VI. IMPLICATIONS FOR KEY FISH, AMPHIBIANS, AND MACROINVERTEBRATES

The combination of increased temperatures and decreased late-summer base flows (low flows) could increase the stress for fish and other aquatic biota in the future.[1049] Low flows can cause a reduction in habitat availability, food production, and water quality, and can heighten the effects of ice on smaller streams during the winter time.[1050] For example, the drying of streams into isolated pools crowds organisms and results in reduced dissolved oxygen levels.[1051] Stream and river biological fish indicators will respond to climate change influences on water temperature and hydrologic regime in a number of ways, as summarized in Table 16.

Based on a search of the scientific and grey literature, sufficient information is available to discuss observed trends and future projections in the NPLCC region for:

1. Pacific lamprey
2. Pacific salmon
3. Amphibians
4. Macroinvertebrates

The following structure will be used to present information on the implications of climate change for fish, amphibians, and macroinvertebrates in the NPLCC region:

- **Observed Trends –** observed changes for southcentral and southeast Alaska, British Columbia, Washington, Oregon, and northwestern California.
- **Future Projections –** projected direction and/or magnitude of change for southcentral and southeast Alaska, British Columbia, Washington, Oregon, and northwestern California.
- **Information Gaps –** information and research needs identified by reviewers and literature searches.

[1049] *Pike et al. (2010, p. 730)
[1050] *Pike et al. (2010, p. 730). The authors cite Bradford and Heinonen (2008) for this information.
[1051] *Poff, Brinson and Day. (2002, p. 12)

1. PACIFIC LAMPREY (*LAMPETRA TRIDENTATA*)

Pacific lamprey co-occur with Pacific salmon and they have a similar life cycle to Pacific salmon (i.e., anadromy, living in both salt and freshwater, and semelparity, reproducing once in a lifetime).[1052] After ceasing their parasitic stage in the ocean, Pacific lamprey return to freshwater during the spring (April–June), and then begin their initial upstream migration during the summer (July–September), before overwintering during October–March.[1053] Like other anadromous lampreys, Pacific lamprey do not feed during this prolonged freshwater residency and somatic energy reserves fuel sexual maturation.[1054] As a result, Pacific lamprey shrink in body size prior to maturing, spawning, and then dying the following spring (April–July).[1055]

This section focuses on climate change impacts during the freshwater phase of lamprey life history. For information on climate change impacts in the marine phase of their life history, please see the companion report *Climate Change Effects and Adaptation Approaches in Marine and Coastal Ecosystems of the North Pacific Landscape Conservation Cooperative Region: A Compilation of Scientific Literature (Phase 1 Draft Final Report).*

Observed Trends

Regional

In recent decades, anadromous Pacific lampreys along the west coast of North America, have experienced broad-based population declines and regional extirpations.[1056] These declines parallel those of Pacific salmonids (*Oncorhynchus* spp.), perhaps because the two groups share widely sympatric (i.e. occurring in the same or overlapping geographic areas) distributions and similar anadromous life histories.[1057]

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

[1052] *Clemens et al. *Do summer temperatures trigger spring maturation in Pacific lamprety, Entosphenus tridentatus.* (2009, p. 418)
[1053] *Clemens et al. (2009, p. 418). The authors cite Beamish (1980) for information on spring, and Scott and Crossman (1973) for information on summer and overwintering.
[1054] *Clemens et al. (2009, p. 418). The authors cite Kott (1971), Beamish et al. (1979), and Larsen (1980) for information on other anadromous lamprey; Beamish (1980) and Whyte et al. (1993) for information on feeding during freshwater residency; and, Kott (1971), Beamish et al. (1979), and Larsen (1980) for information on somatic energy reserves fueling sexual maturation.
[1055] *Clemens et al. (2009, p. 418). The authors cite Beamish (1980) and Whyte et al. (1993) for information on shrinking in body size, and Beamish (1980) and Pletcher (1963, as cited in Scott & Crossman, 1973) for information on maturing, spawning, and dying in spring.
[1056] *Keefer et al. *Variability in migration timing of adult Pacific lamprety (Lampetra tridentata) in the Columbia River, U.S.A.* (2009, p. 254). The authors cite Beamish and Northcote (1989), Kostow (2002), and Moser and Close (2003) for this information.
[1057] *Keefer et al. (2009, p. 254). The authors cite Scott and Crossman (1973), Simpson and Wallace (1978), and Moyle (2002) for information on sympatric distributions, and McDowall (2001) and Quinn and Myers (2004) for information on Anadromous life histories.

Washington and Oregon

At the Bonneville Dam, Keefer et al. (2009) found that lamprey run timing shifted progressively earlier from 1939 to 2007, coincident with decreasing Columbia River discharge and increasing water temperature.[1058] In a 41-year time series of adult lamprey counts in the Columbia River, migration timing was earliest in warm, low-discharge years and latest in cold, highflow years.[1059] However, as one reviewer noted, this may be an example of behavioral adaptation to climatic change, not simply vulnerability to negative impacts.[1060] Key findings include:

- Threshold temperatures associated with run timing were similar throughout the dataset despite significant impoundment-related warming, suggesting that temperature-dependent migration cues have been temporally stable.[1061]
- In both historical (1939–1969) and recent (1998–2007) periods, very few lampreys passed Bonneville Dam before water temperatures reached 59°F (15°C) and the midpoint of the run typically passed by about 66°F (~19°C).[1062]

A lamprey passage study by Vella et al. (1999a and 1999b) revealed that up to eighty percent of radio-tagged lamprey failed to pass Bonneville Dam.[1063] The cause for this apparent passage failure has yet to be determined, and potential reasons could be behavioral disorientation, swim performance limitations, physiological stress or exhaustion, depletion of energy reserves, thermal stress, or a combination of any of these factors.[1064]

In a laboratory study of stream temperature and maturation in Pacific lamprey (*Entosphenus tridentatus*) collected from the Willamette River near Oregon City (OR), Clemens et al. (2009) hypothesize that warm, summer temperatures (>68°F, 20°C) would accentuate shrinkage in body size, and expedite sexual maturation and subsequent death.[1065] The results confirmed predictions:

- Lamprey from a warm water group (68-75.2°F, 20-24°C; mean 71.2°F, 21.8°C) showed significantly greater proportional decreases in body weight following the summer temperature treatments than fish from a cool water group (56.5°F, 13.6°C).[1066]
- A greater proportion of warm water fish sexually matured (100%) and died (97%) the following spring than cool water fish (53% sexually mature, 61% died).[1067]
- Females tended to mature and die earlier than males, most obviously in the warm water group.[1068]

[1058] *Keefer et al. (2009, p. 258)
[1059] *Keefer et al. (2009, p. 253)
[1060] Comment from Reviewer (June 2011).
[1061] *Keefer et al. (2009, p. 253)
[1062] *Keefer et al. (2009, p. 261)
[1063] *ISAB. *Climate change impacts on Columbia River Basin Fish and Wildlife (pdf).* (2007, p. 47). The authors cite Vella et al. (1999a, 1999b) for this information.
[1064] *ISAB. (2007, p. 47)
[1065] *Clemens et al. (2009, p. 418)
[1066] *Clemens et al. (2009, p. 418)
[1067] *Clemens et al. (2009, p. 418)
[1068] *Clemens et al. (2009, p. 418)

Northwestern California

Information needed.

Future Projections

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

Information needed.

Oregon

Information needed.

Northwestern California

Information needed.

Information Gaps

Future projections for Pacific lamprey are needed. Additional studies throughout the NPLCC region are needed to supplement the information on observed trends presented here. Research on the freshwater life stages of anadromous Pacific lamprey, including projected effects of climate change, is especially needed.

2. PACIFIC SALMON (*ONCORHYNCHUS* SPP.)

Pacific salmon have complex life histories that span diverse environments across the Pacific Rim.[1069] Pacific salmon as a group occupy habitats that range from the Beaufort Sea where they occur in relatively small numbers to San Francisco Bay where they are nearly extirpated.[1070] They spawn in fall in fresh water and their embryos incubate in the gravel during the winter and emerge in spring.[1071] Juveniles then spend days to years in habitats ranging from small creeks to large rivers, and small ponds to large lakes.[1072] Most juveniles then migrate downriver, through estuaries and coastal waters, to the ocean.[1073] These "anadromous" individuals spend anywhere from a few months to as much as seven years at sea, before migrating back to spawn and die at their natal sites in fresh water.[1074] This great diversity of environments and behaviors suggests that climate change could influence selection on multiple traits in multiple phases of the life cycle.[1075]

The primary climate change impacts on anadromous fishes in the freshwater phase of their life history are increased water temperature and altered streamflow (Figure 27); for information on climate change impacts in the marine phase of their life history, please see the companion report *Climate Change Effects and Adaptation Approaches in Marine and Coastal Ecosystems of the North Pacific Landscape Conservation Cooperative Region: A Compilation of Scientific Literature (Phase 1 Draft Final Report).*

Water temperatures fundamentally affect the health and distribution of salmon and steelhead.[1076] An increase of even a few degrees above optimum range can change migration timing, reduce growth rates, reduce available oxygen, and increase susceptibility to toxins, parasites, predators, and disease (Box 19).[1077]

Streamflow changes due to global warming will have large effects on salmon, especially coupled with warmer temperatures.[1078] Reduced summer flows exacerbate warmer temperatures and make it even more difficult for adult salmon to pass obstacles in their struggle to reach their natal spawning grounds.[1079] In extreme cases, low flows will stop fish short of their spawning grounds.[1080] Excessively high flows in winter, due to rapid melting or increased rainfall, can cause "scouring" events that wash away the gravel beds salmon use as nesting sites.[1081] And once spawning occurs, reduced flows can dewater nests, exposing eggs to the elements.[1082]

[1069] *Crozier et al. *Potential responses to climate change in organisms with complex life histories: evolution and plasticity in Pacific salmon.* (2008, p. 253). The authors cite Groot and Margolis (1991) and Quinn (2005) for this information.
[1070] *Bryant. (2009, p. 184). The author cites Craig and Haldorson (1986), Nehlson (1997), and Groot and Margolis (1991) for this information.
[1071] *Crozier et al. (2008, p. 253)
[1072] *Crozier et al. (2008, p. 253-254)
[1073] *Crozier et al. (2008, p. 254)
[1074] *Crozier et al. (2008, p. 254)
[1075] *Crozier et al. (2008, p. 254)
[1076] *Martin and Glick. *A great wave rising: solutions for Columbia and Snake River salmon in the age of global warming.* (2008, p. 13)
[1077] *Martin and Glick. (2008, p. 13). The authors cite Poole et al. (2001) for this information.
[1078] *Martin and Glick. (2008, p. 14)
[1079] *Martin and Glick. (2008, p. 14)
[1080] *Martin and Glick. (2008, p. 14)
[1081] *Martin and Glick. (2008, p. 14). The authors cite Spence et al. (1996) for this information.
[1082] *Martin and Glick. (2008, p. 14)

Box 19. Thresholds & Salmon.

Threshold crossings occur when changes in a system exceed the adaptive capacity of the system to adjust to change. Environmental managers have a pressing need for information about ecosystem thresholds because of the potentially high-stakes consequences of exceeding them, which may limit future management actions, force policy choices, and in some circumstances be non-reversible. Effects of crossing climate change-related thresholds might include extirpation or extinction of species or expansion of nonnative invasive species. Maximum weekly temperature thresholds and ranges for salmon species (based on the EPA's 2007 guidance for all salmon species) include:

- 55.4 to 58.1°F (13-14.5°C) is the range for spawning, rearing, and migration
- 59.9 to 67.1°F (15.5-19.5°C) is the range for elevated disease risk in adults
- 68.9 to 70.7°F (20.5-21.5°C) is the threshold for adult lethality
- Greater than 70.7°F (21.5°C) is the threshold for juvenile lethality

Sources: Baron et al. (2009); Groffman et al. (2006); Mantua et al. (2010); U.S. Climate Change Science Program (2009).

Observed Trends

Southcentral and Southeast Alaska

Please see Chapter IV Section 1 for information on salmon in this region.

British Columbia and Washington

Natural origin abundance of most Evolutionarily Significant Units/Distinct Population Segments (ESUs/DPSs) has increased since the original status reviews in the mid-1990s, but declined since the time of the last status review in 2005.[1083] Crossin et al. (2008) tested the hypothesis that exposure of sockeye to higher temperatures, ~64°F (18°C) and above, reduces migration success compared with that of sockeye exposed to a lower temperature.[1084] Late-run sockeye from the Weaver Creek (BC) population were caught en route to spawning grounds and were experimentally exposed to temperatures that have commonly been encountered by early migrants (~64°F, 18°C) and to temperatures historically encountered by normal-timed fish (50°F, 10°C).[1085] These temperatures also bracket the optimal temperature for swimming performance (57-59°F, 14-15°C) for this population.[1086] The holding temperature also spanned a threshold for *Parvicapsula minibicornis* infection (a kidney parasite implicated in the mortality of early-migrating Fraser River sockeye salmon).[1087] The temperature experienced during treatment had a significant effect on survival:

- Thirty-one fish (62%) survived at 50°F (10°C; 15 females and 16 males) and,

[1083] *Ford. *Status review update for Pacific salmon and steelhead listed under the Endangered Species Act: Northwest. Draft.* (2010, p. 5)
[1084] *Crossin et al. *Exposure to high temperature influences the behaviour, physiology, and survival of sockeye salmon during spawning migration.* (2008, p. 128)
[1085] *Crossin et al. (2008, p. 128). The authors cite Patterson et al. (2007) for information on normal-timed fish.
[1086] *Crossin et al. (2008, p. 128). The authors cite Lee et al. (2003) for this information.
[1087] *Crossin et al. (2008, p. 128). The authors cite Wagner et al. (2005) for this information.

- Seventeen fish (34%) at ~64°F (18°C; 8 females and nine males).[1088]

The expression of *P. minibicornis* in moribund fish (dead < 2 hours) was temperature-dependent:[1089]

- The kidneys of ~64°F-treated fish (18°C ; N=14) had significantly higher levels of *P. minibicornis* than 50°F-treated fish (10°C; N=13, P = 0.002).[1090]
- The infection scores were maximal (25) in seven of the fourteen fish that were exposed to ~64°F (18°C) and that had accrued more than 350 degree days (i.e., the cumulative freshwater temperature experienced by the fish; ~400 degree days is the cumulative temperature threshold for full expression of *P. minibicornis*), whereas none of the 50°F (10°C) fish showed histological evidence of infection.[1091]

Exposure to high but sublethal temperatures had a negative effect on migratory performance and survival in both sexes after their release back into the Fraser River:[1092]

- Eight of thirteen (62%) of control salmon and twenty-one of thirty-one (68%) of 50°F (10°C) salmon reached spawning areas.[1093]
- The ~64°F (18°C) fish were half as successful (6 of 17; 35%).[1094]
- The only physiological difference between treatments was a change in gill Na^+, K^+-ATPase activity.[1095] This drop correlated negatively with travel times for the ~64°F-treated males (18°C).[1096]
- Reproductive-hormone levels and stress measures did not differ between treatments but showed significant correlations with individual travel times.[1097]

In an earlier study of temperature and flow effects on salmon in the Fraser River watershed, Morrison, Quick and Foreman (2002) concluded:

- Water temperatures between 71.6 and 75.2°F (22-24°C) over a period of several days can be fatal for salmon.[1098]
- Temperatures over 75.2°F (24°C) can cause death within a few hours.[1099]
- Even water temperatures as low as 68°F (20°C) can have an adverse effect on spawning success rates.[1100]
- On the migration route back to the spawning beds the [sockeye] salmon are sensitive to the river water temperatures and there is a strong correlation between pre-spawning mortality and high river temperature.[1101]

[1088] *Crossin et al. (2008, p. 131)
[1089] *Crossin et al. (2008, p. 131)
[1090] *Crossin et al. (2008, p. 131)
[1091] *Crossin et al. (2008, p. 131)
[1092] *Crossin et al. (2008, p. 133)
[1093] *Crossin et al. (2008, p. 127)
[1094] *Crossin et al. (2008, p. 127)
[1095] *Crossin et al. (2008, p. 127)
[1096] *Crossin et al. (2008, p. 127)
[1097] *Crossin et al. (2008, p. 127)
[1098] *Morrison, Quick and Foreman. (2002, p. 231). The authors cite Servizi and Jansen (1977) for this information.
[1099] *Morrison, Quick and Foreman. (2002, p. 231). The authors cite Bouke et al. (1975) for this information.
[1100] *Morrison, Quick and Foreman. (2002, p. 231). The authors cite Gilhousen (1990) for this information.

Alternatively, in regions or specific water bodies where temperatures are below thermal optima for fish or temperature sensitivity is not a concern, increased water temperatures may promote fish growth and survival.[1102] Even minor temperature increments can change egg hatch dates and increase seasonal growth and instream survival in juvenile salmon.[1103] At Carnation Creek on the west coast of Vancouver Island, minor changes in stream temperatures in the fall and winter due to forest harvesting profoundly affected salmonid populations, accelerating egg and alevin development rates, emergence timing, seasonal growth, and the timing of seaward migration.[1104]

Mantua et al. (2010) report upper thermal tolerance of cutthroat and rainbow trout, and pink, chum, coho, and Chinook salmon (Table 13).

Table 13. Maximum weekly temperature upper thermal tolerances for salmonids

Species	*Upper thermal tolerances (°F with °C in parentheses)*
Cutthroat trout (*Oncorhynchus clarki*)	73.9 (23.3)
Rainbow trout (steelhead; *O. mykiss*)	75.2 (24.0)
Chum salmon (*O. keta*)	67.6 (19.8)
Pink salmon (*O. gorbuscha*)	69.8 (21)
Coho salmon (*O. kisutch*)	74.1 (23.4)
Chinook salmon (*O. tshawytscha*)	75.2 (24)

Based on the 95th percentile of maximum weekly mean temperatures where fish presence was observed (Eaton and Scheller, 1996) *Source: Reproduced from Mantua, Tohver, and Hamlet. (2010, Table 2, p. 194) by authors of this report.*

Oregon and Northwestern California

The Klamath River and its tributaries support populations of anadromous fish species with economic, ecological, and cultural importance.[1105] Coho salmon (*Oncorhynchus kisutch*, Southern Oregon/Northern California Coasts Evolutionarily Significant Unit) are listed as threatened under the U.S. Endangered Species Act.[1106] In addition, steelhead trout (*Oncorhynchus mykiss*) and Chinook salmon (*Oncorhynchus tshawytscha*) in the lower Klamath Basin are of special concern.[1107] Habitat degradation, over-exploitation, and reductions in water quality and quantity have been implicated in declines of these species.[1108] In particular, low late-summer and early fall streamflow in several tributaries is a major factor limiting survival of juvenile coho salmon.[1109] Increasing late-summer tributary flow is a major objective

1101 *Morrison, Quick and Foreman. (2002, p. 231). The authors cite Gilhousen (1990), Rand and Hinch (1998), and Williams (2000) for this information.
1102 *Pike et al. (2010, p. 730)
1103 *Pike et al. (2010, p. 730)
1104 *Pike et al. (2010, p. 730). The authors cite Tschaplinksi et al. (2004) for this information.
1105 *Van Kirk and Naman. (2008, p. 1036)
1106 *Van Kirk and Naman. (2008, p. 1036). The authors cite Good et al. (2005) for this information.
1107 *Van Kirk and Naman. (2008, p. 1036-1037). The authors cite Nehlsen et al. (1991) for this information.
1108 *Van Kirk and Naman. (2008, p. 1037). The authors cite Nehlsen et al. (1991), Brown et al. (1994), and Good et al. (2005) for this information.
1109 *Van Kirk and Naman. (2008, p. 1037). The authors cite NRC (2003) and CDFG (2004) for this information.

of coho salmon recovery efforts, particularly in the Scott River (CA), the most important coho salmon spawning and rearing stream in the basin.[1110]

Future Projections

Southcentral and Southeast Alaska

Southeast Alaska supports a diverse set of salmonids that depend on freshwater ecosystems.[1111] The five Pacific salmon include pink (*Oncorhynchus gorbuscha*), chum (*O. keta*), coho (*O. kisutch*), sockeye (*O. nerka*), and chinook (*O. tshawytscha*) salmon.[1112] Life history strategies of anadromous salmonids in Alaska separate into two groups on the basis of how they use the freshwater environment; general patterns are shown in Figure 27.[1113] Extreme variation occurs within the group, however, and these variations are significant in as much as they illustrate the plasticity of salmonids to adapt to a range of environmental conditions and may be important in an environment of rapidly changing climatic conditions.[1114]

Pacific salmon as a group occupy habitats that range from the Beaufort Sea where they occur in relatively small numbers to San Francisco Bay where they are nearly extirpated.[1115] Furthermore, they have been introduced to diverse geographic locations in both the northern and southern hemispheres.[1116] They readily exploit new habitats opened with fish ladders and major changes in watersheds.[1117] These characteristics suggest that Pacific salmon in southeast Alaska may be fairly resilient in the face of global temperature increases.[1118] If the temperatures in southeast Alaska increase by 3.6 to 7.2°F (2–4°C), then the climate might be similar to that in southern British Columbia or Washington State.[1119] Both locations have climates that are generally favorable to Pacific salmon and have or had robust salmon stocks.[1120] As noted earlier in this report, Alaska-wide average annual air temperature is projected to increase 5-13°F (2.8-7.2°C) after 2050.[1121]

In southcentral Alaska, several major systems of lakes support large runs of sockeye salmon and include the Kenai, Tustamena and Skilak lakes, all glacially influenced.[1122] Climate-induced increases in glacial runoff into these lakes in summer could cause concomitant increases in turbidity and reductions in primary productivity.[1123] The offsetting effects of a shorter period of ice cover and warmer water

[1110] *Van Kirk and Naman. (2008, p. 1037). The authors cite Brown et al. (1994), NRC (2003), and CDFG (2004) for this information.
[1111] *Bryant. *Global climate change and potential effects on Pacific salmonids in freshwater ecosystems of southeast Alaska.* (2009, p. 170).
[1112] *Bryant. (2009, p. 170)
[1113] *Bryant. (2009, p. 170). The author cites Groot and Margolis (1991) for this information.
[1114] *Bryant. (2009, p. 171)
[1115] *Bryant. (2009, p. 184). The author cites Craig and Haldorson (1986), Nehlson (1997), and Groot and Margolis (1991) for this information.
[1116] *Bryant. (2009, p. 184). The author cites Quinn et al. (2001) and Hansen and Holey (2002) for this information.
[1117] *Bryant. (2009, p. 184). The author cites Hendry et al. (1998, 2000) and Bryant et al. (1999) for this information.
[1118] *Bryant. (2009, p. 184)
[1119] *Bryant. (2009, p. 184)
[1120] *Bryant. (2009, p. 184)
[1121] *US-GCRP. (2009, p. 139)
[1122] *Melack et al. (1997, p. 986)
[1123] *Melack et al. (1997, p. 986)

temperatures could enhance zooplankton and salmon fry growth.[1124] With increasing latitude, overwintering mortality becomes a significant factor in the production of salmonids.[1125] Consequently, a reduction in the length of ice cover in streams may enhance overwintering survival.[1126]

However, many of the predicted outcomes from scenarios for climate change are not favorable for anadromous salmonids.[1127] For example, increased winter flows and spring peaks may reduce salmonid egg to fry survival, particularly if the cumulative effects of altered land use are considered, e.g. increased erosion and runoff.[1128] Higher spring peaks in flow and warmer water temperatures may cause earlier emergence of fry and migration of pink and chum salmon fry to estuaries at a time when their food sources have not developed adequately.[1129] Lower summer flow may reduce the amount of suitable spawning and rearing habitat.[1130]

Bryant (2009) summarizes potential effects of climate change on anadromous salmonids in freshwater habitats of southeast Alaska (Table 14). The three major climate change variables are temperature, precipitation (hydrology), and sea level.[1131]

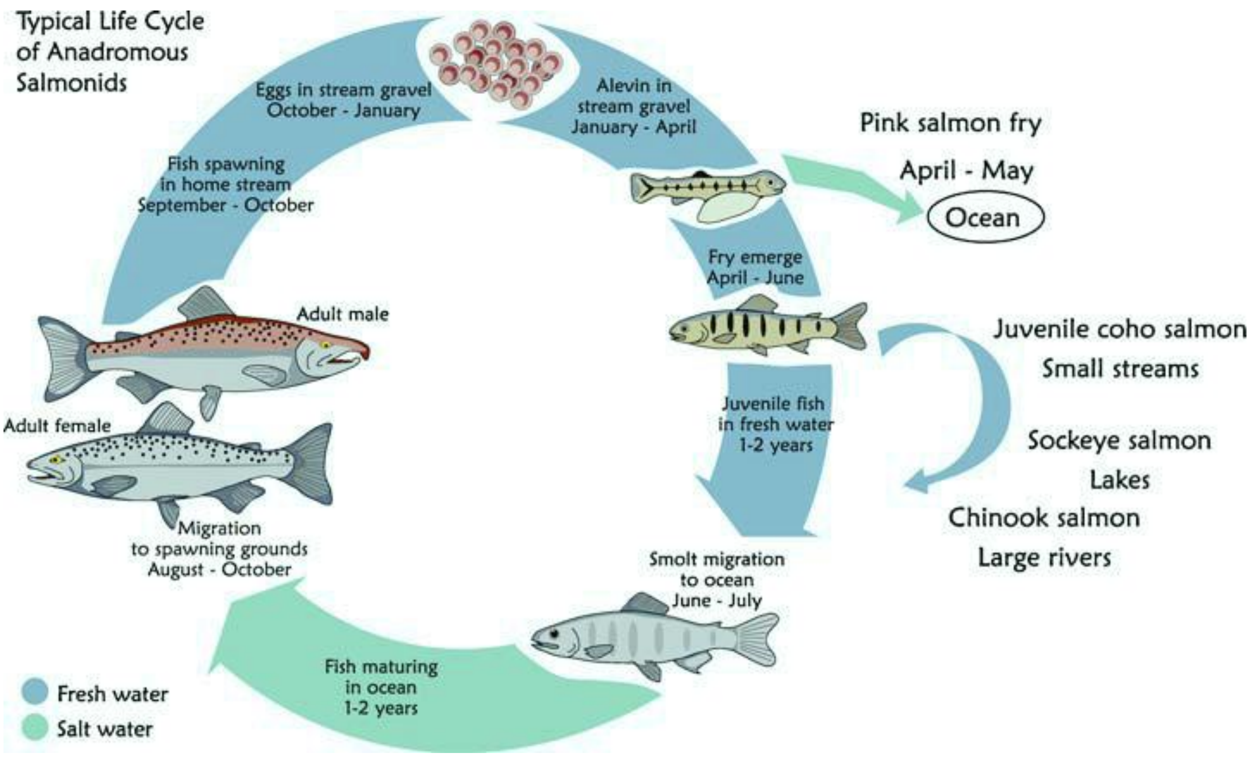

Figure 27. Life cycle strategies of the five species of salmon (*Oncorhynchus*) found in southeast Alaska with those that rear in freshwater and those that migrate directly to the ocean.
Source: Reproduced from Bryant (2009, Fig. 1, p. 171) by authors of this report.

[1124] *Melack et al. (1997, p. 986)
[1125] *Melack et al. (1997, p. 987)
[1126] *Melack et al. (1997, p. 987)
[1127] *Bryant. (2009, p. 182)
[1128] *Melack et al. (1997, p. 987)
[1129] *Melack et al. (1997, p. 987)
[1130] *Melack et al. (1997, p. 987)
[1131] *Bryant. (2009, p. 172)

Table 14. Summary of potential effects of climate change on anadromous salmonids in freshwater habitats of southeast Alaska.
Source: Reproduced from Bryant. (2009, Table 1, p. 183) by authors of this report.

Pink salmon and chum salmon

- Increased frequency and extent of pre-spawner mortality resulting from increasing temperatures and decreasing summer flows
- Earlier emergence time and entry into the marine environment with less favorable conditions for early feeding and growth
- Deterioration of spawning habitats
  - Greater upslope landslide activity increasing scour and sediment infiltration
  - Incursion of saltwater from rising sea levels into spawning areas
  - Alterations in sediment dynamics with changes in sea level
- Alterations in run timing as a result of shifts in temperature and discharge

Sockeye salmon

- Shifts in spawning time with subsequent changes in time of emergence of fry
- Spawning habitat deterioration from upslope landslides induced by increased rainfall intensity
- Changes in growth and survival resulting from alteration of trophic status of lakes
  - Shifts in zooplankton availability
  - Changes in lake physical and chemical dynamics resulting from either increases or decreases in water recharge
  - Decreasing rearing capacity and secondary production from saltwater intrusion
- Increased predation as thermal characteristics become more favorable for natural or introduced predators

Chinook salmon

- Changes in run timing forced by temperature and/or discharge regimes
- Increased stress and mortality during spawning migration resulting from loss of thermal refuges in large pools
- Deterioration of spawning habitat caused by increased frequency of upslope landslides
- Loss of rearing habitat as thermal refuges are lost

Coho salmon

- Deterioration of spawning habitat from landslides that scour spawning beds and deposit sediment on downstream spawning areas
- Changes in fry emergence timing and emigration
- Effects of climate change induced temperatures on growth and survival of juvenile coho salmon
  - Increased growth as temperatures in streams increase above 50°F (10°C) but remain below 64°F (~18°C)
  - Decreased survival as metabolic demands increase but food supplies become limited
- Loss of rearing habitats
  - Decrease in summer rearing habitats as flow decreases and pool abundance and quality decrease
  - Deterioration of off-channel habitats as temperatures exceed optimum ranges
  - Loss of off-channel habitats through more frequent high intensity rainfall events that remove instream structure and beaver dams during fall and winter
  - Intrusion of salt water into low elevation rearing areas

British Columbia

In regions or specific water bodies where temperatures are below thermal optima for fishes or temperature sensitivity is not a concern, increased water temperatures may promote fish growth and survival.[1132] For example, even minor temperature increments can change egg hatch dates and increase seasonal growth and instream survival in juvenile salmon.[1133] However, trends toward decreased autumn and increased winter precipitation on the coast can lead to increased stress, followed by winter flooding and stream erosion with negative consequences for survival.[1134] An increase in annual precipitation without an increase in summer precipitation offers little benefit to species that need moisture during the hot, dry season, and summer precipitation is indeed projected to decrease.[1135]

Additional impacts to salmon in British Columbia are summarized in Table 15 and Figure 29.

Table 15. Species and life stage-specific summary of *potential* biological vulnerabilities of salmon to climate-induced changes in water flows and temperatures *Linkages among climate drivers, physical changes in freshwater habitats, and biological mechanisms are summarized in Figure 29* *on page 143.*
Source: Reproduced from Nelitz et al. (2007, Table 2, p. 17) by authors of this report.

Type	Eggs	Fry	Parr	Smolts	Spawners
Chinook, Coho, and Sockeye	• Scour • Stranding • Change in hatch timing • Change in sex ratio of eggs	• Change in growth rates • Thermal mortality • Oxygen stress • Change in prey density • Change in competition	• Change in growth rates • Thermal mortality • Oxygen stress • Change in prey density • Change in competition	• Increased predation and competition • Change in growth rates • Oxygen stress • Delayed outmigration • Change in age of outmigration • Change in physiological function	• Change in run timing • Increased incidence of disease • Thermal mortality • Bioenergetic stress • Increased predation
Chum and Pink	• Scour • Stranding • Change in hatch timing • Change in sex ratio of eggs				• Change in run timing • Increased incidence of disease • Thermal mortality • Bioenergetic stress • Increased predation

1132 *Pike et al. (2010, p. 730)
1133 *Pike et al. (2010, p. 730)
1134 *Austin et al. (2008, p. 184)
1135 *Austin et al. (2008, p. 184). The authors cite Pacific Climate Impacts Consortium (PCIC, no date) Climate Overview for this information.

Washington and Oregon

Mantua, Tohver, and Hamlet (2010) state that stream temperature modeling predicts significant increases in water temperatures and thermal stress for salmon statewide for both A1B and B1 emissions scenarios.[1136] For the fifty-five western Washington stations included in the study, Mantua, Tohver, and Hamlet project:

- At seventy-one percent of stations, estimated weekly maximum stream temperature (T_w) is projected to be less than 67.1°F (T_w < 19.5°C) for the 2080s, compared to eighty-seven percent of streams in the 1980s (an estimated sixteen percent decline).[1137]
- A prolonged duration of water temperatures unfavorable for salmon is predicted for the Lake Washington/Lake Union ship canal, where T_w > 69.8°F (T_w > 21°C) persisted up to ten weeks in the late 1980s.[1138]
- The expansion of the T_w > 69.8°F (T_w > 21°C) season is predicted to increase considerably for the warmer streams in western Washington like the Stillaguamish River at Arlington, where in recent years these conditions were observed zero to at most a few weeks each summer.[1139] For this station the period with T_w > 69.8°F (T_w > 21°C) lasts up to thirteen weeks by 2100 and is centered on the first week of August.[1140]

Additional impacts on salmonid species due to climate change include impacts on spawning, migration, egg incubation, and stream rearing (see also, Figure 28):

- **Spawning and migration**
    - Reductions in the volume of summer/fall low flows in transient and rainfall-dominated basins might also reduce the availability of spawning habitat for salmon populations that spawn early in the fall.[1141] In combination with increased summertime stream temperatures, reduced summertime flow is likely to increase mortality rates during spawning migrations for summer-run adults.[1142]
    - Reductions in springtime snowmelt may negatively impact the success of smolt migrations from snowmelt dominant streams where seaward migration timing has evolved to match the timing of peak snowmelt flows.[1143]
    - In the absence of thermal cues for initiating spawning migrations, temperature impacts on adult spawning migrations are projected to be most severe for stocks having summertime migrations.[1144] These include summer-run steelhead, sockeye and Chinook salmon populations in the Columbia Basin, and sockeye and Chinook salmon in the Lake Washington system.[1145]

1136 *Mantua, Tohver and Hamlet. *Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State*. (2010, p. 196)
1137 *Mantua, Tohver and Hamlet. (2010, p. 199)
1138 *Mantua, Tohver and Hamlet. (2010, p. 199)
1139 *Mantua, Tohver and Hamlet. (2010, p. 199, 201)
1140 *Mantua, Tohver and Hamlet. (2010, p. 201)
1141 *Mantua, Tohver and Hamlet. (2010, p. 207)
1142 *Mantua, Tohver and Hamlet. (2010, p. 209-210)
1143 *Mantua, Tohver and Hamlet. (2010, p. 207)
1144 *Mantua, Tohver and Hamlet. (2010, p. 207)
1145 *Mantua, Tohver and Hamlet. (2010, p. 207)

- **Egg incubation and stream rearing, including survival rates**
  - Predicted increases in the intensity and frequency of winter flooding in Washington's transient runoff basins will negatively impact the egg-to-fry survival rates for pink, chum, sockeye, Chinook, and Coho salmon due to an increased intensity and frequency of redd and egg scouring.[1146] However, the impact of increasing winter flooding will likely vary across species or populations because redd depth is a function of fish size (deeper redds will be less vulnerable to scouring and the deposition of fine sediments). [1147]
  - Parr-to-smolt survival rates will likely be reduced for Coho and stream-type Chinook salmon and steelhead because increases in peak flows reduce the availability of slow-water habitats and cause increases in the displacement of rearing juveniles downstream of preferred habitats.[1148]
  - In combination with increased summertime stream temperatures, reduced summertime flow is likely to limit rearing habitat for salmon with stream-type life histories (wherein juveniles rear in freshwater for one or more years) (Figure 28).[1149] For example, increased stream temperatures pose risks to the quality and quantity of favorable rearing habitat for stream-type Chinook and coho salmon and steelhead (summer and winter run) throughout Washington because these stocks spend at least one summer (and for Washington's steelhead typically two summers) rearing in freshwater.[1150]

As mentioned previously, excessively high flows in winter, due to rapid melting or increased rainfall, can cause "scouring" events that wash away the gravel beds salmon use as nesting sites.[1151] This is likely to be a particular problem in transient snowmelt/rainfall basins in western Washington and Oregon that experience increased fall/winter flooding[1152] and in river reaches where channel connection to the floodplain is compromised, reducing availability of winter refugia from high flows.

<u>Northwestern California</u>

Information needed.

Information Gaps

Information is needed on observed trends particular to southcentral and southeast Alaska. Information is also needed for future projections throughout the NPLCC region. For example, information is needed to understand the genetic adaptation and phenotypic plasticity of salmonids in response to climate change, and the consequences for abundance, distribution, and survival.

[1146] *Mantua, Tohver and Hamlet. (2010, p. 207)
[1147] *Mantua, Tohver and Hamlet. (2010, p. 207)
[1148] *Mantua, Tohver and Hamlet. (2010, p. 207)
[1149] *Mantua, Tohver and Hamlet. (2010, p. 209-210)
[1150] *Mantua, Tohver and Hamlet. (2010, p. 207)
[1151] *Martin and Glick. (2008, p. 14). The authors cite Spence et al. (1996) for this information.
[1152] *Martin and Glick. (2008, p. 14). The authors cite Battin et al. (2007) for this information.

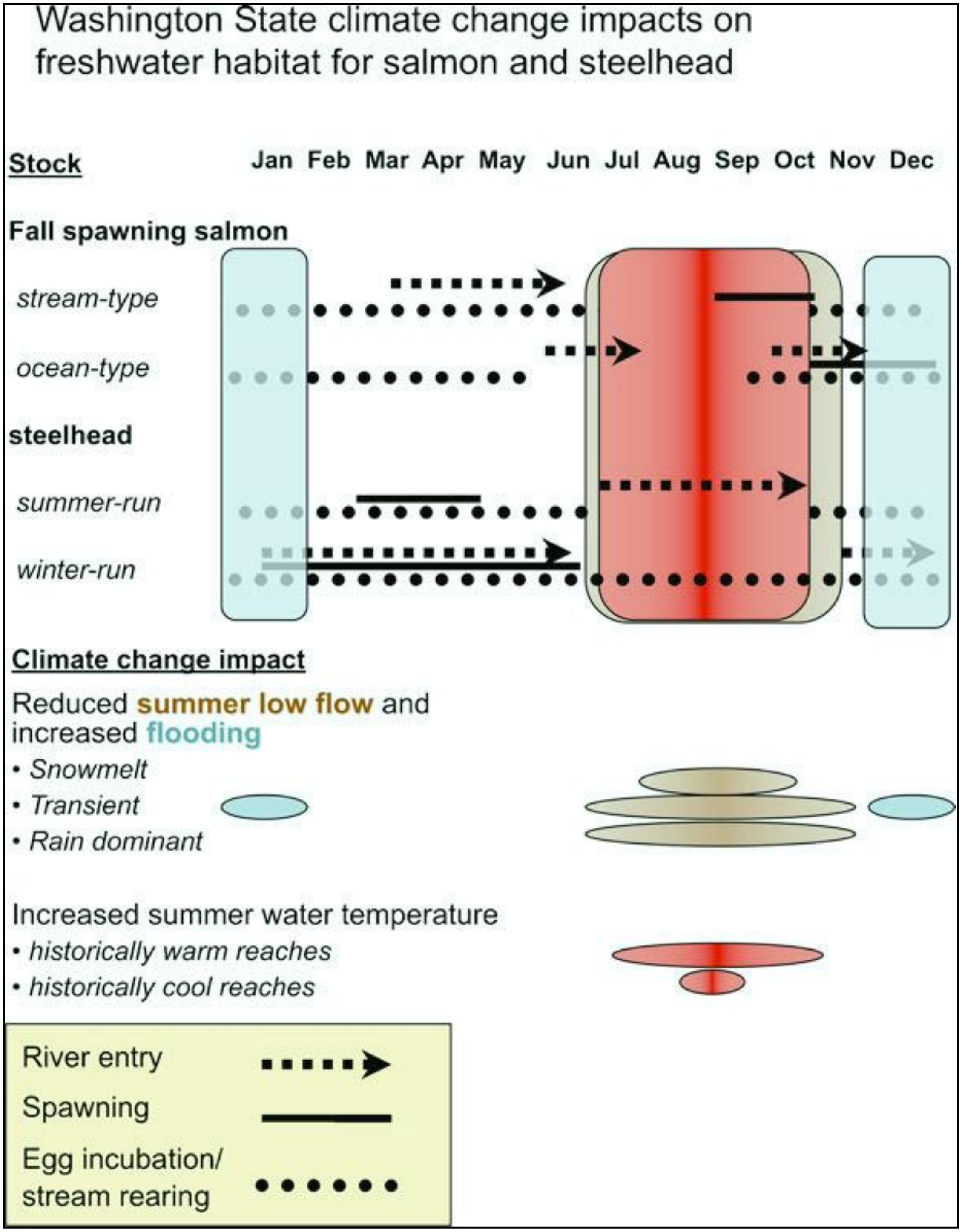

Figure 28. Summary of key climate change impacts on Washington's freshwater habitat for salmon and steelhead, how those impacts differ for streams with different hydrologic characteristics, and how the timing for different impacts compare with the life history for generalized salmon and steelhead life history types. Example life history stages are shown for adult river entry (*broken arrows*), spawning (*solid lines*), and egg incubation and rearing periods (*dotted lines*) for generalized stocks. *Tan shading* highlights periods of increased flooding, *brown shading* indicates periods with reduced summer/fall low flows, and *red shading* indicates periods with increased thermal stress *Source: Reproduced from Mantua, Tohver and Hamlet. (2010, Fig. 11, p. 208) by authors of this report.*

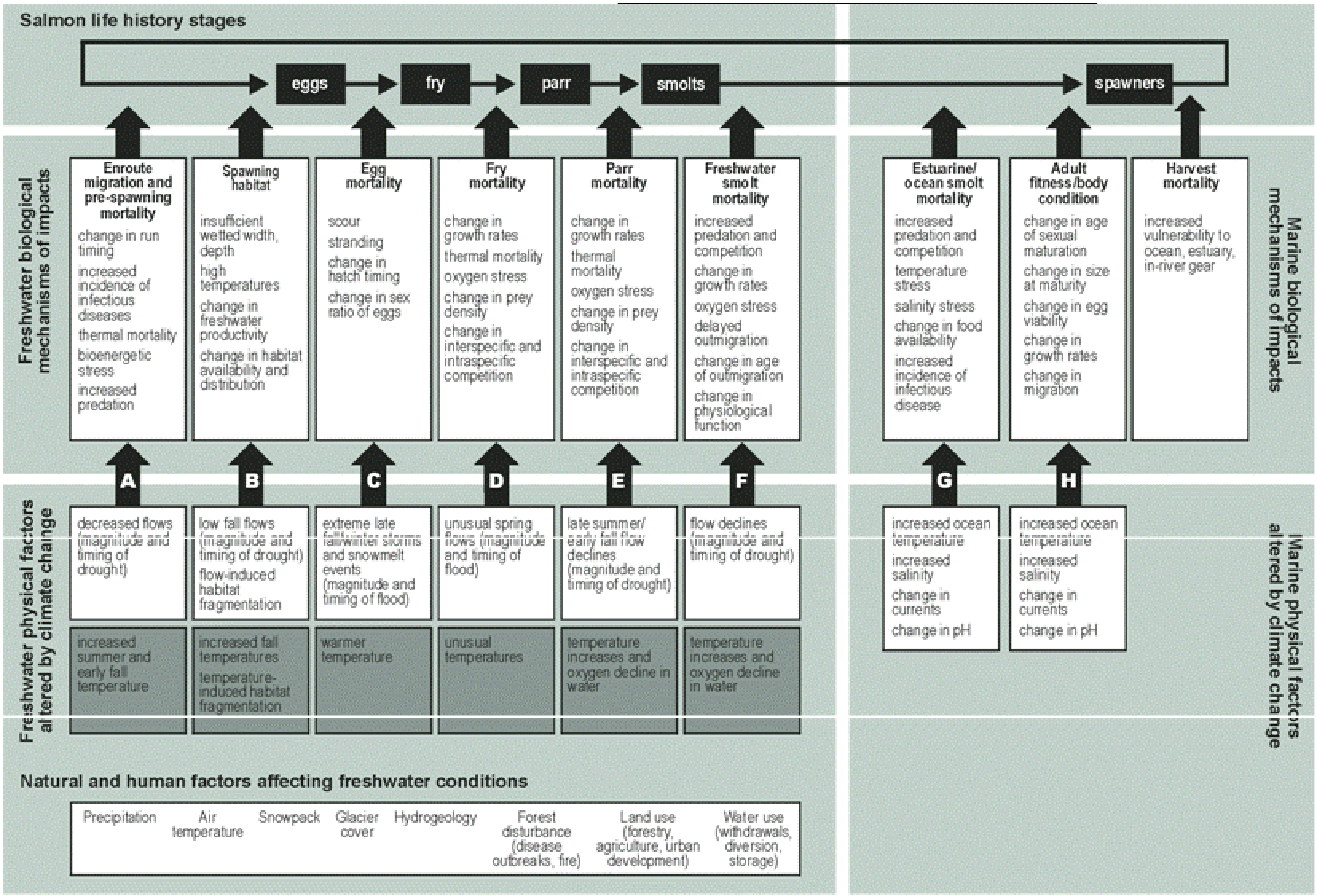

Figure 29. Conceptual diagram illustrating linkages among freshwater physical habitat factors altered by climate change (e.g., water flows and temperatures), freshwater biological mechanisms affecting survival, and life stages of salmon. *Source: Reproduced from Nelitz et al. (2007, Fig. 1, p. 15) by authors of this report.*

3. AMPHIBIANS

Amphibians may be especially sensitive to climatic change because they are ectotherms (i.e., body temperature is determined externally).[1153] Changes in ambient temperature may influence amphibian behaviors, including those related to reproduction.[1154] Potentially, changes in ambient temperature on a global scale could disrupt timing of breeding, periods of hibernation, and ability to find food.[1155]

Global warming could potentially affect amphibians at the population level and could potentially contribute to widely reported population declines.[1156] Because amphibians are key components of many ecosystems, changes in amphibian populations could affect other species within their communities, such as their predators and prey, even if these species were unaffected directly by global warming.[1157]

Global warming could also have a number of indirect effects on amphibians.[1158] For example, one potential consequence of global warming is the increased spread of infectious disease.[1159] Immune-system damage from multiple stressors could make amphibians more susceptible to pathogens whose ranges may change due to global warming.[1160] Moreover, recent evidence suggests that amphibians compromised by ultraviolet radiation are more susceptible to certain pathogens.[1161]

Observed Trends

Global

Amphibians have been shown to be undergoing precipitous declines and species extinction on a global basis, and the recent Global Amphibian Assessment has shown that out of 5743 species, 1856 (32.5%) are globally threatened.[1162] While a large percentage of these declines are attributable to direct anthropogenic effects, such as habitat loss, a substantial amount (48%) are classed as 'enigmatic' declines with no identifiable cause.[1163]

Chytridiomycosis is an emerging infectious disease of amphibians that is causing mass mortality and population declines worldwide.[1164] The causative agent, a non-hyphal zoosporic fungus, *Batrachochytrium dendrobatidis* (Bd), is a recently described species of the chytridiales which is known to infect over ninety-three species worldwide.[1165] Bosch et al. (2007) use long-term observations on amphibian population dynamics in the Peñalara

[1153] *Blaustein et al. *Amphibian breeding and climate change.* (2001, p. 1808). The authors cite Donnelly and Crump (1998) for this information.
[1154] *Blaustein et al. (2001, p. 1808)
[1155] *Blaustein et al. (2001, p. 1808)
[1156] *Blaustein et al. (2001, p. 1808). The authors cite Blaustein and Wake (1995), Stebbins and Cohen (1995), and Ovaska (1997) as examples for this information.
[1157] *Blaustein et al. (2001, p. 1808). The authors cite Burton and Likens (1975) and Blaustein (1994) for information amphibians as key components of ecosystems, and refer the reader to discussion by Donnelly and Crump (1998) for information on predator-prey interactions.
[1158] *Blaustein et al. (2001, p. 1808)
[1159] *Blaustein et al. (2001, p. 1808). The authors cite Cunningham et al. (1996) and Epstein (1997) for this information.
[1160] *Blaustein et al. (2001, p. 1808). The authors cite Blaustein et al. (1994c) for this information.
[1161] *Blaustein et al. (2001, p. 1808). The authors cite Kiesecker and Blaustein (1995) for this information.
[1162] *Bosch et al. *Climate change and outbreaks of amphibian chytridiomycosis in a montane area of Central Spain; is there a link?* (2007, p. 253). The authors cite Stuart et al. (2004) for this information.
[1163] *Bosch et al. (2007, p. 253). The authors cite Stuart et al. (2004) for this information. Quotes in original.
[1164] *Bosch et al. (2007, p. 253). The authors cite Berger et al. (1998) and Daszak (2003) for this information.
[1165] *Bosch et al. (2007, p. 253). The authors cite Longcore et al. (1999) for information on *B. dendrobatidis* and refer the reader to www.jcu.edu.au/school/phtm/PHTM/frogs/chyglob.htm for information on the number of species infected.

Natural Park, Spain, to investigate the link between climate change and chytridiomycosis.[1166] Their analysis shows a significant association between change in local climatic variables and the occurrence of chytridiomycosis within this region.[1167] Specifically, they show that rising temperature is linked to the occurrence of chytrid-related disease, consistent with the chytrid-thermal-optimum hypothesis.[1168] They show that these local variables are driven by general circulation patterns, principally the North Atlantic Oscillation.[1169]

Regional

The Global *Bd* Mapping Project provides a map of *Bd* surveillance in the United States, available at http://www.bd-maps.net/surveillance/suveil_country.php?country=US (accessed 8.29.2011). A global map is available at http://www.bd-maps.net/maps/ (accessed 8.29.2011).

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

Information needed.

Oregon

Blaustein et al. (2001) conducted an analysis of the breeding phenology of four species of North American anurans (i.e. frogs) for which they have long-term data sets.[1170] They found:

- At four sites, neither western toads nor Cascades frogs (*Rana cascadae*) showed statistically significant positive trends toward earlier breeding.[1171] However, at three of four of these sites, breeding time was associated with warmer temperatures.[1172]
- At one site, in Oregon, a trend (nonsignificant) for western toads (*Bufo boreas*) to breed increasingly early was associated with increasing temperature.[1173]

Based on Blaustein et al.'s (2001) data for North American species and a report by Reading (1998) on toads in Europe, Blaustein et al. conclude that the suggestion that amphibians in temperate regions are breeding earlier due to climate change may be premature.[1174]

In a study of downed wood microclimates near three headwater streams and their potential impact on plethodontid salamander habitat in the Oregon Coast Range, streamside and upslope maximum air temperatures measured during July 2006 along all three streams were near or exceeded 86°F (30°C), the critical thermal tolerance

[1166] *Bosch et al. (2007, p. 253)
[1167] *Bosch et al. (2007, p. 253)
[1168] *Bosch et al. (2007, p. 253)
[1169] *Bosch et al. (2007, p. 253)
[1170] *Blaustein et al. (2001, p. 1804)
[1171] *Blaustein et al. (2001, p. 1804)
[1172] *Blaustein et al. (2001, p. 1804)
[1173] *Blaustein et al. (2001, p. 1804)
[1174] *Blaustein et al. (2001, p. 1808)

threshold for western plethodontid salamanders.[1175] Streamside and upslope temperatures inside small logs, large logs, and soils stayed below critical temperatures.[1176] This demonstrates the ability of soil, small logs, and large logs to protect against thermal extremes that are harmful to plethodontid salamanders.[1177] Temperature regimes are especially critical for these lungless salamanders because gas exchange and water balance occurs through the permeable surface of their skin, making them highly susceptible to dehydration.[1178]

Northwestern California

Information needed.

Future Projections

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

Likely impacts on reptiles and amphibians in Washington's Olympic Peninsula include:

- Reduction in snowpack and changes in timing of runoff with warmer temperatures will likely lead to drying of some wetland habitats, such as alpine ponds and wetlands, reducing habitat quality for dependent species such as the Cascades frog, northwestern salamander, long-toed salamander, and garter snakes.[1179]

Oregon

Oregon represents the northern margin of the range of the black salamander (*Aneides flavipunctatus*), and includes habitats that are particularly vulnerable to predicted patterns of global climate change.[1180] In particular, a change in storm patterns that alters precipitation, either annual accumulation or seasonal pattern, could affect this species.[1181] The association of this species with bioclimatic attributes was supported by Rissler and Apodaca (2007).[1182] Warming trends could increase the elevational extent of the species range and increase occupancy of north-facing slopes, and also restrict its distribution at lower elevations or south-southwest aspects.[1183] A smaller band of habitat might result if the current foothills of the Siskiyou Mountains become less suitable for the species.[1184] Also, it is possible that additional "new" habitats might become available for this species in Oregon,

1175 *Kluber, Olson and Puettmann. *Downed wood microclimates and their potential impact on plethodontid salamander habitat in the Oregon Coast Range.* (2009, p. 25)
1176 *Kluber, Olson and Puettmann.. (2009, p. 25)
1177 *Kluber, Olson and Puettmann.. (2009, p. 32)
1178 *Kluber, Olson and Puettmann.. (2009, p. 25-26)
1179 *Halofsky et al. *Adapting to climate change at Olympic National Forest and Olympic National Park (pdf).* (n.d., p. 143)
1180 *Olson. *Conservation Assessment for the Black Salamander (Aneides flavipunctatus) in Oregon.* (October 7, 2008, p. 13)
1181 *Olson. (October 7, 2008, p. 13)
1182 *Olson. (October 7, 2008, p. 13)
1183 *Olson. (October 7, 2008, p. 13)
1184 *Olson. (October 7, 2008, p. 13)

which is at the northern extent of the species' range.[1185] Although more extremes in conditions might forestall the ability of these animals to use habitats that on average appear suitable.[1186] Warming trends also could alter fire regimes and vegetation conditions, further restricting habitats.[1187] Indirect effects from changes of prey or predator communities are likely, but are difficult to predict.[1188] Interactions of warming trends with reduced cover from timber harvest are likely.[1189] Amelioration of climate changes may be possible by retaining canopy cover and large down wood, which moderate temperature extremes in their forested habitats.[1190]

Northwestern California

Information needed.

Information Gaps

Additional studies throughout the NPLCC region are needed to supplement the information on observed trends and future projections presented here. Studies assessing the effects of projected habitat changes (e.g., wetland extent and drying) on amphibians throughout their lifecycle are especially needed.

[1185] *Olson. (October 7, 2008, p. 13)
[1186] *Olson. (October 7, 2008, p. 13)
[1187] *Olson. (October 7, 2008, p. 13)
[1188] *Olson. (October 7, 2008, p. 13)
[1189] *Olson. (October 7, 2008, p. 13)
[1190] *Olson. (October 7, 2008, p. 13)

4. MACROINVERTEBRATES

Macroinvertebrates are organisms without a backbone, generally visible to the unaided eye.[1191]

Macroinvertebrates, as biological indicators of stream water quality, can be utilized to identify impaired waters, determine aquatic life stressors, set pollutant load reductions and indicate improvement.[1192] For example, benthic (bottom-dwelling) macroinvertebrates are sensitive to changes in temperature, precipitation, and the associated flow regimes, which should make them particularly responsive to the effects of climate change.[1193]

Observed Trends

Global

Warmer water may increase the growth rates of aquatic invertebrates and result in earlier maturation.[1194] For example:

- In a mesocosm experiment using the mayfly *Cloeon dipterum*, temperature increases alone had little effect on nymph abundance, and only small effects on body length, though emergence began earlier in the year.[1195]
- McKee and Atkinson (2000) show that for treatments with both increased temperatures and nutrients, both nymph abundance and size increase.[1196]

In general, nutrient enrichment leads to changes in the algal and diatom community composition of a stream, and sometimes, in some streams, to increased production and chlorophyll concentrations, leading to changes in primary invertebrate consumers which could cascade through the community.[1197]

Southcentral and Southeast Alaska

Information needed.

British Columbia

Information needed.

Washington

Information needed.

Oregon

Information needed.

[1191] *NH-DES. *Glossary of Terms (website).* (2008)
[1192] *Kenney et al. *Benthic macroinvertebrates as indicators of water quality: the intersection of science and policy*. (2009, p. 2)
[1193] *Lawrence et al. (n.d., p. 200). The authors cite Bunn and Arthington (2002) and Lytle and Poff (2004) as examples for the sensitivity of benthic macroinvertebrates to changes in temperature, precipitation, and flow regimes.
[1194] *U. S. EPA. (2008a, p. 1-7). The authors cite Poff et al (2002) for this information.
[1195] *U. S. EPA. (2008a, p. 1-7). The authors cite McKee and Atkinson (2000) for this information.
[1196] *U. S. EPA. (2008a, p. 1-7). The authors cite McKee and Atkinson (2000) for this information.
[1197] *U. S. EPA. (2008a, p. 1-7). The authors cite Gafner and Robinson (2007) as an example of the effects of nutrient enrichment on primary invertebrate consumers. The authors cite Power (1990) and Rosemond et al. (1993) for information on changes cascading through the community.

Northwestern California

Information needed.

Future Projections

Global

Table 16 summarizes some observed and projected changes to macroinvertebrates due to climate change. Reduced stream temperature from increased contributions of glacial meltwater and decreased channel stability from changed runoff patterns and altered sediment loads, will, potentially, reduce the diversity of zoobenthic communities in glacier-fed rivers and cause an increase in the relative abundance of a number of key taxa, most notably *Diamesa* spp.[1198]

There is evidence that projected increases in CO_2 will reduce the nutritional quality of leaf litter to macroinvertebrate detritivores (i.e., organisms that obtain nutrients from decomposing organic matter, thereby contributing to decomposition and nutrient cycles).[1199] Reduced litter quality would result in lower assimilation and slower growth.[1200] While seemingly a secondary climate-change effect, changes in these processes could have food web implications: altered stream productivity that impacts fish and other consumers.[1201] In contrast to this, Bale et al. (2002) found little evidence of the direct effects of CO_2 on insect herbivores and instead discuss a range of temperature effects (including interactions with photoperiod cues) on various life history processes that affect ecological relationships.[1202]

Southcentral and Southeast Alaska

Oswood et al. (1992) considered the biogeographical implications for freshwater invertebrates of a less rigorous thermal environment at higher latitudes.[1203] Increased water temperature and decreased permafrost in areas south of the Alaska Range allow for potential redistributions of benthic invertebrate communities with the possible arrival of new predators (e.g. Megaloptera) and the loss of some cold water stenotherms at their southerly ranges.[1204] The altitudinal range of invertebrates in mountain streams may also change with the extension of some species to higher elevations and the reduction in the amount of habitat for cold water stenotherm taxa.[1205]

British Columbia

Information needed.

Washington

Information needed.

Oregon

Information needed.

[1198] *Melack et al. (1997, p. 985)
[1199] *U. S. EPA. (2008a, p. 1-8)
[1200] *U. S. EPA. (2008a, p. 1-8). The authors cite Tuchman et al. (2002) for this information.
[1201] *U. S. EPA. (2008a, p. 1-8)
[1202] *U. S. EPA. (2008a, p. 1-8). The authors cite Bale et al. (2002) for this information.
[1203] *Melack et al. (1997, p. 985). The authors of the cited report are summarizing the work of Oswood et al. (1992).
[1204] *Melack et al. (1997, p. 985)
[1205] *Melack et al. (1997, p. 985)

Northwestern California

Information needed.

Information Gaps

Additional studies throughout the NPLCC region are needed to supplement the information on observed trends and future projections presented here. For example, to support the use of macroinvertebrates as indicators of climate change, detailed information on the current range and distribution of macroinvertebrates (e.g., species and community composition in small geographic areas such as specific streams) is especially needed.

Table 16. Expected climate change effects and sensitivities, and potential novel indicators of climate change, in macroinvertebrates *Source: Modified from U.S. EPA (2008, Tables 3-1 & 3-2, p. 3-4 to 3-7) by authors of this report. Note: The species names Protoneumura, Nenoura, and Neumera were changed to Protonemoura (the former) and Nemoura (the latter two) in response to reviewer comments and online verification.*

Impacts	*Effects, Sensitivities, and Potential Novel Indicators*	*References*
Phenology	Early emergence of mayfly species (also stonefly and caddisfly species); Accelerated development and earlier breeding of the amphipod *Hyallela azteca*	Harper and Peckarsky, 2006; Briers et al., 2004; Gregory et al., 2000; McKee and Atkinson, 2000; Hogg et al., 1995
Longer growing season	Altered sex ratios for certain insects (e.g. trichopteran *Lepidostoma*)	Hogg and Williams (1996)
Life-stage specific	Smaller size at maturity and reduced fecundity of plecopteran *Nemoura trispinosa* and amphipod *Hyallela azteca* due to increased temperature	Turner and Williams, 2005; Hogg et al., 1995
Hydrologic sensitivity	Differential mortality of drought-intolerant mussel species (e.g., *Lampsilis straminea claibornensis*, *Villosa villosa*, *Lampsilis subangulata)* results in changes in relative abundance, extirpation of vulnerable species	Golladay et al. 2004
Measures of richness and abundance	Overall richness generally expected to decline due to temperature sensitivity and hydrologic stresses including increased flashiness, increased instances of summer low flows, drought, etc. However, replacements over time with tolerant forms may ameliorate this in some situations. Abundance or eurytolerant species may increase in some habitats.	Durance and Ormerod, 2007; Bradley and Ormerod, 2001
Measures of community composition and persistence	Compositional changes resulting from reductions in temperature and/or flow sensitive taxa (examples potentially include *Chloroperla*, *Protonemoura*, *Nemoura*, *Rhyacophila munda*, *Agabus* spp,, Hydrophilidae, and *Drusus annulatus*) and increases in less temperature and/or flow sensitive taxa (examples potentially include *Athricops*, *Potamopyrgus*, *Lepidostoma*, *Baetis niger*, *Tabanidae*, *Hydropsyche instabilis*, *Helodes marginata*, *Caenis* spp.), and/or from shifts in range; patterns of persistence or community similarity that track climatic patterns; changes may also occur in functional roles of species.	Daufresne et al., 2003; Durance and Ormerod, 2007; Bradley and Ormerod, 2001; Burgmer et al., 2007; Golladay et al., 2004; Parmesan, 2006; Hawkins et al., 1997
Measures of tolerance / intolerance	Climate-change sensitivities related to temperature or flow regime may be documented as decreases (potentially resulting from local extinctions and/or range shifts) in richness (number of taxa) of temperature or flow-regime sensitive groups. Dominance by tolerant taxa also may increase.	Daufresne et al., 2003; Durance and Ormerod, 2007; Burgmer et al., 2007; Golladay et al., 2004; Parmesan, 2006
Measures of feeding	Variable responses expected, driven by interactions between temperature, which may increase phytoplankton and periphyton productivity and thus increase associated feeding type; hydrologic factors which may decrease periphyton if habitat stability is decreased or sedimentation is increased; CO_2 concentrations, which can directly affect leaf litter composition and decomposition; and changes in riparian vegetation.	Gafner and Robinson, 2007; Dodds and Welch, 2000; Tuchman et al., 2002
Measures of habitat	Number and percent composition of clingers likely to decrease if hydrologic changes decrease habitat stability, increase embeddedness, or decrease riparian inputs of woody vegetation.	Johnson et al., 2003; Townsend et al., 1997