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Historical Changes to the San Francisco Bay-Delta Watershed: Implications for Ecosystem Restoration

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Introduction

The Sacramento and San Joaquin rivers drain over 160,000 km^2 (over 40% of the land area of California), receiving most of their runoff from tributaries draining the Sierra Nevada and Cascade ranges. The mainstem Sacramento flows southward and San Joaquin northward along the axis of the Central Valley of California, meeting in an inland delta (The Delta) and then flowing westward through the San Francisco Estuary and debouching into the Pacific Ocean through the Golden Gate of San Francisco. Over the last century and a half, the estuary, delta, river channels, and catchment have been altered to an extent not commonly appreciated. Populations of native fishes that formerly inhabited the system have declined, with many races extinct or nearly so. Most notable among these native fish were the chinook salmon (Oncorhynchus tshawytscha), of whom an estimated average of 2-3 million ascended the Sacramento-San Joaquin River system to spawn in freshwater stream gravels prior to the beginning of extensive European settlement about 1850. Since then, populations of these fish have declined precipitously, such that many runs are now extinct, and others are listed as threatened or endangered under federal and state legislation to protect endangered species (Yoshiyama et al. 1996).

Over-fishing and competition from introduced species have been important factors in the declines. In addition, the geomorphic, hydrologic and ecological processes in the watershed that formerly supported these native fish species have been fundamentally changed by human activities. This paper reviews the effects of these human activities affecting the ecosystem, such as dams, diversions, groundwater pumping, conversion and filling of floodplain and inter-tidal wetlands, gold and gravel mining, levees, artificial bank protection, pollution, and land-use changes in the watersheds draining to the rivers, Delta, and Estuary.

Two parallel, large-scale ecosystem restoration programs are now underway in the Sacramento-San Joaquin River system: the Anadromous Fish Restoration Program of the US Fish and Wildlife Service and the Calfed Bay-Delta Program. From the mid-1990s through 1999, these programs spent USD 394 million and 284 million respec-

Continued on page 2

Continued from page 1
tively on restoration projects, not including administrative expenses. However, most of these restoration projects were selected on an ad-hoc basis, not based on a larger, system-wide ecosystem model as a basis for prioritization. An overarching framework for prioritizing restoration actions is being developed, and standards for proposals have been raised to increase the likelihood that lessons learned from restoration projects can inform future restoration planning, through an explicit adaptive management approach (Healey et al. 1998).

It is essential that we understand the nature and extent of the historical changes to the ecosystem if we are to develop sound restoration goals and understand constraints upon what we can realistically achieve, even in a massive restoration program (Kondolf and Larson 1995).

Hydrology, Dams, and Native Fishes

The flow regimes of the Sacramento-San Joaquin River system reflect the prevailing Mediterranean climate and elevation gradient of the Sierra Nevada range from sea level to well over 4000 m, resulting in a combination of winter rainfall runoff and spring snowmelt. The largest floods were generated by winter rains, especially warm rains falling on a snowpack. Less extreme high flows resulted from spring snowmelt in late spring and early summer. High winter flows were essential for maintaining the open, active channel form, for flushing fine sediments from gravels needed by salmon for spawning, and providing the intermediate disturbances that maintained the structure of the food chain. Spring snowmelt flows were important for seaward migration of juvenile salmon, which as poor swimmers, depended upon the downstream current to take them to the open ocean where they spent their adult lives.

The salmon came upstream in several *runs*, each timed to take advantage of certain parts of the hydrograph. The fall-run migrated in October-November (after temperatures cooled off) up as far as the wide, gravel-bedded reaches in the valley or foothills, and spawned shortly after arriving in the spawning reaches. With this strategy, the fall-run adults spent little time in the freshwater habitat (where they would be vulnerable to predation or high water temperatures), but in dry years they might encounter difficulties in passing shallow reaches and other barriers in their upstream migration. By contrast, the spring-run took advantage of the reliably high snowmelt flows for their migration, moving farther upstream into mountainous reaches with cooler temperatures year-round, where they passed the summer, spawning in September and October.

The young of both spring and fall runs emerged from the gravel in the spring and migrated downstream in late spring-early summer with the spring snowmelt flows. (Genetically-distinct winter- and late-fall runs also occurred.) The spring-run were formerly the most abundant in this system, supporting numerous canneries in the Central Valley in the 19th century (Yoshiyama et al. 1996).

Dams constructed in the late 19th and early 20th centuries blocked access to natal spawning grounds of the spring run, exterminating most of these runs by 1945. The remnant runs are on small tributaries that would have seemed inconsequential in 1850 but are now highly treasured. Healthy runs of wild spring run salmon persist on Butte Creek, Deer Creek, and Mill Creek. Fall-run still occur in the habitat remaining in some channels downstream of dams, but their numbers have declined in response to habitat losses, changes in flow regime, and reduced gravel supply from upstream (discussed below).

Besides blocking access to upstream habitats, dams, the reservoirs they impound, and their associated diversions, substantially alter the downstream flow regime. Relatively small reservoirs built prior to 1940 have since been replaced and supplanted by massive reservoirs, generally located in the foothills transition. These reservoirs impound varying percentages of the rivers' annual runoff, with corresponding ability to regulate seasonal and inter-annual variations in flow. Reservoir storage capacity in the Sacramento-San Joaquin system now totals about 3.5 billion m^3, with storage in the Sacramento River basin equivalent to over 80% of the runoff and in the San Joaquin River basin equivalent to over 80% of the annual runoff. As a result, frequent floods (important for maintaining channel form and habitat) have been eliminated or drastically reduced on most reaches. In addition, the annual snowmelt peak has been largely eliminated, as this water arrives at a time when it can be stored in the reservoirs, i.e. after the flood season and at the beginning of the irrigation season. Loss of frequent floods eliminated the frequent, intermediate disturbances that maintained channel form and gravel quality in many downstream channels, allowing fine sediment to accumulate in spawning gravels and changing the aquatic trophic structure by favoring predator-resistant macroinvertebrates over scour-resistant forms (negatively affecting food availability for young salmon) (Power et al. 1996).

Continued on page 3

Continued from page 2

Habitats and their Direct Alterations

The assemblage of native species depended on a mosaic of habitats, including extensive tidal wetlands in the estuary and delta, which provided a wide range of habitats of various life stages of many species. Species such as Chinook salmon utilized habitats throughout the river system, from cold mountain streams (for spawning) to seasonally inundated floodplains and delta channels (for juvenile rearing). Unfortunately, we lack good information on how many habitats were utilized by various species and their life stages, but more research is now being undertaken to provide insights into the role of these habitats. For example, recent observations of use of inundated floodplains by juvenile Chinook salmon and other species during floods in 1997 on the Cosumnes, the last undammed river in the system, has demonstrated the critical role of these habitats in development of juvenile salmon, resulting in greater growth rates than for salmon without access to the floodplain resources, and presumably increasing their success as adults.

These wetland habitats have been variously filled, drained, dyked, leveled, and converted to other uses, notably agriculture. Riparian floodplain forests have been reduced in extent by 90% since 1850. Of the estimated 160,000 ha of tidal wetlands in the Delta, all but 2% have been dyked off since 1850. And of the inter-tidal wetlands in the San Francisco and Suisun Bays, only 8% remain (Bay Institute 1998). In the Delta, the so-called "islands" protected by dykes are now typically 2-5 m below sea level because once dried out and exposed to the atmosphere, the organic-rich soils oxidized and shrank. This complicates attempts to restore inter-tidal habitats. It is not enough to simply breach the offending dykes, as has been successfully done in deltas that have not subsided such as the Danube River delta (Danube Delta Biosphere Reserve Authority 1997), because in the Sacramento Delta this would simply create open-water lakes with little chance of infilling with sediment or establishing inter-tidal vegetation.

Even where wetlands have not been physically altered, their hydrology typically has. For example, the Delta experienced enormous seasonal and inter-annual fluctuations in salinity. During large floods, the estuary system was fresh all the way to the Golden Gate, while during the fall of dry years, saline water intruded up delta channels nearly throughout the Delta. Native organisms were adapted to these salinity variations. However, with reductions in flow variability caused by dams and diversions, the saline-freshwater boundary is controlled

Continued on page 4

CALIFORNIA COLLOQUIUM ON WATER

The Water Resources Center Archives gratefully acknowledges the support of the Metropolitan Water District of Southern California for generously co-sponsoring the Spring 2002 California Colloquium on Water.

This lecture series is co-sponsored by the UC Berkeley Center for California Studies, College of Engineering, Divisions of Biological Sciences and Social Sciences, College of Letters & Sciences, College of Natural Resources, Bren Fund, Boalt School of Law and the UC Water Resources Center Archives.

April 9

MANAGING GROUNDWATER RESOURCES

David K. Todd

President, Todd Engineers and Professor Emeritus, University of California, Berkeley

May 14

ROLE OF DAMS IN WATER RESOURCES

Dr. John Cassidy

Consulting Water Resources Engineer

A reception is held at the Water Resources Center Archives, 410 O'Brien Hall from 4:15 - 5:00pm, prior to each lecture. The lecture is held at 105 North Gate Hall from 5:10 - 6:30pm.

Each lecture is videotaped and available for loan at the Water Resources Center Archives. For more information about the Colloluium or viewing tapes of previous lectures, please contact, Linda Vida at: (510) 642-2666 or lvida@library.berkeley.edu.

Continued from page 3

and kept downstream of the Delta (through reservoir releases during dry months) to maintain water quality in the large diversions from the Delta. The loss of salinity fluctuations has probably facilitated establishment of exotic organisms. A number of pilot projects have been undertaken using fill to recreate inter-tidal habitats in the Delta and San Francisco Bay, but it is still unclear to what extent physical habitat creation benefits native species or simply provides more habitat for exotic species (many of whom prey on natives), and these projects are typically expensive (in excess of USD 100,000/ha).

Levees and Flood Control

Most river floodplains have been isolated from the channel by levees (dykes). The hydrologic connectivity between channel and floodplain is thereby lost, reducing ecological complexity (Ward and Stanford 1995). Elimination of overbank flooding and storing floodwaters on the floodplain eliminates the downstream attenuation of flood stage, and flood peaks are translated downstream rapidly and without attenuation, typically resulting in greater flood damage downstream. The increased depths contained within the levees also increase the bed shear stress, and tend to cause channel incision, which in turn increases the channel capacity and makes overbank flooding even less likely.

One of the main restoration actions frequently discussed is levee breaching or setback, to permit floodplains to flood once again. Levee breaches have been effected on the Cosumnes River, San Joaquin River, and a levee setback on the Sacramento River near Hamilton City (about 100 km north of Sacramento) to permit a large area of floodplain to flood each year is now being considered. Levee setbacks are among the most promising options for restoring the physical processes that in turn can be expected to restore the habitats needed by native organisms, although it requires purchase of fee title or flood easements to floodplain lands formerly protected from frequent flooding.

Changes in the Sediment Budget

The supply of sediment to the bottomland of the Sacramento-San Joaquin Rivers has changed substantially since 1850. This has been most noticeable in the coarse fraction of the sediment load, the sand and gravel that move mostly as bedload (Vanoni 1975), because 100% of this fraction is trapped by dams, even those impounding relatively small reservoirs and so effecting only modest changes to the flow regime. The discovery of gold in the Sierra Nevada in 1848 triggered a gold rush, which led to extensive landscape alterations. A major impact on rivers was increased sediment supply from hydraulic mining for gold, which produced an estimated 1.3 billion m^3 of sediment (mostly to the Yuba, Feather, and American Rivers) from about 1860 until 1884, when hydraulic mining (without retaining the sediment thereby produced) was outlawed. Upon reaching the valley floor, the sand and gravel portion of this hydraulic mining sediment resulted in massive channel aggredation and instability. Since the late 19th century, however, a larger human effect on the sediment budget has been the dams that have been built on most tributaries to the river system. Coarse sediment was trapped behind the clams, causing a reduction in coarse sediment supply. The pre-1850 rates of sand and gravel supply (estimated from reservoir sedimentation rates), the five-fold increase in sediment yields during the hydraulic mining era, and post-dam yield of sand and gravel (from the remaining non-dammed tributaries), reduced to about 20% of the pre-dam yield, are displayed for the entire river system. This figure also includes an estimate for what is now the largest component of the coarse sediment budget: extraction of sand and gravel (for construction aggregate) from the channels and adjacent floodplains. The net effect of these changes has been to create a substantial sediment deficit in the Sacramento-San Joaquin Rivers and delta. Sediment starvation downstream of dams is recognized as a significant limitation on salmon spawning success, and projects to artificially add gravels to rivers below dams and/or to construct riffles with imported gravel have been undertaken on 18 rivers within the system.

Transformation and Restoration of the Sacramento-San Joaquin River System

A broad historical and geographic perspective yields a number of insights for restoration planning in the Sacramento-San Joaquin River system. For example, the magnitude of change in the ecosystem implies that restoration of all reaches is simply not possible given fiscal and political constraints. Political considerations create a tendency for restorations funds to be distributed more or less equitably across the geographical region affected, but this means a little bit of restoration in each of many rivers and reaches. The effectiveness of this allocation of restoration funding is highly questionable, and even if a positive effect is achieved, it will probably not be possible to detect in a measurement program. An alternative is to concentrate funding in selected tributaries such that processes and habitats can more effectively be restored and ecosystem response detected. This

Continued on page 5

Continued from page 4

is an option because the channels of the Sacramento-San Joaquin system are laid out as a system of parallel channels. The geological setting, an alluvial valley ringed by mountains, meant that dams were built on the tributaries in the foothills upstream of the alluvial valley floor. Thus, though the tributary branches are dammed, there is no master dam downstream that controls the entire river system, and individual tributary reaches are still connected to the ocean up to the foothills dams. This implies that it should be possible to restore anadromous salmon habitat in individual rivers below dams, even if neighboring rivers are not restored. Thus, restoration investments are not wasted if the entire system is not restored.

Prior to the effects of European settlement, the Sacramento-San Joaquin River ecosystem was characterized by pronounced longitudinal connectivity, with the flow of water, sediment, and nutrients downstream, and the movement of anadromous fish up and downstream (as adults and juveniles respectively). The net effect of the historical changes described here has been to reduce or eliminate the longitudinal connectivity, natural dynamics of the river system through reduced high flows, sediment load, and overbank flooding. Some restoration projects in the Sacramento-San Joaquin river system to date have been unsuccessful because they did not adequately take geomorphic processes into account (Kondolf et al. 1996). In evaluating proposed restoration actions, a hierarchy of actions can be described, with the most sustainable and ultimately most effective generally being the cases in which ongoing physical and ecological processes can be maintained (such as through purchases of flood-prone lands to eliminate conflicts between flooding and human occupancy). Cases in which the process has been modified but can be restored (such as through re-operating reservoirs to pass or release higher floods) would be the second priority, while projects that preserve relict habitats no longer supported by physical processes or attempt to physically create habitats not maintained by current processes would receive a lower priority.

For example, we understand that extensive flooding was an important process in maintaining habitat for salmon and other native fish, but we cannot realistically move large cities from the floodplain, nor is it likely that we will remove most existing dams. However, it may be possible to restore floodplain flooding along some rivers and streams, permitting natural processes to shape channel and floodplain habitats. This implies that we should prioritize acquisition of land or flooding/erosion easements along rivers that still flood (i.e., rivers that have not been so dammed that they no longer have high flows), or below dams where restoration of a flooding regime may be possible. Restoration of floodplain functions in these reaches can also reduce flooding pressure downstream (Healey et al. 1998).

To be effective and sustainable, restoration must be based on a real understanding of geomorphic and ecological processes, which can inform restoration goals and choice of implementation strategy. Recognizing that uncertainty is unavoidable in light of our limited understanding of the functioning of the system, an adaptive management approach has been adopted by the CALFED ecosystem restoration program, emphasizing that restoration actions can be taken that serve to increase our understanding of the system's responses (Healey et al. 1998).

Acknowledgements

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Farewell Randal Brandt

By Linda Vida

In December 2001, the Water Resources Center Archives reluctantly bid farewell to Randal Brandt. Randy was the Cataloging Librarian and Assistant Director at WRCA for over seven years. Since the Water Resources Center Archives is a small unit (two librarians and two library assistants), Randy was involved in practically every project the WRCA undertook. His contributions to WRCA were extensive and I will attempt to summarize some of the highlights of his career.

As Cataloging Librarian, Randy was responsible for managing the cataloging workflow. His primary responsibilities were determining and applying cataloging practices, as well as overseeing the cataloging quality of the unit. He was renowned for his excellent writing and editing abilities. He edited the *Selected Recent Accessions List* and contributed regularly to *WRCA News*. He was also responsible for the photographic content and overall production management of three annual calendars co-published by WRCA and the Harmer E. Davis Transportation Library. He worked extensively with the manuscript collections and was responsible for re-organizing, and re-housing many of these collections. He became WRCA's expert photographic curator and assisted many writers and researchers in using the collections. One of Randy's major accomplishments was converting all of the Archives' print Finding Aids (approximately 130) to an online resource (http://www.oac.cdlib.org/dynaweb/ead/berkeley/wrca/), thereby increasing the use and accessibility of the collections. He became the web master for the Archives, developing the first website and all subsequent websites. Over the years, he played a significant role in the development and expansion of WRCA's collections and services.

Randy was co-curator of an exhibit entitled *Liquid Gold*: *California's Water* which was installed in the Bernice Layne Brown Gallery in UCB's Doe Library January – March 1997, and subsequently installed in the UCD Shields Library October – December 1997. He was also the web master for an award winning online exhibit entitled *Bridging the Bay: Bridging the Campus* (http://www.lib.berkeley.edu/Exhibits/Bridge/).

He contributed enormously to the Water Resources Center Archives' and will be greatly missed, not only for his excellent work, but also for his intelligence, easy going manner, musical taste, baseball knowledge and sense of humor. Please join us in wishing Randy all the best as he enters the next exciting phase of his career as Principal Cataloger at The Bancroft Library.

Congratulations Jessica!

by Katie Hornstein

Jessica Jaramillo is certainly no stranger to the Water Resources Center Archives. Having worked at the WRCA for nearly two years, she continues to dazzle patrons and staff alike with her thorough knowledge of the collection and her witty remarks. Jessica graduated from UC Berkeley with a degree in art history, specializing in Italian Renaissance art. She can often be heard mumbling phrases in Italian under her breath, the result of having taken four years of Italian language classes at UCB. Jessica works at the WRCA four days a week. Her primary responsibilities include managing the periodicals, ordering, answering reference questions, and also serving as the WRCA's official ambassador of Good Will. When asked several hard hitting questions about the nature of her life outside of the library, Jessica revealed her love of capirotada, mexican bread pudding: "It's bready, raisny, nutty, chewy goodness." Like a forest forager, Jessica also indulges in nuts and berries whenever they are available. Jessica looks forward to the day when she will obtain her own degree in library science and follow in the footsteps of her esteemed boss, the prolific Linda Vida.

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WELCOME TO THE WRCA KATIE!

by Jessica Jaramillo

The Water Resources Center Archives would like to welcome Katie Hornstein as the new Head of Circulation. Katie is a 22-year-old California native who enjoys good food, good wine, and good company. She loves indie rock, but is definitely anti-scenester. In her spare time Katie follows the teachings of Julia Child. She's a lover of philosophy and art; she is, dare I say it, a Renaissance woman. Here at the Archives, Katie can generally be seen behind the circulation window checking out material to patrons, and ordering, ordering, ordering! The library is a madcap, fast-paced place; Katie fits in quite well, because, as they say on the radio station KMEL, she's sooooo fierce! A graduate of UC Berkeley herself, Katie is at home in this collegiate environment, and is knowledgeable about the campus and the surrounding area, making her a real resource to the Water Resources Center Archive. So come on down to the WRCA and check her out (no pun intended)!

NEW COLLECTION OF COASTAL AERIAL PHOTOGRAPHS

By Linda Vida

The Water Resources Center Archives (WRCA) accepted a large collection of coastal aerial photographs early last year. The collection contains over 65,000 black & white photographs primarily of the coast of California as well as the coasts of Oregon, Washington, Guam, and Hawaii. Most of these photographs were taken by the U.S. Navy and flown in the 1940's.

Maria Escobar, a graduate student interested in coastal studies, is in the process of finalizing a spreadsheet that includes the title of the photograph, state and county, angle of the photograph (vertical, oblique, stereoscopic, negative, etc.) date flown, description (i.e. river outlet, sandy beach, explosions in water) and call number. Maria is completing the spreadsheet that was originally compiled by Hung Thai, an undergraduate student. The information will be converted into an Access database and by summer 2002, the database will be searchable on WRCA's website.

We are very excited that this extensive collection of coastal aerial photographs will be organized and accessible to students and the public. Watch for this addition to the web site at www.lib.berkeley.edu/WRCA/.

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