SAN FRANCISCO ESTUARY & WATERSHED SCIENCE
Sponsored by the Delta Science Program and the UC Davis John Muir Institute of the Environment

Forecasting the Most Likely Status of Wild Salmon in the California Central Valley in 2100*

Sierra E. Franks[1] and Robert T. Lackey[2]

Volume 13, Issue 1, Article 1 | April 2015

doi: *http://dx.doi.org/10.15447/sfews.2015v13iss1art1*

1 Corresponding author: *Sierra.Franks@lifetime.oregonstate.edu;* Master of Natural Resources Program, Oregon State University, Corvallis, Oregon 97331

2 Department of Fisheries and Wildlife, Oregon State University, Corvallis, Oregon 97331

ABSTRACT

Since the mid-1800s the Sacramento–San Joaquin river system in the California Central Valley has experienced a dramatic decline in the distribution and abundance of wild salmon, along with many extirpations. The causes of the decline are many, and have been well studied. Despite restoration efforts spanning decades and involving large expenditures, runs of wild salmon in the Central Valley continue to decline. Using the most probable policy and ecological scenarios (i.e., effects of continued harvest, continued stocking from hatcheries, changing climate, continued human population growth and associated demands for scarce water resources) and based on expert judgment, we assessed the most likely future of wild salmon runs in the Central Valley in 2100. We posed seven open-ended questions to senior salmon science and policy experts in federal and state agencies; local, regional, and national organizations; non-governmental organizations; and universities. With a promise of complete and permanent anonymity, these experts provided answers. Most experts concluded that by 2100 wild salmon in the Central Valley will be extirpated or minimally abundant if current trends continue.

* This article is based on research conducted by the senior author as part of the requirements for a Master of Natural Resources degree at Oregon State University. The views and opinions are those of the authors and do not necessarily represent those of any organization.

INTRODUCTION

Chinook salmon (*Oncorhynchus tshawytscha*) is the only semelparous anadromous salmon that currently exists in the Sacramento–San Joaquin river system in the California Central Valley. The majority of the four Chinook runs (spring, fall, late-fall, and winter) are currently supported by releases from hatcheries (Fisher 1994), but much of the policy and legal conflict revolves around the status of wild salmon. We define "wild" salmon as those born in rivers, a result of parents who spawned in rivers. Our analysis covers the Central Valley, but also briefly touches on the San Francisco Bay–Delta estuary because it is the only route for wild salmon to migrate between the Pacific Ocean and the Central Valley.

The pre-1848 salmon runs in the Central Valley most likely numbered in the several millions. Yoshiyama et al. (1998) conservatively put the number of historical Chinook salmon spawners in the Central Valley at 1 to 2 million, while Gesh et al. (2000) estimated the number at 2 to 4 million. Drawn by the allure of gold, a large influx of settlers to the Central Valley greatly altered waterways and riparian habitat with large-scale mining operations (Holmberg 1971), substantially reducing viable spawning habitat, and thus greatly reducing the once robust salmon population. Subsistence and commercial fishing was also intense throughout the late 1800s. By 1882, the Sacramento

River hosted 19 canneries producing 200,000 cases of salmon annually, nearly 4.3 million kg (Gesh et al. 2000). In response, the salmon rapidly diminished.

Rim dams have eliminated most of the spawning and rearing habitat in the Central Valley. The resulting highly regulated flows and diversions are substantially different from natural flow regimes to which these species are evolved. The rivers have been levied, channeled, and disconnected from floodplains to such an extent that river habitats for natural spawning and rearing conditions are largely absent. Additionally, changes in environmental conditions for fish in the Delta associated with water exports, altered water quality, entrainment, and predation have significantly increased mortality of migrating salmon (Cummins et al. 2008). By 2009, total returns of Chinook runs were just over 70,000 fish ("natural" and hatchery fish combined), around 5% of the average historical abundance (Katz and Moyle 2012); and of these, only a small proportion were of wild origin.

Similar to the approach taken by others (Lund et al. 2008; Hanak et al. 2013; Null et al. 2012), we posed seven open-ended questions to senior salmon science and policy experts from federal and state agencies; local, regional, and national organizations; non-governmental organizations; and universities. This analysis differs from aforementioned work in that it focuses on widely known risk and asks salmon science and policy experts open-ended questions with a promise of anonymity. All respondents were intimately familiar with the current stressors described below as they pertain to the past and current salmon situation in the Central Valley, as well as with current recovery efforts. This paper is broken into two parts: a brief review of California's Central Valley's current stressors and an analysis of an anonymous survey about the effects of those stressors. Four runs of Chinook salmon are endemic to California's Central Valley, and some stressors provide different effects to these runs. The purpose of our analysis is to provide the broadest overview of the stressors to give context for our survey of the polled experts' responses.

CURRENT STRESSORS

Water Diversions

Nearly all analyses attribute effects on salmon runs in the Central Valley to multiple stressors. Most analyses point to direct and indirect effects of water diversions as an important factor in the decline of salmon populations in the Central Valley (Moyle et al. 2008; Holmberg 1971; Kjelson et al. 1981). Demand for water from a rapidly growing human population in California now causes severe resource conflict, and the level of conflict is likely to continue to increase. Currently, 27 million Californians receive water from the Central Valley (Delta Stewardship Council 2010). State and federal contracts provide for export of up to 7.5 million acre-feet per year from two massive pumping stations in the southern Sacramento–San Joaquin Delta (CDWR 1995).

Almost every tributary to the Sacramento and San Joaquin rivers has a major dam on it. Dams, along with water diversions, alter the natural hydrology, temperature, salinity, turbidity, etc., to which wild salmon are evolutionarily adapted. Further, these dams block access to nearly 82% of the overall spawning and rearing habitat that was once available to salmon, but the specific percentage of accessible habitat is highly variable by watershed (Yoshiyama et al. 1996). There are over 3,300 diversions in the Sacramento and San Joaquin rivers and the Delta, of which approximately 98.5% were either unscreened or screened insufficiently to prevent fish entrainment (Herren and Kawasaki 2001).

Freshwater habitats across the Central Valley watershed have been altered in myriad ways that no longer favor salmon. While water diversions continue to pose threats to existing Chinook salmon production in the Central Valley, the long-term decline in abundance, productive capacity, and diversity of Central Valley Chinook cannot be understood without addressing the massive loss of tributary and floodplain habitats that formerly supported diverse and productive spawning and rearing areas (Lindley et al. 2009). To restore the capacity for natural production in Central Valley Chinook salmon, it seems likely that salmon would require access to tributary and floodplain habitats that have been blocked by dams,

dikes and levees, in addition to improved habitat and migration conditions in the mainstem Sacramento and San Joaquin rivers and the Delta.

Hatcheries

Salmon hatcheries have a long history in California. In response to the dramatic declines in salmon runs in the 1850s and 1860s, the State of California established in 1870 the Board of Commissioners for Fisheries. One of the Board's responsibilities was to establish "fish breederies" to stock and supply streams, lakes, and bays with both foreign and domestic fish (CDFG 2010). This legislation led to the creation of an extensive hatchery program that has sustained runs of Chinook salmon in the basin. However, abundance of these hatchery returns has obscured the fact that wild salmonid runs have greatly declined and now constitute a minimal component of most runs (Kormos et al. 2012). For example, a recent study by Johnson et al. (2012) on the Mokelumne River (a tributary to the San Joaquin River) estimated that 90.7% to 99.3% of returning adults (total fish in river and hatchery), were produced in a hatchery. An earlier study (Barnett–Johnson et al. 2007) estimated the contributions of wild Chinook salmon to the California coastal fishery and concluded (assuming this is the case basin wide) that hatchery management practice would need to be dramatically altered. Specifically, if the goals and strategies as outlined in the California Hatchery Scientific Review Group Report (2012) for Central Valley salmonids or the United States Fish and Wildlife Service Anadromous Fish Restoration Program (AFRP) which aims to "make all reasonable efforts to at least double natural production of anadromous fish in California's Central Valley streams on a long-term, sustainable basis" (USFWS 2001) are to be achieved. Some scientists have argued that it will be impossible to restore wild salmon unless interbreeding with hatchery produced stock is eliminated (Katz et al. 2012).

Harvest

Commercial fishing in the Sacramento–San Joaquin River basin began soon after the discovery of gold in the region. Later, with the adoption of increasingly effective fishing techniques, coupled with the ability to pack salmon in cans for shipment worldwide, harvest hit an all-time high. Eventually most salmon were taken by trolling in the ocean, though until 1956, fishing continued in-river and in the bay, primarily with gill nets. During World War II for example, gill nets caught nearly half of the salmon landed (Fry 1949). Annual catches of Chinook salmon by the early Sacramento–San Joaquin in-river fishery commonly reached 4 to 10 million pounds (1.8 to 4.5 million kilograms), and generally were higher than the total statewide catches made during the most recent several decades (Yoshiyama et al. 1998). Mixed-age ocean fishing has also resulted in shifts in the size and age distributions of spawning fish. It is believed that age distribution has been truncated by about a year, resulting in fewer large fish than there were historically. In 2008 and 2009, the salmon runs collapsed, and for the first time, commercial and sport fishing off the coast of California was suspended (Michael 2010).

CURRENT TRAJECTORIES

Population Growth

Human population growth and the associated human demands on already heavily used natural resources (i.e., water, land) will be a critical policy driver that determines whether wild salmon can be expected in significant, sustainable numbers in the Central Valley in 2100. The inverse relationship between the increasing human population of California and declining salmon runs has long been recognized in California and elsewhere (Holmberg 1971; Lackey 2005). The population in California in 2010 was 37 million (U.S. Census Bureau 2012), but is projected to be around 50 million in 2050 (CDF 2015). By 2100, these projections hover at around 90 million (Landis and Reilly 2003), almost triple the current population of California. With additional population growth will come additional demand for land and water, and the options for sustaining (much less restoring) wild salmon will be increasingly constrained.

Climate Change

Climate change is another factor to consider when forecasting the most likely status of wild salmon in the Central Valley in 2100. Global and localized climate changes (e.g., El Niño ocean conditions, prolonged drought conditions) affect the suitability of salmon habitat and, hence, viability (Ficke et al. 2007) especially in the southern edge of the distribution (i.e., California). Through this century, the Sierra Nevada snow pack is expected to decrease with the long-term trend of increasing temperatures in California (CDWR 2006). Thus, the majority of runoff in the Central Valley will be from winter rainfall rather than from melting snow pack in the spring and early summer. Given this change in runoff, summer temperatures and flow levels will likely become unsuitable for salmonid survival (National Academy of Sciences 2012).

Current Recovery Efforts

Currently, major and costly salmon restoration efforts are occurring in the Central Valley aimed at increasing wild salmon numbers. Some notable projects include outright dam removal (Battle Creek), removal or closure of water diversion gates (Red Bluff Diversion Dam), stream and river restoration (sections of Clear and Battle creeks, the San Joaquin and Stanislaus rivers), reintroduction of salmon to an extirpated system (San Joaquin River Restoration Program), and introduction of measures to incorporate fish passage above large rim dams (Shasta Dam). In addition, there are many legal and policy conflicts over how Central Valley water is to be allocated. Many of these recovery efforts are a result of listing certain runs of Chinook salmon under terms of the Endangered Species Act. Evaluating the probability of success of these efforts (from a wild salmon perspective) is critical to determining the most likely status of wild salmon in the Central Valley in 2100.

METHODS

There are a relatively small number of experts who have been working on the joint issues of salmon science and policy management of Central Valley salmon for many years. Based on anecdotal experience, what these experts say publicly is not necessarily what they think or believe (Lackey 2001; Lackey et al. 2006). The agencies that employ these experts are often active in political debates about the future of wild salmon, exposing their employees to covert, or even overt, pressure to align their stated views with agency-specific policy goals. University employees, who are, in principle, independent and not subject to such policy pressures, nonetheless often depend on grants from organizations with a vested interest in the outcome of salmon policy debates. Thus, obtaining unbiased, candid, and complete answers about the future of wild salmon in the Central Valley is a challenge.

To obtain a candid assessment of the future of wild salmon in the Central Valley from those most knowledgeable, we contacted colleagues to create a list of experts who we believed were both knowledgeable about salmon recovery and had many years of relevant experience. From this list, we selected 33 who we regarded as being the most credible, based on expertise and experience. As expected, most of these experts worked for organizations that have been deeply engaged in salmon science and policy. We solicited input from these experts with the assurance that their identity would not be disclosed and their responses would be anonymous. Providing anonymity was intended to allow respondents to be open and truthful—and free from worry about possible repercussions from their current employer or possible feedback from colleagues or others if their personal viewpoints differed from those of the rest of their agency/university/organization. To further assure respondents of our intention of anonymity, the Oregon State University Institutional Research Board formally reviewed and approved our study before the survey was conducted.

Most of the selected individuals have published numerous peer-reviewed articles and hold (or held) high-level positions within their organizations. In general, respondents could be classified as senior salmon science and policy experts in federal and state agencies; local, regional and national organizations; non-governmental organizations; and universities, averaging approximately 20 years of experience.

Of the 33 requests, 26 (79%) agreed to participate. Of this group, 13 held a doctorate degree (50%), 12 held a master's degree (46%), and 1 held a bachelor's degree (4%). Participants' backgrounds varied, with most having worked throughout California's Central Valley basin for many years; and were familiar with the situation. Others have dealt with similar issues in Oregon and Washington. Our assumption was that these individuals collectively would be the best to gauge the future of wild salmon in the Central Valley. We asked all participants the same seven core, open-ended questions. Interviews were conducted in person, over the phone, or by email. Responses were analyzed subjectively.

RESULTS

Question 1: Given current policies and trajectories, what is the most likely status of wild salmon in the Central Valley in 2100?

Responses: As with all questions, the focus was on wild salmon—those resulting from parents who spawned naturally in streams and rivers, and respondents were given this definition before answering the question. Salmon originating from hatcheries were not included. The nearly universal conclusion from the 26 experts was that few, if any, wild salmon populations will persist in the Central Valley in 2100. In short, current policies and trajectories are leading to the demise of wild salmon in the Central Valley. Specifically, 20 of the 26 respondents (77%) concluded that wild salmon will not be present in the Central Valley by 2100. One of the 26 (4%) believed that wild populations would be larger than they are now, and 5 of the 26 (19%) believed that extirpation was possible, but still had some hope based on current recovery efforts. The following is a cross-section of the responses:

> "Poor to non-existent. I think climate change will be the main determinant of whether remnant populations of wild salmon remain in the Central Valley."

> "Marginal at best, but also depends on our definition of 'wild.'"

> "Complete extinction of individual stocks is more likely in the Central Valley than in most places due to the water demands, power demands, etc. that completely blocks access and/or dries up streams."

> "Even among the agencies managing the Central Valley salmon there is no consensus on the value of historical or wild runs of fish. California Department of Fish and Game is just as happy with hatchery fish as with wild fish — and what is really the difference?"

The one contrasting assessment for wild salmon was:

> "I would project the major salmon runs to be surviving and somewhat more robust by 2100. This projection assumes that the policies and practices of the past decade have been adjusted in light of increased scientific information, and that the social will to preserve and rebuild the runs will continue. I think the key question is whether we will soon identify and address the major factors limiting recovery."

Question 2: What would it take to restore and sustain significant, sustainable (a third of historical) runs of wild salmon in the Central Valley through 2100?

Responses: Most respondents recognized that there were a multitude of causes of the historical decline and changes would have to take into account most, or perhaps all, of these to restore and sustain significant, sustainable runs of wild salmon in the Central Valley through 2100. Some of the suggested changes were to eliminate harvest (4%, 1/26), reform hatchery practices (12%, 3/26), fix the Delta (4%, 1/26), improve habitat issues (4%, 1/26), remove dams (4%, 1/26), and reduce population growth (8%, 2/26). Most respondents (73%, 19/26) named a combination of these rather than pointing to any one in particular. Here are some of the replies:

> "I don't believe it is feasible, either economically or socially, to contemplate restoration to a third of historical levels. One can forecast by hind casting. The problem and the issues are not new: we have known of them for decades."

> "Less (human) population growth, critical needs of salmon first."

> "Valley-wide analysis of total water consumption and modeling to determine appropriate levels of water use for environmentally and economically sustainable agriculture."
>
> "Remove dams, decrease demands from human population."
>
> "If wild runs are preferred, the elimination of harvest will be required, salmon habitat will have to be preserved or restored, the role of hatcheries will need to be changed, and agricultural practice will have to change significantly."
>
> "Reformation of the hatchery system—not eradicating the hatchery system, but rather establishing best practices within the hatchery system to produce genetically diverse fish with the intention of re-establishing them as wild populations over time. Also, solving the Delta problem: it is a singular bottleneck for all Central Valley populations. Lastly, thinking way ahead about the impact of a changing Sierra snow pack on water supply, water supply reliability, and the environment and then subsequently in solutions to these challenges."

Question 3: What, exactly, does society need to do to change the downward trajectory and restore runs of wild salmon to significant, sustainable levels?

Responses: All suggested actions to change the long-term downward trajectory in wild salmon involved major modifications to current policies. These changes would be costly and politically divisive. A few responses (30%, 8/26) came back to human population growth and the effects this will have on the resource. Other responses (46%, 12/26) noted society's unwillingness to make salmon recovery a social and economic priority. (From the author's perspective, the residents of California appear to have a lot less emphasis on the culture surrounding salmon than is typical of those in the Pacific Northwest who regard their salmon as somewhat of an iconic symbol.) One respondent (4%, 1/26) also suggested rewarding agricultural and municipalities for conserving, not overusing water resources. A consistent theme (46%, 12/26) was planning for climate change and the ability of public policies to aid in salmon recovery because of these assumed pressures. Some specific comments:

> "To give salmon the best chance of dealing with the effects of climate change I think society would need to: (1) curtail additional cumulative pressures on salmon (fisheries, agricultural demands on water, pumping), (2) invest in actions to improve/restore habitats (restore flows to the San Joaquin, use technologies to cool river temperatures during migration)."
>
> "Make a concerted effort to save the species—and it will require difficult choices. To be effective at things like efficient water use, energy efficiency, and improving water quality, I think it will require potentially unpopular changes through federal, state, and local legislation. People should be rewarded for conserving not overusing. We may need to make fundamental changes in the way we manage land—like not growing crops in areas that require excessive irrigation, and requiring buildings to use the highest energy and water efficiency measures available."
>
> "Maintain functional habitat, which will require human population control, reduction in the total footprint of each individual, reservation of watersheds to provide for human needs at the expense of other natural resources (triage)."
>
> "Stop growing water-intensive crops, i.e., rice and cotton. Create a valley-wide land planning initiative."

Question 4: Is it possible to restore wild salmon in the Central Valley while supplemental stocking from hatcheries continues?

Responses: The consensus (76%, 20/26) was that current hatchery practices would have to be changed to restore and sustain wild salmon in the Central Valley. About half (46%, 12/26) of the respondents went further and concluded that supplemental stocking would have to be terminated if wild salmon were to be restored. It was clear from all respondents' answers that there are deficiencies in the current way hatcheries are being managed in California in relation to restoring wild salmon. More than half (53%, 14/26) thought that hatcheries needed to, at minimum,

implement 100% tagging of hatchery stock. Other suggestions (11%, 3/26) were to relocate hatcheries to the mouth of river systems to reduce genetic mixing of hatchery stock with natural producing (i.e., wild) salmon. Here is a sample of the participants' responses to this question.

> "I don't think so. Hatcheries support fisheries, which impose additional pressures on wild populations, thus making it more difficult for them to recover. Moreover, the genetic mixing between hatchery and wild salmon makes it more difficult for us to define/identify a truly wild salmon."

> "Yes, but hatcheries and harvest will need to be managed differently"

> "Yes. In fact, it may be the only way if one is going to allow for consumptive harvest of salmon. But, it will be necessary to design and operate the hatcheries in such a way that they do not damage the wild stocks."

> "No, salmon farming should produce salmon for consumption as a food and use hatcheries only to create brood stock for experiments in restoring lost runs to restored habitats."

> " . . . it matters a great deal whether the hatchery stock closely shares the genetics of any co-located or spatially overlapping ESUs. If it does not, and there is the nearly inevitable escapement of hatchery fish to the wild, then there is a high likelihood of genetic introgression. This obviously has an adverse impact on the fitness of the naturally spawning fish, likely resulting in maladaptation in the next generation. On the other hand, if the hatchery fish have identical genetics, there may be less of an issue, and potentially a restoration benefit in some supplementation. In general, I think there are good examples available of the beneficial use of hatchery fish, sometimes captive broodstocks, in rebuilding runs, and, on the other hand, examples of where the presence of hatchery fish with non-local genetics were devastating to local runs. The middle ground, use of closely-related hatchery fish as part of a continuing supplementation program, is still under study, with mixed results thus far."

Question 5: Is it possible to restore wild salmon in the Central Valley while still harvesting adults?

Responses: Respondents (35%, 9/26) were skeptical about whether harvest of hatchery-bred fish could continue without hindering recovery of wild salmon. Some of the respondents (15%, 4/26) pointed out the irony that salmon are still being allowed for commercial, recreational, and/or tribal harvest purposes at all given that wild salmon populations are highly depressed across the region. The advisability of creating a terminal fishery (moving fisheries usually to the mouth of rivers or bays where the targeted species is returning to spawn) also came up (27%, 7/26) in responses to this question. Specific comments included:

> "In the near term I do not think it possible to have both harvest and recovery of wild salmon."

> "It is often possible to rebuild naturally-spawning runs where there is slight harvest pressure, and very difficult to do so where there is intensive harvest pressure. First, where tribal treaty rights are involved, maintenance of some level of harvest may be essential to partially fulfill the expectations of the treaty, and maintain tribal culture. Secondly, and often overlooked, is the fact that the opportunity for some level of harvest, especially, sport harvest, may help sustain and support the recovery efforts needed to rebuild naturally-spawning runs."

> "No. We cannot continue harvest rates AND restore the species. It would be a good experiment to quit harvesting for an entire generation (3 to 5 years) and see what happens. This is one of those arguments where folks are typically in favor of restoring salmon, but not of cutting of harvest."

Question 6: How likely is society to reverse these major policy drivers relative to wild salmon?

Responses: More than three-quarters of respondents (77%, 20/26) answered that society is unlikely to make the shifts in policy necessary to restore wild salmon in the Central Valley.

> "I believe it very unlikely that society can/will take sufficient action to restore wild salmon in the Central Valley."
>
> "Society will reverse the policy drivers when they see the benefits of restoring wild salmon as greater than the costs. Currently, the commercial focus on salmon harvest produces very pricey fish for a very narrow set of consumers."
>
> "Since this issue is entangled with political and economic pressures I don't think any major policy drivers are likely to change soon. And by the time they do change, it will likely be too late for salmon."

Question 7: Are current and likely planned wild salmon recovery efforts likely to make much difference?

Responses: Sixty-five percent (17/26) of the respondents (most of whom were aware of the current ongoing efforts) thought that current and likely planned recovery efforts would not make much difference in the overall, long-term trajectory of wild salmon in the Central Valley. The following specific comments capture the flavor of the overall conclusion:

> "Based on a goal of restoring salmon to 1/3 of historical abundance, I do not believe that the current recovery efforts related to habitat manipulations, hatchery, and harvest will make much of a difference to the long-term status of wild salmon in the Central Valley."
>
> "No. Society will not take out key dams; it will need increasingly more water; it will generate more impervious surfaces and alter more of the landscape . . . "
>
> "No. The current efforts are more of a holding action until the next election or until one retires."
>
> "I think the problems are difficult, but I'm optimistic that they will be sufficiently addressed for most, if not all, of the runs to be sustained and recover to some degree."
>
> "Recovery efforts will make a difference. The difference probably will not be what the designers of these recovery efforts expect."

CONCLUSION

In the confidential opinion of 26 nationally recognized experts on salmon science and policy, it is likely that wild salmon will be largely eliminated by 2100 unless drastic and pervasive changes in current policies are implemented—changes such as major sustained reductions in harvest level of wild salmon, addressing issues associated with water diversions, and reducing releases from salmon hatcheries. To thrive, wild salmon populations must have the sufficient water of an appropriate temperature and quality, access to enough high-quality spawning and rearing habitat, and reasonable harvest levels. Even under the best scenario, the future of Central Valley wild salmon is tenuous. In these experts' opinions, salmon have been subject to altered hydrographs, habitat loss, genetic stress, fishing pressures, compromised water quality, etc.—and this outlook has no foreseeable change, except to become ever-increasing because of an escalating human population and their associated resource demands, as well as the additional stressors climate change will likely create. The respondents were nearly uniform in their conclusion that current policy projections through this century show no indication that the current course will lead to recovery of wild salmon runs.

Effective policy choices are based on a credible assessment of ecological and political reality. Based on this cross-section of expert opinion, we have provided a credible assessment of the future of wild salmon in California's Central Valley. Assuming that society wishes to restore wild salmon, a substantial reduction across the breadth of human effects to the natural ecosystem of the Sacramento–San Joaquin river system will be required. Without these changes, the realistic expectation is that few, if any, wild salmon runs will persist by 2100. The changes required to reverse the downward trajectory are not easy, quick, or cheap, and will require many socially and politically divisive policy trade-offs, but something dramatically different needs to be done if society wishes to have significant, sustainable runs of wild salmon in the Central Valley in 2100.

REFERENCES

Barnett–Johnson R, Grimes CB, Royer CF, Donohoe CJ. 2007. Identifying the contribution of wild and hatchery Chinook salmon (*Oncorhynchus tshawytscha*) to the ocean fishery using otolith microstructure as natural tags. Can J Fish Aquat Sci 64(12):1683–1692. doi: *http://dx.doi.org/10.1139/F07-129*

[CDF] California Department of Finance. 2015. Interim population projections for California and its counties 2010-2060. Available from: *http://www.dof.ca.gov/research/demographic/reports/projections/P-1/*

[CDFG] California Department of Fish and Game. 2010. Final hatchery and stocking program. Environmental Impact Report/Environmental Impact Statement. Chapter 2. ICF J&S 00264.08.

[CDWR] California Department of Water Resources. 1995. Sacramento–San Joaquin Delta atlas. Sacramento(CA): State of California. 121 p.

[CDWR] California Department of Water Resources. 2006. Progress on incorporating climate change into planning and management of California's water resources. Technical Memorandum Report. Sacramento (CA): State of California Department of Water Resources. 339 p.

California Hatchery Scientific Review Group. 2012. California Hatchery Review Report. Prepared for the U.S. Fish and Wildlife Service and Pacific States Marine Fisheries Commission. 100 p.

Cummins K, Furey C, Giorgi A, Lindley S, Nestler J, Shurts J. 2008. Listen to the river: an independent review of the CVPIA fisheries program. Prepared under contract with Circlepoint for the U.S. Bureau of Reclamation and the U.S. Fish and Wildlife Service. Available from: *http://www.usbr.gov/mp/cvpia/docs_reports/indep_review/FisheriesReport12_12_08.pdf*

Delta Stewardship Council. c2015. Water supply [Internet]. [cited 11 Feb 2015]. Available from: *http://deltacouncil.ca.gov/water-supply*

Ficke AD, Myrick CA, Hansen LJ. 2007. Potential impacts of global climate change on freshwater fisheries. Rev Fish Biol Fisheries 17.4(2007):581–613. doi: *http://dx.doi.org/10.1007./s11160-007-9059-5*.

Fisher F. 1994. Past and present status of Central Valley Chinook salmon. Conserv Biol 8(3):870–873.

Fry DH, Jr. 1949. Salmon in the commercial fish catch of California for the year 1947 with an historical review 1916–1947. Fish Bulletin 74. Sacramento (CA): California Department of Fish and Game. p. 37–49.

Gesh T, Lichatowich J, Schoonmaker P. 2000. An estimation of historic and current levels of salmon production in the northeast Pacific ecosystem: evidence of a nutrient deficit in the freshwater systems of the Pacific Northwest. Fisheries 25:15–21.

Hanak E, Lund J, Durand J, Fleenor W, Gray B, Medellín-Azuara J, Mount J, Moyle P, Phillips C, Thompson B. 2013. Stress relief: prescriptions for a healthier Delta ecosystem. San Francisco (CA): Public Policy Institute of California. [cited 11 Feb 2015]. Available from: *http://www.ppic.org/main/publication.asp?i=1051.*

Herren JR, Kawasaki SS. 2001. Inventory of water diversions in four geographic areas in California's Central Valley. In: Brown RL, editor. Contributions to biology of Central Valley salmonids. Vol. 2. Fish Bulletin 179. Sacramento (CA): California Department of Fish and Game. p. 343–355.

Holmberg J. 1971. Salmon in California. Cal–Neva Wildlife. Sacramento (CA): Bureau of Reclamation. p. 91–99.

Johnson RC, Weber PK, Wikert JD, Workman ML, MacFarlane RB, et al. 2012. Managed metapopulations: do salmon hatchery 'sources' lead to in-river 'sinks' in conservation? PLoS ONE [Internet]. [cited 23 Feb 2015];7(2):e28880. doi:10.1371/journal.pone.0028880

Katz JP, Moyle PB, Quiñones RM, Israel JA, Purdy SE. 2012. Impending extinction of salmon, steelhead, and trout (Salmonidae) in California. Env Biol Fish 96(10–11):1169–1186. doi: *http://dx.doi.org/10.1007/s10641-012-9974-8*

Katz JP, Moyle PB. 2012. Have our salmon and eat them too: re-thinking salmon hatcheries in the Central Valley. California Water Blog [Internet]; [cited 23 Feb 2015]. February 29, 2012. Available from: *http://californiawaterblog.com/2012/02/29/have-our-salmon-and-eat-them-too-re-thinking-salmon-hatcheries-in-the-central-valley/*

Kjelson, M, Raquel P, Fisher F. 1982. Life history of fall-run juvenile Chinook Salmon, *Oncorhynchus tshawytscha*, in the Sacramento–San Joaquin Estuary, California. Stockton (CA): Academic Press. p. 393–41.

Kormos, B, Palmer–Zwahlen M, Low A. 2012. Recovery of coded-wire tags from Chinook salmon in California's Central Valley escapement and ocean harvest in 2010. Sacramento (CA): California Department of Fish and Game.

Lackey RT. 2001. Defending reality. Fisheries 26(6):26–27. [cited 23 Feb 2015]. Available from: *http://fw.oregonstate.edu/system/files/pdfs-lackey/2001_defending_reality.pdf*

Lackey RT. 2005. Economic growth and salmon recovery: an irreconcilable conflict? Fisheries 30(3):30–32. [cited 23 Feb 2015]. Available from: *http://fw.oregonstate.edu/system/files/pdfs-lackey/2005_economic_growth_and_salmon_recovery_an_irreconcilable_conflict.pdf*

Lackey RT, Lach D, Lackey RT, Duncan SL. 2006. Salmon 2100: the future of wild Pacific salmon. Bethesda (MD): American Fisheries Society. 629 p.

Landis JD, Reilly M. 2003. How we will grow: baseline projections of the growth of California's urban footprint through the year 2100. Working Paper. Berkeley (CA): Institute of Urban and Regional Development, University of California, Berkeley. 116 p.

Lindley S, Grimes C, Mohr M, Peterson W, Stein J, Anderson T, Botsford L, Bottom D, Busack C, Collier T, Ferguson J, et al. 2009. What caused the Sacramento River fall Chinook stock collapse? Report to the Pacific Fishery Management Council. March 18, 2009.

Lund JR, Hanak E, Fleenor W, Bennett W, Howitt R, Mount J, Moyle P. 2008. Comparing futures for the Sacramento–San Joaquin Delta. Appendix E. San Francisco (CA): Public Policy Institute of California. 219 p. Available from: [URL?]

Michael J. 2010. Employment impacts of California salmon fishery closures in 2008 and 2009. Stockton (CA): University of the Pacific, Business Forecasting Center. Available from: *http://forecast.pacific.edu/water-reports.html*.

Moyle PB, Israel JA, Purdy SE. 2008. Salmon, steelhead, and trout in California: status of an emblematic fauna. Davis (CA): UC Davis Center for Watershed Sciences. 316 p.

National Academy of Sciences. 2012. Sustainable water and environmental management in the California Bay–Delta. Washington, D.C.: The National Academies Press. 280 p.

Null et al. 2012. Managing California's water: insights from interviews with water policy experts. San Franc Estuary Watershed Sci [Internet]. [cited 3 Mar 2015]; 10(4). Available from: *http://escholarship.org/uc/item/9x0062wn*. doi: *http://dx.doi.org/10.15447/sfews.2012v10iss4art5*

U.S. Census Bureau. 2012. State and county quick facts. Data derived from population estimates, American community survey, census of population and housing, state and county housing unit estimates, county business patterns, non-employer statistics, economic census, survey of business owners, building permits, consolidated federal funds report. Available from: *http://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=bkmk.*

[USFWS] United States Fish and Wildlife Service. 2001. Final restoration plan for the anadromous fish restoration program: a plan to increase natural production of anadromous fish in the Central Valley of California. Stockton (CA): Central Valley Project Improvement Act, Anadromous Fish Restoration Program. [cited 23 Feb 2015]. Available from: *http://www.fws.gov/stockton/afrp/*.

Yoshiyama RM, Gertstung ER, Fisher FW, Moyle PB. 1996. Historical and present distribution of Chinook Salmon in the Central Valley drainage of California. Davis (CA): University of California, Davis.

Yoshiyama RM, Fisher FW, Moyle PB. 1998. Historical abundance and decline of Chinook salmon in the Central Valley region of California. N Am J Fish Manag 18:487–521. doi: *http://dx.doi.org/10.1577/1548-8675(1998)018<0487:HAADOC>2.0.CO;2*