

# NOAA Technical Memorandum NMFS



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## A FORWARD-LOOKING SCIENTIFIC FRAME OF REFERENCE FOR STEELHEAD RECOVERY ON THE SOUTH-CENTRAL AND SOUTHERN CALIFORNIA COAST

David A. Boughton

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U.S. DEPARTMENT OF COMMERCE  
National Oceanic and Atmospheric Administration  
National Marine Fisheries Service  
Southwest Fisheries Science Center

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## Abstract

1. To identify promising recovery opportunities for steelhead, I outline a conceptual framework focusing on self-organization of three key entities: steelhead, stream systems, and climate.
2. Anadromous steelhead probably facilitate innovative evolutionary change and provide biotic insurance against population extirpation, relative to fluvial trout that do not migrate to the ocean. Anadromous fish also have a natural fecundity advantage over fluvial fish. Recovery should focus on rehabilitating stream systems so that existing *O. mykiss* populations can express the anadromous life-history trait while inhabiting natural habitats. This is preferable to raising anadromous fish in hatcheries, which will tend to produce fish adapted to hatcheries.
3. Stream systems are dynamic conveyers of water and sediment that tend to self-organize silt, sand, gravel and boulders into characteristic forms based on maximum flow resistance. This process operates relentlessly, so that channel morphology may quickly re-organize in response to externally imposed constraints such as certain types of dams, levees and fish ladders. Over time this reorganization tends to eliminate function of infrastructure. At the same time, in freely-adjusting channels the self-organization process tends to spontaneously produce steelhead habitat, such as pool-riffle systems in low-gradient areas and step-pools in steeper areas.
4. Many strategies have the potential to release both the adaptive capacity of steelhead and the sustainability of hydrological services for people. Setback levees can potentially allow streams to self-adjust in ways that sustain fish habitat and provide amenities to people. Off-channel dams combined with certain kinds of diversion dams can pass both steelhead and sediment, the latter producing beneficial channel morphologies downstream. Existing natural capital, such as groundwater storage basins or reconnected floodplains, can potentially support sustainable hydrological services with low construction and maintenance costs. Institutional “lock-in” and other transaction costs can impede the implementation of these strategies.
5. Rapid climate change is the new normal, for the foreseeable future. Existing water infrastructure, as well as many concepts of environmental restoration, are based on the assumption of a stationary climate. This assumption is obsolete.
6. Past emissions of greenhouse gasses constitute a prior commitment to at least a century of change. Structural uncertainty about climate change involves a “fat-tail problem,” in which rational assessment of an uncertain future inevitably gets dominated by non-negligible worst-case scenarios. In a fat-tail context, conventional cost-benefit analysis is deeply misleading.
7. Due to structural uncertainty in the climate system, social-ecological systems will be better prepared for the future if they design for resiliency to whatever comes, rather than anticipating some particular future. Future precipitation patterns are particularly uncertain. The resiliency paradigm suggests that ecological scientists should consider being designers, rather than predictors.
8. Some predictions for the future appear somewhat reliable. Computer simulations agree that the Mediterranean wet-winter/dry-summer pattern will probably continue. Basic physics indicates that coastal areas will be more stable climatically than inland areas, due to the proximity of the ocean. Mountains will continue to be resources for generating orographic precipitation.
9. Climate stabilization requires net-zero greenhouse gas emissions, which involves a global-scale assurance problem that has yet to be solved. Solving an assurance problem about a public good involves establishing sufficient mutual trust to sustain ongoing cooperative behavior among actors who are free to cooperate or not. In California, controversies about water and stream corridors also tend to involve assurance problems about public goods. Learning how to routinely solve assurance problems involving fluid public goods would obviously be very valuable.
10. Game theory suggests that collective-governance of public goods is most sustainable when stake-holders know they will have repeated interactions for the indefinite future. This creates incentives for reciprocity and cooperation and weakens, but does not entirely eliminate, perverse incentives. Reciprocity, leadership and accurate information can over time create trust and social capital that improves the efficiency of decision-making about shared goods and resources.
11. A focus on shared goals for the long-term future may be more likely to engage cognitive models that favor cooperation over conflict. Some success in this strategy has been achieved in river restoration in

other parts of the world. Consensus around a “guiding image” has been useful for coordinating the decision-making of large, diverse groups of people, even when engaged in restoration of large river systems with half-century planning horizons across international boundaries.

12. Self-organized systems are expected to have emergent properties that cannot be completely anticipated. Over time, shared decisions will need to be

revisited to adapt to and learn from unanticipated events. The history of adaptive management and governance has included many failures. “Strategic” adaptive management, which focuses not on changing the status quo, but on achieving some future shared goal, has had some success and appears more promising. Like the “guiding image” approach in river restoration, it appears to invoke cooperation in stakeholders by focusing on their long-term future together.

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## Introduction

Steelhead (*Oncorhynchus mykiss*) occur in stream systems of the southern and south-central California coast (Swift *et al.*, 1993; Boughton *et al.*, 2005) but have been placed on the US Endangered Species List due to population declines (Busby *et al.*, 1996; Good *et al.*, 2005). Recovery of steelhead requires the improvement of abundance, productivity, diversity and spatial structure in a series of populations distributed broadly throughout the various biogeographic regions of the coast (Boughton *et al.*, 2007; McElhany *et al.*, 2000). Because the intent of the Endangered Species Act is “to provide a means whereby the ecosystems upon which endangered species and threatened species depend may be conserved” (16 U.S.C. §§1531§2(b)), the basis for a species’ recovery lies in its natural habitats and the processes that maintain those habitats over both the short and the long term.

Steelhead depend on a diverse series of marine and freshwater habitats to complete their lifecycle. Although this complexity in itself creates a challenge for recovery, the nature of the fish’s various freshwater habitats adds another layer of challenge. Interaction of water flow with topography and sediments is the central organizing process that generates and maintains habitats in stream systems (Stanford *et al.*, 1996; Ward *et al.*, 2002; Thorp *et al.*, 2006). As a result, the ecosystem mechanisms that maintain freshwater steelhead habitat are highly responsive to both climate, which provides the water; and the condition of the terrestrial watershed, which feeds water and sediment into the stream system. In south-central and southern California, the climate is rapidly changing (IPCC, 2007; Moser *et al.*, 2009) and the watersheds are inhabited by 23 million human beings, who have extensively modified not just the watersheds but the stream systems themselves, as well as the dynamics of the water passing through both.

The situation may give the impression that recovery of steelhead populations is intractable, because watersheds cannot be restored to a pristine condition. But this may not be the most useful way to think about steelhead recovery. For though it is often true that people disrupt nature, it need not be inevitably true. But to assume it must be true will vastly limit options going forward.

It is possible to see recovery is as a technical problem, in which scientists and engineers identify and solve well-defined problems with habitat quality, stream functioning, or fish productivity. Obviously, this can be very useful. But there are fundamental limitations with this conceptual framework of disciplinary problem-solving (reviewed in Marshall, 2005). Indeed one could argue that in the Pacific Northwest and the Central Valley, the disciplinary framework has already been applied to salmon and steelhead conservation for 130

years, with decidedly mixed success (Taylor, 1999; Lichatowich, 1999).

A core problem appears to be that elements of complex systems often respond to technical solutions in ways that are unexpected and frequently undesirable (Wu and Loucks, 1995; Carpenter, 2002). Coupled social-ecological systems are no exception to this general finding (Liu *et al.*, 2007): Both people and nature inevitably adapt and conspire so that solutions to old problems engender new problems, apparently in infinite regress (*e.g.* Reisner, 1993; Lichatowich, 1999). Apparently, the problem of complexity cannot be solved (Carpenter, 2002; Carpenter *et al.*, 2009).

In short, the future stream systems of the south-central and southern coast will be neither pristine nature nor a flawlessly engineered system; neither vision is suitably broad. The stream systems of the future will be something new, an outcome of natural, cultural, and climatic processes, all of which are now rapidly changing in novel and complex ways. Perhaps it would be useful to adopt a conceptual framework that embraces this reality and is broad enough to allow novelty and complexity to have not just downside potential, but upside potential too.

Here I review steelhead recovery using a conceptual framework based on the ideas of C. S. Holling (2000; 2001), who views people and nature as a single system, exhibiting emergent properties, cycles of creative-destruction, and capacity for adaptation. Unlike the conventional scientific view, in this framework human understanding is fundamentally distinct from human control (Carpenter, 2002); unlike the pristine-nature view, it does not treat complexity as a black box to protect but as something with which to engage. People cannot themselves count on controlling a coupled social-ecological system, but with a suitable understanding they may be able to position themselves profitably with respect to the system’s inherent tendencies. As exemplified by the invisible “hand” of the market, or the natural “selection” of evolution, the inherent tendencies of complex systems are sometimes conceptualized as a kind of endogenous agency, which emerges from the system itself. This endogenous agency is often called self-organization (Levin, 1999, 2003; Keller, 2005).

Self-organization emerges from complex causal networks when certain pathways of causation begin reinforcing one another. Self-organization in this view is inherently unpredictable, but only partially so, and the key is in framing the issue most usefully to take advantage of unpredictability, as a form of adaptive capacity. In other words, saying that things are fundamentally irreducible and unpredictable is only a way of saying that the future is always, to some extent, open-ended. Perhaps that is a good thing.

But only perhaps. Whether the open nature of self-organization suits the needs of people, or any other



particular species, is another question entirely, and the answer is always provisional in this framework. The problems of the future are different from the problems of the recent past. But it is a corollary that the opportunities of the future are different from the opportunities of the recent past, too. And so the perspective of self-organization should clarify what are, and what are not, opportunities going forward. By most accounts this future is going to be quite different from the past, in terms of climate, human culture, and ecosystem structure. The past generally serves as a default frame of reference for thinking about the future, but a new frame of reference is needed, one that is explicitly forward-looking (Carpenter and Folke, 2006). Here I attempt to outline what science has to say about this forward-looking frame of reference.

The motivation to consider steelhead recovery from a broad perspective stems from the realization that there is no meaningful way to discuss the science of steelhead recovery without fully embracing its many intricate connections with the human population of the region and the climatic changes now underway. More so than many species, these fish embody John Muir's claim that "When we try to pick out anything by itself, we find it hitched to everything else in the universe," (Muir, 1911, entry for July 27), and it is unscientific to pretend otherwise. Therefore, this review is intentionally broad rather than detailed, and it makes an attempt to identify and describe the essential nature of key processes (climate, stream systems, human interventions), rather than make a comprehensive list of their effects.

As such, I have been forced to grapple with scientific literatures unfamiliar to me. A poor conceptual framework for the commerce between disciplines can apparently lead to huge intellectual inefficiencies that do not serve society particularly well (Benda *et al.*, 2002; Thompson, 2009). Rather than attempt comprehensive reviews, I have simply highlighted findings that address the issues raised within the chosen framework of self-organization.

Most ecologists believe that ecological systems are hierarchically structured (O'Neill *et al.*, 1986; Frissell *et al.*, 1986; Wu and Loucks, 1995; Holling, 2001), and thus possess the property of near-decomposability (Simon, 1962, 1973). This means that particular components of a self-organizing system can be understood themselves as a self-organizing system, loosely coupled with the larger entity, and themselves composed of smaller components, also loosely coupled. Thus one can get meaningful insight by looking at pieces of nature, "carved at the joints," provided the apparent joints are well-chosen and the larger system and smaller components are not forgotten. The components I focus on here are the steelhead themselves, the stream systems they inhabit, and the climate.

## Steelhead

The rationale for saving species from extinction is that each species has unique capabilities. This is true regardless of whether you view their value as intrinsic or instrumental: species are not "things" but a lineage in the ongoing process of life. The various Pacific salmonids take this to a further level. Their remarkable homing ability provides a focusing force for evolutionary processes, so that salmonids in different regions tend to become locally adapted to the environmental character of that region (Waples, 1991).

The steelhead populations in the coastal ranges of California embody a particularly potent form of this focusing, with each stream basin supporting a genetically divergent population (Clemento *et al.*, 2009; Garza *et al.*, 2004). Specimens from the early 20th Century show a classic genetic pattern of isolation-by-distance (J. C. Garza, personal communication), usually interpreted as evidence for a long-term balance between the creative process of local adaptation; and the dispersive process of inexact homing (commonly called straying). We can view this arrangement as a biotic innovation generator, in which individual populations probe for useful innovations (via genetic drift, recombination, and natural selection), and dispersing fish communicate the innovations among the basins, where they can be combined with other innovations from elsewhere.

Evidently, this generator of adaptive creativity was inadvertently set adrift by the activities of people during the 20th Century, though much of the raw data known as genetic diversity still appear extant in the remaining *O. mykiss* populations (Aguilar and Garza, 2006). Much of this diversity, or creative potential, is locked up in populations of the fish known as rainbow trout, the form of the species that completes its life cycle in freshwater rather than migrating to the sea (Clemento *et al.*, 2009; Boughton *et al.*, 2005). Populations presumably continue to innovate, but the communication of innovations, by way of steelhead migrating to the ocean and dispersing to new basins, has been profoundly disrupted; and without steelhead we cannot expect *O. mykiss* to innovate as they once did. They are suffering a creative block.

That is one reason to specifically recover steelhead, despite the widespread occurrence of their conspecifics, the rainbow trout. It is the evolutionary reason. But steelhead also play an even more fundamental role, as a biotic form of insurance for the rainbow trout. Life can be precarious. For example, tree rings show that the Southwest has suffered at least 4 multi-decade droughts since the year 800 A.D., of far greater magnitude than anything in the historical record (Cook *et al.*, 2004). Yet somehow the species got through these episodes and today is found in nearly every watershed that is at all suitable for it.

It seems unlikely that this could have happened without steelhead to recolonize the watersheds from which the species got extirpated by drought. Because of ocean-going steelhead, extirpation, at least at the population level, is not forever. It can be reversed by steelhead recolonizing a creek system, as they have done in San Mateo and perhaps Topanga Creeks over the last few decades (Hovey, 2004; Tobias, 2006).

But the steelhead themselves did not persist because they spread innovations, or provided insurance. They persisted because the steelhead life-history pattern, of going to sea and returning, was an effective method for making more *O. mykiss*. It is, or was, a strategy with high fitness, in the technical jargon. In fish, body size means eggs. A typical female rainbow trout might attain a length of 35cm, enabling her to produce 1800 eggs annually, whereas a medium sized steelhead female at 60cm can produce over 3½ times that number (Shapovalov and Taft, 1954). Each of these eggs produces an environmental probe of sorts: a small fish probing to find a successful pathway through to adulthood and reproduction, and one can clearly see that in a time of uncertainty, the more probes the better. These fish are well suited to accompany us as we adapt to the period of profound uncertainty in climate and landscape that is upon us for the foreseeable future (Moser *et al.*, 2009).<sup>1</sup>

These probes are not just numerous; they are open to possibility. Figure 1 is a schematic of the diversity of life-history pathways believed to lie within the competence of this species in this region. It can perhaps be contrasted with the much smaller diversity of pathways within the competency of coho salmon *Oncorhynchus kisutch* (e.g. See Fig. 2 in Fujiwara, 2007), a species that cannot colonize further south than the coniferous forests of Santa Cruz County. *O. mykiss* also have a broader potential to occupy different parts of stream networks compared to coho salmon (Buffington *et al.*, 2004; Burnett *et al.*, 2007).

To describe this open potential of *O. mykiss*, biologists often say the species is “opportunistic,” a word with negative connotations. Perhaps biologists are annoyed that *O. mykiss* are so hard to predict and to

model. But this inability to be boxed into a model is really the point. The fish are entrepreneurs.

In our region, *O. mykiss* populations are still found in most of the stream networks in which steelhead historically occurred, though many now consist solely of rainbow trout, due to blockage of ocean migration routes by dams, etc. (Boughton *et al.*, 2005). There are very good reasons to believe that they still retain the capacity to express the anadromous life-history pattern (Boughton *et al.*, 2006), though the quality of the adaptation (ability to survive in the ocean) is probably being gradually eroded, as has been observed in a comparable situation in Alaska (Thrower *et al.*, 2004b,a; Thrower and Joyce, 2004).

Thus, despite the current rarity of the anadromous form in this region, there appears to be time and opportunity to restore it to many creeks and rivers, by providing the existing *O. mykiss* populations the opportunity to once again express the anadromous life-history. But providing these opportunities sooner is definitely better than later. Otherwise, the anadromous ability will probably deteriorate gradually due to evolutionary processes associated with dis-use.

There do appear to be some non-negotiable aspects of recovery. Though the species seems generally quite entrepreneurial, in a range of genetic, ecological, and physiological senses, still it appears to have little scope for adaptation to much warmer water temperatures (Myrick and Cech, 2004; McCullough *et al.*, 2009). It needs cool water. Successful spawning is constrained by the need for well-oxygenated gravel, which sets a limit on the kind of sediment and hydrological regimes in which the fish can prosper. Finally, *O. mykiss* apparently require a flow regime in which fry, after emergence, have a safe period from flooding (Fausch *et al.*, 2001), probably due to evolutionarily constrained habitat requirements of the early juvenile stage (McCullough *et al.*, 2009). Migratory access, clean gravel, and low scour for juveniles—this species is sensitive to the descending limb of the hydrograph.

If recovery should fail, the loss of steelhead would attenuate the entrepreneurial probing for opportunity that the species pursued in the past. The insurance function would be lost, opening a process of irreversible cumulative extinctions of trout populations in the region, and evolutionary innovations would no longer be communicated among the populations that remain. The remaining populations of resident *O. mykiss* would likely continue on the path of gradual differentiation and perhaps even speciation (Hoelzer *et al.*, 2008), but with a vastly reduced ability to innovate and survive in a changing environment.

Perhaps one can start to see in a general way how to assess the relative promise of various recovery actions. Some actions, like removing barriers to migration, or diversifying the types of habitats that young fish can use, can have clear benefits to restoring the

<sup>1</sup> Carpenter and Folke, 2006: 314: “Ecologists can help to create visions for the future that involve new approaches for the relationships between humans and ecosystems. Scenarios with positive visions are quite different from projections of environmental disaster. Doom-and-gloom predictions are sometimes needed, and they might sell newspapers, but they do little to inspire people or to evoke proactive forward-looking steps toward a better world. Transformation requires evocative vision of where we can go. In fact, we need multiple visions of better worlds to compare and evaluate the diverse alternatives available to us... Although we cannot predict the future, we have much to decide. Better decisions start from better visions, and such visions need ecological perspectives.”

evolutionary processes that allow the species to track the changing environment. In contrast, something like a production hatchery, while boosting the number of fish, actually shifts the steelhead system away from adaptation to rivers and creeks, and toward adaptation

to hatchery conditions. The innovation-generating mechanism takes the fish further and further from being able to sustain itself in the wild, and closer and closer to relying on huge inputs of effort from humans, in perpetuity.

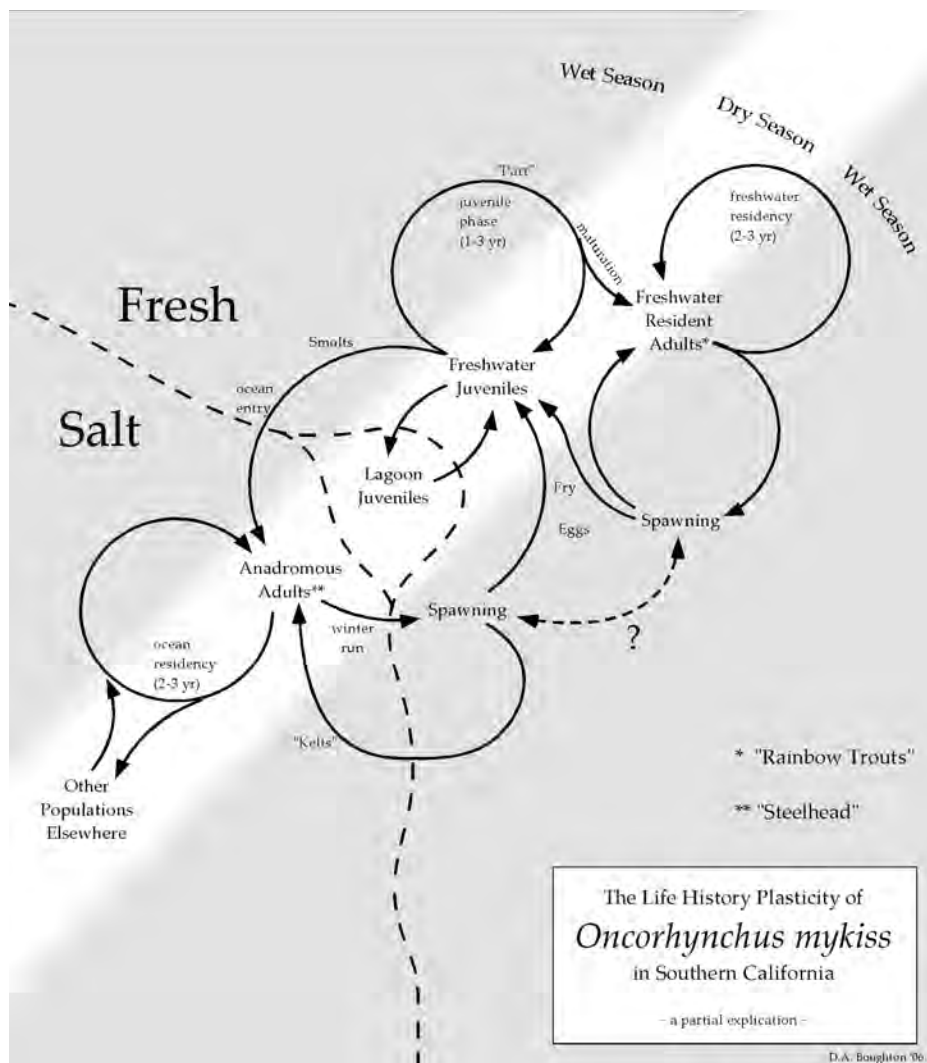


Figure 1: Life-history pathways believed to lie within the competence of *O. mykiss* in southern and south-central California

## Stream Systems

Networks of creeks, rivers and estuaries can be viewed as self-organizing features of the landscape (Rodríguez-Iturbe and Rinaldo, 1997). This is true whether or not they have been dammed, channelized, or protected in National Parks. Some of the most visible aspects of self-organization are physical, having to do with movement of water and rock particles of various sizes. As originally configured prior to the development of water resources, coastal river basins took in rain from the atmosphere in a distributed and intermittent manner. Some of this water was discharged to the sea immediately, moving sediment particles in the process; this is known as run-off, resulting in high-flow events. Some water was stored for awhile in the soil, where a fraction was used by plants and transpired to the atmosphere; and a fraction was released gradually to the drainage system, where it made its way to the ocean in the form of baseflow.

### Stream Network Evolution

Over time this draining-and-eroding process literally breaks up and transports mountains, generating a dendritic network of channels in the process. The structure of the dendritic network changes slowly, tending to move toward a state in which it minimizes and equalizes the energy expenditures of water across the entire network (Rodríguez-Iturbe *et al.*, 1992). This trajectory of increasing drainage efficiency plays out relentlessly over tens of thousands of years and is what gives stream networks their most characteristic features: a dendritic branching structure; longitudinal profiles that are concave (steepest in the headwaters; gentlest in the lowlands); and a pattern of erosion in the headwaters, sediment transport in the middle regions of the network, and alluvial deposition in the lowlands (Montgomery, 1999). The tendency for drainage networks to evolve toward this sort of self-maintaining dynamic endpoint, often called an “attractor,” is ongoing and relentless.

But strictly speaking, this vision of stream evolution only applies to areas with a very homogeneous geology (Montgomery, 2001). The coastal ranges of California are really quite complex (Harden, 2004). They push back against these conductive and erosive processes with rock types of various hardness and uplift, vegetation of varying character, and human settlements of varying pattern. There are many features of stream networks that persistently resist the trajectory toward increasing drainage efficiency, with effects lasting from decades to millennia.

One such feature is abrupt reductions in steepness (channel gradient) where tributaries join mainstems, leading to persistent deposits of large rocks, logs, and the like that can serve as important habitat features for

fish (Benda and Dunne, 1997). If cleared out by people, such deposits tend to re-establish themselves, at least if the up-tributary sediment and wood supply still exists. Over the very long term, well beyond human lifetimes, the abrupt gradient change smooths out as the mountain range erodes away.

Another such feature is knick points, or “bumps” in the longitudinal profile (Mount, 1995), which the self-organizing process of drainage and erosion is always attempting to smooth out by depositing sediment above and below the knick point, while eroding away the knick point itself. Whether deposition or erosion dominates depends on sediment supply versus erosiveness of the knick point.

Dams can be viewed as extreme examples of knick points, specifically designed by engineers to withstand the erosive force of streams (Mount, 1995). Therefore, the stream smooths them out by dropping sediment in the slack waters behind the reservoir. In southern California erosion is so great that this dropping process occurs at human timescales rather than over millennia (Warrick and Mertes, 2009). A flood pulse entering a human-built reservoir slows down and drops much of its sediment load, which is one reason why you sometimes see meadows at the head rather than the foot of aging reservoirs. Provided that dam operations do not alter the water levels in a certain way, a riparian habitat can develop that is suitable for the endangered southwestern willow flycatcher (Graf *et al.*, 2002).

The steelhead is not so fortunate as the flycatcher: the dam blocks its migration, impounds its spawning gravel, and stores the gravel for decades out of reach. In some areas the steelhead innovated: they now treat the reservoir like the ocean. This has been observed, for example, in the Juncal Reservoir on the Santa Ynez River, and in Old Creek Reservoir in San Luis Obispo County. But these steelhead can no longer communicate evolutionary innovations to populations in other basins, nor receive them from other populations, nor provide a form of biotic insurance.

People also self-organize around a dam. A system of engineers, craftsmen, governance, and taxpayers develops to maintain the dam’s resistance to the stream’s power and channel it into a set of services: water supply; flood control; perhaps electricity, all with a strong emphasis on reliability (Roe and Van Eeten, 2001). Other people may construct homes in the former floodplain below the dam, and thus develop into a constituency (Marshall, 2005), vested in channeling society’s resources into the dam’s continued functioning. People and other species all self-organize around the dam in a characteristic way, though with many variations depending on many factors such as geological context, biological history, the interactions of the people involved, and so forth (Gumprecht, 1999).

Eventually, as experience has shown in southern California, the dam fills with rocks, sand and gravel.

Many people lose interest in it then. Either people or water begin removing the dam and its sediment load; and a new process of social and ecological self-organization initiates along a different trajectory (Graf, 2003).

### Stream Channel Behavior

Within the self-organized drainage network, other self-organization emerges at finer levels of resolution and faster time scales. During peak flows, the steeper, narrower headwater streams have greater power to move large objects, which only the largest boulders can resist. Downstream, the channel is a little less steep and a little wider, and big rocks being bounced along the bottom finally come to a stop. Farther still and the gravel comes to a stop, then sand, then mud (Brummer and Montgomery, 2003; Church, 2006). These objects interact with each other, and with the water, creating characteristic forms. In steep sections of the stream profile, large rocks lock together into big channel-spanning steps caulked by fine gravel, forming step-pools (Montgomery and Buffington, 1997). Farther down, cobbles get bounced around randomly, and farther still, gravel collects into convex bed deposits called bars and riffles, alternating with deeper spots called pools at a characteristic spatial rhythm of 5 to 7 channel-widths.

Here again, streams seem to be iteratively inching toward a self-sustaining dynamic endpoint of maximum dissipation of energy or maximum flow resistance (Nanson and Huang, 2008; Eaton *et al.*, 2004): high flows keep re-arranging rock particles until the re-arrangements converge on a self-perpetuating dynamic pattern. Much of this can be understood from the stream-power principle: steeper, deeper flows can move more and larger pieces of sediment (Buffington *et al.*, 2004). For example, in steep areas the water moves so powerfully during high flow events that most everything gets washed away, except for large boulders. Step pools form because the high flows keep jostling and rearranging the boulders until they eventually get locked together into a stable dam-like configuration (Chin *et al.*, 2009).

Lower down in the network, in the alluvial sections where water moves more slowly and fine sediment gets deposited over the long-term, the self-organization depends on whether the sediment is mainly in the form of particles suspended in the water; or in the form of bedload—larger gravel or rocks that the water bounces or slides along the bottom of the channel (Mount, 1995). Bedload-dominated flows produce complex systems of braided channels and islands, such as the Santa Maria River in Santa Barbara County; whereas suspended-sediment dominated flows produce single channels with distinct banks and floodplains (Kondolf *et al.*, 2002).

The size of the channel—its width and its incision into the floodplain—tends to adjust to the prevailing pattern of flows, so that eventually, over-bank flows (floods) spill into the floodplain an average of every two years, slowing down as they do so, and thus dropping large amounts of fine sediment on the floodplain (Eaton *et al.*, 2004; Eaton and Millar, 2004; Doyle *et al.*, 2007). The transient storage of water in floodplains tends to attenuate the declining limb of peak flows, giving steelhead more time to migrate in these very flashy systems; it also produces a large surface area for infiltration to groundwater. The channels themselves tend to develop meander patterns, as slight undulations are accentuated by sediment being deposited in the slow moving water at the inside of a bend and eroded by the fast moving water at the outside of the bend. This meandering process coils up the channel, then straightens it, then recoils it in an ongoing process.

Although stream behavior is dominated by the physical processes of water and sediment movement, some groups of living organisms play key roles in shaping river behavior through their effect on those physical processes. Terrestrial vegetation plays a key role by its attenuating effect on water and sediment movement before it gets to the channel. It also affects summer baseflows, both by helping to slow runoff from storm events and diverting it into groundwater storage; and by using a significant amount of that groundwater for transpiration. Summer baseflows of creeks in our region dwindle on hot afternoons, when riparian trees suck out water to continue photosynthesizing during the heat; by next morning the baseflows are up again. I have even observed reaches that are dry in August to be flowing in September, before the first rains but after the cooling of the weather.

Riparian trees, growing along the channel, play some additional key roles, by shading the stream and keeping the water cool enough for steelhead during the summer; by stabilizing banks and thus sometimes constraining movement of the stream channel toward its dynamic endpoint (or creating a new endpoint; Eaton and Millar, 2004; Eaton, 2006); and by dying and falling into the stream, where they can get lodged and create very robust local disruptions to flow that both dig pools and deposit gravel in close proximity, of much benefit to steelhead (Montgomery *et al.*, 1995). Even some mammals play key roles in some regions: notably beavers, who are being deployed by people in the Pacific Northwest as economical means to reverse the problem of channel incision (Pollock *et al.*, 2007).

Riparian vegetation also supports a community of plant-eating insects, some of which fall in the water and provide food for juvenile steelhead (Rundio and Lindley, 2008); it also discards leaf detritus etc. into the stream, which supports an in-stream community of invertebrates for steelhead to feed on.

The tendency of stream systems to construct floodplains that get regularly flooded has been noticed by the people of California. One response has been upstream dams, which in the process of impounding water also impound sediment, which starves the channels below. Such starving creates “hungry waters” (Mount, 1995) that eat at the floodplain and deepen or widen the channel over time. Another response of people has been channelization, the construction of levees, concrete sluices, and so forth, intended to eliminate the behavior of channels by deepening, smoothing, and straightening, thus speeding the movement of high-flow events out to sea.

The streams still adjust, however: they may deposit sediment where water slows just above or below the channelized section, thus creating a need for further channelization; or the loss of transient floodplain storage may increase the peak flow, creating a need for greater downstream flood control (Mount, 1995; Gumprecht, 1999). At the same time, the equilibrium of channelized conditions may prove unstable: a small increase in sediment supply may cause deposition in the channelized section, which roughens it and slows flow, leading to a cycle of more deposition and more slowing, eventually creating a need for an upgrade of the channelization.

Thus at the scale of years, a channelized stream is a device for local flood control, but over the longer term it has the potential to create demand for more channelization, a positive feedback loop between flow regimes, human land-use patterns, and public works projects (Mount, 1995). While this allows the settlement and farming of the floodplain, it has various costs. With respect to the fish, the increase in water velocities and shortening of the high flow event likely makes upstream migration of steelhead less successful. With respect to people, the floodplain is disconnected and its fertility is no longer replenished by water and silt. The natural stream and many of its species and amenities are gone. And a large financial investment in the construction and maintenance of robust flood control structures is required into perpetuity, because the stream is going to be attempting to re-establish its inherent behavioral tendencies forever.

### Steelhead Recovery and Hydrological Services

In the distinction made above between stream evolution—a slowly unfolding process—and stream behavior—a faster process unfolding on a human timescale—I have used the labeling system of Brierley and Fryirs (2005). But this distinction is actually an illustration of the principle of near-decomposability in a hierarchical system (Simon, 1962, 1973). The stream system is near-decomposable because the geometry of the stream network evolves so slowly that it can be approximated as a constant that constrains stream be-

havior to move toward particular endpoints within a faster frame of reference. For example, steep channels tend to develop toward step pool systems, whereas flat channels tend to develop flood plains; but valley steepness itself changes much more slowly, generally at geologic time scales. The problem of complexity means that it is not necessarily practical to predict, say, step-pool formation based on first principles. But the property of near-decomposability means that we can use inductive reasoning to predict the conditions under which we expect to see step-pools form and maintain themselves over the long term.

An example of the inductive approach is a regression model in which a snapshot of channel evolution is treated as a fixed constraint and is used as a predictor (independent variable) for emergence of particular channel behaviors (dependent variable). Buffington *et al.* (2004) describe just such an example, using channel constraints and regression to predict the parts of a stream network in which the dynamic endpoint is spawning gravels. These self-sustaining dynamic endpoints are often called “channel potentials.”

One useful scientific contribution might be to develop this sort of reasoning into a complete analysis system, which could then be applied to particular basins by anyone interested in steelhead recovery or stream restoration. Something like this is being done in the Pacific Northwest (*e.g.* Naiman and Bilby, 1998; Beechie and Bolton, 1999; Beechie *et al.*, 2008), though this system is not directly applicable here because our arid Mediterranean climate creates different sorts of stream systems. Something like this is also being done in Australia, in the River Styles framework (Brierley *et al.*, 2002; Brierley and Fryirs, 2005, 2009; Chessman *et al.*, 2006), for an arid climate similar to California’s, but without the focus on salmonid recovery. Hierarchical conceptual tools are also being developed for other parts of the world as well, especially in Europe under the water framework directive (Orr *et al.*, 2008; Newson and Large, 2006). These are parts of the world where people are thinking very hard about how to integrate the nature and culture of stream systems.

Some adaptation of these various systems to the California situation should prove useful for matching stream restoration efforts to appropriate channel potentials (*e.g.* Trush *et al.*, 2000). Brierley and Fryirs (2009) calls this matching principle “Don’t fight the site,” and Beechie *et al.* (2010) outline a general set of principles for process-based restoration. The fundamental idea of channel potentials is to align human aspirations to derive value from stream corridors with the inherent tendencies of the stream corridors themselves.

Alterations such as dams and channelization have often pushed stream corridors far away from their inherent tendencies. But if the broader channel constraints retain their original creative potential, flow and

sediment regimes will continually try to move the stream back toward its natural behaviors. This is why the self-sustaining endpoint of a dam is not necessarily water storage but may be a meadow instead.

One can perhaps begin to see that in people's quest to secure hydrological services, some strategies attempt to push the stream's behavior further from its inherent tendencies than others. And it also seems likely that distance the stream is pushed will be related to the level of investment required to construct and maintain a given hydrological strategy over time. Just on first principles, strategies that secure services by only moderate pushing seem likely to survive longer before losing function, to require less expensive maintenance to maintain function, and to be more consistent with the creative potential of natural stream behaviors (Trush *et al.*, 2000).

At the same time, strategies that push the stream less far from its self-sustaining endpoint are likely to engender less uncertainty about the future behavior of the stream. Its emergent behavior under the new, imposed constraints cannot really be predicted from first principles. But it may be somewhat predictable, via inductive reasoning, from the behavior of other existing streams under similar constraints.

This kind of reasoning is starting to influence a new generation of design strategies for securing hydrological services. These strategies include setback levees (which partially reconnect floodplains to channels) (Dwyer *et al.*, 1997; Gergel *et al.*, 2002; Larsen *et al.*, 2006), off-channel dams (whose diversion points are designed to pass certain water and sediment pulses), and constructed step-pools (to stabilize steep channels running through residential neighborhoods) (Chin *et al.*, 2009). The two key ideas are 1) that the self-adjusting behavior of streams can be viewed as a strength to be built upon, rather than a problem to be solved; and 2) that this requires inductive reasoning from constraints to emergent behaviors (mutually-reinforcing processes), rather than attempts to predict complex behaviors from first principles. The problem of complexity cannot be solved, but nature's empirical solutions can sometimes be reconciled with human designs (Trush *et al.* 2000).

Salmon biologists are already firmly behind this vision of the road forward, emphasizing that the only realistic solution to the West Coast salmon crisis is to restore natural processes to streams (Schindler *et al.*, 2008; Waples *et al.*, 2009; Beechie and Bolton, 1999; Reeves *et al.*, 1995; Bisson *et al.*, 2009; Benda *et al.*, 2007; Burnett *et al.*, 2007; Ebersole *et al.*, 1997; Pess *et al.*, 2002; Naiman and Latterell, 2005). The fish were adapted to the original natural stream behaviors, whereas the new channel behaviors in highly-modified systems tend to favor exotic fish species over salmonids (Stanford *et al.*, 1996; Marchetti *et al.*, 2004, 2006). At the same time, a century's worth of technical solu-

tions, such as hatcheries and highly-engineered fish ladders, have not proven terribly effective (Lichatowich, 1999; Taylor, 1999). It is as if people systematically destroyed a free-standing system of salmon production, so that they could try to recreate it themselves at great effort and cost. There was evidently a resilient set of mutually-reinforcing natural and social processes that sustained this trajectory, driving inefficient substitution of technical capital for natural capital. Taylor (1999) named this process a "durable crisis."

In summary, streams self-organize due to processes that are powerful and unending, and these can be viewed as a problem or as a form of foundational natural capital. Past strategies for securing hydrological services involved "armoring" against these processes, but going forward, strategies seem more likely to be economical and sustainable over the long term if they accommodate these processes somehow, which in turn better accommodates steelhead recovery. There is a confluence of diverse interests here, so to speak, but with many details to be worked out, involving a range of scientific fields and stakeholders. Perhaps an attractive guiding image for the future is this vision of usefully rehabilitated stream behaviors that support steelhead and other biota over the long term, efficiently sustain hydrological services for people, and intelligently sidestep the self-organizing layer of sediments that gets relentlessly conveyed down the region's creeks and rivers.

Realizing this vision of rehabilitated river systems, though attractive, is a change in direction from past practices. Such changes are not necessarily easy to make: they involve what political-economists call "transaction costs" (Hanna, 2008; Marshall, 2005). These include the substantial efforts required to change social institutions and to effect social learning about the possibilities opened up by the new direction.

Ecologists frequently lament these transaction costs without calling them such, and see them as intractable. One promising method for lowering transaction costs is to apply the concepts of natural capital and ecosystem services (Brauman *et al.*, 2007; Nelson *et al.*, 2009; Levin and Lubchenco, 2008; Daily and Matson, 2008). These concepts explicitly account for the contributions of natural stream behaviors (and other ecosystem processes) in sustaining human welfare (Lubchenco, 1998; Daily and Matson, 2008). The characterization and valuation of such services is difficult and necessarily imperfect; and so ecosystem services have tended to be undervalued or ignored in the past. This has introduced cost-benefit distortions in systems designed to secure such services.

At the same time, the potential for engineered systems to completely control hydrological systems has tended to be overvalued, by assuming that the problem of complexity could indeed be solved. Engineered systems are typically designed for control within defined

parameters, but the likelihood for ecosystems to exceed those parameters may often be unknowable. Perhaps the most unknowable thing will be the capacity of the encompassing social-ecological system to adapt, when the engineering solution reaches the end of its key design parameter, its useful lifetime. When an engineered solution reaches the end of its lifetime, not only are its services lost, but also a deferred or overlooked problem becomes someone's actual problem.

Often, the overlooked or deferred problem seems to be coarse sediments. Every time a dam creates reliable water provisioning, or a levee creates usable real estate, the sediment-reworking patterns of the stream network are altered, and sediment that used to end up doing one thing, such as creating channel habitat or constructing a floodplain, is quite likely to end up doing something else, or doing the same thing in a different part of the stream network. Or something, to someone, perhaps even in the far future after the dam fills with sediment. Due to the self-organizing capacity of stream systems, water allocation, floodplain allocation, and sediment allocation are part of the same uncertain social-ecological process, though some of the stakeholders may not realize that they are stakeholders, or may be unborn. Those people impacted by altered

sediment allocation may have a shared interest with steelhead, for whom the altered channel morphology tends to mean a loss of suitable habitat.

The valuation distortions for ecosystem and engineered services are now widely recognized, and perhaps they could be characterized and maybe even estimated using a system of inductive reasoning within a hierarchical framework (see Box 1, next page). Cowling *et al.* (2008) describe a framework for "mainstreaming" ecosystem services, meaning a procedure for bringing them into mainstream decision-making by stakeholders, etc. This is an inherently social process of valuation and decision-making, but science has a role in developing meaningful methods.

There are potentially many other such scientific contributions that could emerge with time, within the context of ecosystem management discussed later in the report. Some of the largest transaction costs will involve convincing people to give the dynamic stream corridor more room in which to behave and more water with which to behave. But if people have an interest in the future, then they have an interest in securing the adaptive capacity of stream systems to respond usefully to that future. There appears to be substantial option value in securing natural capital (Lubchenco, 1998).



### Box 1: Transaction Costs

Marshall (2005) provides a useful economic framework for implementing this program of characterizing transaction costs. In his view, mainstream economic methods ignore them, focusing instead on market efficiency, usually Pareto optimality, under the assumption that resource systems produce value at a stable equilibrium determined by the law of diminishing returns. This aids precision in cost-benefit analysis but distorts accuracy, so that cost-benefit analyses are precisely wrong. Indeed, the assumption implies that social-ecological systems cannot be reconfigured to reflect updated understanding, thus obtaining increasing returns on investment over time.

In short, mainstream methods apparently attempt to solve the problem of complexity by assuming perfect foresight by people and a particular form of stability in ecosystems, neither of which are particularly realistic. Thus, they condemn social-economic systems to getting “locked into” paths (Marshall’s term) with increasingly poor returns on investment (unsustainable paths). They do this simply by denying that such systems can learn and adapt as the system produces new emergent (unexpected) patterns of behavior. They deny that updated understanding of natural capital can lead to increasing returns on investment.

Through iterations of these distorted cost-benefit analyses, people take over more and more responsibility for self-organization of the entire system, requiring great effort (and investments) to maintain systems of environmental control, which engender unforeseen consequences, bringing about need for more control and more construction of capital to make up for lost natural capital, etc. This creates a self-reinforcing loop that consumes time and money just to maintain services at previous levels.

Marshall (2005) lays out a broader economic framework, in which management and governance institutions adapt as they learn. Unfortunately, this sort of adaptation involves not just the Pareto optimality of deal-making, but also “transaction costs” related to social learning, issues of trust and leadership, and so forth. These transaction costs do indeed cost time and effort (and thus money) in the short term, but they have the potential to create great returns on investment in the long term. Unfortunately, these near-term costs are not easily estimated. In short, the process by which people adapt social institutions has emergent properties whose net monetary cost is hard to estimate from first principles. Marshall (2005) proposes that transaction costs be estimated using hierarchically framed induction. Case studies of adaptation would empirically measure transaction costs and use the estimates to infer costs for other stakeholder groups in comparably structured situations.

To bring these abstract concepts down to Earth, consider Habitat Conservation Plans (HCPs). HCPs essentially lie within the framework of Pareto optimality. They attempt to negotiate the optimal tradeoff of short-term take versus long-term viability of species on one side, and economic benefits versus opportunity costs on the other. This is conventionally done by drawing geographic boundaries between lands open for development and lands preserved for nature, typically also involving commitments to manage the preserves at some level.

But to negotiate this consensus point, the HCP must assume reasonably good foresight about the costs and benefits of both sides of this tradeoff, and a stable ecological system. These structural assumptions create the conditions for diminishing returns, and thus a negotiated compromise point (“price”) that is stable over time.

The structural assumptions are approximately true for terrestrial ecosystems of reasonably large geographic expanse and stable climate. Space structures the interactions of most wild plant and animal populations, so a large enough geographic expanse can approximately capture the entirety of these interaction processes indefinitely into the future, thus matching the assumption of a stable ecosystem. Similarly, stability is approximately true if the preserve is large enough to encompass the spatial extent of disturbance processes (*e.g.* large enough to retain unburned areas in a typical wildfire). Some additional stability needs, for migration connectivity with other reserve systems, can be met by adding wildlife corridors to the basic preserve design.

Stream systems are different: their processes are strongly translational, dominated by flows of water and sediment across watersheds, down channels, in and out of flood plains, and so forth. Responding to the unfolding nature of these processes, to sustain both natural communities and hydrological services for people, is ongoing. A one-time, negotiated solution creates “lock-in” costs if more efficient solutions are later found, or if the ecosystem itself changes but the solution cannot efficiently adjust. So HCPs create “certainty” at the expense of adaptability. But the “certainty” is not certainty, because reality itself (the social-ecological system) may undermine the conditions necessary to maintain the arrangement. At the same time, the solution creates “transaction costs,” which involve the difficulty in renegotiating an agreement that was thought to be settled.

It is as if we demanded that all corporations always make profits in a highly dynamic economy, and had no way to adjust if they didn’t.

## Climate Change

Climate is the overall pattern of water, wind, and heat that animates the Earth's atmosphere. Diverse lines of evidence indicate that climate is changing, and the change is accelerating, due in large part to activities of people (Karl and Trenberth, 2003). This rapid change is expected to continue at least for several human generations. To our immediate descendants, the idea of a stable climate will likely appear very foreign, or at least very nostalgic.

At the same time, a stable climate is something to which current agricultural systems, water provisioning systems, and flood-regulating systems, are all finely tuned. As such, stable climate is an assumption that underlies California culture. Steelhead in turn possess adaptations that evolved in the past climate, and in a sense embody a comparable assumption of a future climate similar to the past. Climate change requires a new set of assumptions. Below I sketch an overview of the essential elements of climate change, with the intent of clarifying this new set of assumptions.

### More Energy in the Climate System

When sunlight strikes the Earth's surface, it transfers energy and warms it so the Earth glows, not visibly, but in the far infrared of the spectrum. This infrared radiation produces a flow of energy back out into space, similar to any other celestial body that is hotter than absolute zero.

The remarkable thing is that the Earth's atmosphere is quite transparent to much of the incoming sunlight, but is significantly opaque to the outgoing radiant energy being emitted by the Earth. The opacity is due in part to atmospheric gasses, such as carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and water vapor (H<sub>2</sub>O) that absorb the infrared light, heat up, and re-radiate at still lower energies (NRC, 2005). This new form of radiant energy propagates in all directions, including on out into space, but also back toward the surface of the Earth, where it heats the surface still more, producing more glowing, and more heating. It sets up a dampening feedback loop that results in a stable temperature gradient, from the warm surface to the frigid outer atmosphere. The feedback process is nicknamed the greenhouse effect. Without it the Earth would be about 33° C cooler than it is (Karl *et al.*, 2009).

Greenhouse gasses—the atmospheric gasses that generate this heating service—have been growing more concentrated in the atmosphere for the past two centuries. More than that, the growth is accelerating, mostly due to the burning of fossil fuels—which convert hydrocarbons stored in the Earth's crust into atmospheric CO<sub>2</sub>—but also due to a variety of other natural and anthropogenic processes (NRC, 2005; Pielke *et al.*, 2009). This accumulation of new greenhouse gasses has

profoundly changed the thermal budget of the Earth, in a way never before seen in human history.

No one is certain how this changed thermal budget will play out over the next century, or even the next few decades. As soon as one tries to predict more specific effects, one must take into account an intricate causal network of heat flow (*e.g.* in ocean currents and atmospheric movement of air masses), and its resulting effect on movement of water, which in the form of water vapor and clouds is itself a strong and intricate greenhouse agent.

The additional energy in the climate system only partly goes to heating it up; it also evaporates water from moist surfaces, including both the ocean and terrestrial vegetation. This increased evaporation drives a seeming paradox: one should expect both more droughts (caused by the drying of vegetation) and also more precipitation packaged into bigger storm systems (caused by the increased energy and water vapor in the atmosphere) (Karl and Trenberth, 2003). Overall, substantial water vapor can get mobilized by the greenhouse effect, in turn creating a bigger greenhouse effect and mobilizing more water and moving it around the planet; but water vapor also precipitates out of the atmosphere as rain or snow when conditions are suitable, thus decreasing the net effect. Water in the atmosphere thus exhibits dynamic spatial and temporal patterning that can locally amplify or dampen the greenhouse effect (Karl and Trenberth, 2003).

### Prior Commitments

Much of the Earth's surface is deep ocean, which makes up a truly colossal heat-storage reservoir due to water's high heat capacity and the ocean's enormous volume. Most of the increase in the greenhouse effect is currently being used to heat up the world ocean, and it will take awhile, perhaps about a century, for the world ocean to heat up to a rough equilibrium with the current heat-trapping capacity of the atmosphere (Solomon *et al.*, 2009). Without the world ocean the climate would be changing much more quickly. But the flip-side is that the existing heat-trapping capacity of the atmosphere, augmented over the past two centuries, has committed the Earth to at least another century of rapid climate change. This would be true even if humanity somehow managed to completely stop emitting greenhouse gasses in the next few decades, or even the next few days.

The world ocean is providing another great service to humanity, by absorbing some of the new CO<sub>2</sub> from the atmosphere and thus further slowing the buildup of energy in the climate system (the ocean is acidifying in the process, likely producing another cascade of effects). But this absorption service is tending toward an equilibrium and will diminish over time. Should humanity stop emitting greenhouse gasses in the next few decades, sometime in the 22nd century the global mean

temperature should plateau at a new level expected to last somewhere around 1000 years as various global pools of stored heat, CO<sub>2</sub>, and other greenhouse gasses find a new balance (Solomon *et al.*, 2009; Matthews and Caldeira, 2008). Of course, this is only a reasoned guess using simple projection models.

Various geo-engineering strategies are being discussed. Some of these seek to reduce the energy in the incoming sunlight, but these would still likely alter the world hydrological cycle, possibly increasing drought conditions globally (Hegerl and Solomon, 2009). Others propose to remove CO<sub>2</sub> from the atmosphere and put it in the ground somewhere, but the necessary magnitude of storage space, transfer infrastructure, and energy cost of such an effort appear to be enormous. Other proposed solutions apply new and existing technologies that substitute new energy sources and increase energy efficiency. These could potentially eliminate future greenhouse gas emissions, but they do not eliminate the extra greenhouse gasses already in the atmosphere, and additional gasses will be emitted while the transition to a new energy system is underway.

So a continuing global warming trend is pretty certain, though its speed, ultimate magnitude, and magnitude for some regions are all much less certain; as are most second-order effects such as changes in precipitation patterns, temperature extremes, droughts, and so forth.

One relatively certain second-order effect (because it follows so directly from the global warming trend) is the shrinking of seasonal snowpack in mountainous areas, which affects the water supply of 1/6 of the Earth's human population (Barnett *et al.*, 2005; Bradley *et al.*, 2006). This includes the population of California that is dependent on the Sierra snowpack (Hayhoe *et al.*, 2004; Moser *et al.*, 2009). Another relative certainty is the continuing role of the ocean in moderating coastal climates, due to its high heat capacity. Thus, coastal steelhead populations, even in the far south of California, appear to have a more predictable future than inland populations, which are vulnerable to faster and more extreme changes in climate. In other respects the future climate of California is difficult to foresee, though it is possible to use simulation models to make reasoned guesses.

### Unforeseeable

Paradoxically, a certainty about climate change appears to be the staying power of uncertainty. Apparently this would be true even if future greenhouse gas emissions were precisely known. The reason is that the climate system contains positive feedback loops, and positive feedback loops are inherently resistant to precise forecast (Roe and Baker, 2007; Knutti and Hegerl, 2008).

If humans emit enough greenhouse gasses to double the natural level of heat-trapping, calculations pre-

dict a warming of only about 1.2° C. But this modest warming appears almost certain to set in motion various chains of events that further increase the heat-trapping capacity of the Earth. These are called positive feedbacks. Other chains of events, known as negative feedbacks, may decrease the heat-trapping capacity of the Earth. Positive feedbacks amplify change; negative feedbacks dampen them. For the Earth climate system, the science indicates that positive feedbacks have a much greater magnitude (Roe and Baker, 2007).

One such positive feedback loop that is already well underway is the melting of arctic sea ice. White, the color of ice, is the color of well-reflected sunlight, and so white ice absorbs much less energy from sunlight than the darker green or blue color of melted seawater. The sea surface warms, sea ice melts to water, which absorbs rather than reflects more of the sun's energy, which melts more ice, which darkens the ocean more, so it warms faster, and so on in a positive feedback loop. The Arctic is observed to be warming this way.

There are other important feedback mechanisms in the climate system, but cloud and water-vapor feedbacks are perhaps the most volatile: heat evaporates water, which is itself a greenhouse gas, driving more energy retention, more evaporation, and so on. Some of the water precipitates back out of the atmosphere, thus diminishing the greenhouse effect. In the unfolding of these heating, evaporative, and precipitative processes, sets of positive and negative feedbacks will compete and co-evolve over time in ways that appear to be fundamentally unpredictable (Roe and Baker, 2007). The revving of this evaporative engine cannot be accurately predicted because it reinforces itself, and small uncertainties about feedback become large uncertainties about outcome (Roe, 2009).

The mathematics of feedback can be used to generate a probability distribution of outcomes in terms of mean global temperature. Unfortunately, there is a long fat tail on the side of extreme outcomes, such as global temperature increases of 6° C or more (Figure 2). This level of extreme outcome is broadly agreed to imply fundamental and catastrophic changes in the Earth's ecosystems (Schneider, 2009). Roe and Baker (2007) estimate the probability of such an event to be small but significant (on the order of 1% to 5% under doubled CO<sub>2</sub>, which is now a best case scenario for the future).

In this situation, traditional cost-benefit analyses (which achieve tractability by assuming thin-tailed distributions of costly events) are simply misleading (Weitzman, 2009). In particular, they radically underestimate the advantages of acting in a precautionary manner to ensure against the worst outcomes. Essentially, conventional cost-benefit analysis assumes that the continued existence of civilization is not worth very much (Weitzman, 2009). However, nations traditionally

treat existential threats of 1% to 5% chance as issues of national security.

The current scientific strategy for dealing with these uncertainties is to simulate climate with an ensemble of different models, each making slightly different assumptions and thus spanning a range of sensitivities to feedback (e.g. IPCC, 2007). A further simplification is to use an ensemble of only two models, choosing the most and least sensitive ones to bracket the range of potential outcomes (e.g. Hayhoe *et al.*, 2004).

The upper end of the bracket is occurs not at some known point in the fat tail, but at some spot chosen subjectively without reference to the fat tail. The fat-tail conundrum is that predictions from a bracketing framework are extremely sensitive to the way in which the fat-tail problem is approximated as a thin-tail problem. If the predictions do settle into some stable, finite range, it could easily be an artifact of scientific convention. Thus, bracketing is doomed to severely distort perception of costs and benefits by unknowable amounts.

But bracketing gives an idea of the broad middle in the distribution of outcomes (Figure 2). Within this broad middle, the ensemble of simulation models tend to agree on the continuation of California's Mediterranean pattern of wet winters and dry summers and the large multi-year variability that leads to cycles of wet years and dry years (Moser *et al.*, 2009; Cayan *et al.*, 2009). Ensembles also tend to agree about increased runoff and water availability in high latitudes (roughly north of 40° N), but significant decreases in water availability in some dry regions and mid-latitudes, including the semi-arid areas of the western USA (IPCC, 2007).

Geographically, California is positioned at the transition between these zones of net gain and net loss of water, and predicted future water availability is sensitive to model assumptions and emissions scenarios (Hayhoe *et al.*, 2004). Climate models appear to make a median prediction of about 10% loss of precipitation statewide by century's end, under the B2 emissions scenario (Cayan *et al.*, 2009), but there is enough scatter in the predictions that a significantly drier or wetter future are also reasonable expectations (Snyder *et al.*, 2002; Leung *et al.*, 2004; Hayhoe *et al.*, 2004). Of course, these expectations ignore the fat tail of bleak possibilities in Figure 2 and under the logic of Weitzman (2009), comprise a form of irrational optimism.

Models evolve, of course. About 10 years ago, the climate models of that time projected that southern California was likely to receive an increase in precipitation by as much as 100% by century's end (Lenihan *et al.*, 2003; Giorgi *et al.*, 1994; Stamm and Gettelman, 1995). This was soon revised in the next generation of climate models, which changed median predictions to a moderate loss of rainfall (c. -10% in Lenihan *et al.*,

2008, 2006; see also Seager *et al.*, 2007), but since that time new discoveries suggest the need to revise climate models yet again (e.g. Raupach *et al.*, 2007; Khatiwala *et al.*, 2009).

This is likely to be the situation for the foreseeable future: unfolding climate change that drives the updating of climate models, which leads to an ongoing revision of expectations for the future. Given the role of feedback loops in the global hydrological cycle, and California's geographic position in a transition zone, the water situation of California appears to be another example of irreducible uncertainty—in addition to the fat tail, there is an uncomfortably broad middle for a substance—precipitation—that comprises both a key resource and a key source of hazards.

Irreducible uncertainty implies that adaptation to climate change at the regional level does not really mean preparing for some expected change in, say, precipitation patterns. It implies that adaptation should emphasize building resilience to whatever may come (Pielke *et al.*, 2009). This could take the form of a drier future, a wetter future, or even the worst of both worlds, a drier future in which the precipitation that does arrive is packaged in bigger storm systems that pose bigger flood risks and less opportunity for groundwater recharge. Indeed this last one does seem a quite plausible outcome, due to the increasing energy in the climate system driving both evaporation and storm patterns.

Traditionally, the science of ecology has emphasized the prediction and explanation of ecological systems, but one can see that it might need to begin emphasizing the design (or redesign) of ecological systems (Kangas, 2004), including the design of management and resource-governance systems that are responsive to unpredictable change (Carpenter, 2002; Walters, 1997), but also the design of ecological systems that are robust or resilient to change (Levin and Lubchenco, 2008).

The behavior of stream systems will adjust to the new climate, however it unfolds, and this can be treated as a problem or as a key design element. The latter seems the smarter stance: The more humanity steps back and lets dynamic stream corridors adjust, the less vulnerable people will be to the new emergent behavior that unfolds. In a sense, a stream corridor that is free to adjust provides a kind of option value for people. It should also provide more latitude for designing productive stream habitats and getting viable steelhead populations back into the system.

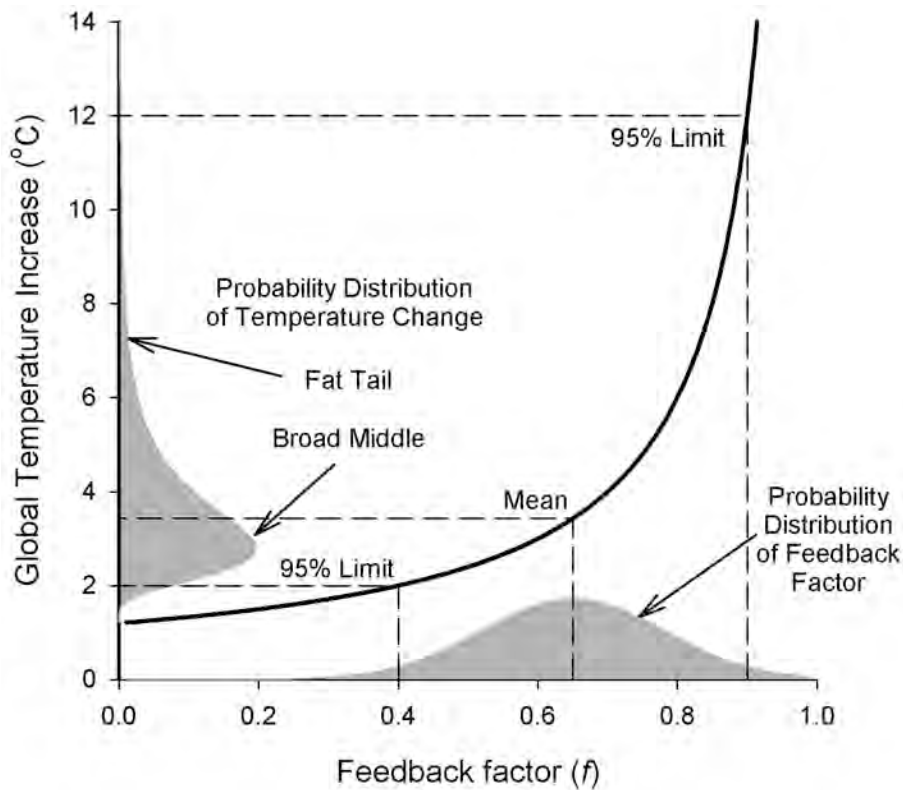


Figure 2: An illustration of the fat-tail problem, after Roe and Baker (2007). Direct forcing by anthropogenic gasses will likely be amplified by positive feedbacks in the climate system, as warming causes reduced albedo and release of additional greenhouse gasses to the atmosphere. Feedback analysis (Roe, 2009) gives a feedback effect of  $\Delta T = \Delta T_0 / (1 - f)$ , where  $\Delta T$  is the new global equilibrium temperature,  $\Delta T_0$  is the temperature increase due directly to anthropogenic gasses, and  $f$  is a “feedback factor” summarizing all the various feedback effects, both positive and negative. The upward-curving line illustrates this feedback relationship for  $\Delta T_0 = 1.2^\circ \text{C}$ , the current best estimate for doubled  $\text{CO}_2$ -equivalent.

Estimates of the feedback factor  $f$  will probably not see much refinement, until climate change toward the new equilibrium has progressed sufficiently to provide better data on the magnitudes of various emerging feedback pathways. Until then, estimates of  $f$  will have a broad probability distribution, portrayed by the gray curve on the horizontal axis (values are mean = 0.65, sd=0.13, taken from Roe and Baker, 2007).

Unfortunately, due to the upward-pointing curve, the corresponding probability distribution for the temperature response has a long fat tail at its upper end, as illustrated by the gray curve on the vertical axis. For the current best estimates (under doubled  $\text{CO}_2$  equivalent), the mean change is expected to be about  $3.4^\circ \text{C}$ . But the 95% confidence limits are lopsided, due to the fat tail: minimum change is about  $2^\circ \text{C}$ , but maximum change is on the order of  $12^\circ \text{C}$ . It is broadly agreed that the latter change would be well into catastrophic territory (Schneider, 2009).

Emergent behaviors of hierarchical systems can sometimes be predicted by inductive reasoning, if two conditions are in place (Marshall, 2005):

1. The controlling hierarchical constraints of the future system could be forecast, perhaps probabilistically.
2. Present-day examples of these constraints could be found and studied to determine the kind of finer-level system behavior they tend to produce.

For example, Buffington *et al.* (2004) used topographic constraints to infer which stream reaches would tend to develop channel morphologies suitable for salmon spawning; and Chin *et al.* (2009) outlined the channel constraints under which step-pool morphologies were likely to be robust to diverse hydrologic regimes. This sort of hierarchically-framed inductive reasoning could potentially be used to identify “management levers” and “design principles,” in which relatively confined efforts on the part of human beings have extensive long-lasting effects on the characteristics of a river system (*e.g.* Kondolf *et al.*, 2002).

If there are no analogous examples from which to learn via inductive reasoning, another strategy is to design management systems capable of learning about change as it happens in the system being managed. The term for this is “adaptive management,” but it is challenging to implement (Walters, 1997). Some key issues with adaptive management are discussed later in this report.

### Assurance

The ramping-up of energy in the climate system depends on the trajectory of future greenhouse-gas emissions, which in turn depends on how people use fossil fuels in the future, which is uncertain. To deal with this uncertainty, in 2000 the IPCC developed a series of scenarios of global human development, intended to capture a range of possibilities (Nakicenovic *et al.*, 2000). These scenarios ranged from a best-case scenario, resulting in 550 ppmv atmospheric CO<sub>2</sub> by year 2100, to a worst-case scenario of 970 ppmv atmospheric CO<sub>2</sub> by year 2100.

Expectations about climate impacts are generated by feeding these emissions scenarios into climate simulations, to bracket the range of outcomes in terms of impacts. Currently, the existing expectations for impacts in California come from work that either

1. Assumed doubled-CO<sub>2</sub> (*e.g.*, Snyder *et al.*, 2002, 2003, 2004; Diffenbaugh *et al.*, 2003), which is close to the best-case scenario just described, or
2. Attempted to bracket the range of possibilities by simultaneously analyzing both the best and worst IPCC cases (*e.g.*, Hayhoe *et al.*, 2004).

Typically, emission-scenarios are fed into a range of climate models that bracket the “broad middle” of climate responses described in the last section. Thus, the projections are “doubly-bracketed” to examine uncertainty both from human actions and from unforeseeable climate sensitivity.

For California, the mid-century response (2035-2064) is remarkably consistent across scenarios: a response by annual maximum temperature of about +1.9° to +2.3°C for sensitive climate models, and a response 1° less for the less sensitive PCM1 model (Shaw *et al.*, 2009, Table 1). The statewide precipitation response is relatively small, staying within ±4cm across the various scenarios and models (Figure 3), though more of it falls as rain versus snow than previously; the snow melts sooner; and more gets evaporated leading to lower soil moisture and streamflows than previously (Null *et al.*, 2010; Cayan *et al.*, 2009). The simulations suggest that predictability is reasonably good at the 40-year time-scale, perhaps because global climate outcomes at this timescale are dominated not by positive atmospheric feedbacks, but by the inertial effect of the ocean, a kind of transient negative feedback that limits the pace of change (Baker and Roe, 2009). The work suggests that mid-century climate in California will be decidedly warmer, independently of any actions taken in the meantime to contain greenhouse-gas emissions and climate change.

By end-of-century (2070-2100), the temperature scenarios diverge much more severely, about +2.5° versus +4.2° C for the B1 and A2 scenarios, respectively (Figure 3). End-of-century in the A2 scenario also marks a period of unprecedented wildfires and significantly more erratic precipitation in the southern and south-central coastal region, and of course the possibility of large decreases in mean precipitation (Cayan *et al.*, 2009; Shaw *et al.*, 2009).

Perhaps more importantly, end-of-century for the A2 scenario marks a period of accelerating greenhouse-gas emissions and climate change, whereas in the B2 scenario it is a period of emissions shrinking toward zero and global change that is decelerating toward an equilibrium (Cayan *et al.*, 2009; Solomon *et al.*, 2009). Thus the harsh changes projected under the A2 scenario are simply the prelude for even faster change in the 22nd Century, with no prognosis for stabilizing greenhouse gas concentrations and climate. This characterizes the broad middle of A2 climate response, without taking account of the fat-tail of more extreme responses discussed earlier.

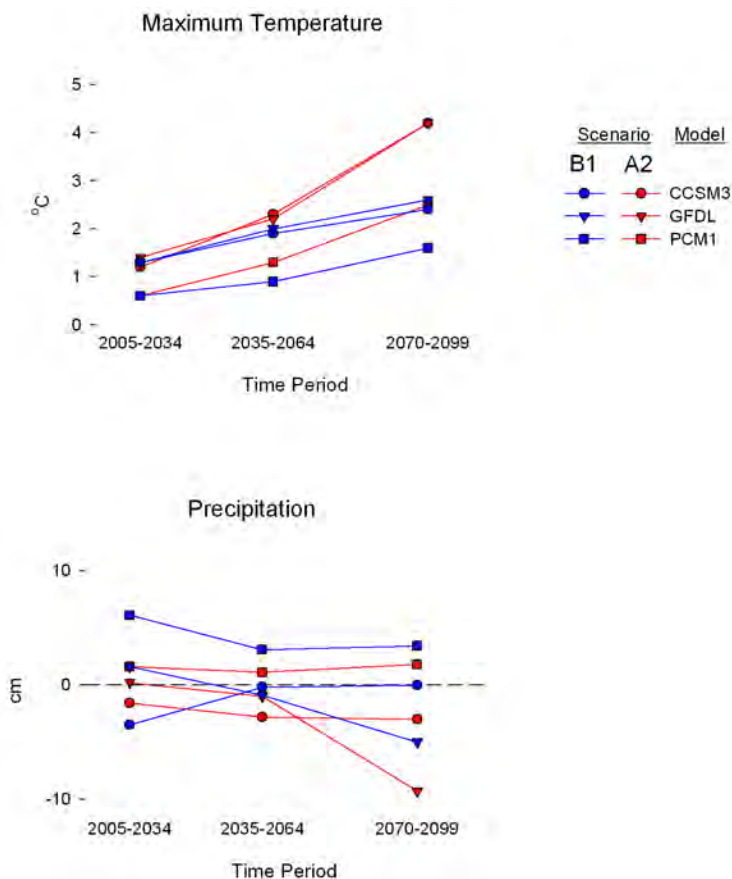


Figure 3: Statewide climate projections for 30-year periods over the next century, taken from Shaw *et al.* (2009). Values shown are relative to the 1961-1990 reference period, for annual maximum air temperature and annual precipitation (annual minimum, not shown, is very similar to the top graph). The B1 and A2 emissions scenarios bracket the various IPCC scenarios; climate model PCM1 is generally considered less sensitive than other climate models, reflected here in its smaller temperature response, and positive precipitation response.

According to this doubly-bracketed analysis, no matter what steps are taken to rein-in greenhouse-gas emissions, the next 40 years is largely predetermined at this point, and global temperatures at least may be somewhat predictable. On the other hand, if one is to rationally attribute value to continuation of human civilization into the 22<sup>nd</sup> Century (Weitzman, 2009), it follows that emissions must be eliminated during the next 40 years, so that the global climate begins to stabilize in the next century.

Scenarios are not predictions, but they are widely regarded as a helpful conceptual tool for planning. Recovery plans envision some future point at which the steelhead DPS becomes viable and thus a candidate for delisting. It is difficult to reconcile this basic structural assumption of viability with the A2 scenario, which stops in the year 2100 with climate stabilization completely unresolved. A planning effort to get steelhead

through the end-of-century conditions would be short-lived, as conditions continue to change at an accelerating pace in the early 22<sup>nd</sup> Century. Even if the scenario and simulations were extended another century, many people believe that ecosystem responses to such change would be so extreme as to be largely unpredictable (Schneider, 2009).

The B2 scenario, and others like it that envision reduction of emissions and stabilization at a new global heat balance, are more amenable to scenario planning for steelhead recovery. There would be a transient phase, and a new global temperature plateau, and recovery measures could account for the transition and plateau in the Earth's heat budget. The new plateau would still retain a fat-tail problem of non-negligible catastrophe that would need to be taken into account.

But this presupposes that the B2 scenario, or something like it, has a realistic chance of occurring,

and at the moment there is little empirical evidence that this is the case. Stabilizing the climate ultimately means stabilizing greenhouse gas concentrations in the atmosphere, which means reducing new emissions to nearly zero (Solomon *et al.*, 2009; Matthews and Caldeira, 2008). Not reducing emissions to 1990 levels or some such interim goal, but to zero.

The world appears to be moving further from this goal rather than toward it. For example, as of 2007 the actual growth of emissions since 2000 exceeded even the worst-case scenario developed by the IPCC (Rau-pach *et al.*, 2007), though the global recession has since slowed it down a bit (Schneider, 2009). The best case of 550 ppmv in 2100 may now be out of reach (Anderson and Bows, 2008; Schneider, 2009). In addition, there are indications that CO<sub>2</sub> uptake by the ocean is slowing down (Khatiwala *et al.*, 2009), which would

cause greenhouse gasses to concentrate in the atmosphere faster per unit of emissions, compared to what is assumed by IPCC scenarios.

The difference between the B2 and A1 scenarios appears to mark the difference between steelhead recovery being possible versus not. Therefore, a description of the science underlying steelhead recovery would be incomplete, and possibly even an irrational act of faith, if it did not examine the explanation for how one scenario versus the other becomes enacted by humanity.

So why would people continue to emit greenhouse gasses when it so obviously poses such costs, uncertainties, and risks over the long term? Many scientists believe the explanation lies in game theory. *The Economist* magazine recently summarized the situation aptly:

The problem is not a technological one. The human race has almost all the tools it needs to continue leading much the sort of life it has been enjoying without causing a net increase in greenhouse gas concentrations in the atmosphere. Industrial and agricultural processes can be changed. Electricity can be produced by wind, sunlight, biomass or nuclear reactors, and cars can be powered by biofuels and electricity. Biofuel engines for aircraft still need some work before they are suitable for long-haul flights, but should be available soon.

Nor is it a question of economics. Economists argue over the sums, but broadly agree that greenhouse-gas emissions can be curbed without flattening the world economy.

It is all about politics. Climate change is the hardest political problem the world has ever had to deal with. It is a prisoner's dilemma, a free-rider problem and the tragedy of the commons all rolled into one. At issue is the difficulty of allocating the cost of coordinated action and trusting other parties to bear their share of the burden (*The Economist*, 5 Dec 2009, "Getting warmer," p. 5).

Specifically, the problem is that if one social group stops using fossil fuels, it simply reduces fuel prices on the world market, stimulating other social groups to increase their use of fossil fuels. So there is a need for everyone to agree on a pathway to zero emissions. But negotiating and policing such an agreement is rife with perverse incentives (Milinski *et al.*, 2006, 2008).

For example, if everyone agrees to stop burning fossil fuels, and just 10 of the Earth's 6.8 billion people cheat (for example, by burning coal to heat their homes), they gain the benefit of cheating with only negligible subtraction from the benefit of group cooperation, which they also gain. But obviously, if enough people cheat, the benefit of group cooperation evaporates for everyone.

This problem creates unstable cooperative alliances and a very broad array of perverse incentives,

such as hiding one's own cheating while exaggerating the cheating of others, or in other words, systematically biasing the costs and benefits involved in group cooperation. Of course, many of these costs (environmental costs, costs to future generations) are inherently difficult to estimate objectively, exacerbating the problem. More intractable still, in a complex issue such as climate change, there is incentive for reasonable people to disagree about what is a fair allocation of costs, or in other words, on the definition of cheating itself.

Anyone who has ever shared a house with friends or family has encountered a mild version of this problem, in the form of unclaimed dirty dishes. Everyone insists they are doing their share; and yet unclaimed dirty dishes accumulate. Where did they come from? Is someone exploiting the situation, or is everyone simply



overlooking their own transgressions? Does this sabotage the trust and good will necessary for reciprocity?

The communication, shared understanding, and trust necessary to resolve such issues is called “social capital,” a concept now being emphasized by political scientists (Pretty, 2003; Folke *et al.*, 2005; Brondizio *et al.*, 2009). In a household with social capital, most dishes most of the time are clean and in a cabinet. In a household without social capital, the equilibrium situation is that most dishes are usually dirty, so that each person has to wash a dish in order to use it. This latter situation produces a stable and fair system in which people wash dishes in proportion to their usage, but at the cost of a perpetually dirty kitchen, reduced counter space, etc.

Obviously the problem of climate change is considerably more complex than dirty dishes, but at heart it stems from a similar social process, often labeled the “tragedy of the commons.” Traditionally the solution to the tragedy of the commons was seen as either privatization of resources, or government regulation of resources (Hardin, 1968), but more recently these have come to be seen as two special cases in a larger class of what are called assurance problems (Ostrom, 2008a; Ostrom and Walker, 2003). The essence of the problem is that no individual has incentive to do their part until everyone does their part; but negotiating and policing such an agreement is impeded by second and third-order “assurance problems” that are vulnerable to the same tragedy of the commons.

An example is the preliminary need to negotiate a shared understanding of the problem itself, which is impeded by individuals wishing to frame the problem in a self-serving way. This is a second-order assurance problem—the commons here is the shared assumptions by which the problem is defined—that must first be solved before potential solutions can even be discussed. This is also an assurance problem in which science has a key role to play. On the one hand, science aspires to objectivity and empiricism, and so has legitimate claims to a special role relative to stakeholders. On the other hand, science is a human institution, itself subject to the dilemmas involved in assurance problems (Nisbet and Scheufele, 2009). Thus public trust of science as an institution poses a third-order assurance problem.

The tragedy of the commons is resolved when individual and group incentives become aligned. For a broad variety of situations, alignment develops when individuals have repeated interactions with each other for an indefinitely long time period (Binmore, 2005)<sup>2</sup>. Participants are then able to negotiate and obey social norms that realize the benefits of cooperation. Such norms include concepts of private property rights, but also a broad variety of other social norms (Ostrom *et*

*al.*, 2007; Ostrom, 2008a; Meinzen-Dick, 2007). The tragedy of the “tragedy of the commons” formulation was that it assumed there to be only two solutions—privatization or government regulation—and thus it artificially restricted options.

This artificial restriction of options is particularly relevant to resources such as air and water, which are fluids with unpredictable dynamics at multiple spatial scales, often with key elements that are difficult to characterize (*e.g.* the terrestrial source and fate of atmospheric CO<sub>2</sub>; the capacity and functioning of groundwater basins, as in Blomquist *et al.*, 2004). Recent research has emphasized empirical study of sustainable resource systems (Marshall, 2005; Ostrom, 2009; Brondizio *et al.*, 2009), to identify a fuller set of social norms that people have hit upon to solve commons problems.

Repeated interactions appear necessary to resolve commons problems, but they are not sufficient. The incentive to cooperate in the present (rather than exploiting) is the potential long-term benefit of cooperating in the future. So to cooperate with someone in the present, a stakeholder needs some sort of assurance that that person will also cooperate, both now and in the future. This is why political scientists now refer to this class of problems as assurance problems rather than commons problems: what is needed is a mechanism for assurance. There are a variety of such mechanisms.

A very simple assurance mechanism, common in immobile plants and animals, is spatial proximity (Levin, 1999). To the extent that neighbors can reciprocate impacts on one another, and cannot escape from each other, they are assured of a long future together that creates incentive to cooperate or at least coexist.

An important mechanism in human systems is the power or ability to restrict access to a resource, monitor its use and abuse, and for the group to reward and punish individuals accordingly. Conventional private property rights are a special case of this mechanism (Ostrom, 2008a). But it is difficult to restrict access to the pollution-absorbing capacity of the air.

A third class of mechanisms involve not power but trust (Ostrom, 2008b). Experiments have shown that during a first encounter, most people tend to offer trust to a potential cooperator, but in subsequent encounters their trust (or lack thereof) is based on their past experience of the other person (Binmore, 2005; Milinski *et al.*, 2006). This pattern holds cross-culturally and under a broad variety of situations (Ostrom and Walker, 2003). Binmore (2005) notes that for most of the evolutionary history of humans, people lived in small groups in which each member had long personal experience of each other member, and in which survival was dependent on successful cooperation. He argues that the emotion called trust was evolutionarily maintained as an assurance mechanism that used past experience to

<sup>2</sup> In game theory, this result is known as the folk theorem

accurately identify whom to cooperate with in the present. For trust to serve as an assurance mechanism, the past pattern of someone's behavior must convey information about future behavior, and the person must be personally identifiable to the truster.

Trust apparently involves two important subtleties. First, concepts of trust appear to be closely bound up with concepts of fairness: people cannot trust someone whom they perceive to have no sense of fair play. This is because trust requires that actions and reciprocated actions be tested for proportionality on a single scale (Binmore, 2005). Fairness is the scale, the emotional yardstick for comparing incommensurate actions. Yet even though trust and fairness are emphasized cross-culturally in humans, fairness norms (the rules by which people determine fairness) are quite different cross-culturally and also labile to change within cultures (Binmore, 2005). Thus, one will see people with different fairness norms that clash in seemingly intractable ways; but at the same time, fairness norms are much more likely to change than the importance people place on fairness itself. Thus, fair play can become the basis for creation of new fairness norms that assure beneficial cooperation into the future. Indeed, Binmore (2005) argues that this process is destined to occur, because the new fairness norms out-perform the old.

The second important subtlety is that assurance mechanisms based on trust apparently fall into two general categories: trust by personal experience, and trust by reputation (Milinski *et al.*, 2006). Trust by personal experience is more robust, but constrained to small groups of people with reasonably long shared histories. Assurance based on this mechanism tends to break down when too many people are involved (Ostrom, 2008a). Trust by reputation has much broader, even global scope (Milinski *et al.*, 2006) but relies on accurate information conveyed by third parties. Thus it involves second- and third-order assurance problems involving the credibility of third parties, which returns everybody to the domain of perverse incentives. Still, reputation-based systems are a natural outgrowth of the smaller more robust personal-experience systems, and people appear to be fairly resilient in the sense that they tolerate some level of unfairness if the benefits of cooperating are large enough (Milinski *et al.*, 2008).

Because trust-by-reputation rests on a foundation of trust-by-personal-experience, human institutions for dealing with assurance problems often involve "path dependencies" (Marshall, 2005). In these path-dependencies, the historical development of institutions for allocating resource use have allowed social-ecological systems to become "locked-in" to poorly-performing paths, with low future returns on current investments, but large (and seemingly insurmountable) transaction costs for moving to a future of increasing returns on investment. It can also require the rebuilding of social capital, in the form of trust and reciprocity

(Folke *et al.*, 2005), if perceived deceptions in the past have eroded that social capital (as in Reisner, 1993). A key transaction cost is the need to invent new fairness norms that better suit the future and then persuade stakeholders to adopt these new fairness norms in a meaningful way. This may be difficult, but Binmore (2005) argues that it is tractable. What is intractable is to convince people to invest in a cooperative solution they view as unfair.

The three assurance mechanisms—immobile neighbors, ability to punish and reward, and freedom to choose trustees—are not mutually exclusive and indeed would be expected to reinforce each other.

I have dwelt here a bit on assurance mechanisms, because they appear to occupy the gap between the A2-type scenario the world is now on, and the B1-type scenario that makes steelhead recovery a meaningful proposition. The science suggests that new technology, personal virtue, a reliance on experts, and so forth can all play a role in stabilizing climate, but none will succeed without a solution to the global assurance problem—which is really a complex of many different assurance problems in human institutions. This suggests that the world needs to learn how to routinely solve assurance problems.

### Implications for Steelhead Recovery

The assurance problem that impedes climate stabilization is structurally similar to social dilemmas having to do with collective governance of water resources. Both are examples of people attempting to overcome perverse incentives to realize the net benefits of cooperation, in the sharing of fluid natural resources with complex cycling patterns. There is a general need to learn how to routinely solve assurance problems, which is as much an issue of social learning as of individual learning.

Cooperation at the watershed scale, though probably a lot harder than overcoming the dirty-dishes problem, is probably a lot easier than containing global climate change. Climate is global; management of watershed processes is more regional in scale, has fewer participants, and possesses geographic boundaries (watersheds) that are more clearly delineated. The fewer participants, smaller scale, and clearer boundaries are all features that increase the likelihood of success in solving an assurance problem (Ostrom, 2008a). Looking backward, steelhead recovery seems a profound change in the trajectory of freshwater social-ecological systems. In the context of the future, steelhead recovery is only a modest assurance problem relative to other assurance problems that need to be addressed.

If smaller scale and fewer participants aid success in solving assurance problems, then assurance problems should be approached at as small a scale as practical. The importance of upstream-downstream processes in stream systems means that the smallest

practical scale is probably that of the entire stream network/drainage basin. Assurance cannot be established at a smaller scale due to activities of people outside the “assurance basin” but inside the drainage basin. To build assurance where there is currently little trust, one might want to begin by addressing a first-order assurance problem, such as personal trust, and once it is established in a small network of people, use it as the basis for addressing second-order assurance problems, such as trust by reputation. Similar thinking would apply to assurance by other mechanisms of reciprocity, including power and physical proximity: build the assurance from the ground up, starting with first-order assurance problems; and do not sacrifice any existing credibility of second- and third-order assurance mechanisms for short-term gains.

Ultimately, steelhead recovery appears to require that both the global-scale climate problem and the basin-scale hydrological problem be solved. If a key need is to learn to routinely solve environmental assurance problems, then one should strategically prioritize assurance problems to maximize not just immediate success but also learning, which enables one to transfer those successes to more challenging assurance problems. In other words, one would prioritize not the “low hanging fruit” but the fruit that is just low enough for success but just high enough to teach one how to jump higher. Transferring this learning to other, more challenging assurance problems appears to benefit from informal information networks, emergence of leaders, and “bridging” or “learning” institutions, both formal and informal (Folke *et al.*, 2005). Unlike the global climate problem, or even the larger West-Coast salmon systems (Central Valley, Columbia basin), the many small coastal basins inhabited by steelhead on the south-central/southern coast offer numerous, relatively tractable and self-contained opportunities for learning to routinely solve environmental assurance problems. The operation of perverse incentives is an intrinsic part of assurance problems and should be expected as a routine occurrence.

### The Resiliency Paradigm

The West Coast’s salmon and steelhead populations have always been sensitive to the variability of the northeastern Pacific climate-ocean system. Multi-year droughts or poor ocean conditions can depress salmon populations for years, or even decades, followed by rebound when conditions improve (Hare *et al.*, 1999; Mantua *et al.*, 1997; Schwing *et al.*, 2006; Peterson and Schwing, 2003; Mueter *et al.*, 2002). So, steelhead recovery as a form of human stewardship has to be judged over a broader timeline, with multi-year setbacks in population size considered to be a normal and expected event, and progress judged at the scale of multiple decades and even multiple human generations. For similar reasons (climatic and ecosystem variability),

river rehabilitation has to be viewed as a long-term process with a 50-100 year timeline (Ryder *et al.*, 2008).

So it is clear that steelhead recovery, stream rehabilitation, and the adaptation of people and natural systems to climate reorganization, will all unfold on similar decadal timescales, in ways that are subject to surprises.

It is also clear that the era of water management via the assumption of “stationarity,” is over (Milly *et al.*, 2008). Stationarity is the idea that the statistical description of climate is unchanging: for example, that the mean and variance of annual rainfall is roughly constant over time, even though rainfall in any given year is uncertain. This assumption, in some form, underlies assessments of water-storage needs to withstand drought, or the idea of the 100-year flood plain, or the interpretation of exceedence curves, and so forth. It was never really true, but during the 20th Century it was a useful approximation, and it was only recently that long-term trends in climate allowed it to be formally rejected as a null hypothesis at the global scale (IPCC, 2001).

Environmental interests have had their own form of the stationarity assumption during the 20th Century, in the idea that impacted ecological systems can somehow be restored to a natural or pristine state. This assumption was never precisely true, since 19th Century climate was a bit different, and the Native Americans had a notable influence on disturbance regimes (*e.g.* Keeley, 2002). But the concept of restoration to historical reference conditions was a useful approximation. As the climate changes, often this will no longer be the case (Harris *et al.*, 2006). What sort of reference should replace it to guide the rehabilitation of natural systems?

To the degree that climate change can be forecast, such forecasts could take the place of the stationarity assumption in water management. But given the structural uncertainties in climate and governance systems that are summarized above, such forecasts—especially for rainfall—seem fundamentally uncertain. If so, water management (particularly water provisioning and flood regulation) will be forced by circumstances from an efficiency/reliability footing, where it appears to be now (Van Eeten and Roe, 2002), towards a resiliency footing. The alternative is simply the failure of existing social institutions to deal with the onslaught of change.

Resiliency can be defined as the magnitude of disturbance or change that can be tolerated before a social-ecological system moves to a different region of state-space, where it is controlled by a fundamentally different set of processes (Carpenter *et al.*, 2001). Under a resilience paradigm, an externally-imposed change, such as climate reorganization, forces some internal components of the social-ecological system to respond quickly, allowing other components to maintain a more gradual adjustment, perhaps orders of magnitude more gradual.

Obviously with large external drivers such as climate reorganization, there is the potential for rapid destructive change. The key question is how to transform the social-ecological process to allow a process of creative destruction to take place, so that the slowly-changing components are the ones for which slow change is valuable to people or other species, and at least some of the fast-changing components are creating value rather than just destroying it. A valuable slow-changing process is one that helps to ensure that fast-moving processes create value as well as destroy it.

For a concrete example, rainfall is a fast-changing annual phenomenon that can drive fast change in market value of crops, and by way of debt financing, the rapid turnover of ownership of family farms. In Chicago in the 19th Century, transparent agricultural futures exchanges were developed. These became slow-changing social institutions, which could serve the purpose of reassigning fast change in market value from farmers to speculators (Cronon, 1992). This allowed ownership of family farms to become a slow-changing variable, which in turn could allow farmers to learn over time how to adapt their techniques to local conditions, providing further stability and efficiency.

Irrigation and water-rights systems can also be viewed as slow-changing institutions with a comparable function of providing stability and efficiency gains. But the existing system tends to assume the stationarity paradigm. Even though annual rainfall is a fast-changing process, its mean and variance were until recently thought to be slow-changing. They are now destabilized: long-term precipitation patterns are now like precipitation itself: uncertain. The climate has become like the weather. In addition, climate change may drive wildfires that release new sediment regimes into the existing hydrological infrastructure. If existing institutions cannot accommodate this change, they will face crisis.

Under the resiliency paradigm, this accommodation is the essence of adaptation and sustainability (Holling, 2000; Carpenter *et al.*, 2001). Crisis, or ideally the anticipation of crisis, opens up the necessity of change and destruction, which opens up the possibility of creative change to deal adaptively and resiliently with the new situation. The destruction and a new form of self-organization are assured; the creative response that rebuilds value along a new trajectory is not.

Indeed, developing such creative responses can be viewed as the challenge of our time (Carpenter and Folke, 2006). The shift from unpredictable weather in a predictable climate, to unpredictable weather, unpredictable climate, and an unpredictable ramping of the energy in the climate system, can be interpreted as creative destruction propagating upwards in a hierarchically structured system. In turn, the global effort to eventually reduce CO<sub>2</sub> emissions to zero is an effort to convert the top one, the energy balance of the climate

system, back into its former status as a slowly-changing (millennial scale) controlling process.

Taking examples like the two just described, and abstracting them to a general resiliency paradigm, has I believe two key benefits:

- The resiliency paradigm provides a productive common framework for the interaction of professionals from various disciplines, especially among ecologists, engineers and social scientists. In short, it provides a forum for creative thinking about building adaptive capacity, composed of an efficient mix of natural, engineered, and social capital. Thus, it may lower the transaction costs for getting off the “armoring” pathway, spoken of in the section on stream systems, and onto a broader pathway encompassing natural capital, with greater option values and more promising return on investment. This brighter future of usefully rehabilitated streams, in turn, releases not just stream behaviors, but the upside potential of steelhead recovery efforts.
- The resiliency paradigm provides a common framework within which stakeholders can think more broadly about these same option values, adaptive capacity, and how it relates to their fundamental values. Stakeholders evidently often confound their fundamental values with “means values” (ideas about how to achieve fundamental values; Keeney, 1994) and are likely to overlook the possibilities of an open future. In a sense, they suffer from the same disciplinary blinders as professionals, but their discipline is their local knowledge and assumptions. At the same time, the magnitude of climate change is expected to begin challenging people’s fundamental assumptions in a very Katrina-like or Dust-Bowl-like way, forcing them to examine fundamental values sooner or later.

Watersheds and hydrological systems will reorganize in response to climate change, in some fashion. Human populations will respond in some fashion, whether it is adaptively or dysfunctionally or catastrophically.

One possible response is to attempt to armor the hydrological infrastructure against the self-adjustment of stream systems in the new climate. Because so much is unpredictable, the armoring response would require infrastructures to be armored across a very broad set of contingencies: unprecedented drought, deluge, sedimentation, etc. This suggests that climate change will amplify the investment costs involved in the armoring approach without much actual gain in provision of hydrological services; such a response may also commit society to high maintenance costs into perpetuity. This implies long-term opportunity costs for the capital that gets drawn into trying to resist the self-organization of

highly dynamic stream corridors. Using the vocabulary of Marshall (2005), the lock-in to a current inefficient path becomes deeper and deeper, creating higher and higher transaction costs for moving to an adaptive system with broader option values.

Securing a more efficient mix of technological and natural capital—dedicating space for natural stream behavior via setback levees, underground or off-channel water storage, etc.—seems more likely to be a much more economical, self-maintaining strategy in the long term: it substitutes natural capital for human and engineered capital, and preserves a broader range of options for adaptation.

However, in the near term it seems likely to be more expensive in a variety of ways, especially in terms of intangible transaction costs involved in the adaptation of institutions (Hanna, 2008). These include both formal institutions (such as water rights systems and zoning laws) and informal institutions (such as attitudes about developing real estate within the dynamic stream corridor). It is commonly assumed to be virtually inconceivable that such institutions will adjust. This appears to be an artifact of using the past, rather than the future, as a frame of reference.

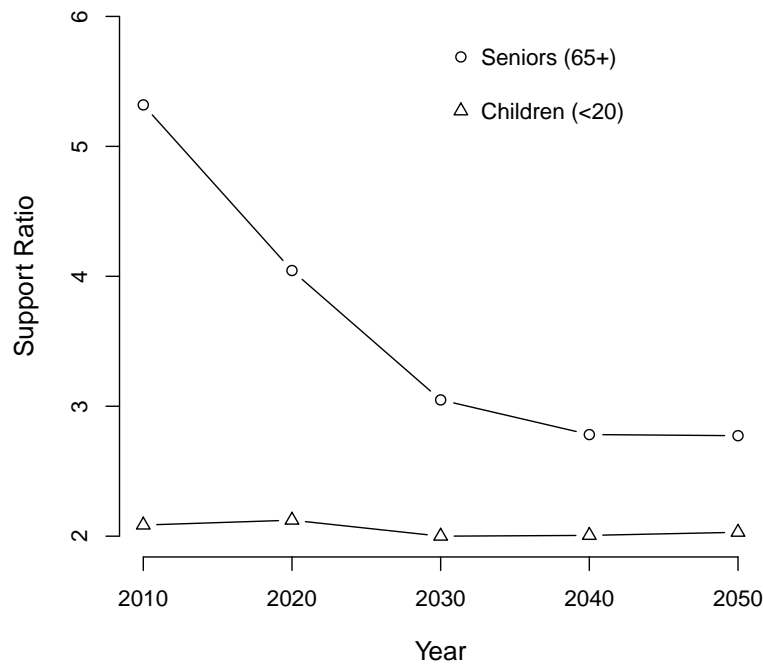


Figure 4: Support ratios for the projected human population of California, through year 2050. Shown are support ratios for non-working seniors (assumed to be people age 65 and older), and support ratios for children (assumed to be people less than 20 years old). Working population is assumed to be people aged 20 through 64. Projections are from the California Department of Finance, July 2007, <http://www.dof.ca.gov/research/demographic/reports/projections/p-3/>.

### The Next 40 Years

The work reviewed so far indicates that the next 40 years holds several fundamental differences from the recent past: accelerating climate change independent of any efforts to reduce emissions of greenhouse gasses during the same time period; a need to adapt to this changing climate; but also a need to reduce greenhouse gas emissions during the same period, not for any immediate benefit but to stabilize climate several decades later. Thus, a minimally hopeful view of the long-term future appears to imply a near-term concurrent process of adaptation, reorganization of the energy system, and rehabilitation of assurance mechanisms over the next 40 years.

Another fundamental shift is the imminent aging of California's human population, and indeed of the world population. Support ratios, the ratio between number of working and non-working people, is a useful metric for thinking about this phenomenon, and projected support ratios for California children and seniors are shown in Figure 4. Currently there are approxi-

mately 5 working people for each senior, and 2 working people for each child in the state, given the assumptions about age and work status in the projections. As the figure shows, the support ratio for seniors is about to undergo a precipitous drop.

As the support ratio for seniors declines, seniors' demand for wealth relative to its creation by working people will grow. Implications are not entirely clear. Here I summarize some conclusions of the UC Berkeley demographer R. Lee and colleagues, who have studied the implications for both the state of California and the world of nations as a whole (*e.g.* Lee *et al.*, 2003; Lee and Mason, 2010a). I then relate the implications to the need to adapt to the new climate and valuation of natural capital.

Some of the increase in wealth-demand may be met by seniors working longer. Some may be offset by a decrease in wealth-demand for children, whose numbers are declining slightly and whose per-capita support expense is much higher than that of seniors, due to education costs (Lee *et al.*, 2003). But education, and other investments in human capital, are a key issue (Lee

and Mason, 2010a), because ultimately the increasing wealth-demand by seniors requires that either the average standard of living decrease or the productivity of working people increase. According to Lee and Mason, the latter requires greater investments in human capital. Thus, whether seniors obtain wealth via investments in the productivity of children and adults, versus direct payments from working adults, is a key decision point. Only the first is expected to prevent declines in average standard of living (Lee and Mason, 2010b). In short, there are resilient conditions in place for a labor shortage whose severity depends on the nature of investment patterns.<sup>3</sup>

Perhaps investment in more productive physical capital could at least partially offset this problem (Lee and Mason, 2010b). In the case of the existing infrastructure for water provisioning, flood and wildfire protection, etc., these gains would have to be achieved even as accelerating climate change degrades the effectiveness of the existing infrastructure.

These trends represent a distinct break from the past, which is the template that most people will tend to use to envision the future. But the recent past is dominated by the progression of members of the post-war baby boom. Their youth and early career in the 1950s and 60s corresponded to a time when large sections of the current water infrastructure were constructed using debt financing (Reisner, 1993). At that time, investment in children had a larger share in the support ratio, and debt-financing of infrastructure could be considered a way to leverage that investment. These investments served not just to support the larger working population that was soon to be, but also to increase their productivity. It was investment in the future.

These investments paid off as people of the baby boom entered the work force, which raised the support ratio. We are now near the apogee of this trend due to the nature of the US economy, in which people tend to be most productive during the last part of their career (Lee and Mason, 2010b). Lee and Mason (2010a) refer to the resulting prosperity as the first dividend of a demographic transition. A possible second dividend occurs if these people now invest their accumulated wealth so as to realize productivity gains in human and physical capital.

Consider climate change. As noted earlier, climate change over the next 40 years is insensitive to efforts to reduce emissions of greenhouse gasses. But it will demand investment in adaptation. The energy density of fossil fuels makes them a tempting source to power this adaptation. Fossil fuels could allow people to insulate themselves from change, rather than prompting them

to look for emerging sources of productivity in the new climate system.

At the same time, investments in solving the fundamental problem (stabilizing greenhouse-gas concentrations) will have no immediate benefit in terms of adaptation. The benefit comes later in the century, and the immediate demands of adaption will tempt people to postpone this longer-term investment. At the same time, climate change will probably be accelerating during this period, requiring more and more adaptation. The temptation to leverage fossil fuels toward adaptation will continue to grow. And yet, reduction of emissions appears to be the one investment that makes all other long-term investments meaningful, by providing a foreseeable future that is hopeful.

To summarize, it appears likely that the most effective long-term investments would be in reduction of emissions and adaptation strategies that focus on natural capital. But these may be in opposition to short-term investments to insulate people from effects of climate change, with two critical points of leverage being the kind of wealth demanded by seniors and the kind of labor available.

The overall trend toward warmer conditions in the Earth will sooner or later produce certain profound changes in the California system. The extent of wildfire in the West has already increased, attributed to the longer warm seasons now occurring (Westerling *et al.*, 2006). These wildfires will likely continue to trend upward, though with much noisiness in the data. Containing wildfires is an inherently labor-intensive process, as is the rebuilding of homes destroyed by wildfire.

Similarly, the water-storage capacity of the Sierra snowpack will be declining, a permanent loss of natural capital upon which the human population is currently dependent. The search for replacement storage will reflexively tend to focus on dams, again during a time of labor shortages, increasing demand for productivity gains, and likely difficulties in debt financing. In addition, the most suitable sites for dams have already been used, and uncertain changes in the wildfire (and hence sediment) regimes may threaten to vastly shorten the working lifetime of dams and other water infrastructure.

The natural solution will be to turn to another form of natural capital, California's vast underground storage basins. Currently, institutions such as complex water rights systems appear to block the efficient use of many groundwater basins for water storage (Blomquist *et al.*, 2004). However, conjunctive management of surface and ground water systems has been successfully achieved in certain situations in the state (Blomquist *et al.*, 2004), and the motivation to implement it more widely is certain to grow.

Similarly, uncertain precipitation and wildfire regimes set up the conditions for problems in maintaining traditional flood-protection strategies based on

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<sup>3</sup> This shortage should occur in the international labor pool as well. Other developed countries of the world will face more severe demographic transitions than the US (Cohen, 2003).

dams, levees and channelization. The relentless self-adjusting of stream geomorphology to new flow and sediment patterns could be viewed as an expensive problem to control by armoring, etc., but it will also be creating something new, a new dynamic stream corridor and flood plain, potentially of value to people and other species and perhaps open to constructive influence by human actions, but never entirely predictable nor controllable. This will be occurring concurrent with a demographic shift in the human population that in-

creases the scarcity and price of human labor relative to its value and thus makes investment in natural capital a relative bargain.

Steelhead recovery can only really occur if the fish are able to find a pathway into the future while this process of reorganization in the freshwater social ecological system is unfolding, and it can obviously draw on synergies with the approach that emphasizes natural capital rather than armoring.

“Merely preserving existing types [of salmon populations] is not sufficient to provide for long-term sustainability. It is at least as important to conserve evolutionary processes such as patterns of dispersal and connectivity, natural selection, sexual selection, and dynamic interactions with physical and biotic features of habitat. Such processes are difficult to manage directly... If we can conserve functioning natural ecosystems, then natural evolutionary processes will develop as a byproduct” (Waples *et al.*, 2009).

“Our ability to accurately predict climate impacts on salmon ecosystems is incomplete and unlikely to improve to the point of accounting for the regional response diversity [observed even in existing salmon populations]. Policies must be robust to these uncertainties rather than reliant upon prescriptive forecasts of climate and associated ecological conditions” (Schindler *et al.*, 2008, p. 503)

“Increasingly, management activities work in harmony with natural processes in an emerging “age of repair” in which contemporary management strategies aim to enhance fluvial environments either by returning rivers, to some degree, to their former character, or by establishing a new, yet functional environment. Notable improvements to river health have been achieved across much of the industrialized world in recent decades” (Brierley and Fryirs, 2008, p. 1).

“Hydrologists and ecologists must not only forge new research partnerships but must bring engineers, geomorphologists, and social scientists firmly into the partnerships...Restoration will be most effective when watershed inhabitants, scientists, planners and designers understand the views, values and cognitive models each has toward rivers and the place of rivers in the lives of people” (Palmer and Bernhardt, 2006, p. 1 and 4).



## Ecosystem Management

Stream systems are becoming new ecosystems, in the sense that they will be shaped by different controlling processes (climatic, cultural) than today or 150 years ago. Of course, people have been transforming these ecosystems into new configurations all along, often inadvertently, as a side effect of other activities. This is conventionally called “disturbance of existing ecosystems” rather than “creation of new ecosystems.”

But nowhere is it written that creation of new ecosystems must be inadvertent; only that it inevitably involves emergent properties that sometimes involve surprises. In principle, ecosystems could be designed and built so that emergent properties support certain, desired, self-organizing properties—Although “built” here means putting into place the conditions that allow the ecosystems to build and maintain themselves. Emergent properties also mean that people need some ongoing mechanism to reposition themselves when surprises occur.

Patrick Kangas (2004) used a diagram like the following to make the point that constructing new ecosystems is the one missing family of methods in ecological science:

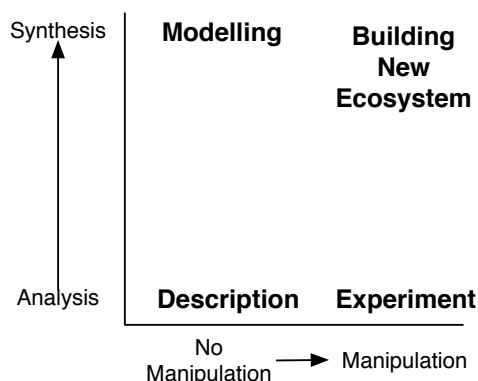


Figure 5: The spectrum of methods in ecology

Description, experiment, and modeling are well-known methods. But the upper right quadrant of the diagram has room for one more family that intentionally combines manipulation of nature and synthesis of understanding. Kangas labeled it “building new ecosystems,” but usually this fourth family is understood as management of existing ecosystems—which seems like good terminology, except that it encourages people to adopt the past as their frame of reference, rather than the future. Focusing too much on the past, it turns out, creates intractable problems along the human dimension.

This finding is scattered throughout the literature on river management (*e.g.* Rogers, 2006; Ryder *et al.*, 2008). To understand it, consider the new ecosystem created by simplified flow regimes below a dam. Because simplified flow regimes tend to encourage exotic species and drive out the native species, one of the principle responses has been to change dam operations so that released flows more closely resemble the original natural hydrograph (*e.g.* Stanford *et al.*, 1996). The idea is that this will re-establish natural channel behavior downstream from the dam, helping the native species and driving out the exotics.

But of course the original flow and sediment regimes cannot be completely re-established. The sediment is still being trapped behind the dam for one thing, although perhaps downstream tributaries can supply sediment that partly compensates for this. For another, the original hydrograph cannot be exactly re-established (the dam was built for a purpose), so there is a need to depart from it, and there is a need to understand which sorts of departures are acceptable and which are not (Palmer and Bernhardt, 2006). From the perspective of the scientist, the natural response is to try various flow regimes over time, and monitor the results to find which comes closest to producing the desired effect. This sort of “learning by doing” is called adaptive management, and is extremely appealing to scientists. More philosophically, accepting that the problem of complexity cannot be solved, means that adaptive management is the only route forward, into the future. But the key concept here is “desired effect,” because it implies some goal for the future. Without a desired effect, there is no basis for adaptive management.

Unfortunately, adaptive management has rarely been successfully implemented in its 30-year history as a concept (Medema *et al.*, 2008; Walters, 1997; Lee, 1999; O’Donnell and Galat, 2008; Gregory *et al.*, 2006; Allan *et al.*, 2008). In practice, most adaptive-management efforts spend inordinate amounts of time preparing to experiment, but they almost never actually perform the experiment. It turns out that stakeholders who are actually responsible for management decisions generally do not want to conduct experiments with uncertain outcomes on valuable resources. Water agencies, for example, tend to have the culture of “high-reliability organizations,” inherently structured to resist uncertainty in their operations (Roe and Van Eeten, 2001). In contrast, ecologists see the unwillingness to experiment as something that gradually erodes the ability of the ecosystem to sustain the resource in the first place. This ability to sustain a resource is a form of natural capital underneath the resource itself.

The lack of success in adaptive management appears to derive from schools of thought that overlook the option-value of perpetual learning and adapting. Instead they focus only on the economic efficiency of

the current allocation of ecosystem services, and whether marginal gains are possible (Marshall, 2005). This focus on the present tends to create lock-in to paths of resource use with decreasing returns on investment, as human and technological capital is substituted for natural capital.

In addition, stakeholders are vulnerable to assurance problems. Apparently, adaptive management has three rather distinct components (Jacobson *et al.*, 2009): 1) Adaptive experimentation, by which scientists learn about ecosystem functioning; but also: 2) Social learning by which stakeholders learn about ecosystem functioning, and 3) Adaptive governance, the structures and processes by which people respond by making shared decisions about how the ecosystem is manipulated, and its services allocated.

These allocation problems are often not easily addressed with conventional market solutions. The conditions for Adam Smith's allocative efficiency in the marketplace are actually quite restrictive, requiring "clearly developed legal systems defining property rights, regularized markets where exchange can occur, extensive information systems about the attributes of relevant goods, well-functioning courts established to clarify contractual obligations, an honest set of police to enforce these laws, goods that have few externalities and are undifferentiated on all relevant respects, and citizen demands that are focused entirely on the quantity and price of these goods" (Ostrom, 2006, p. 6)

The services provided by freshwater ecosystems rarely conform to these conditions. For example, the legal systems defining water rights are not at all clear in California, involving ambiguous priority between state, tribal, and Federal law (Doremus and Tarlock, 2008). Externalities and unenforceable property rights prevent efficient markets from developing around the state's vast groundwater storage capacity, effectively making it a public good in most parts of the state (Blomquist *et al.*, 2004). Pollution, especially diffuse forms of it such as fine sediment or invasive species, tend to comprise intractable "externalities," which are costs of economic activity that are external to the markets regulating that economic activity. Human communities and natural amenities in California tend to be anything but "undifferentiated in all relevant respects;" oftentimes they have unique values that effectively function as local public goods. Finally, water, wildlife, fish and other natural amenities are often considered a public good outright.

### Deliberation

Successful adaptive management is thus vulnerable to undervalued learning and assurance problems. For this reason, governance of public goods is often seen to

exhibit a "tragedy of the commons," and the resulting dysfunctional management of ecosystems is sometimes viewed as a "wicked problem" (Ludwig, 2001; Meinen-Dick, 2007; Ostrom *et al.*, 2007; Ostrom, 2008a; Carpenter *et al.*, 2009), resilient to any kind of satisfying resolution.

But the occasional successes are telling. Rogers (2006) gives a compelling and succinct description of successes in South Africa. One of the key elements is getting scientists and stakeholders to deliberate about the issues with the goal of developing a shared vision for the future. Adaptive management then becomes a means for getting to the future, rather than for changing the status quo or recapturing the past. Rogers (2006) refers to this forward-looking framework as "strategic adaptive management."

A parallel is found in the literature on river restoration. In various parts of the developed world, it is proving desirable to reverse some of the engineering approaches used to control river systems in the past, by removing levees, reconnecting floodplains, re-establishing riparian forests, and so forth (Brierley and Fryirs, 2008). These efforts cannot occur without agreement across a broad diversity of scientists of different fields and stakeholders from different towns and even different countries (*e.g.* Piegay *et al.*, 2008). One of the broad findings is the usefulness of the participants developing a *leitbild*, or "guiding image," of the river condition and behavior desired several decades in the future (Ryder *et al.*, 2008; Piegay *et al.*, 2008; Brierley and Fryirs, 2005). Again, this shared vision of the future serves to help coordinate the complicated process of restoration, and the diverse interests involved in it.

How does a group construct a shared vision for the future? Social scientists emphasize three key factors (Folke *et al.*, 2005): 1) A deliberative venue, in which the issues can be worked through to construct the shared vision; 2) social capital, which involves the trust and reciprocity that allows meaningful deliberation to take place; and 3) information networks, which allow social learning to take place more broadly. Here I focus on deliberation, where scientists can potentially contribute much direct value.

A deliberation venue is not the same as a bargaining table, because it only really functions if people are willing to reconsider their assumptions and their positions in a back-and-forth exchange. The quote below is by Rogers (2006), who works in another part of the world having a Mediterranean climate and a large human population. It is interesting that Rogers emphasizes a durable solution, in contrast to the term "durable crisis," applied to the century-plus decline of Pacific salmonids (Taylor, 1999).

In our work on the Kruger Park rivers we use a negotiation process that is based on the process used in the successful negotiations for a transition from apartheid to democracy in South Africa. Our reasoning is that if it can work for a nation with eleven official languages and the cultures that go with them, then surely it must have the potential to solve environmental conflicts.

In the [typical] compromise seeking approach, parties generally come to the table with the problem already defined in their terms and a list of the solutions/demands they want. They then trade solutions and outcomes off against each other. Unfortunately the problem is never defined in terms that are mutually acceptable to the various parties and they tend, instead, to see each other as the problem. Outcomes of this type of negotiation can be arrived at relatively quickly but they are not durable ... and are of little value in focusing the long-term co-operative decision-making processes needed in environmental problem solving. These processes need an exciting, shared vision to maintain impetus and adaptability to cope with changing circumstances.

The purpose of consensus negotiation should be to design a shared future. As such, consensus negotiation is heavily dependent on moving beyond current problems and on developing a set of shared values that guide future decision-making. ... A focus on values and the future has the remarkable tendency to dissipate the conflict that often arises from defense of current territory, personal desires or present ownership. ... It is also the first step in exposing the disparate mental models of stakeholders and developing the common purpose on which consensus thrives (Rogers 2006).

Why would a focus on fundamental values dissipate conflict? Values are important because stakeholders tend to confound means values and fundamental values. Means values are things for which the question “why is this important?” has an answer leading to another, more fundamental value; ultimately one reaches an endpoint at which something is simply important because it is important (Keeney, 1992), and this is a fundamental value. The distinction is important because fundamental values can often be pursued by diverse strategies, but stakeholders tend to overlook unfamiliar means for achieving familiar ends. This limits options and creativity. If fundamental values are identified, however, scientists can help to construct solutions that may not at first be self-evident (Keeney, 1994; Gregory and Keeney, 2002). Thus a focus on fundamental ends can create option value. Of course, without a focus on the future, stakeholder attitudes will tend to focus on the present value of these new options. This will not solve the underlying assurance problem about sustaining ecosystem services.

Why would a focus on the shared future dissipate conflict? A plausible answer appears to come from game theory, and the evolutionary history of conflict and cooperation in humans. Game theory suggests that cooperation in the collective-governance of public goods should emerge when stakeholders know they will have repeated interactions for the indefinite future (Binmore, 2005). This indefinitely long future sets up

the conditions for cooperation and self-interest to become aligned, rather than antagonistic, when people participate in social dilemmas. Reciprocity and deliberation are specific strategies that enable groups to overcome the assurance problem, but for individuals they are only good strategies when people realize they share an indefinitely long future together.

Due to our evolutionary history, humans probably have cognitive mechanisms for partitioning the incentives of long-term cooperation and short-term competition (Binmore, 2005). A focus on shared goals about the long-term future may be more likely to engage these mechanisms for cooperation. Human trust can be understood as a heuristic mental model, by which people remember past patterns of reciprocation, when considering future opportunities for cooperation and vulnerabilities to cheating. Trust can come from personal experience with a person, or a person’s reputation as gleaned from a trusted source of information (Milinski *et al.*, 2006, 2008).

Other concepts emphasized by the social scientists include leadership, information networks, a deliberative venue, all for building this capacity for trust and deliberation, and thus a capacity for adaptive governance. These various capacity-building components are considered elements of social capital, defined as “features of social organization, such as trust, norms, and networks, that can improve the efficiency of society by facilitating coordinated actions.” (Marshall, 2005;

Pretty, 2003; Folke *et al.*, 2005). Social capital can improve the efficiency of decision-making about shared goods (Ostrom, 2008b; Dietz *et al.*, 2003; Marshall, 2005; Folke *et al.*, 2005).

In short, a shared vision for the future can align interests and encourage cooperation, which in turn has the potential to improve rather than undermine the adaptive capacity of public goods, such as the functioning of watersheds and stream systems. However, the initial construction of a shared vision is still vulnerable to the second- and third-order assurance problems mentioned earlier, as are later decisions within the context of a shared vision. Different stakeholders will have incentive to frame issues and to bias costs and benefits differently, and these various frames will compete to become the shared frame. Some tactics will tend to undermine social capital, and others will tend to build social capital.

Thus, trust, reciprocity, and other forms of social capital are second-level public goods that are necessary for the process, but are themselves highly vulnerable to the tragedy of the commons (Ostrom, 2008a; Marshall, 2005). A subtle point is worth mentioning: Reciprocity can involve reciprocating lack of cooperation, as well as cooperation, because it signals to other people that the potential cooperator is monitoring this possibility for erosion of trust, and is responding rationally: itself a form of trust-building (Binmore, 2005). This can work because it builds trust in the short term, which is necessary for cooperation in the long term. The reason for non-cooperation, and openness to cooperation, must be clearly signaled for this to be an effective strategy at building social capital. This is part of the reason for establishing a tradition of meaningful deliberation.

What is the ideal scope and scale of a deliberative venue? Ostrom (2009) summarized evidence that the difficulty of cooperating increases with size of the resource system and the number of stakeholders, suggesting that scale should be as small as possible. At the same time, discreteness of boundaries helps with cooperation (Ostrom, 2008a), and there are upstream-

downstream conflicts and feedback loops in human-creek interactions (Mount, 1995). So the scale for deliberation should strive to be no smaller than an entire stream network, if it is to avoid being sunk by externalities.

Where to start? The goal is not simply to pursue the “low-hanging fruit.” It is to learn how to help initiate deliberation traditions that propagate via social learning (Holling, 2001). So one would want to start in basins where the issues are not too easy, but not too difficult either: they should be just right for learning how to succeed, and then moving on to more difficult situations. At the same time, examples of success themselves could potentially propagate the social learning process autonomously. In this context, pursuit of “low-hanging fruit” can have a broader benefit if it creates assurance by establishing social capital and accurate reputations. In short, the idea is a capacity-building, social-learning process that gathers steam rather than dissipates it. The NMFS integrative assessment framework (Levin *et al.*, 2009; Ruckelshaus *et al.*, 2008; Tallis *et al.*) provides a general map by which a shared vision could be developed and pursued.

### Deliberation and Science

Recovery of steelhead along the south-central and southern California coast requires scientific research on the regions’ fire regimes and on the flow and sediment regimes of its stream systems (Boughton *et al.*, 2006, 2007). However, the operation of these regimes is deeply intertwined not just with steelhead ecology, but also with the human population of the region. Thus, research on these topics will be most useful if it occurs within the context of ecosystem management and meaningful stakeholder deliberation, just described.

Let us frame the role of scientists in deliberation by creating a new version of Kangas’ (Figure 5) diagram, annotated with concepts from the fields of river management and restoration (see Figure 6 next page).

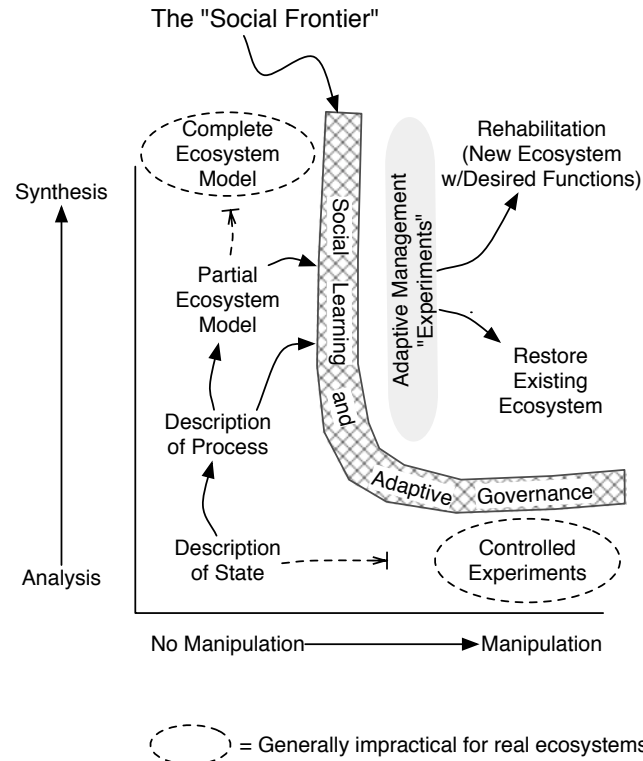


Figure 6: Pathways through the spectrum-of-methods for restoring fluvial processes to steelhead streams.

River systems are too big and unique for controlled, replicated experiments, and too complex to be completely understood via models, so these scientific methods are impractical. Much preliminary progress can be made along the left side of the diagram, by describing the systems, interpreting key processes, and attempting to assemble those processes into some sort of partial model of ecosystem function.

However, the point of all this preliminary work is ultimately to cross “the social frontier” and alter the function of the actual ecosystem, either to learn or to achieve some uncertain goal, or both. Adaptive management seems to falter because too much effort is spent churning around on the left side of the diagram, without much progress in crossing the social frontier. Apparently there is not incentive to do otherwise.

There are various practical tools from the social sciences that seem likely to be useful for improving the quality of deliberation right away, and other tools that could be developed over time. To guide the selection of tools, consider again the left side of Figure 6. The values of scientists lead them to steadily work their way up from bottom (description of state) to top (complete ecosystem model), although at the same time it is widely acknowledged that the ultimate endpoint, a complete quantitative model, is unattainable. This

steady progression may not always be a good investment of time and effort, if it is simply another form of Marshall’s (2005) “lock-in” to a path with poor return on investment. The larger goal is not to move to a more complete model, but to cross the “social frontier,” and the optimal spot from which to cross is not necessarily at the end of the sequence.

Nor is simple description of state an optimal point at which to cross. A description of state with insufficient appreciation for process and core causes does not convey the essential nature of self-organization (Beechie *et al.*, 2010). Thus one can fail without learning much (Kondolf *et al.*, 2001).

At the other end of the spectrum, highly technical, quantitative models have other weaknesses: they are difficult to explain, and require many specific assumptions that can be difficult to justify, especially to skeptics. Indeed, skeptics may deploy models with alternative assumptions, so that modeling decisions devolve to the framing-competition mentioned earlier. Although this competition may be an inevitable part of the process, ultimately it is only useful if it helps movement across the social frontier. Finally, highly technical models tend to “hog the bandwidth” of stakeholders, who need to grasp the essential nature of a problem rather than technical details.

Descriptive process models may have promise for crossing the social frontier, though to convey the nature of self-organization they must strive to be comprehensive even if they are not quantitative. Examples of widely used descriptive process models are the stream classification system of Montgomery and Buffington (1997) and the River Styles Framework used in Australia (Brierley and Fryirs, 2005). The latter is an open-ended analysis system based in hierarchy theory and geomorphology. It is specifically designed to help people learn how to look at streams and “read” fluvial processes from pattern.

What Rogers (2006) is arguing is that if scientists wish their work to contribute to a durable solution, they need to take seriously this issue of models optimized to facilitate social learning rather than prediction or conditional precision (see also Dollar *et al.*, 2007; Pickett *et al.*, 1999; Steyaert and Ollivier, 2007). Otherwise, they risk taking sides in a transitory duel of mental models, which may erode social capital rather than building it up for adaptive decision-making.

Currently, it appears many ecologists have adopted a pragmatic approach to crossing the social frontier. For example, they construct a box-and-arrow diagram illustrating key ecosystem processes and label it a conceptual model. The box-and-arrow diagrams are constructed collaboratively by a group of interested scientists, for the purpose of achieving consensus in their own group and communicating the result. There may be ways that this approach could draw on insights from the social sciences, and thus develop more effective strategies to support social learning. Below are my thoughts, in the form of tools that could be deployed now and scientific products that could be developed over time.

### Three Existing Tools for the Deliberative Process

Here are three tools to help groups develop shared understanding about the functioning of complex systems. These tools are 1) general purpose, 2) simple to use, 3) analyze problems comprehensively, and 4) provide discipline to group deliberations. Each provides a structured process for a specific aspect of deliberation:

1. Concept-mapping (Novak, 2002) helps groups come to a shared understanding of how the world works.
2. Morphological analysis (Ritchey, 1998; Coyle *et al.*, 1994) helps groups creatively explore how the future might unfold.
3. Values-focused thinking (Keeney, 1992, 1994) helps groups identify their fundamental values and construct creative decisions.

**Concept mapping.** Concept mapping is just a set of conventions for developing box-and-arrow diagrams, optimized to reflect findings from learning theory (Novak, 2002). It has been effective for science teaching in schools (Novak, 2005), transferring scientific knowledge from experts to novices in a professional setting (Hoffman *et al.*, 2006), and developing conceptual models in integrated water management and ecosystem management (Kolkman *et al.*, 2005; Delgado *et al.*, 2009).

Concept mapping is based on the distinction between rote learning and meaningful learning. The key idea is that people actively construct meaningful knowledge by integrating it into their existing cognitive structure, or mental model. Rote learning is not integrated, causing two problems: it is soon forgotten, and it does not modify, or get modified by, any contradictory ideas in the person’s existing mental model. According to Novak, meaningful learning requires three conditions: 1) the material must use clear language and syntax; 2) The learner must possess relevant prior knowledge; and 3) the learner must choose to learn meaningfully.

The first condition is met by giving the boxes and arrows standardized roles in depicting knowledge. Boxes are concepts, which are defined as a perceived regularity or pattern in events or objects, designated by a label. Arrows are used to construct propositions, defined as a statement that uses linking phrases to combine concepts into a meaningful statement.

The syntax for propositions is different from the informal syntax used by many ecologists, which typically has unlabelled arrows whose meaning is ambiguous. The arrows represent the vague notion of logical connections, rather than specific propositions. I often find them hard to understand unless I already know what they are trying to say.

The second condition (learner having prior relevant knowledge) is met by developing concept maps collaboratively, or by structuring the concept map to connect familiar and unfamiliar propositions. Free, web-based software is available for collaborative concept-mapping at <http://www.ihmc.us>. The benefit of connecting new knowledge to the learner’s prior knowledge might be why geographic information systems are so effective, by placing new information in the context of a familiar map. But geographic maps tend to be static and thus a poor medium for describing natural processes rather than conditions. Concept maps can be about processes, including the graphic depiction of feedback loops and hierarchical structures.

The third condition concerns emotional motivation, which is related to the incentives and social capital surrounding the deliberation process. Rogers (2006) argues that excitement about an attractive future provides strong motivation for people to modify their existing mental models, and this gets back to the idea of

strategic visioning of the future as an effective context for concept mapping.

**Morphological Analysis.** Morphological analysis is a simple, qualitative tool for systematically constructing and exploring scenarios (Ritchey, 1998). It is used to support a group of people engaged in scenario planning about complex, uncertain situations, and thus aids in getting stakeholders to think strategically about the future.

Everyone has their own ideas about what sorts of unfolding events will shape the future. In morphological analysis, these ideas are described, and synthesized into a set of environmental and social “sectors.” Examples of sectors might include things like “Habitat restoration efforts,” “Precipitation patterns,” “Status of Hydrological Services,” “Status of steelhead,” “Public sentiment toward bond measures,” and so forth. Each of these sectors is then further subdivided into a set of distinct plausible situations. For example, Habitat restoration efforts might be subdivided into “few and far between,” “robust, coordinated effort,” “many, but success not monitored,” and so forth. An effort is made to limit the number of sectors and factors per sector: Greater than a few, but less than 10 factors per sector, to stimulate creative thinking without getting overwhelmed by sheer magnitude.

In principle, the future could unfold as any one of the giant number of all possible combinations of factors. The method involves simple procedures for pruning logical contradictions, and lumping similar situations. These two elements underlie the value of the method: they allow participants to identify logical inconsistencies that rule out some scenarios; to identify scenarios previously thought to be distinct but that may be quite similar; and to discover new scenarios that they had not foreseen.

The potential value of morphological analysis is that it could 1) help stakeholders expose and deliberate their various mental models about the future; 2) synthesize a shared understanding about the broad set of possible futures; and 3) think strategically about desired futures.

Ritchey (1998) gives a good introduction to the method. Coyle *et al.* (1994) describe a specific set of steps to work through, and Coyle and McGlone (1995) give an illuminating example using a regional geopolitical setting. The method benefits from computer support that would have to be developed, but the actual math is quite straightforward. Ritchey and de Wall (2007) describe combining the method with Bayesian belief networks for application to hierarchically structured problems.

**Values-focused thinking.** Values-focused thinking is a procedure for improving decisions. Keeney (1992) argues that most decisions are made by identifying existing alternatives and choosing the best one. But this is a poor method because it only explores existing

opportunities, rather than creating new opportunities that may better reflect people’s fundamental values. Keeney (1992) provides a procedure for specifying general goals, deconstructing them into fundamental values, and then using those values as the basis for actively constructing new opportunities.

The reason this tool is useful is that most people confound means and ends when it comes to values. Thus they fail to think creatively about the full range of options that may be open to them, or indeed that they can actively work to create. The tool obviously has potential to help reduce the transaction costs for expanding adaptive capacity. Rogers (2006) reports that values-focused thinking was central to the success of strategic adaptive management in Kruger National Park, South Africa. Gregory and Wellman (2001) report on its usefulness in estuary restoration in Tillamook, Oregon, and Levin *et al.* (2009) incorporate it in ecosystem management, under the NOAA Fisheries Integrated Assessment model. Naiman and Latterell (2005) discuss values-focused thinking as a key element of managing fish habitat in general.

### New Analytic Frameworks to Support Deliberation

Based on findings described in this report, a durable solution for steelhead recovery is process-based stream rehabilitation that reconciles three conditions: steelhead viability, self-adjustment of stream systems, and the provision of hydrological services for people.

The necessary scientific framework for a durable solution involves two key principles: 1) solutions that focus on fundamental causes for stream degradation, rather than superficial fixes (Brierley and Fryirs, 2005; Beechie *et al.*, 2010); and 2) solutions that emphasize resilience in the face of an unpredictable future (Levin and Lubchenco, 2008; Schindler *et al.*, 2008). Here are four complementary frameworks that could be developed to help implement these principles. Each involves a sustained long-term effort.

#### 1. *Descriptive Process Models for River Behavior.*

This would involve a southern-California adaptation of existing river-restoration frameworks, such as the River Styles framework used in Australia (Brierley and Fryirs, 2005), hierarchical frameworks used in the wetter Pacific Northwest (Frissell *et al.*, 1986; Ebersole *et al.*, 1997; Benda *et al.*, 2007), and frameworks developed under the European Framework Directive (Orr *et al.*, 2008; Bruen, 2008; Newson and Large, 2006; Vaughan *et al.*, 2009).

#### 2. *Descriptive Process Models for Human Interventions.*

This would be an analytic framework for learning how to assess and design resiliency in the development of river-management options. There are potentially many principles involved, including

redundancy/degeneracy, adaptive capacity, learning institutions, and the like (Levin and Lubchenco, 2008; Edelman and Gally, 2001; Rogers, 2006; Allan *et al.*, 2008). The idea here is to lay the groundwork for ecologists, engineers and social scientists to collaborate on solutions, as recommended by Wohl *et al.* (2005) and Palmer and Bernhardt (2006).

### 3. *Characterization of Natural Capital and Ecosystem Services.*

The goal is to provide a framework for better characterizing how stream systems provide hydrological services, perhaps drawing on concepts from Brauman *et al.* (2007), and the general implementation model of Cowling *et al.* (2008). This would aid in identifying where rehabilitation has the most promise for building capacity, or lack of rehabilitation poses the greatest lock-ins to expensive solutions.

### 4. *Descriptive Process Models for Viable Steelhead Populations.*

In developing guiding images for stream rehabilitation, there will need to be an analytic framework for qualitatively assessing the consistency between an envisioned system of rehabilitated channel behaviors (including human interventions), and potential viability of steelhead populations. The framework could draw on the general approach of Moberand *et al.* (1997), which frames how stream systems enable salmonid opportunities in terms of abundance, productivity, diversity, and spatial structure. For economy and simplicity one might avoid a detailed quantitative application of the Moberand approach (see Steel *et al.*, 2009), instead staying with descriptive process models in a hierarchical framework. I've briefly sketched a mock-up of the basic idea in Figure 8. The idea is to create a qualitative

system of analysis to implement some key design principles for dealing with climate change: widening the opportunities for fish to pursue diverse and abundant life histories; promote evolvability of populations and metapopulations; systematically evaluate fundamental physical limits, such as access, baseflows and thermal refugia; and maintain key capacities for adaptive management to respond to changes as they occur.

In a sense, the four elements listed above would be a refinement of the intrinsic potential concept (*i.e.* Burnett *et al.*, 2007; Boughton and Goslin, 2006), modified to be more specific about fluvial processes, riparian vegetation, VSP parameters, and amenable to scenario-planning with respect to human interventions and climate change. The goal is to support the emergence of a system of stream behaviors and human interventions that

- Looks forward, not backward
- Usefully rehabilitates streams in steelhead-friendly ways.
- Provides diverse opportunities for steelhead within their competence
- Sustains hydrological services by reinforcing natural capital and self-organization of stream systems
- Builds natural and social adaptive capacity to deal with climate change

Opportunities for other native freshwater and riparian species would likely emerge from this system.



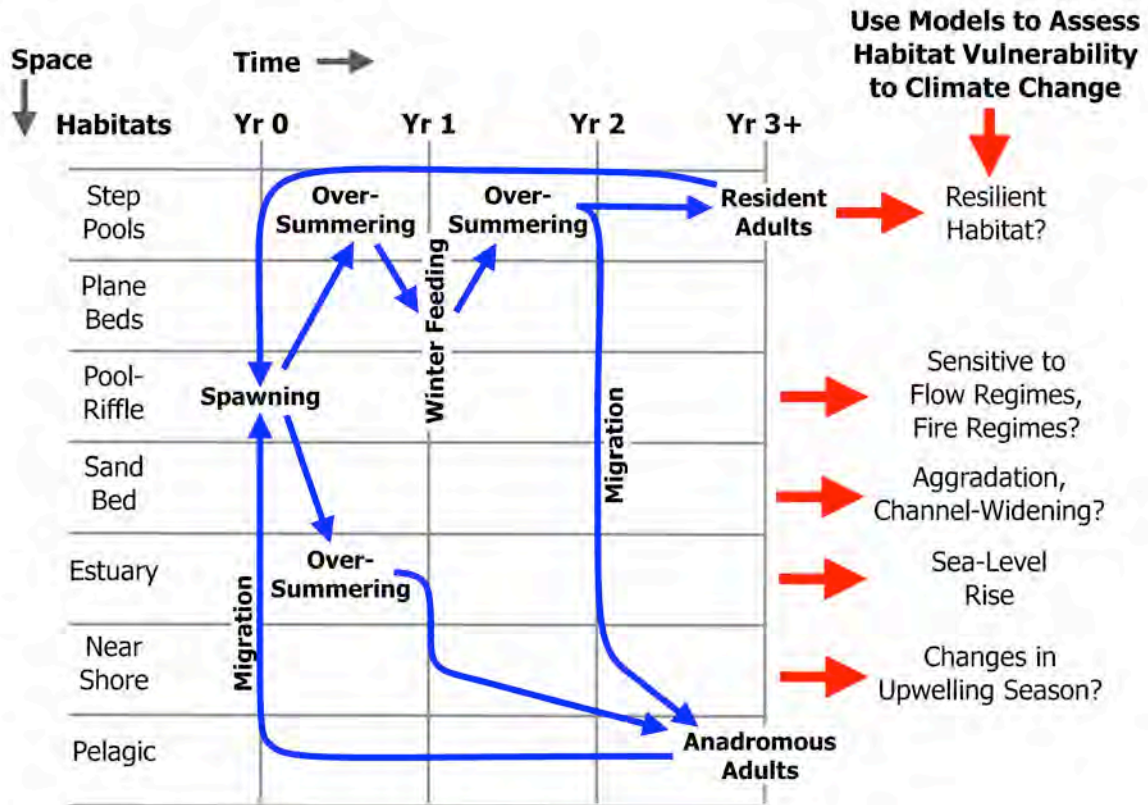


Figure 8: A descriptive process model for a hypothetical steelhead stream in southern California. The vertical axis shows position along the creek channel, from headwaters to ocean; and the horizontal axis shows time. The attractor, or tendency, for stream behavior (left side: step pools, plane-beds, etc.) can be predicted by hierarchically-framed induction (Montgomery and Buffington, 1997; Buffington *et al.*, 2004). Blue pathways represent life-history opportunities for steelhead, which can be characterized in terms of diversity, capacity, productivity, and spatial structure (Moberg *et al.*, 1997).

## Stream Restoration and Learning Institutions

Bernhardt *et al.* (2005) warned that river restoration would not be able to learn from its mistakes, and thus progress as a science, if suitable learning systems fail to be instituted. A learning institution in this sense is a set of social conventions that provide an informational feedback loop, like the data-collection/ peer review/ publication cycle pursued by most scientists, or indeed any system of trial and error that tracks successes and failures and learns from them.

Palmer *et al.* (2005) propose a general, open-ended standard for judging the ecological success of river restoration projects. They distinguish ecological success as distinct from other types of success such as cost-effectiveness or social acceptability, noting that ecological restoration or rehabilitation is the explicit goal of many projects, and that progress in the practice of river rehabilitation is hampered by a lack of agreed criteria for judging ecological success. They propose five general criteria for ecological success:

***A guiding image exists:*** A dynamic ecological endpoint is identified a priori and used to guide the restoration. This criterion derives from the *leitbild* concept that originated in German channel restoration efforts (Piegay *et al.*, 2008). Development of guiding images, usually via interaction of scientists, restoration practitioners, and local communities, is now common practice in Europe under the water framework directive (Piegay *et al.*, 2008) and is also a central tenant of the River Styles framework in Australia (Brierley and Fryirs, 2005). Five alternative sources for synthesizing a guiding image are 1) Information on historical condition of the stream; 2) Undisturbed stream systems nearby that can serve as a reference condition; 3) Analytical or process-based approaches, often based on empirical relationships observed in specific functions, such as sediment transport; 4) Descriptive classification systems, though these are prone to failure if they do not account for geomorphic and hydrologic processes (Kondolf *et al.*, 2001); and 5) Common sense for straightforward situations such as the removal of anthropogenic stressors (cattle fencing, removal of culverts) or planting of riparian vegetation. A guiding image should be consistent with the dynamics of the larger ecosystem (stream network, watershed). The identification and commitment to guiding images for entire watershed systems appears to be a key step in the turnaround of steelhead.

***The ecosystem is demonstrably improved:*** Ecologically successful restoration will induce measurable changes in physical, chemical and biological components of the stream that move it towards the agreed upon guiding image. It should be recognized that such movements may take time (Palmer *et al.*, 2005), and indeed the rehabilitation of natural processes and disturbance regimes will often increase the variability and

heterogeneity of conditions in the short term and the perception of “movement” should take this into account (Reeves *et al.*, 1995). This criterion presupposes a system of ecological indicators by which condition is evaluated. In the context of steelhead recovery, there are two levels of indicators. One level of indicators is the set of population viability criteria described for steelhead by Boughton *et al.* (2007). These will rarely be appropriate for specifically assessing stream restoration efforts, which require a second level of indicators. Due to disturbance regimes and natural variability, it may take many years to detect unambiguous upward movement in either the viability indicators or the restoration indicators (Waples *et al.*, 2009).

***Resilience is increased:*** The river is more self-sustaining than prior to the restoration. This is where the rehabilitation of natural river processes comes in: allowance for channel movement, river-floodplain exchanges, organic matter retention, biotic dispersal, etc. (Palmer *et al.*, 2005). The ideal restoration activity requires no further maintenance or repair, having been conceived so that the self-organizing capacity of the system itself sustains the movement of the stream toward the guiding image. There are of course situations in which “hard” engineered structures may enhance the resilience of a stream network. Some examples given by Palmer *et al.* (2005) are 1) grade restoration structures in incised streams, which if well conceived will prevent further incision and encourage lateral channel movement; 2) culvert redesigns that allow fish passage and lateral channel movement; and 3) establishment of channel pathways to a floodplain that was formerly cut off. The latter two examples represent a “softening” of an existing hard infrastructure, judged by the ecological processes in the system (fish movement, floodwater dynamics) becoming more similar to the guiding image. The astute placement of engineered structures within an ecological context is one promising route forward.

***No lasting harm is done:*** Implementing the restoration or rehabilitation effort does not inflict irreparable harm to the stream system.

***Ecological assessment is completed:*** Some level of both pre- and post-project assessment is conducted and the information made available.

It should be noted that these standards are not specific, measurable standards, but instead require reasoned judgment to apply and assess. There are various ways that these standards could be implemented. One possibility is a system modeled on peer-review, in which a proposed rehabilitation effort must explicitly argue its merits in terms of each of these standards, and pass review by peers drawn from the community of river-restoration practitioners. A similar peer-review process, perhaps coordinated by a central clearing house similar to an editorial board or review board, could periodically conduct follow-up assessments of success.

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