RECLAMATION

Managing Water in the West

Assessment of Sockeye Salmon Production Potential in the Bumping River Basin

Storage Dam Fish Passage Study
Yakima Project, Washington

Technical Series No. PN-YDFP-010

U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Region
Boise, Idaho

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U.S. Department of the Interior

Mission Statement

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian tribes and our commitments to island communities.

U.S. Bureau of Reclamation

Mission Statement

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Introduction

This technical report presents information regarding sockeye salmon production potential in the Bumping River Basin above Bumping Lake Dam. This information is a key component in determining estimates of biological and economic benefits attributable to proposed fish passage features at the dam.

Objectives

The Bureau of Reclamation (Reclamation) is leading a cooperative investigation with the Yakama Nation (YN), state and Federal agencies, and others, to study the feasibility of providing fish passage at the five large storage dams of the Yakima Project. These dams—Bumping Lake, Kachess, Keechelus, Cle Elum, and Tieton—were never equipped with fish passage facilities. Four of the five reservoirs were originally natural lakes and historically supported Native American fisheries for sockeye salmon and other anadromous and resident fish.

Implementation of passage features at the dams has the potential to reintroduce sockeye salmon to the Yakima River basin; increase populations of upper basin steelhead, coho salmon, and Chinook salmon; restore life history and genetic diversity of salmon; and reconnect isolated populations of bull trout. Two species in the basin, bull trout and Mid-Columbia River steelhead, are listed as threatened under the Endangered Species Act (ESA).

Project Purpose

Authority

Authority to undertake a feasibility study is contained in Public law No. 96-162, *Feasibility Study, Yakima River Basin Water Enhancement Project*, (Act of December 28, 1979, 93 Stat. 1241). The study area is in the Yakima River basin in south central Washington on the east side of the Cascade Range and includes most of Yakima, Kittitas, and Benton counties.

Core team

Reclamation is supported in this effort by a core team of biologists, engineers, and other specialists from Federal, state, and local entities. Partners include the YN, National Oceanic Atmospheric Administration (NOAA Fisheries), the U.S. Fish and Wildlife Service (USFWS), Washington Department of Fish and Wildlife (WDFW), Washington Department of Ecology, Washington Department of Agriculture, and local irrigation districts.

Background

Reclamation's commitment to study the feasibility of fish passage at the five large storage dams of the Yakima Project is documented in agreements, permits, and litigation settlements associated with the Keechelus Dam Safety of Dams (SOD) construction. Early in 2001, many Yakima Basin interests viewed the proposed Keechelus SOD construction as an opportunity to add fish passage features at Keechelus Dam. Reclamation carefully considered this issue but determined that fish passage facilities could not be added to Keechelus Dam under existing SOD authority.

To respond to the stated fish passage concerns, Reclamation negotiated a "mitigation agreement" with WDFW and also agreed to certain conditions contained in the State of Washington Hydraulic Project Approval (HPA) permit for the Keechelus SOD modifications. These conditions included specific tasks and milestone dates regarding the feasibility study, and the installation of interim (temporary, experimental) fish passage features at the dams. Reclamation also agreed to seek funding and implement passage where determined to be feasible.

Phase I Assessment

Reclamation completed a *Phase I Assessment Report* in 2003 (Reclamation 2003). The Phase I assessment process examined a range of options and opportunities for providing fish passage and potentially reestablishing populations of anadromous salmonids in some tributaries of the five Yakima Project storage reservoirs. From this initial assessment, it appeared that some form of upstream and downstream passage for anadromous salmonids and bull trout connectivity would be technically possible at all the storage projects.

Change in Scope

Early in the study process it became apparent that programmed funding was not sufficient to evaluate all five storage dams in detail. For this reason, the scope of the study was reduced to reflect detailed evaluation of passage features only at Cle Elum and Bumping Lake dams. Successful implementation of fish passage at Cle Elum and Bumping Lake dams could eventually lead to future detailed study of the other three dams (Kachess, Keechelus, and Tieton). The intent, to the extent possible, is to meet all of the essential Keechelus Dam SOD requirements outlined in the Record of Decision, the HPA, and the Mitigation Agreement.

Feasibility Study

In fiscal year 2004, following completion of the *Phase I Assessment Report*, Reclamation began detailed studies to evaluate the feasibility of providing fish passage at Cle Elum and

Bumping Lake dams. The Yakima River Basin fisheries co-managers (WDFW and YN) developed an *Anadromous Fish Reintroduction Plan* that outlines the sequence and timing for reintroducing anadromous salmonids above the reservoirs (Fast and Easterbrooks 2005). They proposed a phased approach starting with coho salmon *(Oncorhynchus kisutch),* followed by sockeye salmon *(O. nerka),* and eventually Chinook salmon *(O. tshawytscha),* and steelhead *(O. mykiss)*. Reclamation's evaluation of production potential follows this phased approach. The following Technical Reports support Reclamation's estimates of coho and sockeye salmon production potential above Cle Elum and Bumping Lake dams.

- *Coho Salmon Production Potential in the Cle Elum River Basin, Storage Dam Fish Passage Study, Yakima Project, Washington, Technical Report Series No. PN-YDFP-007,* Bureau of Reclamation, Boise, Idaho, March 2007.

- *Assessment of Sockeye Salmon Production Potential in the Cle Elum River Basin, Storage Dam Fish Passage Study, Yakima Project, Washington, Technical Report Series No. PN-YDFP-008,* Bureau of Reclamation, Boise, Idaho, March 2007.

- *Coho Salmon Production Potential in the Bumping River Basin, Storage Dam Fish Passage Study, Yakima Project, Washington, Technical Report Series No. PN-YDFP-009,* Bureau of Reclamation, Boise, Idaho, March 2007.

- *Assessment of Sockeye Salmon Production Potential in the Bumping River Basin, Storage Dam Fish Passage Study, Yakima Project, Washington, Technical Report Series No. PN-YDFP-010,* Bureau of Reclamation, Boise, Idaho, March 2007.

Sockeye Salmon in the Yakima and Upper Columbia River basins

Four natural glacial lakes in the Yakima River Basin supported sockeye salmon *(Oncorhynchus nerka)* populations historically (Fulton 1970; Tuck 1995), but the salmon were extirpated in the early 1900s when timber crib dams were constructed at the outlets of the lakes. Bumping Lake Dam was constructed in 1909 to 1910.

Currently there are three stocks or evolutionarily significant units (ESUs) of sockeye salmon in the interior Columbia River basin: Lake Wenatchee ESU (Washington), Okanogan River ESU (Washington), and the Snake River ESU (Idaho). The Snake River sockeye salmon ESU was federally listed under the ESA on November 20, 1991 (56 FR 58619). A subsequent final listing determination issued by NOAA Fisheries on June 28, 2005 reconfirmed the endangered status of the Snake River sockeye salmon ESU, which primarily occurs in the upper Salmon River basin in Redfish Lake. The Lake Wenatchee and Okanogan River sockeye salmon ESUs were found not to be warranted for listing under the ESA, and are therefore potential source populations of sockeye salmon for reintroduction into Bumping Lake. Lake Wenatchee and Bumping Lake are both oligotrophic. Lake Wenatchee, however, does not undergo the annual water level fluctuations that occur in

Bumping Lake as a result of seasonal water storage and release for irrigation and other purposes in the Yakima Basin. Lake Osoyoos on the Okanogan River extends into Canada and is shallower, warmer and meso- to eutrophic. Lake Osoyoos sockeye salmon smolts are generally greater than 100 mm in length, while Lake Wenatchee sockeye salmon smolts are generally less than 100 mm in length and the two are easily differentiated at downstream juvenile fish facilities. Fisheries co-managers are assessing the advantages and disadvantages of using either one or the other of these as donor stock for sockeye salmon reintroduction into Bumping Lake. Recent production estimates in Lake Wenatchee may provide some indication of sockeye salmon production potential in Bumping Lake.

Some aspects of sockeye salmon life history

Sockeye salmon spend from one to (occasionally) three growing seasons in freshwater and from one to four years in the ocean and return to spawn in their natal streams as 2- to 7-year-old adults (Foerster 1968). Unlike coho and Chinook salmon, juvenile sockeye salmon rear predominantly in lakes; fry migrate into lakes soon after emerging from the gravel.

Water temperature for upstream migration of adult sockeye salmon generally ranges from 7.2 to 15.5°C (Bell 1991). Spawning is reported to occur at various water temperature ranges: 3 to 7°C (Scott and Crossman 1973), 8 to 13°C (Shepherd et al. 1986 cited in Bjornn and Reiser 1991), 10.5 to 12.2°C (Bell 1991), and 10.6 to 12.2°C (Pauley et al. 1989). Incubation temperatures range from 4.4 to 13.3°C (Pauley et al. 1989). Bell (1991) reported preferred water temperature for sockeye salmon as ranging between 11.6 and 14.4°C, while Brett (1952) reported that a temperature range of 12 to 14°C is close to the optimum for maximum growth efficiency.

Reiser and Bjornn (1979 cited in Pauley et al. 1989) note that sockeye salmon require at least 5.0 mg/L dissolved oxygen (DO) for successful incubation. Foerster (1968) reported that sockeye salmon appear to tolerate DO levels lower than those tolerated by chum and pink salmon. Semko (1954 cited in Lorenz and Eiler 1989) reported that sockeye salmon can incubate at lower levels of DO than many other salmonids, but spawning adults avoided areas with intra-gravel DO levels below 3.0 mg/L (www.fisheries.ubc.ca/grad/abstracts/scopeab.pdf). Dissolved oxygen concentrations at or near saturation, generally around 8 to 9 mg/L, are required for best swimming performance and growth (Brett 1965). However, a substantial sockeye salmon population exists in eutrophic Lake Osoyoos on the Okanogan River in Washington and British Columbia that is warmer and presumably less well oxygenated than the typical oligotrophic lake habitat occupied by sockeye salmon.

Sockeye salmon spawn over a range of habitat types but in streams generally spawn at the downstream end of pools at the pool-riffle interface (www.fisheries.ubc.ca/grad/abstracts/scopeab.pdf). Sockeye salmon also spawn in inlets and outlets of lakes in water velocities of 0.3 to 0.91 m/sec (Bjornn and Reiser 1991), normally in riffles or where groundwater seepages occur, in minimum water depth of 0.15 m (Bjornn and Reiser 1991), but they prefer a depth of 0.3 to 0.5 m (Burgner 1991). Fukushima and Smoker (1998) reported that sockeye salmon utilized channel gradient lower than about 1.6 deg (≈ 2.8 percent). Sockeye salmon have been documented to spawn successfully over coarse sand substrate as well as over cobble too large to move and in which to construct a redd (Foerster 1968). Sockeye salmon also spawn in lakeshore locations at deeper depths where groundwater seepage occurs. Lake Wenatchee sockeye salmon, a potential donor stock for re-establishment of sockeye salmon in Bumping Lake, are tributary spawners (John Easterbrooks, WDFW, Yakima, WA, December 2004, pers. comm.; Mike Tonseth, WDFW, Wenatchee, WA, December 2004, pers. comm.).

Sockeye salmon fry in tributaries move downstream at a size of 25 to 31 mm soon after emerging from the gravel beginning about mid-April to juvenile rearing habitat in lakes (Pauley et al. 1989). Fry are relatively light-sensitive and generally move at night (Pauley et al. 1989), which is also a behavioral mechanism to avoid or reduce predation. Once in the lake, fry initially occupy shallow, littoral zone water, feeding on insects. As the juveniles grow, they move into deeper offshore water, feeding principally in the pelagic zone, generally in waters from 10 to 20 m deep (Foerster 1968, Burgner 1991). Rearing juvenile sockeye salmon are sight feeders and make diel vertical migrations from deep water around dusk to feed primarily on cladoceran and copepod zooplankters in the epilimnion, and then descend at night, driven by concentrations of prey, optimal temperature for metabolism, and to avoid or reduce predation (Quinn 2005).

Methods

We used several methods to assess sockeye salmon production potential in the Bumping River basin. We estimated potential sockeye salmon smolt production from the amount of available spawning habitat in the Bumping River and Deep Creek up to impassable barriers based on results of several stream surveys conducted by the U.S. Forest Service. We primarily considered substrate composition, the size of riffles and pools and the areal extent of riffles with substrate in the size range reported to be used by spawning sockeye salmon, stream gradient, and distance to impassable fish barriers. We considered the average size of sockeye salmon redds and area "recommended" per redd (Burner 1951), and estimated the number of redds that the area would support and the number of spawning females that would be needed to fully and uniformly utilize or seed the estimated amount of spawning habitat available based on substrate composition and stream gradient, without superimposition of redds, then incorporated an average fecundity of 2,700 eggs per female for sockeye salmon. We estimated the number of smolts that could be produced at several egg to smolt survival rates and the number of adults that would return at smolt to adult return (SAR) rates of one to six percent. SAR is smolt to adult return for smolts outmigrating from Bumping Lake to adults returning to Bumping Lake. Using SARs eliminates the need to consider life stagespecific survival rates during outmigration, during time spent in the estuary and ocean, and during the adult upstream migration; and harvest in the ocean or the Columbia River.

Since juvenile sockeye salmon typically rear in lakes, we adapted three methods of estimating production reported by BioAnalysts (2000): 1) number of smolts per lake surface area, 2) lake euphotic volume, and 3) number of spawners per lake surface area. Where appropriate, we incorporated information from the September 2003 to October 2004 limnological study of Bumping Lake (Lieberman and Grabowski 2006). After estimating the number of smolts that could be produced by these methods, we estimated the number of adults that would return at SARs of from one to six percent. We also considered some environmental constraints to sockeye salmon production in Bumping Lake, such as abundance of copepod and cladoceran prey, inter- and intra-specific competition (with resident kokanee), and the seasonal water level fluctuations and temperature regime that could influence production.

Available Spawning Habitat

Overview

In general, sockeye salmon spawning substrate consists of small- to medium-size gravel with a limited amount of coarse sand, through which a good flow of water can be maintained (Foerster 1968). Sockeye salmon prefer spawning gravels ranging in size from 13 to 102 mm (Bjornn and Reiser 1991), and similar in size to that reported for coho salmon. Salmon reportedly can spawn in gravels with a median diameter up to about 10 percent of their body length (Kondolf and Wolman 1993), which explains in part the size range of gravels used by spawning salmon; larger adult fish can move and therefore spawn in larger-sized gravel than smaller fish. Lorenz and Eiler (1989) reported that in the Taku River in Canada, mean composition of sockeye salmon redd substrate was 67.3 percent gravel measuring from 2 mm to 10 cm. Burner (1951) reported that in the Wenatchee River, sockeye salmon redd substrate consisted of 94 percent medium and small gravel, that is, gravel less than 15 cm in size. Sockeye salmon have been observed to spawn over large boulders (Foerster 1968) and in lakes to depths of 30 m in coarse granitic sand in areas of strong upwelling (Olsen 1968 cited in Burgner 1991).

Substrate suitability

Fisheries biologists from the Wenatchee National Forest, Naches Ranger District (WNF NRD) conducted late summer stream surveys in 2003 in several reaches of the Bumping River totaling 16.5 km (10.09 miles) upstream from the reservoir following a modified Hankin and Reeves (1988) protocol. A natural impassable barrier exists at about Bumping rkm 1.28 (RM 0.78), so only this lower reach was considered in this assessment. An extensive network of side channels exists in reach B-1. Three reaches of Deep Creek, a tributary of Bumping Lake, were surveyed in 2005 by fisheries biologists from the Cle Elum Ranger District (CRD). Deep Creek has a natural fish barrier at the upstream end of reach 3 at about rkm 8.33. Information such as stream substrate composition and physical attributes were gleaned from these stream survey reports and summarized. Less information was available for the side channels, so we were unable to estimate the availability of suitable spawning and/or rearing habitat in the side channels, although fisheries biologists indicated that a substantial although undocumented amount of spawning substrate and rearing habitat existed there (Yuki Reiss, USFS, Naches WA, pers. comm.).

The WNF stream surveys of the Bumping River reported the percentage of sand, gravel, cobble, boulder, and bedrock at numerous locations in riffles in each of the reaches indicated in Figure 1, which is shown for each reach in Table 1. Particle size categories are shown in Table 2.

The size range of suitable spawning substrate for sockeye salmon based on the reported literature values would fall within the mid range of gravel up to the lower range of cobble, that is, medium through very coarse gravel and small cobble (Table 2). Pebble counts and sizes at selected transects were conducted during the stream surveys, and from these data we then calculated the percent of the substrate sample in the size range 12 to 128 mm. This size range mostly bracketed the size range of suitable spawning substrate reported above.

Table 1. Percent substrate composition in riffles in one reach of the Bumping River and three reaches of Deep Creek surveyed by USFS WNF staff in 2003 and 2005.

<table>
<tr><th>Reach</th><th>Length, km</th><th></th><th>Sand[a]</th><th>Gravel</th><th>Cobble</th><th>Boulder</th><th>Bedrock</th></tr>
<tr><td rowspan="2">B-1
n = 1[b]</td><td rowspan="2">1.25</td><td>Avg. %</td><td>10</td><td>40</td><td>50</td><td>0</td><td>0</td></tr>
<tr><td>Range</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">B-1 side channels[c]</td><td rowspan="2">3.18</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">D-1
n = 2</td><td rowspan="2">1.45</td><td>Avg. %</td><td>22</td><td>41</td><td>38.5</td><td>1.7</td><td>0</td></tr>
<tr><td>Range</td><td>5-39</td><td>38-44</td><td>27-50</td><td></td><td></td></tr>
<tr><td rowspan="2">D-2
n = 1</td><td rowspan="2">2.68</td><td>Avg. %</td><td>7</td><td>33.3</td><td>44</td><td>17.1</td><td>0</td></tr>
<tr><td>Range</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">D-3
n = 2</td><td rowspan="2">4.2</td><td>Avg. %</td><td>7.5</td><td>68.0</td><td>24.6</td><td>0</td><td>0</td></tr>
<tr><td>Range</td><td>0-15</td><td>36.8-99.0</td><td>1-48.1</td><td>0</td><td>0</td></tr>
</table>

Source: U.S. Forest Service stream inventories for the Bumping River and Deep Creek.

Note: The Bumping River reach is designated B-1; Deep Creek reaches were surveyed in 2005, and are designated D-1 through D-3.

[a] Substrate size range: Sand, silt and clay (< 2 mm); Gravel (2-64 mm); Cobble (64-256 mm); Boulder (256-4096 mm); Bedrock (> 4096 mm).

[b]. n = number of sites sampled during the Forest Service stream survey.

[c] Data were insufficient to estimate substrate composition of side channels.

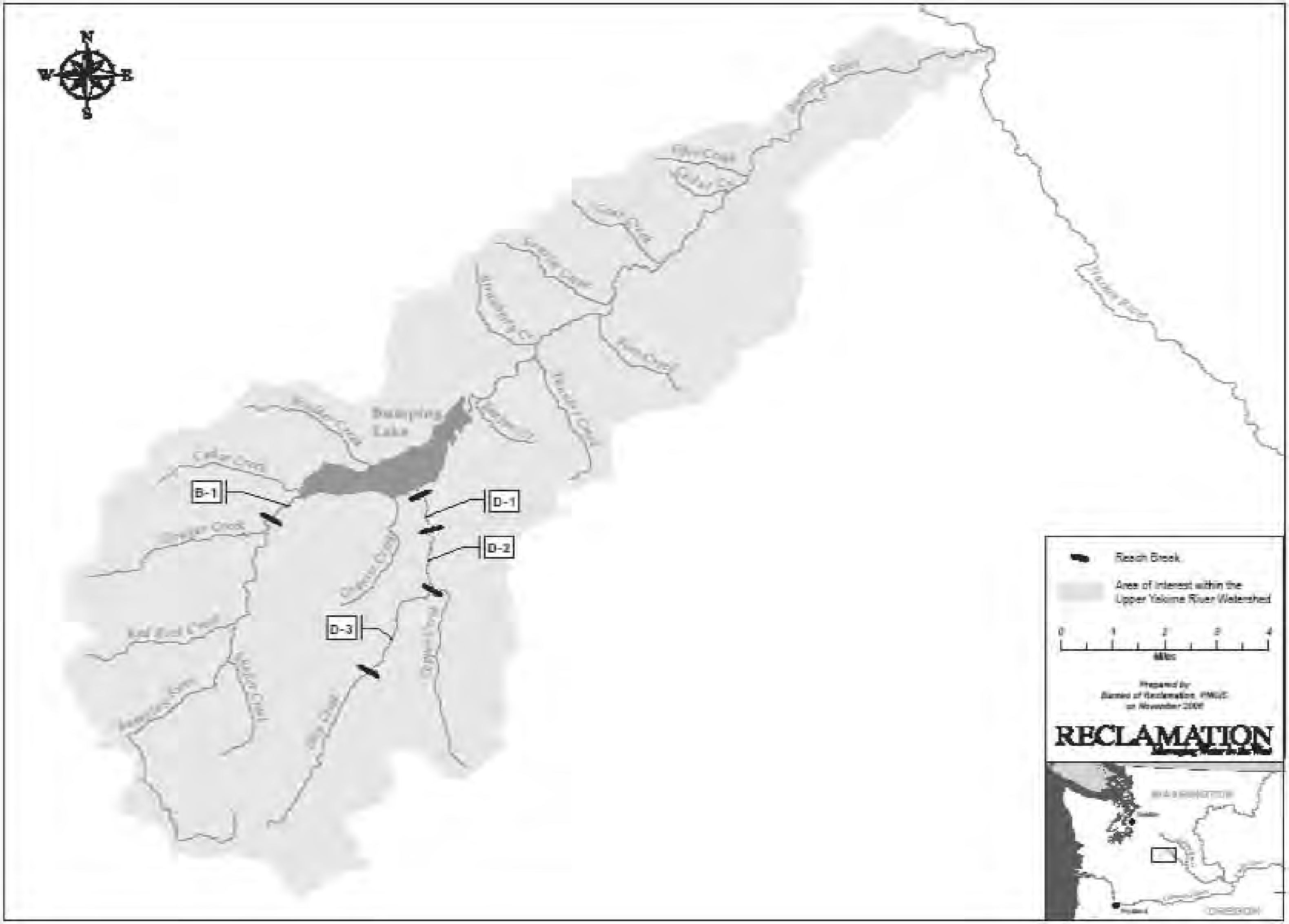

Figure 1. Location of Bumping River and Deep Creek reaches.

We calculated the area of riffle habitat in each reach from the recorded length and width of riffles. We then adjusted the area of riffle habitat by the percentage of gravel/cobble within the 12 to 128 mm size range. The USFS reported only two habitat types, riffles and pools, in most stream surveys. This somewhat coarse habitat delineation could likely overestimate the extent of riffles, since other habitat types might have been present but not identified as such. In addition, less information was recorded and reported for side channels, which were extensive in reach B-1 (Yuki Reiss, USFS, Naches, WA, pers. comm.).

The Wenatchee National Forest Land and Resource Management Plan (WNF 1990) states that spawning gravel contains no more than 20 percent fine sediment (sediment less than 1.0 mm in size); excessive fine sediment results in embedded substrate conditions, and at high concentrations reduces the quality of salmonid spawning habitat.

Table 2. Particle sizes of several gravel and cobble categories identified during surveys of the Bumping River and Deep Creek. Particle type and size categories highlighted in bold are considered suitable spawning substrates for sockeye salmon based on values in the literature.

	Particle type	Size, mm
Sand		<2
Gravels	Very fine	2-4
	Fine	4-6
	Fine	6-8
	Medium	8-12
	Medium	**12-16**
	Coarse	**16-24**
	Coarse	**24-32**
	Very Coarse	**32-48**
	Very Coarse	**48-64**
Cobble	**Small**	**64-96**
	Small	**96-128**
	Large	128-192
	Large	192-256

Source: USFS, 2003

Note: The duplicate categories for several particle types were reported as such in the USFS stream survey data.

Watershed Analysis ratings (Schuett-Hames et al. 1999) are based on the percent of a gravel sample that is less than 0.85 mm in diameter. Cederholm and Reid (1987) reported that coho salmon eggs and alevins are severely affected by particles smaller than 0.85 mm, and this is likely true for sockeye salmon as well. Samples with less than 12 percent fine sediment are considered GOOD, samples with 12 to 17 percent fine sediment are considered FAIR, and samples with greater than 17 percent fine sediment are consider POOR. Geometric mean diameter (D_g) of spawning gravel is the most sensitive measure of salmonid survival to emergence, and percentage of particles less than 0.85 mm is the most sensitive indicator of changes to substrate induced by land management activities (Young et al. 1991). The percent sand in reach B-1 is 10 percent (Table 1), and ranges from 0 to 39 percent for Deep Creek, with the 39 percent occurring in reach D-1, mostly within the "good" category for salmonid spawning habitat according to the criteria discussed above, except for D-1 with a "poor" rating at 39 percent sand, but this is based on only one sample.

The lower reach of the Bumping River to the passage barrier and the lower three reaches of Deep Creek have reported average gradients of less than two percent. Sockeye salmon would likely be able to utilize these reaches for spawning.

Redd size

Bocking and Gaboury (2003) reported that the minimum area required for a sockeye salmon redd is about 1.75 m^2; Burner (1951) reported that the average size of sockeye salmon redd is about the same. Foerster (1968) reported redd sizes of 1.67 m^2, 1.76 m^2, 1.5 m^2 and 2.0 m^2 for the White River, Okanogan River, Wenatchee River, and Little Wenatchee River, respectively. Under competitive conditions for space, a female averages a spawning territory of about 3.7 m^2; when competition for space is eliminated a female occupies an average area of 6.97 m^2 (http://fwie.fw.vt.edu/WWW/macsis/lists/M010588.htm). Salmon are also believed to require some additional defensible space larger than the redd itself to reproduce successfully. Burner (1951) recommended that the area for sockeye salmon spawning should be about 4 times the redd size, which based on 1.75 m^2 would be about 7.0 m^2.

Fecundity

Fecundity of adult sockeye salmon varies with size and age (Foerster 1968), and size of females and the number of years spent in the ocean (Burgner 1991). Larger fish have more eggs, but the increase in number of eggs is not linear with increase in weight (Foerster 1968). Fecundity of Lake Wenatchee sockeye salmon, a potential donor stock for Bumping Lake, averages from about 2,500 eggs per female (Mike Tonseth, WDFW, Wenatchee, WA, December 2004, pers. comm.), 2,700 eggs per female (Andrew Murdoch, WDFW, Wenatchee, WA, February 2005, pers. comm.), or 3,000 eggs per female (John Easterbrooks, WDFW, Yakima, WA, December 2004, pers. comm.). For this assessment, we used fecundity of 2,700.

Estimation of smolt production

We estimated the number of redds that the adjusted riffle area could potentially support and the number of spawning females that would be needed to fully utilize or seed the estimated area of suitable spawning habitat available. We estimated the number of smolts that would be produced at egg to smolt survivals of 1, 2, and 5 percent. We then estimated the number of adults that would return at SAR rates of 1 to 6 percent. SAR is smolt to adult return for smolts outmigrating from the Bumping Lake to adults returning to Bumping Lake.

We also considered some environmental constraints to sockeye salmon production in Bumping Lake, such as abundance of copepod and cladoceran prey, potential inter- and intra-specific competition (with resident kokanee), predation by other resident fish, and the seasonal water level fluctuations and temperature regime that could influence production.

Smolts per Lake Surface Area and Morphoedaphic Index

We assessed production potential of sockeye salmon smolts in Bumping Lake using a smolts per lake surface area and morphoedaphic index (MEI) method BioAnalysts (2000) used to estimate sockeye salmon yield for Lake Chelan, Washington. BioAnalysts (2000) used smolt production information from Lake Wenatchee from 1998 to 2000 (Murdoch 2000 cited in BioAnalysts 2000) and calculated the number of sockeye salmon smolts produced per hectare (ha). Murdoch (2000 cited in BioAnalysts 2000) reported 1,177,000 to 1,815,000 sockeye salmon smolts from Lake Wenatchee from 1998 to 2000. From this information, BioAnalysts (2000) calculated a range of from 1,190 to 1,835 smolts per ha, with a midpoint of about 1,500, based on Lake Wenatchee surface area of 989 ha. We used these values to estimate smolt production in Bumping Lake, as well as a lower value of 500 smolts per ha; BioAnalysts (2000) had used an additional lower value of 430 smolts per ha based on estimates of smolt production on a series of lakes with a morphoedaphic index (MEI)

Table 3. Some limnological characteristics of Bumping Lake, Lake Wenatchee, and Lake Chelan.

	Bumping Lake	Lake Wenatchee	Lake Chelan
Surface area	565.18 ha; 5.65 km^2	989 ha; 9.89 km^2	13,494 ha; 134.94 km^2
Mean/max depth, m	13.75 / 35.6	46/73 (151/240 ft)	145/457
Secchi depth, m	8.85 (5.9-11.2)	6.5 (6-7)	7-17, 6.8-14.6
Chlorophyll *a*, µg/L	0.93 – 1.95 µg/L		0.3-1.6 µg/L
TP, µg/L, epilimnion	3-8 µg/L	5.0 µg/L	ND-10 µg/L, 0.9-2.3 µg/L
OP, µg/L, epilimnion	2.8 µg/L (1-5 µg/L)		
Specific cond., µS/cm	29.3 (25.0-35.1)		31-70
TDS, mg/L (est.)	18.75 (16-22.5		40
MEI	1.36 (1.16-1.64)	0.17 - 0.51	0.08 [2], 0.28 [3]
Euphotic volume units	135.0 at full pool 101.5 at median pool	173.6 at full pool	

1 Calculated from specific conductance times 0.64 (Davine Lieberman, USBR, Denver, February 2005, pers. comm.).
2 MEI value from BioAnalysts (2000), apparently based on maximum depth of 457 m.
3 MEI value calculated from TDS = 40 mg/L and mean depth of 145 m.

of less than 0.50. We estimated potential production at full pool surface area of 565.2 ha at el. 3426.2 ft, a lake surface area of 324 ha for the lowest water surface elevation of 3401.9 ft encountered during the September 2003 to October 2004 limnological study, and a surface area of 410.8 ha corresponding to the median water surface elevation of 3410.2 ft for the 15-water-year period 1990 to 2004.

The morphoedaphic index is one of several estimators of lake productivity and is the ratio of total dissolved solids (TDS in mg/L) to mean depth in m, so that

$$MEI = TDS\ (mg/L) \div \text{mean depth}\ (m)$$

For Bumping Lake, total dissolved solids were estimated from measures of specific conductance obtained during the September 2003 to October 2004 limnological study; TDS = 0.64 x specific conductance (Davine Lieberman, USBR, Denver, CO, February 2005, pers. comm.). Specific conductance in Bumping Lake at station BMP2 for all depths and sampling dates ranged from 25.0 to 35.1 µS/cm and averaged 29.3 µS/cm. The average specific conductance yielded an average TDS of 18.6 mg/L, ranging from 16.0 to 22.5 mg/L. Bumping Lake has a surface area of about 565.18 ha at full pool and a mean depth of 13.75 m (based on an estimated dead storage volume of 26,966 ac-ft (USBR, Ed Young, 2005) plus the active storage volume of 36,051 ac-ft for a total volume of 63,017 ac-ft, resulting in a mean depth = volume ÷ surface area at elevation 3426.2 ft. = 13.75 m). For Bumping Lake, MEI was about 1.36 units, ranging from 1.16 to 1.64. For the median water surface elevation of 3410.2 ft, mean depth was 12.62 m and MEI averaged 1.47, ranging from 1.27 to 1.78. BioAnalysts (2000) reported an MEI of 0.17 for Lake Wenatchee and 0.08 for Lake Chelan, although Gustafson et al. (1997) reported an MEI of 0.51 for Lake Wenatchee. The differing results for Lake Wenatchee may be due to calculation of MEI based on data from different years or different times of the year. Since MEI is an index of production, the MEI of 1.47 for Bumping Lake at median elevation suggests that it is potentially more productive than Lake Wenatchee and Cle Elum Lake.

Euphotic Volume Method

Koenings and Burkett (1987) found a relationship between euphotic volume and total abundance of sockeye salmon smolts in some Alaskan lakes, although Hume et al. (1996) found that this relationship was inappropriate for British Columbia sockeye salmon lakes. However, this method was applied to Lake Chelan (BioAnalysts 2000), and we use it in this assessment.

The euphotic zone volume (EV) is calculated from the euphotic depth (ED), depth in m where light intensity falls to 1 percent of that at the surface and is the limit of photosynthesis and the surface area in km^2, so that

$$EV = ED\ (m) \times \text{surface area}\ (km^2)$$

and

$$ED = \text{Secchi depth}\ (m) \times 2.7$$

For Bumping Lake, the Secchi depth at the midlake site BMP2 averaged 8.85 m during the 2003 to 2004 limnological study and ranged from 5.9 to 11.2 m, resulting in an average ED of 23.9 m (range 15.9 to 30.2 m). From this, we calculated EV units for full pool water surface elevation; to account for fluctuating water levels in Bumping Lake and the possible effects on lake productivity, we calculated EV units using average Secchi depth at the median lake elevation for the 15-water-year period 1990 to 2004, and also when Secchi depth was minimum, maximum, and at the lowest lake elevation encountered during the limnological study. For example, at full pool elevation of 3,426.2 ft, surface area of 5.65 km^2, and ED = 23.9 m, Bumping Lake had 135.0 EV units.

Lake Wenatchee Secchi depth ranged from 6 to 7 m, and BioAnalysts (2000) used a midpoint Secchi depth of 6.5 m to calculate an ED = 17.55 m, and from the Lake Wenatchee surface area of 9.89 km^2, an EV of 173.6 units. From this result, and an average smolt production of 1,481,000 (Murdoch 2000), BioAnalysts (2000) estimated 8,531 smolts per EV unit, which we use as a starting point to estimate smolt production potential. For the low and high estimates of smolts produced in Lake Wenatchee, 1,177,000 and 1,815,000, respectively, we calculated 6,780 and 10,455 smolts per EV unit. We used these estimates from Lake Wenatchee under the several scenarios described above to estimate smolt production in Bumping Lake.

Spawners per Lake Surface Area

Sockeye salmon smolt production of lake systems has been estimated from the number of adult spawners per lake surface area in ha (BioAnalysts 2000). Estimates vary widely, and Burgner (1991) noted that average spawner densities per lake ha were generally less than 30 adults in Bristol Bay and Fraser River lake systems. We estimated smolt production for Bumping Lake with 10 and 30 spawners per ha, assuming 50 percent females, fecundity of 2,700 for Lake Wenatchee sockeye salmon (Andrew Murdoch, WDFW, Wenatchee, WA, 14 February 2005, pers. comm.) and egg to smolt survivals of 1, 2, and 5 percent. Chapman et al. (1995) reported that average egg to smolt survival for Lake Wenatchee sockeye salmon was estimated at 5.5 percent, ranging from 1.7 to 12.3 percent. Bocking and Gaboury (2003) assumed 5 percent egg to smolt survival in their euphotic volume method. Egg to smolt survivals for sockeye salmon in the literature range from 0.005 to 17.4 percent (Chapman et al. 1995). The egg to smolt survivals used here represent values at the lower end of the range.

We estimated potential production at three lake surface areas of 565.18 ha, 424.69 ha, and 323.97 ha corresponding to full lake elevation of 3,426.2 ft, median lake elevation of 3,410.2 ft for the 15-water-year period from 1990 to 2004, and the lowest lake elevation of 3,401.9 ft encountered during the 2003 to 2004 limnological study, respectively.

Related Study

Limnological study of Bumping Lake

Since sockeye salmon juveniles rear in lakes, comprehensive limnological information was needed for Bumping Lake to assess production potential of sockeye salmon in the Bumping River basin. Some limited sampling had been done in recent years, but additional information was required. Of particular interest was the trophic status of the lake and information about the seasonal abundance and distribution of zooplankton prey for juvenile sockeye salmon, and data on water temperature and dissolved oxygen levels. Haring (2001) stated that lake level fluctuations and drawdown likely reduces the production of phytoplankton, zooplankton, and aquatic insects, important in the food web of fish in Bumping Lake. Staff from Reclamation's Technical Service Center in Denver, Colorado, conducted monthly limnological surveys at three stations on Bumping Lake, including the deepest point at midlake station BMP2, from September 2003 to October 2004, except for the winter months. Samples for nutrient analyses were also collected in the inflow and outflow waters of Bumping Lake.

Water column profiles for water temperature, dissolved oxygen, specific conductance, and pH were recorded with a Hydrolab® multiparameter probe from surface to bottom at 1-m increments through the thermocline (if present), and thereafter at 5-m depth increments to the bottom. Secchi depth transparency was recorded using a 20-cm-diameter black and white round disk. Other parameters were generally sampled by depth strata of 0 to 10 m, 10 to 20 m, and 20 to 30 m and included chlorophyll *a* (chl *a*), an indicator of algal biomass; composite phytoplankton samples, to determine species composition and biovolume (μm^3/mL). Zooplankton samples were collected with a 30-cm (opening of net) by 120-cm (length) x 64-µm (mesh size) simple closing net from each of the three depth strata and identified to species (or genus in some cases). Discrete water samples for total phosphorus (TP), orthophosphorus (OP), dissolved nitrate and nitrite nitrogen, ammonia-nitrogen, total Kjeldahl nitrogen (TKN), total organic carbon (TOC), and dissolved organic carbon (DOC) were collected with a Van Dorn water sampler at each of three stations from 1 m below the surface and 0.5 m above the bottom. Water samples were analyzed by Reclamation's

Environmental Chemistry Laboratory at the Technical Service Center in Denver. Additional details of sampling, preservation, and analytical methods are provided in the report of the limnological study (Lieberman and Grabowski 2006).

Results

Available Spawning Habitat

We estimated that the lowermost 1.28 km reach of the Bumping River upstream from the lake and Deep Creek upstream about 8.33 km to a natural impassable barrier had about 18,218 m^2 of potentially suitable spawning habitat that could accommodate about 2,602 female sockeye salmon, assuming a redd size of 7 m^2 (Table 4). The four reaches had average gradient less than 2 percent. The area of suitable spawning gravel is shown in Table 4 as adjusted riffle area. Table 4 also shows the number of redds this estimated spawning area could support and the estimated total number of eggs expected to be produced from an estimated 2,700 eggs per female. We estimate that 70,254, 140,508, and 351,270 sockeye salmon smolts could potentially be produced at 1, 2, and 5 percent egg to smolt survival rates, respectively (Table 4). We estimate that the accessible reaches of the Bumping River and Deep Creek have the potential to produce anywhere from 702 to 21,076 adult sockeye salmon assuming one to six percent SAR rates (Table 5). The higher estimates may be optimistic, and assumes that all suitable habitat in all reaches is being fully utilized by spawning sockeye salmon. We calculate that a 2 percent egg to smolt survival and about a 3.7 percent SAR rate would be needed to produce sufficient adults to seed the estimated spawning habitat. For comparison, the Yakima Coho Master Plan (Yakama Nation 2003) reported SARs in 2001 for hatchery and wild adult coho salmon as 1.8 percent and 3.8 percent, respectively, and in 2002, 0.04 percent and 0.87 percent, respectively. Counts of adult sockeye salmon at Tumwater Dam on the Wenatchee River were 27,628, 5,040, and 30,142 in 2002, 2003, and 2004, respectively (Andrew Murdoch, WDFW, Wenatchee, WA, June 2, 2005, pers. comm.).

We did not attempt to estimate smolt production based on spawning habitat availability in side channels. Reach B-1 has an additional 3.18 km of side channels that likely provide some suitable spawning substrate, but we had insufficient data to quantify its contribution to the overall extent of spawning habitat. Deep Creek reaches D-1 through D-3 also had extensive side channels. Information to estimate areal extent of riffles and pools was not available, so no attempt was made to quantify extent of spawning substrate in these side channels. Forest Service biologists indicated that the side channels had what they considered to be suitable spawning habitat throughout. Therefore, we consider the estimate of sockeye salmon smolt production for the Bumping River basin to be a minimum estimate.

Smolts per Lake Surface Area and Morphoedaphic Index

At the midpoint value of 1,500 smolts per lake ha at full lake elevation 3,426.2 ft and surface area of 565.2 ha, we estimated that Bumping Lake could produce about 847,770 sockeye salmon smolts, ranging from 672,564 to 1,037,105, for the low and high smolt per ha estimates derived from Lake Wenatchee, respectively (Table 6). At the median lake elevation of 3410.2 ft and surface area of 424.7 ha, we estimated that 637,035 smolts could be produced, ranging from 505,381 and 779,306 (Table 6). During the September 2003 to October 2004 limnological study, Bumping Lake depth was close to maximum at elevation 3,426.68 ft in mid May 2004, but water level was lower at elevation 3,401.93 ft. in mid October 2003. Surface area at elevation 3,401.93 ft is 323.97 ha. Estimated smolt production at this lake surface area would be 485,955 smolts, ranging from 385,524 to 594,485 (Table 6).

Table 4. Estimated number of sockeye salmon smolts that could potentially be produced in the Bumping River and Deep Creek at one, two, and five percent egg to smolt survival rates, based on number of redds and adult female spawning sockeye salmon that can be supported based on amount of suitable available gravel and average area associated with a redd.

Reach	Reach length, m	Average gradient (range)	Total riffle length, m	Total riffle area (m^2), calculated from USFS stream surveys	Percent suitable substrate, 12-128 mm, from pebble counts	Adjusted riffle area (m^2)	No. of potential redds at 7 m^2 each	No. of potential female spawners required at one per redd	Estimated no. of eggs produced per reach if fecundity is 2,700 eggs per female	No. smolts at 1% egg to smolt	No. smolts at 2% egg to smolt	No. smolts at 5% egg to smolt
B-1	1,252	1.9	524	4,968	55	2,732	390	390	1,053,000	10,530	21,060	52,650
D-1	1,445	1.4	626	3,244	60	1,946	278	278	750,600	7,506	15,012	37,530
D-2	2,690	1.0	1,743	11,047	54	5,965	852	852	2,300,400	23,004	46,008	115,020
D-3	4,209	1.8	2,161	12,839	59	7,575	1,082	1,082	2,921,400	29,214	58,428	146,070
Total	9,596		5,054	32,098		18,218	2,602	2,602	7,025,400	70,254	140,508	351,270

Table 5. Number of returning adult sockeye salmon to the Bumping River and Deep Creek at various SARs, at 1, 2, and 5 percent egg to smolt survival. Production potential for sockeye salmon in the Bumping River and Deep Creek considering the number of smolts that could be produced based on estimated extent of suitable spawning substrate.

	No. smolts at 1 % egg to smolt	No. smolts at 2 % egg to smolt	No. smolts at 5 % egg to smolt
	70,254	140,508	351,270
SAR	Estimated number of returning adults		
1 %	702	1,405	3,513
2 %	1,405	2,810	7,025
3 %	2,108	4,215	10,538
4 %	2,810	5,620	14,051
5 %	3,513	7,025	17,564
6 %	4,215	8,430	21,076

BioAnalysts (2000) reported that some other sockeye salmon lakes with some limnological characteristics similar to Lake Wenatchee produced fewer numbers of smolts per ha. In their estimate of potential smolt yield for Lake Chelan, they used a median of 430 smolts per ha from six lakes that had an MEI less than 0.5. We applied this approach to Bumping Lake but increased this slightly to 500 smolts per ha to account for the higher estimated average MEI of 1.35 for Bumping Lake at median water surface elevation, and we estimated that about 282,590 sockeye salmon smolts would be produced at full pool and corresponding lake surface area, 212,345 at median lake surface area, and 161,985 smolts at low elevation and corresponding lake surface area (Table 6).

Table 6. Potential sockeye salmon smolt production and estimated number of returning adults at several SARs in Bumping Lake based on several estimates of smolts per lake surface area in ha at full pool elevation, median elevation, and low elevation.

	Smolts per lake surface area method			MEI
Lake elevation and surface area	1,190 smolts/ha	1,500 smolts/ha	1,835 smolts/ha	500 smolts/ha
3426.20 ft (565.18 ha) [1]	672,564	847,779	1,037,105	282,590
3410.22 ft (424.69 ha) [2]	505,381	637,035	779,306	212,345
3401.93 ft (323.97 ha) [3]	385,524	485,955	594,485	161,985
SAR	Estimated number of returning adults from the estimated number of smolts produced at median pool elevation and lake surface area.			
1%	5,054	6,370	7,793	2,123
2%	10,107	12,741	15,586	4,247
3%	15,161	19,111	23,379	6,370
4%	20,215	25,481	31,172	8,494
5%	25,269	31,852	38,965	10,617
6%	30,323	38,222	46,758	12,741
	Estimated number of returning adults from the estimated number of smolts produced at low pool elevation and lake surface area.			
1%	3,855	4,860	5,945	1,620
2%	7,710	9,719	11,890	3,240
3%	11,566	14,579	17,835	4,860
4%	15,421	19,438	23,779	6,479
5%	19,276	24,298	29,724	8,099
6%	23,131	29,157	35,669	9,719

[1] Full pool elevation.
[2] Median pool elevation for 15-water-year period, 1990 to 2004.
[3] Low pool elevation on October 15, 2003 during 2003 to 2004 limnological study.

Euphotic Volume

We estimated that at full pool Bumping Lake could produce 1,151,685 smolts assuming an average of 8,531 smolts per EV unit, ranging from 915,300 to 1,411,425 sockeye salmon smolts for 6,780 and 10,455 smolts per EV unit, respectively (Table 7). At median water surface elevation and average Secchi depth, estimated production ranged from 688,170 to 1,061,183 smolts.

Estimates of potential smolt production at minimum and maximum Secchi depths, as well as at lowest reservoir water surface elevation encountered during the limnological study (in September 2004), are also shown in Table 7. Estimated sockeye salmon smolt production is lowest at the low water surface elevation and highest when secchi depth was maximum in late July. Estimated number of returning adults at median and low water surface elevations at several SAR rates are shown on Table 7.

Table 7. Potential sockeye salmon smolt production in Bumping Lake from the euphotic volume method at full and median pool and several lower water surface elevations.

				Estimated number of smolts produced at:		
Condition		ED, m	EV	6780 smolts/EV	8531 smolts/EV	10455 smolts/EV
Avg. Secchi depth, full pool	Secchi = 8.85 m, el. = 3426.2 ft Area = 565.18 ha	23.90	135.0	915,300	1,151,685	1,411,425
Avg. Secchi depth, median pool	Secchi = 8.85 m, el. = 3410.22 ft Area = 424.69 ha	23.90	101.5	688,170	865,897	1,061,183
Oct. 15, 2003 minimum Secchi depth	Secchi = 5.9 m el. = 3401.93 ft Area = 323.97 ha	15.93	51.6	349,848	440,200	539,478
July 22, 2004 maximum Secchi depth	Secchi = 11.2 m el. = 3422.41 ft Area = 532.15 ha	30.24	160.9	1,090,902	1,372,638	1,682,210
Note: The minimum secchi depth of 5.9 m occurred on the same sampling date as the minimum lake elevation, October 15, 2003.						
SAR				Estimated number of adults returning from estimate of smolt production at median pool elevation and average Secchi depth		
1%				6,882	8,659	10,612
2%				13,764	17,318	21,224
3%				20,645	25,977	31,835
4%				27,527	34,636	42,447
5%				34,409	43,295	53,059
6%				41,291	51,954	63,671
				Estimated number of returning adults from estimate of smolt production at low pool elevation		
1%				3,499	4,403	5,395
2%				6,998	8,806	10,790
3%				10,497	13,209	16,184
4%				13,997	17,611	21,579
5%				17,496	22,014	26,974
6%				20,995	26,417	32,369

Spawners per Lake Surface Area

For Bumping Lake at full pool, assuming 10 spawners per ha, 50 percent females, and fecundity of 2,700, we estimate that about 2,826 females could potentially produce 7,629,930 eggs, or about 13,500 eggs per ha. With egg to smolt survival of 1, 2, and 5 percent, the Bumping River system could produce 76,299, 152,599, and 381,497 sockeye salmon smolts, respectively (Table 8). At median lake surface area, potential smolt production estimates range from 57,333 to 286,666. At 30 spawners per ha and median lake elevation, 171,999, 343,999, and 859,997 smolts could potentially be produced at the three survival rates, respectively. At low water surface elevation and a lake area of 324 ha, the estimate of smolt production is reduced to about 57 percent of that at full pool elevation (Table 8). If we assume 40 percent females in the spawning population (BioAnalysts 2000), about 20 percent fewer smolts would be produced.

Estimated number of returning adults at median and low water surface elevations at several SAR rates are shown on Table 8.

Table 8. Potential sockeye salmon smolt production in Bumping Lake at two spawner abundance levels, two proportions of females in the spawning population, and three egg to smolt survival rates. Estimated number of returning adults at various SARs is based on smolt production at median and low water surface elevation.

	Smolts production at 1 % egg to smolt survival				**Smolts production at 2 % egg to smolt survival**				**Smolts production at 5 % egg to smolt survival**			
Surface area	10 spawners/ ha at 50% fem	10 spawners/ ha at 40% fem	30 spawners/ ha 50% fem	30 spawners/ ha 40% fem	10 spawners/ ha 50% fem	10 spawners/ ha 40% fem	30 spawners/ ha 50% fem	30 spawners/ ha 40% fem	10 spawners/ ha 50% fem	10 spawners/ ha 40% fem	30 spawners/ ha 50% fem	30 spawners/ ha 40% fem
565.18 ha	76,299	61,039	228,898	183,118	152,599	122,079	457,796	366,237	381,497	305,197	1,144,490	915,592
424.69 ha	57,333	45,867	171,999	137,600	114,666	91,733	343,999	275,199	286,666	229,333	859,997	687,998
323.97 ha	43,736	34,989	131,208	104,966	87,472	69,978	262,416	209,933	218,680	174,944	656,039	524,831
SAR	Estimated number of returning adults from the estimated number of smolts produced at median water surface elevation											
1%	573	459	1,720	1,376	1,147	917	3,440	2,752	2,867	2,293	8,600	6,880
2%	1,147	917	3,440	2,752	2,293	1,835	6,880	5,504	5,733	4,587	17,200	13,760
3%	1,720	1,376	5,160	4,128	3,440	2,752	10,320	8,256	8,600	6,880	25,800	20,640
4%	2,293	1,835	6,880	5,504	4,587	3,669	13,760	11,008	11,467	9,173	34,400	27,520
5%	2,867	2,293	8,600	6,880	5,733	4,587	17,200	13,760	14,333	11,467	43,000	34,400
6%	3,440	2,752	10,320	8,256	6,880	5,504	20,640	16,512	17,200	13,760	51,600	41,280
	Estimated number of returning adults from the estimated number of smolts produced at low water surface elevation											
1%	437	350	1,312	1,050	875	700	2,624	2,099	2,187	1,749	6,560	5,248
2%	875	700	2,624	2,099	1,749	1,400	5,248	4,199	4,374	3,499	13,121	10,497
3%	1,312	1,050	3,936	3,149	2,624	2,099	7,872	6,298	6,560	5,248	19,681	15,745
4%	1,749	1,400	5,248	4,199	3,499	2,799	10,497	8,397	8,747	6,998	26,242	20,993
5%	2,187	1,749	6,560	5,248	4,374	3,499	13,121	10,497	10,934	8,747	32,802	26,242
6%	2,624	2,099	7,872	6,298	5,248	4,199	15,745	12,596	13,121	10,497	39,362	31,490

Related Study

Limnological Study of Bumping Lake

Water temperature and dissolved oxygen – Bumping Lake strongly thermally stratifies during the summer, typical of temperate dimictic lakes. Surface water temperature at midlake station BMP2 warms from May through July, and then begins decreasing up to the fall (Table 9). The lake was inaccessible to sample in April 2004. In May, surface water temperature was 8.6°C, decreased to 5.5°C at 10 m, 5.2°C at 20 m and 4.9°C at 30 m. In June, water temperature ranged from 13.4°C at the surface to 7.48°C at 10 m, and ranged from 7.48 to 5.83°C in the 10 to 20 m depth stratum, and 5.4°C at 30 m. Water temperature was 20.38°C in July at the surface, and 10.79°C at 10 m depth. In the 10 to 20 m depth strata, water temperature ranged from 10.79 to 6.1°C, and was 5.6°C at 30 m. By August, the surface water temperature decreased slightly to 18.39°C and was 9.73°C at 10 meters depth. In the 10 to 20 m depth strata, water temperature ranged from 9.73 to 6.11°C, and was 5.5°C at 30 m. By September, the surface water temperature had decreased to 14.52°C and was 9.87°C at 10 m depth. In the 10 to 20 m depth stratum, temperature ranged from 9.87 to 6.14°C, and was 5.6°C at 30 m. Juvenile sockeye salmon rearing in lakes make diel vertical migrations to feed, metabolize, and seek refuge from predators. The range of water temperatures documented during the limnological study is not expected to impact diel migrations of juvenile sockeye salmon.

Table 9. Water temperature (°C) at station BMP2 in Bumping Lake.

	Sep 03	Oct 03	May 04	Jun 04	Jul 04	Aug 04	Sep 04	Oct 04
Surface	13.77	11	8.61	13.4	20.38	18.39	14.52	10.65
10 m	8.06	7.85	5.49	7.48	10.79	9.73	9.87	9.85
20 m	5.96	6.24	5.15	5.83	6.1	6.11	6.14	6.23
30 m	5.47	5.65	4.96	5.37	5.58	5.53	5.56	5.73

Dissolved oxygen was near or above saturation in the lake, and exhibited a slight orthograde profile during thermal stratification. DO was 8.6 mg/L at the surface in July and increased to 11.2 mg/L at 10 m, 9.98 mg/L at 20 m, and 8.85 mg/L at 30 m. At station BMP2, pH averaged 6.74 and ranged from about 5.89 to 7.59. Specific conductance average 29.3 and ranged from 25.0 to 35.1 µS/cm.

Secchi depth at midlake station BMP2 ranged from 5.9 to 11.2 m and averaged 8.85 m (Table 7).

Nutrients - Epilimnetic total Kjeldahl nitrogen (TKN) levels at midlake station BMP2 were generally low, with a sampling period average of 0.16 mg/L and ranging from 0.06 to 0.26 mg/L. Hypolimnetic (TKN) levels were also low, averaging 0.17 mg/L and ranging from

0.05 to 0.22 mg/L. Epilimnetic nitrate-nitrite nitrogen at BMP2 averaged 0.007mg/L, while near the bottom it averaged 0.018 mg/L. Nitrate-nitrite nitrogen concentrations in the Bumping River inflow were 0.010 mg/L and outflow was 0.006 mg/L.

Epilimnetic orthophosphorus levels were low, averaging 0.002 mg/L and ranged from 0.001 to 0.004 mg/L. Hypolimnetic orthophosphorus levels were also low, averaging 0.004 mg/L and ranged from 0.002 to 0.008 mg/L. Orthophosphorus concentrations in the Bumping River inflow were 0.003 mg/L and the outflow was 0.003 mg/L.

Phytoplankton – Forty-two species of phytoplankton were identified in Bumping Lake. The great majority of species collected were dinoflagellates (Division Pyrrhophyta) and diatoms (Division Chrysophyta). Some blue-green algae (Division Cyanophyta) were collected in September and October 2003. *Anabaena flos-aquae* and *Aphanocapsa* sp. were present in low levels.

Chlorophyll *a* levels are used as an indicator of phytoplankton biomass. It is a more convenient metric to measure and includes the nanoplankton as well as the larger phytoplankton. Chlorophyll *a* in the composite samples ranged from 0.56 µg/L in August 2004 to 1.84 µg/L in September 2004 in the 0 to 10 m depth stratum, from 0.72 µg/L in April 2004 to 1.63 µg/L in September 2004 in the 10 to 20 m depth stratum, and from 0.35 µg/L in September 2003 to 1.39 µg/L in July in the 20 to 30 m depth stratum (Table 10). Higher concentrations of chl *a* occurred in the 10 to 20 m depth stratum in June, July, and August, coincident with strong thermal stratification. All chl *a* concentrations were low and indicative of oligotrophic conditions. Koenings and Kyle (1997) reported chl *a* for four oligotrophic Alaskan lakes ranging from 0.35 to 0.86 µg/L.

Table 10. Secchi depth (m) and chlorophyll a concentrations (µg/L) at station BMP2 at the surface and in three depth strata from September 2003 to October 2004.

Date	Secchi depth, m	Chlorophyll *a*, µg/L			
		1 m	0-10 m	10-20 m	20-30 m
Sept. 18, 2003	7.1	0.85	1.63	0.85	0.56
Oct. 14, 2003	5.9	1.7	2.7	1	0.9
May 12, 2004	9.01	0.91	1.42	1.55	0.91
June 17, 2004	10.6	0.4	0.8	1.15	0.8
July 22, 2004	11.22	0.64	0.77	1.28	1.23
Aug. 24, 2004	8.51	0.96	1.5	1.95	0.99
Sept. 13, 2004	8.27	1.12	1.6	1.74	1.04
Oct. 19, 2004	10.2	1.39	1.98	1.54	1.07

Zooplankton - Twenty-seven species of zooplankton were collected from all stations in Bumping Lake. *Daphnia rosea, Bosmina longirostris,* and *Holopedium gibberum* were the dominant cladocerans; *Diacyclops thomasi* and *Hesperodiaptomus francisanus* were the dominant copepods. Rotifers were abundant and seasonally comprised the major portion of the zooplankton (Table 11). Maximum cladoceran density was about 16.14 individuals/L in the 10 to 20 m depth stratum in July 2004; maximum adult copepod density was about 1.30 individuals/L in July 2004 in the 20 to 30 m depth stratum. The combined densities of cladocerans and copepods, which together constitute the principal prey items for rearing juvenile sockeye salmon, were most abundant at about 17.38 individuals/L in 10 to 20 m depth stratum in July and 9.43 individuals/L in the 0 to 10 m depth stratum, also in July (Table 11, Figure 2).

The water surface elevation during the September 2003 to October 2004 limnological survey varied from 3.401.93 ft on October 15, 2003 to 3,426.68 ft on May 12, 2004, as shown in Figure 3.

Table 11. Total zooplankton (individuals per L) and total cladocerans, copepods, nauplii and rotifers at Bumping Lake midlake station BMP2, in three depth strata 0 to 10, 10 to 20, and 20 to 30 meters, September 2003 to October 2004.

Stratum / Date	Total cladocerans	Total copepods	Total cladocerans and copepods	Total nauplii	Total rotifers	Total zooplankton
0-10 m						
Sept. 18, 2003	4.18	0.70	4.87	0.58	9.40	14.86
Oct. 14, 2003	1.19	0.15	1.34	0.02	16.56	17.92
May 12, 2004	0.75	0.00	0.75	0.70	10.20	11.65
June 16, 2004	6.44	0.64	7.08	1.47	17.01	25.56
July 22, 2004	8.71	0.73	9.43	2.54	14.51	26.49
Aug. 24, 2004	6.28	0.54	6.82	0.43	24.24	31.49
Sept. 13, 2004	7.10	0.34	7.45	0.57	21.43	29.45
Oct. 19, 2004	1.95	0.49	2.44	0.00	11.69	14.12
10-20 m						
Sept. 19, 2003	3.35	0.38	3.73	0.10	14.56	18.39
Oct. 14, 2003	0.44	0.05	0.49	0.02	8.62	9.13
May 13, 2004	0.51	0.25	0.76	1.27	30.05	32.09
June 16, 2004	0.53	0.40	0.93	0.27	22.74	23.94
July 21, 2004	16.14	1.24	17.38	0.21	48.21	65.79
Aug. 23, 2004	2.54	0.60	3.14	0.00	64.59	67.74
Sept. 14, 2004	1.05	0.00	1.05	0.00	43.67	44.72
Oct. 19, 2004	2.44	0.00	2.44	0.00	24.65	27.09
20-30 m						
Sept. 19, 2003	1.66	0.38	2.04	0.13	7.52	9.69
Oct. 14, 2003	0.07	0.01	0.08		1.27	1.36
May 13, 2004	0.18	0.30	0.48	1.02	13.17	14.67
June 16, 2004	0.25	0.13	0.38	0.09	7.86	8.33
July 21, 2004	2.38	1.30	3.68	0.00	42.64	46.32
Aug. 23, 2004	0.17	0.25	0.41	0.25	28.39	29.05
Sept. 14, 2004	0.80	0.30	1.10	0.00	38.38	39.48
Oct. 19, 2004	0.05	0.05	0.11	0.00	0.91	1.01

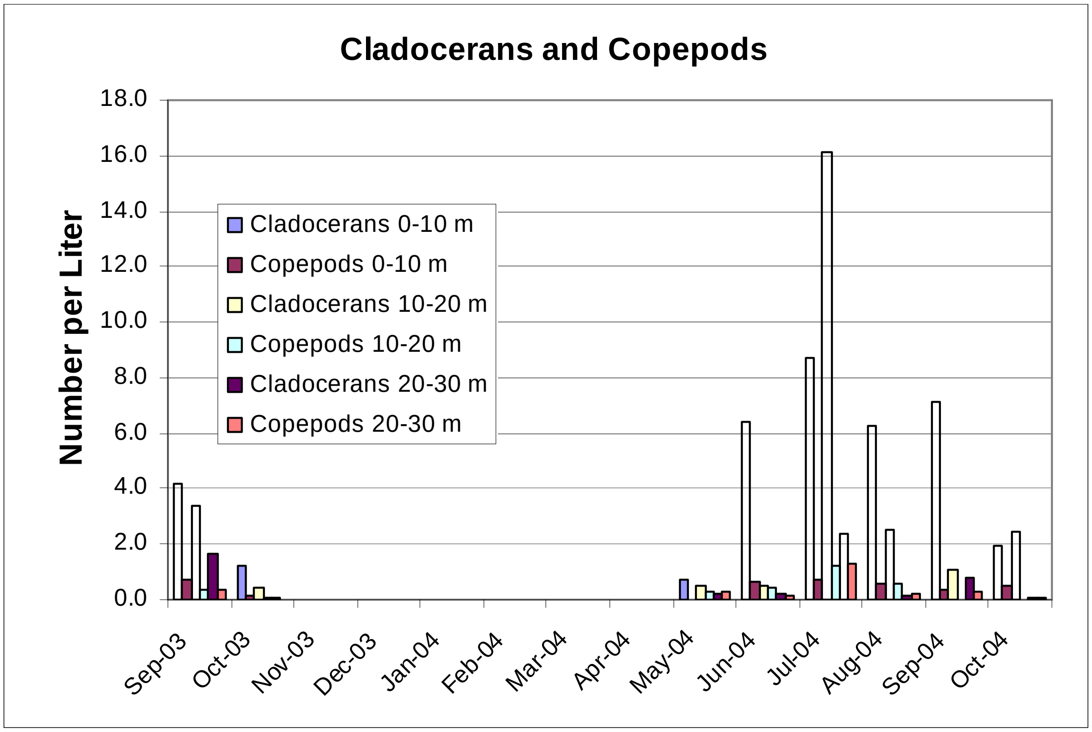

Figure 2. Seasonal abundance of cladoceran and copepod zooplankton in three depth strata at Bumping Lake station BMP2 from September 2003 to October 2004.

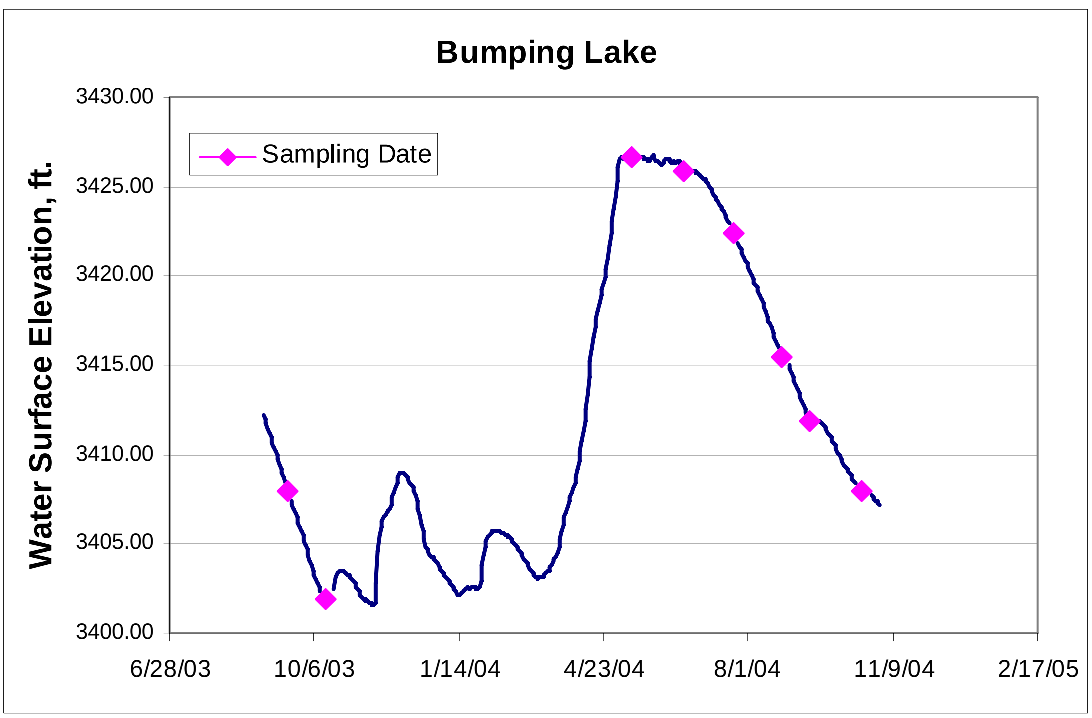

Figure 3. Bumping Lake water surface elevations and sampling dates during the September 2003 to October 2004 limnological study.

Discussion

The several methods that we used to assess sockeye salmon smolt production in the Bumping River basin above Bumping Lake produced a range of estimates. We estimated that the lowermost reach of the Bumping River and three reaches of Deep Creek up to impassable barrier had 18,218 m^2 of suitable spawning habitat for sockeye salmon, based on USFS stream survey data. Microhabitat conditions may not be uniform or homogeneous across the entire estimated area of spawning habitat, and spawning sockeye salmon will likely select spawning areas based on some additional factors such as water flow and depth, gradient, groundwater influences, etc. (Geist and Dauble 1998). We did not include water flow and depth in estimating areal extent of suitable spawning habitat for sockeye salmon. These factors, including the preference for spawning salmon to select areas for redds at the downstream end of pools at the pool-riffle interface (www.fisheries.ubc.ca/grad/abstracts/scopeab.pdf) might concentrate spawning in more limited areas, which will not be known until a sufficient number of adult sockeye salmon return to spawn in the Bumping River upstream from the reservoir are tagged and tracked to spawning areas, or the rivers are surveyed for redds and carcasses.

The results of the available spawning habitat approach are relatively low compared to the estimates of sockeye salmon smolt production using lake-based methods; the estimate of suitable spawning habitat did not include the extensive side channels in the lower Bumping River and Deep Creek for which we had few data and which may provide substantial suitable spawning habitat (Yuki Reiss, USFS, Naches, WA, pers. comm.).

The three lake-based methods used to estimate sockeye salmon smolt production produced a range of results, for the most part greater than the spawning habitat approach (Table 12). The available spawning habitat approach is estimated to provide habitat for about 5204 adults. At median lake elevation and surface area of 424.7 ha, this amounts to about 12 spawners per lake ha and about 51 spawners per euphotic volume unit. We may be underestimating the amount of available spawning habitat since we were unable to estimate the extent of spawning habitat available in the extensive side channels, so the estimate of spawning habitat is likely conservative.

For the euphotic volume approach we applied the range of number of smolts per EV unit, calculated by BioAnalysts (2000) for Lake Wenatchee, at several water surface elevations representing several different lake surface areas that resulted in a range of EV units in Bumping Lake. Koenings and Burkett (1987 cited in Hume et al. 1996) reported that adult sockeye salmon production in some Alaskan lakes was maximal with an average spawning density of 425 adults (or about 213 females, assuming an even sex ratio) per EV, which produced 23,000 smolts per EV unit. This represents about a 4 percent egg to smolt survival. At the low Bumping Lake water surface elevation of 3401.93 ft in October 2003, lake surface area of about 324 ha, and 51.6 EV units, 10,991 females would be required, a little more than twice the number of adult female sockeye salmon we calculated would be needed to fully utilize the available spawning habitat in the Cle Elum basin upstream from the lake. We suggest that the lower end of the range of potential production of sockeye salmon is a more appropriate estimate for the upper Bumping River basin.

Table 12. Summary of potential sockeye salmon smolt production for the Bumping River basin using four approaches.

Available spawning habitat	1% egg to smolt	2% egg to smolt	5% egg to smolt	
	70,254	140,508	351,270	
				MEI
Lake surface area	1,190 smolts/ha	1,500 smolts/ha	1,835 smolts/ha	500 smolts/ha
565.18 ha	672,564	847,779	1,037,105	282,590
424.69 ha	505,381	637,035	779,306	212,345
323.97 ha	385,524	485,955	594,485	161,985
Euphotic Volume		6,780 smolts/EV	8,531 smolts/EV	10,455 smolts/EV
Avg. Secchi 8.85 m, full pool		915,300	1,151,685	1,411,425
Avg. Secchi 8.85 m, median el.		688,170	865,897	1,061,183
Max Secchi 11.2 m		1,090,902	1,372,638	1,682,210
Min Secchi 5.9 m, low elev.		349,848	440,200	539,478
Spawners/ha		50% females, 1% egg-to-smolt	50% females, 2% egg-to-smolt	50% females, 5% egg-to-smolt
10 spawners/ha at 565.18 ha		76,299	152,599	381,497
at 424.69 ha		57,333	114,666	286,666
at 323.97 ha		43,736	87,472	218,680
30 spawners/ha at 565.18 ha		228,898	457,796	1,144,490
at 424.69 ha		171,999	343,999	859,997
at 323.97 ha		131,208	262,416	656,039

To produce about 500,000 sockeye salmon smolts at a five percent egg to smolt survival rate would require about 3,704 females with fecundity of 2,700, for a total of about 7,408 adult sockeye salmon. This would result in about 17 adults per lake ha at median water surface elevation and lake surface area of 424.7 ha, or about 23 adults per lake ha at low pool elevation and lake surface area of about 324 ha. For comparison, about 30,000 adult sockeye salmon were counted at Tumwater Dam on the Wenatchee River in 2004. If these 30,000 fish reached Lake Wenatchee, it would result in about 30 spawners per lake ha.

Additional and more detailed stream survey information from the Bumping River and Deep Creek including side channels is needed to document physical features of the habitat such as substrate size and distribution, flow, depth, and areas of upwelling and refine the estimate of suitable spawning habitat for sockeye salmon and other anadromous salmonids proposed for re-introduction above Bumping Lake Dam. Selection of spawning areas by the fish may concentrate redds in certain stream locations and result in redd superimposition and lower survival if earlier deposited eggs are dislodged during subsequent spawning activity.

Lakeshore spawning by sockeye salmon in Cle Elum Lake was suggested by Haring (2001) but it is unknown if this might have occurred historically in Bumping Lake prior to the construction of the dam. Even with lakeshore spawning possibly occurring at depths to 30 m (Chapman et al. 1995), it is unknown if the seasonally fluctuating water level in present-day Bumping Lake would provide or maintain suitable lakeshore spawning habitat.

Water temperature in Bumping River reach B-1 in 2003 ranged between 12 and 18°C and averaged 15.8°C. No long-term water temperature data logger was placed in this reach, but a data logger has been in place in reach B-2 since 1991. Thermograph data for this reach indicate that for the period June 24 to October 6 water temperature exceeded the Forest standard of 61°F (16.1°C) for 11 days. This may be similar for reach B-1. Lukas (1999) reported that most mid-Columbia sockeye salmon spawn in October through November. Water temperature is probably suitable for spawning by October. Maximum surface water temperature in Bumping Lake measured during the limnological study was 20.38°C at station BMP2 in July 2004. The lake was strongly stratified at this time, water temperatures dropped to 6.1°C at 20 m, so water temperatures within the preferred range would be available for rearing sockeye salmon.

Water temperature for upstream migration of adult sockeye salmon generally ranges from 7.2 to 15.5°C (Bell 1991). Migration can proceed at higher water temperatures, although Hyatt et al. (2003) reported that migration of adult Okanogan River sockeye salmon essentially stops when water temperature reaches 21°C. The fish can survive at temperatures a few degrees warmer, and will resume migrating when the water temperature decreases to below 21°C. Exposure to water temperatures higher than about 17°C can increase susceptibility to disease, impair maturation, reduce swimming performance, reduce viability of gametes, and reduce efficiency of energy use (Hyatt et al. 2003).

Daily average water temperatures in the lower Yakima River at Kiona (RM 29.0) exceed the 21°C threshold for delay of migration from about the third week in June until about the beginning of September; this time period varies from year to year. This is just about the time migrating adult sockeye salmon begin arriving at McNary Dam. Figure 4 shows the water temperature in the Yakima River at Kiona from June through the end of September for the years 2000 to 2004, and the count of sockeye salmon at McNary Dam for 2002, 2003, and 2004. The high water temperature in the Yakima River may delay entry of the fish into the river, except for the earlier returning adults. Later returning adults may delay migration, stray elsewhere or possibly hold in the Columbia River until water temperature in the Yakima River decreases sufficiently for migration to resume.

The damming of Bumping Lake eliminated anadromous salmonid access to the lake and the annual infusion of marine-derived nutrients that likely contributed to a more productive system upstream from the lake and in the lake itself. In an example from a nearby lake, an analysis of Cle Elum Lake sediments found that before 1906, there was an average of 19 percent more phosphorus in lake sediments each year (Dey 2000). No sediment core analysis information is available for Bumping Lake, but if a phenomenon similar to that which occurred in Cle Elum Lake occurred in Bumping Lake, nutrient input into the lake would likely have been reduced over historic levels. When passage for adult anadromous salmonids is re-established at Bumping Dam, and the number of returning adult salmonids increases over time, one might expect a gradual increase in stream and lake nutrient levels and productivity from the infusion of marine-derived nutrients.

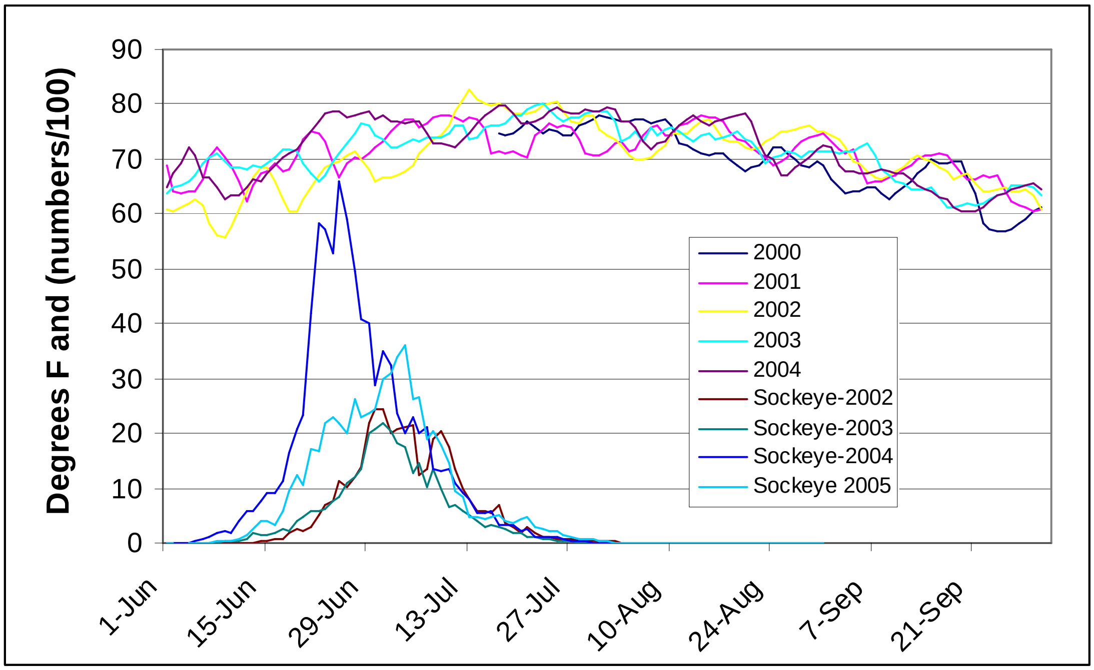

Figure 4. Daily average water temperature in the Yakima River at Kiona (2000 to 2004) and number of sockeye salmon counted at McNary Dam (2002 to 2004).

Total cladoceran and copepod abundance was greatest in July. Combined cladocerans and copepods were about twice as abundant in the 10 to 20 m depth stratum as they were in the 0 to 10 m depth stratum in July, but lowest in May 2004 (Figure 2). In most months, cladoceran abundance was much greater that copepod abundance. Zooplankton abundance decreased in the 20 to 30 m depth stratum during most sampling periods. So in July when water temperatures in the top 10 m of the lake are higher than the temperature for maximum growth efficiency for rearing sockeye salmon, and when they likely seek deeper depths with lower water temperatures, the preferred prey is available.

Sockeye salmon production potential might be affected by predation in the lake and by interspecific competition from native resident fish, both salmonids and non-salmonids. In addition, if reintroduction of other anadromous salmonids proceeds as planned, additional interspecific competition may occur. Long-term fisheries studies on Bumping Lake and its tributaries would increase understanding of predator-prey dynamics.

Mullan (1986) reported that 631 acres (255.3 ha) of sockeye salmon habitat was lost when passage into Bumping Lake was blocked in 1910. If the historical level of sockeye salmon production in the original Bumping Lake was similar to that estimated for Cle Elum Lake, about 38.8 adults per ha (Yakama Nation et al. 1990), Bumping Lake would have produced about 9,900 fish. Based on a median lake elevation of 3410.22 ft and a corresponding surface area of 424.69 ha, we can expand this estimate to about 16,478 adults. Using the smolts per lake surface area method with 1,500 smolts per ha and the median lake surface area, about a 2.6 percent SAR would be required to produce about 16,500 adults. With the euphotic volume method using the median number of smolts per EV of 8,531, a 2 percent SAR would produce about 17,000 adults. With the number of adults per lake surface area method, with 30 spawners per ha and five percent egg to smolt survival, a two percent SAR would produce about 17,200 adults, while at two percent egg to smolt survival, a five percent SAR would produce 17,200 adults. With the available spawning habitat approach, a five percent egg to smolt survival and a five percent SAR would result in about 17,500 returning adults.

Summary

The Bumping River basin supported sockeye salmon historically, and it is likely that over time a population could be re-established. The lake is oligotrophic, similar to other lakes that have viable sockeye salmon populations. Sockeye salmon smolt production estimated in Bumping Lake range from 43,736 to 1,682,210 using several methods and a range of assumptions. Similarly, the estimate of the number of returning adults ranged from 573 to 63,671. These estimates represent extreme low and high survivals and environmental conditions. A more reasonable estimate would be that obtained using median values for survival and a median lake elevation with corresponding lake surface area. Using mid-range values, and considering the estimated historic production of perhaps 9,900 sockeye salmon adults, we estimate that Bumping Lake could produce from about 10,000 to 17,000 adult sockeye salmon when the species is fully restored there. Some factors that might limit a sockeye salmon population in the basin would be the low abundance of preferred prey items in the lake until marine-derived nutrients improve production, and summertime average daily water temperatures greater than 21°C that might delay adult sockeye salmon entry into the Yakima River.

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