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Watershed Collaborations: Entanglements with common streams

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Watershed Collaborations: Entanglements with Common Streams

By

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Abstract: Watershed Collaborations: Entanglements with common streams

Along California's North Coast, where salmon hover on the cusp of extinction, scientists and local residents seek new collaborations. Agencies, tribes, and watershed councils commission competing studies to determine links between human water use, oceanic cycles, and salmon decline. Modelers turn to ranchers' expert opinions to condition hydrologic models. Ranchers import beavers to build dams that may raise the water table. These watershed collaborations begin to transcend boundaries of human institutions, scientist / lay person, and even species. Restoring salmon-bearing streams is a project to reconfigure human relationships to water and inhabitation practices. In the western U.S., this project necessarily entails a serious grappling with Manifest Destiny legacies of Native American sovereignty, property regimes, legal doctrines, and water infrastructures.

My dissertation investigates how watershed collaborations transform scientific practices, environmental subjectivities, and trans-species relations, using Salmon Creek (Sonoma Co., CA) as a case. Salmon Creek is typical of thousands of small watersheds in the Pacific West in that summer water extractions by farmers and rural residents dry many tributaries into a series of disconnected pools. This anthropogenic drought compounds historic beaver removal, logging, and road building that have altered water, sediment, and large wood supply to the stream, limiting steelhead *(Oncorhynchus mykiss)* and coho salmon *(O. kisutch)* recovery. I argue that collaborative watershed research that refuses to privilege expert science over local and Indigenous knowledges can create novel modes of scientific practice, discursive shifts, and new governance approaches. I stretch the limits of the terms ‘watershed’ and ‘collaboration’ to encompass interactions among (1) scientists and local knowledge holders, (2) living species and the landscapes they inhabit, and (3) humans and other species that depend on riverine ecosystems. Though disparate in methodology, the fields this dissertation contributes to—Science and Technology Studies, Environmental Politics, and Eco-hydrology—share a commitment to critically re-working social-natural boundaries.

Natural flow regimes—dynamic streamflow patterns that drive riverine biodiversity—arise from a kind of collaboration between climatic factors, geology, plants, and animals in a river basin, and are then further shaped by human ground and surface water diversions. Regarding the ecosystem as a collaboratory in which humans play a role, Quantifying abiotic habitat characteristics to determine thresholds for salmonid oversummer survival in intermittent streams investigates the role of different flow-mediated factors (dissolved oxygen, temperature, groundwater inflow, and pool volume) affect juvenile coho and steelhead occurrence in two Salmon Creek tributaries. Drawing on three years of juvenile fish surveys, synoptic water and isotope monitoring and streamflow gauging to populate statistical models, I found that low dissolved oxygen and pool volume limit survival; however both salmonid species can survive in spring-fed intermittent pools that contain sheltering logs or overhanging banks. Citizen science surveys of stream drying patterns and salmon occurrence can complement agency monitoring and should be incorporated into salmon recovery efforts.

Regarding human collaboratives of knowledge and practice, ‘Thinking with salmon about rain tanks: stream commons as intra-actions’ puts forth the argument that cultural practices of water use evolve in response to new understandings of other species' dependence on shared streams. Some Salmon Creek residents who install rain cisterns to curtail summer water use do so out of concern for salmon, and describe salmon and other riverine creatures as having rights to enough water to survive that are of the same status as human rights to water. Other residents are unwilling to reduce water use because the connection between their wells and the stream are poorly understood and difficult to measure. ‘Rain tanks, springs, and broken pipes as emerging water

commons along Salmon Creek, CA, USA' develops a method for studying up from household water practices and local knowledge of springs, aquifers, and rainfall. Residents who participate in monitoring salmon populations, water quality, and their own springs and rain tanks report that these activities have increased their sense of interdependence with other human and nonhuman neighbors who rely on the watershed's limited water sources. Drawing on Barad's (2007) concepts of apparatus and intra-action, I argue that the notion of water as an interspecies commons is co- evolving with rainwater harvesting and that collective choice frameworks that embrace both management practices and environmental imaginaries represent a coherent alternative both to state and market frameworks of water governance and to traditional adaptive management methods and discourses.

Mobilizing approaches from feminist Science and Technology Studies, the introduction extends the idea of watershed collaborations to encompass humans and other species. I draw on extended interviews with scientists, policy-makers, and local residents to argue that members of knowledge practice collaboratives foment discourses that bring humans and other species — especially beaver and salmon, which affect water and nutrient cycles and thus are considered "ecosystem engineers"— into symbiotic relations with mutual responsibilities. In the conclusion, I explore how these concepts of multi-species collaboratives may filter up from local collaborations into public water and species recovery debates, and consider limitations to more entangled approaches to watershed governance.

Salmon Creek is geographically small and removed from major river basins, yet functions as a kind of microcosm of the political, cultural, and ecological tempests these salmon recovery and ecological restoration projects stir up at any scale. Salmon are simultaneously a global fishery resource, a key subsistence and cultural resource for traditional peoples around the Pacific, a scientific project to avert extinction, and a contested site of knowledge production. In asking what forms of collaboration are productive, and how collaborations transform those who undertake them, this research contributes to debates on practice and ethics inherent in environmental governance in the Anthropocene era.

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Introduction: Multiple valences of watershed collaboration

Where salmon hover on the cusp of extinction, some scientists and people who live along salmon-bearing streams seek new collaborations. Agencies, tribes, and watershed councils commission competing studies to tease out links between human use of land and water, global oceanic cycles, and the precipitous decline in salmon populations (Sarna-Wojcicki 2014). Tribal resource managers turn to ecological models to validate traditional knowledge in the eyes of state fisheries boards (ICTMN 2014). Scientists enlist commercial fishers and seals fitted with pressure and salinity sensors to study ocean conditions (Ohshima et al. 2013). Hydrologic modelers turn to long-time ranchers' expert opinions to condition model predictions of where streams dry up (Hines 2014). Ranchers import beavers to build dams and raise water tables (Millman 2011). These watershed collaborations begin to transcend boundaries of human institutions, scientist / lay person, and even species.

To understand watershed collaborations, it is not enough to discuss what projects scientists and others pursue in the name of salmon recovery. It is also important to look back at how scientific knowledge shaped earlier U.S. projects to tame rivers and harness their flows of water, power, and fishes for particular political and economic ends. Scientific practices in disciplines of engineering, social science, forestry, geology, and hydrology coevolved with— and indeed were instrumental to— the project of Manifest Destiny.[1] Legacies of Manifest Destiny thinking are sedimented into infrastructures such as dams and aqueducts and land use conversion to logging, agriculture, and urban development, while the practice of dismissing indigenous and traditional land management practices infuses water, forest, and fisheries governance institutions.

Now, some bottom-up and collaborative efforts to rehabilitate ravaged land- and waterscapes are turning scientific methods to new uses. These appropriations, hybrids, and reworkings of scientific practice by Native American tribes, rural communities, and urban environmental groups (among others) are transforming the practice of riverine science, and prompting renegotiations of what kinds of knowledge should inform environmental governance. Some of these new configurations ultimately challenge legacies of Manifest Destiny thinking by transforming legal doctrines, dismantling dams and levees, and inspiring new cultural water use practices.

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[1] I am indebted to July Cole for thinking on Manifest Destiny and its legacies in landscapes, infrastructures, hydropolitics, and relations among humans and other species. In a call for proposals (Cole and Woelfle-Erskine 2014), Cole and I articulated these legacies thus:

> "Manifest Destiny is the major phenomenon unleashed on the heels of Lewis and Clark, Wilkes, Gibbons, Stevens, and other U.S. expeditions (e.g. Herndon and Gibbon 1853; Jackson 1978; Stevens 1860; Tyler 1968). This Destiny is generally identified with westward and outward movement, divine favor, white supremacy, resource exploitation, and insistently policed boundaries.... [T]he tendency can be traced at least as far back as Jefferson's 1803 directives to Lewis and Clark (Jackson 1978). World Bank and IMF policies have exported Manifest Destiny's physical and political/economic infrastructures world-wide (D'Souza 2008; Woelfle-Erskine et al. 2007). Contemporary global military U.S. missions echo frontier settlement patterns: rogue deployment, swarm tactics, and establishment of corridors.
>
> One of Manifest Destiny's prime characteristics is its assumption of hegemony. Oral histories and folk literatures and suppressed accounts are rife with narratives of how, under Manifest Destiny, humans have been variously recruited, chased, displaced, imported, abandoned, enslaved, shot, employed, deployed, corralled, rewarded, experimented on, and over-written (Conway 1995; Davis 2002; Scott 1998; Kosek 2006). These manipulations occur at the demand of the logics of U.S. national expansionism and consolidation, and render those logics over-determined and nearly self-perpetuating. Yet, despite the cathedral assurance Manifest Destiny radiates, it has met continued, vigorous, and multi-faceted resistance from the moment of its inception to the present hour. The first and foremost of Manifest Destiny's opponents, its fiercest critics and most clairvoyant refuseniks, are Native American and other indigenous people (Deloria 1988; Howe, TallBear, and Oak Lake Writers' Society 2006; Mooney 1965; Kimberly TallBear 2013; C. Wilkinson 2006; C. F. Wilkinson 2006; Weir 2009)."

My dissertation investigates how watershed collaborations transform scientific practices, environmental subjectivities, and trans-species alliances, using Salmon Creek (Sonoma Co., CA) as a case. From the outset, I sought to undertake research as a collaborative process, bringing together local residents, agency representatives, grassroots groups, independent scientists, and tribal representatives. By drawing the diverse 'partial perspectives' informed by their different situated knowledges (Haraway 1988) into a lively composite, I hoped to develop a set of research questions that addressed dynamic interactions among salmon, water, and land use, livelihood, and politics, and to develop collaborative methods that brought together different scientific, indigenous, and local knowledge to address questions of social and ecological concern to collaborative members. This approach produced many different kinds of knowledge, only some of which can be wrangled into the confines of an academic dissertation, even an interdisciplinary one. These findings—on factors that influence juvenile salmonid over-summer survival in intermittently-flowing streams, on bottom-up methods for investigating household water use practices in the face of scarcity and a desire for interspecies reciprocity, and on incipient notions of groundwater and streams as interspecies commons—comprise the bulk of the dissertation. In this introduction, I reflect on social and scientific implications of my collaborative approach. But first, let me bring a few different meanings of "watershed" and "collaboration" into play.

Headwaters and new tributaries in watershed collaborations

Several scholars trace the emergence of U.S. watershed partnerships back to the influence of Gary Snyder and Mattole River hippies, whose grassroots scientific and 'place-making' projects inspired federal initiatives to fund "friends of the creeks" groups in the 1990s (Woolley, McGinnis, and Kellner 2002). These citizen groups often formed to seek funding or technical assistance from federal, state or local agencies, or to organize volunteer labor for stream monitoring and rehabilitation projects. Watershed restoration efforts were characterized by formal or informal collaborations between citizens, scientists, and regulatory agencies united in their desire to improve hydro-ecological conditions on degraded rivers (Palmer 2009). Groups such as the Mattole Restoration Council in northern California formed citizen science brigades to monitor water quality and count the number of salmon and steelhead that spawned and reared in the watershed, and often used the data to challenge forest management and water diversion policies (House 2000). As federal funds and the possibility of decision-making influence flowed to watershed councils during the 1990s and 2000s, some attracted local ranchers, tribes, and timber corporations and in many cases played out old conflicts and power dynamics (Woolley, McGinnis, and Kellner 2002; Ferreyra, de Loë, and Kreutzwiser 2008). Still other watershed groups dissolved once funds ran out, or were captured by particular interest groups fundamentally opposed to restoring flow regimes or recovering threatened habitats, leading some to question implicit notions of community in watershed governance, the practicality of discursive democracy as a decision making process, and the potential for such participatory processes to entrench existing power dynamics within a community (Ferreyra, de Loë, and Kreutzwiser 2008; Saravanan, McDonald, and Mollinga 2009; Smith 2008).

Another kind of watershed collaboration—intertribal fisheries management councils that work to regulate and increase salmon runs—formed after the 1974 Boldt decision affirmed Native American tribes the right to participate in fisheries management with equal standing to states (Cassidy and Dale 1988, 65–69). The Nisqually Tribe, for example, formed a natural resources division that brought together elders' traditional knowledge of plants and animals with scientific research into ecological conditions, and used this knowledge to challenge harvest limits in state fisheries' agencies management plans (Wilkinson 2006).

Still earlier forms of watershed collaborations predate Manifest Destiny. Inter-tribal strategies for monitoring and sharing salmon runs along the Klamath (and other) rivers mobilized empirical observation of ecological dynamics to set harvest limits and the timing of the First Salmon ceremony, which influenced how many salmon passed upstream before the harvest began (King, Thomas for Klamath River Intertribal Fish and Water Commission 2004). Traditional water management institutions—such as the *acéquia* system adapted to the Colorado Plateau by Spanish settlers and Pueblos, and the Andean *Cómision de Regantes*—combined sharing of riverine resources that varied from year to year with a political governance role (Vera Delgado and Zwarteveen 2008; Rivera 1998). Rather than being examples of vanished cultural practices, these governance structures continue to pose a material and political challenge to the hegemony of centralized scientific management, not least because they assert that governance processes must account for multiple uses of water and rivers.

I would like to extend the idea of watershed collaborations still further, by bringing in other species — beavers, salmon, redwood trees—into entangled and symbiotic relations with humans who manage waterscapes. In this view, through a process of engaging in stream monitoring or rearing salmon eggs in sluice boxes, humans recognize (to borrow Donna Haraway's phrase), that "the partners do not precede their relating; all that is, is the fruit of becoming with"(Haraway 2008, 17). Such collaborations may not involve government agencies or non-governmental institutions, yet still often reshape material-semiotic configurations "from below" as they discursively affect human practices of using water, stone, soils, plants, and animals. Or sometimes, concepts of humans as collaborators with other species, as situated within a reciprocal web of becoming, may filter into policy discourses or political debates.

Alternatively, hydro-ecological concepts such as the natural flow regime (Poff et al. 1997) can be imagined as arising from a collaboration or integration of all of the climate, geology, plants, and animals in a place, and further shaped by human diversion of ground and surface waters. This view makes a break from modernist binaries of passive nature / active human, replacing what Barad (2007) calls the Cartesian cut between subject and object with an 'agential cut' that highlights interconnections among entities entangled by material flows of water, nutrients, sunlight, and carbon. This is all basic watershed science: trees, intercepting rain, or infusing fog into their needles, or pumping water from a riparian aquifer, or falling down across a stream do influence flows of water and sediment—these trees change soil chemistry, break down rock, and shelter small fishes in their submerged roots. Each living creature and molecule of rock or soil or water is simultaneously acting –or as Barad has it, intra-acting—to collectively produce phenomena like floods, forests, and salmon runs. Numerical techniques in ecology are increasingly aimed at modeling feedbacks among different actors in order to discover emergent properties of such complex systems, and the sensitivity of such models to different parameters shape ecologists' ideas of which living and non-living elements matter to a focal species such as salmon. These models justify particular interventions in salmon-bearing watersheds—adding large woody debris to create scour-holes that provide summer refugia, burning forests to reduce summer evapotranspiration (and thereby increase streamflow), or regulating water pumping to reduce stranding of young fish—that transform hydro-ecological landscapes. An open question—one that I plan to explore in future work—is to what extent ecologists and non-scientists relate to this ecological concept of watershed processes as a kind of collaboration among different creatures and entities.

One thread linking disparate kinds of comings-together around streams is a dynamic interplay between local, indigenous, and scientific ways of knowing. Local knowledge held by settler descendants is qualitatively different from indigenous ecological knowledge in that it has not been passed down for many generations, arises from fundamentally different ontologies, and has developed on shorter time scales and with different concerns (e.g. maintaining fodder for cattle rather than elk, catching salmon offshore rather than in rivers) (Deloria 1997; Nadasdy 2004; Corburn 2003; Fischer 2000). Local knowledge also differs qualitatively from agency and academic scientists' knowledge that serves, at different times, as a way of generalizing about ecological processes across large spatial scales, an arbiter of human land use and its ecological effects, and a foundation for regulatory and legal interventions. Local knowledge, on the other hand, is used to manage land and waterscapes at small scales, and places less weight on standardizing methods among practitioners (Turnbull 2000). Furthermore, cultural norms about privacy and the sanctity of private property often limit what data local knowledge practitioners are willing to share. Motivations for collecting data, data collection instruments and archiving methods, and the degree of collaboration with outside entities varies greatly among local knowledge practitioners, which I define broadly to include citizen scientists, agricultural landowners who monitor pasture, orchard, or forest health, rural residents who monitor their own well levels and spring flows, as well as urban and rural residents who monitor the timing of plant and animal life history events or conduct citizen science monitoring of streams, estuaries, and upland areas. In discussing three watershed collaborations below, I explore how concepts of the watershed and the collaborative, inflect science and governance processes, and consider the particular ways these terms have been mobilized, and by whom, in negotiations over salmon and riverine research.

Salmon Creek as a microcosm of anthropocene[2] *phenomena*

Top down approaches have long dominated environmental governance in California, and environmental governance is increasingly science-driven—as evidenced by major statewide initiatives like the Delta Stewardship Council's Delta Science Program and climate adaptation strategy known as Safeguarding California (California Natural Resources Agency 2015). However, local governance is also important in California, where local environmental activism has driven changes in environmental governance over threatened species, dams and other infrastructure, air quality, and toxics. Many water systems, irrigation districts, and open space initiatives are governed by local or private entities. Furthermore, vast areas of private land and private wells that are nominally subject to state regulation escape de facto regulation by agencies because they are too small or remote to warrant attention, or are managed cooperatively with funding from resource conservation districts and other agricultural entities (Deen et al. 2005). In these areas, landowners or citizen groups manage wildlife, forests, rangelands, wetlands, waterways, and groundwater, and changes in management practices that affect endangered species, water quality, and climate adaptation will be carried out largely by local residents, or local collaborations. Thus, it is important to understand local monitoring, data sharing, decision-making, and management strategies, and how they interact with formal agency and policy approaches.

Salmon Creek (Sonoma Co., CA) is an un-dammed stream that drains a 91-square-kilometer watershed characterized by scattered rural development amidst pasture, vineyards, and mixed hardwood and redwood forest (Figure 1). Land use conversion, channel modification, water extractions, and water pollution have altered the quantity, quality, and timing of in-stream flows, limiting the recovery of threatened steelhead (*Oncorhynchus mykiss*) and endangered coho salmon (*O. kisutch*). Coho salmon went extinct in the watershed in the 1990s, and have been reintroduced through the Russian River Captive broodstock program; steelhead never disappeared, but their

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[2] My use of the lowercase 'a' anthropocene responds to Tsing's (2012) call to resist globalizing tendencies of Anthropocene thinking that erase the situated ways that different places experience phenomena such as climate change. See Woelfle-Erskine and Cole (in press).

numbers have dropped precipitously since the 1970s (UC Cooperative Extension 2015). California's Mediterranean climate delivers most rain between October and April; many tributary reaches dry into disconnected pools between July and September. Anthropogenic drought compounds historical watershed modifications (e.g. beaver removal, logging, road building) that have drastically altered fluxes of water, sediment, and large woody debris to streams like Salmon Creek. Reducing human diversions of freshwater during summer is a key objective in salmon recovery, since summer is when this "anthropogenic drought" compounds natural drying, reducing habitat volume and concentrating pollutants, thereby increasing stress to aquatic organisms.

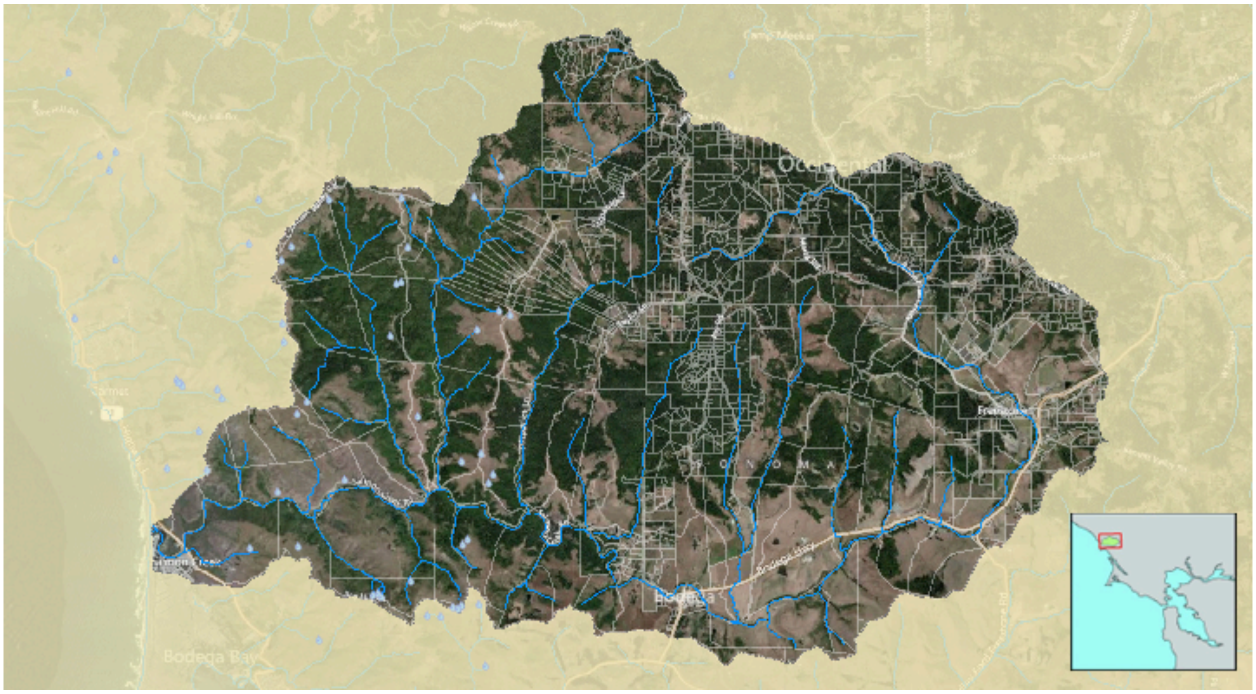

Figure 1: Map of the Salmon Creek watershed showing streams (blue lines), parcel boundaries (white lines), and springs mapped by the USGS (water droplets). The high-density development in the center of the map is the Joy Ridge area. Large parcels are mostly used for unirrigated ranching, and several are protected with conservation easements.

Salmon Creek is geographically small and removed from major river basins. Nonetheless, my study will contribute theoretical and pragmatic knowledge to watershed recovery projects elsewhere because the Salmon Creek watershed functions as a kind of microcosm of the political, cultural, and ecological tempests these kinds of projects stir up at any scale. Salmon are simultaneously a global fishery resource, a key subsistence and cultural resource for traditional peoples around the Pacific, a technoscientific project to avert extinction, and a contested site of knowledge production. Salmon Creek's hydrology is typical of many streams in this area, and may become increasingly typical as the region experiences the effects of climate change. Furthermore, small watersheds are worthy of study in and of themselves, especially if the sites of study are community institutions, local knowledge practices, and scientific field interventions. Small watersheds are more abundant than large ones, which comprise multiple nested smaller basins. Small coastal streams provide key population refugia for anadromous species such as salmon, because they often lack dams or storm channels that block fish passage from the ocean, and may select for different traits and life histories than nearby large rivers. As social sites, small watersheds provide an opportunity to study the interplay between communities that think of themselves as such, and the biophysical settings that shape and get shaped by that identity. Finally, my study watershed is adjacent to the larger, more conflicted, and much better-studied Russian River watershed, and is subject to many of the same regulatory, political, and legal issues that accompany the Endangered Species Act listing of coho salmon in this region.

Transgressive collaborative knowledge practices

Given tensions and even incommensurability among expert, indigenous, and local forms of science, how might we evaluate or understand collaborative efforts to talk across those divides? I'm interested in collaborative knowledge practices that seek to transgress or break down boundaries between expert and object, scientific and indigenous knowledge, and scientific and local knowledge, among others. Collaboration amongst agency, academic, and community researchers is widely praised across environmental, public health, and development studies, yet defining what constitutes a collaborative, what counts as knowledge, and how power relations and privileges may be addressed is widely disputed (Fox 2003; Agrawal 1995; Smith 2008; Corburn 2003). Feminist, indigenous, and postcolonial scholars have challenged narrow or token collaborations among experts and other knowledge-holders, drawing attention to power relations, epistemic violence, and the partial perspective of all science, including western science (Harding 1995; Subramaniam 2014; Nadasdy 2004; Haraway 1988; Mohan and Stokke 2000; Mosse 1994; Robbins 2006). Researchers have developed participatory, action-based, and justice-seeking methodologies as alternatives to outsider investigations of environmental and environmental health problems (Balazs and Morello-Frosch 2013; Corburn 2007; Agrawal 1995; Weir 2009; Edmunds et al. 2013; Berkes, Berkes, and Fast 2007). These approaches, while divergent in method and content, share several key commitments: to reflexivity, to setting goals together, and to shared authorship, though these commitments do not always hold up in practice.

Transgressive collaborative knowledge practices seem well suited for adaptive management along rivers because they can integrate fishers' water users' ways of measuring and monitoring with agency or academic methods. The promise of adaptive management—to undertake environmental management as a series of scientific experiments, incorporate interdisciplinary evaluation methods, and apply lessons learned to future projects— has rarely been realized, due to funding constraints and institutional barriers (Innes and Booher 2010; Bernhardt et al. 2005). Furthermore, large, agency-driven adaptive management processes rarely include local residents in goal setting, monitoring, and evaluation (Medema, McIntosh, and Jeffrey 2015; Engle et al. 2011; Fernandez-Gimenez, Ballard, and Sturtevant 2008). Indigenous, postcolonial, and feminist science and technology studies (STS) scholars propose new ways of doing science that trouble boundaries between disciplines and assert considering the situated knowledges of scientists, practitioners, and local residents yields a stronger objectivity, and more robust results (Harding 1995; Kim TallBear 2014; Diver and Higgins 2014; Finney 2014; Fortmann 2014). Few, however, conduct collaborative technoscientific research projects that enact these principles (but see Subramanian (2014)).

Seeking to field test transgressive collaborative knowledge practices in hydro-ecologic research, I undertook a collaborative inquiry into social and ecological dimensions of water scarcity in the Salmon Creek watershed (Sonoma Co., CA) between 2011 and 2015. Ad-hoc collaborations between the local watershed council, consultants, and federal and local agencies had identified groundwater pumping as a factor in stream drying and water quality impairment, and secured funding for a large rainwater harvesting project to replace pumped groundwater for municipal and agricultural supply near the town of Bodega. My first year of research involved meetings, interviews, and field visits with many of the groups with a stake in watershed rehabilitation projects. Through these meetings, I developed several possible research questions, then asked collaborators which ones touched on their own goals. I found that while scientists and local residents agreed that water scarcity was a key concern, they cared about different dimensions of water scarcity. Many biologists believed that stream disconnection into isolated pools caused juvenile salmon mortality, but did not know whether lack of food, lack of oxygen, high temperature or predation killed the fish; they were also concerned with fine sediment and nutrient runoff and lack of complex stream habitat that affected spawning success. Rural residents and agricultural users were primarily concerned with protecting groundwater from depletion by new wells or drought and from regulation under new statewide rules. Some scientists are also local residents, some agriculturalists have scientific training, and nearly all residents express support for recovering salmon from the brink of extinction, complicating a neat division of participants into stakeholder groups.

Consultation alone does not make a collaboration transgressive. Indeed, alternatives to top-down modes of research, in which a researcher arrives in a community with their questions selected, and then perhaps consults with local residents and collaborators on details of method or interpretation, has become increasingly common in development studies and public health (Minkler and Wallerstein 2011; Cornwall 2011; Wallerstein and Duran 2010; Israel et al. 1998, and this a good thing. However the approach I pursued takes collaboration further than these studies. I spent my first six months in the field accompanying different citizen scientists, creek walkers, agency scientists, and consultants on field surveys, observing what they measured and asking what questions they thought were most important. I made my own commitments explicit in these conversations—commitments to studying how water scarcity affected humans and other species, to understanding feedbacks between social and ecological systems, and to bringing together local and scientific practices. In my second year of research, I began a hydroecological study of how stream drying affects juvenile salmonid survival, which grew out of these consultations. The study included a biological assessment in partnership with the Gold Ridge Resource Conservation District (hereafter RCD), a hydrologic mapping effort in partnership with the watershed council and local residents, and a groundwater flow paths study in cooperation with local residents, utilizing samples collected from their wells. In years 3, 4, and 5 of the project, I conducted annual research collaborative workshops that each brought together forty participants representing all of these interests to explore different ways of monitoring and interpreting social–ecological processes evolving in the watershed.

Through my dissertation research, I investigated transgressive collaborative knowledge practices, using a case study from a collaborative I spearheaded in a small watershed in central California. Here, I focus on three examples of monitoring and analyzing hydro-ecological phenomena: 1) salmon spawning success and juvenile salmonid presence, 2) well and spring dynamics, and 3) streamflow recession and wet / dry patterns of streamflow.

In each case, I address a set of questions related to measurement: Who does the measuring? What do they measure? What motivates them to collect this data? What data do they no longer collect, and why? Are their methods commensurable with other methods for measuring the same thing? How have new technologies changed their strategies for managing and sharing data? How do reasons for collecting data and the ways it is put to use differ among groups of data collectors? I also address a set of questions related to collaboration: With whom do people collaborate and share data, and how did they come to do so? Who chooses not to collaborate? Which collaborations have been sustained, and why? After examining each of the three field collaborations as possible cases of transgressive collaborative knowledge practices in action, I discuss collaborative workshops as crucibles for forging new modes of science. I then discuss the commensurability of different kinds of knowledges and the potential to mobilize them in different watershed governance frameworks (top down, decentralized, watershed scale). Following feminist STS scholars, I pay attention to the social nature of knowledge production, the boundaries people draw around their study systems, and the resulting views of agency, collaborative possibilities, and inter-species reciprocity that result.

1. Counting salmon

After the first big storm of 2015, I received a flurry of phone calls and emails. Biologists at the Gold Ridge RCD, the California Department of Fish and Wildife, the Russian River Captive Broodstock Program, and a local consulting biologist wanted to know of any sightings and coordinate surveys. A watershed council citizen scientist reported that flows were still high and turbid, and that they had seen no fish. A local resident and self-described creek walker reported seeing ten large steelhead leaping over a log he'd thought might block passage. He had made detailed notes on their number, size and behavior, and their degree of shimmer. The next day, he and I hiked down a precipitous trail through cut-over redwood forest to the channel-spanning log he called "steelhead city". Within thirty minutes we observed several carcasses and a male and female coho salmon on a redd, identifiable by the bright tags affixed through their dorsal fins at the hatchery where they had spent their lives until traveling by truck to the mouth of Salmon Creek for release.

In Salmon Creek, some residents, the Gold Ridge RCD, and some environmental consultants observe and count salmon. Among residents, creek walkers monitor a given reach of stream, on their own or a neighbor's property. They time their walks to take place after large rains to look for spawning adult salmon, and also visit periodically during the summer to check refuge pools for juveniles. Some keep detailed notes of their counts, including the number of minutes spent surveying, the species of fish observed, and the location based on local landmarks, and photograph or video record their sightings. Several creek walkers reported walking their creeks after every storm (two to six visits per spawning season), and could report the location of gravel salmon nests—called redds—and the species months after the fact. Others keep more cursory records, or none at all. Ranchers often also visit creeks after storms, on multi-purpose visits to inspect pumps and culverts and monitor changes in wood and sediment. They often report the number and species of fish observed to partners at the RCD or to neighbors by telephone, while creek walkers report to their neighbors or to the watershed council list serve. Consultants who work locally in habitat enhancement sometimes undertake their own snorkel surveys for juvenile salmonids or observe spawning adults while conducting project planning visits. They typically report their observations to the RCD, who funds or partners on many of these efforts.

For three years after the release of captive broodstock coho into the watershed in 2008, the Gold Ridge RCD conducted spawning surveys and snorkel surveys under contract from the National Marine Fisheries Service. They recorded observations on data sheets, tracking the observer; the exact location of spawning fish and redds; the size, sex, species, and their confidence in identification; the air and water temperature; and characteristics of the pools including the presence of large woody debris and size of gravel. They also flagged redd locations on site. The RCD conducted summer juvenile surveys once per season on reaches of five tributaries plus the Salmon Creek mainstem. The length of stream surveyed varied among years based on access agreements with landowners, and the timing of the surveys ranged from June through September. During annual wet-dry mapping surveys (described below), citizen scientists were asked to record where salmonids were present. They noted these observations on a data sheet by circling "salmonids", entering a GPS coordinate, and sometimes making notes on the number or size of the fish. They also noted the presence of large wood, and springs.

Across all spawning surveys they conducted in Salmon Creek 2011-12 and 2012-13, the RCD visited each of twelve reaches 1.5 times, on average. Because of their many other responsibilities, access issues, and the need to coordinate with volunteer assistants, these visits sometimes missed the peak spawning period after each storm, and did not capture each spawning period on each reach. I volunteered with the RCD for spawning surveys in 2012-13, and conducted my own spawning survey in 2014-15. On several occasions, we walked a creek when flows were too high and muddy to observe fish clearly; on others we missed the peak spawning period because of the Christmas or New Year holidays. In contrast, creek walkers and riparian landowners reported visiting their study stream several times after a storm, and were thus more likely to observe spawning events. However, each creek walker only surveyed the one or two creeks on their property, and some surveyed only short (less than 1 km) reaches. Only the RCD aggregated data collected on multiple tributaries and made it available to other agencies and to the general public. They report the number of fish per tributary (rather than per parcel) in order to accommodate landowners who did not want state or federal regulators to know that endangered species were present on their property (Figure 2).[3]

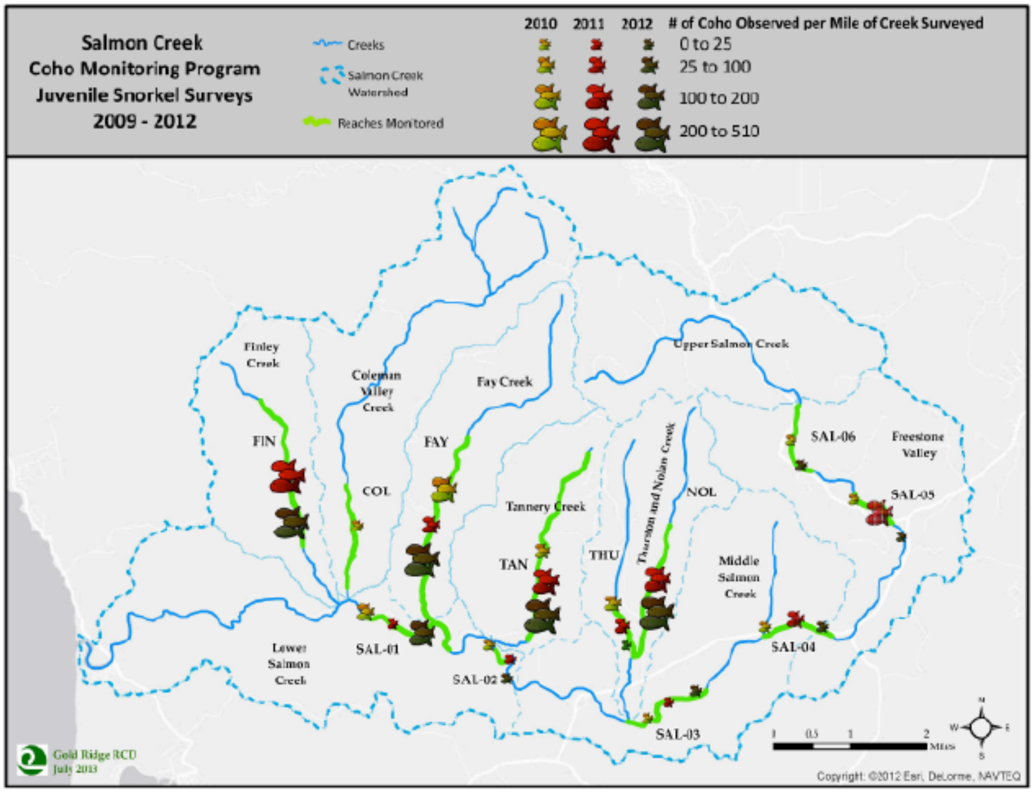

Figure 2: Map created by the Gold Ridge RCD aggregating data from three years of salmon snorkel surveys. Used with permission.

During surveys with different creek walkers, I noted that all made accurate identification of adult and juvenile salmonids and redds, several made detailed notes, and wanted to share their observations with agencies. When I conducted training walks and snorkels with creek walkers, we used the RCD data sheets, and creek walkers were able to fill them out easily, though they did not always fill them out completely. Several creek walkers and citizen scientists asked me to train them in spawning survey or snorkel survey methods, and five took part in training surveys in 2014 and 2015. I found that citizen scientists who were not habitual creek walkers had difficulty spotting and identifying juvenile salmonids and redds on training surveys, though creek walkers spotted and identified them accurately.

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[3] Landowners are responsible for not killing endangered species, and can be fined if pumping or alterations to streams kill endangered salmonids. The National Marine Fisheries Service is developing "Coho Safe Harbor" agreements that will protect landowners from sanction if they follow agreed-upon land and water management practices, and may encourage more landowners to allow salmon monitoring (Woelfle-Erskine field notes, Salmonid Restoration Federation conference, Santa Rosa, CA, March 12 2015).

I saw little evidence of new technology use. The RCD used handheld GPS units, flow meters, measuring tapes, and thermometers, but in a routine way they had been doing for years. Creek walkers rarely used more than a camera and pencil. Once, I witnessed a creek walker using Google Earth to show a consultant where their observation reach was located. A few citizen scientists who participated in wet-dry surveys obtained smartphone GPS apps or purchased their own GPS devices for that project, and later used them to collect coordinates and photographs of spawner sightings. However, because GPS signal is limited in many of the watershed's deep canyons, topographic maps, sketch maps, and landmarks were more commonly used to locate and communicate salmon sightings.

As of 2013, the Gold Ridge RCD no longer received funding to monitor or aggregate fish count data, and thus lacks staff time to enter volunteer observations and create maps and reports. Watershed council members repeatedly expressed frustration that Gold Ridge has no funding for salmonid monitoring, and that coordinated monitoring of fish populations ended just four years after coho reintroduction began. The Gold Ridge staff are frustrated by the lack of funding, which they see as emblematic of state and federal agencies' dismissal of the creek as potential salmon habitat. The agency continues to apply for funding and one Gold Ridge biologist does occasionally conduct snorkel surveys on her own time. Drawing on local residents' salmon observations would be one way to continue monitoring in the absence of funding, but several barriers limit the transfer of fish count information from residents to agencies. Several agency biologists expressed doubt that residents could accurately identify and report salmonid sightings. The Gold Ridge biologist also reported that some creek walkers, agricultural landowners, and consultants are unwilling to fill out data sheets and leave flags marking the location of fish and red sightings. Watershed council members mentioned that it often takes months for agency and academic scientists to aggregate, analyze and release spawning data, and that these delays decrease their interest in collecting data for agency use.

2. Measuring springs, wells, and rainfall

On my first visit to a spring in the watershed, I met three residents at the paved road. One was the landowner whose spring we were to visit, the other two lived on neighboring properties, and one was active in the watershed council. We climbed in the landowner's jeep and set off down a steep dirt track about a quarter mile and 2000 feet straight down, through dead tan oak trees he had recently worked to clear from the road, past an old road washed out by a flood. Then we walked a few minutes through poison oak and underbrush until we came to an old redwood tank. The spring itself was a shallow depression at the base of a sandstone outcrop, covered by a custom-cut plywood lid and diverted to the tank inflow pipe via a short poured-concrete weir. Only about half of the water flowed to the pipe; the rest flowed around the weir into a tributary that fed a pond full of Pacific salamanders, and thence to a large tributary of Salmon Creek. The spring, the landowner explained, had previously supplied two neighboring homes, now on separate properties, and a rickety pipe still supplied a back-up tank at the neighboring property. He grabbed an old mayonnaise jar from the base of a ladder leaning on the tank, then climbed up and checked his watch to see how long the jar took to fill. He recorded the rate—three gallons per minute—in a red logbook that held monthly records dating back, sporadically, to the 1980s. Since 2009, when the spring nearly went dry, there were no gaps in the data.

Residents in the Salmon Creek watershed monitor their own wells and springs, and almost universally maintain rain gauges. Many regularly share rainfall data informally by phone with neighbors, and some keep detailed records for their own use or contribute to CoCoRaHS, a national citizen weather monitoring network (cocorahs.org). People who rely on spring water for domestic supply typically keep detailed records, while those with springs on their property who rely on bore wells do not, and most people didn't consider spring flow proprietary data. On the other hand, people consider well data privileged information and rarely share it with officials or their neighbors, since knowledge of failing wells can lower their property value. However, during the extraordinarily dry year of 2014, when several wells and springs dried up for the first time in living memory, several residents formed collaborative well level monitoring effort, with one neighbor measuring static water levels at five adjoining properties at monthly intervals.

On the whole, residents use low-tech methods to monitor wells and springs—static measurements using homemade devices, watches and mayonnaise jars, and paper record keeping are the norm. Residents used manufactured rain gauges and followed established agency methods for siting gauges and recording rainfall (e.g. installing the gauge in an open area and checking and emptying it at the same time each day). These methods are equivalent to methods that government agencies use to gather point data on rainfall, groundwater level and springs, and in some cases provide sufficient resolution to calculate aquifer characteristics. One resident with an open well keeps detailed records going back two decades, making hand-drawn plots of rainfall and well levels at monthly intervals. Through these records, she had determined that the transit time (the time for water to reach the aquifer feeding her well) was sixty days. She presented these records at a collaborative workshop I organized, where an agency scientist asked if he could install a sonde to measure pressure, conductivity, and temperature at half-hourly intervals. She agreed, and two seasons of data confirmed the trend her analysis had measurements had identified.

Groundwater availability and spring flow varies widely across the watershed, influenced by local aquifer characteristics and groundwater recharge potential (Figure 3). In water-scarce regions such as the densely-populated Joy Ridge area, increasing residential development—and concomitant well drilling—has stressed formerly productive wells. In my interviews and focus groups, residents noted that some residential wells go dry every year, and in drought periods more wells dry up, placing financial burdens on residents who must purchase trucked in water. Since the 1970s, planning documents and some local residents have advocated for a development and well-drilling moratorium in the Joy Ridge area. However, large landowners want to be able to subdivide and sell off parcels, and the county has not put any development limits into place. As a result, the rate of parcel use has increased rapidly since 1980, with estimated water use increasing proportionally.[4] Assuming that all water diverted from the aquifer would have contributed to base flow, a GIS analysis I conducted shows this monthly average deficit exceeds 200 acre-feet in some tributary reaches (Woelfle-Erskine and Merenlender 2012). This estimate overestimates the impact of residential water withdrawls because the model assume that water pumped by residential wells would otherwise have reached the stream. In fact, plants would have transpired some water, and some would have seeped into deep aquifers. Nonetheless, the model provides the best order-of-magnitude estimate we have to date of how residential water use diminishes summer base flow.

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[4] Between 1934 and 1980, subdivision occurred at a rate of 2 parcels per year and the number of parcels in the watershed increased from 84 to 169; between 1980 and 2014, the rate increased to 23 parcels per year, with 974 parcels in the watershed in 2014. Assuming 1 residential well per parcel, residential water demand increased from ~588,000 gallons in 1934 to 15 million gallons in 1980 and 88 million gallons in 2020. See Gonzales 2015 for methods and details on analysis.

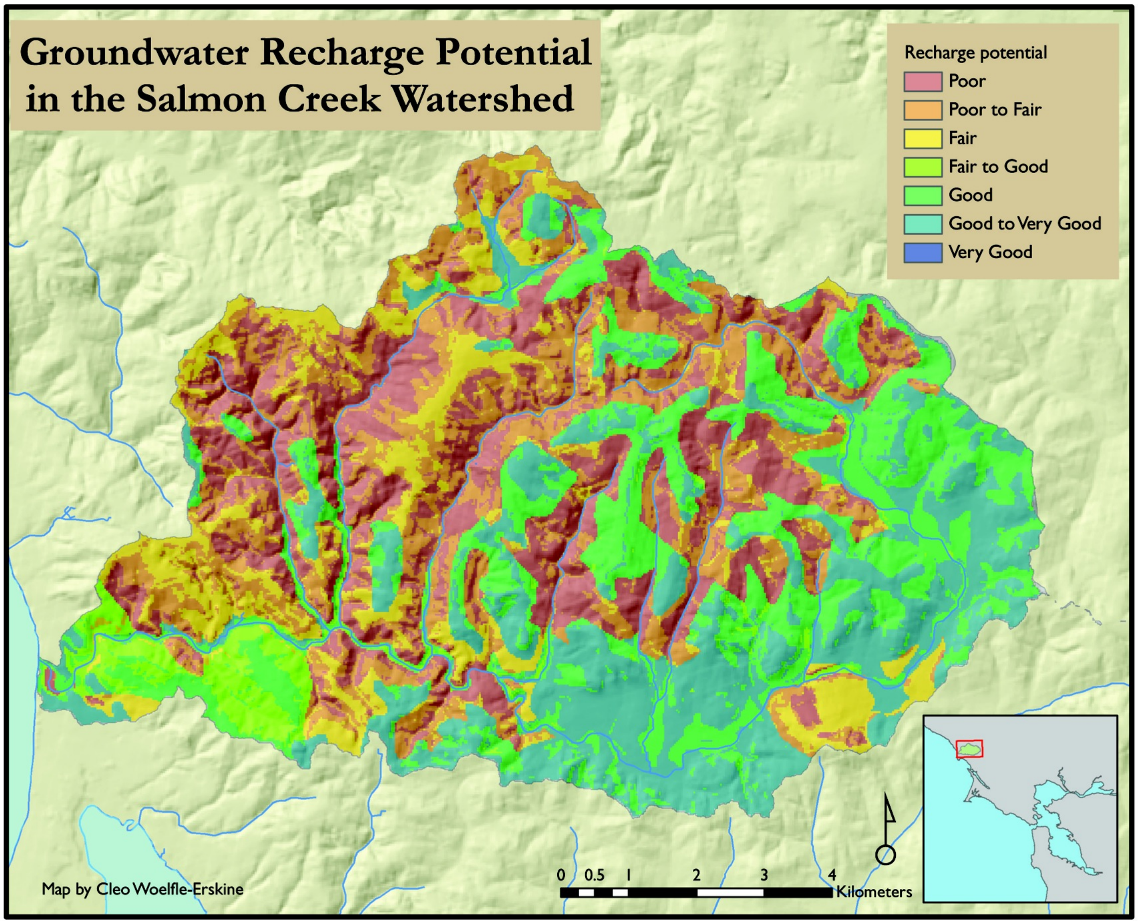

Figure 3: Groundwater recharge potential map showing high potential in the eastern and southern parts of the watershed, and low potential in the northeastern portion. The recharge potential score integrates qualitative scores from the underlying geology, soil type, slope, and vegetation cover.

Riparian landowners typically own large parcels and often rely on wells adjacent to streams that may be connected to the stream directly, or may intercept subsurface flow that would have otherwise contributed to base flow. These landowners are typically agriculturalists who rely on a mix of water sources—wells, springs, and agricultural ponds—for household, home garden, and stock use (there is very little irrigated agriculture in the watershed). Several of these landowners experience water scarcity in drought years. The impact of near-stream groundwater pumping and riparian diversion is easily measured with pressure transducers, and earlier studies demonstrated that shallow municipal and agricultural wells cause downstream reaches of Salmon Creek to dry up in the summer (Hammack, Hulette, and Prunuske 2010). In the Russian River basin, pressure transducer data has been used for exploratory and regulatory purposes by the National Marine Fisheries Service (Hines 2014). Because the legal status of shallow groundwater diversions is questionable, many riparian landowners are unwilling to allow agencies access to continuously monitor streamflow levels because they fear that the National Marine Fisheries Service could use the data to levy fines for ‘take’ (inadvertent killing) of endangered steelhead and coho.

However, some landowners have been willing to allow the Gold Ridge RCD to monitor stream and pond conditions as part of a project to install large rain tanks and off-channel ponds to increase water security and eliminate summer water withdrawals. To date, four ranchers, seventeen residential users, and the Bodega Volunteer Fire Department have collaborated with Gold Ridge to install rainwater storage to increase water security and eliminate summer pumping from the creek. These projects typically involve a ten percent cost share by landowners and are sized to capture all of the water they require for dry-season operations. In exchange, landowners agree to refrain from pumping from streams or near-stream wells during the summer months, and to allow streamflow monitoring for several years after implementation. These projects have been partially funded by National Marine Fisheries Service and the California DFW because of their salmonid habitat benefits.

Compared to US Geological Survey monitoring programs in the nearby Sonoma Valley, there is little sharing of groundwater data in the watershed, and not enough wells are measured to allow aquifer delineation, track infiltration rates, and monitor seasonal changes in groundwater levels. I see two ways to increase monitoring and coordination. One way would be through collaborations between residents and Resource Conservation Districts that would install continuous water level loggers in a larger number of wells, with disclosure agreements regulating how the resulting data would be used. Salmon 'safe harbor' agreements, which release landowners from liability for salmon mortalities as long as they follow specific management practices, could also alleviate landowner resistance to monitoring; such agreements are in development in the Russian River Basin. Resident-agency collaboration could be expanded in rainfall monitoring as well, through enrolling more rainfall monitors in CoCoRHAS. This approach would require a higher level of trust between property owners and agencies that hold the data, such that residents were assured that county or state water agencies would not use the data to limit their ability to pump water, tap undeveloped springs, or drill new wells in the future. Given the mistrust that many residents expressed towards the county and regulators, and the expanded authority that new California groundwater monitoring requirements give to the state to regulate groundwater levels, this approach seems unlikely to be adopted widely.

Another way to increase monitoring and coordination would be for residents themselves to expand their well monitoring efforts. One such effort began in 2014, when a group of five neighbors on a water-scarce ridge started measuring their well levels monthly and sharing the data among themselves. This effort might be modeled on a voluntary monitoring program run by ranchers in the Scott Valley in Northern California, who monitor levels at more than 100 agricultural wells and have used that data to drive regional groundwater modeling in collaboration with UC Davis hydrogeologists. This ability to control the raw data, and to determine when and how it is shared, may be attractive to Salmon Creek residential landowners wary of county and state regulation.

3. Mapping wet and dry stream reaches

On a Saturday morning in September, twelve local residents meet at the Bodega coffee shop, equipped with sun hats, rubber boots, clipboards, and GPS devices. Some work as environmental consultants or regulators at their day jobs, some participate regularly in watershed council activities, and some are ridge top residents curious to walk creeks that are usually inaccessible behind no trespassing signs. On this day I was training two "reach captains" in GPS operation, while two local creek walkers came along to help and learn the method so that they could implement it on their own streams. We split off and headed up a ranch road to a parched field next to a cattle barn, talked to the rancher for a minute, and then set out on foot towards the dense willows that mark the stream. The stream flowed across a gravel bed in an incised clay channel cloaked in native blackberry and alder. I marked a starting point on the GPS, showed the others how to check the number of satellites that the device used to triangulate and estimate its position error, and another volunteer recorded all the numbers on the data sheet. Walking downstream, we soon reached a place where the stream had gone subsurface beneath gravels. The reach captains practiced marking the point, marking a few extra by accident. Meanwhile, one creek walker—a small farmer who showed up with ripe melons for the crew—spotted some salmonids and a sculpin in a pool, and we recorded those observations on another data sheet. By the end, all four were confidently using the GPS device, and the two watershed council members had picked up the knack of spotting fish from the creek walkers. The whole survey took three hours of scrambling up steep banks, jumping deep pools, and noting observations of tires, a river otter, anoxic water, and the pattern of wet and dry reaches that characterizes this stream. It was more difficult than I had predicted. No one complained, but no one offered to join me on the afternoon survey, either.

In 2013, I began this wet-dry mapping initiative in the watershed, modeled on an approach used by the Nature Conservancy on a trans-border reach of the San Pedro River in Arizona and Sonora (Turner and Richter 2011). My goal was to track annual variation in the extent of wet and dry reaches at the end of the dry season. With several years of data, we could then identify reaches that always went dry, sanctuary reaches that always remained wet, and intermediate reaches where streamflow enhancement could increase the extent of high-quality habitat. The watershed council wanted to shift its monitoring efforts from monthly water quality sampling, which required finicky calibration of a failure-prone device and generated data that was not being used to inform management. Together, we had discussed "eyeball methods" that made use of eager volunteers to collect data that agencies had no resources to collect. By working through informal neighbor networks, we thought we could gain access to parcels where agency monitoring was unwelcome. At the first collaborative science meeting I organized, in 2013, representatives from the RCD and independent consulting biologists expressed interest in the data and volunteered to participate in the effort. In 2013, a dozen participated and surveyed approximately seven km of the stream. Reach captains—local stream side landowners who knew adjacent landowners—coordinated access, while I tracked volunteers and assigned them to a reach, conducted a training in the method, entered the data, and created GIS maps to visualize it. In 2014, I asked watershed council members to partner in organizing the effort, to build their capacity to continue it in the future and to engage their local knowledge of social networks and technical capacity to improve the mapping process. We expanded the effort to include ten km of stream, adding two new tributaries, and involving twenty volunteers.

In contrast to salmon counting and water source monitoring, the wet-dry mapping project was an entirely new method that I, an academic outsider, introduced from scratch. However, it drew on existing creek walking and stream inspection practices discussed above, with some landowners volunteering to walk their own section of creek rather than enlist volunteers to do so. The initiative brought together local knowledge networks of local residents affiliated with the watershed council, independent biological consultants, and the Gold Ridge RCD. These different actors have non-overlapping networks—due to past conflicts, some landowners will allow the RCD but not the watershed council to access, some will allow their neighbors or biologists they know personally to access, but not either group, and some will survey the stream themselves rather than allow any outside access. Some watershed council members who are relative newcomers to the area got to walk stream reaches for the first time, and met and interacted with agricultural landowners they knew by sight but had rarely talked to. The mapping walks also provided opportunities for residents to interact with agency and biologist volunteers, sharing local knowledge of streams and land use and expert knowledge of fish and other species. In the second year, several volunteers said they wanted to go out with the National Marine Fisheries Service biologist volunteer in order to learn more about identifying fish and their habitat requirements.

The effort also brought to light an ongoing tension between the Gold Ridge RCD and the watershed council. RCD employees were uncomfortable with the watershed council contacting landowners for access, because they worried that additional requests would fatigue landowners and make them less likely to grant the RCD access in the future. They also worried that volunteers might trespass unwittingly, being unfamiliar with local landmarks that indicated property boundaries, and thus declined to officially co-sponsor the effort, though they did loan equipment and provide staff volunteers.

The data processing and visualization effort also revealed technological and capacity barriers to continuing the effort once I move on. Several members of the watershed council are skilled in data management, and developed procedures to streamline data entry in 2014. Although this step was time consuming, the volunteers thought that with teamwork, it was not too onerous. However, the use of GIS to visualize the data is a technical barrier, as the watershed council members have neither the software nor expertise to manipulate the data in GIS. I see two ways to surmount this barrier. First, the watershed council might contract with the Gold Ridge RCD, which has an in-house GIS specialist, or with the UC Cooperative Extension, which conducts wet-dry surveys on several Russian River tributaries. Second, an outside researcher could develop a web-based visualization protocol that accepted spreadsheet data as an input, and allowed users to compare streams between years, calculate summary statistics, and print custom maps. Such an interface could be used in other watersheds and could be configured to accept input from GPS-enabled smartphones in areas where topography and tree cover allows those devices to receive a GPS signal. (This is not the case in most parts of Salmon Creek).

Collaborative workshops: Transgressive epistemologies in practice

Throughout my dissertation research process, I sought to make use of different kinds of hydrological and ecological knowledge, and challenged agency scientists to take seriously data and other knowledge that different residents possess. I did this informally, by passing records and information among citizen scientists, RCD and National Marine Fisheries Service scientists, consulting scientists, and local residents. I also organized two collaborative science workshops, inviting agency scientists, UC Berkeley academics, local experts such as creek walkers and well drillers, watershed council citizen scientists, ranchers, and residents.

The first workshop focused on salmon science, while the second focused on groundwater by request of local residents. Upon arrival, participants self-identified by the discipline they represented—the choices were aquatic biology/ fish, hydrology/groundwater, geomorphology/ soils, social science, and terrestrial biology/ forestry and range management. I invited different kinds of experts to make short presentations, and introduced them by stating that all different kinds of expertise—including that of ranchers and amateur naturalists—was a critical partial perspective that, taken together, would increase collective knowledge of the system. Participants then broke up into disciplinary groups, and discussed key knowledge gaps and research goals around salmon, groundwater, roads and sediment, upland forests and prairies, and household water use. Each group ended up with representatives from different agencies and citizen groups, and a lively discussion ensued. Over lunch, participants examined different data collection instruments that they used to sense the watershed. At an afternoon field activity that took place in the creek, I asked different participants to explain how they saw the stream: what specifically they looked for and recorded when they went into the field (Figure 4). This activity was particularly rich as scientists from different disciplines realized how different their practices were, and also considered how lay science methods might complement their own.

Figure 4: A retired DFW biologist explains freshwater shrimp habitat preferences to participants in the first Salmon Creek Research Collaborative Workshop, which took place in July 2013. Photo by Heather Hochrein.

Several concrete collaborations resulted from the first workshop. First, a geomorphologist at the Gold Ridge RCD saw a resident's long-term measurements of her well level and rainfall through time and the homemade device she uses to measure it. He arranged to install a monitoring sonde in her well that winter, and confirmed her measurements to his satisfaction. Second, the watershed council decided to organize a wet-dry mapping initiative with me, after hearing from National Marine Fisheries Service and RCD scientists that this data would inform future coho recovery efforts; we began that effort that fall. At the second workshop, residents expressed interest in participating in a groundwater study I was conducting, and were interested in organizing an ongoing well level monitoring study. I collected water samples from several residents, but to my knowledge no ongoing well monitoring is taking place. One watershed council member has begun aggregating rain gauge data from neighbors in her residential area, and seeks to make this data available for local and broader use.

The workshops seem to have had other impacts on relationships among participants, though these are harder to evaluate. The watershed council and a local land trust asked me to facilitate an annual workshop after attending the first one, and helped with organization; many agency and watershed council participants in the first workshop attended the second. Watershed council members also sought stronger collaborations with UC Berkeley, co-mentoring an undergraduate student who conducted archival research on land subdivision for their watershed timeline, and coming to Berkeley to meet with my faculty collaborators. But to my knowledge, none of the agencies have pursued substantial new engagements with local knowledge holders, nor sought to incorporate residents' own measurements of rainfall, springs, well levels, or salmon counts. The Department of Fish and Wildlife has little presence in the watershed; the Gold Ridge RCD is currently conducting monitoring on individual parcels where they are conducting habitat and streamflow enhancement projects, but this relationship is a consultative one, with landowners granting access and expert biologists conducting species surveys and water quality monitoring. The UC Cooperative Extension wet-dry monitoring efforts in the adjacent Russian River basin is similarly consultative, although focused on ongoing monitoring of established study reaches rather than post-project monitoring of individual parcels.

If ongoing collaborative efforts between agencies and residents do not constitute transgressive knowledge collaboratives, what of my own study? I made use of Gold Ridge snorkel data in my first year of study, and learned snorkeling methods from Gold Ridge and consultant biologists. I frequently called creek walkers to ask about salmon sightings, spawning conditions, and whether particular reaches were still flowing. In my hydrologic study, I drew on a creek walker's local knowledge of springs to identify sampling points. I documented well and spring measurements that residents keep, but have not yet figured out how to incorporate them into my own hydrological research. I do think these measurements and the wet-dry mapping data will aid greatly in calibrating and interpreting any hydrologic model of the watershed, though I currently have no plans to undertake such modeling myself. By the third year of my study, creek walkers, consultants, and agency biologists regularly called or emailed me to coordinate survey efforts and report sightings and water levels. I was drawn into existing networks—informal neighborhood phone trees and unofficial agency email chains—that already existed. The Salmon Creek Watershed Council, Gold Ridge and UC Cooperative Extension scientists are interested in collaborating with me to develop a web portal to collect and visualize citizen scientist wet-dry mapping and salmonid survey data; this project could represent an important tool for increased integration of citizen science, local knowledge, and expert science.

These relationships alone do not make my knowledge practices transgressive or collaborative, but the way I used them to define and refine my research questions is quite different from typical academic or agency practices. Rather than coming to my research with an already-articulated area of study, I spent a full year talking with all different knowledge holders. In these conversations, I discovered what they already knew, knowledge gaps that mattered to them, their existing working collaborations, and tensions and refusals to collaborate. These questions, methods, and future goals differed significantly among groups, but intersected around water scarcity. I then designed my study explicitly to study scarcity as a phenomenon involving entangled social, ecological, and infrastructural actors. As my study progressed, I refined my approaches in conversation with these collaborators, in the field, at community gatherings, at scientific meetings, and at the local watering hole. When I shared my findings and new questions, I always emphasized how human and ecological water use were bound up together, and how social phenomena mattered equally *as* ecological phenomena, and vice versa. Many collaborators found this reasoning provocative, and responded with their own views of interdependencies among systems that status quo governance regimes keep separate. I found these exchanges extremely transgressive, and where they may lead is yet unsettled.

Contributions of this research: integrating and building bridges

In this dissertation, I advance basic knowledge of salmonid ecology in intermittent streams (chapter 3), analysis of surface and groundwater commons governance in US rural areas (chapter 2), and methods for studying up from household water infrastructures such as wells, springs, and rain tanks (chapter 1). I also contribute theoretically to three fields. To political ecology, I contribute the idea that other species and water itself matter to people involved in conflicts and negotiations over scarce water in ways not captured by hydro-social thinking and other political-economic approaches; I discuss these issues in "Rain tanks, springs, and broken pipes as emerging commons along Salmon

Creek, Sonoma Co., CA. To people bound up in these conflicts, nature is not a flat field, mere background, but an active phenomenon that humans are inextricably entangled in. To multi species ethnography, I contribute a political analysis informed by indigenous studies, arguing that attention to unfinished colonial projects like Manifest Destiny are critical in making sense of the practices settler descendants develop to manage stolen land. Legacies persist in the form of private property regimes and lack of indigenous co-management authority on private and many public lands in California, limiting the scope and impact of salmon recovery efforts. Compared to regions like the Pacific Northwest, where tribal natural resource management and intertribal collaborations wield broad authority in river management, central California tribes are less visible in regional fish and land management forums, and frequently dismissed by rural residents as legitimate stakeholders in managing their ancestral territories. To hydrology and ecology, I contribute a reflexive and collaborative approach for comparing and evaluating expert and local scientific methods, and a process for scaling up wet-dry mapping via decentralized collaborations; at national scientific meetings, geomorphologists and ecologists were excited by the prospect of expanding wet-dry mapping using a common web portal. To feminist science and technology studies, I contribute an empirical test of feminist STS theory in environmental governance, by extending Barad's (2007) theory of agential realism to rural water systems and explicitly incorporating Harding's (1995) and Haraway's (1988) concept of strong objectivity into my collaborative research process. All flavors of binaries infect (inflect) watershed management—human / nature, knowledge producer / consumer, indigenous / modern, to name a few—yet are rarely called out in management processes. By pointing out convergences and commensurability between different forms of knowledge in public forums and designing interventions that explicitly contest some of those binaries, my field research forged new collaborations and ways of thinking among some collaborators and challenged existing concepts of whose expertise matters in watershed management.

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Quantifying abiotic habitat characteristics to determine thresholds for salmonid over-summer survival in intermittent streams

Cleo Woelfle-Erskine, Laurel G. Larsen, Stephanie M. Carlson

Introduction

Intermittent streams are common throughout the world in regions with pronounced wet and dry seasons. In the United States, intermittent streams constitute the majority of stream length (59%, Nadeau and Rains 2007). This number may grow with climate change, particularly in the western US, where regional climate change models predict increasing drought intensity and duration through the 21st century (Seager et al. 2007). These changes will inevitably lead to decreased stream flows and longer low- or no-flow periods (Seager and Vecchi 2010; Tang and Lettenmaier 2012). In addition, earlier winter precipitation (Pierce et al. 2013) may lead to earlier drying and longer dry seasons. In the southwestern US, streamflow is already peaking earlier in the year than the historical average (Barnett et al. 2008), and the transition of streams from perennial to intermittent due to long-term drought has caused the extinction of long-lived or flightless invertebrate species (Bogan, Boersma, and Lytle 2014; Bogan and Lytle 2011). System response to increased intermittency and reduced flow is poorly understood (Power, Parker, and Dietrich 2008; Souchon et al. 2008).

Fragmentation of streams into isolated pools during the dry season is prevalent in low-order streams that are spawning and rearing habitat for stream fishes, yet only recently have impacts of drying on stream communities and food webs received significant attention (Datry 2012; V. Acuña et al. 2014; Lake 2003). Studies show that benthic macroinvertebrates achieve the highest densities and diversity at the onset of fragmentation, before they decline (Bravo et al. 2001; Pires, Cowx, and Coelho 2000; Gasith and Resh 1999). Consistent with the telescoping ecosystem concept (Fisher et al. 1998; Ward and Tockner 2001), drying-induced fragmentation concentrates organic matter food stocks (Acuña et al. 2005) but then depletes dissolved oxygen (DO) (Caruso 2002; Stanley, Fisher, and Grimm 1997; Towns 1985), due to high microbial respiration and low air-water gas exchange rates (Acuña et al. 2005). Stream-aquifer dynamics determine the concentration and composition of dissolved organic carbon and the proportion of groundwater and surface water in the stream at different times of the summer. In Australian dryland rivers, organic matter differed in concentration between pools, depending on the degree to which the pools interacted with the shallow aquifer. Upon isolation, pools differed in carbon and nutrient concentrations and functioned as distinct ecosystems (Fellman et al. 2011). In Mediterranean streams, pools disconnected from the alluvial aquifer had more labile carbon than pools that remained connected and transitioned to low-DO conditions more rapidly (Vazquez et al. 2011). Clearly, hydrologic and biogeochemical differences between pools can contribute to heterogeneity in habitat during dry periods.

In Mediterranean-climate California, intermittent streams play a vital but under-studied role in providing rearing habitat for juvenile salmonids, where changing land and water use has placed salmonid populations at risk of extinction. Summer stream temperatures in California approach the upper lethal limits for all three species of anadromous salmon that occur in the state (Moyle 2002), ~25 C. Even without accounting for future climate warming and shifts in precipitation, Katz et al. (2013) project that 78% of California's salmon taxa will be extinct within the next century if present trends continue. Climate change will inevitably accelerate that trajectory of decline (Moyle et al. 2013). Long- term observational studies of streams in the region suggest that multi-year droughts strongly shape both fish and invertebrate community composition (Bêche et al. 2009). Although salmonids have adapted to climate variability and can thrive in intermittent reaches they also experience high mortality in dry years (Grantham et al. 2012; Power, Parker, and Dietrich 2008; Wigington et al. 2006). Seasonal low flows exert strong effects on fishes in the northern California region (Bêche et al. 2009; Kiernan and Moyle 2012; Resh et al. 2012). Flow drives invertebrate drift, temperature regime, and DO concentrations, but whether hydrologic/ carbon/ oxygen dynamics are the dominant driver of patterns in salmonid survival (rather than desiccation, food web dynamics, or temperature) in intermittent streams remains a significant scientific question, with implications for how we manage these streams in a changing climate.

Central California represents the southern end of coho salmon (*Oncorhynchus kitsuch*) range and also supports anadromous steelhead (*O. mykiss)* populations; both species have local adaptations that reflect the region's precipitation dynamics. Coastal streams, located in rainfall-dominated watersheds, experience high flows only between late October and early April. Drying peaks in August and has variable manifestations. While some streams continue to flow, supplied by groundwater, others become a disconnected series of pools or may dry completely. The rate and extent of drying also varies from year to year, depending on antecedent precipitation (Hwan and Carlson 2015) and anthropogenic withdrawals, which have been associated with linearly decreasing survivorship (Grantham et al. 2012). Flow influences salmonid energetic requirements and growth rates via invertebrate drift (Rosenfeld 2003; Nielsen 1992), and also mediates temperature and dissolved oxygen concentrations (Milner, Cowx, and Whelan 2012; Richter and Kolmes 2005; Herrmann, Warren, and Doudoroff 1962). DO concentrations below 5 ppm are associated with salmonid avoidance and decreased swimming speed and growth rates (Herrmann, Warren, and Doudoroff 1962; Brett and Blackburn 1981); salmonid growth ceases below 2 ppm DO. In intermittent streams, salmonids occupy persistent, isolated pools during the dry season (Grantham et al. 2012; Bogan, Hwan, and Carlson in press; Hwan and Carlson 2015). Some studies suggest that coho salmon may grow larger in intermittent stream pools than perennial stream pools (Wigington et al. 2006). However, mortality is inevitable in the pools that dry out completely.

Flow regime and geomorphic setting determine when, if ever, a stream becomes intermittent. Bedrock streams are typically steeper than alluvial streams and have higher peak flows. Given the same discharge, a bedrock stream will remain connected—with surface flow over riffles—longer than a stream flowing through deep alluvium (May and Lee 2004); depth to an impervious bedrock or clay layer and local groundwater and surface water dynamics also influence flow, nutrient, and water quality dynamics in intermittent streams (Figure 1). Previous studies have identified threshold levels of temperature (reviewed in Richter and Kolmes 2005) and dissolved oxygen (Henning, Gresswell, and Fleming 2006; Plumb and Blanchfield 2009) for salmonid persistence, but none have studied these metrics in combination in intermittent streams. Furthermore, few studies have compared survival among species in a field setting across a gradient of intermittency or identified abiotic factors that influence survival in intermittent pools. Identifying a duration of intermittent conditions that salmonids can survive requires disentangling food, predation, water quality, and DO effects. Our study focuses on dissolved oxygen effects and a comparative analysis of abiotic factors that influence survival for the two different species across a gradient of intermittency from continuously flowing to nearly dry. We investigate two research questions:

1. Do intermittent reaches sustain spawning and over-summer rearing of salmonid fishes, and how does recruitment and over-summer survival vary across reaches, species, and drought condition? We test the hypothesis that intermittent reaches sustain high recruitment to the fry stage, but low over-summer survival in dry years. We expect that summer survival depends on the proportion of shallow and deep water habitats and the date of riffle disconnection, which are influenced by geomorphic setting, antecedent rainfall, and the local aquifer dynamics (May and Lee 2004).

2. What abiotic factor(s) drive salmonid mortality during the dry season? Here we assess whether DO—rather than temperature or contiguity of flowing water—is the proximal (immediate) driver of salmonid disappearance during the dry season.

From a methodological standpoint, we compared two different methods for assessing abiotic drivers of over-summer salmonid survival: (1) logistic regression in a generalized linear modeling framework and (2) classification trees using the random forests ensemble learning method (Liaw and Wiener 2002; P. Vezza 2015; Cutler et al. 2007; Olden, Lawler, and Poff 2008). These approaches are complementary because regression trees can reveal hierarchical dependencies among variables, thereby suggesting mechanisms behind interaction terms in generalized linear models; generalized linear models are less sensitive to the inclusion of specific variables than classification trees, and thus results can be generalized (cautiously) to intermittent streams beyond the study system. Both analyses tested the influence of all candidate abiotic variables in predicting the survival of each species.

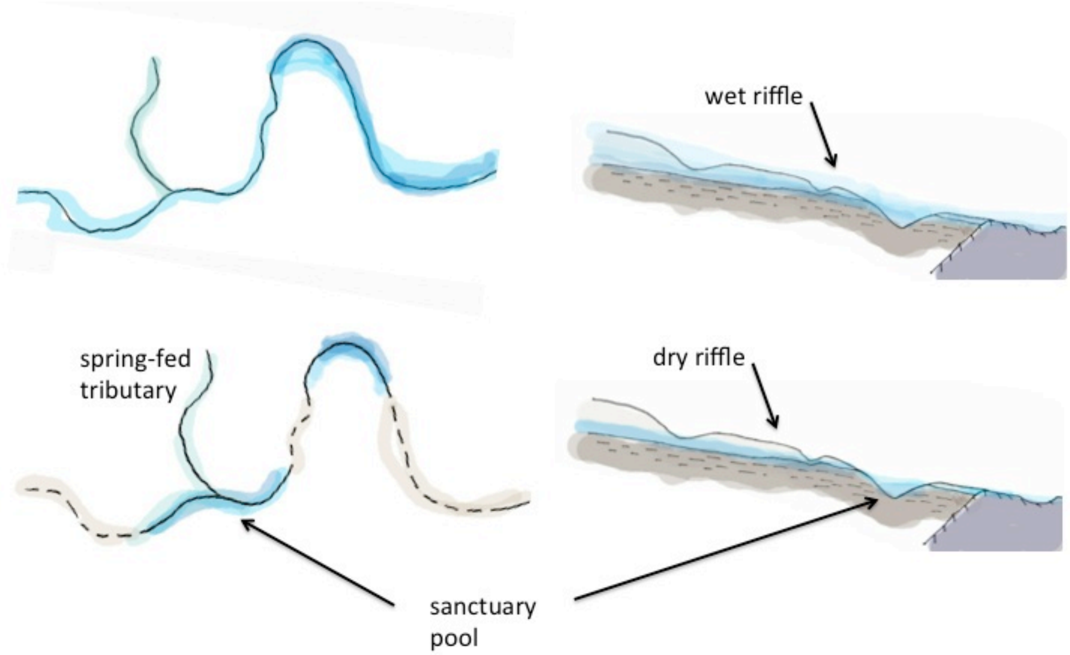

Figure 1: Conceptual model of geomorphic influences on stream disconnection and water quality. The cross sections (right) show alluvium overlaying clay (brown) and bedrock (gray) strata. During continuous flow (top), water flows over and through alluvium, maintaining high DO. Once surface flow ceases (bottom), shallow pools in alluvium may dry completely, or may become anoxic if separated from upstream flowing waters by long stretches of subsurface flow. Spring fed tributaries maintain high DO levels and elevate DO above lethal limits in sanctuary pools.

Methods

Study System

Steelhead trout and coho salmon breed in low-order coastal streams of California, migrating upstream during December-February, when elevated flows permit access to the breeding sites. Juvenile salmon and trout emerge from the nests in the late spring and typically spend one to two years in the stream before migrating to their ocean feeding grounds. In this region, coho have a strict three year life cycle, while steelhead have a more complex life history, often spending 1, 2, or 3 years in the ocean before returning to freshwaters to spawn. In this region, coho salmon are federally endangered and steelhead are federally threatened. Coho salmon have been in severe decline for several decades. Beginning in the 1980s, year-classes of coho began disappearing from the Russian River and other coastal California streams. During this time, coho became locally extinct in several streams including our Salmon Creek study watershed in the mid-1990s, and have only recently been introduced through a captive broodstock program (Obedzinski et al. 2009; Spence et al. 2008).

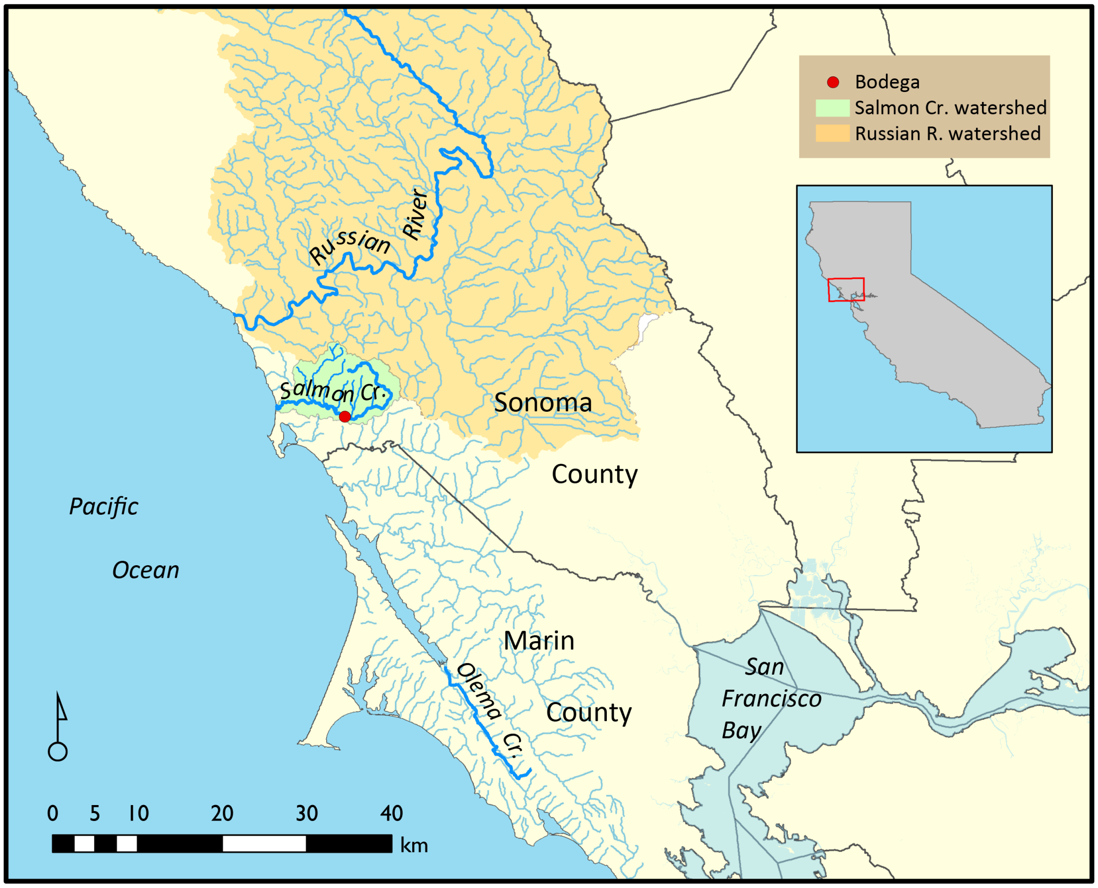

Figure 2: Location of Salmon Creek on California's central coast.

Study Area

We designed our study to assess thresholds for salmonid over-summer survival in intermittent streams and the hydrologic and biogeochemical conditions in sanctuary reaches where salmonids survive. During the summer drydown period in 2012, 2013, and 2014, we conducted intensive habitat and water quality surveys on Tannery Creek and Fay Creek, tributaries to Salmon Creek (Sonoma Co., CA) (Figure 2). We selected two study reaches in each tributary, each containing a representative variety of pools, for monitoring and repeated sampling during drydown events; each reach was approximately 200 m in length except for the lower Fay Creek reach which was 400 m in length. The four study reaches spanned a range of eco-geomorphic settings (confined and unconfined valleys, bedrock and alluvial beds, and a variety of vegetation types) and were chosen to represent a gradient of intermittency, from continuously flowing to intermittent dry stretches to isolated pools spaced at intervals of 100 m or more in the driest reach on upper Fay Creek. In 2013 and 2014, we surveyed 21 pools on Fay Creek and 14 on Tannery Creek; in 2012 we surveyed a subset of 17 Fay Creek pools and 12 Tannery Creek pools, for a total of 99 survey events across the three-year study.

During the study period, regional precipitation and streamflow declined steadily. Below normal conditions in the winter of 2011-12 gave way to moderate drought in the summer of 2012, severe drought in the winter and summer 2013, and exceptional drought in the winter and summer of 2014. The timing of large atmospheric river storm events in each year affected salmonid spawning, recruitment, and summer flow recession patterns. Notably, the lack of rain between February and July of 2013 caused early flow recession in summer 2013, followed by a rare ~ 6 cm rainfall event in late June. In 2014, the first large storm did not arrive until late February, leaving many tributary mouths closed to migration during the coho spawning period and excluding coho from Fay Creek entirely. This variability in climatic factors led to extreme variability in recruitment among study reaches across years and influenced the number of juveniles that survived through the summer. We thus chose to focus on over-summer survival with the pool as the unit of analysis, rather than the fall salmonid count.

Data collection: pool characteristics

We combined synoptic sampling of water quality, flow status, and wetted volume with continuous water level, temperature, dissolved oxygen, conductivity (a measure of groundwater inflow), and pH measurements. In 2013, we installed 1 continuous water quality sensor in Fay Creek; in 2014, three pools were equipped with continuous water quality sensors (Onset Corp. Hobo U26 and U20 and YACorp. 660 V2 4 and 600XLM V2) that recorded a datapoint every 15 or 30 minutes. Barometric pressure was recorded at the same time stamp from one location in the watershed using a pressure transducer (Solinst Levelogger Edge M10) to obtain DO percent saturation values and derive water levels from in-stream pressure transducers.

In each study year, the study pools were revisited once per month for six months from May to October and twice per month during the period of steepest transition to dry conditions (which varied between years and reaches between June and August). During each monthly visit, we measured pool depth and volume and recorded whether riffles were flowing or dry; during 2012 we also measured riffle volumes. In 2012 we calculated volume at each site and date by measuring overall length, width at five evenly spaced points along the length transect, and 20 depths at random points. In 2013 we measured water depth at monthly intervals at a staff gauge in each pool and also surveyed pool topography with a total station (Nikon DTM 322). We calculated pool volume as the volume between the topography and a plane at the water elevation, using the 3D Analyst extension in ArcGIS 10.2. Once per season, we assessed the presence of large woody debris, undercut banks, presence of a visible clay or bedrock layer, and the presence of spring-fed tributaries in each study pool.

Within the pool, we obtained *in situ* DO, conductivity, temperature, and pH readings at each sampling visit. On each creek, we had two water quality sampling regimes: a) one continuous site per reach, with a sonde in the selected pool measuring DO, temperature, and depth, and b) monthly spot measurements in study pools. We plotted the hourly DO value against the minimum DO value for a given day, calculated a creek-specific slope and intercept, and used the spot measurement data to extrapolate, for other pools on each creek, probable minimum daily DO (Appendix, Figure SI 7).

Data collection: salmonid over-summer survival

We assessed over-summer survival with paired early-summer and late-summer snorkel surveys along 1.5 km of Fay Creek and 2 km of Tannery Creek in all study years. We snorkeled all study pools and an additional 15-30 pools on each creek, depending on year. The first survey, conducted in June-July, measured recruitment while the September-October survey, conducted just before fall rains, measured the number remaining following summer mortality. The early-late summer counts were used to estimate over-summer survival. The early-summer survey occurred just after riffle drying limited fish movement between pools; we estimated the depth threshold that prevented movement as 20 mm in the riffle thalweg following J. Hwan (personal communication). Because our sampling occurred during the summer base flow period, we assumed that movement among pools was limited and that changes in the total number of fish between the start and end of the summer reflected mortality. Snorkel surveys were conducted by a single observer (C. W.-E.) to limit observer bias, except for the early-summer 2012 survey, which was conducted by Gold Ridge RCD biologists. We employed a single-pass method because snorkeling in the shallow conditions increased turbidity markedly and impeded detection on subsequent passes. We selected a subset of pools (n = 12) for additional seining surveys in 2013 and 2014 and assessed snorkeling detection efficacy in a linear regression framework. Overall, we found that for pools with low counts (< 100 salmonids) snorkel surveys provided a good estimate of salmonid abundance and species identification (intercept = 1.075, slope = 1.001, $R^2 = 0.85$, suppl. 1), but under-counted by half in pools with high counts (> 100 salmonids). We applied a correction factor of 2 to pools where snorkel counts exceeded 100 salmonids.

Visualization and statistical analysis

Determining thresholds related to salmon survival during the dry season requires synthesis of a large set of hydroecological data. Candidate variables limiting salmonid persistence include days disconnected, days at sublethal DO, initial pool volume, initial salmonid count, and seasonal minimum pool volume and DO and maximum conductivity and temperature. Based on visual inspection of histograms, we log-transformed volume and surface area to achieve normality. We then z-transformed all variables and assessed multicolinearity due to significant correlations between candidate variables through Varimax-rotated principal component analysis and variable inflation factor calculations (with a cutoff value of 2). Based on those analyses, we reduced the number of candidate explanatory variables in our statistical models through elimination of collinear variables (discussed below) and known distal variables (e.g., combining clay and bedrock categorical variables into a 'ClayBedrock' variable, since both indicate shallow alluvium). After visualizing univariate logistic regressions, we removed density from the analysis because the steelhead response was strongly influenced by a few outliers (Appendix, Figure SI 1). For both logistic regression and ensemble classification tree analysis, we excluded pools where no fish were found in the June survey and pools that went dry; for logistic regression we also excluded pools where only one species was present in June. We performed PCA and constructed mosaic plots in JMP (*MP*®, Version 11, SAS Institute Inc., Cary, NC, 1989-2007), and conducted all other analyses in R (version 3.1.2) using the packages arm, RandomForest, MuMIn, ggplot2, and texreg.

Mixed methods approach to identifying key abiotic limiting factors

We used logistic regression in a Bayesian generalized linear modeling framework (Gelman and Su, 2014) to estimate survival of stream fish from paired sampling of discrete habitat units. We split the dataset by species and removed pools from the analysis where no fish spawned (n = 40) or that dried completely (n = 14). We identified the most parsimonious fixed-effect model for each species using a full information criterion-based approach (Burnham and Anderson 2002), considering year, abiotic variables, and their interactions as fixed effects. We evaluated models with different combinations of the explanatory variables using the small-sample Akaike information criterion (AICc) (Burnham and Anderson 2010) and Nagelkerke adjusted R^2 (Nagelkerke 1991) to assess the fit of models to the data and to guide model selection. We also compared the structure and significance of the best-fit model with an averaged model incorporating all of the models within 2 AICc units of the most parsimonious model.

Next, we constructed single classification trees (Breiman et al. 1984) for coho and steelhead to identify critical thresholds and hierarchical relationships among candidate variables. We then used an ensemble approach to classification tree analysis using the Random Forest method (Liaw and Wiener 2002), again conducting. Classification tree analysis is a machine learning procedure that predicts presence or absence based on a decision tree constructed repeatedly splitting the data set into a hierarchical series of mutually exclusive groups; the final 'leaf nodes' are nearly homogeneous with respect to the response variable. The splitting rules indicate threshold levels of response variables; bootstrapped forests of many classification trees indicate the relative importance of different biotic and abiotc factors in predicting salmonid over-summer survival.

Results

Flow and habitat conditions

Our study began in the moderately dry year of 2011-12 and continued through deepening drought in 2013 and 2014. Study reaches ranged in flow status from continuously flowing to isolated pools, with both Tannery Creek reaches maintaining continuous flow in 2012 and 2013, lower Fay Creek becoming moderately intermittent in all years, upper Fay Creek becoming extremely intermittent in all years, and no reaches maintaining continuous flow through the extraordinarily dry summer of 2014 (Figure 3).

K-means clustering with four clusters grouped all pools from the 2014 extraordinary drought year together, all pools from the continuously flowing reach-years together, and split the moderately intermittent pools into two groups (Appendix Figure 2). After riffles become disconnected, dissolved oxygen decreases and conductivity increases (indicating groundwater's influence), but at different rates depending on geomorphic setting (Figure 4a); these data also show daily and weekly flow response to day/night and cloud cover (Figure 4b). Sonde data confirms spot measurements of extremely low DO in the late summer, and maximum temperatures <18° C across all summer study periods.

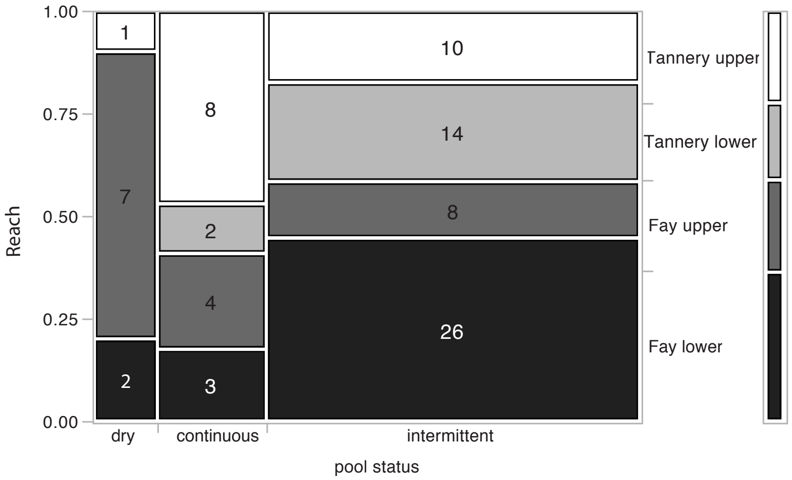

Figure 3: Mosaic plot of intermittent status by reach (across all years) showing a gradient of intermittency (x axis) across reaches (y axis). The box area corresponds to the number of pools in a given category. Intermittent pools comprised the most common habitat overall, with lower Fay and Tannery dominated by intermittent pools, upper Fay dominated by dry pools, and upper Tannery dominated by continuously flowing pools.

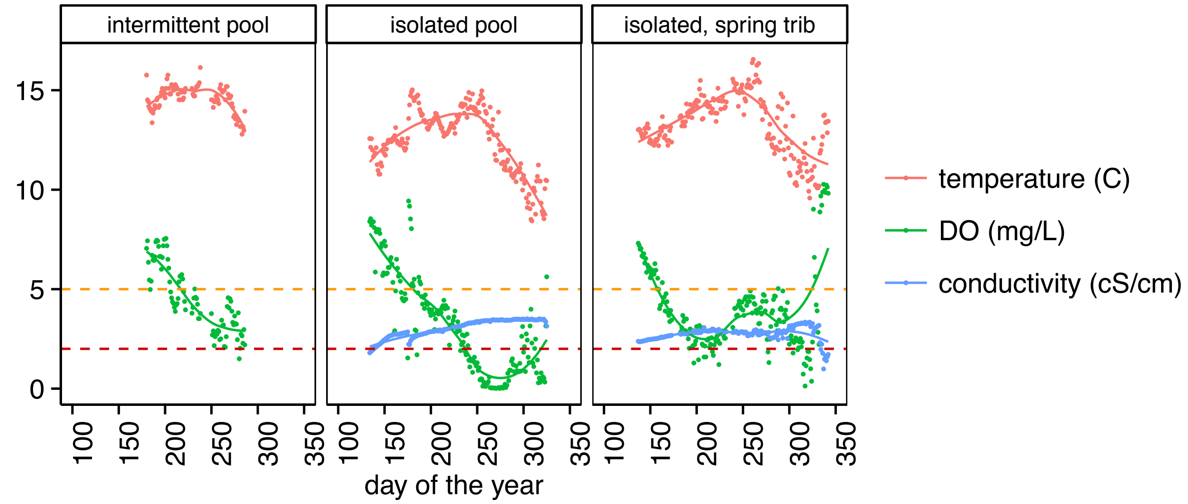

Figure 4a: Continuous water quality data from three pools representing a gradient of intermittency; data is filtered to daily minima and smoothed with a loess smoother. The intermittent pool on upper Tannery Creek (left pane, 2014) maintained DO in the sublethal range, the isolated pool on upper Fay Creek (center pane, 2013) is below lethal DO limits for more than 60 days, while the spring-fed sanctuary pool on upper Fay Creek (right pane, 2014 data) maintains DO levels between the lethal and sublethal limits for ~150 days, and experienced levels below the lethal limit for several short periods in late September. Salmonids survived at high rates in the intermittent and isolated, spring-fed tributary pool (which we characterize as sanctuary pools below), but did not survive in the isolated pool.

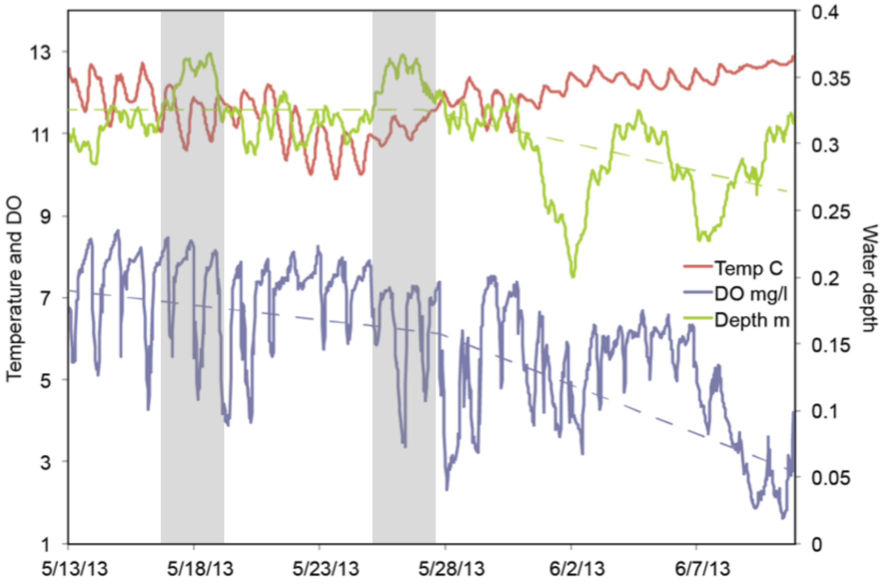

Figure 4b: Continuous sonde data over the course of one month during the transition from continuous to intermittent flow shows declines in depth and DO beginning around May 28. The plot shows daily fluctuations in depth, temperature, and DO, as well as indications of a riparian pump effect, which causes water levels to rise on cool, cloudy days (highlighted in gray).

Principal components analysis required seven components to explain 95 % of the variance in the abiotic habitat data, with the first three components explaining 33 %, 25% and 11% of the variance, respectively (Figure 5 and Appendix Figure SI 3). The first axis is primarily defined by volumetric variables (minimum depth, surface area, and volume). The second axis is defined by days of low DO and conductivity, which are negatively correlated with dissolved oxygen. The third axis is defined by temperature. These axes make ecological sense, however we decided not to perform regressions along these components because we wanted to preserve the extra information in the days of disconnection and June count variables, which were uncorrelated with the first three PC axes. We performed subsequent statistical analyses on raw data, omitting volume from models containing maximum depth (Pearson's product-moment correlation coefficient r =0.57) and surface area (r =0.80) because of its high correlation with these variables. Depth and surface area, on the other hand, were only moderately correlated (r = 0.39) so were both retained in subsequent analyses. All other variables were uncorrelated correlated (r<0.5).

Flow recession curves show volume and DO recession rates varying among reaches and years following stream disconnection, with earlier recession and lower DO and volume in the drought year of 2014 in three out of 4 reaches (Figure 6). Surface flow maintains pool volumes and reduces the duration of low DO conditions below lethal limits; once surface flow ceases, both water level and DO drop steeply (Figure 6).

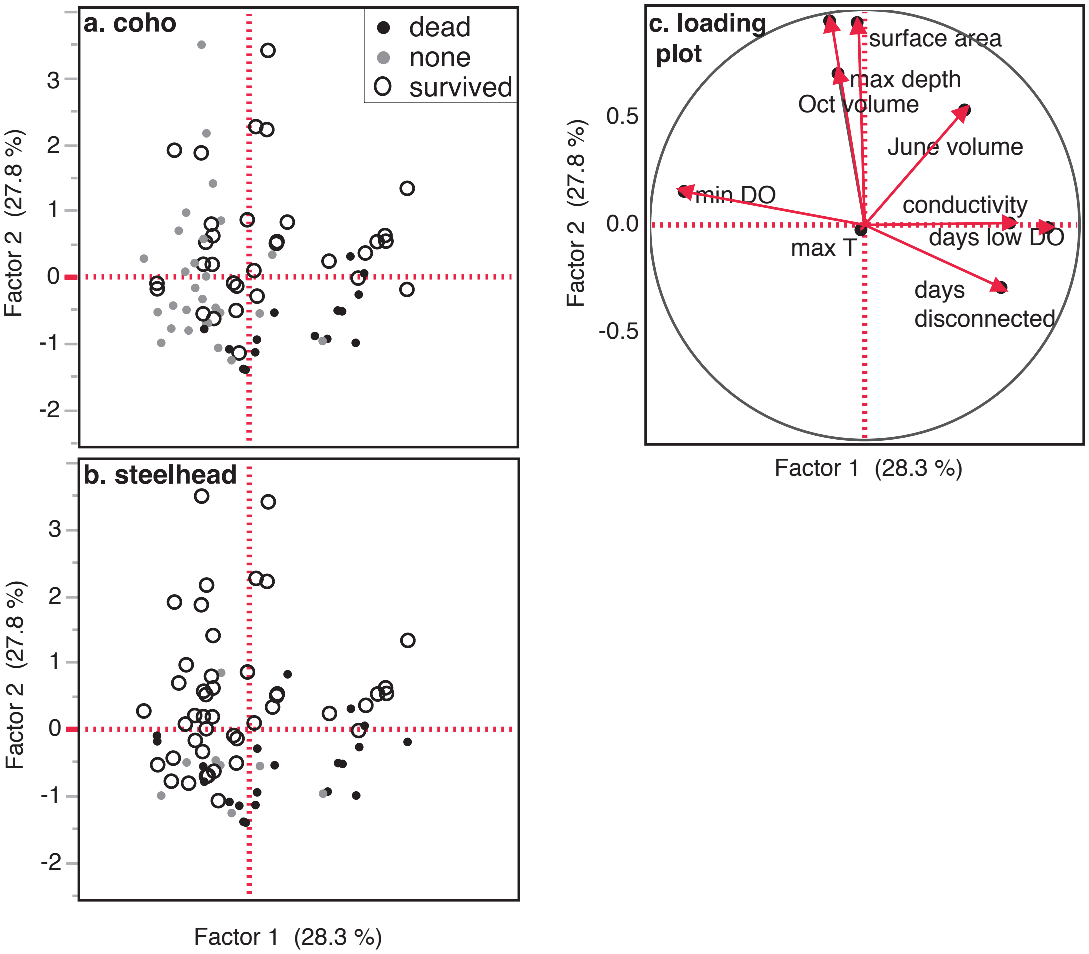

Figure 5: Varimax-rotated principal component analysis for abiotic factors; factor 1 is influenced by October width, depth, and volume, while factor 2 is influenced by DO and conductivity (a measure of groundwater inflow). The lower right quadrant shows—representing small, low DO pools—low shows low survival for both species. Both coho and steelhead are able to survive in most large, low-DO pools (upper right quadrant) and all large, high-DO pools (upper left quadrant). Fewer fry were found in early-summer surveys in the lower left

quadrant, representing small, high DO pools, with steelhead encountered more frequently than coho. Maximum temperature is orthogonal to these first 2 axes but strongly influences the third PC axis (Appendix Figure SI 2).

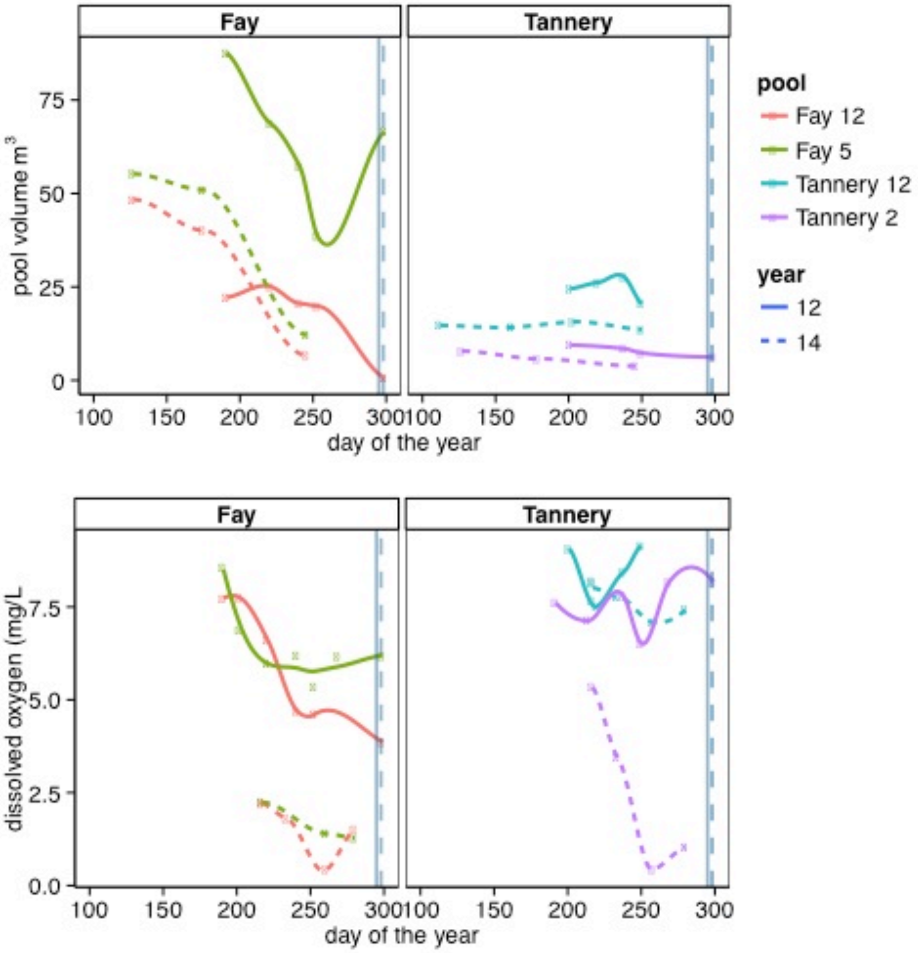

Figure 6: Volume (top) and DO (bottom) recession for four representative pools, showing patterns of DO and volume recession for 2012 and 2014. Pool Tannery 12 is spring influenced, and maintains high DO levels even in the 2014 extreme drought year. Pool Fay 5 is a large free-formed alluvial sanctuary pool. The Tannery pools are both confined by a clay layer. Salmonids survived in all pools in 2012, and in Tannery 12 and Fay 5 in 2014. Pool Fay 2 went dry in 2014.

Salmonid recruitment and over-summer survival

Salmonid recruitment and survival varied by tributary and species across the three study periods (Figure 7). Recruitment was higher in the more intermittent stream (Fay Creek) than in the continuously flowing stream (Tannery Creek) for both species, except in 2014 when extremely late rains likely excluded coho from Fay Creek (cite paper in prep). Complete pool drying accounted for some mortality in Fay pools but none in Tannery pools (Appendix Figure SI 4). Coho survived at higher rates compared to steelhead in all years (Figure 8), and survival for both species was higher in the moderately dry and dry year on intermittent Fay Creek. Both species survived at the highest numbers in pools with DO below 5 ppm; this measurement reflects conditions in a single location per pool, and fish may have survived in regions of pools where DO levels were higher than sampled locations.

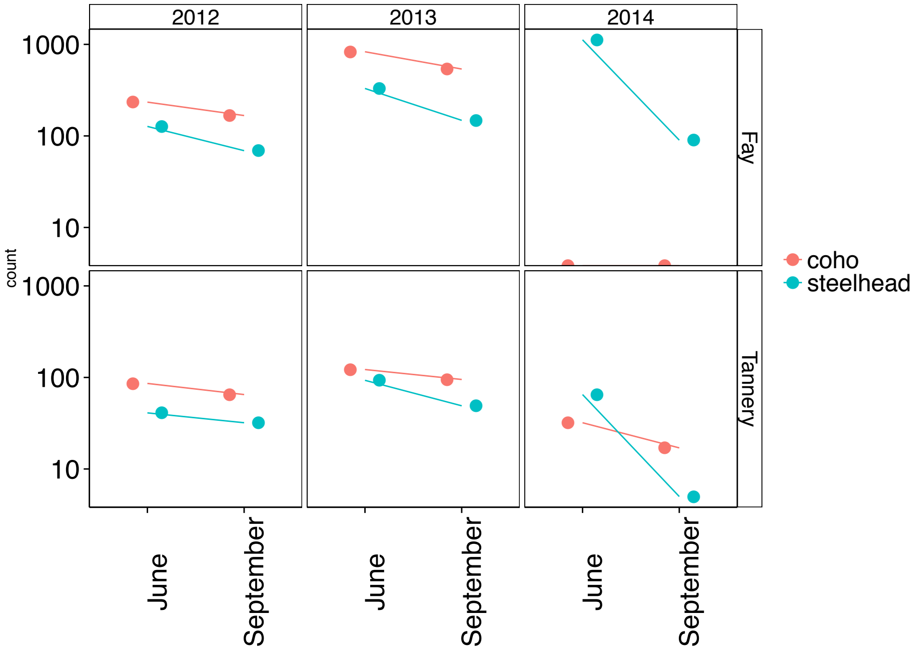

Figure 7: Salmonid counts and mortality across reaches, years, and species; note the log scale. June and October count was lowest in 2014, the extreme drought year, except for steelhead on Fay Creek. The highest proportion of fish survived in 2012, the wettest year, and many more fish died from complete desiccation in Fay Creek than in Tannery Creek across all years.

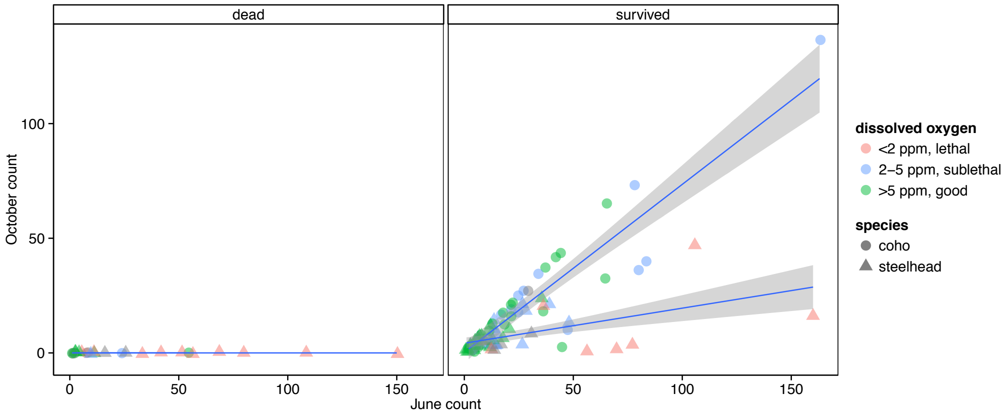

Figure 8: In pools where all fish were dead in October (left panel), many but not all pools had minimum DO levels below 3 ppm. In pools where some fish survived through October (right panel) minimum DO levels ranged from < 1 ppm to >8 ppm. Steelhead survived in the highest numbers in pools with DO < 2 ppm while coho survival was highest in pools with DO < 5 ppm, likely in DO refugia at the very surface of the water or near seeps.

Logistic regression analysis of survival in pools that remained wet across all three years (n pools = 38) indicates that stream disconnection creates harsh conditions that strongly influence salmonid survival in our study area. Both species-specific best models included June count, maximum conductivity, and minimum DO (Table 1). The most parsimonious coho model also included maximum depth, June volume, and squared temperature; the most parsimonious steelhead model also included temperature and surface area, but not depth (Table 1). Categorical variables indicating the presence of large woody debris and the presence of clay or bedrock were somewhat important in a multi-model inference framework, but decreased model fit and thus were excluded from further analysis.

	coho GLM	steelhead GLM
Intercept	1.42 (0.73)	3.52 (1.28)
max depth	0.93 (0.69)	
log(surface area)		0.84 (0.71)
June count		3.35 (2.51)
June volume	0.86 (0.53)	
max conductivity	−1.15 (0.69)	−0.68 (0.57)
min DO	0.55 (0.70)	0.07 (0.68)
max temperature		1.33 (0.65)
squared max temperature	0.41 (0.54)	
AICc	29.21	27.78
Log Likelihood	-8.61	-7.89
R^2 (Nagelkerke)	0.51	0.56
Num. obs.	38	38

Table 1: Summary of most parsimonious models for steelhead and coho over-summer survival

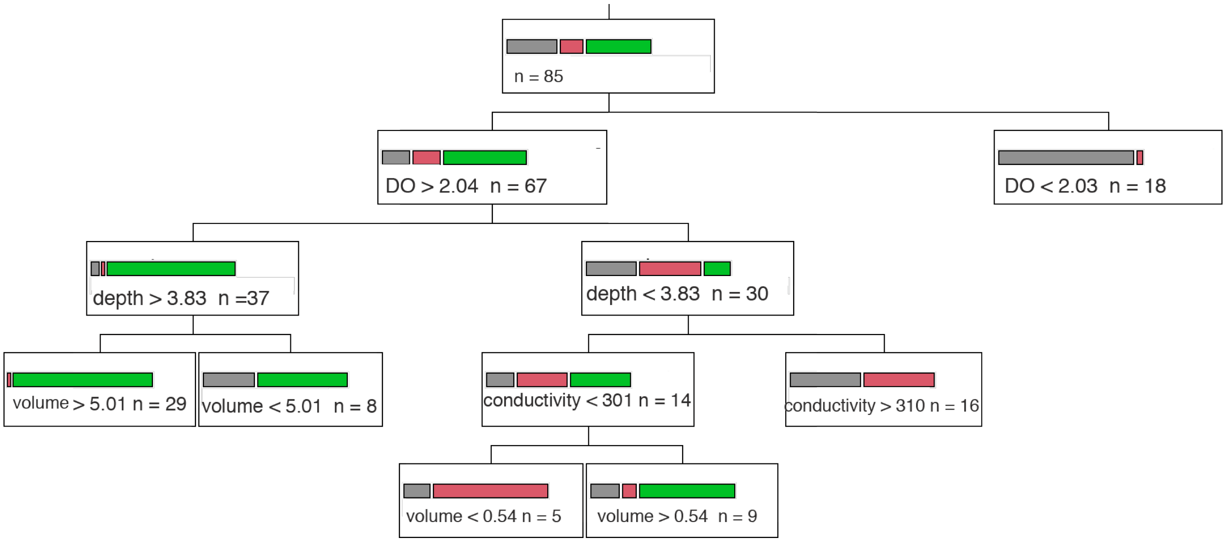

Figure 9: Classification tree for coho, using all candidate abiotic variables. No coho survived in pools with DO levels < 2 ppm; most coho survived in pools deeper than 0.38m, and in shallower pools, no coho survived in pools with high groundwater inflow (conductivity > 310 mS/cm) or volume < 0.5 m^3.

Averaged models with delta AICc < 2 revealed several additional ecologically meaningful parameters (Supplemental Table 1). Both averaged models contained main effects of June and October volume, days disconnected, year, and June count. They also contained several interaction terms that differed in sign between the two species.

Ensemble classification tree analysis identified many of the same important variables as the logistic regression models, providing independent confirmation of GLM results and suggesting interpretations for some of the interaction terms. Ensemble tree analysis (n trees = 2000) had low prediction error for both species, with the larger steelhead sample size yielding a lower error rate (n pools = 77, error rate 10.34 %) than for coho (n pools = 54, error rate = 16.33 %). Importance measures indicated that pool volume, depth, and surface area contribute significantly to splitting at nodes and accuracy for both species (Appendix Table 2). Depth was more important for coho while surface area was more important for steelhead, with volume intermediate in importance for both taxa. June count was somewhat important in both steelhead and coho analyses. Minimum DO, maximum conductivity, and days of disconnection were of secondary importance for both species, while temperature was secondarily important for steelhead and unimportant for coho. The remaining factors were unimportant for both species (days below 3 ppm DO, clay or bedrock presence, large woody debris, June count, and year).

Discussion

Our results indicate that salmonid recruitment can be very high in intermittent streams (up to ~75%), but varies among reaches, years, and species (Figure 4). Overall, over-summer survival was higher on Fay Creek (intermittent flow) than on Tannery Creek (continuous flow) in 2012, 2013, and 2014 (Figure 3). A lower percentage of salmonids survived in Fay Creek compared to Tannery Creek in all years. However, overall abundance was higher in Fay than in Tannery at the end of the summer in both 2013 and 2012, suggesting that even in an intermittent state, Fay Creek salmonids play an important role in overall productivity of the population complex.

Our study confirms Wigington et al.'s (2006) finding that intermittent reaches can support high densities of juvenile salmonids, with overall survival and growth being higher in than in continuously-flowing tributaries in some years. On Salmon Creek, reaches with deep alluvium become intermittent before bedrock reaches, but also contain deep pools and complex habitat that characterize preferred habitat for juvenile coho. Lower Fay Creek flows through a broad, low-slope alluvial valley and through thick alluvium, where large pools form at bedrock outcrops, sharp bends, and large woody debris jams. In contrast, lower Tannery Creek flows through a steep canyon into an incised channel in a confining clay and bedrock layer, and as a result has many more shallow, bedrock-influenced pools. Fay Creek's alluvial setting, open canopy, and higher floodplain connectivity may result in higher nutrient levels and drive higher macroinvertebrate productivity, thereby increasing summer salmonid growth rates. Furthermore, Fay Creek experiences much higher recruitment for both coho and steelhead in some years, because the tributary is accessible to salmonids at lower flows and because lower stream power deposits the small gravels that salmonids prefer for spawning.

In drought years, however, these same eco-geomorphic characteristics drive high mortality. Measurements from continuous water level and DO measurements indicates a "riparian pump" effect is at play in the watershed, with water levels rising at night and on foggy days (Figure 4b), and recovering in mid-September after deciduous riparian trees lose their leaves (Appendix Figure SI 9). While streams flow, mixing over riffles maintains dissolved oxygen levels above 6 ppm, but once flow ceases, dissolved oxygen levels recede (Figure 4a and 4b). Once streams become intermittent, pool characteristics determine whether salmonids survive the dry period. We found evidence that mortality can result from total desiccation, low water levels that may leave fish vulnerable to predation in small, shallow pools, or DO depletion. Thus, in accordance with our hypothesis, low DO is a proximal cause of mortality among juvenile salmonids in Fay and Tannery creeks, but it is not the only abiotic driver. Periods of disconnection shorter than ~15 days are correlated with a high probability of survival while at longer than 80 days without surface flow, the probability of survival is ~ 0.4 for coho and 0.2 for steelhead; both species survive only in large, spring-fed sanctuary pools.

Primary drivers of salmonid over-summer survival

Pool depth and surface area exert an overriding and positive influence on survival, with coho responding more strongly to depth and steelhead responding to surface area. The high importance of late-summer depth, volume, and surface area both species' ensemble tree analysis indicates that the water quality factors and / or predation may affect salmonids differently in large and small pools; large, heterogeneous habitats may provide heterogeneous DO conditions and more cover. Survival is decreased for both species in low-DO pools, but both species are able to survive extended periods in pools with extremely low DO levels, making minimum DO a poor univariate predictor of survival. The biological significance of these main effects is straightforward: as pool volume increases, feeding and resting habitat increases, and food supply increases. Exposure to lethal DO levels kills juvenile salmonids quickly, while exposure to sublethal DO levels reduces growth rates and can cause other metabolic problems and eventual death. Our finding of survival for several weeks in pools with daily maximum DO < 2 ppm is surprising. One interpretation of this result that some juvenile salmonids exhibit higher tolerances for low DO than has been previously reported; an alternate hypothesis is that they survive low-DO periods in refugia, perhaps in the saturated zone at the pool surface. During late-summer snorkel surveys in low-DO pools, we often observed salmonids clustered near areas of hyporheic inflow and in surface waters, and on one occasion observed a 1+ steelhead parr air breathing at the surface of an anoxic pool (C. Woelfle-Erskine, personal communication).

A second line of evidence supports the hypothesis that the variation in dissolved oxygen recession rates is a crucial driver of over-summer survival. Hierarchical and k-means clustering showed pools clustering along a gradient of intermittency, with all pools in the extreme drought year (2014) clustering together, all pools from the continuously flowing upper Tannery reach in 2012 and 2013 clustering together, and the intermittent pools falling into one or two clusters. Dissolved oxygen levels are similar—but not uniform—within these clusters, suggesting that heterogeneity in ecohydrology and geomorphic setting mediate the effect of stream disconnection. It is in these clusters of moderately intermittent pools that the variability in over-summer survival, the number of fish surviving, and growth rates is greatest. In the most severely dry study site, a deep-alluvium reach on upper Fay Creek, almost all pools dried in every year, suggesting that without large changes in water management practices that increase late-summer baseflow, this reach will never be important rearing habitat for either species.

Secondary drivers

Conductivity (indicating reduced surface flow) and days of disconnection are secondary drivers of survival via their influence on stream metabolic processes that influence DO and productivity. Groundwater affects temperature, dissolved organic carbon concentration, and nutrient levels; these factors may be considered as distal drivers of salmonid survival that all contribute to dissolved oxygen dynamics via primary productivity, microbial metabolism rates, and reaeration. While DO drops to critical levels in many isolated pools, other isolated pools maintain oxygen above lethal levels, and we expect that variability in these factors across small spatial scales explains the heterogeneous DO levels we observe among nearby disconnected pools. We consider temperature a distal effect of survival via its influence on growth rates, dissolved oxygen saturation rates, and productivity. These systems are heavily shaded, and hyporheic flow through streambed sediments could also be cooling water to levels that are not stressful for juvenile salmonids, and may be driving low stream productivity and salmonid growth rates.

Differences among species and implications for survival

The variables selected as significant predictors of over-summer survival in the species-specific modeling results indicate different microhabitat selection by steelhead and coho. Our finding that steelhead selected shallow water habitats while coho selected deep pools is consistent with other researchers who found that when steelhead and coho occur sympatrically, steelhead often select shallower water habitats (Sheppard and Johnson 1985; Bisson, Sullivan, and Nielsen 1988), or may be excluded from preferred deep water habitats by the larger coho juveniles (Bugert and Bjornn 1991; Young 2004) . These selection preferences are usually attributed to size differences, especially in the northern end of the sympatric range where coho emerge much earlier than steelhead and are typically larger than co-occurring steelhead (Young 2004). In in our system coho may exclude steelhead from deep-water habitats in the early summer, and steelhead may then get trapped in shallow pools after riffles become disconnected. In 2014 (the exceptional drought year), the extent of shallow water habitat was much smaller than in other years; in addition, the total number of pools where steelhead could survive was lower than in either 2013 or 2012; this difference may explain why steelhead survived at much lower rates than coho in 2014.

Steelhead survival increased as maximum temperature increased. This result may seem counterintuitive as high temperatures cause salmonid mortality. However, temperatures in the Salmon Creek watershed are well below the lethal limit of 20 degrees C, and were below 18 degrees for all but 2 pools. This suggests that rather than high temperatures driving mortality, low temperatures may limit growth, especially early in the summer when riffles are still flowing and food supply is abundant. Water temperatures fluctuate more near the surface than in shallow pools, and drop in deep areas. Steelhead, occupying shallow habitats, thus likely experience higher temperatures than coho, which occupy cooler deep waters. Steelhead thus likely experience an increased effect of temperature on growth compared to coho.

In upper Fay Creek, coho preference for deep water habitats during the early summer may increase their probability of survival compared to steelhead, because coho will have found deep water habitats before flow recession cuts off shallow habitats that subsequently dry. In contrast, we observed many steelhead trapped in shrinking pools, and found that across years, complete pool drying occurred more frequently in steelhead-only pools than in pools where coho were present.

Our concept of sanctuary reaches can be applied to other systems where spring-fed reaches occupy a relatively small proportion of overall stream length, yet can support high densities of both coho and steelhead. Thus an important second avenue of research is to determine what characterizes these sanctuary reaches. Spring-fed tributaries are critical in maintaining DO levels: tributaries that flowed into our study pools at < 1 L/s maintained pool DO levels > 7 ppm through the dry season in the wetter years, and maintained sublethal DO levels (> 3 ppm) in the extraordinarily dry year despite more than 100 days of disconnection. Other key characteristics are depths greater than ~0.3 m (the approximate length of an egret's leg or raccoon's reach), which offer protection from terrestrial predators, and large woody debris which provides cover.

Implications for salmonid recovery in a changing climate

Climate change will likely increase the intensity of drought, shift the timing and frequency of atmospheric river storms that trigger spawning, and decrease ocean productivity in California coastal waters, thereby affecting salmonids at every life history stage. Our study highlights the extreme precarity of juvenile salmonids that rear in intermittent streams that have been dewatered and radically altered by anthropogenic changes since European settlement. Land use changes in the over the last two centuries have undermined hydro-ecologic systems that buffered salmonid vulnerability to this seasonal and inter-annual variability in precipitation. Historical analysis suggests that the extent and duration of intermittent conditions has probably increased due to European settler land management practices, and limits recovery of central coast coho populations (National Marine

Fisheries Service 2012).In contrast, indigenous land management practices preserved floodplain wetlands and beaver meadows as a source of food and fiber plants. Controlled burning and other cultivation practices favored early-successional riparian forests, lower forest densities, and a higher proportion of grassland, likely reducing overall transpiration and driving higher base flow compared to contemporary conditions (Anderson and Blackburn 1993; Martinez 2003; King, Thomas for Klamath River Intertribal Fish and Water Commission. 2004).

In coastal California, European settlement disrupted watershed processes by replacing mature forests with early successional ones, diverting spring fed tributaries for household and agricultural use, building roads and other infrastructures, extirpating beaver and removing their groundwater-recharging dams, and further reducing infiltration by increasing impervious surfaces. These activities promoted stream incision, mobilized fine sediment that clogged spawning gravels, and diverted summer spring flow from salmonid rearing habitat (Pollock et al. 2014; National Marine Fisheries Service 2012). Many stream reaches that once flowed year round now flow intermittently, drying into a series of disconnected pools during the late summer. Several recent historical studies document that intermittent streams that once provided spring-fed refugia now dry completely in drought years (cite SFEI Alameda Cr and Napa R). Other formerly-intermittent streams have become perennial because they are used to convey irrigation water to farms from upstream dams, thereby driving shifts in aquatic communities (Marchetti and Moyle 2001).

Human ground and surface water diversions affect streamflow, and can increase the duration of stream intermittency (Deitch and Mathias Kondolf 2012; Grantham et al. 2012; Deitch, Kondolf, and Merenlender 2009). Our research shows that while juvenile steelhead and coho can survive for several weeks in disconnected pools, protracted disconnection can drive DO depletion and pools shrinkage, with lethal consequences for juvenile salmonids. The correlation between days of disconnection and both lethal and sublethal dissolved oxygen ($r = 0.45$ for steelhead, $r = 0.49$ for coho) suggests that days of disconnection may be a good proxy for low DO effects. Stream disconnection can be measured much more easily than dissolved oxygen, including by citizen science volunteers equipped with handheld GPS units (cite Nature Conservancy paper, UCCE), and can reveal spatial and temporal trends in local base flow and groundwater-surface water dynamics. We implemented this approach in Salmon Creek in 2013 and 2014, and are creating a data visualization web tool that can foster adoption of this approach in other watersheds.

Our results demonstrate the importance of increasing of late-season groundwater flow to benefit juvenile salmonids, and suggest that salmonid recovery and stream restoration strategies should target “sanctuary reaches” that possess adequate flow and structural complexity to support summer rearing, and restore flow to moderately intermittent reaches. More broadly, our research affirms the ecological significance of intermittent streams and identifies some of the relationships between abiotic habitat characteristics and juvenile over-summer survival in these systems. With climate change, more streams will become intermittent or undergo earlier and more severe summertime drying and conflicts between human and ecological need for water will likely increase. Valuing, understanding, and protecting these habitats will become critical for conserving Pacific salmonid species throughout their range.

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Rain tanks, springs, and broken pipes as emerging water commons along Salmon Creek, CA, USA

Introduction

In California (USA) and elsewhere in the industrialized world, the material and socio-political characteristics of large waterworks have removed any clear-cut connection between local watersheds and urban water supply (Sofoulis, 2005). Large waterworks helped to produce California's cities, agricultural bounty, and attendant discourses of progress, private property, and human control over riverine ecosystems (Woelfle-Erskine, 2007). However, over the past two decades, water governance has been decentralized and some infrastructure diversified, creating new local waterscapes in the interstices of California's 'hydraulic society' (California Department of Water Resources, 2005; Worster, 1992). These local waterscapes emerge entangled with alternate discourses of human-ecological collaboration and water as a public trust or commons, which in turn generate new cultural practices and governance strategies (Woelfle-Erskine, in press). How can we make sense of new waterscapes in places where concern for riverine ecosystems motivates household water conservation, and climate change undermines supply-driven managerial approaches? Methodology is not well established to research how changes in household-scale water and wastewater infrastructures affect water practices and how people conceive of water sources. Several recent studies investigate perceptions and use of greywater systems (e.g., Mahmoud, 2008; Naylor et al., 2012; Pinto and Maheshwari, 2010) and the effects of rainwater harvesting or greywater reuse on household water use (Jones and Hunt, 2010; Muthukumaran et al., 2011). However, to date research largely focuses on social and infrastructural factors in isolation (for an exception see Domènech and Saurí, 2010). 'Scaling down' research to the household scale can reveal strategies that people use to track and regulate water use, and describe values that inflect their conservation efforts.

To address this gap, I developed a field interview approach to investigate how rural water use practices may shift in response to new knowledge about how human water use threatens salmon with extinction. Working as part of a collaborative of citizens and scientists, I asked research participants living near salmon in Salmon Creek, Sonoma County, California, to bring me into the field, where together we examined springs, well, rain tanks, and the homemade devices they used to track water levels and spring flows. Studying down to the household level in this way, I also traced local knowledge networks that residents use to share rainfall and well level data, and found that discourses of groundwater and salmon as commons are co-evolving along with rain tank programs and new watershed governance institutions. My attention to the co-evolution of decentralized infrastructures, cultural practices, and conceptions of water's role (as public good, as private good, as commons) differs from the managerial move that has been the decentralization literature's central focus (e.g., Larson and Soto, 2008; Wiek and Larson, 2012; Plummer et al., 2013). Moreover, the beliefs, perceptions, and actions that emerge in these early interviews do not map onto Ostrom's (1990) design principles for common property resource governance. Instead, new environmental imaginaries (cf. Peet and Watts, 1996) emerge as understandings of salmon hydro-ecology travel from agency and private sector scientists – some of whom are also watershed residents – through existing monitoring and data sharing networks. In these new imaginaries, subsurface water connects humans to streams and to other species in lively and reciprocal relationships, and people describe an ethical responsibility for regulating their own water use so that other species can also thrive.

This case is a microcosm of issues debated across California and the western U.S. as drought deepens and climate change promises even scarcer and more erratic precipitation. As I began my study on Salmon Creek, new scientific understandings of groundwater-stream interconnection were challenging regulatory orthodoxies that arbitrarily separate ground and surface waters (Naiman et al., 2010). Residents sought ways to procure water without drying up streams and killing juvenile salmon. Arguing that harvesting rain in tanks could offset groundwater pumping, but only if residents changed watering practices and carefully monitored water use, local agencies designed a large-scale rain tank subsidy program that won federal salmon recovery funds (Gold Ridge RCD, n.d.). Understanding sociotechnical change in this context requires an approach that integrates salmon ecology, existing water infrastructures and practices, and social norms that regulate water use. In this paper, I present one such approach, articulating a relationship between a feminist theoretical approach and a commensurate method for studying emerging cultural waterscapes empirically.

Context: decentralising turns in water infrastructure and governance

California instituted decentralized water governance in 2002 through the Integrated Regional Water Management process, which funded multi-stakeholder groups to develop new water management plans. (Conrad, 2012; Hanak et al., 2011). Who participates in these groups, what infrastructural changes they consider, and what ethical frameworks they adhere to influences how the resulting plans negotiate competing claims for water, both amongst different human users and between human consumption and other species' needs for flowing streams. Rainwater harvesting has gained currency in recent years for its potential to alleviate pressure on rivers and improve conditions for juvenile salmon on the brink of extinction by restoring natural flow regimes (DeBusk et al., 2010; Poff et al., 1997). Northern California communities are increasingly examining rain tanks and shallow aquifer recharge as ways to protect aquifers and increase late- summer groundwater flow to streams. Whether this potential is realized depends on a mix of social, economic, and hydrological factors.

Rain tanks can improve water security and water quality for well-dependent residents. However, state laws prohibit residents from using rainwater for drinking, cooking, washing, or flushing toilets, thereby limiting conservation potential. Moreover, rainwater systems are beyond many residents' means unless subsidies offset costs (Sofoulis, 2014; WATER Institute et al., 2011). Whether residents decide to adopt and maintain these systems, and whether the systems reduce water consumption overall, depends on how people use water in their homes and gardens. Understanding this decentralizing turn thus requires a parallel research turn away from dominant technical approaches – a turn that is charted in this special issue. By investigating how people use water in their homes and gardens, and why they do what they do, this research turn challenges conceptions of water as an abstract fluid best regulated by technical bodies. Linton (2010) and other hydrosocial theorists focus on how hydraulic engineering and state water agencies rendered water into 'purified' H20 in order to abstract (in the sense of extract) water from streams via dams and aqueducts. In contrast to the hydrological approach, I join other practice theorists (e.g., Shove et al., 2009; Sofoulis, 2005; Strengers and Maller, 2012) in focusing on everyday water practices as a window into local and ad-hoc water governance regimes that persist in the interstices of large technical waterworks, and in examining how water users monitor and understand local water sources and cycles.

As noted earlier, my research site is Salmon Creek, Bodega County, California, where two charismatic and economically important salmonid fishes – coho salmon (*Oncorhynchus* *kisutch*) and steelhead (*O. mykiss*) – spend their early lives in local streams but have declined in response to habitat degradation . Earlier collaborative research by citizen scientists and resource conservation agencies demonstrated that pumping by the Bodega Water Company and local ranchers accelerates stream drying, thereby jeopardizing salmonid recovery (Hammack et al., 2006). Their watershed assessment provided the scientific rationale for a pilot project that installed large rain tanks (ranging from 34,000 to 148,000 litres) at nine residences and two large systems at local ranches. The total installed capacity as of December 2014 was approximately two million litres.

My study of this rain tank project yielded a novel finding. By working to recover salmon – either as watershed monitors or by installing rain tanks to reduce their pumping from streams – all participants reconsidered how their water source connected with other aquifers and the stream, and a small minority argued that groundwater and salmon should be understood and governed as commons. In this paper, I briefly outline how the theoretical framework I used contributed to the field interview method I developed. I then offer some preliminary findings on how household water practices are co-constituted with infrastructures, local water sources, and ecosystems. In tying theory, method, and findings together in this way, I offer readers the outlines of a new approach to conceptualising water use and governance practices that may co- evolve with a shift to rain tanks as supplemental water sources, and argue that this approach is well-suited for new governance and institutional water contexts.

The paper unfolds as follows. I first use Karen Barad's (2007) concepts of apparatus and intra-action to investigate whether participating in watershed monitoring and living with rain tanks constitute intra- actions that increase residents' sense of interdependence with riverine species. I then locate sites where the concept of water as a commons is co-evolving with rain tank installation and salmon recovery efforts. I argue that concepts of streams as inter-species commons, born of citizen entanglements with their neighbours, their water, and its fish, can support new institutional arrangements of collective governance. The paper concludes by discussing the research method's participatory and reflexive potential in other water governance contexts.

Entanglements: infrastructures, knowledges, social networks

Karen Barad develops her theory of agential realism from quantum physics. An observer viewing atoms through a scanning tunneling microscope influences the atoms she observes; this influence is intrinsic to the measurement process, so that separating the phenomenon of measurement into constituent parts is impossible (Barad, 2007). In Barad's view all matter is entangled with meaning in a similar way, through relationships she terms "intra-actions" between humans, their measurement tools, and nonhuman agents, including other species and human constructs. Extending Fernandes' (1997) analysis of mechanic agency in a Calcutta jute mill, Barad argues that when a loom breaks down, the crisis creates a cascade of conflicts, between weaver and mechanic, workers and union, etc. Barad conceptualizes these conflicts as intra-actions between humans, machines, cotton, and cloth. In her agential realist frame, the looms are not passive hunks of wood and metal, but active agents that collaborate with humans to create social arrangements within the factory. Workers, machines, factories, cotton plants, and unions all co-constitute the apparatus of cloth production that stretches out into the regional and local economy, and comes to matter (she plays deliberately on the multiple valences of the word "matter") by their engagements with each other. Challenging Cartesian cuts between humans and nature that produce a mediated, representational view of the world, Barad's theory de-centers the human and re-figures phenomena as lively and entangled relationships. Barad's attention to measurement practices is important to my task because measurement figures prominently in the household water systems that Salmon Creek residents monitor and maintain themselves.

White's (1996) figure of the Columbia River as organic machine could easily serve as another example for Barad because, like Fernandes' jute mill, White's river possesses a lively agency that emerges from its constituent elements. For White, the Columbia is a 'mixture' of its dams, fish, fishers and other workers who "knew the river through the work the river demanded of them" (White, 1996, 4). In arguing that "there is no easy way to disentangle the natural and the cultural [on the Columbia]," White challenges human-nature binaries that have led people to treat nature as "a machine that can be disassembled and redesigned largely at will, as if its various parts can be assigned different functions with only a technical relation to other parts and functions" (1996, 111). The organic machine is lively, beyond human control. White's water body is a kind of cyborg body in which the machinic pieces cannot be separated from the living ones: "What is real is the mixture" (White, 1996, 111). My project resonates with White's in that I examine how people come to know a stream and its waters through laboring to maintain springs, measure water quality, and count salmon. Reading Barad's entanglements in relation to White's, I account more fully for affective connections that residents develop with salmon, which they watch return from extinction to swim again in local streams. These residents come to see the stream as something possessing an animacy that circulates through all of the watershed's channels and bodies.

In extending agential realism to think about water policy, I see an opportunity for a radical shift in perspective that may reveal new ways to reconcile human and ecosystem needs for water. Hydrosocial thinking highlights the need for this shift: theorists see waterworks as hybrid apparatuses that variously determine, constrain, and enable people's social relationships with water (e.g., Bakker, 2003; Linton and Budds, 2013; Swyngedouw, 2009). The hydrosocial approach studies down from institutions to social practices, making water a tool for tracing power through political landscapes. These thinkers all acknowledge water's materiality and the sometimes unruly agency that drives hydrosocial cycles. Barad's concept of entanglement develops a more sophisticated ontology of entities like like fish and dams than the hydrosocial approach achieves. In an agential realist view, the natural and the social are not just connected: they only come to matter in relation to one another. The co-constituents do not precede their becoming and thus have no chance of disentangling their shared futures. An agential realist approach helps explain why practicing frequent spring monitoring and maintenance might lead a resident to describe their water systems as containing human, manufactured, plant, animal, mineral, and atmospheric elements. Adopting Barad's ontological stance regarding apparatus – that measurement, measurer, and object are co-constituted through lively entanglements – inspired me to develop a research method that connects how people measure, track, ration, use, and share water in the home to whether they decide to share scarce water with riverine ecosystems.

Research setting: scarcity, regulation, and watershed imaginaries

I began my inquiry with an empirical question: How does a lived experience of scarcity tangle with particular forms of infrastructure? In Salmon Creek, variable rainfall and local geology mean that water has always been scarce locally, influencing both plant and animal species' adaptations and human settlement patterns. Ninety-five percent of the watershed is privately owned, and only nine landowners have permits to divert water from the stream; most residents rely on wells or springs that dry up or drop to a trickle in the late summer. In the absence of central monitoring and regulation, residents track rainfall, spring flow, and aquifer levels using hand-made instruments, and know in a general sense that their groundwater use affects local streams. This knowledge is spatially incomplete, in that there is no central repository for data, nor standardized collection and reporting methods, and often relative, in that people compare the current year's rainfall and streamflow with past years. Residents use this local knowledge to police others' water use through informal social networks ("Someone should tell her not to water her lawn," one respondent told me), and they curtail irrigation when sources seem to be drying up.

The Bodega Water Company (BWC) has just 39 connections, two gallery supply wells that tap shallow groundwater, and no storage reservoir; as a result, customers face frequent service interruptions and pay high water rates. They are 'strong-armed' by their neighbors into serving on the water board, where they experience firsthand the difficulties of maintaining a small water system. Residents without a BWC connection must maintain their own spring or well. All residents historically coped with water scarcity on an individual basis, by attempting to drill more wells, buying water from tanker trucks, limiting summer water use, or installing rain tanks or greywater irrigation systems. The idea to diversify water supply infrastructure at the municipal scale by installing rain tanks throughout the town of Bodega emerged in response to twin prerogatives: increasing reliability for BWC customers and ranchers, and augmenting flows for near-extinct salmon.

Beginning in the 1990s, scientific evidence that BWC pumping dried up salmon habitat downstream began to circulate. At watershed council meetings and through informal networks, residents' understandings of local water expanded to include a sense of salmonids' dependency on flowing streams. Two environmental imaginaries emerged: the notion of the watershed and the idea of water and salmon as commons. Although these imaginaries may seem unrelated to the problem of household water provision, they surface again and again in residents' descriptions of their water use.

The field interview as window into watery entanglements

Through scoping interviews with local residents, I articulated three specific research questions as windows into entanglements between scarcity, water infrastructure, and water practices. Does local knowledge inform scientific goals and understandings of water scarcity and salmon decline, and if so, via what processes? How do different residents understand local streams and aquifers: as private, public, commons, or something else? Are design principles for collective governance (Ostrom, 1990) emerging along with the idea of the commons?

In the U.S., and particularly in the water-scarce western states, gaining access to private well and spring data poses a challenge for household water researchers because few public repositories exist and landowners are reluctant to release data that could reveal that their water supply is unreliable. I developed a field interview approach to gain a ground-level view of the landscape (geology, topography, land use, and settlement patterns) while discussing household water use practices with residents. I conducted 21 field interviews with residents who relied on some combination of wells, springs, rain tanks, and municipal systems for household water. My four years of participant observation in the local watershed council and regional scientific meetings facilitated follow-up conversations with 12 participants.

I met with residents at their homes, individually or in self-selected groups of neighbors. Conversations typically began inside homes in a somewhat formal context, with me asking questions about the water source, water use patterns, and conservation measures. Next, I asked to see the local sources that supplied household water – the well, spring, and, in some houseolds, rainwater tank. This part of the interview was less formal, and respondents often took the lead in explaining how their system worked. At the time, I lived nearby with a small spring for my water source, and often discussed my experiences of leaks and frozen pipes; this shared experience gave the field interviews a more conversational tone. On visits to springs – often located several hundred meters from dwellings – I asked about soil characteristics, runoff patterns, and seasonal variations in flow; participants responded with comments on local history and ecology. The first resident I interviewed demonstrated how he measured flow from a spring with his watch and a mayonnaise jar and showed me a log book containing 30 years of monthly measurements. I subsequently asked others if they measured spring flow or kept records of well depth or rainfall. Nearly all did. I also asked whether they compared their records with rainfall data collected by weather bureaus or neighbors. Most could recall exactly how much rain several of their neighbors had measured during the last rainfall; four long-time residents discussed systematic differences between their measurements and a local weather station.

At the end of the interview, typically after returning from the water source, I asked two questions designed to elicit responses about groundwater regulation watershed governance: Who should decide who can withdraw water from Salmon Creek and its source aquifers?; and, Who should decide how much water must stay in Salmon Creek?

Findings: Linking water apparatus to common waters

Residents use their own measurements to decide when to curtail water use and to interrogate state- supplied rainfall and groundwater data. They are blending their own and neighbors' experiences with information gained from agency scientists to explain why wells and springs dry up. Some residents believe water should be shared among humans and also with nonhuman animals (cows, salmon, otters, and raccoons were all mentioned). All respondents thought that water should be allocated fairly or equitably, but few thought that the government could effectively regulate water use, and only one desired additional government regulation of residential water use.

The analysis of field interview revealed an unexpected finding: that people extend their own experience of scarcity to nonhumans and their human neighbors. They can relate to the hassle and uncertainty of running out of water, and this allows them to consider scarcity's effect on others, including nonhuman others. Often, residents’ responses to the question "Who do you think should decide how much water must stay in Salmon Creek?" indicated that they consider the water they drink, wash, and garden with to be interdependent with a multiplicity of living and nonliving things. For example, one resident who recently installed a rain tank said the following:

> What is the benefit of those creeks to those people who live here, and do the other animals that live here have any rights at all? Who's going to provide a habitat for the fish and the animals – the bobcats and the deer and the coyotes and the raccoons and all of those other animals that go down to the creek to drink? You can hear them down there. Do they have a right to clean water?

How should we interpret this shift in focus – that in response to a question about regulating water withdrawals, a resident responds that animals who drink from the stream have a right to clean water? Extending Barad's concept of apparatus to household water infrastructure offers one explanation: Salmon Creek residents understand their water supply as complex entanglements of infrastructures and agents. This shift in ethics – to considering other species as residents with rights to water – is not typically considered in decentralizing projects, but should be considered as plans to scale up rain tanks and greywater irrigation proceed.

My attention to the co-evolution of infrastructures, practices, and understandings of water differs from managerial approaches to decentralization (e.g., Daigger, 2009; Pahl-Wostl, 2007). Seeing infrastructures, practices, and water users' ecological ethics as bound together lends credence to residents' claims that if given a certain amount of autonomy they will regulate their own use. Several residents voiced this perspective, including this BWC customer with a rain tank:

> I happen to think that we all live here together as a living network. . .The creek should bepreserved for the benefit of all living people [he corrects himself] all living beings, as well as for humans... If that means a regulation of consumption, then maybe we need to self regulate in some regards.

That is not to say that formal regulation should be abandoned; California's 2014 regulations have increased interest in rain tanks and large rain-fed ponds among residents and ranchers (John Green, personal communication). What my findings imply is that practices of monitoring and maintaining rain tanks are also practices of cultivating a sustainability ethic and should be encouraged, not minimized, as managerial approaches often advocate. In places like Salmon Creek, where commoners initiate water conservation action on behalf of another species, rain tank installation projects have the potential to be more contextually situated if they incorporate practical knowledge (cf. Scott, 1998) residents have gained through monitoring their other household water systems.

At this early stage, it would be premature to draw conclusions about the state or structure of common pool resources or common property regimes along Salmon Creek. However, it seems like the beliefs, perceptions, and actions that emerge in these interviews are only distant kin to Ostrom's design principles. I found evidence of only two of her eight principles at work in the watershed in an informal manner. Those are, to match rules governing use of common goods to local needs and conditions, and to develop a system, carried out by community members, for monitoring resource use. The other six principles – to clearly define group boundaries, to ensure that people affected by the rules can participate in modifying them, to ensure outside authorities respect community members' rule-making rights, to use graduated sanctions against rule violators, to provide accessible, low-cost dispute resolution forums, and to build responsibility for governing the common resource in nested tiers from the lowest level up – are not evident in the material my method generated.

Institutions for managing ground and surface water may instead be emerging through a process of institutional bricolage, "the patching together of institutional arrangements from the cultural resources available to people in response to changing conditions" (Chase Smith et al., 2001, 42, cited in Cleaver and Franks, 2005, 4). Like bricoleurs, Salmon Creek residents already participate in some self-regulation in response to social pressure and a lived experience of scarcity; however, it is unclear whether residents would accept more regulation by peers via some form of collective governance. Groundwater is clearly seen as a common pool resource, but strategies to govern groundwater withdrawals are contested.

The monitoring and data sharing networks I found are seeds of commons governance institutions. The common resource at stake is not just a non-living fluid, but rather an animate substance that connects humans to other species. Governing this commons will need to consider all of these actors. Although not explicitly on the table, a collective governance structure could improve water reliability and ecological flows compared with the status quo (which lacks clear rules and procedures for monitoring and enforcing use) or government regulation (which is unwelcome politically, and unlikely given government funding shortfalls). Key questions remain – who would serve as the rulekeeper and which constitutional and distributional rules would need to be in place? – but it seems plausible that the small, close-knit community that lives in the watershed could grapple with them.

Conclusion: Field interviews as a method in water policy

Open-ended interviews with landowners and residents open a window onto understandings of local hydrology, daily water interactions, social norms that regulate use, and attitudes towards regulators. Together, the sit-down and field interviews can reveal residents' perceptions of *de facto* water governance regimes – whether water is considered a private good, common property resource, or public good – and identify consensus and dissent about which regime is in effect. Putting this approach into practice should probably involve assessment by an interviewer who is perceived as having no stake in local politics, as residents are unlikely to disclose rule-bending to regulators, and might tell funding agencies what they think they want to hear. Familiarity with local water practices is also important: knowing something about local aquifers and rainfall patterns, or knowing how to clean out a sediment trap on a rain tank system, can elicit rich details about local hydrology and people's daily interactions with water. More than mere observer, the well-informed researcher serves as a conduit for information between residents, scientists, and regulators who may never meet face-to-face, and may be asked to arbitrate between contested scientific and local ways of knowing.

What if living with scarce resources and some autonomy over use creates qualitatively different water use practices, compared to living with reliable Big Water supplies? Rain tanks provide the ability to adapt to fluctuations in municipal or borewell supply. In Salmon Creek, scarcity and proximity lead to greater interest in the source of household water, awareness of its interdependence with climate, ecological, and human factors, and concern for its continued integrity as both human resources and ecological habitat. One couple who recently retired in the watershed mobilized this awareness to argue that water and salmon should be managed in common, as follows:

> Female householder: I do consider it a commons, but I don't think I'm in the majority in this community. People in this community respond more to a specific argument, like "The fish need it, we want the fish, we're going to go get them and eat them." I consider it a commons, don't you?
> Woelfle-Erskine: I do
> Male partner: I think there are two resources that need to be managed like that, and one of them is air quality, and the other one is water. Everything else – the mineral contents, the gold they find on your property – that seems to be built into our political system that it's yours. But . . .we're all using the same water and the same air. There has to be consensus and agreement on how to use them most effectively. People can't get greedy.

These and similar responses are evidence of an incipient discourse of water as a commons that is akin to Ostrom's (1990, 38) insight that "[t]he key fact of life for coappropriators is that they are tied together in a lattice of interdependence so long as they continue to share a single [common-pool resource]".. My interviews uncovered several status-quo rules that govern *de facto* governance of groundwater and groundwater-fed streams, suggesting that collective governance in Salmon Creek is at an incipient stage: when people begin to consider scarce groundwater as a commons that should be managed collectively to sustain another common-pool resource, salmonid fishes. Residents' accounts of extreme scarcity and uncertainty in rainfall and water supply suggest that the watershed is akin to Ostrom's (1990, 59) cases in that "the harshness of these environments [functions] as a stimulus toward improvement...". Understanding local water supplies as commons shared by many species may increase residents' willingness to change their water practices and to intervene in others' wasteful use.

Decentralizing water governance and infrastructure involves more than a change in water management. The literature on decentralized water systems has underplayed these complexities to date. But unless people's relationships to their water sources change, a mere shift in infrastructure – be it rain tanks, greywater systems, or groundwater recharge schemes – is unlikely to conserve sufficient water to restore ecological flows. Further exploring the ways in which particular decentralization strategies shift social relationships around water should become an integral part of decentralized infrastructure planning, because new water relationships spur behavioural changes, and often motivate broader political engagement in water issues (Woelfle-Erskine, in press). In combination, decentralized infrastructure, heightened water awareness, new social water use norms, and political action could succeed in recovering salmon by creating new governance strategies that embody interspecies ethics of reciprocity and care.

The method I presented for investigating household water practices pair field interviews with theoretical frameworks of entanglement and intra-action. The method reveals social adaptations to scarcity and uncertain supply that arise in response to local climatic conditions and are conditioned by cultural preferences around washing and watering. These practices are not fixed (as water managers often assume), but shift in response to new knowledge about local water sources and changing perspectives on other species. In rural areas where people manage their own springs, wells, and rain tanks, autonomous water governance regimes regulated through social pressures may represent a sustainable alternative to state or local governmental regulation. Sofoulis (2014) argues in an Australian suburban context that this anarchic character of rain tanks governance increases their sustainability potential. Faced with mandatory water restrictions, many residents with rain tanks enthusiastically adopted other alternative infrastructures like greywater systems as a way to maintain gardens and to do their part for drought response (Sofoulis, 2014, 9- 10). However, in several Australian cities water managers derided and discouraged these enthusiasms because they perceived residents' drought innovations as economically irrational (Sofoulis, 2014, 13-14). In contrast, the local Resource Conservation District that has funded and implemented Salmon Creek area rain tanks engaged personally with residents and ranchers in the rain tank pilot project and incorporated residents' design ideas into second-phase tank installations. Neither the District nor the Bodega Water Company owns or maintain the tanks, and indeed required tank recipients to sign maintenance contracts. Rain tank owners connected to the BWC supply felt no responsibility for maintaining that system, but complete responsibility for their rain water supply.

Research that scales up from household water practices complements top-down hydrosocial analysis of water supply. It responds to Cleaver and Franks' (2005, 17) call for research that attends to "how people understand the relationship between themselves and the natural world, the socially embedded principles of decision-making on which they draw to manage their natural resources, and the effect of such processes on inclusion and access". The Baradian approach I have outlined here is useful because it brings entanglements of matter and meaning in household water practices to light, revealing differences between household water practices that are co-constituted by particular people, plants, animals, pumps, storms and streams.

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Thinking with salmon about rain tanks: commons as intra-actions

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The construction of California's large waterworks was inextricably entangled with a discourse of progress through technoscientific control over unruly rivers. In recent years, a turn towards decentralised governance and diversified infrastructure has produced alternate discourses of human–ecological collaboration and water as a commons. I investigate how water is understood by residents along Salmon Creek (Sonoma Co., CA) engaged in efforts to increase streamflow and restore salmon runs. Drawing on Barad's theory of agential realism, I find that living with springs and rainwater harvesting cisterns enacts intra-actions that increase residents' sense of interdependence with other human and nonhuman watershed residents. I argue that commons frameworks represent a coherent alternative to state and market frameworks of water governance.

Keywords: rainwater harvesting; agential realism; commons; salmon recovery; local knowledge

Introduction

In California, large waterworks spread as a key project of Manifest Destiny, fostered by industrial agriculture and real-estate boosterism (Worster 1982, 1985, Woelfle-Erskine *et al.* 2007). Their construction over the first half of the twentieth century was inextricably entangled with a discourse of progress through technoscientific control over unruly rivers (Worster 1985, Woelfle-Erskine *et al.* 2007). These dams and aqueducts produced a sustained agricultural, industrial, and real-estate boom, while decimating aquatic ecosystems and indigenous and traditional lifestyles connected to rivers and wetlands (King 2004, Katz *et al.* 2012). By freeing farmers and municipal water companies from dependence on local streams and aquifers, this unprecedented engineering project created an artificial divide – in policy and in legal discourse – between ground and surface waters. Large waterworks also severed urban water users from direct access the source of their water as urban streams were turned into concrete flood channels or put underground.

In recent years, a shift towards decentralised governance and diversified infrastructure has produced alternate discourses of human–ecological collaboration and water as a commons (Pahl-Wostl *et al.* 2008, Bakker 2010). Whereas the twentieth-century water planners prioritised economic uses of water and considered in-stream flows wasted water, the 2005 California Water Plan Update "strives to meet all future water demands – urban, agricultural,

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and environmental" and encourages decentralisation of some water governance processes through Integrated Regional Watershed Management Plans (California Department of Water Resources 2005). Integrated water resources management frameworks acknowledge that questions of livelihood, land use, and decision-making frameworks are central to decisions about where and how water should be used (Allan 2003). However, critical research into this integrated framework has questioned its implicit notions of community, the practicality of discursive democracy as a decision-making process, and the potential for participatory processes to entrench existing power dynamics (Ferreyra *et al.* 2008, Smith 2008, Saravanan *et al.* 2009). More recently, water governance scholars have drawn on institutional analysis approaches developed by Ostrom (1990) to design governance frameworks that explicitly account for equity and sustainability (e.g. Larson and Soto 2008, Wiek and Larson 2012, Caves *et al.* 2013, Plummer *et al.* 2013). This approach, and indeed the commons governance literature more broadly, emphasises procedural and managerial aspects of collaborative governance: deciding on decision-making procedures, reconciling local and expert knowledge, and detailing the decisions that emerge (e.g. Kerr 2007, Sarker *et al.* 2008, Innes and Booher 2010, Larson and Lach 2010).

Simultaneous with the decentralising turn in governance, a parallel turn in water infrastructure is coming into view. Sometimes called a "soft path" approach because it turns away from "hard" infrastructures such as dams and sewage treatment plants, this turn emphasises eliminating water use (i.e. through composting toilets), adopting water-efficient technologies, and abandoning wasteful water practices (Brooks *et al.* 2009, Christian-Smith and Gleick 2012). A key premise is that different qualities of water can satisfy different kinds of water demands – for example, untreated rainwater can supply toilets and laundry, and reused laundry "greywater" can irrigate gardens. Rainwater harvesting and shallow groundwater recharge are decentralising infrastructures that have gained ground with water managers in recent years. California climate change adaptation plans encourage utilities to reduce water use by 20% by the year 2020; these targets and deepening drought have spurred several utilities to decentralise water supply infrastructure and promote household rainwater harvesting and greywater use (State Water Resources Control Board 2010). Research that explores how people interact with household water infrastructure is critical to this effort because it identifies opportunities for sustained conservation and reveals how practices and infrastructural factors combine to drive water use.

Whether people adopt a practice such as rainwater harvesting – and whether that practice actually reduces water use – is complex, because savings depend on both infrastructural and social factors. For example, a household that installs water-intensive gardens and a rainwater cistern may use the same amount of municipal water as they did with a low-water landscape and no rain tank; if they water with the hose from time to time, their overall municipal water use may increase despite the rain tank. Several recent studies investigate perceptions and use of greywater systems (Pinto and Maheshwari 2010, Naylor *et al.* 2012), while others analyse how rainwater harvesting or greywater reuse affects household water consumption (Jones and Hunt 2010, Pinto *et al.* 2010, Muthukumaran *et al.* 2011). Most studies have focused on either social/behavioral or infrastructural factors in isolation, without considering feedbacks between infrastructures, values, and social water practices.[1]

However, as practice scholar Shove argues, water practices co-evolve with particular infrastructures, social norms, and values, so studying water systems as complex social–ecological systems is more revealing (2003). Researchers increasingly pursue this approach using a variety of frames. Resilience scholars (e.g. Groenfeldt and Schmidt 2013) characterise water systems as complex social–ecological systems that co-evolve in response to natural, regulatory, and social pressures. In the mainstream of science and technology studies (STS), actor–network theorists conceive of water systems as networks of human and nonhuman actants that mutually influence each other. For example, Teh uses actor–network theory to understand London's toilets and sewer system as a set of material and social relations, while Wagner applies some aspects of actor–network theory to map networks of water governance in the Okanogan Valley (Latour 1993, Wagner 2012, Teh 2013). These perspectives draw attention to dynamic interactions between human societies and local ecosystems, in the first case, and between water users and nonliving nonhumans (such as toilets and pipes) in the second. While my own sense of water systems is also invested in dynamic human–ecological systems, I find that complex systems theory and actor–network theory miss the ways that people's water practices change in response to their relationships with particular streams and the plants and animals that also use those waters.

I take a different tack. I mobilise Barad's theory of agential realism to demonstrate how household water systems emerge through intra-actions[2] between people, their wells and rain tanks, the climate, and local streams (2003, 2007). Like actor–network theory, agential realism considers a home water system as co-constituted by various infrastructural, climatic, human, and ecosystem agents. Both optics trouble the nature/culture binary by making an ontological claim: no discrete, "natural" objects exist that can be discovered by human inquiry, rather, the phenomena that make up the world are always co-constituted with human perception and engagement. Where Barad and other feminist STS thinkers depart from mainstream science studies approaches is radically questioning other binaries – male/female, human/animal, and animate/inanimate – and by focusing on the way that boundaries of race, gender, class, and humanity are constructed discursively (2007, p. 57). De-centering and de-privileging the human re-figure phenomena as lively and entangled relationships between human and nonhuman agents. In extending agential realism into water policy, I see an opportunity for a radical shift in perspective that may open up new approaches to reconciling human and ecosystem needs for water.

Whereas "soft path" approaches emphasise infrastructural and behavioural drivers of water use, and water governance approaches emphasise managerial and institutional factors, my agential realist analysis considers water practices as phenomena that emerge through "intra-actions" between people, salmon, local climate, particular water sources and infrastructures, and institutional arrangements. In exploring how rain tanks are changing water practices in a rural California community, I demonstrate that changes in one of these factors can cascade through a water system, disrupting old water use patterns, reconfiguring values, and opening a space to replace private property approaches to water governance with commons arrangements. Whereas institutionalists focus on property regimes that are already in place, I explore incipient commons. Beginning from Ostrom's insight that "[t]he key fact of life for coappropriators is that they are tied together in a lattice of interdependence so long as they continue to share a single [common-pool resource]," I draw on Wagner's concept of a "commons imaginary" to explain why polycentric governance approaches emerge through citizen science and community water planning (Ostrom 1990, p. 32, Wagner 2012).

Site, methods, and methodological commitments

On Salmon Creek (Sonoma Co., CA), a decade of collaborative research by citizen science groups and resource conservation agencies suggests that rainwater harvesting can restore more natural flow regimes in local streams, which dry up almost completely during the rainless summer (Poff *et al.* 1997). By storing winter rain for late-summer use, agricultural and municipal water users can reduce pumping from the stream and shallow groundwater during the dry season, thereby maintaining flow to isolated pools that become critical refugia for fishes and aquatic invertebrates. Rainwater harvesting may also improve water security for rural residents who source household water from wells, springs, or the Bodega Water Company. (The Bodega Water Company is a small water system with just 39 service connections that lacks a storage reservoir, and thus supplies water from a shallow aquifer connected to Salmon Creek (Hammack *et al.* 2010, WATER Institute *et al.* 2011).) The company lacks the resources to maintain ageing infrastructure and upgrade treatment facilities to remove manganese and iron; as a result, Bodega's water rates are some of the highest in the state of California (WATER Institute and others 2011). In 2009, a grant from the National Oceanic and Atmospheric Administration (NOAA) made large rain catchment storage available to members of the Bodega Water Company and local farmers at 10% of cost (J. Green, Gold Ridge Resource Conservation District, personal communication, 8/7/2012). The 10 systems installed through the pilot programme – eight at residential homes, one at the town fire station, and one on a dairy farm – have a combined storage capacity of approximately 2.2 million litres. This is the highest concentration of such systems in California, yet has an impact on streamflow that is too small to measure (Brian Cluer, NOAA, personal communication, 7/12/2013), suggesting that more widespread rain catchment and recharge projects are needed to achieve salmon recovery and drought resilience goals.[3]

In this study, I investigate how water is valued and understood by rural residents engaged in this watershed-scale effort to increase streamflow and restore salmon runs. This research is part of an on-going study that employs hydro-ecological methods, participant observation in local water monitoring activities, structured interviews with residents and scientists, and collaborative research forums that bring together residents and scientists to formulate goals for restoration and monitoring projects. I developed my research questions in conversation with local residents who are watershed council members and also scientific consultants; they suggested that I focus on measuring unmapped local springs and qualitatively evaluating the Bodega rainwater harvesting pilot project.

From May 2012 to April 2013, I conducted open-ended interviews with 22 Salmon Creek residents from 17 different households who rely on different sources of water: private wells, the Bodega Water Company, springs, rain cisterns, or some combination. I contacted pilot project participants through the Gold Ridge Resource Conservation district, and interviewed six of the eight residential rainwater recipients and the dairy farmer. I recruited the remaining participants through the Salmon Creek Watershed Council list serve and a snowball sampling method, in which participants introduced me to neighbours who were willing to show me their wells and springs. Participants included watershed council members who were concerned about salmon decline and actively involved in salmon recovery efforts, long-term residents who knew about salmon recovery efforts but were primarily motivated to conserve water by their own experiences of water scarcity, and newcomers and part-time residents who possessed little knowledge of the salmon recovery process. In all but three of the interviews, I visited the respondent's water source and asked them to demonstrate how they measured available water and maintained water infrastructure. Several participants shared their written records of rainfall, spring flow, and well depth.

My interview questions explored (1) how different sources and modes of water supply affect people's water use behaviours and overall water use and (2) how current water governance processes monitor and allocate water resources locally and regionally. For residents with rainwater harvesting systems, I asked what motivated them to install a rainwater catchment system and whether living with the system changed their water practices, awareness of local hydrology, or attitudes about waste and conservation. I asked residents with springs and wells about their experience of water scarcity and plans to develop new water supplies (including rain tanks). I asked all participants what factors they thought contributed to the local salmonid decline, who they thought should regulate groundwater development and diversions from Salmon Creek, and what types of policies (e.g. increased state groundwater regulation, county limits on new water development, and watershed restoration efforts) would promote salmon recovery and increase drought resilience for residents and farmers. Interviews were transcribed, augmented with field notes, and coded by hand; prominent themes that emerged (see next section) were explored using the optics of agential realism and commons.

View from above and from the ground

I grew interested in the Salmon Creek watershed because I was interested in what new human–water relationships could emerge in the social and political contexts of twenty-first-century California, yet in a place where no outside water sources would be tapped. I also wanted to understand how much people would change their water use out of concern for another species. Coho salmon (*Oncorhynchus kitsuch*) went locally extinct in the mid-1990s, while steelhead (*Oncorynchus mykiss*) are threatened with extinction; both species of salmonids spawn in Salmon Creek tributaries and spend their first summer in spring-fed sanctuary pools. Understanding how this small region is trying to adapt human livelihoods to local water supplies and balance human–water withdrawals with the needs of local riverine ecosystems can inform water planning in other parts of California and beyond.

On a map, Salmon Creek looks like a fish leaping up a waterfall, or twisting through the air to get free of a hook (Figure 1). Its mouth is at the edge of the Pacific Ocean, and its tail twists up towards the redwoods. Consultants and agency scientists adopt this view from above via satellite images and geographic information systems maps of geology and land use, which become inputs for distributed hydrologic models that produce estimates of streamflow under different climate and pumping scenarios. This exercise is an instance of what Haraway calls the "god trick", because such disembodied views purport to reveal "what is simply there" (1991, p. 582). From above, the view of the stream and built waterworks is fuzzy, obscured, and partial. Maps of springs, landslides, and geological features are incomplete, perhaps because landowners have denied mappers access. Only nine permits to divert water from the creek are registered, yet many more people admit diverting water from the stream. Acting on Haraway's call for mobile positioning and attention to local knowledge is not simple here.

From the road, the Salmon Creek watershed looks rural, with cows, old barns, and an upscale country store that sells oysters. The watershed boundary is marked with signs at road crossings. Descendants of Italian settlers run dairy cows on the grassy slopes above the main stem of Salmon Creek. In part because of water scarcity, these agricultural parcels have not been subdivided into suburban tracts. The ranchers tap wells or small springs; some have permits to divert Salmon Creek water. Up on the redwood-cloaked ridges, newer developments on small parcels rely on individual wells that tap sandstone lenses on the ridge tops, or water secreted in fractured metamorphic rock. Here live recent, often well-off migrants from cities where, as several told me, "we didn't have to

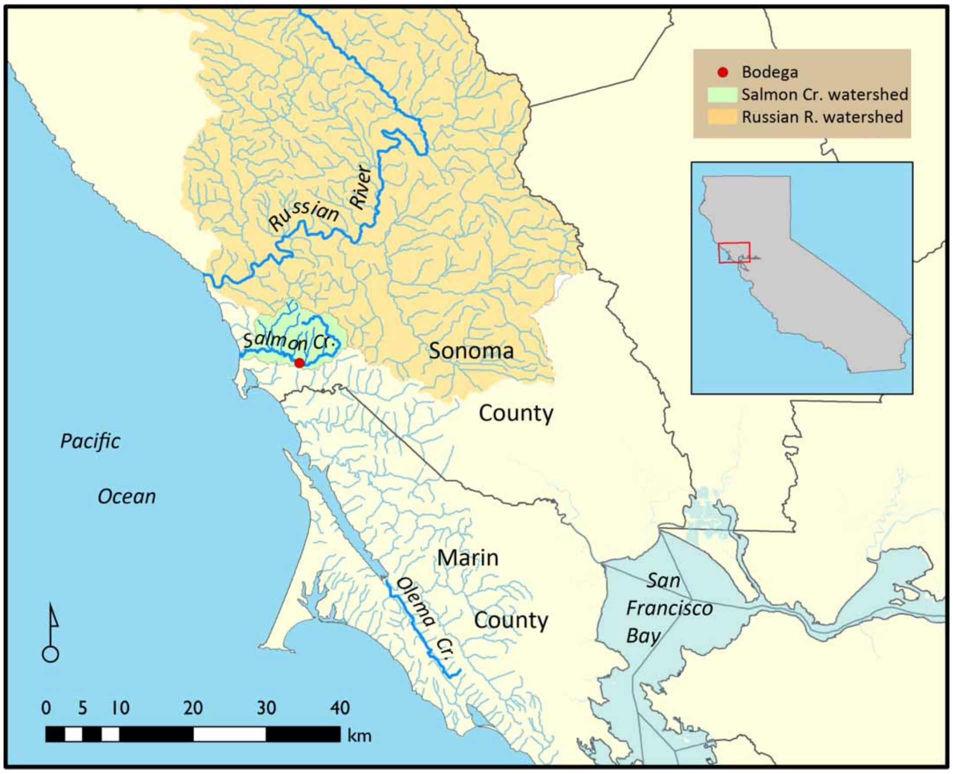

Figure 1. Map of the Salmon Creek region showing the Russian River and Olema Creek. These streams maintain small wild salmon populations that are now bred in hatcheries through the Russian River Captive Broodstock Program, then released in Salmon Creek. This map is also an example of what Donna Haraway calls the "god trick" – a view from everywhere and nowhere.

think about water". On a few ridges in the headwaters live back to the landers who arrived in the late 1960s and tap springs for water. Small towns – Bodega and Freestone – host a motley assortment of retirees (many on fixed incomes), artists, scientists, and service workers. Most residents know each other by face, and many know that their water use affects streamflow. "The Salmon Creek watershed wraps itself around this community and goes out into the ocean. We know it's us," one resident told me. Many residents contrast the local thrifty water culture to profligate habits in nearby cities and towns, which have (comparatively) abundant water because they tap the regulated Russian River. Larger socio-political factors including regional water scarcity and regulatory obstacles in permitting new reservoirs have left this watershed without access to these pipelines. Thus, residents are wholly dependent on local rainfall and what water can be stored in aquifers, ponds, and tanks, or pumped from the stream.

Economic constraints (e.g. the cost of improving the small Bodega Water Company or trucking in water), a lived experience of scarcity, and a desire for salmon and other creatures to return from the brink of extinction are shaping cultural relationships to water along Salmon Creek. These emerging water cultures foster household water use practices and social norms different from those that coevolve with large urban water systems, including:

(1) a different awareness of water supply apparatus, which arises from an acute awareness of scarcity and extends to concern for nonhuman creatures that depend on Salmon Creek;
(2) a detailed local knowledge of one's own water source, of neighbours' wells and water use practices, and of local hydro-ecological cycles; and
(3) the conviction that local self-regulation is preferable to outside regulation.

Below, I elaborate on these three themes, then argue that they evidence an emerging "commons imaginary" that influences discussions of how to manage Salmon Creek's ground and surface water.

Apparatus

In *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning*, Barad argues that humans, their scientific and everyday apparatus, and all the living and nonliving matter of the universe co-constitute phenomena, which are made real by their engagements with each other (2007). Barad argues that, at the quantum level, observation and influence are inseparable and complementary. She posits intra-action (a neologism that calls attention to the inseparability of the observer and what she observes) as an alternative to a mediated, representational view of the world. Since quantum phenomena operate at all scales of space and time, insights from quantum mechanics are not simply metaphorically applicable to everyday, macroscopic phenomena, but suggest the inseparability of epistemology, ontology, and ethics in all realms of research and action. All matter has agency, which does not inhere in beings, human or nonhuman; rather "[a]gency is the enactment of iterative changes to particular practices through the dynamics of intra-activity." (Barad 2003, p. 827).

Phenomena in Barad's view are intra-actions between differently empowered agents that are co-constituted with particular apparatus. What happens if the phenomena of interest are water systems? I think of waterworks (dams, levees, wells, pipes, pumps, and treatment plants) as a kind of apparatus that variously determines, constrains, and enables people's tangles with water. Water infrastructure beckons people to particular places, making certain economies and lifeways possible, and precluding others. Water development often imposes a human/nature binary when water is extracted from "natural" water systems for human use; this binary reappears during droughts as conflicts between human and ecosystem uses of water.[4]

Larger municipal water systems in the region imported water from dammed rivers following a pattern Sofoulis describes:

> In exchange for being inextricably entangled with Big Water via the meter, the meter-reader, water bills, pipes and drains, users receive the security and abundance of an ever-flowing supply, the comfort of an all-accepting drain, and convenience of doing nothing to maintain water supply except pay the water bills (2005, p. 455).

Such was the pattern that began on Salmon Creek when municipal and agricultural water systems were developed to divert most of its flow. Yet the stream is so small and permitting on-stream reservoirs is near-impossible, the phenomenon of water use evolved differently in Bodega. Service interruptions are common, users receive poor-quality water during the summer, and people often coerce their neighbours into serving a stint on the water board, where they experience the difficulties of maintaining a small water system first hand. Those without a connection from the Bodega Water Company must maintain their own spring or well. In short, all water users interact regularly with their water infrastructure. Perhaps as a result of this frequent interaction, most participants spoke of their household water system as an apparatus made up of human, manufactured, plant, animal, mineral, and atmospheric elements. Many saw the water they drink, wash, and water with as interdependent with a multiplicity of living and nonliving things.

The water source is always local and known. Several residents showed me the sandstone layers that held the water and springs that emerged at the contact between sandstone and metamorphic rock formations. One retired resident who lives on a ridge described the aquifer his well taps as a shallow bowl of sandstone perched atop an impervious metamorphic layer:

> It's a mess – there's fingers and little separate depressions. The only water we get, basically, is what we get in winter. It's saved there in this bowl until we run out. There are places in the woods here that are seeps, where it's overflowing from these bowls year round.

A long-time resident who lives near the stream described his shallow well as being recharged by seasonal pond:

> It's variable, but in the beginning of June or the end of June and the well dries up. During the time when the water table is high and the earth is full of water it works just fine.

Another long-time resident, a fisheries biologist who conducts annual surveys of Salmon Creek, sees the stream dry up downstream from wells, including the Bodega Water Company well on his property. Yet, even where the characteristics of the aquifer and rainfall patterns were mapped and charted, water remained a mysterious force. This force is often elusive when one goes drilling for it, and several people reported resorting to dowsers when engineers failed to find water (with mixed results). One long-time resident said,

> We tried to drill into [the sandstone hill above the spring] from the side in back of the house, nothing. The source of the water is mysterious. We got a dowser to find places where three springs converged – nothing.

Infrastructure is something people build and maintain themselves, though some may call experts in emergencies. When no water comes out of the tap, it could be because of a break in the pipe, because someone left the water on, or because the source went dry. Things break or leak frequently, and people have devised elaborate systems of valves and maintenance checks to make sure a leak does not drain the whole water supply. A recent immigrant from San Francisco who runs a bed and breakfast explained,

> I have all the tanks closed. I open one tank at a time, in case of an accident, or somebody that leaves a faucet on, so I don't lose two or three tanks of water. I only lose one.

In relating how he fixed a leak, one long-time resident describes water as an animate force:

> Once there's a leak, that's the most important thing that's going on, anywhere . . . I was out poking around . . . and I heard something. When I hear water running I stop and go investigate. I walked towards the sound and I saw that there was water gushing out of the pipes and the joint had separated. But I got it about the first fifteen minutes so I only lost 800 gallons.

Human error is seen as a mechanism of leakage. The human–pipe interface is a frequent point of failure, with high economic and sometimes interpersonal costs. Perhaps leaks, and the urgent human action they inspire, make articulation most apparent. A retired couple, recent immigrants from a water-rich region, said:

> Husband: In fact somebody left the hose on last week, and the tank went down to zero, and it couldn't pump enough to fill up the tank. We had to haul in 3000 gallons of water to get it started up again.
>
> Wife: It was me. I was on my way to one of those darned Salmon Creek Watershed Council meetings.
>
> Husband: I'm not trying to point out what a klutz you are, it's just an example. 'Cause I didn't know what was wrong with it, it was just dry all of a sudden.

Climate is articulated with the natural source in that, at least in shallow aquifer areas, it governs how much water will be available in a given year, and how long into the dry season that water will last. Every person I interviewed maintains a rain gauge, and five participants track the flow of their spring, or the level of their well or rain tank. The knowledge of climate is partly held in handwritten records people keep of their rain gauge measurements, but also partly discursive, generated when neighbours meet up and talk about rain. Climate and hydrologic knowledge circulates through informal networks and informs how people manage their own water supplies, and factors into the near-universal opposition to more water-intensive development. Two long-time neighbours said,

> Neighbour 1: This year, I measured 62.9 inches of rain, cumulative. We haven't had 60 inches of rain for the past 20 years. [He consults his rain gauge records.] There's a big variation from year to year.
>
> Neighbour 2: Last year we had rain into June. That's good for fish.
>
> Neighbour 1: We had 1.5 inch on June 3 and 1 inch on June 28. Now the average is around 40 inches. If there is an average. Next year we could have floods. But we probably wouldn't ever go below 30 inches. That's our water supply, that's what we rely on.

Many users practice water monitoring (Figure 2); however, the way they regulate use differs depending on the source of their water. Only users with metered municipal connections can report their daily usage in gallons. Those with cisterns know how much rainwater they have left, how much they use for irrigation, and how much they should have left at a given time of the year. Two residents who installed rain tanks through the pilot programme described how they respond to diminishing stores:

> Watching the tank level go down, I'm thinking well, let's see, I've got this much left, and I've got to make it to the end of October when it starts to rain. So is my consumption too much for what I have available? Perhaps I am thinking a little bit more about level of consumption [now that I have a rain tank].
>
> It's like draining your bank account. When you see it going down, down to almost zero, you're saying well, wait, I can't use too much more.

Users with rain tanks and wells understand water supply in relation to climate and demand. Residents with springs think in terms of flow rates. One resident told me that if flows drop below three gallons per minute in August, he will run short in September. Although he has adapted to water-scarce summers, the prospect of even less spring flow scares him:

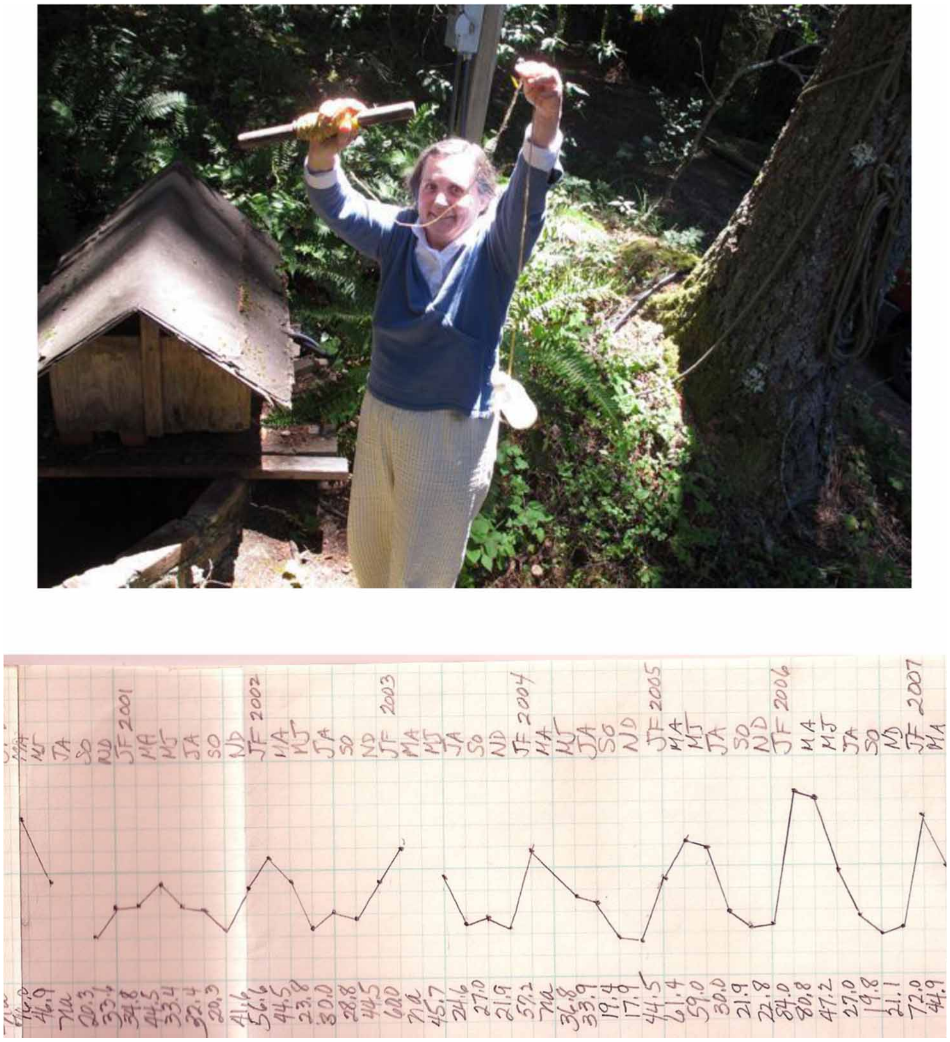

Figure 2. Salmon Creek watershed resident Diane Masura displays a home-made device that she uses to measure the depth of water in her well (top). She maintains detailed records of rainfall and well level that date back 25 years and show a consistent 60-day lag time between rainfall and maximum water level in the well. Many watershed residents maintain such records.

> I've lived here since 1974. Even in droughts, the spring never dried up, never went below 3 gallons per minute in September, except in 2009. That scared me – to see it get down almost to a drip. I had to put a tin chute inside the spring to direct more flow to the pipe that leads to the tank.

Conservation, then, requires action at different articulation points of the apparatus. To cope with scarcity, all participants have installed water-saving devices, commonly low flow toilets, aerators and shutoff valves on fixtures, and water-efficient dish and clothes' washers. Many have also abandoned devices designed for water-rich areas – sprinklers lose water to evaporation, and pressure hoses are prone to leakage:

> Once the garden's started, I just let it be on drip irrigation. I have to check it all the time to make sure the batteries are working.

The particular form of the apparatus – what source people rely on, what appliances and devices it flows through, and people's lived experience of scarcity or running out of water – partly determines water practices and consumption. Two Bodega Water Company members expressed the idea that people with adequate water were disconnected from the impacts their water use had on the creek:

> There's not enough water in Salmon Creek. And they're definitely endangering the salmon by using it. I'm appalled when people misuse the Bodega water. I can't believe people are so asleep. People are so privileged. They think that if they own that property they have a right to use any resource on it. Have you seen [local farmer's place] yet? Oh my god. He was watering all these cattle, and he was using hundreds and thousands of gallons coming right out of the creek. Excuse me! He's a nice man. And he would blithely use as much water as he wanted out of the creek until he was offered this grant.
>
> [Pumping from the creek] is really bad. And the vineyards do it. [Landowner name] is taking right out of Salmon Creek . . . I think that's not right for profit making people to take from the commons.

This same resident also adopted water-saving habits that she teaches to children and visitors:

> We have a special low flow toilet, we have a graywater system. . . . We turn off the faucets, we don't leave them running, unless you have a [visiting] ten year old who doesn't have any sense. You say they have to learn sometime, well, he's going to start learning when he wakes up tomorrow morning.

Newcomers learn to adapt their gardens to dry summers, abandoning lawns in favour of xeriscape and fruit trees that need water only for the first three years. One gardener adjusts water use, even selecting plants to sacrifice or take off irrigation if he runs out:

> I only have so much water available, 46,000 gallons, so I plan accordingly . . . I tend to plant things like potatoes, garlic, onions early on so that when it stops raining I have already harvested . . . In case of an emergency, if I have some plants, I wouldn't let them die. I will use the Bodega water company water. But this will be the last resort.

Several residents said that they only grow plants that have a purpose, and hate to see water thrown away. However, whether a resident considers a particular use of water to be wasteful depends on their conceptual model of local hydrology. For example, most people thought that using well water in the home was not wasteful, since all the water recharged the aquifer via the septic system. As these three residents described, certain watering practices (unattended hoses and daytime use of sprinklers) and crops (lawns) were considered wasteful, but merely having a garden was not:

> Nothing [in my garden] gets water that isn't useful or chosen.
>
> Being conscious about water conservation is perhaps the biggest thing. You know, what happens when you turn on the tap? Do you have to turn it on? . . . Coming out of the faucet and running down the driveway, I don't think that's a good use of water.
>
> Most of my trees are not irrigated. They just drain their own water from the depths that they need. I don't believe that anybody should have sprinklers. The grass and all of that stuff shouldn't even be permitted, if they have to drain water from close to a creek.

All participants reported adopting some water conservation measures, but most also reported indulging in what they considered wasteful, luxury uses of water. Two participants said that they take long hot baths, one builds tile fountains, one has a fish pond, several maintain lush vegetable and flower gardens, and one couple installed an extra rain tank to top off their swimming pool. Some people admitted to refilling their rain tanks from the municipal supply in order to expand their gardens.

In summary, all participants reported adopting water-saving practices and/or developing new infrastructures to increase their own water security. Some residents were motivated to do so by their desire to see salmon return to Salmon Creek, while others were motivated by desire to expand their gardens and improve reliability during dry periods.

Regulation, local knowledge, and commons

One rainy day early in 2009, a small group of humans carried 300 salmon from a truck to the edge of the water, and released them.[5] The fish slithered and splashed upstream, then spawned. That year, local rain gauges measured the lowest rainfall in decades, and one resident watched his spring dry up for the first time in the 35 years he had lived there. Water trucks rumbled back and forth, bringing Russian River water to residents whose wells had gone dry at $150 per 3000-gallon truck. By summer the streams had gone nearly dry, and dissolved oxygen in the small pools that remained dropped towards zero. Biologists working for the Department of Fish and Game collected the finger-length fry in nets, and took them back to the hatchery. Once the rains began in November, biologists returned the fish to the stream, where they lived for a few more months before swimming out into the ocean (M. Fawcett, personal communication, 8/8/12).

Each winter since then, a few humans re-enact the release of spawners in the estuary, hoping to re-establish each year-class[6] of extinct fish with hybrids of hatchery-raised fish from the Russian River and Olema Creek watersheds (Figure 1). In one sense, this slight change in materiality – a mere 600 pounds of fish that swam upstream, spawned, and died – has transformed the social and material interactions of the watershed's human residents. Now, everyday practices such as flushing the toilet or bringing water to the horses resonate with significance for tiny fry growing up, unseen, in the tributaries. One long-time resident who installed a rain tank said,

> That tree line is Salmon Creek. It's three miles out there, and you probably can't kayak it because of the trees to go across. There are people that seem to remember that there were a lot of fish in this stream at one time, and you could go spear them after school. And we see now, there's Coho in there, and otters, and turtles. There was a deficit of wildlife there from 2002 to 2008 or 2009, but it's coming back now. It's really good to see.

Instead of asking about a commons outright, I ask it aslant:

> Who do you think should be responsible for making sure that residents of the watershed have enough water? Who do you think should decide how much water can be pumped out of Salmon Creek, and whether any needs to remain for the ecosystem?

The answers range from "the state", "the county", "individual water users", "the Bodega Water Company" to "only the federal government can protect the salmon."

All participants believe that the watershed already has been degraded, and will be degraded further if humans withdraw more water for agricultural or household use. Groups of neighbours have organised meetings to discuss strategies for increasing adaptive capacity in the face of a deepening 3-year drought, and are interested in building infiltration basins to recharge winter rain into ridge-top aquifers (Darlene LaMont, personal communication, 12/24/13). To date, these incipient collaborations have not yielded institutional structures for managing groundwater as a common-pool resource. Indeed, my interviews suggest that residents are divided on how best to regulate groundwater use.

More than half of my participants echoed the view that outsiders (county, state, and federal governments) do not know enough about local water needs, sources, and practices to regulate this intricate system. Residents have detailed knowledge of how long their neighbours' water lasts, and who violates community conservation norms, yet few believe that the state should step in and punish people for over extracting. Most preferred incentives for existing development, such as grants for rainwater systems and education. The others thought that some amount of regulatory pressure from state or federal agencies is necessary to motivate conservation and habitat recovery projects.

Several residents who have lived in the watershed for between 10 and 30 years expressed the view that long-term residents have evolved conservation practices to cope with water scarcity, and are capable of self-regulating water use in times of drought. These residents saw newcomers from cities as a threat to aquifers and the local water culture because they lack local knowledge of water scarcity, and may not bow to social pressures to conserve. Half of the participants thought that the county should mandate rainwater catchment for new development, and several participants supported a total ban on new wells in the watershed.

Arguing for government regulation, several participants cited relentless development pressure as the cause for declining water tables. Groundwater is unregulated in California, and only recently have developers had to prove to the county that property has a one gallon per minute (four litre per minute) well. They argue that developers have no incentive to leave land un-developed, particularly since vineyards command high profits. One person said that the county is tightening groundwater regulations, but has been ineffective in monitoring how much water is extracted via wells, determining how new wells affect old wells, or slowing development. Because the county's tax revenues increase with land values and subdivision, they believe that state agencies must regulate water use by regulating development:

> I think there have to be state level rules, regulations, and the townships have to live within those regulations. It has to be monitored, for one thing. That's gonna be the tough part. People don't want a meter on their water supply ... They're the only authority that can take care of this. Because the county and these little towns can't do it, or won't do it.

Others think that the watershed is already over-regulated, and resist the idea that state or county agencies would meter and enforce withdrawals from streams or aquifers. In California, data on the level of the water table is not publicly available, and some residents want to keep it that way:

> People are going to ask you, what are you going to do with [your spring and well] data. People are going to be less frank if they think there's any way the county or anyone else is going to monitor them ... It's the principle in part – how much should be in the public domain?

For another resident, the rejection of state authority opens the way for some form of collective management:

> I think it would be bizarre to think that there would be a state water agency that could regulate the amount of water that we take out of here. They are remote and they have other issues to pay

> attention to. But I think that . . . thinking as a watershed unit . . . we should be able to regulate our own.

In my interviews and participant observation of local water planning meetings, I found evidence that status quo rules govern de facto governance of groundwater and groundwater-fed streams. These rules operate informally, suggesting that collective governance in Salmon Creek is at an incipient stage, in which people begin to consider scarce groundwater a commons that should be managed collectively to sustain another common-pool resource, salmonid fishes. However, the specific forms of that management – the rules, monitoring, and enforcement that would cohere in an institution to manage the watershed commons – have not yet emerged, despite a decade's effort to foster collaborative watershed management here:

> I think that collaborative efforts work better, but until people get educated – people are angry when they're made to do things. I understand why they have to regulate fisheries because . . . greed takes over and then people don't have any good sense about taking care of Mother Earth and all of her different creatures, and sensibly harvesting, sensibly growing. I hate the vineyard industry because they have big monocultures and they overuse water and they're only doing it for their own gratification.

Only tentatively do people say – or talk around the idea – that water, the watershed, or the riverine ecosystem are commons in need of protection.

> Wife: I do consider it a commons, but I don't think I'm in the majority in this community. People in this community respond more to a specific argument, like "The fish need it, we want the fish, we're going to go get them and eat them." I consider it a commons, don't you?
>
> Woelfle-Erskine: I do
>
> Husband: I think there are two resources that need to be managed like that, and one of them is air quality, and the other one is water. Everything else – the mineral contents, the gold they find on your property – that seems to be built into our political system that it's yours. But . . . we're all using the same water and the same air. There has to be consensus and agreement on how to use them most effectively. People can't get greedy.

In contrast to other studies of water commons, the common-pool resource discussed here is not only (inanimate) water that provides economic goods or social benefit. The commons is the watershed – an animate agent in the Baradian sense – that collects water in ponds and streams for the benefit of humans and nonhumans alike:

> What is the benefit of those creeks to those people who live here, and do the other animals that live here have any rights at all? Who's going to provide a habitat for the fish and the animals– the bobcats and the deer and the coyotes and the raccoons and all of those other animals that go down to the creek to drink? You can hear them down there. Do they have a right to clean water? . . . I happen to think that we all live here together as a living network . . . The creek should be preserved for the benefit of all living people [he corrects himself] all living beings, as well as for humans . . . If that means a regulation of consumption, then maybe we need to self regulate in some regards.

Thus, the idea that the Salmon Creek watershed is commons is, in a Foucauldian sense, sayable and plausible in the Salmon Creek watershed five years after Coho salmon reintroduction, though collective management institutions have not yet emerged (Foucault 1991). Also sayable now is that fish should have water and habitat. During the twentieth century, dams were built on nearby streams with full knowledge that they would decimate salmon runs. At early salmon recovery meetings here in the 1990s, some people opposed reintroduction because they thought that it would threaten agricultural livelihoods and tenuous water rights. Now, "you'd be crucified" if you stood up in a meeting and said that agriculture should trump salmon.

> Wife: At those early community meetings there would always be someone who said the fish were not really important, that agriculture was really important. No one says that anymore.
>
> Husband: [interjecting] You'd be crucified.
>
> Wife: Yeah, right. The whole community has changed . . . Maybe the naysayers aren't coming because they think people would boo them down. But still, they didn't used to be booed down, so I think things have changed.
>
> Husband: I think it's a realization that there's a shortage, or there will be a shortage, of these generally accessible things like water, fresh air, clean air, all that stuff. We're all stuck in this together. Some of the farmers that have stood up recently at some of the water meetings have been very articulate and quite understanding about this.

In community meetings and conversations at the post office and the bar, ranchers, environmentalists, and newcomers alike now say that watershed can sustain agriculture, salmon, and residential use, and believe that restoration strategies should increase the resilience of all three.

My interviews with watershed residents – early adopters, potential adopters, and non-adopters of rainwater harvesting – suggest that interest in rainwater tanks has increased markedly now that people have had a chance to observe the first installations, for several seasons. According to one Bodega Volunteer Fire Department member, fire-fighters were initially sceptical of the project. But when a fire threatened the town and there was not enough water in the creek to fight it, they saw the large storage tank in a new light. With a grant from the NOAA available to help fund a fire station upgrade, the department decided to install a 132,000-L tank, and in the process became supporters of the rain tank effort. During this same time, Bodega residents have witnessed runs of Coho salmon increase from zero, to several dozen, to hundreds. It is as if the materiality of the tanks and the salmon is now entering the discursive practices of public meetings and outreach, and has precipitated a shift in discourses around the stream, fish, water use, and how to reconcile different needs and desires for water.

Conclusion

Through the lenses of Baradian apparatus and intra-action, I see signs that participating in citizen science and living with rainwater cisterns increases residents' sense of interdependence with other human and nonhuman watershed residents. In residents' reflections on their daily water practices and their practices of returning Coho salmon to their watershed, I find the concept of water as a commons co-evolving with small-scale rainwater harvesting infrastructure. This commons differs from many water commons discussed in the literature in that bodies of water are not merely resources for human use, but are lively agents that sustain salmon, humans, cows, trees, frogs, and humans alike.

By incorporating rainwater harvesting into the (partly) centralised[7] Bodega Water System, the system is taking on the qualities of proximal materiality, diversity, and scarcity that, according to Strengers and Maller (2012), characterise decentralised water systems. Like the people Strengers and Maller interviewed, most Salmon Creek watershed residents live with household water infrastructure that is indistinguishable from their urban and suburban neighbours. They have flush toilets, washing machines, and pressure hoses to mist down flowerpots – devices that Sofoulis (2005) describes as “baked in” to large centralised water schemes. In response to scarcity and a large government cost share, some residents are evolving practices and modifying infrastructures in ways that makes their intra-actions with water much richer in social and ecological meaning. In particular, rainwater cisterns foster a sense of connection to local rainfall cycles and increase residents’ awareness of seasonal fluctuations in water supply.

These findings suggest that decentralising water governance and infrastructure involves more than a change in water management. Managing one’s own water system seems to increase entanglement with local water sources and shift dynamics between oneself and one’s neighbours (both humans and other species). In my account of emerging interspecies commons, these entanglements may precipitate changes in culture – specifically, in the social meaning of water – because the apparatus of water use expands to include riverine species that embody a lively materiality that is bound up in human–water relationships. To date, the literature on decentralised water systems has underplayed the cascading social and interspecies effects that can accompany a shift in water infrastructure. But unless these cultural relationships change, a mere shift in infrastructure – be it rain tanks, greywater systems, or groundwater recharge schemes – is unlikely to lead to the far-reaching changes in water provision that will be necessary to avert extinction of most salmonid taxa in California (Katz *et al.* 2012). More research into how particular decentralisation strategies shift social water relations should become a central focus of decentralised infrastructure planning.

Collective choice frameworks represent a coherent alternative to state and market frameworks of water governance. Although changes in human–water relationships along Salmon Creek may not map onto other watersheds directly, they do point to social changes that can be anticipated where people, water, and other living beings jump barriers erected by infrastructures and see that they swim through common currents. Water mains and dams separate city and suburban residents from their water sources and from the other creatures that inhabit them just as surely as redlining and prison walls separate urban residents of different socioeconomic backgrounds. In both cases, out of sight is out of mind, and at a conceptual distance, we rob those people, animals, plants, and waters of agency and animacy.[8] Active, daily involvement with water reminds of its life force. When people have built channels and vessels to store water, awaited the first storms, and seen silver bodies flashing upstream after the first big flow, water can no longer be seen as a dead resource for human use alone.

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Notes

1. In an exception to this trend, Domènech *et al*. (2013) evaluate changes in water use and water practices following installation of decentralised household water infrastructure.

2. Barad explains the term intra-actions as follows: "[T]he notion of 'intra-action' queers the familiar sense of causality (where one or more causal agents precede and produce an effect), and more generally unsettles the metaphysics of individualism (the belief that there are individually constituted agents or entities, as well as times and places). According to my agential realist ontology, or rather ethico-onto-epistemology (an entanglement of what is usually taken to be the separate considerations of ethics, ontology, and epistemology), 'individuals do not preexist as such but rather materialize in intra-action." (Barad 2012)
3. Phase two of the project began in 2013, and will install eight more rainwater harvesting systems in the Bodega area.
4. For example, see news coverage from California's 2013 to 2014 drought (Clarke 2014, The News editorial board 2014).
5. This release is part of the Russian River Captive Broodstock Program, an experimental collaboration between various state and federal agencies in which individual salmon are raised to adulthood in a hatchery, then bred to maximise genetic diversity. The surplus adults are released into the Salmon Creek estuary, where they swim upstream and spawn without further human interference. Their young are then "wild" in the sense that they are subject to all the natural selection pressures at work in a stream habitat.
6. A year-class is a distinct sub-population of an anadromous fish that hatches in a given year. Coho spawn three years after they hatch. In Coho salmon and other anadromous fishes that have high temporal fidelity in their life history, a year-class becomes locally extinct can only recover if spawning fish stray into the depopulated stream or are re-introduced by humans.
7. Only 'partly centralised' because many Bodega Water Company users also have a well or used to pump out of the creek.
8. This insight into acknowledging agency and animacy in humans and nonhumans comes from Kimberly Tallbear's comment on a draft of this paper.

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Conclusion

After staying so long in one little out of the way watershed, what can I say about what my research might mean for other fish, people, and rivers?

My study took place against a backdrop of deepening drought across the state. This drought is presented as spawning conflict: between fish and farms, farms and cities, and humans and nature; these entities are seen as in conflict because they are seen as fundamentally separate. The agriculturalist slogan 'Food grows where water flows' appears on signs and banners along interstates in the Central Valley, and signals a dominant discourse: food can (only) be produced by water diverted from rivers for exclusively human uses. The grassroots Salmonid Restoration Federation recently printed a bumper sticker that says "Salmon Grow Where Rivers Flow". The slogan is a direct challenge—a discursive challenge—to this binary: salmon are also food, not only for humans but for bears, otters, and trees, and they grow in rivers where humans have left some water to flow to the sea.

The 2012-14 drought has challenged the ability of statewide and regional efforts meet the 'co-equal goals' of the 2009 Delta Reform Act. That act mandated that state water policy balance two goals: to provide a reliable water supply for human use and to protect and restore aquatic ecosystems. So far this mandate has failed to avert the impending extinction of wild salmon runs, the Delta smelt, and other sentinel species in aquatic ecosystems. This failure—and the increasing conflict between fish and farmers and farms and cities—points to the challenges of epistemological convergence among disparate scientific and non-scientific actors. Water-governing entities can only coordinate and collaborate when dialog flows freely between engineering, scientific, indigenous, and local community actors—dialog that feeds mutual goals and converging conceptions of hydro-ecological processes. How can such a flow develop in this drought, and in what ways might it contest scientific understandings of California's water systems?

The California Water Action Plan and emergency drought measures provide evidence that statewide drought policy still overwhelmingly emphasizes command-and-control notions of water delivery. In the engineering logic behind twentieth-century California waterworks, water futures can be fixed, controlled, and anticipated. In recent years, other epistemologies have influenced regional and local projects. For example, the ecological notion that resilience depends on maintaining dynamism in fluvial systems has entered into Delta science plans and Endangered Species Act recovery plans for salmonids, and ecological models have been grafted onto hydrologic models of Russian River and Delta dynamics. Farmers and other land managers sometimes enact their own management plans, such as the rice farmers experimenting with "sashimi" methods, flooding rice fields to create habitat for salmon smolts during their downriver migration; and Scott Valley ranchers encouraging beavers whose dams recharge aquifers. Co-management agreements between tribes and federal agencies in the Klamath Basin have broadened the scope of inquiry into fire dynamics and cultural foodscapes.

Over years and with increasing collaboration across boundaries of rancher / scientist, tribe / agency, and resident / water manager, narrow disciplinary views may give way to more complex and entangled views. Participants in more collaborative processes often come to characterize systems as complex hybrids of social and ecological elements. This is what I see happening on Salmon Creek, and also in some of the Klamath collaborations and at the annual Salmonid Restoration Federation conference. However, the approaches arising from these new epistemologies (e.g. hatcheries where salmon fry grow up in natural-seeming streams, or floodplain restoration that conceives of a river as its entire geomorphic floodplain) have largely been marginalized in state-wide water discourse. Entrenched political interests—large agricultural and urban water districts dependent on centralized aqueducts and reservoirs—often succeed in suspending environmental and endangered species regulations that create a rationale for ecological flows and habitat rehabilitation. Drought—both meteorological and anthropogenic—creates a crisis response, akin to what Naomi Klein called the 'shock doctrine' in economics, that often constrains collaborative efforts and experimental approaches.

Thinking across scales

Shasta Dam, completed in 1936, was hailed as the keystone of the Central Valley Project, which re-routed rivers from the north of the state to agricultural lands in the arid San Joaquin Valley. This dam submerged traditional territory of the Winnemem Wintu, and also blocked almost the entire spawning grounds of the winter-run Chinook salmon. When they staged a war dance atop the dam in 2004, to protest Bureau of Reclamation plans to raise the dam, the Winnemem emphasized that these two destructions were not separate, and that the legacies of salmon extirpation, flooding of sacred sites, and dispossession are very much alive today. Shasta Dam's construction was a manifestation of frontierist expansion policies—Manifest Destiny inscribed upon rivers—instrumental to westward expansion in the US. This doctrine is sedimented into our dams and waterworks, and is implicit in the way we regulate water and in the institutions that have developed to send water from place to place. And these ideas manifest as injustices in the distribution of water, in water quality, and also in injustices to everything not-human in the world.

The old top down modes of governance would attempt to scale up from 'success stories' like Salmon Creek, developing centralized programs to create generalizable strategies for managing water in human and environmental systems. As James Scott (1998) notes, the state perspective, which divides the landscape into a grid and then attempts to separate out the productivity of the land from the productivity of the ecosystem, yields failures and vulnerabilities. These top down perspectives have not proven resilient in dealing with complex problems such as water allocation in the face of climate change. Given the scale at which our waterworks operate, some top-down approaches will be necessary to re-balance human water use with ecological processes. Katz and Moyle mention several such actions—removing dams and levees in the Sacramento-San Joaquin system, or changing the operation of dams—in their seminal paper on the impending extinction of salmonids in California streams. Such actions are absolutely needed on the Klamath, on many Sacramento and San Joaquin River tributaries, and within the Delta. Action at the river basin scale should not preclude action along smaller tributaries, however; both are needed.

One new trend in water management—and in governance generally—is neoliberal decentralization that devolves state functions to smaller scales of governance, often privatizing tasks such as monitoring or water provision. This has increasingly happened in water management, via the Integrated Regional Water Management process and the proposed groundwater management entities, and in fisheries management via funding of salmonid monitoring programs through competitive grant processes that leave. With this devolution comes uncertainty in funding that can jeopardize long-term monitoring of groundwater and fisheries, and compromise collaborative partnerships that require ongoing effort to coordinate. Rivers, aquifers, and fisheries are simultaneously a public trust and a commons, and should be managed as such, with public funding and support.

Through my research I have come to reject the idea that local approaches must be scalable as fallacious and counterproductive. As Tsing (2004) noted regarding biodiversity initiatives, action on the level of an abstracted whole often loses sight of local specificities, and can erase important differences amongst local strategies that arise from particular cultural-ecological circumstances. Salmon live and die in little streams, especially during their first summer, and local places are where these alternative strategies for land and water management are evolving. So I argue that if salmon are to survive it will be in these small tributaries and localities—places that until recently have largely been written off by large environmental agencies. My research on Salmon Creek suggests rich epistemological and strategic yields from small watersheds, ones that lie beyond the reach of centralized infrastructures, and are only lightly regulated by state, regional, or local agencies. I find that these are places where we should look for different approaches for dealing with and managing water and fish. Instead of scaling up from these local approaches, however, I suggest a process of replication, from below, through articulated networks already in place; a fractal approach relying on face to face learning, experimentation through social networks. I see Salmon Creek and other such localities as lower-case-A anthropocenes (Tsing 2012): places where, in coping with the effects of massive human transformations to ecosystems, people develop new governance strategies, epistemologies, and watershed management practices. In other words, these small localities where people with different backgrounds hash out management strategies together are sites of epistemological convergence.

I do think there are ways for regional collaborations to coordinate projects at medium scales, or for ideas to travel from locality to locality. Any watershed might replicate some of the processes that led to this convergence in Salmon Creek: collaborative workshops, wet-dry mapping, spawning and snorkel surveys. Inquisitive, long-term, and dialogue-based methods will foster that convergence, and facilitate new kinds of research and approaches to recovery / restoration work. Local knowledge practices that are largely unknown and unappreciated by agency and academic scientists, including residents' protracted observations of streams, can be incorporated with scientists' periodic field data and remote sensing measurements of flow, land cover, and fish movement. One such method I have begun to develop is a web platform that can collect and visualize citizen science data from wet-dry mapping and fish surveys and local knowledge records of well level rainfall, and spring flow. Other interventions like the rainwater tank project can be transferred from one place to another. At the regional scale, strengthening and fostering more coordination amongst relatively autonomous collaboratives will be key. Agencies would be well-served to employ a person to coordinate with local citizen scientists; alternatively, university extension agents could serve as conveners and mediators of these regional collaborative efforts, and could also play a role in shaping state policies to encourage such collaborations.

Another way that ideas of entanglements may travel across scales is by people from places like Salmon Creek taking political action in regional, state, or national politics. Many changes in environmental policy have come about through action and advocacy by a relatively small number of citizens acting to correct local environmental harms. It may be that through engaging in collaborative watershed rehabilitation projects, and thereby developing relationships with local species, people would then organize to act politically at wider scales through legislative action, protest, or other means.

Limitations to collaborative approaches

There are several limitations to collaborative approaches that bear further analysis; I will briefly note two of them here. The first concerns specific regulatory or governance modes that follow from the Salmon Creek case; the second concerns replicability, and constraints that may hamper the application of similar processes in other localities.

First, compared to urban residents that I and others have studied elsewhere, I found that Salmon Creek residents described an awareness of watery entanglements among humans, fish, and the watershed, arising from an acute awareness of scarcity and extending to concern for other creatures. This awareness arose from a detailed local knowledge, of one's own water source, of neighbors' water use practices, and of local hydro-ecological cycles. Many residents expressed the idea that since local residents know more about local aquifers and streamflow than government regulators, they could self-regulate effectively; a minority thought that county or state regulation of well-drilling and pumping was necessary to keep streams wet in dry years. However, in the absence of collaborative monitoring or collective governance structures, it seems unlikely that all water users will individually regulate; indeed, in the extremely dry year of 2014, as many more individual wells dried up, dozens of residents drilled new wells, and many expressed concern that wells on neighboring properties would threaten their water supply. The 2014 California Groundwater Management Act allows the state to regulate groundwater in basins where local entities fail to prevent groundwater overdraft; the act may spur local entities to self-organize and regulate groundwater in order to avoid regulation by the state. However, Salmon Creek and most of the North Coast is in a 'very low priority' zone, and it is unlikely that state managers will target the region.

Second, I found among Salmon Creek residents—including ranchers, retirees, hippie descendants, and urban transplants—a refusal of economic reductionism and the 'fish versus farms' discourses that dominate water discourse statewide and regionally. This refusal seemed to arise from an ontological commitment to finding solutions that sustain salmon and agriculture as essential to local lifeways and culture. Members of the watershed council and the Gold Ridge Resource Conservation District described a series of community meetings early in salmon recovery planning where these differences got hashed out. In private landownership contexts, there is potential for collaboration among scientists and local landowners where there is convergence between agency and landowner goals, and rainwater harvesting and aquifer recharge can improve streamflow somewhat. However, no one doubts that there are hard constraints on how much more water can be extracted from local aquifers without driving salmon to extinction and, eventually, threatening agricultural livelihoods. Most residents believe that there should be limits to new development in water-stressed areas of the watershed. But those with large parcels want to maintain their right to subdivide and sell off their property for residential or vineyard development, and the county seems unlikely to regulate subdivision in the short term. This issue of private property thus poses a major challenge to rolling out entangled and collaborative commons governance strategies in Salmon Creek, and the dominance of private property regimes in the low-gradient habitats favored by coho and necessary to all salmonids suggests that replicability in other locales will at best be a constrained replicability.

The Gold Ridge RCD, the Occidental Arts and Ecology Center, and other project proponents argue that the rain tanks simultaneously increased water security for ranchers and rural residents and reduced their need to pump water from the creek. No formal monitoring schemes have been developed to date; no outside agencies monitor or enforce the compact that prohibits rain tank recipients from using well or municipal water for irrigation during the summer months. Some recipients of the Bodega rainwater tanks reported an increased sense of responsibility for and connection to local aquifers and waterways, but they did so without subsuming their private interests within the interests of the collectivity. In an "Ostrom-like" commons with collective governance arrangements determining how a resource is used, one would expect to see individuals perceiving collective benefits over individual ones; here I saw no evidence of such behavior.

Conclusion

Small coastal watersheds—and their intermittent streams—are important sanctuaries for salmonids, and foster collaborative management if given regulatory autonomy to develop recovery strategies. My ecological study of dissolved oxygen dynamics confirms but also explains late-summer mortality documented by local creek-walkers and agency biologists. My research question was strengthened by my incorporation of local residents and researchers 'partial perspectives' into my approach, and I may not have come to some of these cross-cutting conclusions without those conversations. Frictions and resonances between local knowledge and scientific regulation create new conceptions of human roles in multi-species worlds. Attention to ontological differences among indigenous, local, and scientific knowledge and management is crucial if we are to advance justice, sustainability, and interspecies reciprocity in a rapidly-changing world.

I see the idea of watershed entanglements and watershed collaborations as a way towards balance in how human society regards and uses water. Top-down water development has begun from a binary, where people extract water from "natural water systems" for human use, setting up potential for conflict between human and ecosystem uses. In a bottom-up approach that begins from interdependence, the water people use daily is seen as entangled with a multiplicity of living and nonliving things, and only arrives and recirculates via intra-actions among these elements. Although this difference may seem subtle, I think it is actually very profound, because it gives us a way to cope with extinction. As Deborah Bird Rose (2015) and Val Plumwood (2001) have noted, refusing to treat human and nonhuman deaths as separate opens a way to consider our entangled responsibilities, and to engage in (nonverbal) dialog with other species and elementals. In an era where extinction's 'double death' (to use Bird Rose's phrase) threatens plants, animals, livelihoods, and cultural relationships, these entangled and collaborative approaches challenge technocratic modes of governance.

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Appendix: Supplemental figures for "Quantifying abiotic habitat characteristics to determine thresholds for salmonid over-summer survival in intermittent streams"

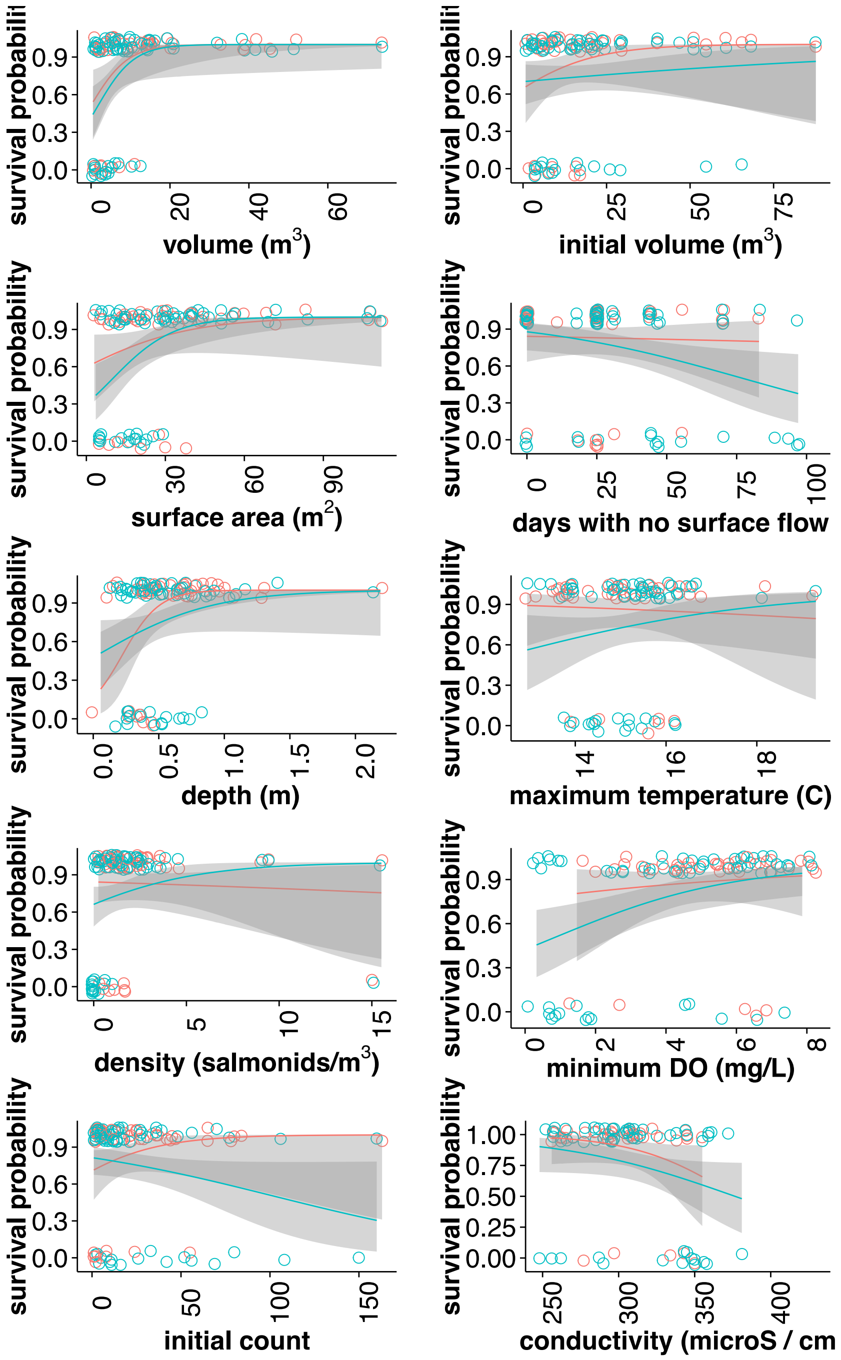


Figure SI 1: Univariate logistic regression of abiotic variables against survival status (shown in jittered points, turquoise for steelhead and pink for coho). The days of disconnection plot suggest that periods of disconnection shorter than ~15 days are correlated with a high probability of survival while at longer than 80 days without

surface flow, the probability of survival is ~ 0.4 for coho and 0.2 for steelhead; both species survive only in large, spring-fed sanctuary pools. At shorter than15 days without surface flow, the probability of survival is 0.75 for both species. Between 15 and 75 days, survival probability declines approximately linearly with increasing duration of intermittent conditions for both species. A threshold response to depths < ~0.4 m suggests that predation by avian and terrestrial predators may be responsible for mortality in shallow pools. The density plot suggests that steelhead survival probability increases with density, but the result is strongly influenced by just a few points, so we excluded this variable from GLM and classification tree analysis.

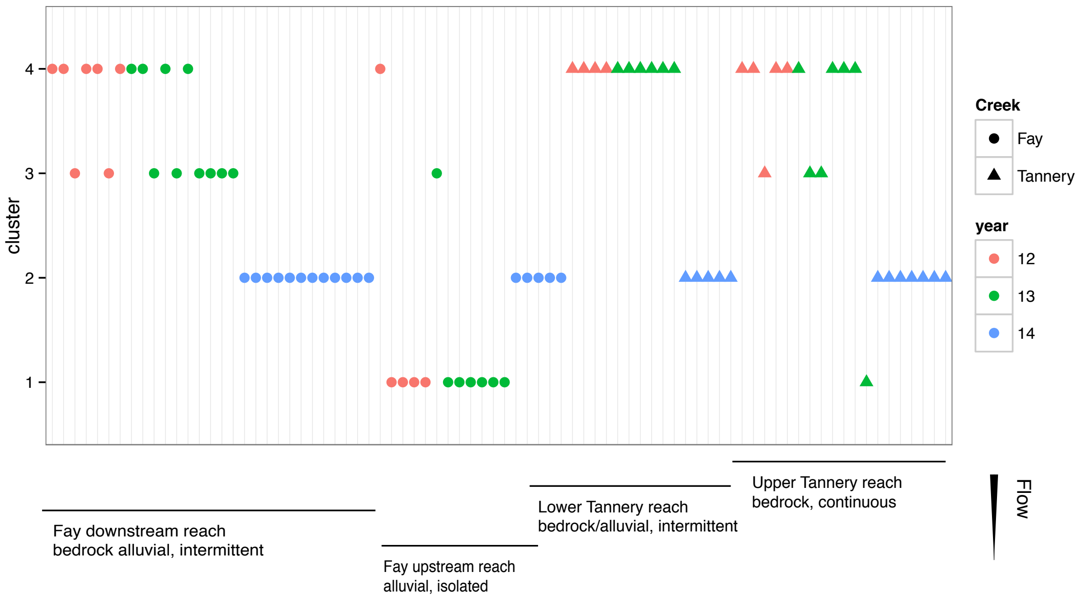
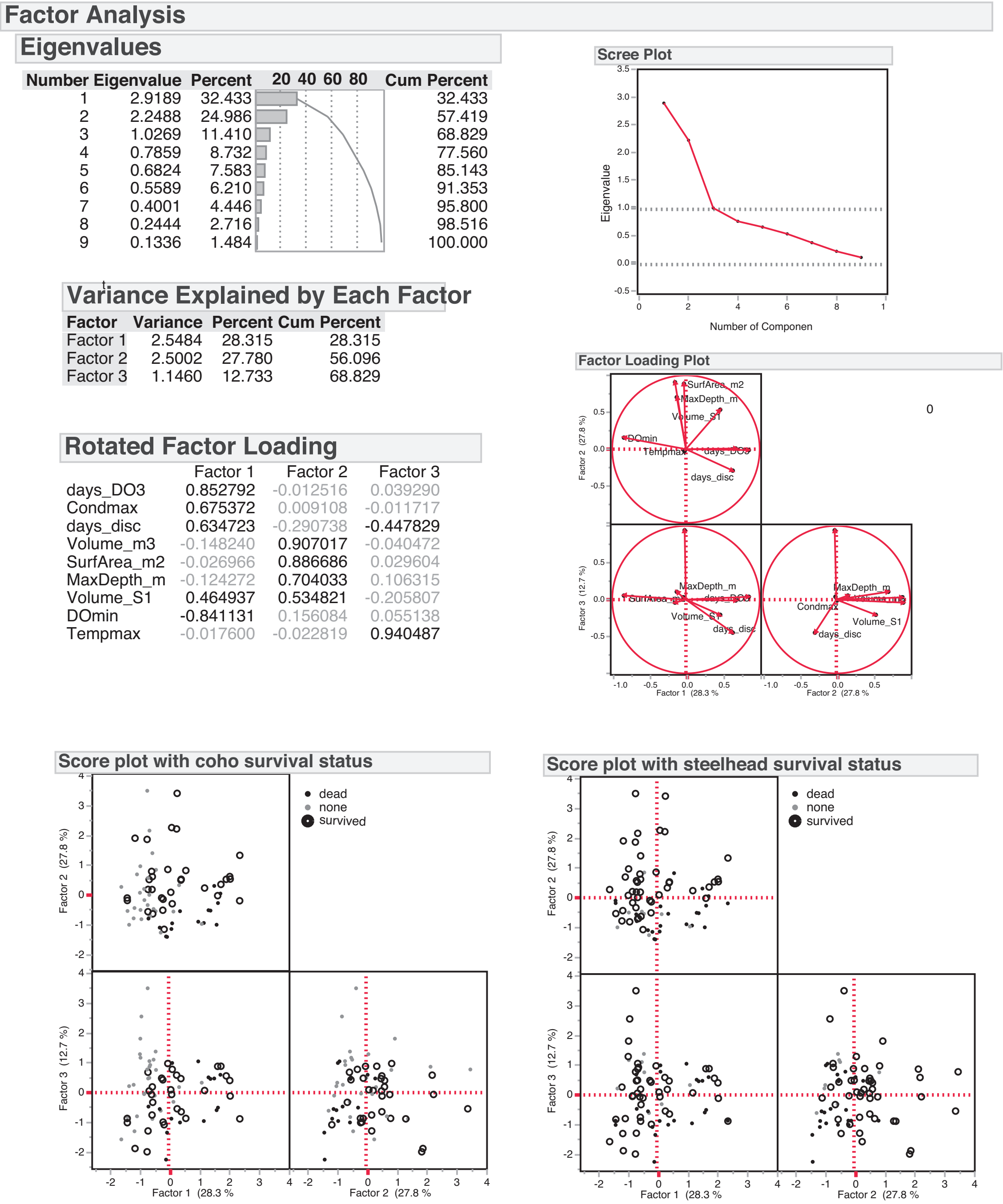


Figure SI 1: Dotplot of K-means cluster analysis (k = 4) using late-summer abiotic factors. Cluster 1 contains almost all of the pools in the isolated reach, characterized by deep alluvium, where many pools go dry. Cluster 2 contains all of the pools from the intermittent and continuous reaches in 2014, the extraordinary drought year, in which pools became disconnected earlier and many developed lethal DO concentrations. Cluster 3 contains the largest pools. Cluster 4 contains pools that are small and only intermittent for a short period.



Factor Analysis

Eigenvalues

Number	Eigenvalue	Percent	Cum Percent
1	2.9189	32.433	32.433
2	2.2488	24.986	57.419
3	1.0269	11.410	68.829
4	0.7859	8.732	77.560
5	0.6824	7.583	85.143
6	0.5589	6.210	91.353
7	0.4001	4.446	95.800
8	0.2444	2.716	98.516
9	0.1336	1.484	100.000

Variance Explained by Each Factor

Factor	Variance	Percent	Cum Percent
Factor 1	2.5484	28.315	28.315
Factor 2	2.5002	27.780	56.096
Factor 3	1.1460	12.733	68.829

Rotated Factor Loading

	Factor 1	Factor 2	Factor 3
days_DO3	0.852792	-0.012516	0.039290
Condmax	0.675372	0.009108	-0.011717
days_disc	0.634723	-0.290738	-0.447829
Volume_m3	-0.148240	0.907017	-0.040472
SurfArea_m2	-0.026966	0.886686	0.029604
MaxDepth_m	-0.124272	0.704033	0.106315
Volume_S1	0.464937	0.534821	-0.205807
DOmin	-0.841131	0.156084	0.055138
Tempmax	-0.017600	-0.022819	0.940487

Scree Plot

Factor Loading Plot

Score plot with coho survival status

Score plot with steelhead survival status

Figure SI 2: Results for Varimax rotated principal components analysis for abiotic habitat data for three factors. The first PC axis is determined mostly by water quality parameters, the second by October volumetric factors, and the third by temperature and disconnection time. June volume is influential in the first two factors. Both steelhead and coho mortality was associated with long disconnection period, shallow pools, low DO, and high conductivity.

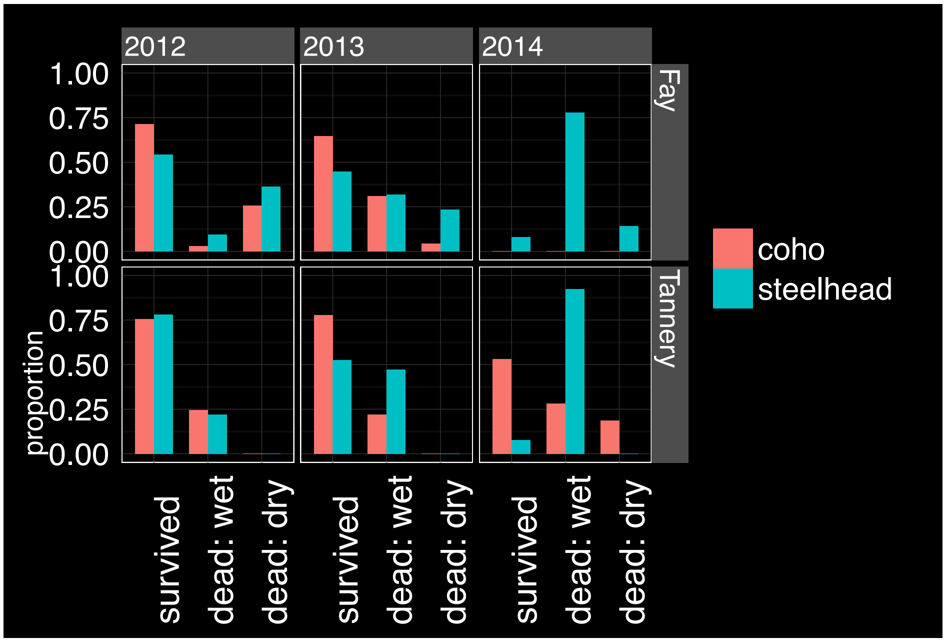


Figure SI 3: Proportion of pools where fish survived, died while the pool remained wet, or died because of complete pool desiccation.

	coho averaged GLM	steelhead averaged GLM
Intercept	3.58 (7.55)	3.33 (6.00)
max depth	1.03 (0.69)	0.26 (0.55)
log (surface area)	0.19 (0.65)	0.96 (0.79)
log (October volume)	0.69 (0.57)	0.54 (0.57)
June count	0.54 (0.64)	3.56 (2.52)
max conductivity	−1.14 (0.70)	−0.69 (0.59)
min DO	0.62 (0.74)	0.13 (0.74)
max temperature		1.26 (0.66)
squared max temperature	0.37 (0.54)	
days disconnected	−0.05 (0.67)	−0.07 (0.68)
year	−0.55 (1.01)	0.17 (1.10)
log (June volume)	0.64 (0.58)	−0.47 (0.67)
June count x log (surface area)	1.03 (0.74)	−0.51 (1.82)
June count x min DO	−0.78 (0.97)	0.74 (2.19)
June count x days disconnected	0.37 (0.78)	−0.64 (1.96)
Num. obs.	38	38

Table 1: Summary of averaged models for steelhead and coho over-summer survival

Table 2: Variable importance in coho multi-model inference

	importance
max depth	0.966
max conductivity	0.833
June count	0.773
min DO	0.429
log (June volume)	0.412
log (surface area)	0.369
squared max temperature	0.349
year	0.284
June count x log (surface area)	0.211
days disconnected	0.197

Table 3: Variable importance in steelhead multi-model inference

	importance
June count	1
max temperature	1
max conductivity	0.745
log (surface area)	0.611
log (June volume)	0.421
max depth	0.230
min DO	0.196
days disconnected	0.193
year	0.172
log (October volume)	0.158
June count x log (surface area)	0.099

Table 4: Random Forest: coho average importance

	abiotic factor	predict dead	predict survived
1	MaxDepth_m	23.377	21.707
2	Volume_m3	19.445	20.727
3	SurfArea_m2	17.207	17.191
4	DOmin	-3.666	2.421
5	Condmax	0.763	5.335
6	count1	-2.548	3.637
7	days_disc	1.748	4.887
8	Tempmax	0.144	1.449

Table 5: Random Forest: steelhead average importance

	abiotic factor	predict dead	predict survived
1	SurfArea_m2	28.836	22.665
2	Volume_m3	18.666	18.407
3	MaxDepth_m	12.391	7.170
4	Condmax	10.469	7.281
5	DOmin	15.142	8.032
6	Tempmax	4.390	-0.286
7	days_disc	8.683	1.169
8	count1	1.453	2.528

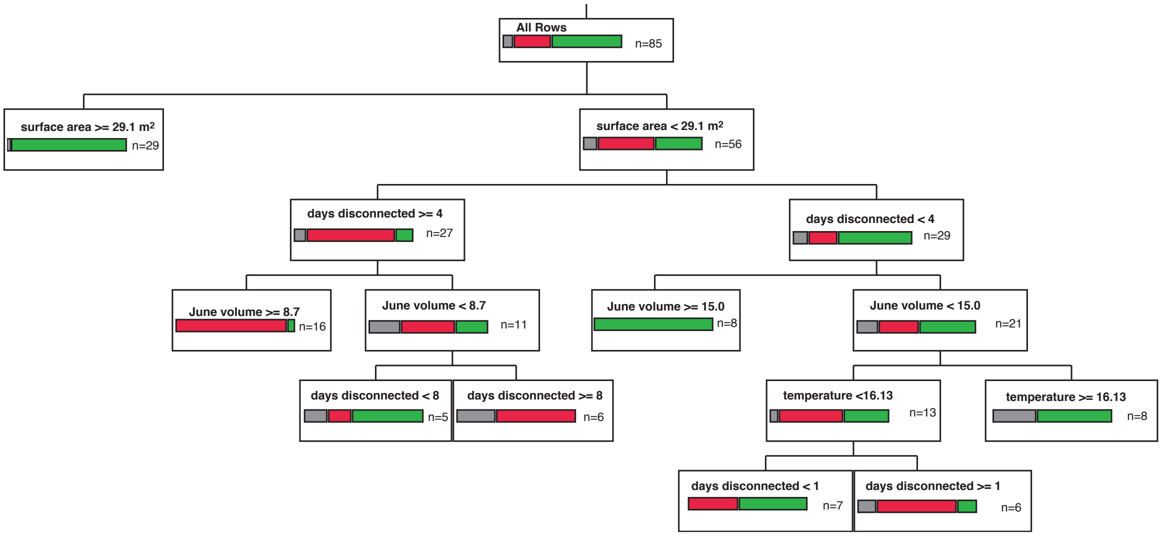


Figure SI 4: Classification tree for steelhead survival, with splits indicating threshold levels of different abiotic variables. In medium and small pools (< 29.1 m^2) steelhead survived only in pools disconnected less than 8 days. In these smaller pools, increased early-summer volume is correlated with survival, and temperatures greater than 16 degrees C also were correlated with survival.

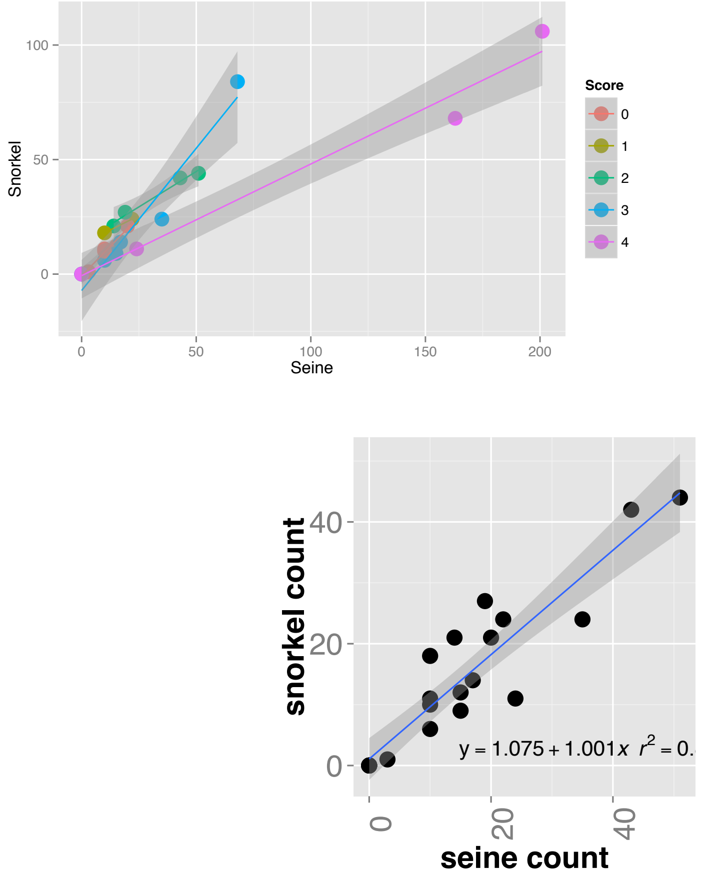


Figure SI 5: Regressions of seine and snorkel counts. The top plot shows all data and separate regressions by score, which indicates the number of factors that impede detection (e.g. high counts, large pool, large woody debris, low visibility). The bottom figure shows a regression for the small pools, with a good fit and accurate detection.

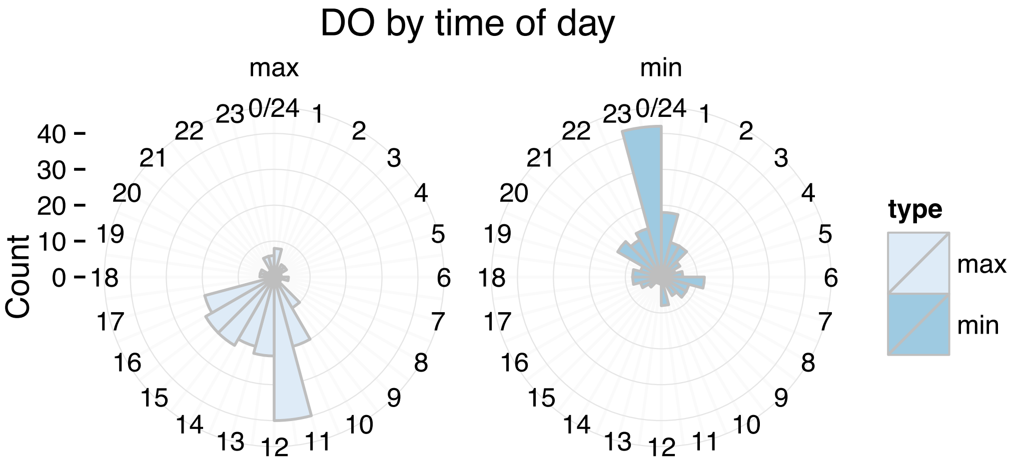


Figure SI 6: Rose plot showing the modal time for minimum and maximum DO values for the isolated pool sonde in 2013. Maximum DO occurred most frequently between 11:00 and 12:00, while minimum DO values occurred just before midnight. This modal hour varied among pools, and was used in regressions between hourly DO and minimum DO (Figure SI 6).

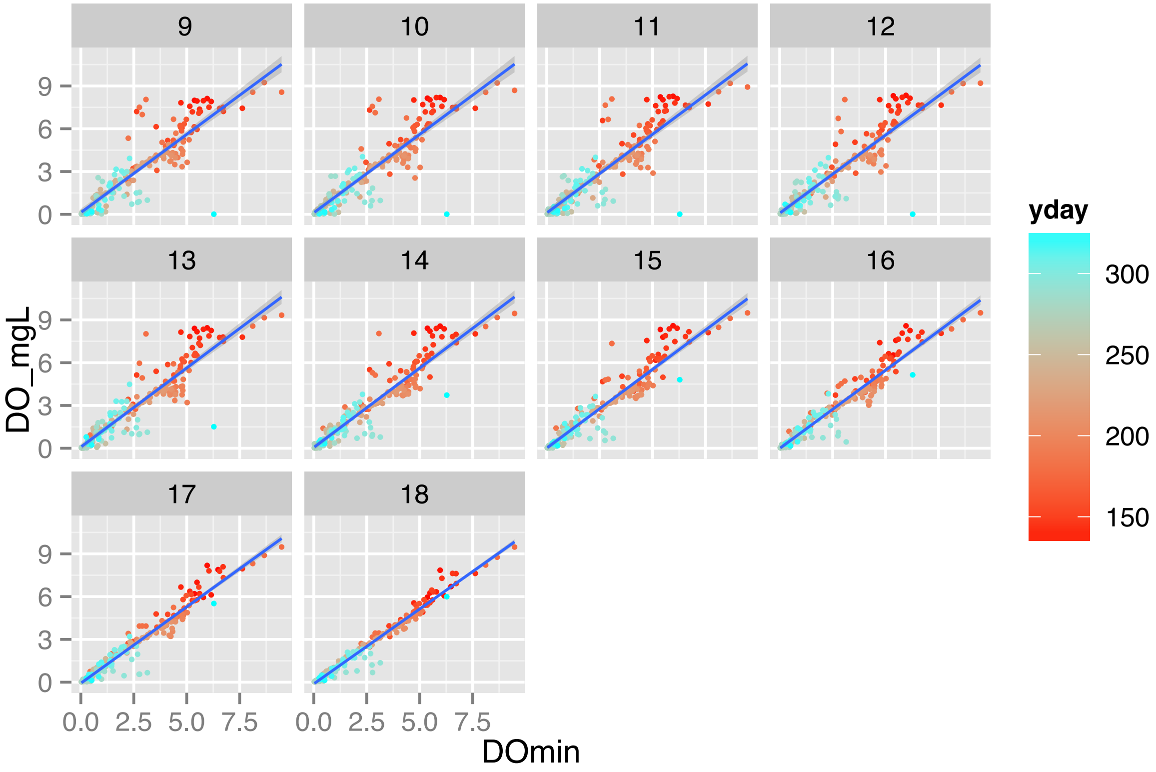


Figure SI 7: relationship between DO values at a given hour and daily minimum DO for the isolated pool sonde in 2013. The slope and intercept of the regression lines differed among reaches; these values were extrapolated to pools with similar characteristics based on the k-means cluster analysis (Figure SI 2).

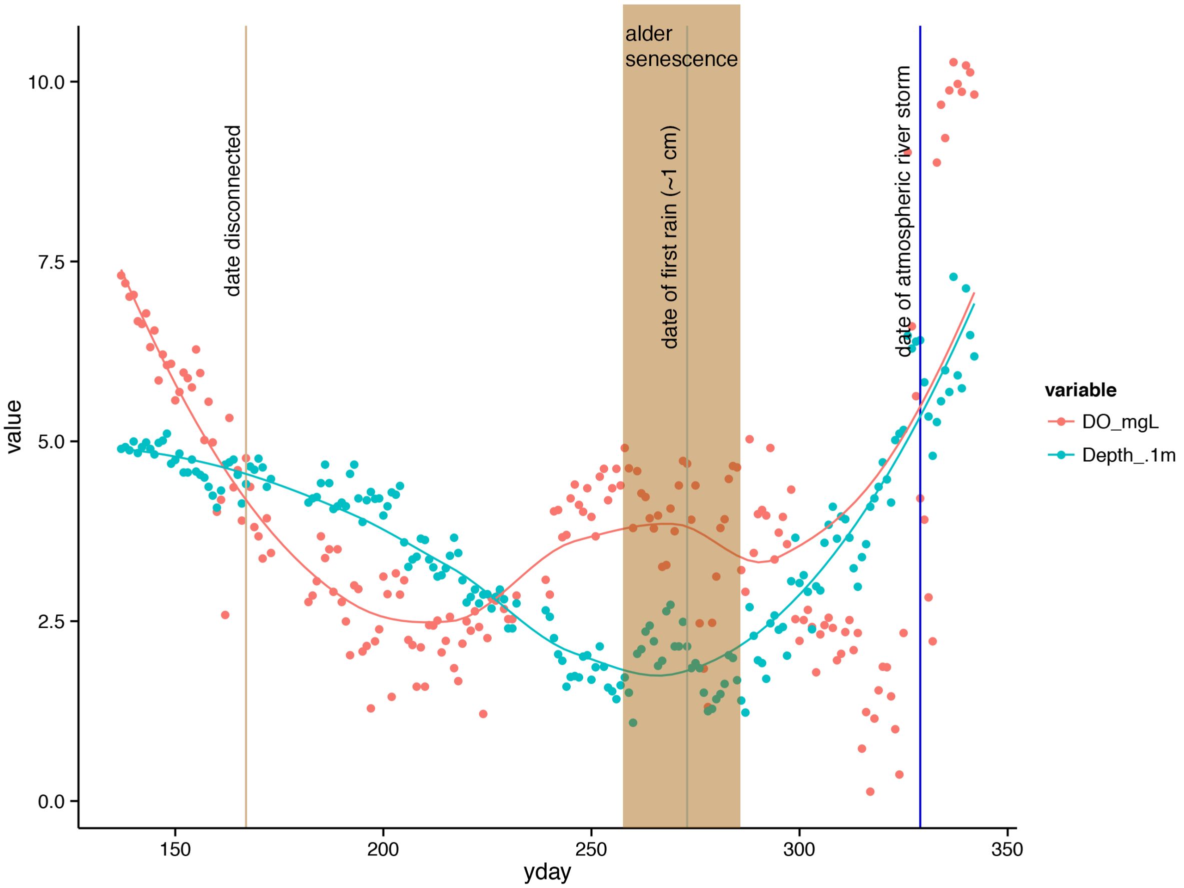


Figure SI 8: Depth and DO from the isolated spring-fed pool in 2014. Vertical lines indicate the date of disconnection, first light rain, and large atmospheric river storm. The the period of riparian tree senescence, indicated in tan, corresponds with an increase in water depth, and may signal a riparian pump effect.