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Incorporating thermal requirements into flow regime development for multiple Pacific salmonid species in regulated rivers

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ABSTRACT

It has long been recognized that altered flow regimes and warm water temperature are among major stressors that have contributed to the precipitous decline of salmonid populations in California's Central Valley, resulting in many of them being listed as endangered or threatened pursuant to the U.S. Endangered Species Act. While it is widely acknowledged that water temperature affects all freshwater life stages of salmonids, it has not been a focus when developing instream flow requirements. In this study, we developed a framework that incorporates water temperature requirements into flow regime development for multiple Pacific salmonid species. We applied this framework to Clear Creek, an upper Central Valley stream that supports three salmonid species and has been regulated by reservoir releases for instream flow since 1963 when Whiskeytown dam was built. The analysis of flow data indicated that from the pre-project (*i.e.*, pre-dam) period to post- project period, flow magnitude was reduced by 45–76% for flood flows, 43% for spring pulse flows, and 27–53% for monthly average flows from January through May. Water temperature from 1996 to 2013 exceeded the U.S. Environmental Protection Agency recommended criteria for salmonids from May to October, with most exceedances occurring in September, followed by May and October. Statistical analyses suggested that the abundances of both adult and juvenile salmonids in Clear Creek were strongly correlated to flow magnitude, water temperature, or both. Higher flows that coincided with adult immigration were correlated to higher numbers of adults spawning in Clear Creek, which in turn produced a higher number of juveniles; however, higher flows that occurred during the early life stages (*e.g.*, fry) appeared to reduce the number of outmigrating juveniles. Higher water temperatures in the immigration, spawning, and juvenile rearing periods were correlated with reduced numbers of both adult and juvenile spring-run Chinook salmon in Clear Creek. High water temperatures in June and July were correlated with reduced number of outmigrating juvenile steelhead. Adult or juvenile fall-run Chinook salmon showed either a curvilinear or linear relationship with water temperature during their immigration, spawning, and rearing periods. Based on the pre-project flow and strong correlation between fish abundance and flow or water temperature, we developed a flow regime that incorporates water temperature requirements and other needs of different life stages of salmonids. The flow regime includes the following elements: winter and spring base flow, summer and fall water temperature sustaining flow, winter floodplain inundation flow, and spring pulse flow. This approach can be applied to other regulated streams for developing flow regimes to conserve and recover listed salmonid species.

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1. Introduction

California's Central Valley rivers and creeks historically were a significant source of salmonid production in California waters, but the populations of native Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*O. mykiss*) have declined dramatically. Increasing rates of decline followed construction of dams and reservoirs, which primarily occurred around the mid-1900s. Many of these water development projects completely blocked the upstream migration of Chinook salmon and steelhead to spawning and rearing habitats; spawning and rearing were therefore confined to river reaches downstream of the dams, where flow

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regimes were often altered and water temperatures were frequently impaired (Cummins et al., 2008; Brown and Bauer, 2009; National Marine Fisheries Service, 2014). Altered flows and warm water temperatures impact adult immigration, spawning, egg incubation, fry emergence, and juvenile rearing and outmigration (McCullough, 1999; Brown and Bauer, 2009; Kiernan et al., 2012; Zeug et al., 2014).

Recovery of these Endangered Species Act listed Central Valley salmon and steelhead populations requires a suite of long-term actions, including reintroduction of the fish to habitats historically accessible but currently blocked by dams (National Marine Fisheries Service, 2014). In addition, short-term remediation measures may include reservoir reoperation and habitat restoration to improve downstream flow, water temperature, and physical habitat for spawning, rearing, and migration of salmonids (U.S. Fish and Wildlife Service, 1995, 2001; Cummins et al., 2008). In this study, we developed a systematic framework for incorporating water temperature requirements into flow regime development for multiple salmonid species. We applied the framework to Clear Creek, a stream near Redding, California. Clear Creek was selected in this study because it (1) supports three salmonid species; (2) has a comprehensive monitoring program for fish, flow, and water temperature; and (3) is regulated for flow almost entirely by reservoir release.

Our framework for assessing streamflow is based largely on the methodology developed by an independent review committee that had considerable experience in developing flow criteria and implementing these criteria in Florida, Texas, and California (Dahm et al., 2014). The methodology is intended to be scientifically defensible, cost-effective, representative at the watershed scale, and timely relative to implementation. It is aimed to addresses multiple species, different life stages, and different fluvial processes in a watershed. The integral parts of the methodology are to determine how and to what degree (1) past and present water management has altered stream flows, (2) the altered flows have affected river ecosystems and associated aquatic biota, and (3) the altered flows may be restored to some level mimicking a natural flow regime in order to reduce the effects that have resulted from the past flow alterations (Richter et al., 1996; Poff et al., 1997; Arthington et al., 2006; Petts, 2009).

To further the methodology, our framework explicitly considers water temperature requirements for salmonid species and integrates water temperature-sustaining flows into instream flows. While the ecological and biological significance of water temperature in riverine ecosystems is widely acknowledged (Richter and Kolmes, 2005; Caissie, 2006; McCullough, et al., 2009; Olden and Naiman, 2010), mitigating for water temperature impairment below dams has received much less attention in the development of instream flows. Clearly, both flow and water temperature are important for aquatic ecosystems and must be simultaneously considered for the successful implementation of instream flow criteria below dams. Without considering water temperature, the resulting flows would be incomplete, reducing the likelihood of successful conservation of focal species. This study is intended to fill this major gap in instream flow development. We illustrate the development of flow regimes that integrate both flow and water temperature requirements for anadromous salmonid species. We first present the natural flow before Whiskeytown Dam was built in Clear Creek and assess changes in flows before and after the dam was complete. We then analyze water temperature data and develop a model to estimate the amount of water needed to meet water temperature requirements downstream of the dam. Finally, we describe the process of developing a flow regime that integrates water temperature requirements for salmonids.

2. Study area

The Clear Creek watershed, 56 km long with a drainage area of 616 km^2, is a tributary to the upper Sacramento River, the largest river in California (Fig. 1). The maximum watershed elevation is approximately 1800 m, but a majority of the watershed area is below 1200 m. Average annual precipitation in Redding, California, varies from 500 mm to 1600 mm, with a mean annual precipitation of about 1000 mm. The climate is Mediterranean and most precipitation falls as rainfall from November to March (77% of the mean annual precipitation), with little or none occurring during the months of May through September. Ambient air temperatures are typically lowest in January (average minimum 3 °C to average maximum 14 °C) and highest in July (average minimum 20 °C to average maximum 38 °C).

"Clear Creek" used in this study refers to the portion of the creek downstream of Whiskeytown Dam. Clear Creek, starting at Whiskeytown Dam at river km 30, flows south before flowing east approximately 14 km to the Sacramento River (Fig. 1). The drainage area between Whiskeytown Dam and the confluence with the Sacramento River is 127 km^2. Separated at the Clear Creek Road Bridge, the upper (almost 16 km) and lower (approximately 14 km) reaches of the creek are geologically distinct (Giovannetti and Brown, 2008). The upper reach flows south from Whiskeytown Reservoir. The stream bedrock in the upper reach is composed primarily of Paleozoic to Mesozoic igneous, metasedimentary, and metamorphic rocks that are largely resistant to erosion. The stream is more constrained by canyon walls and a bedrock channel and has a higher gradient, less spawning gravels, and greater pool depths than the lower portion of Clear Creek. The lower reach flows in an easterly direction to the Sacramento River. The stream bedrock in the lower reach is composed of sedimentary rocks that are much less resistant to erosion. The stream meanders through a less constrained alluvial channel, and has a lower gradient, more spawning gravels, and fewer deep pools (Giovannetti and Brown, 2008).

Construction of the earthfill, 80 m tall Whiskeytown Dam began in 1959 and was completed in 1963. Whiskeytown Reservoir has an approximate capacity of 300 million m^3 with a surface area of 14,000 km^2. The reservoir, part of the federal Central Valley Project in California, is operated by the U.S. Bureau of Reclamation for flood control, irrigation water, electricity generation, fish and wildlife, and recreation. The majority of the reservoir water (73% of the annual inflow on average) comes from Lewiston Reservoir supplied by the Trinity River downstream of Trinity Reservoir. Whiskeytown Dam entirely blocks fish from accessing the upper stream and has dramatically altered hydrology downstream of the dam. Furthermore, the reservoir, acting as a sediment trap, has starved lower Clear Creek of gravel, resulting in a substantial reduction of spawning habitat in lower Clear Creek (McBain et al., 2001).

A large portion of the Whiskeytown Reservoir water (85% of the annual outflow on average) leaves through the Spring Creek Tunnel, which has a discharge capacity of 108 cubic meters per second (cms) equivalent to 3800 cubic feet per second (cfs), to Keswick Reservoir on the upper Sacramento River (Fig. 1), whereas a small portion of the reservoir water (15%) discharges to Clear Creek. There are two intakes at Whiskeytown Dam that discharge reservoir water to Clear Creek. The upper intake at the elevation of 340 m has a discharge capacity of 17 cms, while the lower intake at the elevation of 301 m has a discharge capacity of 35 cms.

Clear Creek currently supports spring-run Chinook salmon (spring- run), fall-run Chinook salmon (fall-run), and late fall-run Chinook salmon (late fall-run) and steelhead trout (steelhead). Spring-run and steelhead have been listed as threatened under the federal Endangered Species Act. Although the life history of