EXPERT REPORT OF PROFESSOR PETER B. MOYLE, PH.D.

I. QUALIFICATIONS AND EXPERIENCE

I have been researching freshwater and anadromous fish in California since 1969. I was appointed Professor of Fisheries Biology at the University of California at Davis in 1972, and held the chair of the University's Department of Wildlife, Fish and Conservation Biology from 1982 to 1987. I have served as Associate Director of the Center for Integrated Watershed Science and Management since 2002. My *curriculum vitae* is attached as Exhibit A.

The principal area of my research and expertise is the ecology and conservation of freshwater and anadromous fishes, particularly in California. A significant portion of my research has focused on regulated streams and the impacts of dams, diversions, and other factors on fish populations in California, including the Central Valley. I have authored or co-authored more than 160 publications, most of which concern freshwater and anadromous fishes. Among my publications is *Inland Fishes of California* (Moyle 2002), the standard reference work on California fishes, as well as four other books and monographs on fishes. A list of my publications is attached as Exhibit B.

I have studied the historical and current distribution and ecology of the fishes of the San Joaquin River watershed since 1970, and have documented the decline of Chinook salmon and other native fishes on that river. Several of my publications on the fish of San Joaquin River watershed are cited below.[1]

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[1] Moyle, P.B. 1970. Occurrence of king (chinook) salmon in the Kings River, Fresno County. *California Fish & Game* 56:314-315; Moyle, P. B. and R. Nichols. 1974. Decline of the Native Fish Fauna of the Sierra-Nevada Foothills. *American Midland Naturalist* 92:72-83; Brown, L. and P. B. Moyle 1992. Native Fishes of the San Joaquin Drainage: Status of Remnant Fauna Pages 89-98 *in* D.L. Williams et al. eds. *Endangered and Sensitive Species of the San Joaquin Valley California*. California Energy Commission, Sacramento CA.: Brown, L. and P. B. Moyle 1993. Distribution, Ecology, and Status of the Fishes of the San Joaquin River Drainage, California Distribution, Ecology and Status of the Fishes of the San Joaquin River Drainage, *California Fish and Game* 79:96-113; Yoshiyama, R.M., F.W. Fisher, and P.B. Moyle. 1998. Historical Abundance and Decline of Chinook Salmon in the Central Valley Region of California. *North American Journal of Fisheries Management* 18: 487-521.; Yoshiyama, R. M.,

In 1993, I was named a Fellow of the California Academy of Sciences. I serve on the editorial boards of several peer-reviewed journals, including *Environmental Biology of Fishes*, *Biological Conservation*, and *Biological Invasions*. I am a member of the American Fisheries Society, American Society of Ichthyologists and Herpetologists, Ecological Society of America, Society for Conservation Biology, American Association for the Advancement of Science, and American Institute of Biological Sciences. I also have received an Award of Excellence from the Western Division of the American Fisheries Society (1991); recognition as a Distinguished Fellow of the Gilbert Ichthyological Society (1993); the Outstanding Educator Award from the American Fisheries Society (1995, with J. J. Cech); and recognition as Distinguished Ecologist by Colorado State University (2001). I currently co-hold the President's Chair in Undergraduate Education at UC Davis.

In 2003, I was one of the co-authors of the National Research Council's final report on the causes of the decline and strategies for recovery of coho salmon and other fishes in the Klamath River Basin (National Research Council 2003). I also was a member of the Science Board of the CALFED Ecosystem Restoration Program and its predecessor (1998-2005), led the USFWS Delta Native Fishes Recovery Team (1993-1995), and served as a member of the USFS Sierra Nevada Ecosystem Project Team (1994-1996). I currently serve as a member of interagency Fish Screen Evaluation Committee.

Over the past thirty years, I have engaged in considerable biological field work on the upper San Joaquin River. During the period 1969 to 1972, when I taught at Fresno State University, I routinely took my classes to sample both the upper San Joaquin River, below Friant Dam, and the Kings River. During the early 1970s, I conducted a survey of fish fauna in the upper San Joaquin River region, including fish fauna below Friant Dam. I jointly conducted a

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E. R. Gerstung, F. W. Fisher, and P. B. Moyle. 2001. Historical and present distribution of chinook salmon in the Central Valley. Pages 71-176 *in* R. Brown, ed. *Contributions to the Biology of Central Valley Salmonids*. California Dept. of Fish and Game. Fish Bulletin 179(1).

similar survey of fish fauna in the 1980s, which also encompassed the San Joaquin River below Friant Dam. In March 2004, I conducted a two-day field investigation on the San Joaquin River, canoeing several miles of the flowing reach of the River below Friant Dam; observing the physical and biological features of the river; and visiting and observing a number of the major features of the River from Friant Dam to the Merced River confluence, including Sack Dam and Mendota Dam.

I have previously served as an expert witness or consultant on fishery impacts of dams and diversions in a number of venues. I was retained as a consultant by the City and County of San Francisco in a re-licensing proceeding before the Federal Energy Regulatory Commission (FERC), and served as an expert witness for the Putah Creek Council, in the *Putah Creek Water Cases*, Judicial Council Coordination Proceeding Number 2565 (Sacramento Superior Court). I also have testified before the State Water Resources Control Board and a congressional committee. In 2000 I was deposed as an expert witness on coho salmon in the case *Environmental Protection & Information Center. Andrea Tuttle*, Case No. 00-0713-SC (N.D. Cal). In March, 2004, I was deposed as an expert witness on the 2002 Klamath River salmon kill in the case *Pacific Coast Federation of Fisherman's Associations, Yurok Tribe, Hoopa Valley Tribe v. Bureau of Reclamation, Klamath Water Users, No.C 02-020006 SBA* (N.D.California).

I became involved in the Putah Creek Water Cases as a result of my research on the fishes of Putah Creek. During a drought in the early 1990s, diversions dried out a long stretch of the Creek below Putah Creek Diversion Dam. Native fishes survived mainly in only the first two to three miles below the Dam. The Putah Creek Council filed suit in Superior Court to restore flows to the Creek, pursuant to Section 5937 of the California Fish & Game Code and the Public Trust Doctrine. I served as an expert witness for the Putah Creek Council, The University of California, and the City of Davis in these proceedings and provided testimony concerning appropriate flow regimes to improve and restore the condition of the Creek's fish. Ultimately, the Putah Creek Council *et al*. won this litigation when, in 1996, the Superior Court ordered enhanced flows to be released from the Dam into the Creek. Today, as a result of the enhanced flows ordered by the Superior Court, native fish have returned to, and now dominate, Putah Creek for almost twenty miles below the Putah Creek Diversion Dam. For the past two winters, I personally have documented the return of fall-run Chinook salmon to the Creek, following the release of augmented flows on a schedule that I had recommended. The condition of other native fish populations has significantly improved as well[2].

As noted above, I also served as a consultant for the City and County of San Francisco ("San Francisco") in FERC re-licensing proceedings concerning New Don Pedro Dam, which is located on the Tuolumne River, a major tributary of the San Joaquin River. The City is a beneficiary of the New Don Pedro Project, which also provides water and hydropower for the Turlock and Modesto Irrigation Districts. In the 1990s, FERC held proceedings concerning the flow regimes necessary to protect and restore fish below New Don Pedro Dam, including in particular fall-run Chinook salmon. San Francisco retained me as an expert for these proceedings. An enhanced flow regime was established, and today, the condition of fall-run Chinook salmon and other native fish appears to have significantly improved on the Tuolumne[3]. I have been called on to provide expertise on salmon and native fish restoration in many other venues and proceedings. For example, I recently presented expert testimony regarding Section 5937 in proceedings before the California State Water Resources Control Board involving the Santa Ynez River (*in re Santa Ynez River Public Trust Proceedings on U.S. Bureau of Reclamation Water Rights Permits, Applications 11331 and 11332*, 2003).

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[2] Marchetti, M. P. and P. B. Moyle. 2001. Effects of Flow Regime and Habitat Structure on Fish Assemblages in a Regulated California Stream. *Ecological Applications* 11: 530-539; Moyle, P. B., M. P. Marchetti, J. Baldrige, and T. L. Taylor. 1998. Fish Health and Diversity: Justifying Flows for a California Stream. *Fisheries* (Bethesda) 23(7):6-15; Moyle, P.B., and M.P. Marchetti. 1999. Applications of Indices of Biotic Integrity to California Streams and Watersheds. Pages 367-380 *in* T.P. Simon and R. Hughes ed. *Assessing the sustainability and biological integrity of water resources using fish assemblages*. CRC Press, Boca Raton, FL.

[3] Ford, T., and L.R. Brown. 2001. Distribution and Abundance of Chinook Salmon and Resident Fishes of the Lower Tuolumne River California. Pages 253-303 *in* R. Brown, ed. *Contributions to the Biology of Central Valley Salmonids*. CDFG Fish Bulletin 179.

II. PREVIOUS TESTIMONY

See qualifications section (last three paragraphs).

III. COMPENSATION

I am not being paid and have not been paid for my work as an expert witness for this legal proceeding or for other similar matters relating to the restoration of the San Joaquin River.

IV. SCOPE OF ASSIGNMENT

I was asked by the Plaintiffs to investigate and provide expert opinion, as a fisheries biologist, on the following questions:
(1) What is meant by the phrase “fish in good condition?”
(2) What was the condition of the fish in the San Joaquin River before the construction and full operation of Friant Dam?
(3) Did Friant Dam change the condition of fish in the San Joaquin River below the dam?
(4) Are the fish in the San Joaquin River below Friant dam in good condition?
(5) Can the fish in the San Joaquin River below Friant Dam be restored to good condition and if so, how?

V. MATERIALS CONSIDERED IN FORMULATING THIS EXPERT REPORT

In formulating the opinions stated in this expert report, I have relied on information I accumulated working on salmon and other California fishes since 1969. Much of this material is summarized in my 2002 book, *Inland Fishes of California* (University of California Press, 502 pp) and in my 160+ peer-reviewed publications. More specifically, I considered each of the publications cited in this report and materials cited in my publications on the San Joaquin River. Thus the opinions that I express in this report are based on my 35 years of experience and publications and on periodicals, texts, research, and historical and other materials that other experts in my field would consider reliable. In addition, I have reviewed the expert reports of Dr. Michael Deas and Dr. G. Matt Kondolf. I also considered material listed in Exhibit C.

VI. SUMMARY OF EXPERT OPINIONS

Opinion 1: The definition of "fish in good condition" used here was one I was instrumental in developing and has been used in at least two prior cases. The definition has three tiers, individual, population, and community (Moyle et al. 1998). By this definition, the fish in good condition below the dam should be in good physical health and also be part of self-sustaining populations, supported by extensive habitat for all life history stages. The third level of good condition, community, refers to the presence complex assemblages of native fishes, including runs of salmon and other anadromous fish, as well as fisheries for both native and non-native fishes.

Opinion 2. Before the construction of Friant Dam and the full operation of its diversions, the San Joaquin River contained runs of fall and spring run Chinook salmon, that were large enough to support fisheries. These were the southernmost runs of the species. There was also a diverse assemblage of native fishes. Until the late 1930s and early 1940s salmon still migrated in large numbers to spawn in a long reach of river that included the present reach below the dam. Until the dam began full diversion operations, the San Joaquin River still supported fish in good condition.

Opinion 3. The operation of Friant Dam has severely altered the flows of the river and in many years has dried up long stretches of river completely. As a result Chinook salmon were extirpated from the river and native fishes were reduced to a fraction of their historic abundance and diversity. Many reaches of the river contained either no fish or only scattered populations of a few hardy non-native species such as common carp and red shiner.

Opinion 4. Fish below Friant dam at the present time are not in good condition because (1) key species, such as Chinook salmon, have been extirpated, (2) whole reaches of the river contain no fish during months when the reaches are dry, (3) habitat for various life history stages of many species is absent or depleted, (4) where fish exist they are part of depleted assemblages dominated by a few species with no guarantee of long-term persistence.

Opinion 5. While there are many factors constraining the restoration of fish to good condition below Friant Dam, it *is* possible to restore both spring and fall runs of Chinook salmon to the San Joaquin River in sufficient numbers to help remove spring run Chinook from the list of threatened species and to improve salmon fisheries. Complete communities of native fishes can also be restored, as can fisheries for non-native warm water species. Restoration can occur through releasing a 'natural' flow regime (which takes a small fraction of the total water available) but can occur more quickly and completely if other restoration activities are undertaken. A model flow regime is presented that takes into account the needs of the fishes and the realistic availability of water.

VII. WHAT IS MEANT BY "FISH IN GOOD CONDITION"?

Section 5937 of the Fish and Game Code, a section dating from the 1930s, states that: "The owner of any dam shall allow sufficient water at all times to pass through a fishway or in the absence of a fishway, allow sufficient water to pass over, around, or through the dam, to keep in good condition any fish that may be planted or exist below the dam." In the early 20th century the utilitarian attitude of resource managers[4] would have made their focus almost certainly to maintain fish in sufficient health and numbers to support fisheries[5] in the streams below the

[4] For a history of attitudes towards conservation see the essays in my on-line textbook at: http://wfcb.ucdavis.edu/www/Faculty/Peter/petermoyle/wildlifereader.htm

[5] The word 'fisheries' is often used as being synonymous with 'fish' in the fisheries and popular literature. I prefer to confine the use of the word to human activities engaged in the capture of fish for consumption or recreation.

dams. The key phrase “good condition”, however, was not defined by DFG until the historic Mono Lake case, in which the trout populations of formerly productive streams that had been dried up by diversions were restored after a diversion dam spilled during a series of wet years. The populations were maintained in the streams as the result of a legal decision based on the Fish and Game Code and the Public Trust Doctrine (Koehler 1996). For this decision, DFG biologist Darrell Wong defined fish in good condition as a large, self-sustaining population of wild trout living in a diverse and healthy stream environment; he specifically linked the health of the stream to the health of the fish populations (Moyle et al. 1998).

Using the Wong definition as a starting place, my colleagues and I developed a definition of “good condition” for the complex assemblages of fishes in Putah Creek, Yolo and Solano Counties. The definition was used successfully in Putah Creek Council vs Solano Irrigation District (Sacramento County Superior Court No. 515766). The definition has three tiers, individual, population, and community (Moyle et al. 1998). By this definition, the fish in the stream below the dam should be in good physical health (i.e., not show obvious signs of stress from poor water quality and quantity) and also be part of a self-sustaining population supported by extensive habitat for all life history stages, much as in the Wong definition. The third level of good condition, community health, reflected the fact that Putah Creek, like the San Joaquin River, historically supported runs of salmon and other anadromous fish and complex assemblages of native fishes, as well as fisheries for both native and non-native fishes. A healthy community (assemblage) of fishes therefore was defined as one that “(1) is dominated by co-evolved species, (2) has a predictable structure as indicated by limited niche overlap among species and multiple trophic levels, (3) is resilient in recovering from extreme events, (4) is persistent in species membership through time, and (5) is replicated geographically (Moyle et al. 1998, p. 11).” This definition reflects recent ecological thinking and recognizes that a fish community is a complex, dynamic entity whose persistence through time requires a complex, dynamic habitat. For streams, in particular, a healthy fish community requires flows and habitats that have attributes of those that existed historically.

Following the publication of this definition of good condition (and my later presentation of it at a SWRCB hearing), DFG used it as their official definition in arguing before the State

Water Resources Control Board for increased flows for the Santa Inez River (Cachuma Project Hearing, Phase 2, USBR Applications 11331 and 11332, Closing Statement, February 2004, p.8).

This definition resulted in establishment of a flow regime for Putah Creek that requires a small proportion of project yield, yet has dramatically improved the condition of the fishes at all three levels (Marchetti and Moyle 2001). The flow regime consists of (1) sufficient flows to keep the creek a living stream for its entire length all year around, (2) elevated spring flows to promote spawning and rearing of native fishes, and (3) a fall ‘pulse’ flow to attract spawning Chinook salmon. In many years, runoff from rain and spillage from Monticello Dam provides sufficient water to satisfy the second two portions of the regime. In addition to the flow regime, the water agency, local environmental groups, the University of California, and the cities of Davis and Winters are actively cooperating to improve habitat conditions on the creek for both fish and wildlife.

VIII. WHAT WAS THE CONDITION OF FISH IN THE SAN JOAQUIN RIVER BEFORE THE CONSTRUCTION AND FULL OPERATION OF FRIANT DAM?

A. HISTORY

The Sacramento-San Joaquin watershed, encompassing the Central Valley and Sierra Nevada of California, was once one of the great producers of Chinook salmon on the west coast of North America. In years of high ocean productivity, as many as 2 million fish probably returned to the rivers, supporting large fisheries (Yoshiyama et al. 1998). Chinook salmon came into the rivers almost continuously throughout the year, peaking as four distinct runs: fall, late fall, winter, and spring (Moyle 2002). Perhaps half of all these salmon came up the San Joaquin River and its tributaries, despite the fact they drained a smaller watershed and had less water on average than the Sacramento River drainage to the north. The main stem San Joaquin River and the adjacent Kings River supported the southernmost major runs of any Pacific salmon species.

The San Joaquin River drains the southern Sierra Nevada, the highest mountains on the west coast. These high mountains, some still supporting small glaciers, collect the winter snowfall and then let it melt slowly through the summer. Historically river flows usually peaked in late May or early June and then gradually diminished before reaching minimum flows in September and October (McBain and Trush 2002). Starting in November, flows gradually increased in response to rain fall and cooler temperatures. Thus, when the natural flow regime was in place, there was often water cold enough to support salmon on the valley floor in all but the hottest weeks (mid-August through mid October) of summer. Above the valley floor, the water was almost always cold enough for salmon rearing year around, except at the lowest elevations during periods of drought. As a result before Friant Dam and its associated diversions began operating, the San Joaquin River supported major populations of at least two distinct runs of Chinook salmon, the spring and fall runs, and possibly a third, the late-fall run (Yoshiyama et al. 2001).

The Chinook salmon is an anadromous species, which means that they spawn in fresh water, where their young rear for varying lengths of time, and then migrate back to sea, where they grow to adult size in 2-5 years.

Adult spring-run Chinook salmon historically returned to the San Joaquin River primarily during the months of March through June and spent the summer holding in deep pools above and below the existing location of Friant Dam. They would then spawn in the early fall (September – November) and embryos incubate in the gravel for 3-4 months, followed by emergence of the alevins (fry with yolk sacs attached). The juveniles would usually rear in the river until the following winter (January-March) when they would migrate seaward with high flows as either juveniles or smolts. Fall-run Chinook returned primarily from September through December and spawned soon thereafter. The juvenile fall-run would typically emerge from the gravel in December through January and out-migrate primarily in January through April, with peaks typically occurring in March.

Historical accounts indicate that salmon populations in the upper San Joaquin River were quite abundant prior to the closure and full operation of Friant Dam. So many salmon migrated up the river during spawning season that some people who lived near the present site of Friant Dam compared the noise to a waterfall. Some residents at the time reported that the noise from the salmon splashing over the sand bars kept them awake at night. One observer noted that salmon were so plentiful that ranchers trapped the fish and fed them to hogs (Yoshiyama et al. 2001). Historically, the upper San Joaquin contained some of the best spring-run Chinook salmon habitat in California. This habitat, which stretched from at least 12 miles (and probably more)[6] below the present site of Friant Dam (i.e., Lanes Bridge) up to the present site of Mammoth Pool Reservoir, included a mixture of deep pools for holding and gravelly riffles for spawning, over which cold stream water flowed (Yoshiyama et al. 2001). After the construction, in 1920, of Kerckhoff Dam and its powerhouse eight miles downstream, at least 14 miles of spawning habitat was still present above the site of Friant Dam (Clark 1942). I have personally observed that a significant amount of spawning habitat still exists in the several miles immediately below Friant Dam and that patches of suitable gravel exist as far downstream as Skaggs Bridge.

Hard data regarding the status of San Joaquin River salmon populations before the 1900s is limited. Nevertheless, the information available indicates that a reasonable estimate of spring-run Chinook salmon for the entire San Joaquin River basin prior to the 1880s would be around 200,000 - 300,000 fish, and perhaps more in years of high ocean productivity. It is likely that about half these fish entered the upper San Joaquin River (above the Merced confluence). Thus a conservative estimate would be that the average number of spring-run Chinook spawning in the upper river would have been around 100,000 fish per year, with the actual number present each year varying widely depending on the combination of ocean and river conditions in previous years. This estimate is based on (1) the fact that final spring runs in the 1940s were as many as 30,000 to 56,000 fish, (2) the historic availability of cold water flows and adult holding habitat in summer, and (3) extrapolations from 19th century canning operations and fisheries. In 1883 alone, 567,000 spring run Chinook were taken in the in-river fishery; if only half these fish were from the San Joaquin River basin, then a total run (escapement + fish taken in the fishery) of at

[6] According to records of the Division of Fish and Game, Bureau of Marine Fisheries, from the 1940s, spawning occurred from Friant Dam down to Lanes Bridge, a stretch of about 12 miles. See California Department of Fish & Game (1942 - 1943). One DFG report suggests the presence of “thirty miles of spawning riffles below Friant Dam.” See California Department of Fish & Game (1944). McBain & Trush (2002), at p. 7-59, states that a survey from 2002 found suitable spawning riffles from Friant Dam to Highway 99, a distance of more than 20 miles.

least 300,000 fish was likely (Yoshiyama et al. 1998). Given that hydraulic mining and small dams were already seriously reducing the spawning habitat available in the Stanislaus, Tuolumne, and Merced rivers, it is likely that a high percentage of these fish were spawning in the upper San Joaquin River. The California Department of Fish and Game has stated that the spring-run Chinook population in the San Joaquin River basin was one of the largest Chinook salmon runs on the Pacific Coast, numbering possibly in the range of 200,000-500,000 spawners annually (California Dept. of Fish and Game 1990).

It is more difficult to estimate the number of fall-run Chinook salmon that historically spawned in the San Joaquin because few fall run were taken in the fishery for the canneries (they were considered too soft for canning). Nevertheless, I believe that a conservative mean annual estimate of fall-run Chinook salmon population numbers for the upper San Joaquin River would be between 50,000 and 100,000 fish, based on anecdotal accounts and the availability of spawning habitat, the size of runs in comparable rivers in the Sacramento River basin, and the size of runs in the Tuolumne River in past decades, which does not have a hatchery on it (e.g., 20,000-130,000 fish in the 1940s).

In addition to salmon, anadromous fish that existed in the San Joaquin River below Friant Dam included Pacific lamprey and possibly steelhead, although records are poor. Collections of fish made in the vicinity of Friant in 1898 and 1934 indicate that the river supported a diverse native fish fauna that included rainbow trout, splittail, hitch, hardhead, and Kern brook lamprey, all species of conservation interest today (Moyle 2002). Following the construction of Friant Dam, most (nine of sixteen species) of the native fishes disappeared from the area and were replaced, where the river still has any fish at all, by hatchery-reared rainbow trout and a variety of non-native fishes (DFG 2004). For the entire reach from Friant Dam down to about a mile above Lanes Bridge, DFG crews collected only seven species of native fish; non-native fishes (eight species) dominated in terms of total biomass (DFG 2004; D. Mitchill, DFG, pers. comm.).

B. IMPACT OF DAMS AND DIVERSIONS BEFORE FRIANT DAM

Dams, diversions, and other factors changed the San Joaquin River and its channel well before the construction and operation of Friant Dam, yet salmon runs persisted, native fishes flourished, and river fisheries were present.

In the uppermost reaches of the river, construction of Kerckhoff Dam in 1920 blocked access of salmon to the upper end of their spawning and holding habitat, as well as dewatering sections downstream of the dam when low summer flows were shunted through a penstock before being returned to the river. This was (and still is) a run-of-river hydroelectric dam, so it did not alter flows in the river below the re-entry point of the water. Thus prior to the construction of Friant Dam, the river had essentially a natural flow regime down at least to the dam site, maintaining spawning and rearing habitat for salmon, as well as habitat for other fishes.

Even before Friant Dam was built, diversions and agricultural developments had degraded salmon habitat and impeded fish migration, especially of fall-run Chinook salmon, below Mendota Pool. The salmon runs persisted, however, despite all the obstacles thrown in their migratory path. The largest dam that may have affected migration was Mendota Dam, first built in 1871 as a seasonal dam but which eventually became the concrete structure with a fish ladder that is present today. 24 miles below Mendota Dam is Sack Dam, which was originally a temporary sandbag dam near Dos Palos that was erected annually (starting in 1878) to divert water into Temple Slough, a natural alternate channel of the river. It blocked the main river until the sandbags were removed or were washed out by flows from late fall or winter rains. In many years, the sandbag dam stayed in place late enough to block or impede upstream migration of fall-run Chinook salmon up the central channel of the San Joaquin. Apparently, these salmon made it up the river anyway by using alternate routes through natural sloughs and canals that paralleled the main river, entering the river again above Mendota Dam (Hatton 1940).

Despite the various impediments to migration, the San Joaquin River flowed in all reaches all year around in most years in the pre-dam era. After farming began in the Valley and before Friant Dam was built some stretches of the San Joaquin River on the Valley floor most likely ceased flowing for varying periods of time, particularly during periods of extreme drought, as the result of a combination of diversions, ground water pumping and naturally reduced flow (the result of reduced snow pack in the Sierras). While historic diversions and pumping, combined with lower natural flows during drought periods, could have resulted in delayed or reduced spawning runs of salmon, especially fall run Chinook salmon, *there is no evidence of interruption of runs caused by drought during the pre-dam period*. In fact, there is ample evidence to the contrary. Clark (1943) reported that the river had "a fair-sized spring run of king salmon for many years" and a fall run that had been "greatly reduced." Hatton (1940) found a juvenile salmon in the spring of 1939 that must have resulted from spawning in the previous year. He also noted that the adult spring run in the dry year of 1939 was about 3000 fish that entered the upper river between April 12 and May 20. He also noted that the fall run was able make it around a reach of river flowing at < 1cfs below a diversion structure (Sack Dam), by "making a hazardous and circuitous journey" around the dam through natural sloughs and irrigation ditches and "miraculously" re-entering the San Joaquin River above Mendota Weir[7].

Even if there had been a complete failure of runs during a drought year, the multiple ages of returning salmon (i.e., some return at ages 2,3,4,and 5 years) provided an insurance policy that would result in quick recovery of the populations when more favorable conditions returned. Likewise, native fishes are adapted for surviving periods of extreme drought and would have quickly re-colonized the re-watered sections of river from the many refuges available such as tributary rivers and deep pools in the existing channel (Moyle 2002).

Friant Dam was built by the US Bureau of Reclamation as part of the Central Valley Project "for the purposes of improving navigation, regulating the flow of the San Joaquin River…., controlling floods, providing for storage and for the delivery of the stored waters… and for the generation and sale of electricity… (Act of August 26, 1937 authorizing the Central Valley Project, Chapter 832 (50 Stat. 844)." The storage and delivery aspect of the project, to

[7] In August, 1942, George P. Miller, Executive Secretary of the state Fish and Game Commission, wrote a letter to the US Bureau of Reclamation documenting the importance of the San Joaquin River to salmon. He assumed the Bureau would either provide water for the salmon or have to conduct salvage operations to keep the runs going. He stated "Additional problems will be encountered when fall-run salmon begin to arrive in the pools below the dam later this fall. Conditions in this river have precluded counting them. However, a minimum of several thousand fall run fish were estimated to have passed Mendota as late as December 1941." Note that he stated "when" the salmon arrive, not "if" the salmon arrive.

provide water for the expansion of agriculture in the San Joaquin Valley, however, soon became its main function (Hundley 2002). Until Friant Dam began full storage and diversion operations in the late 1940s, the San Joaquin River supported a spring-run Chinook population. Population estimates for the spring run for the years immediately preceding and after the closure of Friant Dam have been reported as: 5,000 in 1939, no counts in 1940, 5,000 in 1941, 9,000 in 1942, 35,000 in 1943, 5,000 in 1944, 56,000 in 1945, 30,000 in 1946, 6,000 in 1947, and just 2000 in 1948 (Fry 1961, Yoshiyama et al. 1998). After 1949, there were occasional records of salmon during the 1950s and 1960s, during wet years, although a small (<500) run was recorded in 1950. The estimates should be regarded as minimum numbers not only because of difficulties in counting all the fish but because the fish had become exceptionally vulnerable to fishing, legal and illegal, in the reduced river and many were captured before they could make it back to their spawning grounds. The numbers are also a minimum estimate of "escapement" from the ocean fishery which captured a substantial percentage of the run before it even entered the San Joaquin River. CDFG biologist Eldon Vestal (1957) made rough calculations that indicated that about 75% of the San Joaquin salmon were lost to all the legal and illegal fisheries in 1946, indicating a total production of about 114,500 salmon.

Likewise, fall-run Chinook salmon persisted below Friant Dam until the dam increased storage and diversion operations in the late 1940s (United States Department of the Interior 1986, United States Department of the Interior 1994, Yoshiyama et al. 2001). Division of Fish and Game (Bureau of Marine Fisheries) monthly reports from May and June 1944 indicate that once a passage structure for fish was installed on Sack Dam, the only barrier to salmon passage was insufficient flows (Clark 1943). According to a January 1947 monthly report of the Division of Fish and Game, a large number of fall-run salmon, perhaps as many as 2000, passed over Mendota Dam in December 1946 when the boards were pulled, providing sufficient flow for passage (California Division of Fish & Game 1941-1950). Despite the numerous dams and diversions that salmon historically encountered ascending the San Joaquin River to find their spawning grounds, the ultimate cause of their demise was the construction and operation of Friant Dam.

It is a tribute to the remarkable resilience of Chinook salmon that they continued to spawn in the upper San Joaquin River for several years after Friant Dam was built. Although Friant Dam blocked passage to upstream habitat, during these initial years, spring-run Chinook successfully held in pools below Friant Dam during the summer months and successfully spawned in habitat below the dam while juvenile salmon had enough water to be able to migrate downstream (Warner 1991, California Division of Fish and Game 1941-1950). Once Friant Dam began sending most of the flow of the San Joaquin River into the Friant-Kern and Madera Canals, and once the Bureau ceased releasing fish flows, stretches of the river dried up and spring-run Chinook salmon were quickly extirpated from the San Joaquin River system. Had the Bureau continued to release sufficient flows from Friant Dam for Chinook salmon to complete their life cycle, there would be salmon spawning below Friant Dam today.

IX. DID FRIANT DAM CHANGE THE CONDITION OF FISH IN THE SAN JOAQUIN RIVER?

There is no question that construction and operation of Friant Dam had a devastating effect on fish populations and communities in the upper San Joaquin River, above and below Friant Dam, far beyond any impacts that had previously occurred. By the mid- to late-1940s, increased storage and diversions caused parts of the river below Sack Dam to dry up during some times of the year. The completion of the Delta Mendota Canal in 1951 resulted in the complete dewatering of approximately 5 miles of river below White House. For brief periods during this time in the 1940s, the Bureau of Reclamation released some additional water from Friant Dam to facilitate passage of adult fall-run and spring-run salmon over Sack Dam during key migration periods. In 1948, two small pulses brought up about 2000 spring-run Chinook salmon (see Kondolf statement). By the 1950s, however, the Bureau ceased releasing any fish flows from Friant Dam, despite requests for flows from the Department of Fish and Game (California Division of Fish and Game 1941-1950). As a result, a 20 mile reach between Gravelly Ford and Mendota Pool became dry (except for agricultural return flows) after 1957 when the Columbia

Canal was connected to Mendota Pool. This is the condition of the San Joaquin River I observed during my field work over the course of the past thirty-three years.

Historical gauging data indicate that flows below Friant Dam plummeted dramatically between the late 1940s and the mid 1950s as a result of dam operations and diversions. More recent data from a Friant gauging station show that the operations of Friant Dam still all but eliminate the natural flow of the river below Friant Dam. Although the Bureau does release small quantities of water from Friant Dam to satisfy riparian water users immediately below the dam, the river becomes a dry sandy wash downstream of Gravelly Ford and remains so for approximately 12 miles to the Chowchilla Canal bifurcation structure, except during high flows. There is still no flow for another 9 miles downstream of this structure, to the Mendota Pool, but higher groundwater levels result in a moister channel, some riparian vegetation, and a few isolated pools. The river is also dewatered for an extended reach below Sack Dam in all but the wettest periods. The flows currently released from Friant Dam are entirely insufficient to reestablish and maintain the salmon and other native fishes that once existed below the dam, except during times when dam was spilling.

In the years immediately after Friant Dam began operation, the California Department of Fish and Game engaged in a vigorous, but ultimately futile, effort to save the San Joaquin River's unique spring-run Chinook salmon (Warner 1991). In 1948, the Department trapped some of the adult spring-run then remaining in the lower San Joaquin River and trucked them past the river's dry stretch, then released them again at a point from where they were able to swim upstream to deep pools immediately below Friant Dam. The salmon were able to hold in these waters successfully all summer and then spawn in the river below Friant Dam in the fall. However, by the end of the decade, when the Bureau stopped releasing sufficient water from Friant Dam, juvenile spring-run Chinook salmon were unable to complete their downstream migration due to the dewatered reaches below White House and Sack Dam. Today, the spring-run Chinook, once the most abundant race of salmon in the Central Valley, have been extirpated from the San Joaquin River and only small populations survive in the Sacramento River system (California Division of Fish and Game 1941-1950 [April 1949 report], Warner 1991, Moyle 2002).

Fall-run Chinook salmon were likewise extirpated from the San Joaquin River in the 150 mile reach between Friant Dam and the mouth of the Merced River, which is the San Joaquin's first major tributary downstream of Friant Dam. The last true run of fall run Chinook in the upper San Joaquin River may have occurred in 1948, because juvenile salmon were reported in a March 1949 monthly report of the Division of Fish and Game (Bureau of Marine Fisheries). However, small numbers of salmon were reported sporadically from the river in the1950s. Fall-run Chinook salmon still survive in the lower tributaries of the San Joaquin River, including the Merced, Stanislaus, and Tuolumne Rivers, where dams release flows to sustain them and other native fishes. However, the Bureau of Reclamation does not release enough water from Friant Dam to provide continuous flows downstream to the Merced River. As a result native fishes (including Chinook salmon and other anadromous and resident fish species) are largely gone from this reach of river and passage of anadromous species between the ocean and the spawning habitat that is available below Friant Dam is denied (California Department of Fish and Game 1941-1950, Yoshiyama et al. 1998, Brown 2000, Yoshiyama et al. 2001).

The storage and delivery of water from Friant Dam into the Madera and Friant-Kern Canals in the 1940s marked the beginning of an accelerated decline of native anadromous and resident fishes, not only on the upper San Joaquin River, but throughout the San Joaquin drainage and in the San Francisco Estuary (into which the San Joaquin River flows). Waters from the upper San Joaquin had been critical to providing habitat for fish species many miles below Friant Dam. San Joaquin River flows are needed to help attract adult salmon to their spawning grounds, to provide habitat for young and juvenile salmon, to move juvenile salmon downstream in the spring through the lower San Joaquin River, and to improve water quality. Failure to release adequate water from Friant Dam into the river has caused massive damage to fish habitat between the dam and the San Joaquin River's confluence with the Merced River, and also has adversely affected water quality along the entire course of the river, from the dam to the Delta.

Loss of water from the river has reduced the habitat available for all fish, increased temperatures of water in the lower reaches, reduced the dilution of agricultural runoff and other pollutants, and substantially degraded riparian vegetation. This has caused not only loss of salmon fisheries but of fisheries for other native fishes as well. The San Joaquin River once supported Native American and Euro-American fisheries for sturgeon, lampreys, and native cyprinids ("minnows" which grew to large sizes) and suckers. The native fish fauna was diverse, endemic, and abundant (Moyle 2002) but is now either gone from the San Joaquin River or reduced to remnant populations (DFG 2004). Although sampling records of fishes in the portions of the San Joaquin River that are not totally dewatered by diversions are few, existing studies indicate that native fishes, such as hitch, splittail, tule perch, and hardhead, have largely disappeared from the river and have been replaced by exotic fishes tolerant of warm irrigation return water (Saiki 1984, Brown 2000, Moyle 2002, DFG 2004).

The present warm-water fishery that exists on portions of the San Joaquin River between Mendota Pool and the San Joaquin's confluence with the Merced River is small and erratic. Many of the fish present are likely affected by or contaminated with pesticides and other agricultural contaminants present in the return water (Brown et al. 1999). From Mendota Pool to Sack Dam, the San Joaquin River is basically used to convey irrigation water. Below Sack Dam the river is dewatered until agricultural drain water provides a small flow of polluted water. Surveys by the U.S. Geological Survey indicate that the fish fauna of this polluted section of the river is made up almost entirely of tolerant non-native fishes, such as inland silverside, red shiner, threadfin shad, and fathead minnow (Saiki 1984, Brown 2000). Dilution of this water with summer flows from Friant Dam would significantly improve conditions for native fishes, as well as for desirable non-native game fishes, such as striped bass. Thus Brown (2000) found that native fishes were able to re-invade mainstem habitats when flows were increased as the result of a wet year.

Despite the major hydrologic changes to the river caused by Friant Dam, salmon do occasionally return to the upper river. Part of the natural behavior of Chinook salmon (and other fishes) includes establishing or re-establishing populations in new streams and rivers by "straying" from their natal streams. In wet years over the last several decades, Chinook salmon and Pacific lamprey returns have been documented in the upper San Joaquin River. In some years, salmon have made it over Sack Dam presumably through leaping over the low dam or passing through a fish ladder, over Mendota Dam (which has a fish ladder) and all the way to the base of Friant Dam (United States Department of the Interior 1986, McBain & Trush 2002, Marston 2003). In 1969, some of my students at Fresno State University observed Chinook salmon spawning immediately below Friant Dam. In the summer of 1970, I personally collected juvenile Chinook salmon in a tributary to the Kings River, below Pine Flat Dam (Moyle 1970). These fish had to make it up the lower reaches of the river, pass over Mendota Dam, and swim through Fresno Slough to find the Kings River. In the 1980s, anglers reported the presence of Chinook salmon in the Fresno and Chowchilla rivers, small tributaries to the upper San Joaquin River (Yoshiyama et al. 2001).

Although salmon return to the San Joaquin River, they cannot survive, spawn, and migrate back to the sea without adequate flows of water. Recognizing this, the California Department of Fish and Game in 1950 constructed a weir just upstream of the mouth of the Merced River to prevent salmon from ascending the San Joaquin River, deflecting them into the Merced River. This diversion of fish into the Merced River did not have an appreciable affect on Merced River salmon runs (Fry 1961). The spring run of Chinook salmon did not become re-established in the lower Merced River and the fall run in the 1950s was often less than 500 fish. The Merced River salmon hatchery was established by CDFG in 1971 to supplement the low runs and presumably is the principal reason why the Merced River maintains a run of several thousand fish each year, although in 1990 less than 100 fish appeared in the river (Yoshiyama et al. 2001). It is possible that the upper San Joaquin fall run made a genetic contribution to the Merced River population but it too, like the spring run, is extirpated.

X. ARE FISH IN THE SAN JOAQUIN RIVER BELOW FRIANT DAM IN GOOD CONDITION?

Overall, using my three-tiered definition of good condition, the fish in the San Joaquin River below Friant Dam are NOT in good condition as the result of the operation of Friant Dam. In the cool-water reach with riparian releases immediately below the dam (roughly to highway 41), there is a limited assemblage of mostly native resident fishes that is missing species, with a fishery supported mainly by domesticated trout released from the Friant hatchery. The key component of the historic community, Chinook salmon, is missing. These salmon not only supported fisheries but were a major source of marine-derived nutrients to support more diverse and abundant aquatic and riparian communities. Below this reach, the river either supports no fish at all, because it is dry, or supports limited and erratic assemblages of non-native fishes, mostly species too small or short-lived to support fisheries (e.g., Brown 2000).

The most recent demonstration of the lack of good condition comes from the ongoing sampling program of the California Department of Fish and Game, of the permanent riparian release waters from Friant Dam down to about a mile above Lanes Bridge (DFG 2004). Their sampling revealed that the number of fish species present is lower than expected (15 vs 30+ in the much smaller Putah Creek) and that some areas are completely dominated by a handful of non-native fish species, especially predatory largemouth bass and western mosquitofish. Ten of their 15 samples were dominated in numbers (>50% of sample) by just one species, often threespine stickleback (a native), indicating that habitat diversity was limited. The encouraging aspects of this sampling were (1) samples taken between highway 41 and Friant Dam contained mostly native species, (2) seven native resident species were present, with the potential to form the basis for restored fish communities, (3) Kern brook lampreys, a state species of special concern, were present in small numbers, and (4) Pacific lampreys were present as larvae. The lampreys, like salmon, are anadromous so their presence suggests that passage up the river is possible in many winters even today. Because Pacific lampreys live up to seven years as larvae before going out to sea, adults can return infrequently and still maintain a small population (Moyle 2002). Thus, while DFG sampling reveals that the fish are not in good condition, the presence of some native species suggests that good condition can be achieved readily (although not instantly) with addition of a better flow regime.

XI. CAN FISH IN THE SAN JOAQUIN RIVER BE RESTORED TO GOOD CONDITION AND IF SO, HOW?

In this section, I will show why, in my opinion, it is possible and reasonable to restore fish in good condition to the San Joaquin River from Friant Dam downstream to the its confluence with the Merced River. To do this, I will present my professional opinion in five sections: (A) goals and objectives for restoration to good condition, (B) why Chinook salmon should be the focus of restoration, (C) apparent constraints to restoration, (D) a general reconciliation strategy for the river and its fish, and (E) a flow regime for different water year types, from very wet years to extreme drought conditions.

A. GOALS AND OBJECTIVES

A key to any restoration program is to have clear and reasonable goals and objectives. In the case of the San Joaquin River, such goals and objective can be achieved through increase and manipulation of flows and through diverse habitat improvement projects, as has been done on a smaller scale on Putah Creek (Moyle et al. 1998, Marchetti and Moyle 2001) and the Tuolumne River (Ford and Brown 2001). Such activities, however, will not result in restoration of the river to some near-pristine state but rather in the creation of river that has many attributes of the original river (as indicated by native fish distribution and abundance) while still providing abundant water for human needs. This type of project fits under the broad term "reconciliation ecology" which is typical of most large-scale restoration projects, even if not widely recognized as such (Rosenzweig 2003). The reconciliation of the San Joaquin River to some state between historic conditions and present conditions requires a clear statement of what the reconciled conditions should be like. I therefore list here what in my opinion are achievable goals and objectives for San Joaquin River fishes that would result in the fish being in "good condition" from Friant Dam downstream to the Merced River.

Goal 1 Restore Chinook salmon and other native fishes in significant portions of the San Joaquin River from Friant Dam down to the mouth of the Merced River.

Objective 1: Re-establish self-sustaining populations of spring-run Chinook salmon

Objective 2: Re-establish self-sustaining populations of fall-run Chinook salmon

Objective 3: Re-establish diverse assemblages of native resident fishes.

Objective 4: Re-establish or expand self-sustaining populations of Pacific lamprey.

Goal 2. Create sustainable fisheries for native and non-native fishes.

Objective 1: Re-establish in-river sport fisheries for Chinook salmon

Objective 2: Enhance the ocean fishery for Chinook salmon

Objective 3: Re-establish or enhance the fishery for native resident fishes

Objective 4: Expand the recreational fishery for non-native sport fishes.

GOAL 1

The first goal is to establish, as a minimum, the annual runs of salmon and Pacific lamprey that existed just prior to the closure of Friant Dam, as well as to create permanent habitat for 10-14 species of native fishes in the reaches below the dam.

The number of salmon needed to satisfy this goal would probably be a minimum of around 500 fish of each run per year, based on the persistence of runs in the Stanislaus, Tuolumne, and Merced Rivers[8]. Higher numbers would be expected when favorable stream flows and ocean conditions increase survival rates of juvenile salmon. Re-establishing a run of spring-run Chinook salmon is particularly critical, not only because they were historically the most abundant run in the San Joaquin River but because they are listed as a threatened species in California. Their present habitats in the Sacramento system (Deer, Mill, and Butte creeks) were historically minor habitats for spring-run (Moyle 2002) and are likely to be strongly affected by global warming (increased temperatures). In Butte Creek, summer temperatures already reach lethal or near-lethal ranges for holding adult Chinook (Butte Creek Watershed Conservancy 1998; Ward et al. 2004). The San Joaquin River, with its cold water from the high-elevation peaks of the southern Sierra Nevada and its cold water releases from Friant Dam will have less of a problem with providing cold-water flows for the salmon in the years to come.

[8] Most models, based on both genetic and random population (stochastic) factors, suggest minimum populations in this general area. Cass and Riddell (1999), for example, suggest that 100 female spawners are needed to maintain a population, which translates into 300-500 fish when males and unsuccessful spawners are taken into account. 500+ is the minimum number suggested by Hedrick et al. (1995) for Sacramento winter-run chinook salmon using fish both spawned in the wild and in restoration hatcheries.

Pacific lampreys are the only other anadromous fish with a specific goal for recovery because they are in severe decline throughout their range and the San Joaquin River clearly has abundant spawning and rearing habitat for them (Moyle 2002). Recent sampling by DFG (2004) indicates that a small population is probably still being maintained in the river. Possibly steelhead (anadromous rainbow trout), for which the Central Valley populations are listed as threatened, will also benefit from a San Joaquin River restoration program. Given that most of their historic habitat was probably above the site of Friant Dam, however, a restoration program that would provide adequate habitat for a self-sustaining population of steelhead would be difficult to achieve, so should not be part of the restoration goal.

If more permanent flows of cool water are provided for the San Joaquin River, diverse resident native fishes will be able thrive in large parts of the river. The downstream extent of the community of native fishes will depend on the annual flow regime. Presumed members of the native fish assemblage in the cool-water reaches would be Kern brook lamprey, hitch, California roach, hardhead, Sacramento pikeminnow, Sacramento sucker, rainbow trout, tule perch, threespine stickleback, prickly sculpin and riffle sculpin (Moyle 2002). Such fish could become established either naturally, from upstream sources, or by judicious stocking from local sources (e.g., Tuolumne River). In warmer reaches Sacramento blackfish and Sacramento perch could also become established, at least experimentally. Non-native fishes (such as largemouth bass, green sunfish and common carp) would no doubt be present as well but well-designed flow regimes that favor native fishes can keep populations of non-native fishes small in native fish reaches (e.g., Marchetti and Moyle 2001)..

A cool-water native fish assemblage could presumably occupy 40-50 miles of river, gradually giving way to a mixed assemblage of native and non-native fishes. In the lowermost reaches, above the Merced River, where summer temperatures would be warm (daily maximums presumably in excess of 28º C) and flows augmented by agricultural return water, the fish fauna would be dominated by non-native fishes, including many favored game fishes (various catfishes, basses, and sunfishes). With permanent flows, their numbers and sizes should be sufficient to support substantial recreational fisheries. In addition, elevated flows, especially spring pulse flows, should allow Sacramento splittail and other native fishes to spawn in the flooded areas, as well as provide additional places for juvenile salmonids to rear (See Sommer et al. 2001a).

GOAL 2

Once the goal of establishing self-sustaining populations of native resident and anadromous fishes has been achieved, the next natural step is to restore fisheries for them. Obviously, the return to the fisheries of the 19th Century, when hundreds of thousands of salmon produced by the San Joaquin River were harvested, is not possible. But more modest goals of an in-river fishery averaging a few thousand Chinook salmon a year with a similar contribution to the ocean fishery is certainly possible. Likewise, establishing a fishery for native cyprinids and suckers, such as pikeminnow and Sacramento sucker, should be possible as well. These large native fishes find favor as food fish with Asian-American anglers of various ethnicities and are likely to increase in popularity as they become better known. An expanded fishery for non-native game fishes, including striped bass, American shad, and various catfish, will develop on its own, as fish move up from the Delta to colonize the lower river. Once a fish-friendly flow regime has been established, it will make other stream-oriented restoration projects both desirable and productive, as has been demonstrated repeatedly for other streams around California. Projects would include restoring riparian and floodplain habitats, increasing channel complexity (e.g., with boulders, trees), and spawning gravel enhancement. These projects are often undertaken by local watershed groups and have extensive community involvement. Their overall impact is to further increase fish production without increasing water demand, making development of fisheries a reasonable expectation in the future.

B. SALMON AS THE FOCUS OF RESTORING FISH IN GOOD CONDITION

Although the ultimate goal of restoring flows to the San Joaquin River is to recreate a healthy river ecosystem that supports a diversity of life, including native fishes in good condition, here I will focus mainly on Chinook salmon. The reasons for this are many, including:

1. They are an “umbrella species.” If conditions are restored to support salmon, conditions will simultaneously be created that are favorable for many other desirable species.

2. A great deal is known about Chinook salmon life history requirements that can be applied to designing restoration strategies.
3. The Chinook salmon is a highly adaptable species that can quickly adjust its life cycle to new conditions, so restoration strategies do not have to be narrowly constrained by historic life history patterns.
4. Salmon were important historically to the river and the people who lived in the watershed.
5. They are a highly visible symbol upon which to measure restoration success.
6. Even after Friant Dam was built, Chinook salmon were able to come back and spawn when conditions were right.
7. There is a long history of successful restoration of salmon populations in the Central Valley that can be used to inform strategies for restoring them to the San Joaquin River.
8. There are ancillary benefits from Chinook salmon restoration in the San Joaquin, such as the potential to restore runs to the Kings River, enhancing the salmon runs in the Merced, Tuolumne, and Stanislaus rivers, and improving water quality in the river.
9. Chinook salmon bring large quantities of nutrients from the ocean into inland systems, benefiting the aquatic and riparian systems (Naiman et al. 2002) and providing nitrogen and other nutrients to crops grown near spawning rivers (Merz and Moyle 2005).
10. Successful establishment of spring run Chinook salmon will the increase the probability of removing spring-run Chinook from the list of threatened and endangered species. This is particularly important now that global warming/climate change is likely to reduce the amount of cold water in streams tributary to the Sacramento River where they now reside (Hayhoe et al. 2004).

Obviously, restoring the San Joaquin River to a point where it can support self-sustaining runs of Chinook salmon will not be easy, but it *is* possible, while minimizing water costs. In the next sections, I will describe how apparent constraints to recovery salmon populations are less constraining than is often assumed. Then I will then discuss the restoration of the San Joaquin River in the broader context of reconciliation ecology (Rosenzweig 2003).

C. APPARENT CONSTRAINTS FOR RECOVERY

For much of the last 50 years, long reaches of the San Joaquin River have been inhospitable to native fishes (or to fish in general). This is largely because of the absence of a flow regime appropriate for the fish. Despite long neglect of the river, its salmon runs can be restored. One of the best demonstrations of the feasibility of restoration is that salmon runs persisted in the river through the early 1940s despite decades of neglect of the river and its fishes. They were extirpated only when the water to the river was finally shut off. Even so in wet years, when dams cannot contain and divert all the water, a few fish can make it up to spawn in both the San Joaquin and Kings rivers (Moyle 1970). Nevertheless, successful restoration of salmon runs, especially to bring enough fish back to support fisheries, requires evaluation of potential constraints[9] to this recovery. I consider possible constraints on the recovery of the river and its fishes in the following categories: (1) passage, (2) flows, (3) habitat, (4) temperature, (5) water quality, (6) homing behavior, and (7) sources of salmon and other fish.

1. PASSAGE

Recovery of salmon in the San Joaquin River requires the fish to migrate up into the reach between Friant Dam and Gravelly Ford where the best spawning and rearing habitat occurs. Factors currently impeding this migration are structures in the channel and dewatered reaches. These factors are described in detail in McBain and Trush (2002) so will only be briefly described here. It is worth noting, however, that many of the problems described here would probably not exist or would have been dealt with incrementally (e.g., construction of fish ladders and screens) if the river had been even minimally managed for salmon after Friant Dam was built. It is also worth noting that with sufficient flows, salmon have several alternative routes (using both main channel and bypasses) to make it up the river to Friant Dam, so passage is possible even if all present structures remain in place.

[9] The word “constraint” is used deliberately here because it implies that restoration of salmon runs and native fishes is possible but that restored condition will not be the same as the pre-dam condition. Use of the word indicates that I recognize that restoration must be conducted within practical limits imposed by human demands for water and land.

The lowest (RM 118.5) structural barrier is a removable one: the Hills Ferry weir, operated by the California Department of Fish and Game to keep salmon, presumably originating from the Merced River, from migrating up the San Joaquin River. Apparently it was not operational during much of the period from 1950 (when first established) through 1991.

The Sand Slough Control Structure (RM 168.5) is probably not a problem for fish passage but the head gate to control flows into the original San Joaquin River channel, at the same location, is clearly a barrier at the present time. The gates have not been opened for years and as a result the channel immediately below them has been reduced in capacity by encroachment of vegetation, woody debris, and general neglect. The presence of once-operable gates and a channel constructed to hold flows of 1500 cfs indicates that a river was once expected to exist at this point and could be restored.

Sack Dam (RM 182) is a low concrete structure that diverts water into the Arroyo Canal. It is called Sack Dam because it historically was constructed annually from sandbags after the high spring flows had receded. Historically, high flows of winter and spring washed it out, so migrations of spring-run Chinook salmon were unimpeded. At the present time, Sack Dam is a low concrete structure that has a fish ladder built into it, so would require little modification to make it passable for salmon. For adult salmon, it is likely that the dam is low enough (<2 m) so fish could pass over it during high flows even without using the fish ladder. The Arroyo Canal might have to be screened, blocked, or specially operated during times of juvenile salmon out-migration (which is mostly at times when demand for irrigation water is low) but this would be determined through studies (see Moyle and Israel 2005).

Mendota Dam (RM 205) is the largest dam and diversion structure on the lower river. Built in 1921, it spans the channel as a concrete dam, with flashboards, and is 7 m (23 ft) high. It is located just below the point where Fresno Slough enters the river which delivers water from the Kings River during wet years. The pool behind the dam is about 1200 acres and today it receives most of its water from the Delta-Mendota Canal, which delivers, on average, 2500-2800 cfs. This water in turn is mostly diverted into 5 canals to various irrigation districts, replacing the San Joaquin River water which the irrigators used before construction of Friant Dam. The remaining 500-600 cfs flows downstream for 22 miles before being diverted into the Arroyo

Canal by Sack Dam. The importance of fish passage over the dam was recognized from the beginning and the dam was built with a fish ladder. The fish ladder apparently functions poorly today because ground underneath the entry way has eroded, making it difficult for fish to find and use. Because Mendota Dam is an aging structure with many problems, plans are being made to built a new dam slightly downstream of the old one (McBain and Trush 2002); presumably the new dam can be constructed to be passable by upstream and downstream migrants. The canals that take water from Mendota Pool are a potential constraint to downstream migrating juvenile salmon but this problem can be reduced through a combination of screening and timing of diversion operations.

Between Mendota Pool and Friant Dam are numerous diversions, at least one of which places a temporary dirt dam across the river, forcing the flow through a culvert. Likewise, access roads that cross the river to the gravel pits in the Fresno area may be a temporary barrier by forcing fish through culverts. However, such structures can easily be modified to allow both upstream and downstream salmon passage or can be replaced by alternative structures and roads.

The Chowchilla Bifurcation structure (ca. RM 215) is a gate which allows high releases or overflows from Friant Dam to be sent down the broad Chowchilla Bypass, which keeps flood waters out of the main channel of the San Joaquin River. If high flows are sent into the bypass system, fish, including juvenile salmon, are likely to be carried in with the water, with potential for stranding if flows are suddenly reduced. Studies of the Yolo Bypass, along the Sacramento River, demonstrate that native fishes and juvenile salmon in particular are very good at leaving the bypass as flows drop; the studies also show that the flooded Yolo Bypass is favorable environment for juvenile salmon and other fish (Sommer et al. 2001a). This issue is largely resolvable by operation of the bifurcation gates and releases from the dam (e.g., avoiding abrupt shut-off of water and using secondary pulse flows to push fish out of the by passes).

The gravel pits between RM 255 and Skaggs Bridge (RM 234) themselves present a more formidable problem for downstream movement of juvenile salmonids. These pits capture part of the channel, degrade some reaches, increase fine material in the stream bed, and provide habitat for non-native predatory fish. The draft report of McBain and Trush (2002) estimates that "3.3 miles of channel would have to be reconstructed to provide a single continuous channel and fully restore sediment routing (p. 3-120)." Fortunately, a great deal has been learned about such restoration in dealing with gravel pits on the Tuolumne and Merced Rivers. Even without channel reconstruction, however, both adult and juvenile salmon should be able to make it through this reach if flows are sufficient.

2. FLOWS

Restoration of diverse fish communities to the San Joaquin River ultimately will require enough water to make it a continuous living stream again from Friant Dam to its confluence with the Merced River. At the present time, sections of the river are dry most of the year for several miles except during times of high run-off or flood releases. Reaches that are not dry are often maintained mainly by warm, polluted irrigation return water. The typical patterns of flow are well illustrated by Figures 2-40, 2-41, and 2-42 in the draft report of McBain and Trush (2002). For the driest months (August- November), flows diminish gradually with distance downstream from Friant Dam as the result of diversions and infiltration; the river is virtually dry below Gravelly Ford (RM 229). Flows pick up again below Mendota Dam because of water dumped into the pool from the Delta-Mendota Canal and the river flows until it reaches Sack Dam, where the entire flow is diverted. The river is generally dry between Sack Dam and the Sand Slough Control Structure. After that the channel is dry for about 25 miles. At roughly RM 150, irrigation waste water starts flowing in the channel and flows gradually increase until the Merced River is reached. The biggest contributors are flows down Salt and Mud sloughs (between RM 130 and 120), which can deliver 275-400 cfs of return water during the summer (see Kondolf statement). Water from the Merced River (RM 119) more than doubles the flow as the result of releases from an upstream dam. Other seasons are variations on this theme, with more or less water depending on the reach.

To restore 'fish in good condition' below Friant Dam (*sensu* Moyle et al. 1998), the following general flow regime is needed: Except during critically dry years, flow regime should have the following characteristics: (1) continuous flow from the Dam to the Merced River at all times of year to maintain habitat for fish in all reaches of the river, (2) flows from November through December for migration and spawning of fall run Chinook salmon, (3) incubation and rearing flows for fall run Chinook, January – February, (4) flows in March through April for emigration of juvenile salmon of both runs, immigration of adult spring –run Chinook salmon, and spawning of native resident fishes, and (5) flows through the summer to maintain holding and rearing habitat for spring-run Chinook salmon from Friant Dam down to somewhere above Highway 41, to maintain a diverse community of native fishes, and to support fisheries for warm water game fishes. Obviously, the amount of water used for each purpose would vary with water year; in drier years, salmon and other native fishes would have reduced habitat. Continuous summer flows on the valley floor, for example, could be dispensed with during severe drought, recognizing that the populations of resident native fishes and non-native sport fishes would be reduced, but could recover once flows returned. A more extensive discussion of the flow regime and its justification is provided in section XI E of this statement, as well as in the statements of Drs. Kondolf and Deas..

It is worth noting that a restored flow regime does not need to track exactly the historic flow regime of the San Joaquin River because the behavior of both fall and spring run Chinook can be manipulated through selection to fit a regime that is practical using available water. Runs maintained by hatcheries, for example, may quickly peak several weeks earlier than they would naturally because of selection for early-run fish by hatchery workers (Quinn et al. 2002). The most remarkable example of such adaptation, however, occurred naturally as the result of transplantation of Chinook salmon from Battle Creek, a tributary to the Sacramento River, to streams in New Zealand, in 1901-1907. Not only do the life histories of New Zealand salmon now differ significantly from those of the origin population but they differ significantly among streams in New Zealand (Quinn and Unwin 1993; Quinn et al. 1996, Kinnison et al 1998). Major adaptations to local conditions apparently took place in less than 20 generations under natural conditions (Quinn and Unwin 1993). This suggests that Chinook salmon will work *with* restoration efforts by adapting both phenotypically and genotypically to the conditions provided.

3. HABITAT

Beyond adequate flows and passage over barriers, adequate physical habitat is important for the restoration of salmon and other fishes. The habitat needs for spring-run and fall-run Chinook in the San Joaquin River are covered in detail in Stillwater Sciences (2003) so will only briefly be discussed here. For salmon, the following aspects of habitat are required: (1) passage for migration, (2) deep pools for holding of over-summering spring-run Chinook adults, (3) gravel riffles for spawning and incubation of embryos, (4) diverse instream habitat for juvenile rearing, and (5) cover for migrating adults and juveniles. Fortunately, the reach between Friant Dam and Gravelly Ford still possesses much habitat that is already suitable, given adequate flows, or can be restored to suitability using known techniques. My experience with Putah Creek, the Tuolumne River, and other streams indicate that once adequate flows are established, watershed groups quickly take the lead to develop and find funding for habitat restoration projects.

Migration passage requires cool water (generally less than <21ºC maximum daily temperatures) in the lower most reaches and adequate flows to surmount barriers. The flow and temperature requirements are discussed in other sections and the barriers are all surmountable (i.e., salmon have made it to the base of Friant Dam even under present conditions).

Deep pools for holding are needed by spring-run Chinook salmon because they migrate to the spawning reaches in the spring as immature fish and then hold through the summer. After the construction of the dam, at least 5000 adult spring run Chinook were observed holding in summer in two pools immediately below the dam (Clark 1942). The largest of these pools has a maximum depth of 8 m (25 ft) and an average depth of 3 m (11 ft) and covers an area of 9300 ft^2 (2800 m^2). Stillwater Sciences (2003) estimated that this pool alone could hold 4300-12900 salmon through the summer. My experiences with studying spring-run Chinook holding habitat in Deer Creek (Tehama County) suggests that this is a reasonable, if conservative, estimate.

Spawning riffles with walnut to apple-sized gravels suitable for spawning and incubation still exist in the reach from the dam to Gravelly Ford, which I have observed. The amount and quality of gravel in many of the areas still needs careful evaluation to determine its suitability for spawning and incubation (along the lines of Sommer et al. 2000a), but there is clearly adequate gravel to support both spring run Chinook (in the reach below Friant Dam) and fall run Chinook (in the reach around Lanes Bridge and below). Cain (1997) estimated there was adequate gravel to support spawning by about 5000 pairs of salmon between Gravelly Ford and Friant Dam. This estimate was 80-90% lower than DFG estimates from the 1950s and reflects the results of vegetation encroachment, instream gravel mining, channel incision, siltation, and reduction in flows. Fortunately, this trend can be readily reversed through a variety of actions, once flows have been restored to the river. For example, techniques for adding spawning gravels to rivers for successful Chinook spawning are well developed for Central Valley streams (Mesick 2001). Dr. Joseph Merz, did his Ph.D dissertation under me evaluating spawning gravel additions on the Mokelumne River, developing techniques for improving the success of gravel addition programs, even under conditions of relatively low flows. Gravel for such additions is available in the river terraces along the San Joaquin River so costs are likely to be relatively low. It is worth noting that once runs become established, the constant digging and movement of gravel by spawning salmon results in improved quality through the mobilization of fine sediment. As the Kondolf report indicates, higher flows in the river will also mobilize gravel, improving its condition for spawning.

Juvenile rearing habitat requirements are complex and are closely tied to temperatures and flows. Once the alevins emerge from the gravel, fry of both runs require shallow (< 1 m) edge habitat, where they can find small prey and hold at relatively low velocities. Such habitat is presently available and could be expanded with increased flows. As the fry grow larger and more active, they move out into deeper, higher velocity water where larger prey is more available and predators are fewer. Juvenile fall-run Chinook often start to move gradually downstream at this stage, the speed of movement and number moving depending on flows. Number of fry (30-53 mm FL) typically peaks in the San Francisco Estuary in January-March but small numbers are found through July (Brandes and McLain 2001). Studies by Sommer et al. (2001b,c) in the Yolo Bypass and my own studies on the Cosumnes River indicate that if provided the opportunity, these juveniles will move on to floodplains where they grow faster and larger than fry that stay in the river. As the floodplains drain, the juveniles move off with the flood waters. These studies suggest the value to salmon of eventually restoring floodplain habitats along the San Joaquin River.

Spring-run Chinook juveniles, in contrast to fall-run Chinook, rear in their natal stream for about a year. They basically require cool water (see next section) through the summer. My observations in Deer and Mill Creeks (Tehama County) indicate that they typically hold and feed in riffles with complex substrates (boulders, logs etc.) and at the tails of pools during the day, where they feed on drifting invertebrates. This type of habitat is already present in the reach below Friant Dam, with adequate summer temperatures, and could easily be improved through addition of structure (logs, boulders) and riparian vegetation. These fish migrate downstream as either large (80-100 mm FL) juveniles or as smolts. Movement can be quite rapid (up to 23 miles /day), depending on size of fish and amount of flow (Healey 1991), so successful movement to the estuary mainly requires unimpeded passage and, in some places, screened diversions. Once spring-run juveniles (or smolts) start to move downstream from their rearing areas below Friant Dam, especially if provided the stimulus of increased flows, it is likely that they will reach the Delta in 5-10 days.

4. TEMPERATURE

Water temperature is a key limiting factor for Chinook salmon and appropriate temperatures must be present at all stages of their life cycle. Water temperature, while easy to measure, is not a simple factor from both a physical and biological perspective. Thus single temperature standards (e,g., 18ºC [64ºF]is often given as maximum permissible temperature for salmon waters) are rarely very meaningful. The temperature at a given spot in a river is the result of interactions among air temperature, flow (river volume), source temperatures, depth, shading, and other factors. The ability of individual salmon to survive, tolerate, or thrive at a particular temperature is the result of a combination of recent thermal history (i.e., acclimation), availability of thermal refuges, length of exposure time, daily temperature fluctuations, genetic background, life stage, interactions with other individuals and species, food availability, and stress from other factors (e.g., pollution). Generally, the ability of a juvenile or adult salmon to survive high temperatures is a function of the degree to which energy expended by dealing with stressful factors (e.g., avoiding predators, length of exposure to high temperatures) is balanced by energy gained from favorable factors (e.g., abundant food, daytime cool-water refuges). This bioenergetic approach to understanding temperature tolerances can explain why some populations that experience high (22ºC [72ºF] or more) temperatures thrive while others experiencing the same temperatures die out.

. Because of the complexity of interactions related to temperature and because of the importance of Chinook salmon throughout their range, temperature requirements have been the subject of intense study and recent reviews (McCullough 1999, McCullough et al. 2001, Myrick and Cech 2004). A restored flow regime in the San Joaquin River has to take into account the temperature requirements of migrating and spawning adults, embryos buried in the gravel, juveniles rearing in the stream, and out-migrating fry and smolts. While there is evidence that adult and juvenile Chinook salmon in the Central Valley have slightly (1-2ºC) higher maximum temperature tolerances than Chinook salmon in more northern populations (Marine and Cech 2004), the conservative course of action is still to plan for tolerances more or less typical of the species (Table 1, end of document).

Adult migration. Adult migration to the spawning grounds in California typically takes place at water temperatures between 10 and 20ºC (51-68º F). Although movement has been observed in warmer water, daily maximum temperatures of 21 or 22ºC (70-72º F) can cause adult salmon to stop migrating (McCullough 1999, Yurok Tribal Fisheries Program 2004). Salmon that experience temperatures greater than 21º C (70ºF) without relief from cool water refuges or cool night-time temperatures usually stop migrating and experience high mortality rates. Nevertheless, adults have been observed surviving temperatures as high as 27ºC (80ºF) for short periods of time, although 25ºC (77º F) is usually regarded as the absolute lethal limit for Chinook salmon (McCullough 1999, McCullough et al. 2001). Curiously, in the 19th Century, Chinook salmon were observed migrating up the San Joaquin River in July and August at temperatures approaching 28ºC (82ºF), although the accuracy of the temperature measurements is problematic (Yoshiyama et al. 1996). It is possible that the migrating fish were moving between pools with cooler bottom temperatures as the result of accretion of ground water. The complexity of temperature effects is illustrated by the kill of 33,000 adult Chinook salmon in the lower Klamath River in September 2001. The high daily maximum temperatures (ca. 21ºC, 70ºF) were not particularly unusual for the river in September but when combined with low flows and exceptionally large numbers of fish, they were lethal because they (and the crowded conditions) created optimal conditions for the diseases which were the ultimate causes of death. The Klamath example suggests that stress can be lethal at temperatures that might be survived under other circumstances.

It is also worth noting that ripe female salmon that survive prolonged exposure to high temperatures may have reduced viability of their eggs, a factor that seems to increase the more the temperatures experienced were above 12-15ºC (53-59ºF, McCullough 1999). The lowered quality of heat-stressed eggs is partially compensated for if incubation temperatures are <12ºC (53ºF). Even with less than optimal conditions, survival rates of heat-stressed embryos are typically 50-80% (McCullough 1999). Thus a reasonable recommendation for migration temperatures for adult Chinook salmon is to minimize exposure to daytime maximum temperatures greater than 20ºC (68ºF) and where possible to keep temperatures during the migration period to <15ºC (59ºF). Data on various species of salmon in Groot and Margolis (1991) indicate that adult chinook salmon are capable of migrating up-river at a rate of 20-40 miles/day. Once they enter the San Joaquin River above its confluence with the Merced River, they could reach their spawning grounds in 4-8 days if there are no delays. This rapid migration time should minimize risks to developing eggs by exposure to high temperatures.

Even if exposure to high daily maximum temperatures for a few days reduced embryo survival and increased adult mortality, if run sizes were adequate, these factors may nevertheless not have much impact on total number of juveniles produced in a given year due to compensatory mechanisms (e.g., less dense populations of juvenile can result in less competition for food, resulting in higher growth and survival rates than would be the case at higher densities). The problem with embryo survival in females exposed to warm temperatures may also be less in spring-run Chinook than in fall run Chinook, because their eggs are immature during the migration period.

Adult holding. Holding temperatures are mainly a factor for spring-run Chinook, which enter freshwater as immature fish, move upstream to deep pools where they can hold through the summer and then spawn in early fall. My studies on spring run holding pools in Deer and Mill creeks, Tehama County, indicate that daily maximum temperatures of 18-21ºC (64-70ºF) during the summer holding period were a regular occurrence (Moyle et al. 1995). Somewhat higher temperatures (to 23.5ºC, 76ºF) are experienced by spring run Chinook in nearby Butte Creek (Ward et al. 2002, 2003). Butte Creek also has a history of mortality of the salmon, usually when adult numbers are high so many fish are confined to a few pools. Generally, for the reduction of temperature stress on developing eggs, daily maximum temperatures of <16ºC (61ºF) are most desirable in holding pools. My experiences on Deer Creek suggest that summer water temperatures usually drop below this temperature at night so salmon exposure to maximum temperatures are usually confined to a few hours in late afternoon. A reasonable thermal regime for holding spring-run Chinook on the San Joaquin, therefore, would be one in which temperatures of <16ºC are most desirable but daily maximum temperatures of 18-21ºC (64-70ºF) are acceptable if they are of short (3-5 hrs) duration.

Because Millerton Reservoir stores cold water from run-off from snowmelt in the highest Sierra Nevada, it stratifies each summer with a large pool of deep cold (7-13ºC, 45-55ºF) water (USBR, unpublished data). Mean temperatures year around in the San Joaquin River just below the dam are typically 9-11º C (48-51ºF), which are optimal for holding. The CDFG fish hatchery at Friant relies on this cold water for their operation and mixes it with warmer surface water to optimize temperatures for rearing trout (McBain and Trush 2002). This indicates that cold water is available to hold spring-run Chinook through the summer, as the fish themselves demonstrated during the last years of the run in the 1940s.

Spawning and incubation are the most temperature sensitive parts of the Chinook life cycle, mainly because survival and development of embryos buried in the gravel requires a narrower range of temperatures than other parts of the life cycle. McCullough (1999) found spawning temperatures in the literature for Chinook salmon ranged from 2.2 to 18.9ºC (36-66ºF); he concluded, however, that temperatures less than 12.8ºC (55ºF) will inhibit spawning to some degree and that at temperatures greater than 16ºC (61ºF) "we can assume spawning will not occur (p. 80). " A similar temperature range is necessary for incubation. Mortality rates of developing embryos increase as temperatures rise above 12.8º C (55ºF) and above 17ºC (63ºF) mortality is typically 100%. To a certain extent, there is a trade-off between mortality and incubation time: at higher temperatures, incubation time is faster so the juveniles emerge from the gravel sooner (McCullough 1999). For salmon at the southern end of their range, rapid emergence time would seem to be advantageous, especially for fall-run Chinook salmon. Thus optimal temperatures for incubation in California are probably about 9-13ºC (48-55ºF), which is the temperature range of the cold water releases from Friant Dam (Stillwater Sciences 2003).

Juvenile rearing. From the time juvenile Chinook salmon emerge from the gravel to the time they migrate out to sea, they are part of a complex stream environment in which biological, physical, and chemical elements all influence the range of temperatures at which they are found and survive. No matter what the conditions, however, temperatures above 24ºC (75ºF) are invariably lethal even for short exposures and high mortality is experienced above 22ºC (72ºF) (McCullough 1999, Moyle 2002). For growth to occur, temperatures have to be in the range of 5-19ºC (41-66ºF) and, for Central Valley Chinook, most rapid growth generally occurs when maximum daily temperatures are 13-20ºC (55-66ºF) . However, rapid growth can still be experienced at higher temperatures if exposure times are short and if temperatures either cool down significantly at night or there are cool-water refuges available (e.g., deep pools with upwelling ground water). Bioenergetic models for salmonids (McCullough 1999) indicate that the ability to handle or even profit from higher temperatures can be increased if food is extremely abundant so the energetic costs of feeding are low. Thus Marine and Cech (2004) reared juvenile Chinook salmon at 17-20ºC in the laboratory. The ability to handle high temperatures may be reduced if food abundance is low and densities of other fish are high, especially those of potential predators and competitors. For juvenile fall run Chinook, temperatures that promote growth and survival are needed mainly for February through mid-May because the juveniles (fry) emigrate at a small size (35-80 mm FL) into the (usually) cooler big rivers, estuaries, or bays before stream temperatures reach lethal levels.

In contrast, most juvenile spring-run Chinook require appropriate temperatures year around in their rearing streams. All other things (predation, competition, food abundance etc.) being equal, bioenergetic models indicate that optimum growth and survival for the juveniles would presumably be found at the upper end of 5-20ºC (41-68ºF) temperature range. High growth rates could still be achieved if temperatures reached higher levels during the day for short periods (< 3 hr) of time, provided food was abundant. In water that is consistently too warm to favor growth, but is productive enough to allow for high survival, juvenile salmon can experience high growth rates in spring and fall and be in good condition (e.g., favorable length to weight ratio) for emigration in the winter. Thus summer rearing temperatures for spring-run Chinook in the San Joaquin River would be optimal in reaches where daily maxima rarely exceeded 20ºC (68ºF) but rearing would still be possible in reaches where daily temperature maxima reached 22-23ºC (71-73ºF), provided minimum temperatures were <19ºC (66ºF) and/or cooler refuge areas were available.

Smoltification. Both spring and fall-run juveniles in Central Valley streams emigrate from their rearing areas at variable sizes (although >80 mm FL) and ages (e.g., Hill and Webber 1999). Many spring-run and some fall-run Chinook juveniles leave their rearing areas as smolts (or near-smolts), a profound morphological and physiological transformation that enables them to swim rapidly downstream and to enter quickly enter salt water. Smolts typically migrate downstream during high flow events in winter months, so temperatures are rarely a problem for them during migration, even in California. In rivers, smolts occur regularly at temperatures of 10ºC or lower. However, Chinook salmon juveniles transform into smolts in the wild at temperatures in excess of 19ºC (67ºF), although in a laboratory study highest growth and survival of smolts was found if they underwent transformation at temperatures of 13-17ºC (52-62ºF) (Marine and Cech 2004). Temperatures >17ºC are unlikely to be encountered in the reaches below Friant Dam during the times when smoltification in spring-run Chinook is likely to be proceeding (November-December). For fall-run Chinook, transformation into smolts can take place either in the estuary or in the river as the juveniles are moving downstream; high temperatures are likely be a problem for smolts mainly if they are prevented from migrating until late in the season (May-June).

5. WATER QUALITY

The water that flows out of Friant Dam is generally of high quality: cold, clear, and free of contaminants, so it is well suited for salmon at all life history stages year around. Water quality in the channel generally deteriorates in a downstream direction, as a function of diversions and quality of agricultural return water. Water in the reach immediately above the confluence with the Merced is warm, nutrient-enriched, and contaminated with pesticides because of agricultural return flows (Brown et al. 1999). If the San Joaquin River was restored as a salmon river, with permanent year-around flows, dilution alone would reduce these negative aspects of water quality. It is likely, however, that as the river receives heavier use by humans for recreation, including fishing, and became better habitat for wildlife, especially various at-risk species, means of reducing risks of exposure to contaminated water will be found. Indeed, there are many forces at work (e.g., TMDL standards) that are already promoting higher water quality in impaired waters of California. It is worth keeping in mind that even under the presumably poor water quality conditions that must have often existed prior to and immediately after the construction of Friant Dam, salmon still managed to make it up the river in numbers to spawn successfully.

6. HOMING BEHAVIOR

Perhaps the most famous characteristic of salmon is their ability to return to spawn in the stream in which they were reared. The general mechanism for this has been demonstrated to be that the young fish are imprinted with the "odor" (distinctive chemical characteristics) of the water of their home stream and the adults follow the odor trail back upstream using their memory of the smell. Thus a constraint to re-establishing Chinook salmon might be their ability to find the signal of Friant water in a river where water in the lower reaches is the result of mixing from a variety of sources or even where the Friant water signal is missing completely. There are a number of reasons think that this constraint is not likely to be a problem, based on studies cited in Groot and Margolis (1991):

1. Homing is not an absolute characteristic of salmon but a statistical one: most salmon return to their natal streams but many do not, choosing instead alternative streams with favorable characteristics.

2. The chemical imprinting is a complex phenomenon; out-migrating fish are presumably also memorizing the odors of other sources of water as they move downstream, as well as that of the natal water.

3. Other cues for migration are used as well as odor, especially once the salmon are some distance from the natal streams, including the Earth's magnetic fields and underwater landmarks.

4. Most straying apparently occurs into streams close to the natal stream. In the San Joaquin River, once the fish have passed the mouth of the Merced River, they really have no place to go but the reach of river below Friant Dam.

5. One of the odors that promote homing is that of juvenile salmon that are resident in a stream (Quinn 2005). Thus once salmon are re-established in the San Joaquin River, the success of homing should increase.

While an indistinct odor trail in the lower river would probably decrease the numbers of fish making it back to spawn, it would not prohibit at least some fish from reaching the designated spawning grounds. If this proved to be a problem, which is unlikely in most years (especially if attraction flows are provided), presumed San Joaquin fish could be captured at their 'wrong' location and moved to the San Joaquin River below Friant Dam.

7. SOURCES OF SALMON AND OTHER FISH

Because Chinook salmon have been extirpated from the San Joaquin River above its confluence with the Merced River, salmon stocks used for restoring populations will have to come from other streams in the Central Valley. Given sufficient time, fall-run Chinook would probably re-establish populations naturally, from strays from the Merced, Tuolumne, and Stanislaus Rivers. Hills Ferry Weir, just above the Merced River, is currently operated by DFG to *prevent* fall-run Chinook from entering the San Joaquin River, suggesting that the potential for natural restoration is high. However, it would also be easy to 'jump start' the run by either planting fry reared in the San Joaquin hatchery at Friant or by using fertilized eggs in hatch boxes, which are buried in the gravel, and allowed to hatch under natural conditions. This could be done over multiple years.

Spring-run Chinook salmon would almost certainly have to be brought into the system from the Sacramento River drainage, although they most likely would re-colonize the system naturally if given enough time. I think the best candidate population for transplantation is the one in Butte Creek, Tehama County. The Butte Creek population is genetically distinct from other spring-run populations (Banks et al. 2000) and has juveniles that emigrate both as fry and as yearlings (Hill and Webber 1999). The outmigration of fry occurs mainly in December through February, when rain naturally increases flows in the creek, while that of yearlings takes place gradually under suitable flow conditions from September through May. In recent years, numbers of adults holding in the creek have been exceptionally high (8,000-10,000, Ward et al. 2002, 2003), so the consequences of removing fish from the population for use in restoration are likely to be small or none. In fact, because some of the holding areas exhibit summer temperatures (up to 23.5ºC) at the upper end of the salmon's tolerances, mortality of adult salmon has been noted, presumably tied to the crowded conditions under stressful temperatures. Interestingly, the spring and fall runs of Chinook salmon in Butte Creek have maintained their separation in time and space, despite the lack of obvious barriers to mixing. Butte Creek overall seems to have one of the most adaptable and numerous populations of spring-run Chinook salmon left in the Central Valley, making it ideal for use in restoration. Other populations that might be available for transplantation are those in Deer and Mill Creek and, perhaps, in the Feather River. Regardless of origin, a population of spring-run Chinook salmon established in the San Joaquin River has the potential to nearly double the number of spring-run salmon returning to California streams, greatly increasing the probability of the fish being removed from the federal list of threatened species.

Other native fishes currently absent from the mainstem San Joaquin River (e.g., tule perch, hardhead) could be acquired from populations existing upstream of dams and planted as either adults or juveniles, to re-establish downstream populations if they did not recolonize naturally.

D. A RECONCILIATION STRATEGY FOR ACHIEVING FISH IN GOOD CONDITION

While the efforts to bring back salmon and other fishes to the San Joaquin River are typically labeled as restoration, it is more realistic to call them an example of environmental reconciliation. As Rosenzweig (2003) points out, large scale "restoration" projects can virtually never bring back ecosystems to pristine conditions, so it is better to find ways to make maintenance of biodiversity and natural processes compatible with humans needs for intense land and resource use. In the case of the San Joaquin River, it is possible to restore modest runs of salmon and desirable populations of resident fishes in ways that do not incur high water costs and actually improve the river itself for human use. In this section, I will first discuss how to make bringing back the salmon runs compatible with this idea and then discuss additional benefits that will accrue if we do allow salmon to return to the San Joaquin River.

The historic hydrograph of the San Joaquin River was optimal for spring-run Chinook salmon not only because of the river's cold water for holding but because the long period of snowmelt assured high flows through early summer. The spring-run salmon as a result often migrated up fairly late compared to the fish in the Sacramento system, although the exact pattern is poorly known. The earlier migration times (late March- mid- May) of Sacramento fish are now more suitable for the San Joaquin River because salmon arriving earlier in the season will require less water. They will require less water because water temperatures will naturally be suitable for them due to lower air temperatures and shorter day lengths. Because the source of fish will have to be from a Sacramento River population (most likely that of Butte Creek), the restoration program will be starting with fish well adapted for an early migration time. The timing of runs is an inherited trait that can be fined tuned even further through natural selection on progeny of fish allowed to spawn in the river and through artificial selection of both spawners and juveniles with appropriate traits (Quinn et al. 2002, Quinn 2005) Fish hatcheries have a long history of inadvertently selecting for early-run fish in a few generations with their practices of filling up their rearing capacity with the first fish that arrived in the hatchery. The state fish hatchery at Friant would be a natural place to ‘jump start’ the runs of spring-run Chinook salmon with carefully planned selection and rearing protocols. Similar selection could be used to produce a fall run as well with optimal traits for the reconciled river. Natural selection would also be a factor in adaptation to local conditions as the New Zealand examples illustrate so well (Quinn et al. 2000).

The key to a reconciled San Joaquin River is minimizing water costs while maximizing benefits to fish and the aquatic ecosystem. Experience with other California rivers suggests that adequate flows can be provided using a small proportion of the inflow to Millerton Reservoir, even during dry and critical years. Flows alone may be enough to restore small runs of salmon and increase populations of native resident fishes, but larger populations can be achieved using restoration techniques that do not necessarily require more water, such as improving spawning gravels, putting dead trees in the water to provide cover, increasing the density of riparian forests to provide shade and food, and creating seasonal floodplains that can provide foraging habitat for juvenile salmonids.

It is not hard to envision the restoration of flows and salmon resulting in the San Joaquin River once again becoming the focal point for use by both humans and wildlife. The river would become more attractive for recreation, from swimming to boating to fishing. Increased flows could result in expanded riparian forests which would be habitat for many endangered birds, mammals, and other species. Salmon from the San Joaquin run could once again colonize the Kings River by moving through Fresno Slough. Given the year-around cold water in the Kings River, it is reasonable to expect that a regular run could develop there as well. Together, as habitat and access improved, the combined runs could once again make contributions to marine and in-river fisheries. In addition, the nutrients brought into the river by the spawning salmon after they die can have a substantial positive effect on riparian plants and animals, and even on near-by agricultural crops, as has been demonstrated by studies that Dr. Joseph Merz and I have conducted on the Mokelumne River. We have found as much of the nitrogen found in wine grape leaves in some riparian vineyards originated from salmon (Merz and Moyle, unpublished manuscript).

E. A FLOW REGIME FOR THE RECONCILED SAN JOAQUIN RIVER

To restore 'fish in good condition' below Friant Dam (*sensu* Moyle et al. 1998), a flow regime is needed that has the basic features of, but not duplicate, the 'natural' flow regime that historically supported diverse fish assemblages and all life stages of the spring and fall runs of chinook salmon. Except during critically dry years, flow regime should have the following characteristics: (1) continuous flow from the Dam to the Merced River at all times of year to maintain habitat for fish in all reaches of the river, (2) flows from November through December for migration and spawning of fall run Chinook salmon, (3) incubation and rearing flows for fall run Chinook, January – February, (4) flows in March through April for emigration of juvenile salmon of both runs, immigration of adult spring –run Chinook salmon, and spawning of native resident fishes, and (5) flows through the summer to maintain holding and rearing habitat for spring-run Chinook salmon from Friant Dam down to somewhere above Highway 41, to maintain a diverse community of native fishes, and to support fisheries for warm water game fishes. Obviously, the amount of water used for each purpose would vary with water year; in drier years, salmon and other native fishes would have reduced habitat. Below I propose, based on my best professional judgment and my review of the reports of Drs. Kondolf and Deas, flow schedules for different year types that are designed to maintain fish in good condition. They are based on the basic ideas of both sharing the water (with the lion's share going for human use) and sharing the pain during times when conditions are extremely dry. As channel and riparian improvements are instituted in addition to the improved flow regime, conditions in the river for fish will improve, increasing the likelihood that productive fisheries will exist for salmon, other native fishes, and non-native game fishes.

The flow regime I propose below differs significantly from that proposed in a draft report by Stillwater Sciences (2003). Their flow regime attempts to restore fish quickly by 'brute force,' simply putting lots of water down the river. I am confident that fish in good condition can be restored using the flow regimes I propose here, and that restoration will be hastened by active, adaptive management that includes extensive habitat restoration and monitoring. As channel restoration/rehabilitation proceeds and as more accurate information on channels and flows in different reaches becomes available, it is likely that the amount of water needed for this flow regime would be less. In addition, inflow from some tributaries, especially Cottonwood and Dry creeks in the Friant reach, will contribute water in some years, reducing the need for Friant water.

The different reaches of the river have different channel characteristics and will support different assemblages of fish, so will have different flow and temperature requirements. While the reaches are treated as discrete entities, as are water year types, as in all rivers they represent a continuum of characteristics from Friant Dam down to the Merced River. **Reach 1** starts at Friant Dam and ends at Gravelly Ford. Under the flow regime presented here, the primary focus in this reach is Chinook salmon but the conditions will also foster a diverse assemblage of native fishes as well. Immediately below the dam and roughly to the Highway 41 crossing, is the sub-reach that can be easily managed for spring-run Chinook salmon because it already has cold water released from the dam, deep pools for adult holding habitat, and extensive riffles and runs for spawning and rearing of juvenile fish. Below this sub-reach, the water will usually be too warm in summer to support spring-run Chinook, but it could be managed for the fall run, which spawn in November and whose fry leave the system before the water becomes too warm, and for Pacific lamprey and other native fishes. **Reach 2**, from Gravelly Ford to Mendota Dam, is a short (20 mi) reach for which minimum flows would be devoted to native fishes, to providing connectivity to downstream and upstream reaches (for fish movement), and to establishing complex habitats generated by riparian vegetation and other factors. The actual assemblage would no doubt wind up being a mixture of native and non-native fishes, with natives predominating in normal or wet years and non-natives predominating in dry years, as I have observed in Putah Creek. **Reaches 3-5**, the rest of the river below Mendota Dam, will be dominated by non-native fishes, such as various basses, sunfishes, and catfishes, which are popular game fishes. With the increase in flows and presumed increase in water quality, some native fishes, especially more warm-water tolerant species such as Sacramento hitch, blackfish, and sucker will also be part of the assemblages. The exact fishes present, and their abundance, will depend on the complex interactions among released flows, irrigation return flows, ground water, riparian vegetation, channel characteristics, restoration projects, and other factors.

In preparing these flow recommendations I reviewed the Kondolf and Deas reports including their temperature and flow recommendations. Their analyses are consistent with recommendations I make below. The flow recommendations below are designed to take into account the interactions of temperature and flow (as modeled by Dr. Deas) so that flows for salmonids and other fishes are provided only if they create suitable temperature conditions for the life history stages present. Along with Drs. Kondolf and Deas, I recognize that the flow regime presented below is not rigid, but as only approximate in terms of dates. Ideally, blocks of water should be available for various purposes and used strategically, to maximize benefits to fish. For example, if air temperatures during a scheduled pulse flow period are high, the pulse could be delayed until air temperatures are a few degrees cooler. Overall, if flexible flow recommendations generated from my review, as well from the reviews of Drs. Kondolf and Deas, were instituted, I am confident that fish could be restored in good condition to the San Joaquin River below Friant Dam.

1. DRY YEARS

For dry years, I recommend the following flows for fish:

1. 350 cfs (including the required riparian releases) released into the river from Friant Dam to maintain holding and incubation habitat for adult spring-run Chinook salmon, rearing habitat for juvenile salmon, general habitat for native resident fishes in Reach 1, and a wetted channel to the mouth of the Merced River. The latter flow would maintain the populations of game and other fishes in Reaches 2-5, as well as adults of native fishes in reach 4, based on temperature models. This would be a minimum base flow, year around, in all reaches, down to the Merced River.

2. A 400-500 cfs pulse flow, measured at the Merced River, for 10 days, including 2 days for ramping up and down at each end, in November. This flow is to bring adult fall-run Chinook salmon upstream to spawn. The exact time of the pulse would be based on monitoring for the presence of fall-run Chinook at the Merced River, but in the absence of monitoring the 'rule of thumb' would be to start releases on early to mid-November . The length the release

presented is here is based in part on estimated travel times of the adults to the potential spawning areas (3-7 days). This pulse should also enable some fry of spring-run Chinook to emigrate (as they do in Butte Creek). It is possible that shorter and lower volume pulses would also work to bring the adult salmon up and the fry down, but this would have to be tested.

3. From the end of the November pulse flow through February, releases of 350 cfs should be maintained for spawning of fall-run Chinook and to maintain flows over their redds. It may be possible to have flows lower than this but this would have to be determined through studies and models.

4. A 1500 cfs pulse flow for two weeks in March plus an additional two weeks of ca. 500 cfs for ramping up gradually.. This flow is designed to bring adult spring run Chinook up into their holding areas and to stimulate the juveniles of both runs (many of the spring-run would be smolts) to emigrate to the estuary. Ideally, the timing of this flow would be based on monitoring the abundance of spring-run Chinook below the mouth of the river, to maximize the number of fish moving up to spawn. It is possible that less water would be needed for this purpose than outlined here if the movement of fish was monitored closely.

2. NORMAL-DRY

The basic idea for flow under the wide range of ‘normal’ conditions is to provide adequate flows to promote the spawning, migration, and rearing of all the fishes of interest, recognizing that differences among years are natural and inevitable, especially if rainfall contributes ‘extra’ water to the river from tributaries. Thus at the low end of the normal range I recommend:

1. Minimum year around flows, same as for Dry years.

2. November pulse flow at 700 cfs to increase the attractiveness of the river to fall-run Chinook salmon and to stimulate emigration in juvenile spring-run Chinook salmon.

3. From the end of the November pulse through February, same as for Dry years,

4. March pulse flow for spring-run Chinook salmon immigration and juvenile salmon emigration, as for Dry years. In addition, I recommend a 2500 cfs flow for the first two weeks of April. The increase in length and volume of the flow would ensure that all salmon would be able to move up or down the river, that juvenile salmon would be able to rear in productive edge

habitat or side channels for 2-3 weeks (growing faster and larger as a consequence), and that the native fishes would have adequate time to spawn (on riffles) and have their young rear in flooded edge habitats. In general, increased flows in this period should considerably increase survival rates of all fishes, with the exception of some non-native species which will be flushed downstream (especially from Reaches 1 and 2). The inundation of floodplain habitat, however, should allow for spawning of Sacramento splittail, hitch, and blackfish, as well as rearing of juvenile salmon under highly productive conditions.

3. NORMAL-WET

In these years, there should be considerable water available to use to increase flows to improve temperature conditions downstream, as well as to use for recruitment of riparian vegetation (e.g., cottonwoods) and for channel processes that improve fish habitat (see Kondolf statement).

1. Minimum year around releases, 350 cfs.

2. November pulse flow, same as for Normal-Dry years.

3. End of November pulse through February, same as for Normal-Dry years.

4. March pulse flow for spring-run Chinook immigration and juvenile salmonid emigration. Same as for Normal-Dry but providing an additional 4000 cfs pulse for two weeks at the end of April. As indicated under the Normal-Dry recommendations, these flows would improve conditions for both runs of salmon and all the native fishes. There would most likely be a considerable downstream shift in the extent of salmon rearing habitat and in the dominance of native fish assemblages as a result of these flows.

4. WET

During these years, if any additional water is required, it would be following the Normal-Wet schedule, with additional flows through June to provide riparian benefits. The higher winter and spring flows, from spills or releases from the dam, would have positive effects on the salmon and native fishes by increasing habitat and presumably keeping temperatures cooler later in the summer. Equally importantly, these flows are likely to do geomorphic work in the channel, improving habitat for fish. A problem with high flows is diversion of fish into bypasses and other areas, from which inflow is usually abruptly cut off, potentially stranding fish. This issue could be addressed through more careful operation of bypass gates. It is also important to operate releases from the dam in ways that do not entail abrupt fluctuations in flow.

5. CRITICAL DRY YEARS/EXTREME DROUGHT

During years of extended drought, the water available for fish will be limited, so I recommend that it be used as much as possible to maintain minimum populations of salmon and other fishes, so these populations can expand again when the water returns. The non-native fishes are of less concern because they have populations downstream in the Delta and will quickly recolonize re-watered sections of river. Multiple critical years in a row especially require that the environment 'share the pain' with agricultural and urban users of water. Thus, in the settlement for the Putah Creek litigation, the Putah Creek Council et al. agreed to give up all the additional water put down the creek for fish (e.g., spawning flows for native fish, attraction flows for salmon) except the requirement to maintain the creek as a living stream where it enters the Yolo Bypass. The ability of the creek fauna to withstand an extended period of drought has been increased by physical improvements being made to the stream that add spawning gravels, create more diverse habitat, and increase shading, as well as by the greater awareness of local citizen groups of the value of the creek, resulting more imaginative solutions to local problems. In the case of the San Joaquin River, at least some water could be provided in wetter critical years to move salmon in and out of the system (see Kondolf report, which is consistent with my recommendations).

What would happen to the San Joaquin River (and its fishes) during a severe drought would depend on many factors, but the worst case scenario would be multiple years with inadequate water to allow spring-run Chinook salmon to either migrate up and/or migrate out to sea, although because of water releases for riparian water rights, there would most likely be holding and rearing habitat below Friant Dam. In cases like this, trap-and-truck operations could be instituted, where humans capture the fish and move them in both directions as a temporary expedient. Some of these fish could be brought into hatcheries to create a backup source for fish if wild populations fail or are greatly reduced, using the experience gained in managing winter run Chinook salmon in the Sacramento River. The Friant Hatchery could be converted to a rescue hatchery or the fish could be moved to hatcheries with cold water supplies on the Sacramento system (e.g., Coleman Hatchery on Battle Creek). It is important to remember that Chinook salmon populations have great resiliency, with 3-4 year classes from each year's run present out in the ocean. Thus even after 2-3 years of no salmon returns to the river, some adult fish could still come back to spawn. The high fecundity of the females (3000-6000 eggs per female) assures rapid recovery of the population once adequate flows return to the system, especially because the oldest fish are the largest and have the highest fecundity. Of course, if habitat improvements had been made to the river, recovery would likely to be more rapid because of higher survival rates of in-river fish and larger populations in the ocean. These comments apply only to desperation measures taken during periods of natural drought. There is ample evidence that maintaining salmon populations by artificial means leads to long term declines with genetic changes that make them less suitable for wild environments (e.g., NRC 1996).

Other fishes, native or non-native, would presumably persist in natural or artificial refuges within the river channel and so could recolonize the river quickly once flows returned. All the species, however, occur in upstream areas (above dams) as well, so could be artificially introduced if necessary. The history of the river indicates that salmon and native fishes have a remarkable ability to persist through severe droughts (e.g., the "dust bowl" era of the 1920s and 30s) and to bounce back quickly once more normal flow conditions return.

XII. CONCLUSIONS

In my opinion, fish in the San Joaquin River below Friant Dam are not in good condition as the result of operation of the dam. However, it is also my opinion that spring run and fall run Chinook salmon, a complete community of native fishes, and a fishery for warm water fishes can be restored in good condition to the San Joaquin River.

Peter B. Moyle

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TABLE 1. CHINOOK SALMON (CHS) THERMAL TOLERANCES. All lethal temperature data is presented as incipient upper lethal temperatures (IULT), which is a better indicator of natural conditions because experimental designs use a slower rate of change (ca. 1°C/d). Information largely from McCullough (1999).

	Sub-Optimal	Optimal	Sub-Optimal	Lethal	Notes
Adult Migration	<10ºC	10-20°C	20-21°C	21-24°C	Migration usually stops when temps climb above 21ºC occurring at 22-24ºC. Lethal temp. under most conditio Fish observed moving at high temps are probably mov refugia.
Adult Holding	<10ºC	10-16°C	16-21°C	21-24°C	Fish in Butte Creek experience heavy mortality above conditions but will survive temperatures as high as 23. short periods of time. In some holding areas temperatu 20ºC for over 50 days during the summer.
Adult Spawning	<13ºC	13-16°C	16-19°C	>19°C	Egg viability may be reduced at higher temperatures
Egg Incubation	<9°C	9-13°C	13-17°C	>17°C	This is the most temperature sensitive phase of life cyc American River CHS exp.100% mortality >16.7°C; Sac. R. fall-run CHS mortality exceeded 82% > 13.9°C
Juvenile Rearing	<13°C	13-20°C	20-24°C	>24°C	*Past exposure (acclimation temperatures) has a large tolerance. Fish with high acclimation temps may survi as 28-29ºC for short periods of time. Optimal conditio stable single temps but under fluctuating temps, with c When food is abundant, fish that live under conditions between 16 and 24ºC may grow very rapidly.
Smoltification	<10ºC	10-19°C	19-24°C	>24°C	Smolts may survive and grow at suboptimal temps but avoiding predators; lab studies suggest optimal temps a and Cech 2004) but observations in wild suggest a grea