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Balancing salmon populations, aquatic biodiversity, and water resource needs during drought in coastal California

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Project Summary

Climate change and water withdrawals pose grave threats to stream biodiversity in arid and semi-arid regions across the world. Streams in these regions are essential sources of municipal and agricultural water, but they also support diverse, complex natural communities. Although many species in these regions have adaptations allowing them to persist through drought, the limits of these adaptations will be tested with increased societal demands for freshwater and intensifying droughts predicted by climate models.

Intermittent streams, which cease flowing during some portion of the year, comprise the majority of stream length in the United States but have only recently received significant scientific attention. In California, intermittent streams represent important breeding habitat for Pacific salmon and trout, but these small streams are particularly vulnerable to flow decreases due to water withdrawals. Innovative water conservation strategies are being implemented in some areas, however, in an effort to balance competing demands for freshwater. In these watersheds, farmers and conservationists are working side-by-side to conserve winter rainfall in off-channel ponds in order to enhance summer dry season habitat for salmonids, but flow targets to guide successful project implementation are lacking.

These basic knowledge gaps are hampering our ability to design, implement, and evaluate the ecological benefits of water conservation projects. In the proposed research, we will address these knowledge gaps by quantifying (1) low flow attributes across a diversity of stream sizes from intermittent headwater tributaries to mainstem perennial streams (including reaches with agricultural diversions and or water conservation projects), (2) the effect of flow intermittency and dry season habitat contraction on aquatic biodiversity and community composition, and (3) the effect of habitat contraction on salmonid distribution and dry season survival.

We will use a combination of hydrological modeling and field studies in the Pine Gulch basin, Marin County, California, to address our three main study questions. This research will include both a broad-scale, short-term study of 20 tributary streams with varied flow regimes (perennial to severely intermittent) and a fine-scale, longer-term study of salmonid population and invertebrate community dynamics in individual stream pools across the dry season. Pine Gulch is an ideal basin for quantifying the ecological impacts of low- and zero-flow events because those data would be immediately used in an innovative water resource management program.

The Pine Gulch Watershed Enhancement Project is a multi-year project, supported by multiple state and federal agencies, in which local farms are constructing ponds for winter rain storage, with the hope of reducing summer flow diversions and enhancing stream habitat for salmonids. Our research will provide guidelines for what water levels are necessary to sustain biotic diversity and salmonid production in this basin. These flow targets will then be used as input into hydrological models to be developed by the Larsen lab at UC-Berkeley to evaluate the impacts of alternative water conservation projects on in-stream habitat during the dry season. The approach and results of this collaboration could serve as a model for managing streams to meet both ecosystem and societal needs in California and beyond.

1. Abstract

Climate change and water withdrawals pose grave threats to stream biodiversity in arid and semi-arid regions across the world. Although many species in these regions have adaptations allowing them to persist through drought, the limits of these adaptations will be tested with increased societal demands for freshwater and climate change. Despite these looming changes, ecologists still know relatively little about aquatic communities in intermittent streams (which cease flowing during some portion of the year), or about the use of these streams by ecologically and economically-important salmonid fish species. These knowledge gaps are hampering our ability to design, implement, and evaluate the ecological benefits of water conservation projects. Throughout California, innovative water conservation strategies are being implemented in an effort to balance competing demands for scarce freshwater.

In many watersheds, farmers and conservationists are working side-by-side to conserve winter rainfall in off-channel ponds in order to enhance summer dry season habitat for salmonids, but flow targets to guide successful project implementation are lacking. We will address these knowledge gaps by quantifying (1) low flow attributes across a diversity of stream sizes from intermittent headwater tributaries to mainstem perennial streams (including reaches where water conservation techniques are being employed), (2) the effects of flow intermittency and dry season habitat contraction on aquatic biodiversity and community composition, and (3) the effects of habitat contraction on salmonid distribution and dry season survival. These results will be a major step towards providing managers with flow targets to support aquatic biodiversity, including Pacific salmon, during drought.

2. Introduction

One of the most pressing conservation challenges in the 21st century will be to balance societal needs for freshwater with the maintenance of aquatic biodiversity in the face of a changing climate (Baron et al. 2002; Poff et al. 2003). Though streams and rivers make up a small portion of the landscape (<0.1%), they are essential sources of municipal and agricultural water and support diverse and complex biotic communities (Vörösmarty et al. 2010; Poff et al. 2012). This high biodiversity is due in part to a wide variety of life history, behavioral, and morphological adaptations that allow species to persist, and even thrive, through natural flow disturbances like drought and stream drying (Lytle and Poff 2004). These adaptations are to natural flow regimes, however, and may not help species persist in flow regimes altered by water withdrawals (e.g., Deacon et al. 2007) or climate change (Barnett et al. 2008; Jacobsen et al. 2012).

The conservation crisis created by the collision of water withdrawals, climate change, and freshwater biodiversity preservation is especially severe in arid and semi-arid regions like southwestern North America (MacDonald 2010). Dams and water withdrawals have reduced in-stream flows across the region and represent grave threats to regional freshwater biodiversity (Deacon et al. 2007; Poff et al. 2007). Additionally, regional climate change models predict increasing drought intensity and duration through the 21st century (Seager et al. 2007), which will lead to decreased stream flows and longer low- or no-flow periods (Seager and Vecchi 2010; Tang and Lettenmaier 2012). Such severe reductions in stream flow could lead to the extinctions of sensitive aquatic species (Bogan & Lytle 2011; Katz et al. 2013), at a time when freshwater species extinction rates are already five times higher than those of terrestrial species (Ricciardi and Rasmussen 1999).

Despite the fact that intermittent streams (which cease flowing during some portion of the year) comprise the majority of stream length in the United States (59%: Nadeau and Rains 2007; 81% in the Southwest: Levick et al. 2008), the impacts of drought and stream drying on stream communities have only recently received significant scientific attention (e.g., Lake 2003; Datry et al. 2011). Even without a complete cessation of flow, drought periods can drive changes in local fish and invertebrate communities (Bêche et al 2009; Kiernan and Moyle 2012).

Additionally, recent studies indicate that aquatic invertebrate diversity may decrease linearly as the length of zero-flow periods increases (Arscott et al. 2010, Datry 2012). In other streams, unprecedented transitions from perennial to intermittent flow due to long-term drought are causing local extinctions of long-lived or flightless invertebrate species (Bogan and Lytle 2011). While total stream drying clearly presents an enormous challenge to fish, many species can survive zero-flow periods in residual stream pools, and coho salmon may even grow larger in intermittent stream pools than in perennial streams (Wigington et al. 2006).

Habitat conditions are highly variable in intermittent stream pools, though, and other studies suggest low survivorship of salmonids in intermittent streams affected by anthropogenic water use (Grantham et al. 2012). Recent research in my lab suggests that survival rates of imperiled salmonids in one intermittent stream vary with drought severity (37% following a dry winter to 81% following a wet winter; Hwan and Carlson, in prep.). **Determining the minimum flow, water quality characteristics, or residual pool size and depth necessary to sustain salmonids and aquatic biodiversity during seasonal drought remains a significant question, with important implications for how we manage limited freshwater resources.**

Intermittent streams in California often occur in “storage-limited” watersheds, meaning that annual rainfall exceeds but does not coincide with periods of peak demand (Grantham et al. 2012). As in many small western watersheds, farmers and small communities in this region draw water from small in-stream diversions rather than large reservoirs. Historically, some of these dry-season withdrawals have conflicted with ecological needs for water (Grantham et al. 2010). Examples in California include stream drying due to diversions for vineyards (Deitch et al. 2009) and reduction or cessation of flow in summer due to municipal groundwater pumping (Fong et al. 2007).

However, many small agricultural and residential communities have a vested interest in managing scarce water resources for both salmon survivorship and human water needs and have taken the initiative to implement water conservation practices to capture and store water during the winter to reduce stream diversions during the summer dry season. **What these communities need are precise scientific guidelines so that their innovative water management practices can maximize biological diversity and the survival of salmonids in local streams.**

One remaining hurdle to implementing holistic water management practices in low-flow or intermittent streams is the difficultly in measuring precise flow regime characteristics on a local scale as the vast majority of streams with flow gauges are perennial. This knowledge gap prevents water managers from determining precisely how their practices affect local stream flow conditions. To this end, hydrologists have recently made a number of advances toward quantifying flow regimes in small and intermittent streams, including using modeling techniques (e.g., ELFMOD: Larned et al. 2010) and remote data loggers (e.g., electrical resistance sensors: Jaeger and Olden 2011). These novel methods can now be used to quantify flow regime characteristics (e.g., frequency and duration of drying events) in ungauged streams, a prerequisite to modeling the effect of low or zero-flow conditions on aquatic biodiversity and salmonid survival in intermittent streams.

The Pine Gulch watershed in Marin County, California, is an ideal setting for constructing these hydrological models and quantifying the ecological impacts of low- and zero-flow events because those data would be immediately used in an important pilot study of innovative water resource management. Pine Gulch flows from forested headwaters in Point Reyes National Seashore, through low-intensity organic cropland, to the ocean, with numerous perennial and intermittent reaches and tributaries. The Pine Gulch Creek Watershed Enhancement Project is an in-progress multi-year project, supported by multiple state and federal agencies (e.g., California Fish and Wildlife, National Park Service, NOAA-Fisheries), in which local farms are constructing ponds for winter rain storage, with the hope of reducing summer flow diversions and enhancing stream habitat for salmonids.

Though the project is scheduled to be implemented in 2014, there are currently no plans for monitoring its impact on stream hydrology or biology nor do the managers have guidelines for what instream water levels are necessary to sustain biotic diversity and salmonid production in this mixed land-use watershed. **Our proposed research will provide these services to the Watershed Enhancement Project, yielding a critical science evaluation component that the managers are eager to incorporate.**

2.1. Objectives and Study Questions

The overarching objectives of the proposed work are to predict the effects of low and zero-flow events on aquatic biodiversity, community composition, and salmonid distribution and survival and use these predictions to guide water management decisions in coastal California watersheds, including the Pine Gulch basin. These objectives will be realized by addressing the following three questions:

Q1: How do flow regime characteristics vary across a network of streams and how are local flow characteristics affected by water management practices such as off-stream storage? For stream basins without flow gauges, hydrologic modeling and flow regime quantification are essential first steps to predicting the effects of hydrology on biotic resources (e.g., salmonid stocks) and understanding the impacts of water management practices on local flow conditions.

Q2: How do low and zero-flow events affect the diversity and composition of aquatic communities? Flow intermittency could be linearly related to local community attributes or there may be intermittency thresholds below which diversity or community structure change drastically. Understanding this relationship is essential to designing water conservation strategies that maximize freshwater biodiversity and invertebrate food sources for salmonids.

Q3: How do low and zero-flow events affect the distribution and survival of ecologically and economically important salmonid fishes in intermittent stream pools? While salmonids can survive in remnant pools for short periods of time (e.g., weeks), their tolerance limits for lack of flow and the drivers of these tolerances (e.g., abiotic vs. biotic factors) are unknown. Understanding these factors is especially important for conserving salmonids at the southern end of their range, where longer low- or zero-flow periods through the next century are a near certainty due to climate change and increased anthropogenic water use.

2.2. Related Research & Funding: Since 2009, my lab has been studying the ecology of Pacific salmon and trout in an intermittent stream, the John West Fork in Point Reyes National Seashore. Jason Hwan's research (funded through an NSF Graduate Research Fellowship) has involved measuring weekly changes in water level, pool habitat availability, and salmonid survival across four recent summer dry seasons. Preliminary results suggest that salmonid survival varies with drought severity (from 37% following a dry winter to 81% following a wet winter, Hwan and Carlson, in prep.), and that water level decreases across the summer also influence over-summer survival (Buoro, Hwan and Carlson, in prep.).

Kristina Cervantes-Yoshida's research (funded through an NSF Graduate Research Fellowship) is exploring how the food web supporting salmon shifts across the summer dry season. A new post-doc in the lab, Dr. Michael Bogan (supported through my faculty startup funds), brings expertise in aquatic invertebrates, and is currently analyzing four years of invertebrate samples collected at the John West Fork to explore invertebrate community shifts within dry seasons and among years. This research is providing insight into how interannual variability in invertebrate communities and salmonid mortality at a single study site is related to antecedent rainfall. The proposed research would extend this work in space, including sites that span a gradient of flow conditions, to quantify flow thresholds below which salmonid survival and aquatic invertebrate biodiversity decline.

Beyond the research in my lab, this project relates directly to a new collaboration with the Laurel Larsen Lab, in Geography at UC Berkeley. Larsen and I have been working to launch a new collaboration to help guide innovative water conservation strategies for supporting aquatic biodiversity in storage-limited basins. Our study sites will be co-located in the Pine Gulch basin, and our data collection and analyses will allow us to meet our overall goal of helping guide water conservation efforts. As an example, I propose to collect information on salmonid distributions and mortality, while Larsen will collect detailed information on flow paths, contributing water sources, and carbon/oxygen dynamics. Together, these data will allow a robust analysis of the environmental factors driving the over-summer survival of salmonids and provide critical flow targets for managers.

These flow targets will then be used as input into hydrological models that Larsen will develop to evaluate the impacts of alternative water conservation projects on in-stream habitat during the dry season. Our approach and results could serve as a model for managing streams to meet both ecosystem and societal needs for freshwater in California and beyond.

Information Transfer/Outreach Program

3. Methods

We will use a combination of hydrological modeling and field studies to address our three main study questions (see below). This research will include both a broad-scale geographic study of 20 tributary streams with varied flow regimes (perennial to severely intermittent) across the greater Pine Gulch basin and a fine-scale study of salmonid population and invertebrate community dynamics in individual Pine Gulch stream pools across the dry season (Jun-Oct). The broad-scale study will act as a 'space-for-time' substitution (cf. Fukami and Wardle 2005) and will be an essential first step to predicting how water diversions, increased drought intensity, and stream drying will impact stream biodiversity and salmonid distribution. In contrast, the fine-scale study will provide a detailed, mechanistic understanding of how progressive drying through seasonal droughts shapes local population and community dynamics in stream pools.

The fine-scale study will be conducted in collaboration with Laurel Larsen, who will quantify abiotic habitat factors (e.g., flow, dissolved oxygen, organic carbon) in these pools and determine how those factors are impacted by water management strategies. **The models developed herein will be immediately used to design flow regimes to maximize aquatic biodiversity and salmonid survival in the Pine Gulch basin, but the approach developed here will be widely applicable to storage-limited stream basins in general.**

Q1 Methods (hydrology): We will identify 20 focal tributary streams within the Pine Gulch basin, along some of which local residents are developing water management techniques (such as rainwater conservation ponds) to minimize diversions during the dry season. We will select tributaries that exhibit a wide range of flow regimes, from perennial to mildly intermittent (e.g., some remnant pools but no flow during summer) to severely intermittent (e.g., total stream drying for > 6 months a year). To precisely quantify intermittence over the study period, we will deploy electrical resistance sensors (Jaeger and Olden 2012) in the streams for one year (March 2014-2015).

Data from these sensors will be used in concert with repeated site visits to measure discharge and stream connectivity (e.g., proportion of wetted riffles), as well as data from nearby gauged streams, to model long-term flow regime characteristics (e.g., frequency and duration of no-flow events) and the degree of connectivity among stream reaches (see Jaeger and Olden 2012). These analyses will be then be used to compare flow conditions in streams near to, and distant from, rainwater conservation ponds to assess the effectiveness of these ponds in enhancing aquatic habitat quality and connectivity during the dry season. Laurel Larsen will independently conduct

GIS-based hydrological modeling of these same streams, and our collaboration will allow cross-validation of our flow models.

Q2 Methods (aquatic communities): Aquatic community sampling at these 20 sites will occur in March-April 2014, in collaboration with graduate and undergraduates students from UC Berkeley. By late April many intermittent streams may begin to dry (Bogan et al. 2013), so this is the best season for sampling intermittent reaches. At each stream, aquatic invertebrate community samples will be collected according to EPA protocols (Lazorchak et al. 1998). We will also sample aquatic vertebrates (including salmonids) at these sites using standard methods to characterize their diversity and abundance. During the same visit, we will quantify water quality, flow, and physical habitat conditions (e.g., substrate, canopy), as these factors may co-vary with flow conditions. We will then use variance partitioning (cf. Peres-Neto et al. 2006) and model selection techniques (Burnham and Anderson 2002) to determine how much variation in biotic factors is explained by flow intermittence versus other physical or chemical factors. We will also quantify the shape of the relationship between flow intermittence and aquatic biodiversity and community composition across the 20 sites.

While these data will serve to quantify the relationship between aquatic communities and flow regime across a wide range of flow types, we also need to understand how communities change within remaining wetted habitats during the dry season, when anthropogenic water demands are at their highest. To address this need, we will measure aquatic invertebrate community structure monthly across the dry season (May-Oct) in a subset of study pools in Pine Gulch. These pools will be also be studied by collaborator Laurel Larsen, and she will provide detailed physio-chemical habitat data that we will then relate to our biological data. We conducted similar dry season invertebrate studies in the nearby John West Fork from 2009-2012, which a postdoctoral fellow in my lab is currently analyzing. These new data from Pine Gulch will be essential to constructing regional models relating drying intensity to ecological processes in streams. These analyses will also allow for more fine-scale predictions of invertebrate community (and, thus, salmonid food resource) responses to changes in flow volume resulting from the Pine Gulch Watershed Enhancement Project.

Q3 Methods (salmonid distribution and survival): Across our 20 focal streams, we will conduct watershed-wide surveys of salmon presence/absence during the low-flow season, targeting multiple land-use types and degrees of intermittency, including some sites identified in Q1. Together with surveys of salmon presence/absence, we will measure a large suite of habitat variables (e.g., stream flow, water depth, pool volume, dissolved oxygen) and quantify invertebrate food resources (see Q2) to determine the abiotic and biotic thresholds below which salmon are unable to utilize a stream. On a finer-scale, we will also quantify salmonid survival in individual intermittent stream pools across the 2014 dry season (May-Oct), using the same subset of Pine Gulch pools as identified in Q2 (which will be selected via collaboration with Laurel Larsen).

We will employ a hierarchical modeling framework to assess the relative importance of flow, fragmentation, and habitat quality to fish distribution across the basin and to oversummer survival within the focal pools. The general approach proceeds in a Bayesian hierarchical framework and estimates the survival probability of fish within each habitat unit as a binomial distribution and then uses a logit link function to express that probability as a linear function of the explanatory variables (Grantham et al. 2012). We will evaluate models with different combinations of the variables using the deviance information criterion to assess the model fit and to guide model selection. Finally, we will validate and refine the salmonid survivorship models developed here using data on oversummer salmonid survival rates from the nearby John West Fork collected by my lab from 2009 to 2012; these refinements will ensure that the survival models are robust with regard to multiple year types and stream basins, making them useful on a regional or national scale.

Notable Achievements

4. Anticipated Outcomes and Benefits

As flow regime can strongly influence ecological communities, we expect intermittency to be a primary driver of aquatic communities and populations, but perhaps in a non-linear fashion. Streams which have perennial flow will likely support the highest diversity of organisms and largest salmonid populations. I expect to see a relatively steep drop in diversity and shift in communities between perennial streams and mildly to moderately intermittent streams (e.g., zero-flow periods lasting from 1 to 4 months), but that there will be minor differences within this range of intermittency.

I expect to see another dramatic diversity and community shift between moderately intermittent streams (with remnant pools) and streams that dry completely (including remnant pools). Salmonid survival will likely change little or even increase between pools receiving perennial and mildly intermittent flows (e.g., Wigington et al. 2006), as terrestrial subsidies could compensate for reduced aquatic prey production. As no-flow periods exceed four months and pool volumes decline, though, poor water quality conditions and increased competition for limited resources may result in decreased salmonid survival and even losses at certain sites.

The results of the proposed research will be essential to predicting the impacts of increased intermittency on stream biodiversity due to water withdrawal or climate change. Though many streams in the study region occur in federally protected areas, groundwater pumping is noticeable reducing stream flows and can cause flow to cease completely in dry years (e.g., Redwood Creek; Fong et al. 2007). Similar stream drying has been observed in California's wine country when surface flows are diverted during summer heat waves for crop protection (Deitch et al. 2009). In the absence of a detailed understanding of the relationships between drought and stream ecosystem health, nearly 80% of California salmonid species are expected to go extinct in the next century (Katz et al. 2013).

In addition to these well-known fish species, numerous invertebrate taxa are also at risk of local or species-level extinctions due to water withdrawals and climate change (Deacon et al. 2007; Bogan and Lytle 2011). **The type of predictive models relating flow permanence to ecosystem health that would be produced by the proposed research would allow managers to craft**

adaptive management plans that determine when and how much water users could withdraw from a stream without significant biodiversity losses. Additionally, the proposed hydrology-biodiversity models could be valuable for setting realistic restoration guidelines for projects where natural flow regimes are being reestablished after a long period of diversions or dam-influenced flows.

On a local scale, **the proposed research will play an immediate and important role in the Pine Gulch Creek Watershed Enhancement Project**. Pine Gulch flows from forested headwaters in Pt. Reyes National Seashore, through low-intensity organic cropland, to the ocean. Supported by a $2.5 million grant from the California Dept. of Fish and Wildlife Fisheries Restoration Grant Program, three local organic farms are collaborating with the National Park Service to construct new ponds for winter rain storage, with the hope of enhancing summer dry season flows. The project will be implemented in 2014 but there are currently no plans for monitoring its impact on stream hydrology or biology nor do the managers have guidelines for what instream water levels are needed to sustain biotic diversity and salmonid populations in the basin. My proposed research will provide these data to guide the Project, yielding a science evaluation component that the managers have identified as a critical knowledge gap.

Finally, the proposed research will help to quantify the role that intermittent streams play in broader stream networks, a much-contested legal issue (Leibowitz et al. 2008). Following recent high-profile Supreme Court cases (e.g., Rapanos v. United States 2006), the protection of intermittent streams under the Clean Water Act hinges on whether they: (1) have “ordinarily dry channels” [not protected] or (2) provide a “significant nexus” that affects the “integrity” of other streams [protected]. The proposed hydrologic models would address the first definition by quantifying the precise duration of dry periods in the study streams. The proposed research addressing salmonid survival in intermittent streams would address the second definition by quantifying salmonid production in streams with varying intensities of intermittence. Salmonids that oversummer in intermittent streams and migrate downstream upon flow resumption would contribute significantly to the dynamics of the larger stock complex, thus providing a “significant nexus”.