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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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