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Consequences of variations in magnitude and duration of an instream environmental flow threshold across a longitudinal gradient

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SUMMARY

Humans are increasingly using individual small-scale projects to meet water needs, creating an array of new challenges for resource managers to maintain healthy aquatic ecosystems. Small-scale water projects such as instream diversions and small storage reservoirs may operate anywhere in a drainage network; to offer basinwide protections from the impacts of surface water abstraction, aquatic resource managers are tasked with adapting protections to apply throughout the catchment. We examined the variation of a particular environmental flow that has been proposed as the threshold for the operation of small instream diversions in northern coastal California, along a longitudinal channel gradient in 2004 and 2005. The magnitude and frequency of threshold exceedence varied among streams draining 2.6–110 km^2: whereas threshold flows occurred continuously through most of the rainy season in larger streams (as much as 100 days), threshold exceedence in headwater streams occurred over fractions of days amounting to less than 10% of the duration recorded at downstream reaches. These differences in threshold duration have important management consequences: water users diverting from headwaters may acquire water over much shorter periods than those users diverting from sites farther downstream, potentially resulting greater pumping rates and causing adverse ecosystem impacts beyond those expected by small-scale projects.

1. Introduction

Aquatic ecosystem sustainability has bridged disciplines to become a central tenet for water resources management in the 21st Century (Richter et al., 2003; Suen and Eheart, 2006; Pahl-Wostl, 2007; Viers and Rheinheimer, 2011; Aldous et al., 2011). Managers, planners, and scientists have acknowledged the value of healthy and functioning aquatic ecosystems (Postel and Richter, 2003; Naiman et al., 2002; Matthews, 2005; Ringler and Cai, 2006; Foley et al., 2007), and practices have been implemented in many regions globally to ensure human water needs are met while sustaining ecological processes (Fitzhugh and Richter, 2004; Bragg et al., 2005; Brown et al., 2006; Postel, 2007). To guide these practices, ecohydrologists have emphasized developing linkages between specific flow regime characteristics (describing the flow magnitude, duration, timing, and rate of change) and valued ecosystem processes to quantify environmental flows (those dynamics of discharge required to sustain ecological functions), as a framework to guide sustainable water management (Arthington et al., 2006; Richter et al., 2006; King and Brown, 2006; Petts et al., 2006).

The use of environmental flows has primarily focused on the management of large reservoirs: large dams can regulate streamflow and release water according to a prescribed regime to ameliorate some hydrologic impacts on ecosystems (Tharme, 2003; Harman and Stewardson, 2005; Richter and Thomas, 2007; Liu et al., 2011). Dams and similar large water projects are not, however, the only means by which surface water abstraction can threaten aquatic ecosystems (Malmqvist and Rundle, 2002). In the absence of large-scale water providers, users may employ small instream diversions and surface reservoirs to meet individual-scale water needs (e.g., Mathooko, 2001; Levite et al., 2003; Liebe et al., 2005; The Economist, 2007; Reinfelds et al., 2006). Small water projects may be seen as a more ecologically sustainable alternative to large projects: they serve smaller numbers of people (and thus entail less abstraction than large projects) and their distribution through a watershed may alleviate hydrologic impacts rather than focusing all pressures at one central location (Potter, 2006), thus avoiding many of the social, economic, and ecological controversies that frequently surround large dams (Scudder, 2005; Shen et al., 2008).

Though small-scale water projects may result in smaller impacts to streamflow when compared to large dams, they are not

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a panacea for aquatic ecosystem sustainability. Water diverted during base flow periods can cause significant reductions in streamflow (Deitch et al., 2009), and such diversions can cause changes in composition and function of macroinvertebrate and fish communities (McIntosh et al., 2002; McKay and King, 2006; Wills et al., 2006; Lawrence et al., 2011). In regions where small diversions are common, policy makers and organizations charged with protecting aquatic biota or ecosystem processes frequently use environmental flows as thresholds to regulate instream diversions (e.g., Reinfelds et al., 2004, 2010). Small diversions do not have capacity to regulate flow like large dams, but the timing of their operation can be adjusted to ensure that specific biological processes occur to a defined extent before diversion can occur. Establishment of a clear threshold with specific ecological relevance is important for maintaining those processes, and for reconciling human and ecological water needs.

Given the capacity for such projects to reorganize aquatic ecosystems, the development of environmental flow thresholds for ecological protection represents an important step for the ecologically sustainable management of small instream diversions. However, the tendency for small diversions to be distributed through the drainage network complicates the derivation and application of environmental flows: variations in flow regime and channel morphology from headwaters to lower reaches may influence environmental flows unpredictably, potentially creating markedly different circumstances for operating diversions through the drainage network. The research below examines a particular environmental flow proposed for managing instream diversions in northern coastal California, where water needs are primarily met through small-scale projects. We examine the variation of hydrologic and morphological factors along a longitudinal gradient, and how those factors affect this particular environmental flow through the drainage network; and how those differences create different circumstances for direct instream diversion from headwater streams to lower reaches.

2. Material and methods

2.1. Study area and methods

Small instream diversions have served as a source for agricultural, domestic, and industrial water needs in northern coastal California for over a century (SWRCB, 1997; Deitch, 2006). The climate of this region is Mediterranean, characterized by cool wet winters and hot dry summers: the region receives from six hundred to over twelve hundred millimeters of precipitation in a typical year depending on microclimatic variations, virtually all of which falls as rain between November and May. The absence of rainfall during the summer growing season necessitates water management to produce a viable wine grape crop (Smith et al., 2004), and small water projects are regionally important because virtually no water providers or irrigation districts exist to supply agricultural water needs. The climate also places pressures on aquatic ecosystems: the absence of precipitation for more than one-third of the year results in a steady flow recession through the dry season, causing all natural-flowing streams to approach or reach intermittence by late summer and early fall.

Beginning in the early 1990s, protections extended to endangered anadromous salmonid species (namely, steelhead trout *Oncorhynchus mykiss* and coho salmon *Oncorhynchus kisutch*) and public trust resources caused state regulatory agencies to change practices in granting water rights (SWRCB, 1997). In addition to proscribing new water appropriations during spring and summer, resource management agencies began to design new guidelines to protect endangered species while still allowing instream diversion into offstream reservoirs during winter for use during the dry growing season. To accommodate human and ecosystem needs, resource agencies in California have proposed a flow threshold called a bypass flow to serve as the minimum streamflow condition that must be exceeded for small diversions to operate.

The particular threshold flow to allow small diversions in northern coastal California focused on protecting ecological processes that occur during winter base flows because the magnitude of small diversions are not large enough to affect winter peak flows, but may appreciably alter streamflow between peak flow events. The bypass flow, defined as the threshold flow magnitude at which adult salmonids can migrate upstream to spawning grounds (the discharge corresponding to a depth of 0.25 m through the thalweg of a riffle, representing the upstream migration requirement for adult steelhead trout), was selected as the threshold to permit diversion because it requires the greatest flow magnitude among several processes that occur during winter base flows such as redd creation and spawning as well (CDFG, 2002; SWRCB, 2010). These protections are especially relevant to headwater streams in the Russian River basin, many of which are designated as critical spawning habitat for anadromous salmonids (Department of Commerce, 2005).

2.2. Data collection and analysis

We measured streamflow, channel properties, and the bypass flow threshold at eight locations in the Maacama Creek drainage network, a 180 km^2 tributary drainage to the Russian River in eastern Sonoma County, California, in water years 2004 and 2005 to examine how streamflow and threshold conditions for salmonid bypass vary with upstream catchment area. The predominant land cover type of the Maacama catchment is forested, with some forest as mixed oak-chaparral and some as conifer. Human land use includes low-density rural residential development and vineyards (less than 10% of the region; Deitch et al., 2009). Study sites were established along Maacama Creek and its main tributary Franz Creek; site names reflect stream name and upstream catchment area relative to the smallest drainages in the study. Five gauges were installed in the Franz Creek sub-basin in a nested design: 01-Franz and 01-Bidwell on Franz and Bidwell Creek (a tributary to Franz), each draining 2.6 km^2 catchments; 05-Franz and 05-Bidwell on Franz Creek and Bidwell Creek (a tributary to Franz), draining 13 km^2 catchments; and 15-Franz on Franz Creek draining a 40 km^2 catchment (Fig. 1). Additionally, three gauges were installed along Maacama Creek: 45-Maacama on (upstream area 107 km^2), 20-Maacama (upstream area 56 km^2), and 03-MillPark (upstream area 6.7 km^2). We used Global Water WL-15 pressure transducers encased in thick flexible PVC tubing securely attached to stable substrate to measure stage and set instruments to record at 10-min intervals; we measured flow at intervals ranging from biweekly to monthly from November 2003 through September 2005 to construct rating curves following standard US Geological Survey gauging procedures (Rantz, 1982).

In addition to measuring streamflow, we measured channel properties, including longitudinal profiles and one to six channel cross-sections (depending on property access) at each study reach. To determine the bypass flow magnitude, we measured depth and width of wetted channel at each measured cross-section during site visits to identify the discharge associated with a 0.25 m depth through the cross-section thalweg. Where field measurements to determine the bypass flow were inconclusive, we used channel measurements and Manning equation velocity calculations to estimate discharge required to provide the 0.25 m depth through each cross section. After determining the bypass threshold flow for each site based on the depth criterion, we used hydrographs from each site to determine the durations over which this environmental flow threshold was exceeded.