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To: David Clugston, USACE Portland District

From: Matthew Keefer, Chris Caudill (University of Idaho) and Chris Peery (USFWS)

RE: Temperature regimes during upstream migration and the use of thermal refugia by adult salmon and steelhead in the Columbia River basin.

Date: 6 May 2010

Introduction

Summertime water temperatures in the lower Columbia River have steadily increased over the last several decades (Figure 1). Annual peak temperatures have exceeded 21 °C in most recent years and have been as high as 24 °C. The warmest period typically occurs in late July to early September, coincident with late-migrating summer Chinook and sockeye salmon and with substantial portions of the fall Chinook salmon and summer steelhead runs (Figure 2). Water temperatures in the 19-22 °C range, like those that routinely occur in the Columbia River main stem, are a significant management concern for adult migrants because a large proportion of adults currently experience thermal conditions thought to be stressful. Such temperatures have been associated with behavioral changes and a variety of sub-lethal effects on physiology, disease susceptibility, reproductive development, gamete quality (i.e., over-ripening), survival, and fitness (e.g., Flett et al. 1996; Lee et al. 2003; Naughton et al. 2005; Richter and Kolmes 2005; Wagner et al. 2005; King et al. 2007; Mann 2007; Reid 2007; Keefer et al. 2008, *in press*). Based on these and other studies, we assume that temperatures above ~18-19 °C induce stress in adult migrants and that higher temperatures are associated with stronger negative costs. This issue may become more acute if warmer regional temperatures predicted by climate models come to pass.

Many adult salmon and steelhead temporarily use thermal refugia when Columbia and Snake River water temperatures are high (Goniea et al. 2006; Keefer et al. 2009). These sites appear to be critically important mid-migration holding habitats for some populations. A series of cool-water refugia are located along the migration corridor at tributary confluences with the main stem rivers. Many of the most-used refugia sites are located between Bonneville and John Day dams in the lower Columbia River, where cool-water tributaries draining the Cascade Range enter reservoirs. These sites are often 2-7 °C cooler than the main stem (High et al. 2006; Goneia et al. 2006). Additional sites that may be thermal refugia for adult migrants include

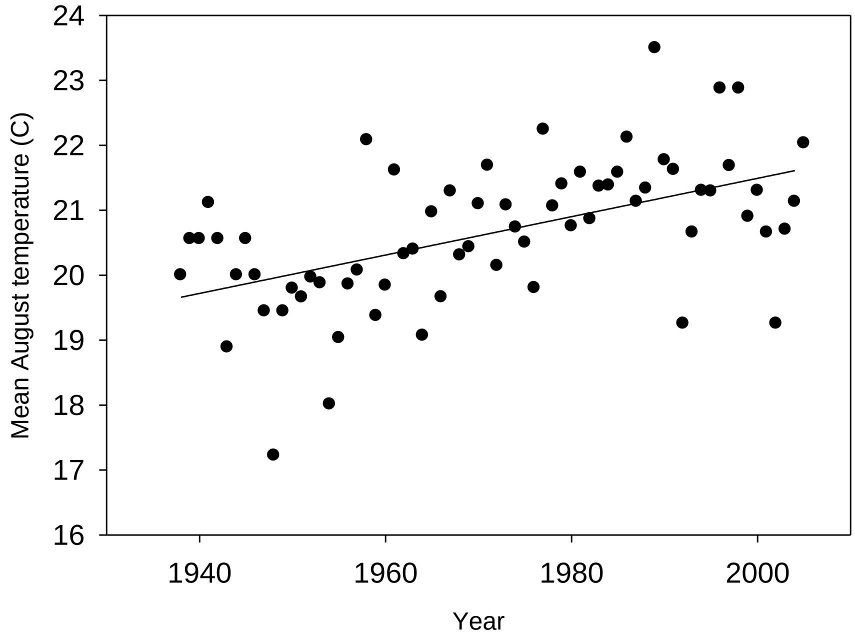

Figure 1. Mean August water temperature (°C) at Bonneville Dam, 1938-2005. Source: Columbia River DART.

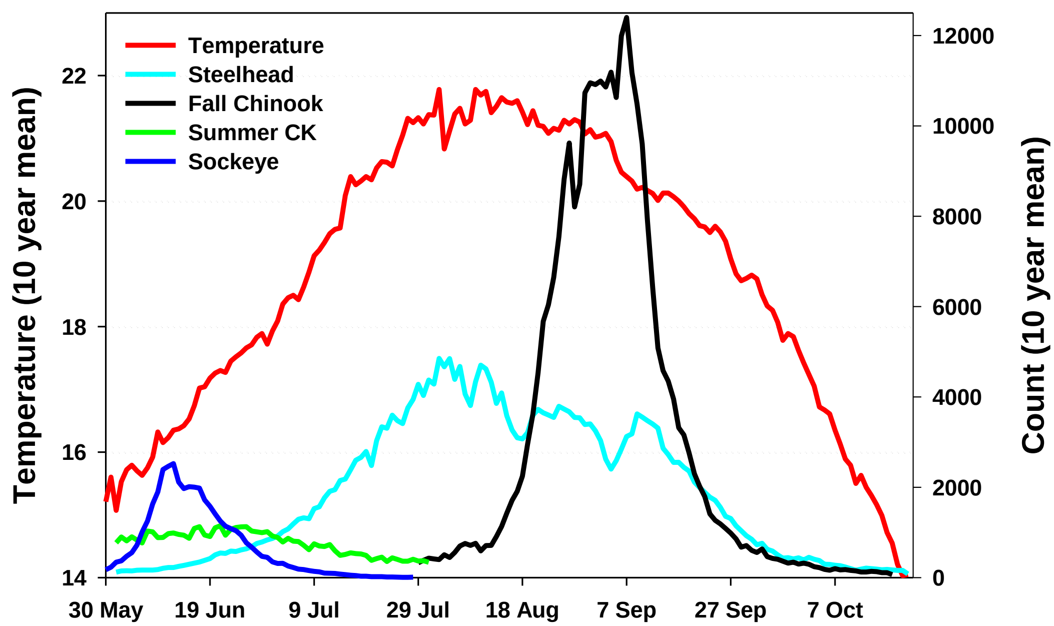

Figure 1. Ten-year (1996-2005) mean lower Columbia River water temperature (°C) and mean run size and timing of adult summer Chinook salmon, fall Chinook salmon, sockeye salmon, and summer steelhead at Bonneville Dam. Thermal refugia use by many adult populations has been associated with water temperatures greater than 19-20 °C.

tributary confluence areas downstream from Bonneville Dam, upstream from the Columbia River-Snake River confluence in the mid-Columbia, and in the Snake River upstream from Lower Granite reservoir. The lower Snake River contains little in the way of cool water refugia but there is evidence that fish will use the limited cool water sources when available. Salmonid use of sites other than in the Bonneville-John Day reach has not been well documented, but there is anecdotal evidence that adult aggregations occur seasonally at several locations. Groundwater-based refugia in the mainstem have not been identified, but may be present in reaches not dominated by bedrock. Potential locations include areas downstream of dams such as tailraces where there is a potential for groundwater input (above the dam) and expression (below the dam). The ecological significance of such areas would depend on the discharge rate and temperature of groundwater. The latter would be strongly influenced by groundwater residence time.

Much of what is known about adult thermal refugia use in the Columbia basin has been gleaned from the large-scale radiotelemetry studies funded by the USACE and conducted by the UI and NMFS. While these studies focused on monitoring adult salmonid behavior at dams, most major tributaries were also monitored to help estimate Hydrosystem escapement and identify individual populations. The antenna arrays at tributary confluence areas and adjacent reservoir sites allowed us to collect behavioral data at several of the critical refugia sites. The following summary describes some of the basic results of this research.

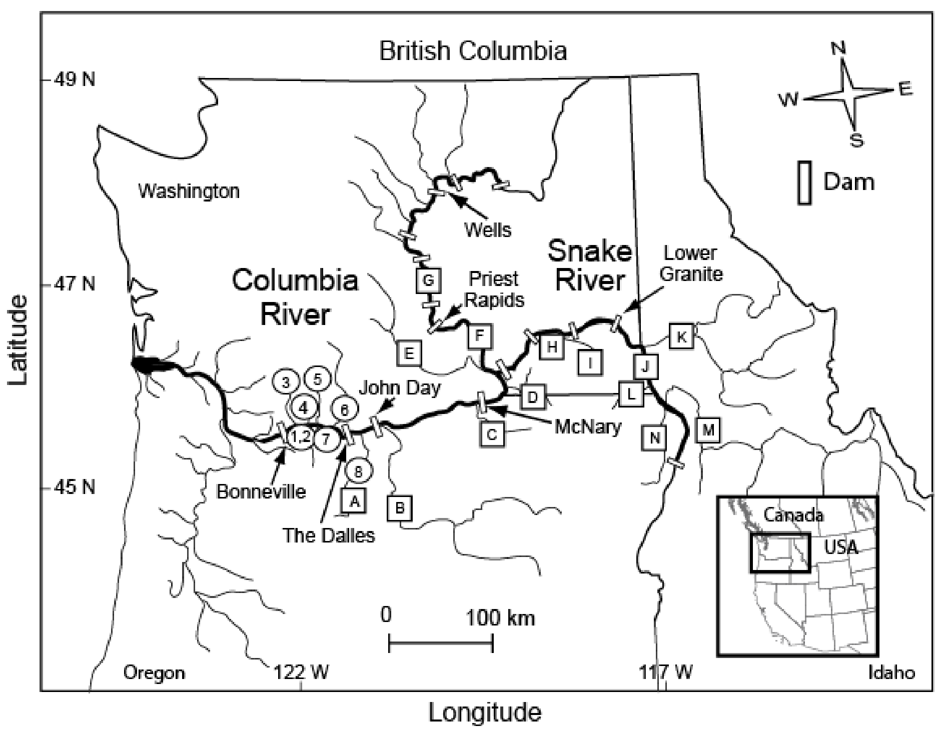

Figure 3. Map of the Columbia and Snake River basins, where radio-tagged adult salmon and steelhead were monitored at dams, in reservoirs, and while using cool water tributaries during migration through the lower Columbia River. Thermoregulatory behaviors were monitored at eight sites: (1) Herman Cr., (2) Eagle Cr., (3) Wind R., (4) Little White Salmon R., (5) White Salmon R., (6) Klickitat R., (7) Hood R., and (8) Deschutes R. Sites A-N were tributary populations used in the steelhead study described in Keefer et al. (2009).

Thermal refugia summary

Spatial distribution – The thermal refugia sites that have been most studied are located at tributary confluences in the Bonneville and The Dalles reservoirs (Figure 3). These include Herman and Eagle Creeks and the Wind, Little White Salmon, White Salmon, Hood, Klickitat, and Deschutes rivers. The most-used among these have been Herman Creek and the Little White Salmon, White Salmon, and Deschutes Rivers. Upstream from John Day Dam, tributaries draining primarily high-desert landscapes like the John Day, Umatilla, and Yakima rivers may provide periodic cool water refugia, but lower reaches of these rivers are often as warm as or warmer than the Columbia River during summer. A large temperature gradient often exists at the confluence of the Snake and Columbia rivers, with the Snake typically being warmer. Some Snake River adults temporarily hold in the cooler mid-Columbia water during warm periods (e.g., Stuehrenberg et al. 1978; Quinn et al. 1997). For example, fall Chinook salmon and steelhead tagged at Ice Harbor Dam with thermal recorders that delayed reascending the Snake River for 2 to 3 weeks had noticeably cooler thermal profiles than adults that did not delay their migrations through the lower Snake River (Mann and Peery 2005).

Likely thermal refugia downstream from Bonneville Dam include the confluence areas of the Cowlitz, Lewis, Washougal, and Sandy rivers as well as several smaller tributaries fed by Cascade Range snowmelt or glaciers. Adult use of these sites for thermal refuge is largely anecdotal. Similarly, we are unaware of any quantitative summaries of refugia use in the mid-Columbia River upstream from Priest Rapids Dam, though confluence areas of the Wenatchee, Methow, and Entiat rivers may be seasonally important when main stem Columbia River temperatures reach stressful levels. In the impounded lower Snake River, there are known thermal refugia frequented by fall Chinook salmon and steelhead migrants (Mann 2007) at the outfall from Lyons Ferry hatchery and periodically at the Tucannon River confluence. In Lower Granite reservoir, Chinook salmon and steelhead will select to migrate in cooler water layers that result from releases from Dworshak reservoir when available (Clabough et al. 2006; 2007). Upstream from Lower Granite reservoir, the confluence of the Clearwater and Snake rivers is an important refugium site for adults *en route* to the Hells Canyon reach of the Snake and to the Salmon, Grande Ronde, and Imnaha rivers. Thermal refugia have also been identified in several Snake River tributaries (e.g., Ebersole et al. 2003; Howell et al. 2010), but these studies have focused on resident salmonids and juvenile anadromous fish. We have observed adult salmon using thermal refugia near spawning grounds in some Salmon River tributaries (e.g., the South Fork Salmon River), but these behaviors have not been quantified. We are also currently examining the relationship between water temperature, adult behavior and prespawn mortality during the post migration-prespawn period in Chinook salmon spawning tributaries in the Willamette River basin (Mann et al. *in review*).

Primary adult populations using refugia – The incidence and duration of thermal refugia use differs widely among populations as a function of migration timing and basic life history. In our research, summer steelhead had both the greatest incidence (~70%) and longest duration (up to several weeks or more) of refugia use (e.g., Figure 4). Many steelhead also used multiple refugia sites. Extended refugia residence times resulted, at least in part, from the relatively flexible migration timetable for steelhead. Many of the summer-run fish enter the Columbia River study area at the warmest time but have 6-10 months to reach springtime spawning areas. In our

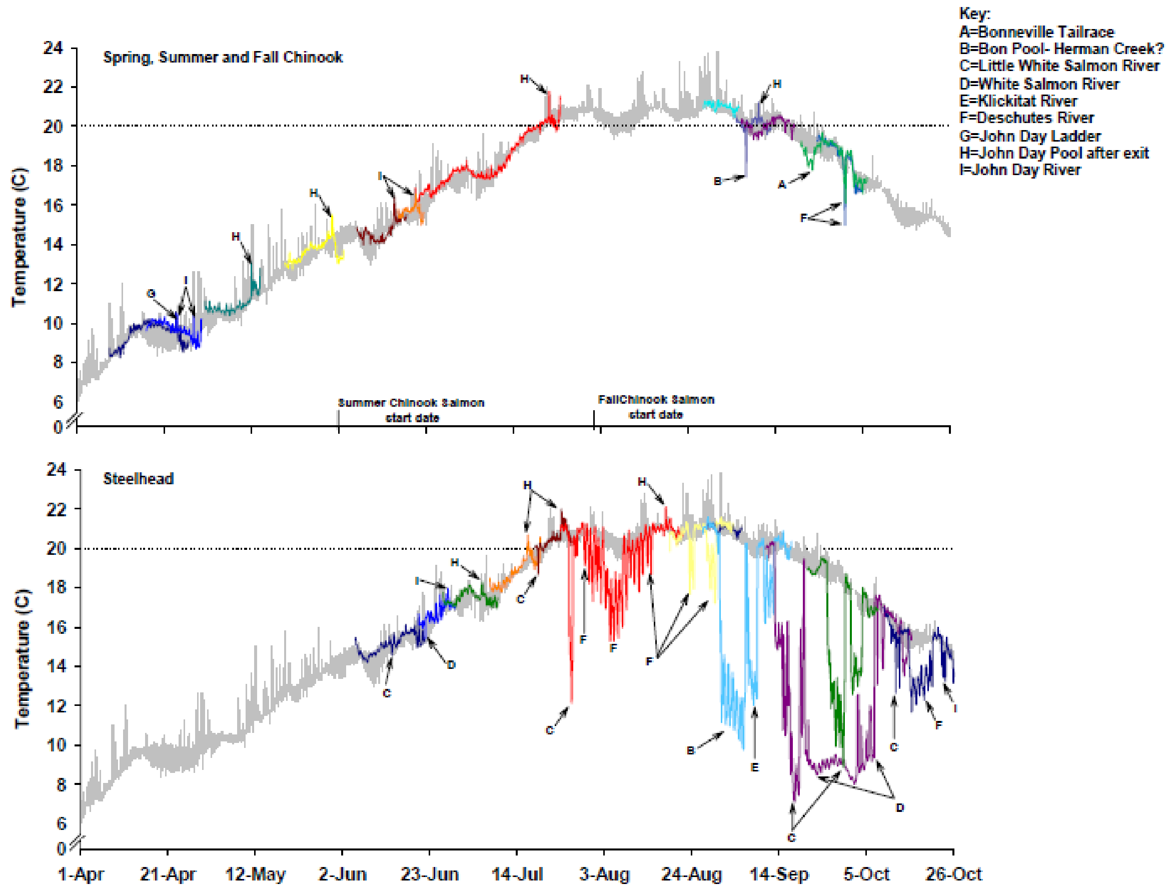

Figure 4. Examples of migration temperatures adult Chinook salmon (top) and steelhead (bottom) experienced during their migration from Bonneville Dam to McNary Dam, 2002. Gray bars represent the range (min to max) of daily mean water temperatures recorded at the four lower Columbia River dams. Colored lines represent fish body temperatures as recorded by internal temperature tags. Body temperatures below the gray bars indicate thermal refugia use: specific migration locations are noted in the key at the upper right. Figure from Caudill et al. *in prep*. Also see Clabough et al. (2008).

research, steelhead populations with relatively early (i.e., May) and relatively late (i.e., late September to October) migration past Bonneville Dam tended to encounter lower main stem temperatures and used lower Columbia River refugia at substantially lower rates than populations that migrated in mid-summer (High et al. 2006; Keefer et al. 2009).

In contrast with steelhead, about 20% of fall Chinook salmon and 15% of summer Chinook salmon were recorded in one or more lower Columbia refugia sites in the radiotelemetry studies (e.g., Goneia et al. 2006). Summer and fall Chinook salmon have typically used refugia sites on a scale of days rather than weeks and mostly when main stem temperatures were highest (e.g., Figure 4). The comparatively limited overall use by Chinook salmon (versus steelhead) is presumably because salmon must reach spawning areas by late summer or fall. Sockeye salmon, which mostly pass through the lower Columbia River prior to the warmest temperatures, have had the most limited refugia use in our study (1 year only), with about 8% recorded in cool water tributaries. In this same year, we found evidence for temperature-dependent mortality in sockeye related to late run timing (Naughton et al. 2005).

Temperature cues associated with refugia use – Initiation of thermal refugia use in the lower Columbia River has been associated with main stem water temperatures of about 19 °C for steelhead (Figure 5) and between 20 and 21 °C for fall Chinook salmon (Figure 6). The incidence and duration of use for both runs rapidly increased as temperatures rose above 21°C. In the Snake River, sockeye salmon similarly used the Clearwater River refugium when the main stem was > 20.5 °C (Keefer et al. 2008).

Effects of refugia use – Adult salmonid use of thermal refugia potentially has both positive and negative effects on upstream migrants. These effects have rarely been quantified in field studies because fish fate, reproductive success, survival of progeny, and other fitness measures are difficult to measure and to link to the thermoregulatory behavior or thermal experience. Presumed benefits of refugia use include reduced metabolic costs, reduced physiological stress, reduced negative temperature effects on maturation and gamete quality, and increased survival. The most obvious direct negative effect is increased harvest risk because fish are spatially and temporally concentrated in refugia, attracting intensive fisheries. We found that Snake River and upper Columbia River steelhead that used refugia in the lower Columbia River were significantly less likely to survive to spawning tributaries, primarily because harvest rates in and near the refugia sites were high (Keefer et al. 2009). We have been unable to assess this harvest effect in Chinook salmon because the proportions using refugia were lower and relatively few fish were of known origin (i.e., with juvenile PIT tags that identified natal sites). The latter distinction is necessary to differentiate harvest of local returning fish from harvest of upstream migrants taken while holding in refugia.

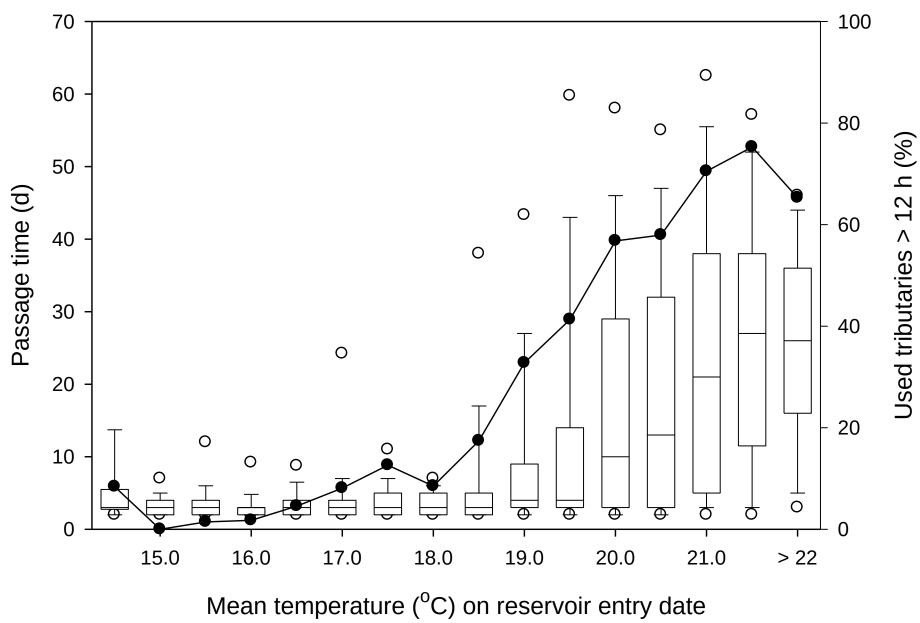

Figure 5. Steelhead passage times (d) from the top of Bonneville Dam to the top of The Dalles Dam, by water temperature at the Bonneville WQM site on the date each fish entered the Bonneville reservoir. Box plots show median, quartile, 10^{th}, and 90^{th} percentiles, pooled across study years; 5^{th}, and 95^{th} percentiles are marked by open circles. Solid line with solid circles shows the percent of steelhead recorded in cool water Bonneville reservoir tributaries for > 12 h. Figure from Keefer et al. (2009).

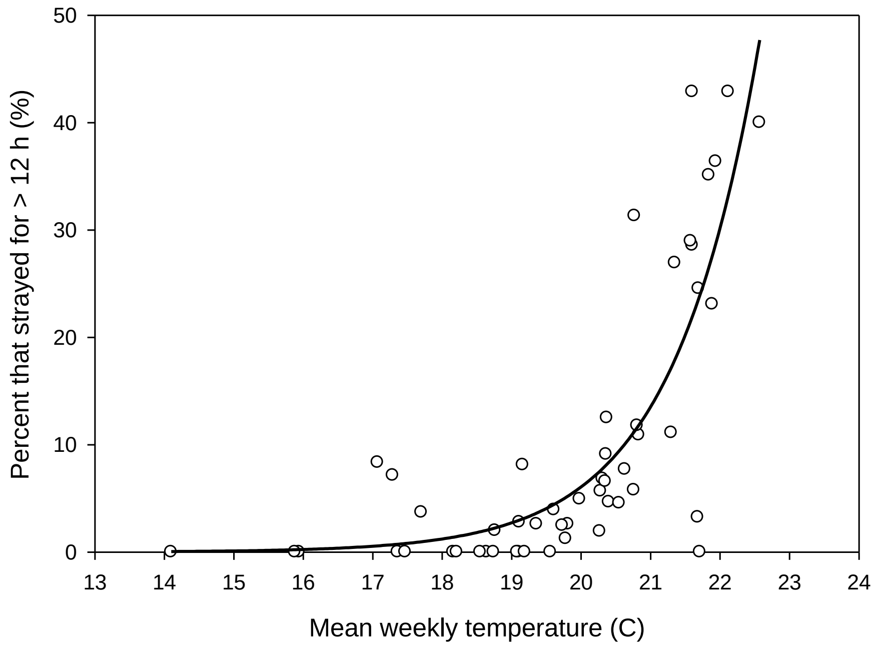

Figure 6. Relationship between the percent of fall Chinook salmon that used (> 12 h) cool-water tributaries and mean weekly water temperatures at Bonneville Dam. Symbols (○) represent 52 weekly bins (*mean* = 41 fish/bin; *range* = 4-122 fish/bin). Curve (▬) is the exponential regression line that best fits the data ($r^2 = 0.80$; $P < 0.0001$; percent = $6.558^{-7}e^{0.802*\text{temperature}}$. Asterix indicates data point with < 10 fish. Figure from Goniea et al. (2006).

Potential indirect negative effects of refugia use include migration delay, exposure to pathogens, permanent straying (i.e., loss from the source population), predation risk, and delayed effects from fisheries contact (i.e., catch and release, gill net fallout, etc.). Refugia sites are typically shallow, and intensive human use of the sites presumably can elevate fish stress levels. With the exception of estimating migration delay, these effects have not been measured.

Typical migration delays for fall Chinook salmon using refugia sites have ranged from hours to about 5 d, though some salmon used refugia for several weeks (Goniea et al. 2006). For most Chinook salmon, upstream passage delays on the order of several days likely have limited negative biological consequences, though this has not been explicitly tested with Columbia River populations. The delays potentially affect arrival timing at spawning grounds and consequently may have fitness effects, but it is certainly possible that the physiological benefits of refugia use outweigh potential negative effects of migration delay.

It is less clear what constitutes a migration ‘delay’ for steelhead given the considerable flexibility in migration timing and rate exhibited by the species. The mean refugia residence times for steelhead in the radiotelemetry studies have ranged from 5-15 d (High et al. 2006; Keefer et al. 2009), but times have varied widely among populations depending on migration timing and main stem temperatures (Figure 5). During the warmest periods, steelhead residence times in refugia have more typically been 3-4 weeks (Keefer et al. 2009). As with Chinook salmon, it is not clear whether steelhead migration delays in refugia affect migration success or fitness (except for the harvest effects mentioned above).

Overall, it is currently unclear whether refugia are currently ecological traps for adult salmonids, where holding was adaptive under historic conditions but now results in a net mortality cost due to increased mortality factors (e.g., fishing), or whether they primarily provide fitness benefits.

Information gaps

• *Spatial distribution*. Aside from the sites along the margins of the Bonneville and The Dalles reservoirs, there has been little systematic mapping of thermal refugia along the Columbia-Snake River migration corridor or in spawning tributaries. Important gaps along the migration route include downstream from Bonneville Dam, in the mid-Columbia upstream from Priest Rapids Dam, and in the Snake River upstream from the Clearwater River confluence. The presence of potential ground-water inputs to the migration corridor that may provide refuge have been speculated on but not verified or disproven. Tributary refugia may be equally or even more important at upstream sites given the lower overall condition of fish at this stage in the migration.

• *Temporal distribution*. Temperature gradients between tributary refugia sites and adjacent migration corridors fluctuate seasonally and make the refugia more or less attractive to adult migrants. Temporal patterns have not been well described, even for the relatively better studied sites.

• *Population differences*. As shown for steelhead, the incidence and duration of refugia use differs among populations within runs. For steelhead this was largely a function of run timing, but there may be other factors that affect refugia use behavior, including among-population differences in metabolic performance, temperature preferences, or other factors. We still only have a coarse understanding of population-specific use of refugia for steelhead. Identifying population-specific refugia use patterns for Chinook, sockeye, and coho salmon may also help prioritize management strategies.

• *Physiological benefits*. Although refugia use is presumably adaptive and confers fitness benefits on adult salmonids, these benefits have not been quantified. Basic physiological metrics such as metabolic rate, stress levels, and reproductive hormone levels have not been measured.

• *Delayed effects*. The effects of refugia use on fecundity and fitness have not been quantified, though these are among the most important uncertainties associated with the behavior. Experimental or field testing of the effects of thermal exposure (including simulated or actual refugia use) would help clarify the role that refugia have on Columbia River salmon and steelhead populations. Example studies include Mann and Peery (2005) and Crossin et al. (2008). Discussions on development of effective methods to identify and quantify delayed effects are needed because it remains largely unknown how refugia use relates to reproductive success.

• *Harvest management*. As shown in Keefer et al. (2009), the concentration of steelhead in lower Columbia River refugia sites (e.g., at Drano Lake at the Little White Salmon confluence and the

Deschutes River mouth) can result in high exploitation rates. Harvest impacts on upriver populations are also possible for Chinook salmon (especially summer and fall runs) and at sites other than those studied by the UI and NMFS. Harvest management at these sites may become increasingly important, particularly if impacts on threatened populations are significant.

Conclusions

A full understanding of the effects of thermoregulation and thermal refugia use during upstream migration will require a better understanding of several inter-related factors: 1) the behavioral flexibility of adults to find and use refugia; 2) species- and population-specific responses to and use of refugia; 3) the spatial and temporal extent and distribution of refugia; 4) the interaction of refugia use with impacts such as fisheries; 5) the delayed effects of thermal stress and the degree to which these effects are ameliorated by refugia use; 6) the interactions among main stem temperature exposure, pathogen exposure, refugia use, and the conditions adults experience in tributaries during spawning; 7) the effects of predicted climate change.

In general, the impacts of climate warming are likely to be greater for spring and summer run salmon than for fall-run populations because spring–summer fish hold in tributaries during summer months, with increased metabolic costs and potential for disease expression. Longer, hotter summers predicted under climate change scenarios would also be expected to differentially affect spring-summer run stocks by increasing metabolic costs of migration. The behavioral flexibility observed in steelhead suggests the potential for greater benefit of thermal refugia use to steelhead than salmon because they can use the sites for extended periods during the warmest time of the year. However, refugia may become relatively more important for salmon under warmer climate conditions, allowing migration in a "stepping-stone" sequence among refugia sites.

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