habitat.— River regulation and specifically operations at REV can limit connectivity among habitats from Arrow Reservoir to the spawning site at the golf course. The proposed minimum flow from REV may provide such connectivity; however, this must be evaluated once the flow is implemented. It is the presence of HLK rather than an activity per se that limits connectivity for the transboundary population. Resolution of this issue is complex, however, as HLK also affects the movement of non-native walleye, hindering expansion of their range into Arrow Reservoir.

Data Gaps.— Significant data gaps include knowledge of historic spawning sites and present connectivity to those sites, the effect of poor connectivity on population recruitment, and the efficacy of different options to address connectivity deficiencies. Data gaps also exist with respect to water quality parameters and limits to sturgeon production.

6.3.5 Remnant Populations

Anecdotal reports from local residents and traditional ecological knowledge have identified that white sturgeon were present in the extreme upper Columbia River prior to construction of Mica Dam and the formation of Kinbasket Reservoir (Prince 2001). There is anecdotal evidence that white sturgeon are still present in the Kinbasket Reservoir. At present, no critical habitat designations are recommended for this portion of the watershed.

6.4 Kootenay River

The Kootenay River population of white sturgeon extends from Kootenai Falls, Montana, located 50 river-kilometres below Libby Dam, downstream through Kootenay Lake to Corra Linn Dam on the lower West Arm of Kootenay Lake, British Columbia. Kootenai Falls likely represents an impassable natural barrier to the upstream migration of white sturgeon, although anecdotal evidence suggests the historic presence of white sturgeon upstream of Kootenai Falls in Montana and British Columbia. A natural barrier at Bonnington Falls downstream of Kootenay Lake has isolated the Kootenay River white sturgeon from the Columbia River population since the end of the Pleistocene, approximately 10,000 years ago (Northcote 1973). Spawning habitat is located in the US, whereas much of the adult and juvenile rearing habitat is located in the Canadian portion of Kootenay River plus Kootenay Lake (e.g., Kootenay delta and tributary creek mouths).

White sturgeon are also found in very small numbers in Duncan Reservoir and Slocan Lake (RL&L 1998b, 1998c). The Slocan River is a tributary of the Kootenay River and white sturgeon in the Slocan are genetically most similar to the Kootenay population. Since the Slocan is downstream of Bonnington Falls any white sturgeon here would have been unable to return to the Kootenay. Five adult sturgeon from the Kootenay population were transplanted into Koocanusa Reservoir, upstream of Kootenai Falls, by BC and Montana government staff in the mid-1970s.

The transboundary nature of the Kootenay River population requires that recovery efforts be coordinated across multiple jurisdictions. Designation of critical habitat is complicated by different jurisdictions and legal requirements. To recover this population will require critical habitats to be designated in both countries in a coordinated manner.

6.4.1 Spawning and Incubation Habitat

Current spawning habitat is located in the US in the Deep Creek - Shorty's Island reach. Some white sturgeon in spawning condition have been documented above Bonners Ferry but only for short (2 – 12 hour) periods (IDFG in prep.). Substrates in the main spawning area are dominated by fines, providing unsuitable incubation conditions (Kock et al. 2006), and are considered a central cause of recruitment failure. Historic spawning sites were likely located at and upstream of Bonners Ferry, where there are rocky substrates and high water velocities. Paragamian et al. (2002) suggest that there is correlation between lake elevation and location within the Kootenai River where spawning is located, and this relationship seems to be due more to river depth than to velocity (Berenbrock 2006). Thus, although spawning and incubation habitats are geographically within the US, a critical influence on this habitat is the elevation of Kootenay Lake, in Canada. The elevation of Kootenay Lake is therefore considered critical habitat. All egg incubation sites are located within the US. Kootenay Lake elevations are believed to influence incubation success indirectly, through selection of appropriate spawning sites.

Likely Critical Habitat.— All spawning and incubation habitat for the Kootenay River population of white sturgeon is physically located within the US. There is a single location and therefore no substitutability for this component of critical habitat.

The viability of this habitat is influenced by releases from Libby Dam and water levels in Kootenay Lake. Canada has jurisdiction over water levels in Kootenay Lake (outflows are regulated, as are some inflows) and therefore has partial control over the functionality of critical spawning and incubation habitat. There remains uncertainty regarding the required operations of water levels, but the argument can be made that lake levels are a component of critical habitat. Trade-offs with socioeconomic concerns have not been assessed.

Activities Likely to Impact Critical Habitat.— As noted, lake levels play a significant role in determining the viability of spawning and incubation habitat in the Kootenai River. Inflows and outflows to Kootenay Lake are regulated, and can be controlled to benefit or impact critical spawning and incubation habitat. Discharges from Libby Dam also have a strong influence on suitability of spawning and incubation habitats.

Data Gaps.— A key data gap is the precise relation between Kootenay Lake levels and viability of white sturgeon spawning and incubation habitat. Studies have been defined and are underway to assess this relationship.

6.4.2 Early Juvenile Habitat

0 - 21 days.— There is uncertainty about whether this life stage occurs or could occur in Canada. This uncertainty is principally related to the lack of understanding of larval drift, such as the duration and distance of drift, as well as a more general understanding of the role of drift within the life history of white sturgeon. Recent laboratory work on larval drift (Kynard and Parker 2006) implies that some larvae would drift from spawning areas in the US to rearing areas in Canada, but this is unverified in the field. Habitats that may be used are main and off channel habitats in the lower end of the Kootenay River, and possibly the river delta at the south end of Kootenay Lake. There is a relatively high level of uncertainty about whether such use occurs.

21 days to 2 years.— There is greater certainty that fish of this age class use habitats located in Canada (Neufeld and Spence 2002, 2004a, 2004b; Neufeld 2005, 2006). Habitats include main channel habitats in the lower end of the Kootenay River, and the south end of Kootenay Lake (Neufeld 2006). 1 yr old hatchery fish are known to use lake habitat and it is therefore assumed that fish throughout this stage would use a range of habitats in the Lower Kootenay River and the Kootenay River delta (Neufeld 2005, 2006).

Likely Critical Habitat.— Given the existing uncertainties, no critical habitat is proposed at this time for the earliest part of this life stage. For the latter part of this life stage, likely critical habitat includes portions of the Lower Kootenay River and the Kootenay River delta (Figure 8). This habitat would be deemed critical year-round, based on habitat needs of white sturgeon during this life stage. The level of confidence in this critical habitat recommendation is moderate, but there remains considerable uncertainty regarding the geographic boundaries of this habitat unit.

Activities Likely to Impact Critical Habitat.— Kootenay Lake levels likely play a role in determining the suitability of habitats for this life stage, as do discharges from Libby Dam.

Data Gaps.— The relation between Kootenay Lake levels and white sturgeon habitat suitability is a key data gap. Studies have been defined and are underway to improve understanding of this relationship.

6.4.3 Late Juvenile and Adult Habitat

Both juvenile and adult life stages use Kootenay Lake and Kootenay River as important rearing habitat. Telemetry data and fish sampling show that white sturgeon are commonly located at the Kootenay River delta at the south end of Kootenay Lake, the Duncan River delta at the north end of Kootenay Lake, and the Crawford Creek delta on the east side of Kootenay Lake (RL&L 1999a; Neufeld 2006). These delta areas are extensively used by white sturgeon to a depth of 100 m where fine substrates exist (Andrusak 1982; RL&L 1999a; Neufeld 2005, 2006). On the Kootenay River delta, this habitat includes the lower kilometre of the river just above the train bridge. These areas are considered important feeding habitat for all these age groups and should be considered for designation as critical habitat. The key feature of rearing habitat in the lake appears to be abundance of important food resources, especially kokanee, mountain whitefish and *Mysis*. Kokanee abundance should be considered in critical habitat assessments since they are an important prey species, and bays at creek mouths where kokanee aggregations occur should be considered for designation as critical habitat.

The following locations are important kokanee areas:

- Boulder Creek – from the mouth upstream to velocity barrier located 10 m upstream of Hwy 3A bridge;
- Crawford Creek – from mouth upstream 4.4 km to velocity chute;
- Summit Creek – from mouth upstream to the confluence with Topaz Creek;
- Goat River – from mouth to deactivated dam located east of Creston, immediately downstream of Sullivan Creek;
- Duncan River – from outlet to lower end the Duncan Dam tailrace;
- Lardeau River – from outlet to Trout Lake;
- Meadow Creek – from mouth to falls located approximately 6 km upstream or Meadow Creek spawning channel.

There is moderate uncertainty in the relative importance of some of these habitats due to the unknown extent of white sturgeon dependence on kokanee, however there is high certainty that the Kootenay River delta is important to these larger fish.

Likely Critical Habitat.— Portions of the Lower Kootenay River and the Kootenay River delta, the Crawford Creek delta and the Duncan River delta are proposed as likely critical habitat for this life stage (Figure 8). This habitat would be deemed critical year-round, based on habitat needs of white sturgeon during this life stage and others. The level of confidence in this critical habitat recommendation is high, but there remains considerable uncertainty regarding the geographic boundaries of this habitat unit. Some areas have been identified as important for feeding, particularly for kokanee, but the information base is insufficient to identify them as critical at this time.

Activities Likely to Impact Critical Habitat.— Kootenay Lake levels likely play a role in determining the suitability of habitats for this life stage, as do discharges from Libby Dam.

Data Gaps.— The relation between Kootenay Lake levels and white sturgeon habitat suitability is a key data gap for this and other life stages. Studies have been defined and are underway to improve understanding of this relationship.

6.4.4 Additional Critical Habitat Factors

Migration.— Juveniles and adult life stages use the Kootenay River mainstem as a migration corridor to and from rearing and spawning areas. Uninhibited passage throughout the mainstem is required to complete the white sturgeon life cycle. At present, no critical habitat is defined in relation to this requirement.

Water Quality.— All aquatic organisms require water of sufficient quality to complete their life cycle. Aquatic species may be at risk when water quality degrades beyond specific thresholds for oxygen, temperature, pH, or pollutants. White sturgeon need cool, clean water. The current provincial water quality guidelines provide general direction for the protection of aquatic life (see http://www.env.gov.bc.ca/wat/wq/wq_guidelines.html#approved for details) and are likely sufficient for describing the general boundaries of required water quality for white sturgeon. Additional research is needed to determine tolerance limits for other water quality factors affecting various white sturgeon life stages. Specific concerns include treated and untreated municipal and private sewage, and various other industrial and urban discharges, and non-point sources of pollution from agriculture, forestry, and urban areas. At present, no critical habitat is defined in relation to this requirement.

6.4.5 Remnant Populations

Duncan Reservoir.— White sturgeon in Duncan Reservoir are considered remnants of the Kootenay Lake population (RL&L 1998c). The area upstream of Duncan Dam was clearly part of white sturgeon historic habitat, but it is not considered critical habitat. This habitat is considered to play at most a minor role in limiting Kootenay River white sturgeon.

Slocan Lake.— White sturgeon can be found in very small numbers in Slocan Lake (RL&L 1998b, 1998c). The Slocan River is a tributary of the Kootenay River and white sturgeon in the Slocan are genetically most similar to the Kootenay population. Since the Slocan is downstream of Bonnington Falls any white sturgeon here would have been unable to return to the Kootenay. Slocan River and Slocan Lake were part of white sturgeon historic habitat, but they are not considered critical habitat. This habitat is considered to play at most a minor role in limiting Kootenay River white sturgeon.

Koocanusa.— Five adult sturgeon from the Kootenay population were transplanted into Koocanusa Reservoir, upstream of Kootenai Falls, by BC and Montana government staff in the mid-1970s. No critical habitat designation is required for the Koocanusa Reservoir, or areas in the Upper Kootenay River. There has been some discussion regarding use of the reservoir to provide habitat for a replicate population. If this plan proceeds, there may be a need to designate critical habitat within Canada at that time.

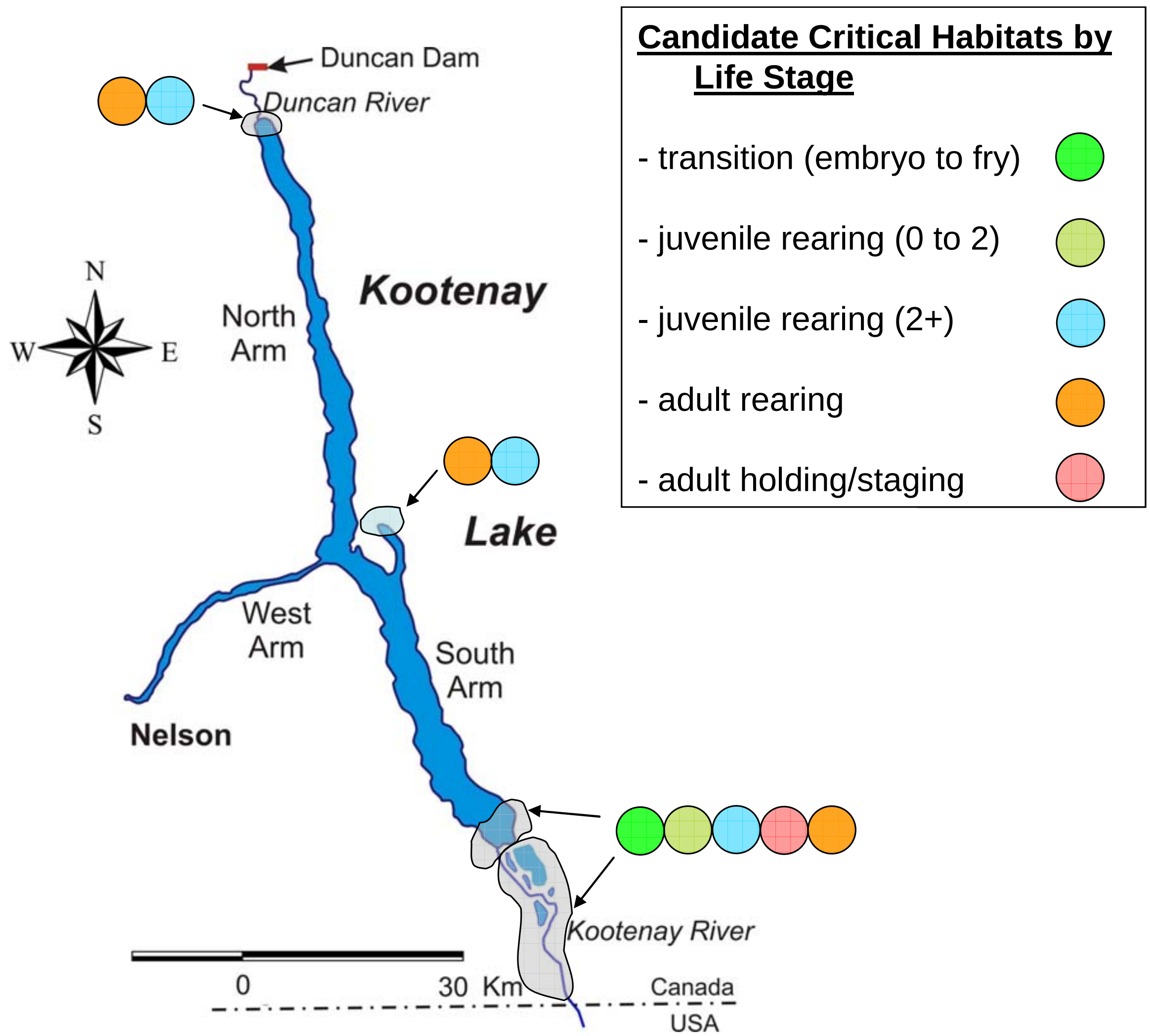

Figure 8. Candidate critical habitats for white sturgeon in Kootenay Lake and the Kootenay River. Note that spawning habitats are in the US, but viability is influenced by water levels of Kootenay Lake (see text). This map uses “adult rearing” as a general category to cover several activities for this life stage.

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Appendix 2*

SIMULATION MODELING TO EXPLORE RECOVERY POTENTIAL OF ENDANGERED WHITE STURGEON POPULATIONS

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* *Erratum*: Appendix 1 and 2 were missing from the original version.

1.0 Introduction

We assess recovery potential of four white sturgeon populations listed as endangered under the Species At Risk Act (SARA) through simulations with an age-structured population model. We simulate a range of habitat restoration actions and hatchery supplementation strategies that lead to improvements in juvenile recruitment rates and investigate the impact of plausible rates of incidental mortality induced by human activities. Recovery scenarios are compared using model performance measures that track the probability of meeting population objectives identified in the draft white sturgeon recovery strategy (NRTWS 2006).

2.0 Methods

2.1 Model Structure

We use the age-structured model described by Korman and Walters (2001) and Walters et al. (2006) to simulate population dynamics. The model uses standard methods for representation of recruitment, survival, maturity, and vulnerability to fishing mortality. The model is initialized based on the current population size and age-structure for each of the four populations and simulates future recruitments and adult populations under a range of assumptions about natural recruitment, hatchery suppplementation, and incidental human-induced mortality.

The number of fish of age ‘a’ alive in year ‘t’ ($N_{a,t}$) is computed from:

(1) $$N_{a,t} = N_{a-1,t-1} S(1 - V_a HM)$$

where, S is the annual age-independent survival rate, V_a is the age-specific vulnerability to fishing, and HM is the incidental human-induced mortality rate for fish that are large enough to be completely vulnerable to such mortality. Prediction of $N_{a,t}$ accounts for demographic stochasticity. The number surviving is determined based on random draws from a binomial distribution with a success rate equivalent to the net survival rate, $S(1-V_aH)$, and the number of trials equivalent to $N_{a-1,t-1}$. Environmental stochasticity due to annual variation in survival after age 1 was not simulated in most scenarios, but the effect of lognormal annual variation in S after age 1 was investigated in a sensitivity analysis where $S_t = S \exp(w_t)$ and w_t follows a normal distribution with mean 0 and standard deviation σ_e.

Table 1. Baseline parameters used in white sturgeon recovery simulations. No values separated by "/" denote estimates for Upper Fraser and other (Nechako, Columbia, and Kootenay) populations, respectively.

Parameter	Description	Value
S	Annual survival rate of wild fish (a>= 1+)	0.923
No	Population size at carrying capacity	1200/8200
k	Goodyear compensation ratio	5
σ_r	Standard deviation of age-1 recruitment	0.6
K	Brody growth (length-at-age) coefficient	0.0231
$L_?$	Asymptotic length (cm)	412.8
W_{100}	Weight at 100 cm (kg)	7
L_{mat}	Length at first maturity (cm)	165
μ_s	Age at 50% senescence	80
σ_s	Slope of age-senescence relationship	5
μ_v	Age at 50% vulnerability	7.7
τ_v	Slope of age-vulnerability relationship	5.1
S_H	First-yr. survival of age-1 hatchery fish	0.2

Relative vulnerabilities to human-induced mortality (e.g., fishing) can be represented as a sigmoid function,

(2) $$V_a = \frac{a^{\tau_v}}{\mu_v^{\tau_v} + a^{\tau_v}}$$

where, μ_v is the age at which vulnerability is 0.5 and τ_v is the slope of the relationship. Other parameter values can be used to represent vulnerability to line (set-line or hook-and-line) and gillnet fishing or other human-induced impacts. Alternatively, the vulnerability at each age can be specified directly (as a histogram).

The number of age-1 recruits is predicted from a Beverton-Holt stock-recruitment function assuming lognormal error,

(3)
$$N_{1,t} = Hab_t \frac{\alpha E_t}{1+\beta E_t} e^{v} + Hatch_t * \frac{S_H}{S}$$

where, Hab_t is a recruitment multiplier used to simulate improvements from habitat supplementation, E_t is the relative egg deposition in year t, α and β are the slope (maximum recruits/spawner) and density-dependent terms of the stock-recruitment relationship, v is an annual random deviate drawn from a normal distribution with mean 0 and standard deviation σ_r, $Hatch_t$ is the number of age-1 hatchery recruits, and S_H is survival rate of hatchery fish in their first year at large. S_H/S is the survival rate differential between hatchery and wild age-1 fish.

Prediction of annual egg deposition requires calculation of length, weight, and maturity schedules. Length at age (L_a) is predicted from a von Bertallanfy growth function,

(4)
$$L_a = L_\infty (1 - e^{-Ka}),$$

where, L_∞ is the asymptotic length (cm) and K is the Brody growth coefficient. Weight at age (W_a) is predicted from,

(5)
$$W_a = W_{100} \frac{L_a}{100}^{3}$$

where, W_{100} is the weight (kg) of a fish of 100 cm in length. Relative egg deposition per spawner by age class (Fec_a) is computed as the product of the weight-dependent fecundity and an index of age-dependent spawning frequency from,

(6)
$$Fec_a = (W_{a-}W_{mat}) \left[1 - \frac{1}{1 + e^{-(\frac{a-\mu_s}{\sigma_s})}} \right]$$

where, W_{mat} is the weight at first maturity computed from equation 5 and the assumed length at first maturity (L_{mat}), and μ_s and σ_s are the mean and standard deviation of a logistic function that predicts reduced spawning frequency at increasing age. Note that $W_a - W_{mat} = 0$ if $W_{mat} > W_a$. The component of equation

6 between the square braces can be set to one at all ages to simulate the hypothesis that senescence does not occur. Total relative egg deposition in year t is computed from

(7) $$E_t = \sum_a Fec_a N_{a,t}$$

Stock-recruitment parameters (α and β) are calculated from the Goodyear compensation ratio (k) and leading parameters adult survival rate (S) and the population size at carrying capacity (No). The total number of fish older than the age of recruitment (a = 1) is simply the surviving number from the year before and new recruitment,

(8) $$N_{t+1} = N_t S + R$$

where, R is the number of new recruits. At equilibrium, $N_{t+1} = N_t$ = No, thus, the recruitment required to balance the population, Ro, is equivalent to No(1-S). Because we are simulating lognormal error (σ_r>0), Ro must be adjusted by a lognormal correction factor, Ro = Ro*exp(-0.5σ_r^2), so that the average of the simulated recruitments approximate the mean recruitment from the balance model. Relative egg deposition at equilibrium (Eo) is calculated from equation 7 using number of fish alive at each age at equilibrium (N_a) and the fecundity schedule determined from equations 4-6. Goodyear's compensation ratio represents the relative increase in the slope of the spawner-recruit relationship relative to replacement. As the replacement slope is simply the ratio of recruitment and egg deposition (Ro/Eo) at equilibrium, α = kRo/Eo. Replacing the terms R, E, and α in equation 3 with Ro, Eo and kRo/Eo leads to β = (k-1)/Eo.

Use of Goodyear's compensation ratio eliminates the need to include age-independent scaling factors (e.g., eggs/kg, % females, etc.) in the computation of reproductive potential as equilibrium egg deposition (Eo) is always in the denominator of stock-recruitment parameter calculations. Parameters that influence age-specific differences in relative reproductive potential matter whereas those that determine the scale or units of reproductive potential do not. More importantly, as there are no direct estimates of the initial slope of the stock recruitment curve, which largely determines the rate of recovery, for any of the four SARA-listed white sturgeon stocks, we can use published estimates of Goodyear's compensation ratio from other sturgeon stocks (such as those from meta-analysis, e.g., Myers et al. 1999) to parameterize the stock-recruitment model. Note that as α and β are calculated based in part on No, the recruitment multiplier Hab_t determines the change in recruitment relative to what is required to balance the population when it is at carrying capacity. A value of Hab_t=0 implies no natural recruitment and a value of Hab_t=1 will result in a population size of No.

Table 2. Summary of parameters defining recovery scenarios. UF denotes the Upper Fraser (UF) population while 'Other' refers to Nechako, Kootenay, and Columbia populations.

Parameter	**Definition**	**Value**
$N_{t=0}$	Population size for initialization year	Upper Fraser = 1200 Nechako = 318 Columbia = 946 Kootenay = 460
Hab_t	Recruitment rate relative to equilibrium value	UF: Hab_{tpre}=1, Hab_{tpost}=1 (default), 2 Other: Hab_{tpre}=0, Hab_{tpost} = 0 (default), 0.25, 0.5, 1.0 t_{pre}/t_{post}=2/5, 5/10, 10/15
$Hatch_t$	Age-1 hatchery recruits	0 (default), 3000, 15000 t=1-20 (short), 1-100 (long)
HM	Scalar for human-induced mortality	0 (default), 1=status quo (2006), 2=twice status quo

One important component of recovery objectives specified in the recovery strategy (NRTWS 2006) is the number of mature fish, calculated here as the sum of fish age 25 or older (M_t). The number of mature fish, while conceptually simple, is a coarse indicator of the reproductive potential of a population. A population which is dominated by fish just old enough to have reached maturity will have a much lower reproductive potential than a population which contains a higher proportion of older more fecund fish. Alternatively, if there is considerable senescence at older ages, a younger population may have much greater reproductive potential. To account for these dynamics we also track the reproductive potential of the population measured as potential annual egg deposition E_T. Recovery objective 1 (NRTWS 2006) requires that reproductive potential is maintained, implying that $M_T \geq M_1$ or $E_T \geq E_1$. We compute the probabilities that these outcomes occur [$P(M_T \geq M_1)$ and $P(E_T \geq E_1)$] by determining the proportion of the 500 Monte Carlo trials where $M_T \geq M_1$ and $E_T \geq E_1$, respectively. Recovery objective 2a (NRTWS 2006) requires that M_t exceed a target threshold of 1000 (M_{targ}) by recovery year T = 50. (We also evaluate a more plausible alternative time frame with T = 100.) The recovery probability $P(M_T \geq M_{targ})$ is again estimated as the proportion of trials where $M_T \geq M_{targ}$.

Populations that have not recruited for extended periods of time will experience a severe bottleneck in the number of mature fish pending the maturation of recruits produced by habitat restoration or hatchery supplementation. To track this issue we compute the minimum number of spawners over the course of the simulation (M_{min}). The relative growth rate of the population to recovery year T (r_T) is computed as $(M_T - M_{t=1})/M_{t=1}$. Recovery objective 2e (NRTWS 2006) requires continuing population growth, implying that $r_T > 0$; again we estimate the probability that this objective is achieved [$P(r_T > 0)$] by determining the proportion of trials where $r_T > 0$.

For hatchery scenarios, we compute the proportion of mature fish in recovery year T that are “wild”, meaning they emerged from natural spawning (pW_T). A natural age structure has been specified as a goal for white sturgeon recovery. We compute an index of deviations from equilibrium age structure (assumed to be natural) by computing a χ^2-like statistic that is the sum of differences between observed and expected proportion-at-age across all ages for each year of the simulation (ASD). The observed proportions-at-age are the simulated values, while the expected ones are those from a population at equilibrium given the assumed survival rate. An index value of ASD < 0.2 indicates a nearly natural (equilibrium) age structure. We estimate the probabilities that $pW_T > 0.5$ and $ASD_T < 0.2$ by determining the proportion of trials where these outcomes occur.

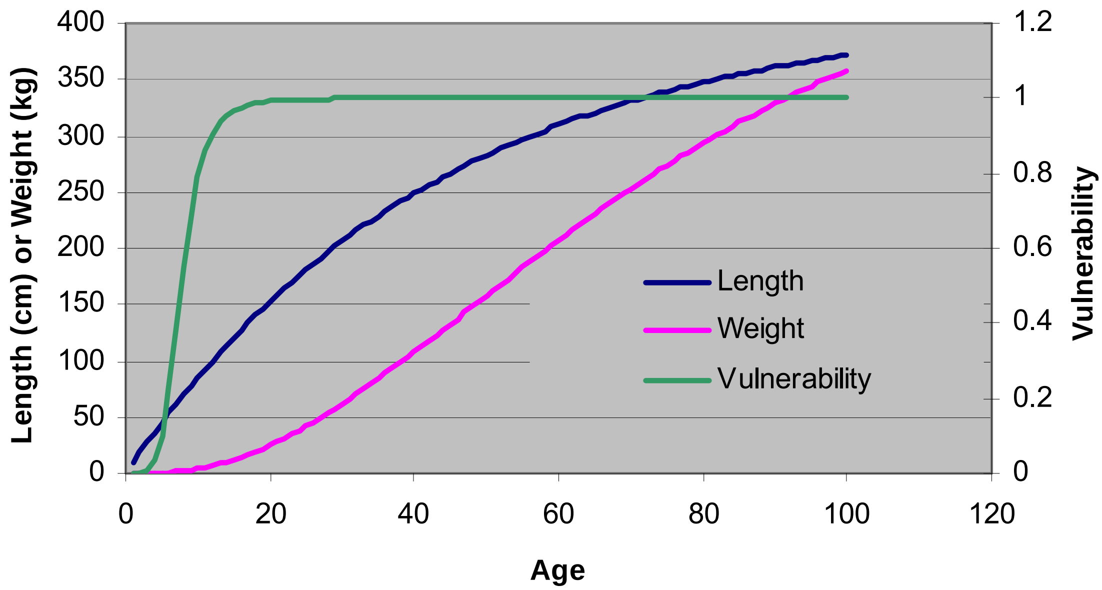
We also report the expected value for each performance measure, estimated as the mean over the 500 simulation trials under each scenario. This sample size was sufficient to reduce the coefficient of variation (CV) across trials for cumulative average performance statistics (i.e. Monte Carlo variance) to <1%.

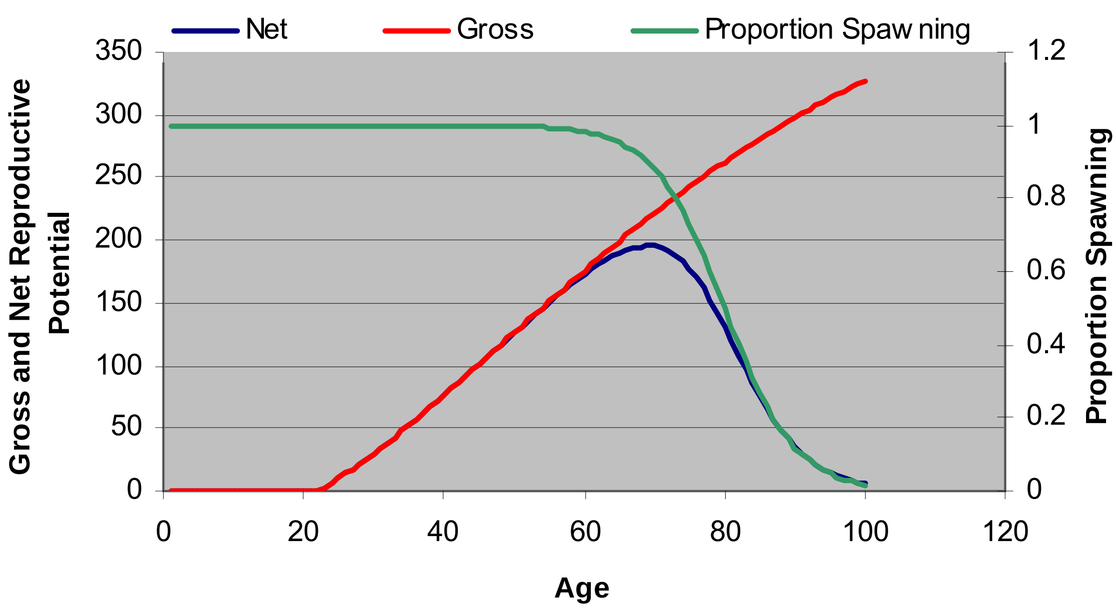
2.2 Parameterization, Initialization, and Scenarios

Parameter values for survival rate (S), recruitment dynamics (k and σ_r), growth (K, L_∞), vulnerability to human-induced mortality (μ_v and τ_v), and maturation statistics (W_{100} and L_{mat}) used in the simulations are identical to those used from Walters et al. 2006 (Table 1). There is little information on senescence so we assumed that $\mu_s = 80$ and $\sigma_s = 5$ for simulations where the senescence function was used (Fig. 1).

Proportions at age - The model was applied to the four populations listed in the white sturgeon recovery strategy: Upper Fraser, Nechako, Kootenay, and Columbia. The model was initialized by specifying a total population size ($N_{t=0}$) and proportions-at-age ($p_{a,t=0}$) for 2006, one year before the first year of the simulation (2007). Initial population estimates (Table 2) were set to values that predicted the current number of mature fish and fish > 50 cm as specified in Table 1 in the white sturgeon recovery strategy (NRTWS 2006). All available ageing data were used to determine the proportions-at-age for the initializing year of the simulation. Sample sizes for ageing data for Upper Fraser, Nechako Kootenay, and Columbia populations were 48, 170, 599, and 476 fish, respectively. Ages of fish in samples were increased by the difference between

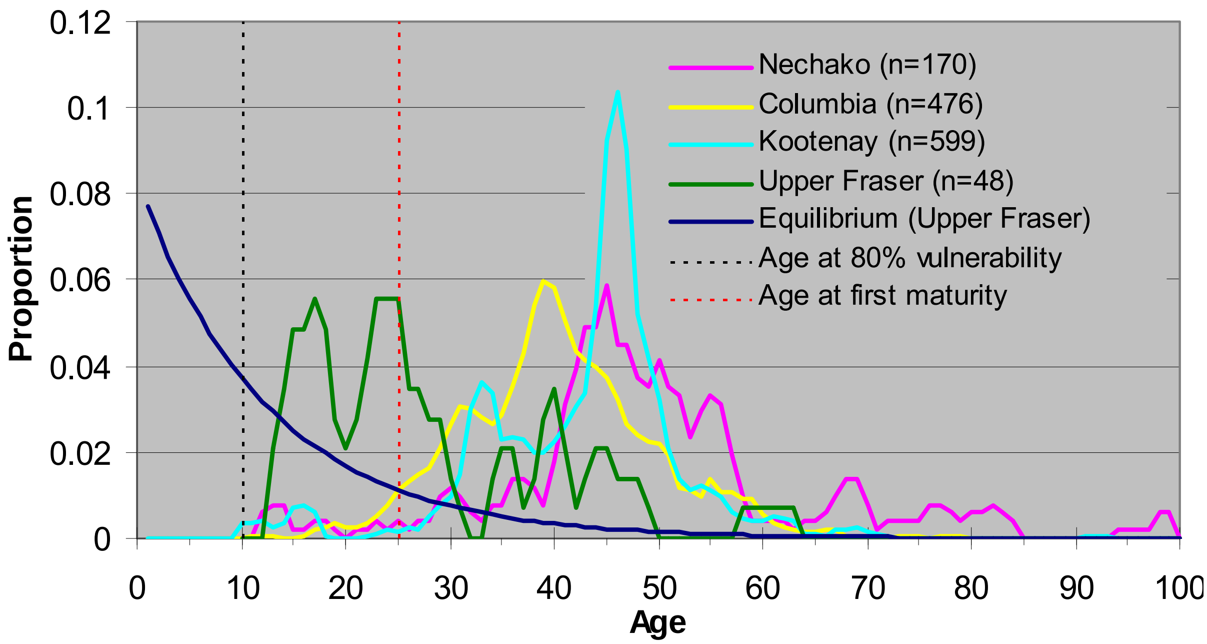
Figure 1. Length, weight, and vulnerability to human-induced mortality (top) and maturation age-schedules (bottom). The net reproductive schedule is equivalent to the gross one when senescence is not simulated. That is, reproductive potential increases steadily with age.





the year the sample was taken and 2006. As fish younger than 10 years of age are less vulnerable to hook-and-line and set-line fishing (the exclusive or very predominant gear type used to collect age samples), we would expect a reduced proportion of fish less than this age in the population samples. However, the almost complete absence of fish less than 30 years of age for all populations except the Upper Fraser, strongly suggests that there has been virtually no recruitment for at least 20 years, and vulnerability effects are very likely negligible for these cases (Fig. 2). We therefore used the age proportions in the samples to initialize the age structures for Nechako, Kootenay, and Columbia populations, and assumed that the age proportion is actually zero for ages 1 to 10. In contrast, the age structure for the Upper Fraser population shows evidence of recent recruitment and the youngest fish in the sample is very close to the age where fish first become vulnerable to hook-and-line fishing. We therefore used the equilibrium age proportions, determined solely by the annual survival rate (S), to initialize the age structure for the Upper Fraser population. This approach provided a reasonable fit to the proportions-at-age from the data (Fig. 2).

Figure 2. Proportions-at-age used to initialize simulations for Upper Fraser, Nechako, Kootenay, and Columbia populations calculated based on 3-yr moving averages. Sample sizes of age data for each population are shown in parentheses. In the case of the Upper Fraser population, the equilibrium age structure is used instead of the structure from the data to account for vulnerability effects.



Equilibrium population size (No) - The population size at equilibrium or carrying capacity is an important leading parameter in the model, and two alternative approaches were used to estimate this value for recovery simulations. In the case of the Upper Fraser population, after accounting for fish too small to capture, existing age data suggests normal recruitment and a relatively balanced population. Thus, it seems reasonable to assume the population is at equilibrium, and to use the current population size as an estimate of No. In the case of Nechako, Columbia, and Kootenay populations that have not recruited for decades, No was estimated using the following backcalculation procedure:

1. Given the current population estimate in 2006 (Table 2) and age structure (Fig. 2), compute the current population of sturgeon that hatched in years prior to recruitment failure (Ňprf).
2. Generate an equilibrium age-structured population using the assumed survival rate and a trial estimate of Ro, and then compute the number of sturgeon that hatched in years before recruitment failure (Nprf).
3. Use an iterative search routine to find the value of Ro that minimizes the difference between the estimated and predicted values from steps (1) and (2) (i.e., Ňprf – Nprf).

Equilibrium population sizes (No) for Nechako, Kootenay, and Columbia populations estimated by backcalculation were approximately 6448, 6054 fish, and 11250, respectively (Table 3). These estimates were based on the assumption that the last years with equilibrium levels of recruitment were 1965 for the Nechako population, and 1970 for Columbia and Kootenay populations. These years were determined by examination of the age composition data (Fig. 2) and professional judgment on the effects of the history of habitat change in each system on natural recruitment levels.

Table 3. Backcalculated estimates of equilibrium population size. The estimates in the first 5 rows were computed using S=0.923. The fourth row is based on a different assumption about what cohorts to include in the computation (1960 for Kootenay) and the last row is based on a higher survival rate (S= 0.95 for Columbia).

Population	**Total abundance in 2006**	**Mature abundance in 2006**	**Annual survival rate (S)**	**Year of last equilibrium recruitment**	**Equilibrium abundance (No)**
U. Fraser	1200	175	0.923	N/A	1200
Nechako	318	304	0.923	1965	6448
Kootenay	460	441	0.923	1970	6054
Kootenay	460		0.923	1960	7657
Columbia	946	915	0.923	1970	11250
Columbia	946		0.950	1970	4230

The number of mature fish (M_t) present in a population is a function of the total number, the maturity schedule, and survival rate. The survival rate estimate used in our analysis (S=0.923) requires a total population size of 8200 fish to meet the maturity target of 1000 fish set out in the recovery strategy. This is surprisingly close to that estimated by backcalculation given the large uncertainty in the estimation procedure. Therefore, for simplicity, we set No=8200 for all 3 populations implying that the recovery objective is simply to achieve the equilibrium population size. We also explored a limited set of scenarios based on the backcalculated estimates of No.

Scenarios - Model scenarios include specification of time series of improved rates of natural recruitment (referred to as “habitat restoration” and specified by the variable Hab_t), hatchery supplementation (specified by $Hatch_t$), and incidental human-induced mortality (specified by HM) (Table 2). To simulate the effects of habitat restoration, natural recruitment rates were adjusted over time from pre- to post-restoration periods ($t = 1\text{-}t_{pre}$, and $t = t_{post}\text{-}100$, respectively) increasing linearly over the pre-to-post time interval ($t > t_{pre}$ and $t < t_{post}$). We assumed that $Hab_{1\text{-}tpre} = 1$ for the Upper Fraser population, while $Hab_{1\text{-}tpre} = 0$ for non-recruiting Nechako, Kootenay, and Columbia populations. That is, prior to any supplementation, recruitment rates are equivalent to those at carrying capacity for the Upper Fraser population, and are 0 for the other populations. Because the estimated equilibrium population size for the Upper Fraser population is much less than 8200, $Hab_{tpost-100}$ must be well above 1 for the Upper Fraser population to achieve recovery objectives. Similarly, by assuming No = 8200 in each of the other three (non-recruiting) populations, Hab_{tpost}=1 is sufficient to eventually meet the objective M_t = 1000 (with no incidental mortality). To achieve M_t = 1000 using the actual backcalculated values for No, Hab_{tpost} would have to be slightly larger than 1 for the Nechako and Kootenay populations, and slightly less than 1 for the Columbia population. We explored scenarios of Hab_{tpost} of 1 and 2 for the Upper Fraser population and 0.25, 0.5, and 1 for the non-recruiting populations. We simulated scenarios of recruitment restoration beginning in 5 years (t_{pre} = 5) and achieving target levels 5 years after initiation (t_{post} = 0). Other time frames could be simulated easily.

We explored the effects of immediate hatchery supplementation by simulating low ($Hatch_t$ = 3000 age-1 fish), and high ($Hatch_t$ = 15000) levels of annual stocking for a short duration (t=1 to 20 years) or over the entire simulation (t=1 to 100 years). At equilibrium (with No = 8200), an annual natural recruitment of 630 age-1 fish would maintain 1000 mature fish in the Nechako, Kootenay, and Columbia populations. Accounting for the reduced survival rate of hatchery fish in their first year (S_H = 0.2), annual stocking of 3000 age-1 fish is required in the absence of any natural recruitment to maintain the same population size. Most of these scenarios involved immediate use of supplementation to boost age-1 recruitment until natural recruitment can be improved by habitat restoration.

Several additional scenarios were designed to assess the implications of different levels and types of incidental mortality under conditions of habitat restoration and hatchery supplementation that otherwise favoured recovery. In each case, separate vulnerability parameters were used to simulate incidental mortality for small (ages 2 to 10) and large (age > 10) size classes. For fish < age 2, human-induced mortality was considered to be primarily indirect, through impacts on habitat or water quality, and thus, best incorporated implicitly within the recruitment scaling parameter (Hab_t); no direct incidental mortality was applied. "Status quo" rates of incidental mortality were estimated (in consultation with the NRTWS) for sockeye gillnet fisheries in the Nechako River, hook and line sampling for broodstock and research in the Kootenay population, hook and line sport fishing for walleye and dam passage in the Columbia population (Table 4). Incidental mortality was increased or decreased by scaling the size-class specific status quo estimates with a scalar multiplier.

Table 4. Estimates of "status quo" rates of incidental mortality by size class and population.

Population	size group	threat	number at risk (2006)	annual rates		probabilities		
				encounter	death	encounter	death|encounter	death
U. Fraser	small	bait fishing	569	0.0016		0.0016	0.04	0.0001
	large	gillnet	539	2	0.1	0.0037	0.05	0.0002
Nechako	small	bait fishing	0	0.0008		0.0008	0.04	0.0000
	large	gillnet	318	5	1	0.0157	0.2	0.0031
Kootenay	small	dam +research	?	?	0	?	0	0
	large	dam +research	461	?	0.5	?	?	0.0011
Columbia	small	bait fishing	30395	500	20	0.0165	0.04	0.0007
	large	bait fishing	941	150	0.3	0.1594	0.002	0.0003
Columbia	small	dam passage	30395	0	0	?	0	0
	large	dam passage	941	?	0.5	?	?	0.0005
Columbia	small	all	30395	?	?	n/a	n/a	0.0007
	large	all	941	?	?	n/a	n/a	0.0009

Table 5. Description of recovery scenarios
a) Scenarios involving neutral or positive interventions (no incidental mortality)

			Natural Recruitment			Hatchery Releases		
Scenario	**Population**	**No**	**Hab_t**	**t_{pre}**	**t_{post}**	**$Hatch_t$**	**t_{start}**	**t_{end}**
A	No human intervention (natural scenario)							
1	Upper Fraser	1200	current (1)	n/a	n/a	0	n/a	n/a
2	Nechako	8200	current (0)	n/a	n/a	0	n/a	n/a
3	Kootenay	8200	current (0)	n/a	n/a	0	n/a	n/a
4	Columbia	8200	current (0)	n/a	n/a	0	n/a	n/a
B	Habitat restoration only							
1	Upper Fraser	1200	2.00	5	10	0	n/a	n/a
2	Nechako	8200	0.25	5	10	0	n/a	n/a
3	Nechako	8200	0.50	5	10	0	n/a	n/a
4	Nechako	8200	1.00	5	10	0	n/a	n/a
5	Kootenay	8200	0.25	5	10	0	n/a	n/a
6	Kootenay	8200	0.50	5	10	0	n/a	n/a
7	Kootenay	8200	1.00	5	10	0	n/a	n/a
8	Columbia	8200	0.25	5	10	0	n/a	n/a
9	Columbia	8200	0.50	5	10	0	n/a	n/a
10	Columbia	8200	1.00	5	10	0	n/a	n/a
C	Hatchery supplementation only							
1	Upper Fraser	1200	current (1)	n/a	n/a	3000	1	100
2	Upper Fraser	1200	current (1)	n/a	n/a	15000	1	20
3	Nechako	8200	current (0)	n/a	n/a	3000	1	20
4	Nechako	8200	current (0)	n/a	n/a	15000	1	100
5	Nechako	8200	current (0)	n/a	n/a	15000	1	20
6	Kootenay	8200	current (0)	n/a	n/a	3000	1	20
7	Kootenay	8200	current (0)	n/a	n/a	15000	1	20
8	Columbia	8200	current (0)	n/a	n/a	3000	1	100
9	Columbia	8200	current (0)	n/a	n/a	15000	1	20

Table 5a. (Cont'd)

Scenario	Population	No	Natural Recruitment Hab$_t$	t_{pre}	t_{post}	Hatchery Releases Hatch$_t$	t_{start}	t_{end}
D	Habitat restoration plus hatchery supplementation							
1	Upper Fraser	1200	current (1)	n/a	n/a	3000	1	20
2	Upper Fraser	1200	current (1)	n/a	n/a	15000	1	100
3	Nechako	8200	0.50	5	10	3000	1	20
4	Nechako	8200	0.50	5	10	15000	1	20
5	Kootenay	8200	0.50	5	10	3000	1	20
6	Kootenay	8200	0.50	5	10	15000	1	20
7	Columbia	8200	0.50	5	10	3000	1	20
8	Columbia	8200	0.50	5	10	15000	1	20

Table 5b. Scenarios involving trade-offs with human-induced incidental mortality.

					Natural Recruitment			Hatchery Releases		
Scenario	**Population**	**No**	**Mortality Type**	**HM**	**Hab_t**	**t_{pre}**	**t_{post}**	**$Hatch_t$**	**t_{start}**	**t_{end}**
1	Upper Fraser	1200	gillnet	0.5	current	n/a	n/a	0	n/a	n/a
2	Upper Fraser	1200	gillnet	1	current	n/a	n/a	0	n/a	n/a
3	Upper Fraser	1200	gillnet	1.5	current	n/a	n/a	0	n/a	n/a
4	Upper Fraser	1200	gillnet	2	current	n/a	n/a	0	n/a	n/a
5	Upper Fraser	1200	gillnet	1	current	n/a	n/a	3000	1	20
6	Upper Fraser	1200	gillnet	1	current	n/a	n/a	15000	1	20
7	Upper Fraser	1200	gillnet	1	current	n/a	n/a	3000	1	100
8	Upper Fraser	1200	gillnet	1	current	n/a	n/a	15000	1	100
9	Upper Fraser	1200	gillnet	2	current	n/a	n/a	15000	1	100
10	Upper Fraser	1200	gillnet	2	current	n/a	n/a	15000	1	100
11	Nechako	8200	gillnet	1	current	n/a	n/a	5000	1	20
12	Nechako	8200	gillnet	1	0.5	5	10	3000	1	20
13	Nechako	8200	gillnet	1	0.5	5	10	15000	1	20
14	Nechako	8200	gillnet	1	0.5	5	10	3000	1	100
15	Nechako	8200	gillnet	2	1	5	10	3000	1	20
16	Nechako	8200	gillnet	2	1	5	10	15000	1	20
17	Nechako	8200	gillnet	2	1	5	10	3000	1	100
18	Kootenay	8200	dam + research	1	current	n/a	n/a	15000	1	20
19	Kootenay	8200	dam + research	1	0.5	5	10	3000	1	20
20	Kootenay	8200	dam + research	1	0.5	5	10	15000	1	20
21	Kootenay	8200	dam + research	1	0.5	5	10	3000	1	100
22	Kootenay	8200	dam + research	2	1	5	10	3000	1	20
23	Kootenay	8200	dam + research	2	1	5	10	15000	1	20
24	Kootenay	8200	dam + research	2	1	5	10	3000	1	100
25	Columbia	8200	dam + sport	1	current	n/a	n/a	15000	1	20
26	Columbia	8200	dam + sport	1	0.5	5	10	3000	1	20
27	Columbia	8200	dam + sport	1	0.5	5	10	15000	1	20
28	Columbia	8200	dam + sport	1	0.5	5	10	3000	1	100
29	Columbia	8200	dam + sport	2	1	5	10	3000	1	20
30	Columbia	8200	dam + sport	2	1	5	10	15000	1	20
31	Columbia	8200	dam + sport	2	1	5	10	3000	1	100

Table 5C. Scenarios involving manipulation of specific variables for sensitivity analysis. Unless specified (shaded values), baseline conditions are as in scenarios E4 (Upper Fraser), E15 (Nechako), E22 (Kootenay), and E29 (Columbia) with human-induced mortality at twice estimated status quo level and hatchery supplementation at 3000 age-1 fish annually for the first 20 years.

Scenario			Number		Senescence	Productivity	Natural Recruitment			Hatchery	Environmental Variability	
Set	number	Population	in 2006	No	μ_s and σ_s	k	Hab_t	t_{pre}	t_{post}	survival (S_H)	< age 1 (σ_r)	age 1+ (σ_e)
F	Survival and backcalculated equilibrium population size (No)											
	1	Nechako	318	6448	none	5	1.0	5	10	0.2	0.6	0
	2	Kootenay	460	6566	none	5	1.0	5	10	0.2	0.6	0
	3	Columbia	941	10760	none	5	1.0	5	10	0.2	0.6	0
G	Timing of habitat restoration											
	1	Columbia	941	8200	none	5	1.0	2	7	0.2	0.6	0
	2	Columbia	941	8200	none	5	1.0	10	15	0.2	0.6	0
H	Senescence and productivity (baseline is E26)											
	1	Columbia	941	8200	μ_s=80, σ_s=5	5	0.5	5	10	0.2	0.6	0
	2	Columbia	941	8200	none	10	0.5	5	10	0.2	0.6	0
	3	Columbia	941	8200	none	15	0.5	5	10	0.2	0.6	0
I	Special concerns for Nechako - lower initial abundance, lower productivity, survival of hatchery fish, more variability in survival											
	1	Nechako	273	8200	none	5	1.0	5	10	0.2	0.6	0
	2	Nechako	318	8200	none	2.5	1.0	5	10	0.2	0.6	0
	3	Nechako	318	8200	none	5	1.0	5	10	0.1	0.6	0
	4	Nechako	318	8200	none	5	1.0	5	10	0.3	0.6	0
	5	Nechako	318	8200	none	5	1.0	5	10	0.2	0.9	0
	6	Nechako	318	8200	none	5	1.0	5	10	0.2	0.6	0.4
J	More annual variability in both age-1 recruitment and later survival											
	1	U. Fraser	1200	1200	none	5	1.0	5	10	n/a	0.9	0.4
	2	Nechako	318	8200	none	5	1.0	5	10	0.2	0.9	0.4
	3	Kootenay	460	8200	none	5	1.0	5	10	0.2	0.9	0.4
	4	Columbia	941	8200	none	5	1.0	5	10	0.2	0.9	0.4

3.0 Results and Discussion

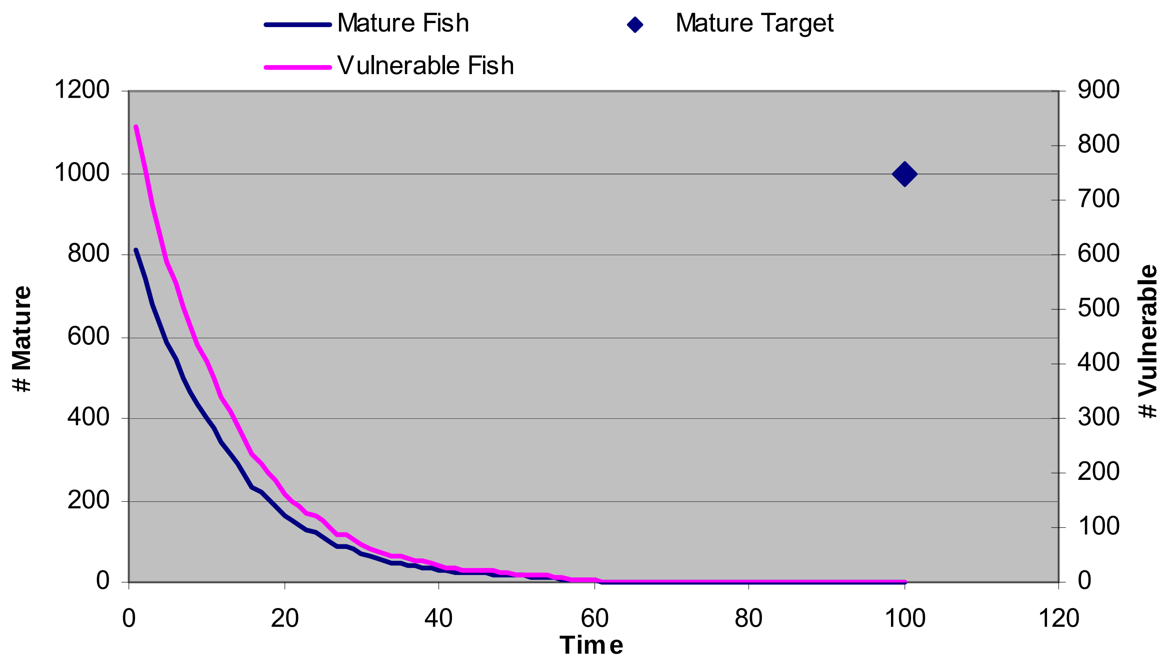
Natural scenarios - In the absence of any restoration of natural recruitment (Hab_t = 0), hatchery supplementation ($Hatch_t$ = 0), or incidental mortality (HM = 0), the simulated Nechako, Kootenay, and Columbia populations declined to <50 mature fish in 22, 30, and 38 years, respectively (Fig. 3). The simulated Upper Fraser population, with Hab_t = 1, maintains itself at equilibrium abundance but never attains the recovery target as there are only 175 mature fish at carrying capacity. All populations require supplementation actions to attain recovery goals and the model predicts that Nechako, Kootenay, and Columbia populations will be extirpated in 70-80 years unless some level of recruitment is restored through habitat or hatchery supplementation (Table 6, scenarios A1-A4). By year 50, all non-recruiting populations have been reduced to <20 mature individuals, and reproductive potential is reduced to a few percent of equilibrium levels.

Backcalculated estimates of equilibrium population size (Table 3) were sensitive to the assumed survival rate and the first year of recruitment failure. For example, the equilibrium size of the Columbia population was 4230 fish based on an assumed survival of 0.95 compared to 11250 based on a survival of 0.923. The No estimate for the Kootenay population increased from 6054 to 7657 when the birth year for the youngest cohort used in the backcalculations was changed from 1970 to 1960. There is considerable uncertainty as to when equilibrium levels of recruitment first declined, so both estimates are about equally plausible. The backcalculated estimates are also inherently uncertain because they involve a large temporal extrapolation given the age of fish used in the calculation. If the survival rate for very old fish was higher than assumed in the backcalculation, the estimates of No would be biased high. Alternatively, the the survival rate of old fish over the last 50 years might have been much lower than under equilibrium conditions because of unknown harvest rates, in which case estimates of No would be biased low. The survival rate we used in the backcalculation is consistent with the majority of data (ages 30-60) for the stocks of concern and others (see review by Paragamian et al. 2005), but is much lower than the rates of 0.95 to 0.97 calculated from growth parameters using the Pauly growth-mortality relationship ($M \cong 1.7K$). We have no formal way of quantifying uncertainty in No, but it seems unlikely that equilibrium population sizes would be more than 50% smaller or larger than the values we have estimated.

Habitat restoration scenarios - Restoring levels of natural recruitment for Nechako, Kootenay, and Columbia populations result in reasonable probabilities (0.39 to 0.70) of achieving M_{targ} by year 100 (Table 6, scenarios B4, B7, B10). The recovery probability is greatest for the Columbia population (B10) because it has the largest initial population size. Doubling the natural recruitment rate for the Upper Fraser population (B1) increases population size but is insufficient to attain M_{targ}. As expected, population response was proportional to the relative rate of natural recruitment (e.g. Hab_t = 0.25, 0.5, and 0.1, B2 to B4, B5 to B7, B8 to B10) and the Hab_{tpost} < 1 scenarios that were evaluated were not sufficient to achieve M_{targ}.

Hatchery supplementation scenarios - The effects of hatchery supplementation assuming that the current recruitment situation continues (Hab_{tpost} = 1 for Upper Fraser and 0 for other populations) are shown in scenarios C1 to C9 (Tables 5a and 6). Long-term supplementation with at least 3000 age-1 hatchery recruits (all scenarios except C5) was sufficient to meet M_{targ} in all cases, whereas stocking with only 1000 fish was not (determined in preliminary simulations not shown). We also simulated one short-term supplementation scenario where 5000 fish were stocked each year but only for the first 20 years (C5, Nechako). The mature population grew initially (r_{50} = 0.59) as hatchery fish were recruited to the mature population, but later declined as these fish eventually died (r_{100} = -0.97). As a result there was no long-term benefit from this approach by itself. The proportion of wild fish under both stocking scenarios is very low for the non-recruiting populations (C3 to C9). Equilibrium age structure (low ASD_T) is restored under

Figure 3. Example trajectories (single trials) of the number of mature and vulnerable (≥ age 10) for the Columbia population (top frame) and Upper Fraser population (bottom frame) in the natural scenario with no further human impacts or interventions to restore natural recruitment or supplement with hatchery fish.



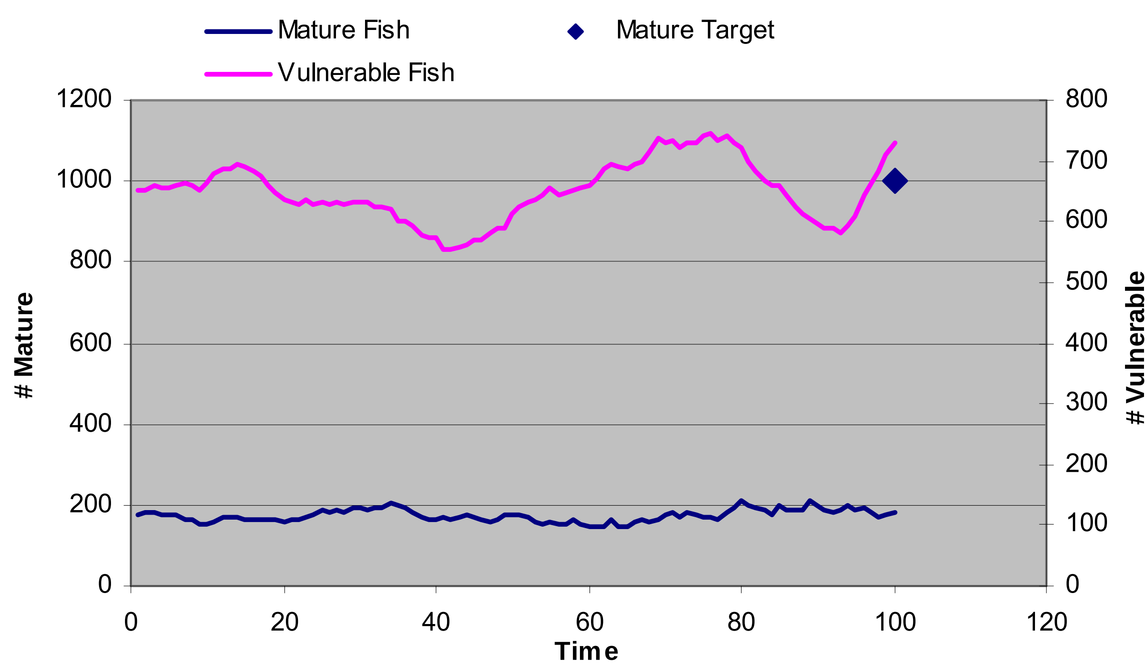


Table 6. Performance measures for simulated scenarios described in Table 4.

a) Performance measures for recovery objectives

Scenario	Population	Objective 1 $P(E_{50}>E_1)$	Objective 1 M_{50}	Objective 1 $P(M_{50}>M_1)$	Objective 2 $P(M_{50}>M_{targ})$	Objective 2 M_{100}	Objective 2 $P(M_{100}>M_{targ})$	Objective 2 r_{50}	Objective 2 $P(r_{50}>0)$
A1	U. Fraser	0.58	180	0.53	0.00	180	0.00	0.04	0.56
A2	Nechako	0.00	4	0.00	0.00	0	0.00	-0.99	0.00
A3	Kootenay	0.00	7	0.00	0.00	0	0.00	-0.98	0.00
A4	Columbia	0.00	15	0.00	0.00	0	0.00	-0.98	0.00
B1	U. Fraser	1.00	321	1.00	0.00	395	0.00	0.85	1.00
B2	Nechako	0.00	141	0.00	0.00	116	0.00	-0.50	0.00
B3	Nechako	0.00	274	0.24	0.00	350	0.00	-0.03	0.36
B4	Nechako	0.00	558	1.00	0.00	969	0.39	0.97	1.00
B5	Kootenay	0.00	165	0.00	0.00	133	0.00	-0.60	0.00
B6	Kootenay	0.00	320	0.02	0.00	382	0.00	-0.21	0.07
B7	Kootenay	0.00	633	0.99	0.00	1016	0.51	0.56	1.00
B8	Columbia	0.00	216	0.00	0.00	162	0.00	-0.75	0.00
B9	Columbia	0.00	416	0.00	0.00	446	0.00	-0.51	0.00
B10	Columbia	0.00	820	0.22	0.07	1081	0.69	-0.03	0.40
C1	U. Fraser	1.00	1260	1.00	1.00	1445	1.00	6.26	1.00
C2	U. Fraser	1.00	5587	1.00	1.00	6374	1.00	31.20	1.00
C3	Nechako	1.00	1082	1.00	0.99	1230	1.00	2.82	1.00
C4	Nechako	1.00	5405	1.00	1.00	6156	1.00	18.09	1.00
C5	Nechako	1.00	3049	1.00	1.00	56	0.00	9.76	1.00
C6	Kootenay	1.00	1089	1.00	1.00	1233	1.00	1.67	1.00
C7	Kootenay	1.00	5409	1.00	1.00	6156	1.00	12.28	1.00
C8	Columbia	0.00	1096	1.00	1.00	1230	1.00	0.29	1.00
C9	Columbia	1.00	5416	1.00	1.00	6159	1.00	5.39	1.00
D1	U. Fraser	1.00	790	1.00	0.00	215	0.00	3.56	1.00
D2	U. Fraser	1.00	3228	1.00	1.00	271	0.00	17.62	1.00
D3	Nechako	1.00	886	1.00	0.03	552	0.00	2.13	1.00
D4	Nechako	1.00	3342	1.00	1.00	712	0.00	10.79	1.00
D5	Kootenay	1.00	937	1.00	0.14	565	0.00	1.30	1.00
D6	Kootenay	1.00	3377	1.00	1.00	723	0.00	7.29	1.00
D7	Columbia	0.00	1031	0.97	0.63	574	0.00	0.22	1.00
D8	Columbia	1.00	3994	1.00	1.00	1427	1.00	3.71	1.00

Table 6a. (Cont'd)

Scenario	Population	Objective 1			Objective 2				
		$P(E_{50}>E_1)$	M_{50}	$P(M_{50}>M_1)$	$P(M_{50}>M_{targ})$	M_{100}	$P(M_{100}>M_{targ})$	r_{50}	$P(r_{50}>0)$
E1	U. Fraser	0.55	179	0.52	0.00	182	0.00	0.03	0.56
E2	U. Fraser	0.57	177	0.52	0.00	181	0.00	0.02	0.56
E3	U. Fraser	0.52	177	0.49	0.00	180	0.00	0.02	0.54
E4	U. Fraser	0.50	176	0.49	0.00	178	0.00	0.02	0.52
E5	U. Fraser	1.00	785	1.00	0.00	215	0.00	3.53	1.00
E6	U. Fraser	1.00	3210	1.00	1.00	267	0.00	17.51	1.00
E7	U. Fraser	1.00	1251	1.00	1.00	1435	1.00	6.21	1.00
E8	U. Fraser	1.00	5552	1.00	1.00	6334	1.00	31.11	1.00
E9	U. Fraser	1.00	5524	1.00	1.00	6292	1.00	30.88	1.00
E10	U. Fraser	1.00	5524	1.00	1.00	6292	1.00	30.88	1.00
E11	Nechako	1.00	937	1.00	0.02	14	0.00	2.31	1.00
E12	Nechako	1.00	818	1.00	0.00	497	0.00	1.89	1.00
E13	Nechako	1.00	3074	1.00	1.00	647	0.00	9.88	1.00
E14	Nechako	1.00	1269	1.00	1.00	1698	1.00	3.49	1.00
E15	Nechako	1.00	972	1.00	0.31	965	0.39	2.45	1.00
E16	Nechako	1.00	3062	1.00	1.00	1173	0.88	9.88	1.00
E17	Nechako	1.00	1407	1.00	1.00	2107	1.00	3.99	1.00
E18	Kootenay	1.00	2964	1.00	1.00	51	0.00	6.30	1.00
E19	Kootenay	1.00	906	1.00	0.05	540	0.00	1.23	1.00
E20	Kootenay	1.00	3280	1.00	1.00	696	0.01	7.07	1.00
E21	Kootenay	1.00	1370	1.00	1.00	1793	1.00	2.37	1.00
E22	Kootenay	1.00	1177	1.00	0.99	1126	0.79	1.90	1.00
E23	Kootenay	1.00	3492	1.00	1.00	1322	1.00	7.59	1.00
E24	Kootenay	0.33	938	1.00	0.25	1466	1.00	1.31	1.00
E25	Columbia	1.00	2969	1.00	1.00	51	0.00	2.50	1.00
E26	Columbia	0.00	997	0.92	0.46	546	0.00	0.18	0.99
E27	Columbia	1.00	3371	1.00	1.00	700	0.00	2.98	1.00
E28	Columbia	0.01	1461	1.00	1.00	1801	1.00	0.72	1.00
E29	Columbia	0.32	1357	1.00	1.00	1142	0.80	0.60	1.00
E30	Columbia	1.00	3659	1.00	1.00	1323	0.99	3.33	1.00
E31	Columbia	0.00	1102	0.96	0.78	1499	1.00	0.30	1.00

Table 6a (Cont'd). Shaded rows are baseline scenarios for sensitivity analyses

Scenario	Population	Objective 1			Objective 2				
		$P(E_{50}>E_1)$	M_{50}	$P(M_{50}>M_1)$	$P(M_{50}>M_{targ})$	M_{100}	$P(M_{100}>M_{targ})$	r_{50}	$P(r_{50}>0)$
E15	Nechako	1.00	972	1.00	0.31	965	0.39	2.45	1.00
F1	Nechako	1.00	923	1.00	0.16	796	0.05	2.28	1.00
E22	Kootenay	1.00	1177	1.00	0.99	1126	0.79	1.90	1.00
F2	Kootenay	1.00	1083	1.00	0.82	868	0.14	1.67	1.00
E29	Columbia	0.32	1357	1.00	1.00	1142	0.80	0.60	1.00
F3	Columbia	0.76	1525	1.00	1.00	1511	1.00	0.80	1.00
E29	Columbia	0.32	1357	1.00	1.00	1142	0.80	0.60	1.00
G1	Columbia	0.67	1407	1.00	1.00	1170	0.84	0.66	1.00
G2	Columbia	0.02	1233	1.00	0.99	1131	0.79	0.46	1.00
E26	Columbia	0.00	997	0.92	0.46	546	0.00	0.18	0.99
H1	Columbia	0.00	960	0.80	0.27	535	0.00	0.13	0.97
H2	Columbia	0.00	997	0.92	0.46	551	0.00	0.18	0.99
H3	Columbia	0.00	1003	0.92	0.47	561	0.00	0.18	0.99
E15	Nechako	1.00	972	1.00	0.31	965	0.39	2.45	1.00
I1	Nechako	1.00	943	1.00	0.22	970	0.37	2.87	1.00
I2	Nechako	1.00	845	1.00	0.01	861	0.14	2.00	1.00
I3	Nechako	0.37	717	1.00	0.07	911	0.31	1.54	1.00
I4	Nechako	0.99	1266	1.00	0.80	1030	0.50	3.50	1.00
I5	Nechako	1.00	1033	1.00	0.54	1048	0.50	2.67	1.00
I6	Nechako	0.90	990	1.00	0.46	956	0.39	2.52	1.00
E4	U. Fraser	0.50	176	0.49	0.00	178	0.00	0.02	0.52
J1	U. Fraser	0.54	186	0.53	0.00	189	0.00	0.08	0.55
E15	Nechako	1.00	972	1.00	0.31	965	0.39	2.45	1.00
J2	Nechako	0.92	1047	1.00	0.52	1025	0.49	2.72	1.00
E22	Kootenay	1.00	1177	1.00	0.99	1126	0.79	1.90	1.00
J3	Kootenay	0.96	1243	1.00	0.77	1203	0.68	2.06	1.00
E29	Columbia	0.32	1357	1.00	1.00	1142	0.80	0.60	1.00
J4	Columbia	0.44	1412	0.94	0.87	1219	0.69	0.67	0.96

Table 6 (Cont'd)

b) Other performance measures

Scenario	Population	Other Performance Measures					
		pW_{50}	$P(W_{50}>0.5)$	ASD_{50}	$P(ASD_{50}<0.2)$	M_{min}	$Yr(M_{min})$
A1	U. Fraser	1.00	1.00	0.5	0.01	139	59
A2	Nechako	0.97	0.97	3850.3	0.00	0	60
A3	Kootenay	1.00	1.00	3131.0	0.00	0	64
A4	Columbia	1.00	1.00	1549.4	0.00	0	69
B1	U. Fraser	1.00	1.00	0.4	0.01	158	19
B2	Nechako	1.00	1.00	0.7	0.00	28	29
B3	Nechako	1.00	1.00	0.5	0.00	28	29
B4	Nechako	1.00	1.00	0.5	0.01	29	29
B5	Kootenay	1.00	1.00	0.8	0.00	44	30
B6	Kootenay	1.00	1.00	0.5	0.00	44	29
B7	Kootenay	1.00	1.00	0.5	0.00	45	29
B8	Columbia	1.00	1.00	0.7	0.00	87	30
B9	Columbia	1.00	1.00	0.5	0.00	90	30
B10	Columbia	1.00	1.00	0.4	0.02	91	29
C1	U. Fraser	0.18	0.00	0.0	1.00	162	13
C2	U. Fraser	0.04	0.00	0.0	1.00	162	13
C3	Nechako	0.02	0.00	0.0	1.00	44	24
C4	Nechako	0.00	0.00	0.0	1.00	44	24
C5	Nechako	0.01	0.00	12.9	0.00	43	31
C6	Kootenay	0.04	0.00	0.0	1.00	67	24
C7	Kootenay	0.01	0.00	0.0	1.00	67	24
C8	Columbia	0.08	0.00	0.0	1.00	137	24
C9	Columbia	0.02	0.00	0.0	1.00	138	24
D1	U. Fraser	0.22	0.00	1.4	0.00	162	17
D2	U. Fraser	0.05	0.00	5.9	0.00	162	13
D3	Nechako	0.24	0.00	0.6	0.00	44	24
D4	Nechako	0.06	0.00	2.3	0.00	43	24
D5	Kootenay	0.28	0.00	0.6	0.00	67	24
D6	Kootenay	0.07	0.00	2.2	0.00	67	24
D7	Columbia	0.34	0.00	0.6	0.00	138	24
D8	Columbia	0.20	0.00	1.0	0.00	137	24

Table 6b. (Cont'd)

Scenario	Population	Other Performance Measures					
		pW_{50}	$P(W_{50}>0.5)$	ASD_{50}	$P(ASD_{50}<0.2)$	M_{min}	$Yr(M_{min})$
E1	U. Fraser	1.00	1.00	0.4	0.00	138	60
E2	U. Fraser	1.00	1.00	0.4	0.00	139	57
E3	U. Fraser	1.00	1.00	0.4	0.01	138	60
E4	U. Fraser	1.00	1.00	0.5	0.00	137	59
E5	U. Fraser	0.22	0.00	1.4	0.00	161	17
E6	U. Fraser	0.05	0.00	6.0	0.00	162	13
E7	U. Fraser	0.18	0.00	0.0	1.00	162	13
E8	U. Fraser	0.04	0.00	0.0	1.00	162	12
E9	U. Fraser	0.04	0.00	0.0	1.00	161	13
E10	U. Fraser	0.04	0.00	0.0	1.00	161	13
E11	Nechako	0.01	0.00	13.1	0.00	14	100
E12	Nechako	0.24	0.00	0.6	0.00	40	24
E13	Nechako	0.06	0.00	2.1	0.00	41	24
E14	Nechako	0.20	0.00	0.1	1.00	40	24
E15	Nechako	0.37	0.00	0.4	0.01	37	24
E16	Nechako	0.11	0.00	0.9	0.00	37	24
E17	Nechako	0.32	0.00	0.1	0.93	38	24
E18	Kootenay	0.01	0.00	12.9	0.00	50	94
E19	Kootenay	0.27	0.00	0.6	0.00	66	24
E20	Kootenay	0.07	0.00	2.2	0.00	66	24
E21	Kootenay	0.23	0.00	0.1	0.99	65	24
E22	Kootenay	0.41	0.01	0.4	0.00	64	24
E23	Kootenay	0.12	0.00	1.0	0.00	64	24
E24	Kootenay	0.62	1.00	0.2	0.50	64	24
E25	Columbia	0.02	0.00	12.8	0.00	51	100
E26	Columbia	0.34	0.00	0.6	0.00	135	24
E27	Columbia	0.09	0.00	2.2	0.00	135	24
E28	Columbia	0.29	0.00	0.1	1.00	134	24
E29	Columbia	0.48	0.27	0.4	0.00	132	24
E30	Columbia	0.16	0.00	1.0	0.00	131	24
E31	Columbia	0.68	1.00	0.2	0.47	133	24

Table 6b (Cont'd). Shaded rows are baseline scenarios for sensitivity analyses

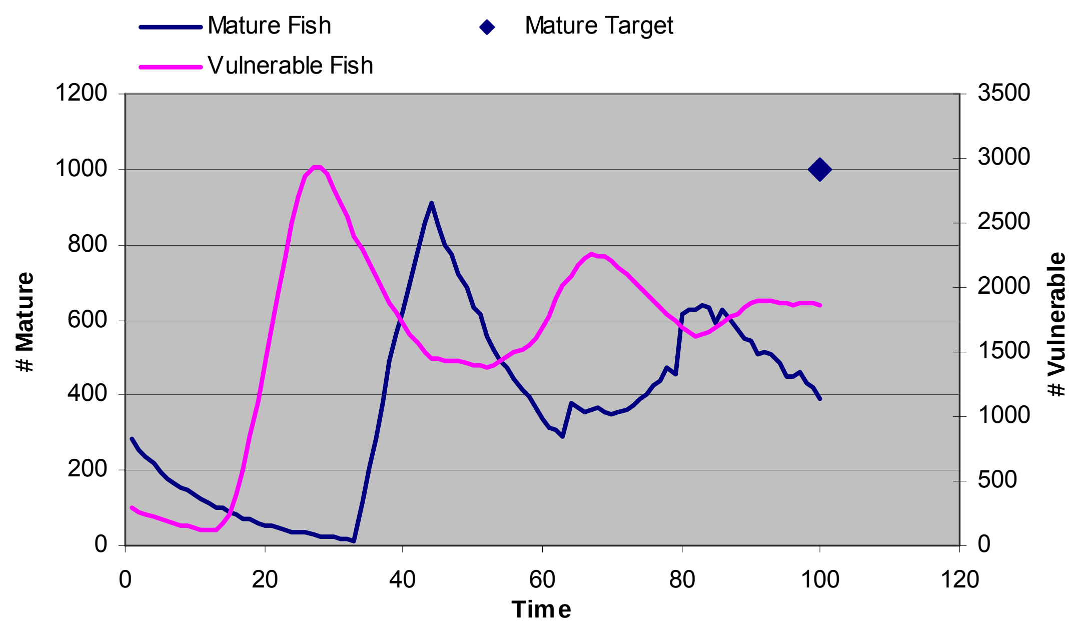
Scenario	Population	Other Performance Measures					
		pW_{50}	$P(W_{50}>0.5)$	ASD_{50}	$P(ASD_{50}<0.2)$	M_{min}	$Yr(M_{min})$
E15	Nechako	0.37	0.00	0.4	0.01	37	24
F1	Nechako	0.34	0.00	0.4	0.00	38	24
E22	Kootenay	0.41	0.01	0.4	0.00	64	24
F2	Kootenay	0.37	0.00	0.4	0.00	65	24
E29	Columbia	0.48	0.27	0.4	0.00	132	24
F3	Columbia	0.53	0.77	0.4	0.02	133	24
E29	Columbia	0.48	0.27	0.4	0.00	132	24
G1	Columbia	0.51	0.65	0.4	0.01	133	24
G2	Columbia	0.40	0.01	0.4	0.01	132	24
E26	Columbia	0.34	0.00	0.6	0.00	135	24
H1	Columbia	0.30	0.00	0.6	0.00	132	24
H2	Columbia	0.35	0.00	0.5	0.00	132	24
H3	Columbia	0.35	0.00	0.5	0.00	132	24
E15	Nechako	0.37	0.00	0.4	0.01	37	24
I1	Nechako	0.36	0.00	0.4	0.01	32	24
I2	Nechako	0.31	0.00	0.5	0.00	38	24
I3	Nechako	0.54	0.82	0.4	0.02	38	24
I4	Nechako	0.28	0.00	0.5	0.00	37	24
I5	Nechako	0.39	0.04	1.0	0.00	38	24
I6	Nechako	0.37	0.00	0.4	0.01	38	24
E4	U. Fraser	1.00	1.00	0.5	0.00	137	59
J1	U. Fraser	1.00	1.00	1.1	0.00	114	59
E15	Nechako	0.37	0.00	0.4	0.01	37	24
J2	Nechako	0.40	0.04	0.9	0.00	38	24
E22	Kootenay	0.41	0.01	0.4	0.00	64	24
J3	Kootenay	0.42	0.09	1.0	0.00	64	24
E29	Columbia	0.48	0.27	0.4	0.00	132	24
J4	Columbia	0.48	0.38	0.9	0.00	133	24

both hatchery scenarios; in fact, age structure for the Upper Fraser population under stocking (C1 and C2) becomes more "natural" than without stocking (A1) because interannual variation in recruitment rates increases the ASD index.

Restoration plus supplementation scenarios - A single simulation trial for the Nechako population illustrates typical trends in scenarios when hatchery supplementation is used as an interim measure (years 10 to 20) while natural recruitment is progressively restored (years 10 to 15) (Fig. 4). Initially, the population declines in the absence of intervention as there is no natural recruitment. Stocking of 3,000 age-1 fish results in a rapid increase from year 15 to 30 in the number of "vulnerable" fish (age ≥ 10 whose abundance can be estimated by research sampling gear). The response of mature fish to stocking is more protracted because of the 24-yr interval between stocking at age-1 and maturity at age 25. In this scenario, one half the natural rate of wild recruitment is achieved by year 20 through habitat restoration. The recruitment rate is much less than that achieved by stocking 3000 age-1 fish annually. However, natural recruitment is still sufficient to increase the population from about 300 mature fish at the start of the simulation to 400 to 600 fish in the last 20 years. The proportion of wild mature fish drops to as low as 0.2 and then gradually increases as the hatchery fish age and die off.

Results from scenarios that combine habitat restoration and hatchery supplementation are summarized in scenarios D1 to D8 (Tables 5a and 6). Increasing recruitment to 50% of natural levels for non-recruiting populations (D3 to D8) and short-term (20 year) stocking with 3000 age-1 hatchery fish was sufficient to meet most but not all recovery objectives; M_{targ} was achieved in 50 years (with 63% probability) only in the Columbia population. A higher level of short-term hatchery supplementation (15000 per year for 20 years) was sufficient to attain M_{targ} in year 50 in all populations, but as before, mature abundance was not sustained above target levels to year 100. It is also noteworthy that with

Figure 4. Example trajectories for the Nechako population (single trial) of mature and vulnerable fish (top), and recruitment dynamics (bottom). The diamond in the top graph shows the recovery target (at 50 or 100 years). The bottom graph shows a recovery scenario where there is no incidental mortality, habitat restoration begins in year 10 and results in 0.5 of the natural recruitment rate by year 15, and hatchery stocking supplements natural recruitment with 3000 age-1 fish from each year 10 to 20.



short-term stocking of only 3000 fish per year in the Columbia population, potential egg deposition actually declines by year 50 despite a high probability of achieving M_{targ}; this is explained by the fact that the relatively large current population is dominated by old, large fish with high fecundity.

Incidental mortality scenarios - Because the Upper Fraser population is near equilibrium and self-sustaining, the (very low) estimated status quo level of human-induced mortality (Table 4) has little effect on population viability. Comparison of results for the natural scenario (A1) with those for the status quo scenario (E2) indicates that if human mortality were eliminated, then by year 50, the average abundance of mature fish would increase only slightly from 177 to 180 (still far below M_{targ}), and the average rate of population growth would increase only slightly from 0.02 to 0.04. Doubling status quo mortality over the same period would decrease the average abundance of mature fish very slightly from 178 to 177, but would not change average population growth rate (because of the compensation ratio used). Long-term hatchery stocking of 3000 age-1 fish per year would be sufficient to meet all recovery targets (except wildness) even at twice the estimated status quo mortality; however, the proportion wild would decline to 5% or less. Short-term stocking of 15000 fish for 20 years with status quo mortality would achieve M_{targ} in year 50, but the average abundance of mature fish would decline to 267 by year 100.

Preliminary simulations revealed that even modest levels of human-induced mortality could eliminate any chance of recovery for the Nechako, Kootenay, and Columbia populations. Fortunately estimates of status quo mortality appear to be sufficiently low that recovery of wild populations should be feasible with a judicious and timely combination of habitat restoration and hatchery supplementation. In simulations with estimated status quo mortality and current stocking rates (continued for 20 years) *but without recruitment restoration* (scenarios E11, E18 and E25), the abundance of mature fish exceeded target levels in year 50, but by year 100, had declined to low levels (14, 51, and 51 for

Nechako, Kootenay, and Columbia, respectively). Moreover, the proportion wild in year 50 did not exceed 5%. Outcomes were improved with less aggressive short-term stocking (3000 per year for 20 years) coupled with 50% restoration of natural recruitment and status quo mortality (scenarios E12, E19, and E26). In these scenarios, the proportion wild in year 50 ranged from 24 to 34% across populations, and the abundance of mature fish almost reached the target in year 50 (range 818 to 997 across populations), then declined (although less severely than before) by year 100 (range 497 to 546 across populations). Longer-term stocking of 3000 fish per year under the same conditions (scenarios E14, E21, and E28) achieved the target in both year 50 and year 100, but the proportion remaining wild in year 50 declined slightly (range 20 to 29%). Outcomes were improved significantly only with full restoration of natural recruitment and modest short-term stocking (3000 fish per year for 20 years); under these conditions, even with twice the estimated status quo level of human-induced mortality (scenarios E15, E22, and E29), all recovery objectives could be achieved, and the proportions wild in year 50 ranged from 37 to 48%.

Sensitivity analyses – To determine whether our conclusions from the preceding simulations were particularly sensitive to uncertainty in any of the assumed parameter values, we systematically manipulated parameters one at a time in scenario suites F through J (Table 5c). Unless noted otherwise (e.g., suite H), the baseline conditions are identical to those in scenarios E4 (Upper Fraser), E15 (Nechako), E22 (Kootenay), and E29 (Columbia) with human-induced mortality at twice estimated status quo level and hatchery supplementation at 3000 age-1 fish annually for the first 20 years.

Equilibrium population value (No) can greatly affect the probability of achieving recovery targets. For example, the probability of achieving M_{targ} by year 100 in the Nechako population decreased from 0.39 to 0.05 (Table 6) using the backcalculated value of No (6448) instead of 8200. In contrast, the probability of

achieving M_{targ} by year 100 in the Columbia population increased from 0.80 to 1.0 using the backcalculated value (11250) instead of 8200.
Survival rate (S) can also affect recovery potential indirectly because the recovery target of 1000 mature fish can be achieved in a smaller population when survival is higher -- only 4500 fish when S = 0.95 compared with 8200 when S = 0.923. Based on only this observation, we might predict that assuming higher survival would increase the odds of achieving the recovery target. However, because the difference between current population size and No (at carrying capacity) is lower under the high survival scenario, density dependent reductions in survival will reduce the rate of population increase relative to the lower S/higher No scenario. Given these conflicting responses, we compared recovery performance for a single population (Columbia) under low S with high No (0.923 and 8200) and high S with low No (0.95 and 4500). The average growth rate of the population was actually reduced in the higher survival scenario, and consequently, the probability of achieving M_{targ} in 100 years declined from 1.00 to 0.72. However, one benefit of higher survival was that the expected minimum population size over the course of the simulation (M_{min}) to be greater (210 versus 92) because of reduced mortality of older fish.

Changes in the timing of restoration of natural recruitment had a minor influence on the abundance of mature fish in 50 or 100 years in scenarios with short-term hatchery supplementation. Initiating restoration of natural recruitment in the Columbia population in year 2 of the simulation (G1) rather than year 5 (E29) increased the probability of achieving M_{targ} by year 100 from 0.80 to 0.84; delaying recovery to year 10 (G2) reduced this probability to 0.79 (Table 6a). However timing of restoration had a greater influence on the proportion of wild fish. The probability that more than half of mature fish in year 50 would be from natural spawning was increased from 27% to 60% by earlier restoration, and decreased to 1% by later restoration (Table 6b).

Senescence, where reproductive potential began to declined after age 75 becoming nil by age 100, had little influence on recovery potential in simulations with the Columbia population (H1). Differences in recovery statistics with and without senescence were no greater than expected due to Monte Carlo sampling error (Table 6). Although older, larger individuals do produce more eggs individually, they are rare in the population because of the cumulative effects of mortality (Fig. 2, equilibrium line). As a result, the net reproductive output for older fish in the simulated population is relatively small even without senescence.

Additional scenarios in suite H were designed to evaluate the consequences of underestimating productivity. Increasing productivity from k = 5 (E26) to k =10 (H2) and k = 15 (H3) slowed the rate of population decline in the Columbia population resulting in slightly higher numbers of mature fish in 50 and 100 years. However, even at the upper limit of compensation, recovery targets were not achieved in the absence of full restoration of natural recruitment or without hatchery supplementation.

Scenarios in suite I were designed to investigate particular concerns raised about the Nechako population which was last assessed to comprise 571 fish in 1999 (Korman and Walters 2001). Our simulations assume a starting population of 318 fish in 2006, derived by applying an annual survival rate of 92.3% to the estimate for 1999 (NRTWS 2006). One concern is that this survival rate may be too high because human-induced mortality in the Nechako River since 1999 might have been significantly higher than it is now (i.e., status quo values in Table 4). If instead, annual survival was only 90% from 1999 to 2006, the starting population would be only 273, which would then reduce the expected number of mature fish in year 50 from 972 (under the baseline scenario E15) to 943 (scenario I1). Similarly, the lower initial abundance would reduce the probability of achieving 1000 mature fish in 50 years from 31% to 22%, and reduce the expected minimum abundance of mature fish over the next 50 years from 37 to 32. Another concern was that productivity might be lower than has been assumed in the Nechako population. Reducing productivity from k= 5 to k = 2.5 reduced the expected number of mature fish in year 50 from 972 (E15) to 845 (I2); reduced the probability of achieving 1000 mature fish in 50 years from 31% to 1%; but did not change the expected minimum number of mature fish (Table 6).

Additional scenarios with the Nechako population were designed to illustrate the consequences of uncertainty in the expected survival of hatchery fish in the first year following release (S_H), and annual environmental variation in rates of survival (σ_e) and age-1 recruitment (σ_r). Reducing S_H from 0.2 (E15) to 0.1 (I3) significantly reduced the probability of achieving both recovery target 1 (from 100% to 37%) and recovery target 2 (from 31% to 7%), but increased the expected proportion of mature fish that were wild in year 50, from 0.37 to 0.54 (Table 6). Increasing S_H to 0.3 (I4) increased the probabilities of achieving recovery targets 1 and 2 to 99% and 100%, respectively, but decreased the proportion wild in year 50 to 28%. Increasing annual variation in the survival of natural fish tended to hasten recovery. The probability of achieving 1000 mature fish in year 50 was increased from 31% to 54% by increasing variability of age-1 recruitment (from 0.6 in E15 to 0.9 in I5), and to a lesser extent, from 31% to 46%, by increasing annual variation in subsequent survival (from 0 in E15 to 0.4 in I6).

The final scenarios (suite J) illustrate the overall effect for each population of increasing annual variation both in age-1 recruitment ($\sigma_r = 0.9$) and in subsequent survival ($\sigma_e = 0.4$). The *expected* abundance of mature fish in year 50 increased for all populations, consistent with the previous simulations for Nechako. However, the *probability* of achieving 1000 mature fish in year 50 declined in the Kootenay population (from 99% in E22 to 77% in J3) and the Columbia population (from 100% in E29 to 87% in J4), reflecting greater variability in outcomes among simulation trials. The probability of achieving 1000 mature fish in year 50 remained negligible in the Upper Fraser population, but increased as before, from 31% to 52% in the Nechako population. These differences among populations likely arise from differences in initial abundance and the dampening effect of density-dependence on net benefits from years of high survival. In sum, these simulations serve to illustrate that recovery remains feasible under the combined scenario of full restoration of natural recruitment and short-term hatchery supplementation, even if environmental variability is higher than has been assumed.

4.0 References

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