JULY 2017

SAN FRANCISCO ESTUARY & WATERSHED SCIENCE

Sponsored by the Delta Science Program and the UC Davis John Muir Institute of the Environment

ESSAY

Is Extinction Inevitable for Delta Smelt and Longfin Smelt? An Opinion and Recommendations for Recovery

James A. Hobbs*,[1], Peter B. Moyle[1, 2], Nann Fangue[1], and Richard E. Connon[3]

Volume 15, Issue 2 | Article 2
https://doi.org/10.15447/sfews.2017v15iss2art2

* Corresponding author: *jahobbs@ucdavis.edu*

1 Department of Wildlife, Fish and Conservation Biology
University of California, Davis, CA 95616 USA

2 Center for Watershed Sciences
University of California, Davis, CA 95616 USA

3 School of Veterinary Medicine
University of California, Davis, CA 95616 USA

KEY WORDS

Hypomesus transpacificus, *Spirinchus thaleichthys*, extinction, endangered species, recovery, Sacramento–San Joaquin Delta, San Francisco Estuary

> *"The basic lesson from the collapse of Delta Smelt is that to save species, ecosystem-based actions have to be taken quickly to halt irreversible change, or at least to guide inevitable change in a more favorable direction. The longer the delay, the harder the decisions, and the less likely they are to produce positive results. For the Delta Smelt, the time to make key decisions for its survival in the Delta may have already passed."* (Moyle et al. 2016a).

Since implementation of the federal Endangered Species Act (ESA), no listed fish species has gone extinct. However, the abundance of Delta Smelt (*Hypomesus transpacificus*), protected under the California and federal ESAs, and Longfin Smelt (*Spirinchus thaleichthys*), protected under the California ESA, declined further in 2014 and are now at historical lows in the San Francisco Estuary (estuary) (Figures 1 and 2). In 2015, the California Department of Fish and Wildlife (CDFW) Summer Townet Survey (TNS) reported the first zero abundance index since the survey began more than 50 years ago. Meanwhile, the Fall Midwater Trawl (FMWT) index for Longfin Smelt narrowly avoided its first zero index with 3 fish caught in December 2015. The apparent collapse of both species triggered alarm among scientists, stakeholders and natural resource managers, resulting in a symposium held at the University of California, Davis (March 29, 2016[1]) that focused on the question: is extinction inevitable for Delta Smelt and Longfin Smelt?

In our opinion, extinction is not inevitable in the short run, if we use the most current scientific understanding to manage the ecosystem and begin to make bold steps towards recovery. However, given climate change projections and our knowledge of the physiological tolerances for Delta Smelt and Longfin Smelt, in the long run, the upper estuary will likely be unable to support the two species without large-scale human intervention (Brown et al. 2013, 2016; Komoroske et al. 2013, 2014; Jeffries et al. 2016). In this essay, we first describe a pathway to assessing extinction, and then present a series of recommendations for how to prevent extinction of Delta Smelt and Longfin Smelt in the estuary. We regard the fate of these species to be a test of society's will to pull threatened and endangered

1 *http://cmsi.ucdavis.edu/events/smelt-longfin/index.html*

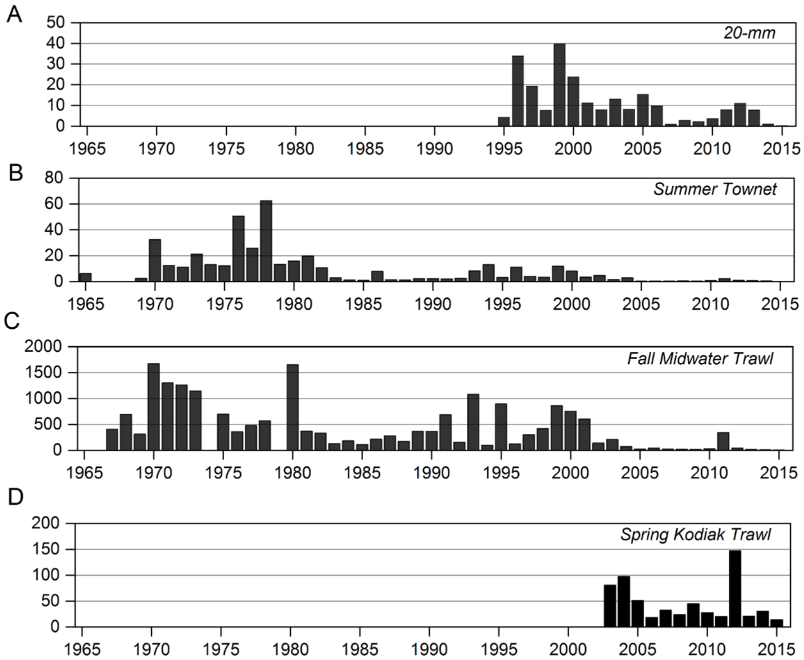

Figure 1 Delta Smelt annual abundance indices for CDFW surveys: larvae and juveniles (20-mm Survey), juveniles-sub-adults (Fall Midwater Trawl), and adults (Spring Kodiak Trawl). The initiation of each survey is indicated by the first bar; missing bars indicating years for which an index was not calculated. (Source: CDFW.)

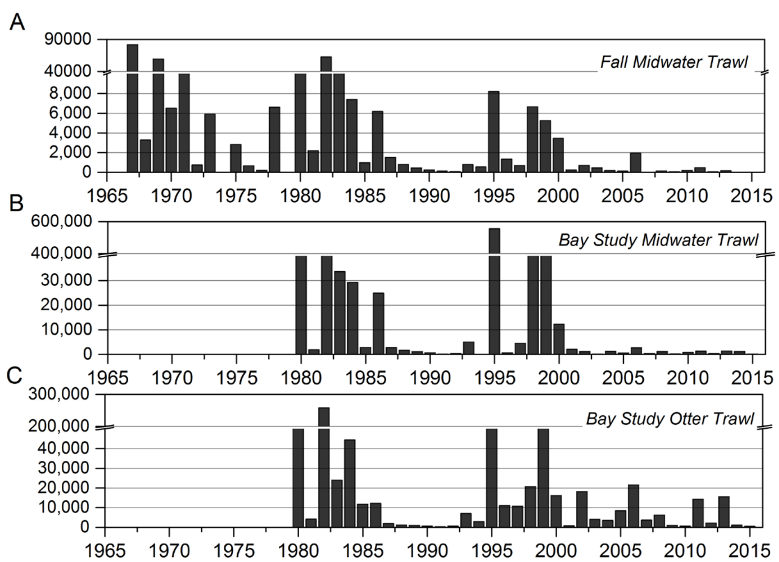

Figure 2 Longfin Smelt annual abundance indices for CDFW surveys: the FMWT index is the abundance of age-0 fish from September to December, the BS-MWT and BS-OT is the index for the May–October period for age-0 fish in each net. (Source: CDFW.)

species back from the brink of extinction and further, to bring about recovery of native fishes. We hope the new information and analyses presented at the symposium, along with the opinions presented in this document, will stimulate innovative approaches to managing the species.

WHERE DO WE GO FROM HERE?

> "*People often ask, 'What is the single most important environmental problem facing the world today?' The single most important problem is our misguided focus on identifying the single most important problem! .... Because any of the dozen problems, if unsolved, would do us great harm because they all interact with each other.*" —Jared Diamond

There is no single factor that could be managed to recover Delta Smelt and Longfin Smelt. Numerous stressors affecting Delta Smelt have been identified and evaluated using a life-cycle based conceptual model by the Interagency Ecological Program's Management, Analysis, and Synthesis Team (IEP–MAST), and synthesis efforts are in progress for Longfin Smelt (IEP–MAST 2015). These synthesis efforts have demonstrated that a lot is known about how smelt respond to stressors. However, many stressors remain understudied, the interactions among stressors unresolved, and too few stressors are under our control. Furthermore, the relative impacts of stressors cannot be simply listed in sequential order of importance; every year the order and magnitude of each varies, and most stressors interact with each other, probably in different ways in different years, making it difficult to recommend single factor management actions. Therefore, we must focus on approaches to build resiliency within these populations. This will require a different approach to managing the Sacramento-San Joaquin Delta and the San Francisco Estuary for Delta Smelt and Longfin Smelt. We cannot solely rely on managing freshwater flows or minimizing loss of fish to South Delta exports. To rebuild resilience in these fish we must employ a multifaceted attack on known stressors, utilize novel strategies to restore habitats, and manage flows based on the life history of the species.

The Natural Resource Agency recently released the "Delta Smelt Resiliency Strategy" (2016), which outlines a series of actions that could be implemented to support resilience in the Delta Smelt population. These actions are targeted on a subset of stressors including turbidity, food availability and quality, and outflow augmentation. We think this approach is a reasonable first step toward what should become a larger collaborative effort to stave off extinction in the near term and provide the foundation for rebuilding resiliency to deal with climate change. We acknowledge that this approach will require substantial political and economic will, given that many factors may have limited, indeterminate, or unknown effects on Delta Smelt and Longfin Smelt abundance. Actions to support population resilience should be taken using an adaptive management framework, led by an independent team of scientists working collaboratively with the IEP and stakeholders using the IEP-MAST conceptual models to guide study design and implement monitoring. Our recommendations are developed with this broad framework in mind. We emphasize that our recommendations are our own, based on the information revealed in the smelt symposium and in Moyle et al. (2016a); they do not represent all viewpoints represented at the symposium.

ASSESSING EXTINCTION

If the two smelt species disappear from the monitoring surveys, how would extinction be declared? Surprisingly, there are no formal procedures to declare extinction; however, Baumsteiger and Moyle (2017) propose such a procedure, which is followed here. The U.S. Fish and Wildlife Service or the National Marine Fisheries Service can effectively de-list an endangered species if agency biologists have evidence that no individuals are left during the regular five-year review process; this is tantamount to declaring extinction. In addition, the 1979 amendment to the Federal Endangered Species Act established the Endangered Species Committee, which is made up of high-level federal officials plus the governor of the state in which the species occurs (USDOI 1978). This committee, commonly known as "The God Squad," has the authority to exempt a federal agency from Section 7(a)(2) requirements under any of a number of circumstances, effectively removing federal protection, indirectly declaring a

https://doi.org/10.15447/sfews.2017v15iss2art2

species extinct.[2] However, the California ESA would still provide protection for Delta Smelt and Longfin Smelt if such a ruling were made. As such, it is unclear how extinction would be declared for Delta Smelt and Longfin Smelt.

Given the economic and political incentives to remove water project pumping restrictions deemed necessary to protect smelt, there is an urgent need to establish a modus operandi for determining extinction in the Delta. If Delta Smelt or Longfin Smelt were absent from IEP monitoring surveys and other surveys (e.g., UC Davis's Suisun Marsh Project) for a minimum of two successive years, we propose the following:

1. All management agencies and stakeholders agree to a memorandum of understanding that keeps all protections for smelt species in place without litigation.
2. IEP agencies, in collaboration with stakeholders, conduct coordinated, spatially and temporally intensive sampling for a minimum of three consecutive years.
3. An annual smelt summit is held, bringing together scientists and stakeholders (e.g., IEP scientists, Delta Stewardship Council, university scientists, water agency representatives) to review the data. Findings of the summit are presented in a public forum to the California Fish and Game Commission, which has the authority to delist species at the state level.
4. Routine IEP monitoring is continued for a minimum of 10 generations for each species with protective measures continued throughout this period (10 years for Delta Smelt and 20 years for Longfin Smelt).
5. If no individuals are found in expanded and routine monitoring for 10 generations, final extinction ruling of the species is the decision of the California Fish and Game Commission.

The final ruling from the California Fish and Game Commission would reflect only the State's opinion on extinction for Delta Smelt, but would be the sole decision for Longfin Smelt, which is not currently listed under the federal ESA, despite the finding that listing the species was "warranted but precluded" from protection (Federal Register 2012). Further, this would only pertain to Longfin Smelt in California, because this species also occurs along the coast from California to Alaska. Concomitant with this process, USFWS could rule the Delta Smelt as no longer protected under the federal ESA, but it is unclear how or if this ruling would influence California state law.

While establishing a pathway to declare extinction is important, the preferable path is one that leads away from declaring extinction. The latter is fraught with problems without revision of current policy. First, the legal take of Delta Smelt is currently established by the USFWS using the IEP's FMWT index as a multiplier to set take limits for the water projects and scientific monitoring. A FMWT index of zero (which is quite different from a catch of zero), will immediately cause problems for establishing minimum take levels and export levels at SWP and CVP, because the product of any multiplier and a zero index will be zero. In 2016, an index of zero was narrowly avoided with increased catch of Delta Smelt in December. Second, an index of zero would similarly affect take for monitoring surveys. At a time when it becomes important to conduct more sampling to determine the extent of Delta Smelt occurrence, USFWS would likely order reduced monitoring efforts to avoid take of the species, and thus compound the problem by limiting our knowledge of the species status. And third, indices of zero in monitoring surveys could spur litigation that would leave the fate of listed species to be decided by the courts. Thus, efforts to provide better estimates of abundance and minimize salvage of Delta Smelt at the CVP and SWP should be implemented with the goal of providing a better tool for allocating take among the monitoring and research community.

To avoid these problems, new policies for devising and allocating take for water projects and scientific monitoring is needed. Scientific monitoring efforts should not be halted to avoid take. As smelt populations decline below detection limits in current monitoring surveys, we will need to increase sampling efforts to continue to assess population status to avoid premature extinction declarations. This will require strong collaboration between state and federal regulatory agencies and stakeholders (a Smelt Squad), similar to the founding arrangement

2 *https://www.gpo.gov/fdsys/pkg/STATUTE-92/pdf/STATUTE-92-Pg3751.pdf*

seen within the Interagency Ecological Program. A memorandum of understanding among these stakeholders should be developed to guide actions as smelt near extinction. Efforts to devise a plan to hold off extinction are now underway, as seen in the Delta Smelt Resiliency Strategy.[3] While many of our recommendations are consistent with the Resiliency Strategy, we provide additional input on the direction management action should take. Our recommendations fall under 11 headings: (1) Developing a Delta flow regime, (2) augmented freshwater flows, (3) managing salvage at the export pumps, (4) tidal marsh restoration, (5) invasive species control, (6) predator removal, (7) wastewater management, (8) artificial propagation, (9) contaminants, (10) simulated flooding and (11) the California WaterFix project.

DELTA FLOW REGIME

We recommend developing a Delta flow regime for native fishes, including smelt, based on modeling studies to integrate historical and modern flow variability with individual-based life cycle models.

Historically, the natural flow regime of rivers entering the Delta interacted with tidal variation to create a highly dynamic habitat in space and time (Whipple et al. 2012a), and the Delta's native species evolved life history strategies to take advantage of this dynamic environment. Development of the Central Valley and Delta for agriculture resulted in enormous loss of seasonal and tidal wetland habitat and has significantly reduced the volume and timing of freshwater entering the estuary. Subsequent water management reduced flow variability (eliminating the peak high and low flows), changed flow direction in the South Delta and altered average flow conditions throughout the year as well as modified the landscape by widening and straightening channels, and building hundreds of miles of rip-rap levees to promote efficiencies in water delivery. These changes altered flows to create an ecosystem to which most native species are no longer adapted. As such, empirical observations of how Delta Smelt and Longfin Smelt respond to flows across this highly-modified landscape likely reflects maladaptive behaviors which could lead to poor management decisions. Modeling studies comparing historical and modern flow regimes and their effects on smelt vital rates (growth, migration and survival) are an important starting point for prescribing better flows for smelt. We recommend modeling studies to elucidate flow-habitat mechanisms.

Integrating Modeling to Design a Delta Flow Regime. Recent reconstructions of the historic Delta landscape and modeling of unimpaired flows provide us with basic tools to examine how a natural flow regime would have functioned in the historical Delta (Whipple et al. 2012a). We recommend integrating quantitative individual-based life-cycle models for Delta Smelt and Longfin Smelt with high-resolution three-dimensional models of historical and modern flows to explore how various flow regimes might influence habitat attributes that drive vital rates. Combining such modeling with empirical field studies of vital rates and laboratory studies should fill key data gaps, and provide the best opportunity for developing a flow regime that is better suited for the life history of the two smelt species. Groundwork for this effort has been developed by K. Rose and others (Rose et al. 2013a, 2013b).

FLOW AUGMENTATION

We recommend providing additional flows when necessary to alternative locations (other than the Sacramento River channel) such as the Yolo Bypass and the Napa River to augment flows for smelt.

The historical Delta received fresh water from a variety of upstream areas, including the Cosumnes River and Mokelumne River, while the bays received freshwaters from many small tributaries such as the Napa River, Petaluma River in North Bay and Alameda Creek and Coyote Creek in South Bay (Figure 3). Streams typically entered the upper reaches of sloughs and likely facilitated the exchange of nutrients and productivity developed in these habitats with the larger sloughs and bays creating a diverse and dynamic habitat. Many of these smaller streams have been dammed or diverted for flood control and local use eliminating this important process. In many streams, urban development may preclude such restoration of flows, however in some locations providing flows may restore this ecosystem

3 *http://resources.ca.gov/docs/Delta-Smelt-Resiliency-Strategy-FINAL070816.pdf*

https://doi.org/10.15447/sfews.2017v15iss2art2

function. Providing flows into managed habitats such as the Yolo Bypass Toe Drain and into the upper reaches of sloughs in Suisun Marsh could provide benefits for Delta Smelt. Restoring flows to tributaries entering the bays could provide additional rearing habitat, particularly for Longfin Smelt as recent studies have found larval Longfin Smelt in the Napa River, Petaluma River (Parker et al., 2017).

The Delta Smelt Resiliency Strategy has called for outflow augmentation in the form of spring or summer releases from dams, recommending that between 85 and 200 thousand acre-feet (taf) be added to flows mandated to meet water quality objectives (CNRA 2016). However, this relatively small volume of additional outflow is unlikely to have a substantial impact on habitat conditions. And if this augmentation occurs when Delta Smelt and Longfin Smelt are already at low abundance, any benefits may be undetectable. We see outflow augmentation as an opportunity to provide flows into novel areas. In 2016, CDWR and stakeholders provided additional flows to the toe drain of the Yolo Bypass, gaining positive results for outflow augmentation on lower trophic levels (CNRA 2017). This action has now become a Delta Smelt Resiliency Strategy element called the North Delta Foodweb Adaptive Management Plan. To make best use of additional water and input locations, outflow augmentation should be done within an adaptive management framework to gain information on the benefits of such actions.

Increasing freshwater outflow to the estuary should be the ultimate priority for promoting resilience in the Delta's native species. Longfin Smelt abundance is higher in wet years, while Delta Smelt numbers tend to be higher in moderately wet years, albeit with cooler temperatures (Moyle et al. 2016a). The State Water Resources Control Board is currently revising the Water Quality Control Plan for the Delta to call for additional outflows from the Sacramento and San Joaquin Rivers. We support increased flows to the Delta from these major sources of fresh water; however, efforts must also be focused on additional attributes of flows and flow variability that could promote smelt recovery, such as the timing, magnitude and duration of flows. Additional freshwater flows, beyond those required to meet water quality standards in the Delta should be implemented adaptively, incorporating modeling and empirical studies to measure responses in smelt behavior and abundance.

SALVAGE MANAGEMENT

We recommend (1) managing and minimizing reverse flows to reduce smelt entrainment at the State Water Project (SWP) and Central Valley Project (CVP) pumping facilities (2) conducting studies to refine entrainment estimates, particularly for larval fishes and (3) considering re-operation or removal of Clifton Court Forebay.

The capture of Delta Smelt and Longfin Smelt at the CVP and SWP export facilities (salvage) in the South Delta has garnered a large share of management focus and blame for smelt declines. Yet export restrictions in most years have had little demonstrable effect on long-term abundance trends of either species. Nevertheless, at times, salvage and estimates of total numbers of fish entrained has been extremely high for Delta Smelt and may have had impacts on adult abundance; both species have very short life spans and events that cause recruitment failure in a single generation can have prolonged effects on population dynamics (e.g., entrainment and salvage events in 1981 and 2003; Moyle et al. 2016a).

Since the 2008 biological opinion for continued operation of the State and Federal Water Projects (USFWS 2008), reverse flows in Old and Middle rivers have been intensively managed on a weekly basis during the winter and spring, and resource agencies have enacted voluntary reductions in exports to protect smelt. Resulting salvage of Delta Smelt and Longfin Smelt has been low, thus we encourage continued collaboration among the regulatory and resource agencies to operate this system. However, the numbers of fish entrained into the South Delta, where mortality is presumably high, and the numbers salvaged at CVP and SWP are still poor estimates of the effects of the pumps on smelt, and better estimates are needed for setting incidental take policy. Therefore, we recommend additional efforts to assess the accuracy of salvage estimates. Clifton Court Forebay (CCF), has been an area of potentially high predation mortality for smelt and salmon, which likely influences salvage estimates. Thus, we recommend evaluating predation loss in CCF in conjunction with salvage studies.

1. **Minimize Entrainment.** We recommend continued efforts to minimize entrainment to avoid the very large events (e.g., 2002-2003) that could further erode population resilience. Management efforts should be focused to create flows that prevent smelt from entering the Central/South Delta, unless sufficient flows from the San Joaquin River can be provided to eliminate reverse flows in Old and Middle Rivers.
2. **Improve Salvage Estimates.** We recommend studies be conducted to improve salvage estimates at the SWP and CVP fish diversion facilities. Current methods to estimate salvage likely yield low estimates of the true numbers of smelt moving through the facilities. Castillo et al. (2012) demonstrated that salvage severely underestimated the actual numbers of fish arriving at the facilities. Also, early life stages (<20 mm) of smelt are not counted and are likely to be much higher than juveniles and adults. Studies to quantify the entrainment of early life-stage fishes in the South Delta, near screening facilities, Clifton Court Forebay, behind louvers, and in the aqueducts, are needed. These studies should conduct louver screen efficiency assessments specifically as they relate to Delta and Longfin Smelt.
3. **Clifton Court Forebay Management.** CCF is a hot spot for predatory sport fish, which likely prey on smelt and salmon in large numbers with unknown effects on salvage estimates. Predator removal is a likely recommendation, however; efficacy of such a program may not produce results that outweigh the costs, thus CCF may need to be redesigned, operated differently, or eliminated so it ceases to be a major source of mortality for smelt.

Further reducing reverse flows in Old and Middle River is also a logical recommendation, though we acknowledge that the very idea of making flows less negative characterizes the larger problems within the Delta. Ideally, flows should not be negative anywhere in the interior Delta and water should not be exported from within the Delta at all. But reality dictates that both are likely to continue. Nevertheless, long-term plans, (e.g., California WaterFix program) should explore alternative means to convey fresh water to users that reduce entrainment of species.

TIDAL MARSH RESTORATION

Our basic recommendation is to restore and manage tidal marshes and other habitats to improve connectivity between food rich marshes and open water habitats for pelagic fishes. Near-term focus should be placed on (1) removing existing barriers to small creeks or backwater habitats to move food into larger areas, and (2) managing duck clubs or large temporary flooded areas to produce and export food into adjacent sloughs.

The historic estuary was dominated by tidal marsh habitats, which provided food and refuge from predators for many fishes (Whipple et al. 2012). Now, very few extant marshes remain, and habitat modifications have blocked the flow of marsh derived production to open water habitats where smelt typically occur. Restoration of tidal wetlands is hypothesized to increase food availability for Delta Smelt and Longfin Smelt and improve feeding conditions locally, although very little direct evidence for this hypothesis currently exists (Herbold et al. 2014). Many restoration projects are underway or in the planning phases (e.g., the Suisun Marsh Plan,[4] FRPA,[5] California EcoRestore[6]), while several properties with high restoration potential are still privately owned; thus, we do not make specific recommendations to restore tracts of land. The focus of tidal marsh restoration should be in lands adjacent to areas where smelt occur, such as the North Delta Arc, an area of connected tidal marsh habitat from the Cache-Slough complex, down the lower Sacramento River through the north side of Suisun Bay, and Suisun Marsh (Figure 3). Basic additional recommendations include:

1. **Remove Barriers to Marsh Productivity.** To facilitate the trophic transfer of marsh-derived food resources to the large sloughs and bays, we need to provide better connectivity between existing marsh habitat and the adjacent channels where smelt feed (Figure 4). Many small culverts, water control structures and small dams block

4 *https://www.wildlife.ca.gov/Regions/3/Suisun-Marsh*
5 *http://www.water.ca.gov/environmentalservices/frpa.cfm*
6 *http://resources.ca.gov/ecorestore/*

https://doi.org/10.15447/sfews.2017v15iss2art2

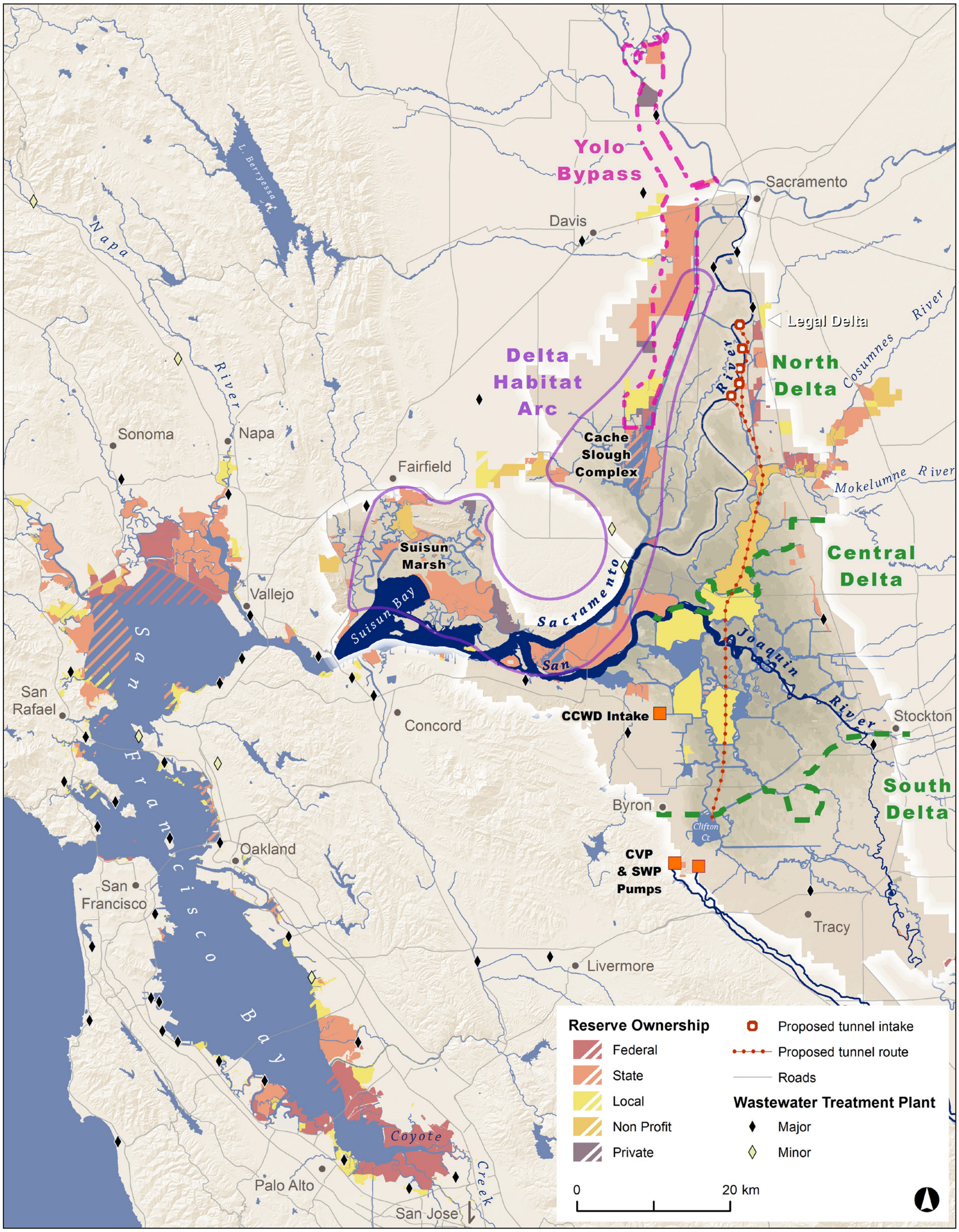

Figure 3 Map depicting areas for tidal wetland restorations by ownership, including the North Delta Arc (Arc of Habitat outlined in blue), Islands in the Central Delta (yellow) and lands in the Napa–Sonoma Marsh, Petaluma River in the North Bay and salt ponds in South Bay (pink hues). (Credit: GIS layers and maps provided by Amber Manfree, Center for Watershed Sciences, UC Davis.)

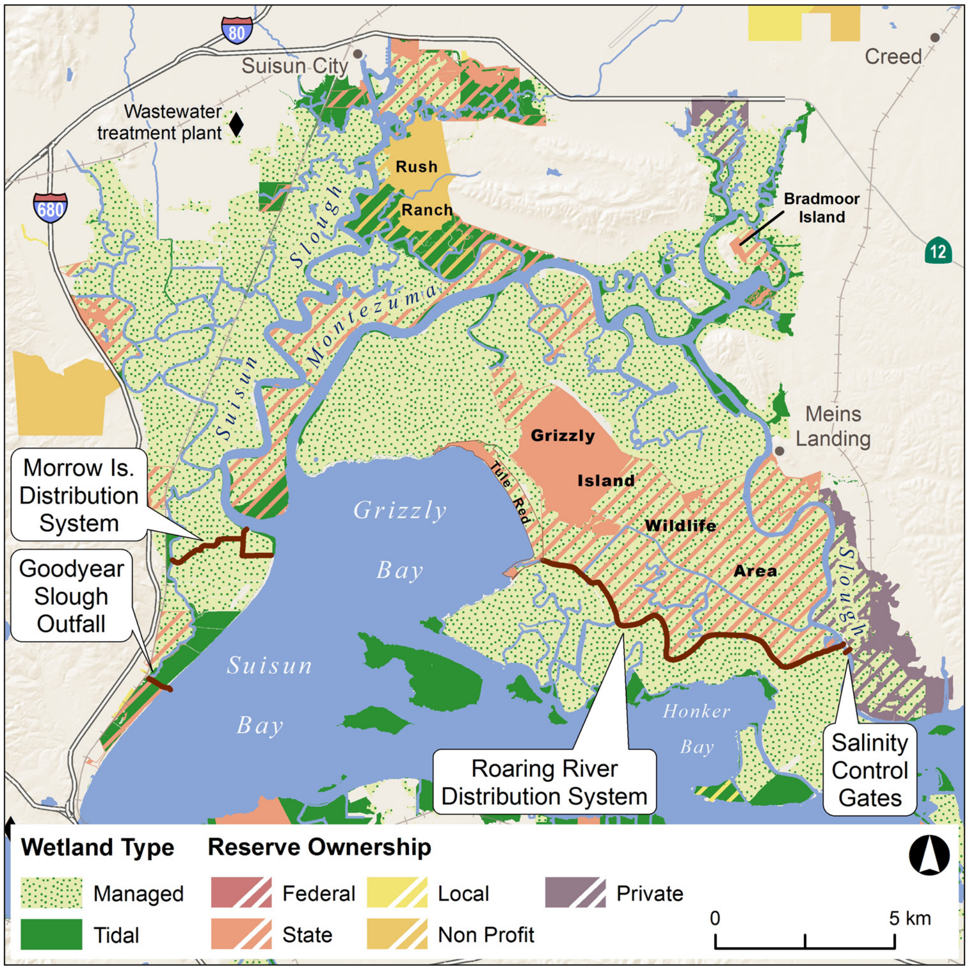

Figure 4 Map of Suisun Marsh and Suisun Bay. Map depicts distribution canals where barriers could be removed to facilitate the distribution of food rich waters to areas occupied by Delta Smelt and Longfin Smelt: the Roaring River Distribution System (RRDS), Morrow Island Distribution System (MIDS), Goodyear Slough Outfall (GYO). (Credit: GIS layers and maps provided by Amber Manfree, Center for Watershed Sciences, UC Davis.)

the productivity of these habitats from entering sloughs and open water habitats. Removing such barriers should facilitate the movement of food supplies for pelagic fishes at least locally. (e.g., the Roaring River Canal in Suisun Marsh)

2. **Manage Flooded Habitats for Fish and Lower Trophic Level Production.** Duck clubs and other temporarily flooded habitats could be operated or re-engineered to facilitate the production of phytoplankton and zooplankton (e.g., flooding and draining frequently) to be released in upper ends of dead-end sloughs or distribution canals to move food downstream (e.g., Joice Island) (Figure 4). They could potentially be operated as nursery areas for deliberately introduced native fishes such as Delta Smelt, Longfin Smelt and Sacramento Splittail (*Pogonichthys macrolepidotus*).

Given that large-scale habitat restoration is in the early phases of planning and not ready to provide benefits to smelt in the immediate future, shorter-term "fixes" should be conducted to simulate the processes that larger-scale habitat restoration will presumably provide. The Delta Smelt Resiliency Strategy identifies modifications to the Roaring River Distribution System (Figure 4), a largely disconnected slough that runs through Grizzly Island connecting Montezuma Slough with Grizzly Bay, near the Tule Red restoration site. This action, which we support, would install drain gates on the western end of the

https://doi.org/10.15447/sfews.2017v15iss2art2

Roaring River that could be operated to drain food-rich water from flooded duck ponds into Grizzly Bay (Figure 4). There are additional canals in Suisun Marsh that could be operated similarly (Morrow Island Distribution System) to increase food supplies in Suisun Bay (Moyle et al. 2016b). Increasing connectivity of distribution canals crossing duck clubs in Suisun Marsh with Montezuma Slough and Suisun Bay may facilitate transfer of marsh productivity to these sloughs presumably increasing food availability for smelt in the area.

We emphasize that large-scale restoration of subsided islands will not provide the habitat attributes that would benefit native species without means to promote the processes that support intertidal marsh vegetation rather than aquatic invasive weeds and invasive clams. For example, simply breaching levees to large tracts of subsided habitat will increase the tidal prism and reduce tidal energy, resulting in shallow, still waters that promote invasive aquatic weeds (e.g., Lindsey Slough Tidal Marsh Restoration). These tracts of land will need to be engineered or managed to promote natural evolution of intertidal marsh formation. In large part, this is being done for several restorations in progress, such as Dutch Slough and Tule Red restoration projects.

INVASIVE SPECIES MANAGEMENT

We recommend continued research in control methods for invasive clams and aquatic weeds, emphasizing small-scale or regional control programs.

The San Francisco Estuary is arguably the most invaded estuary in the world. Invasive clams and aquatic weeds have altered the structure and function of the fresh and brackish regions of the estuary and have likely had significant impacts on smelt by reducing food resources and eliminating access to shallow water habitats. The control and management of invasive species is possibly the most difficult stressor to manage. In the Delta, herbicide treatments have had limited success in the control of aquatic weeds, and herbicides, besides posing risks to phytoplankton production, are potentially an additional stressor to Delta Smelt and Longfin Smelt larvae, as well as to their zooplankton prey. Such treatments should be used sparingly and monitored for deleterious effects on lower trophic levels and fish larvae. In addition, the following actions are needed:

1. **Control Research.** Research into factors that limit abundance of overbite clam (*Potamocorbula amurensis*) and Asian clam (*Corbicula fluminea*) in order provide tools for their control. No method has successfully eradicated bivalves in natural water bodies thus far, but novel strategies continue to be developed and tested (Sousa et al. 2014; Wittmann and Chandra 2015).
2. **Mechanical Removal.** Experimental mechanical removal of floating vegetation in areas where smelt are likely to occur, particularly in potential spawning/nursery habitats in the North Delta region.

The Interagency Ecological Program recently formed a project work team to address the invasive aquatic vegetation issues in the Delta and the Delta Region Areawide Weed Project[7] has invested millions to combat the spread of invasive weeds in the Delta. Meanwhile USFWS is spearheading an effort to tap into outside expertise for control of invasive bivalves. These groups should evaluate alternatives for invasive aquatic vegetation and bivalve control linking potential eradication efforts with conceptual models of ecosystem function and historical data to develop study plans to adaptively manage invasive weeds in the Delta. Invasive species management remains the largest knowledge-gap for the Delta and will require a significant investment of resources to address this stressor.

PREDATOR REMOVAL

Predator removal should be conducted on small experimental scales. However, we recommend limiting resources devoted to the control of predatory fish to benefit smelt.

There has been much interest in implementing new fishing regulations to facilitate removal of non-native predatory fishes such as Striped Bass. Striped Bass diet studies have revealed that very few smelt are eaten, although DNA techniques have identified Delta Smelt DNA in the stomachs of many species, including Striped Bass (Baerwald et al. 2012; Schreier et al. 2016). Predation by large predators does not

7 *http://ucanr.edu/sites/DRAAWP/*

appear to be a limiting factor for adult Delta or Longfin Smelt, but smaller predatory fishes could potentially be an important source of mortality during early life stages. We issue caution with efforts to remove large predatory fishes, because the indirect trophic cascading effects of removing Striped Bass, or other predatory fishes (e.g., White Catfish) on food web interactions have not been assessed (Grossman 2016). Further, reduction of large predators could result in the increase of smaller predators. One of the smaller predators, the Mississippi Silverside, is a likely predator on Delta Smelt eggs and larvae but its removal is not feasible, given it is one of the most abundant species in the estuary. Before any large-scale efforts to remove large predatory fishes are implemented, we must have a better understanding of the trophic interactions among these species. Dietary and other predation-related studies would provide important insights into the potential effect of predators on the smelt but need to be designed to address whether predation can limit adult abundance or recruitment success. The effect of non-native predators on native species remains an area of limited research and a significant knowledge gap.

We recommend predation studies only if they assess the potential for large predatory fishes to limit the abundance of Delta Smelt and Longfin Smelt, and are tied to studies of cascading food web effects. Large predatory fishes would most likely have greatest impact during the spawning migrations into the interior Delta and North Delta for Delta Smelt and the confluence for Longfin Smelt. Studies could be focused most profitably during the winter-spring spawning seasons when smelt are densely aggregated. However, evidence of predatory events need to be coupled with population estimates of smelt, and conducted on many predatory fishes to assure adequate quantification of predation. Because smelt are relatively soft-bodied fishes, coupling traditional diet studies with genetic techniques would be required.

WASTEWATER MANAGEMENT

The upgrade of the Sacramento Regional Wastewater Treatment Plant (SRWTP) (Echo Water Project) should be approached as an adaptive management experiment with the goal of improving water quality for fish in the Delta. We recommend careful monitoring of nutrients, contaminants, water quality, primary productivity, zooplankton and pelagic fish populations to determine upgrade efficacy and impacts.

Nutrient loads from publicly owned wastewater treatment facilities have been steadily increasing (Cloern and Jassby 2012; Senn and Novack et al. 2014a, 2014b). Recent studies suggest increased ammonium concentrations in the Delta and stochiometric ratios of nitrogen and other nutrients may be limiting phytoplankton production in the Delta, a phenomenon referred to as the "Ammonium Paradox" (Dugdale et al. 2007; Glibert et al. 2011, 2014, 2016; Dahm et al. 2016; Wilkerson and Dugdale 2016). Decreased ammonium concentrations during high flow periods have coincided with beneficial phytoplankton blooms in the North Delta, suggesting lowered ammonium concentrations may have a positive at least locally (Parker et al. 2012a, 2012b; Dugdale et al. 2013; Glibert et al. 2014). However, it is uncertain whether ammonium is having such a pervasive impact throughout the estuary and given the body of research on the effect of the invasive clam population on phytoplankton in Suisun Bay, this phenomenon has received considerable scrutiny and stimulated debate among researchers in the estuary. For review of the topic we suggest Dahm et al. (2016).

High ammonium concentrations from wastewater have also been strongly implicated in the increased prevalence of *Microcystis* blooms in the Delta since 1999 (Dahm et al. 2016). However, *Microcystis* blooms in the Delta have also been associated with high irradiance, increased water clarity, warm waters, and low flows (Lehman et al. 2008, 2013). Wastewater effluent also contains a large number of pharmaceutical and personal care products, which can have deleterious effects on aquatic organisms (Fong et al. 2016).

The Sacramento Regional Wastewater Treatment Plant (SRWTP) is upgrading their effluent treatment to tertiary-level (EchoWater Project, *http://www.regionalsan.com/echowater-project*), which will reduce ammonium concentrations and total nitrogen loading to the Sacramento River. This may reduce stress on the Delta ecosystem, however, we do note that removal of ammonium and other nitrogen species

https://doi.org/10.15447/sfews.2017v15iss2art2

from wastewater effluent will result in overall reduced nitrogen, including nitrate, the form of nitrogen thought to feed into the beneficial diatom-based food web utilized by smelts. Thus, further altering nitrogen loads to the Delta could have uncertain effects on food webs.

The upgrade to the SRWTP should be approached as an adaptive management experiment. There have been several synthesis efforts that have provided conceptual models for nutrient effects, harmful algal blooms (HABs) and contaminant effects. We recommend integrating these models to design an effect-based monitoring experiment that includes food web effects, HAB formation and proliferation and contaminants effects including a broad-spectrum chemical analysis, along the gradient from the discharge point, downstream to Suisun Bay. In addition, studies on Delta Smelt and Longfin Smelt residence in effluent laden waters should be linked to bioindicators of condition, health and growth.

It is also important to recognize, that there are numerous municipal WTPs besides the SRWTP that discharge effluent into the Delta and estuary; exposure to wastewater effluent, and specific effluent contaminants, should be included in future studies.

Develop a Monitoring Program. We recommend field experiments and systematic monitoring to determine the effects of operational changes on water quality downstream of wastewater facilities. These studies should monitor primary and secondary production, harmful algal and other phytoplankton production, and biomarkers of endocrine disruption on zooplankton and fishes. The San Francisco Estuary Institute is currently developing the "San Francisco Bay Nutrient Management Strategy Observation Program" to monitor wastewater nutrient effects throughout the estuary.

CONTAMINANT EFFECTS

We recommend developing a comprehensive effects based monitoring program for contaminants with appropriate biological end-points, greater spatio-temporal coverage, and better integration among scientists, agency managers and stakeholders.

The estuary has been identified as an impaired water body for many contaminants from industrial pollutants, urban runoff and agricultural pesticides and herbicides (SWRCB 2010). Over the years, insecticide use for example, has changed as regulations have limited use of some products (e.g., organophosphate pesticides) replacing them with new ones (e.g., pyrethroid pesticides). Thus, establishing the impact of specific contaminants on aquatic organisms has been a moving target. Moreover, synergistic effects of the many contaminants are largely unknown, and their degradation byproducts are thought likely to be more toxic than their parent compounds in isolation. Recently, Fong et al. (2017) used a weight of evidence approach to suggest contaminant stress, particularly from pyrethroid use in the Central Valley, is a potential driver of Delta Smelt abundance. Contaminants have been considered one of the important stressors for Delta Smelt (IEP-MAST 2015); however, the lack of a direct empirical measure of impact on fish abundance has made this factor difficult to assess. Importantly, laboratory studies using Delta Smelt have demonstrated that ambient Delta waters result in a variety of measurable impacts to Delta Smelt gene regulation, physiology, growth and fitness (Connon et al. 2009, 2012; Hasenbein et al. 2014; Hammock et al 2015; Jeffries et al. 2015), making this a critical topic to include in future study and manage decision-making.

While long-term efforts have been ongoing to monitor contaminants in the Bay as part of the Regional Monitoring Program, monitoring of Delta waters has been limited. The limited data from the Delta has been obtained primarily from short-term special studies. While providing important findings, this piecemeal approach has resulted in a substantial data gap, hindering our understanding of how contaminants may limit Delta Smelt and Longfin Smelt populations. This has largely been due to the lack of funding for a long-term systematic program to monitor contaminants.

Therefore, we recommend establishing a long-term contaminant monitoring program that incorporates effect-based assessments alongside targeted and non-targeted chemical analyses. Such a program could be integrated with existing IEP monitoring surveys, sharing monitoring costs. Monitoring shallow waters and dead-end sloughs in marshes, and other locations where early life stage smelt are found, would allow for better spatial and temporal overlap for contaminant and fish data. This information should be used to inform management. However, the diversity of regulatory and management agencies responsible for the variety of contaminants entering the Delta is large and to the best of our knowledge a framework for communicating science to this broad group does not exists. The Delta Science Program should develop such a framework, if one does not already exist.

ARTIFICIAL PROPAGATION

We recommend developing a management plan for artificial propagation of Delta Smelt and Longfin Smelt. In the immediate term, we recommend (1) extensive mesocosm experiments using captive Delta Smelt, and that (2) efforts to culture Longfin Smelt be fully funded and implemented in the longer term.

The successful culture of Delta Smelt is one of the few success stories so far, resulting in important insights into their physiological and behavioral responses to stressors. Delta Smelt are currently reared in laboratory culture at the Fish Conservation and Culture Laboratory (FCCL) run by UC Davis, and supported by the adjoining facility run by CDWR and USBR, located in Byron California (Lindberg et al. 2013), with an additional population at the USFWS Livingston Stone Hatchery below Shasta Dam. Delta Smelt have been successfully reared through their entire life cycle and genetically managed to maintain genetic integrity of the cultured population (LaCava et al. 2015). To keep genetic integrity of cultured populations intact, wild fish are collected annually, genotyped, and crossed with F1 generations to maximize diversity. However, this is likely to change, as progressively fewer fish become available for genetic supplementation from the wild. The fish produced by these facilities have been used solely for scientific studies; to date, no plans have been made for their reintroduction to the wild.

Reintroduction of laboratory-cultured smelt directly into the wild without careful planning and experimentation has a high probability of failure. Artificial propagation and reintroduction is a practice regularly used for endangered species recovery, often incorporating outdoor ponds or mesocosms (Hard et al. 1992; Kirchhofer and Müller 2012; Archdeacon 2016). For example, Rainbow Smelt are successfully reared in outdoor ponds[8] and stocked into lakes throughout the state of Maine to bolster populations.[9]

At present, California's facilities capable of culturing Delta Smelt are too few and too small. Additional space or sites would be required to increase the numbers of cultured individuals in any significant way. Further, developing a large-scale propagation program for smelt would require rigorous scientific studies in order to design best practices. Such a program takes years to develop. If this approach is taken, it must be initiated soon. The USFWS is currently working toward building a "Fish Technology Center" in Rio Vista. The proposed facility could be a valuable resource for implementing ideas presented here, however; we feel it is important to use a rigorous experimental approach and continue a strong collaboration with university scientists.

1. **Prepare Cultured Fish for the Wild.** One challenge to experimentally releasing captively reared smelt is training fish to switch from artificial feed to live prey. The FCCL could begin to culture smelt larvae using natural prey either from additional cultures of prey organisms or potentially raw water with prey organisms from Clifton Court Forebay.
2. **Controlled Mesocosm Studies.** We recommend studies using outdoor mesocosms in the near term. This would entail a series of experiments investigating use of different life stages, live prey, tagging techniques, genetic analyses, fish health, and physiological responses, and would be amendable to multi-stressor studies.
3. **Longfin Smelt Culture.** We recommend additional investment to culture estuary Longfin Smelt. This will likely require additional facilities and staff beyond the resources provided by the FCCL.

SIMULATED FLOODING

We recommend investigation into simulating flood conditions annually by moving Sacramento River water through the Yolo Bypass via Freemont and Sacramento

8 *http://www.harmonbrookfarm.com/*

9 *http://www.maine.gov/ifw/fishing/pdfs/smelt.pdf*

https://doi.org/10.15447/sfews.2017v15iss2art2

weirs, and flooding managed islands as habitat for native fishes in Suisun Marsh and the North Delta Arc.

Yolo Bypass

Strategic flooding of the Yolo Bypass as part of the North Delta Foodweb Adaptive Management Project is a management action from the Delta Smelt Resiliency Strategy we feel should be implemented. Periodic flooding of the Yolo Bypass has been well documented as providing benefits to many native species of fish and lower trophic levels (Sommer et al. 2001a, 2001b, 2004). Even during drought conditions, infrastructure could be modified to allow flows to the east side of the bypass, along the Tule Canal and Toe Drain, stimulating primary and secondary production which could flow into the North Delta as far downstream as Suisun Bay. This could also provide spawning and rearing habitat for Delta Smelt and Longfin Smelt, as supported by recent studies demonstrating successful spawning and rearing in the toe drain (Mahardja et al. 2015).

This action integrates many of our previous recommendations, including increasing spatial variability of freshwater flow inputs to the Delta and increasing connectivity of marsh habitat to the larger system. It provides ecosystem subsidies that would supplement those accomplished with tidal marsh restoration, and could provide opportunities to experimentally study predation and artificial propagation. It could also indirectly affect wastewater impacts by diluting effluent entering the toe drain from the Davis and Woodland wastewater treatment plants, and potentially reduce effects from the Sacramento Regional Wastewater Treatment Plant in the North Delta Arc. Furthermore, tidal wetland restoration could potentially be implemented along the toe drain, down into the northern reach of Liberty Island where active restoration is ongoing. This tidal wetland restoration effort could be integrated into the agricultural landscape with little impact to existing farm acreage.

Central Delta

It is increasingly likely that one or more islands (polders) in the Delta will become flooded as the result of levee collapse, especially in the central Delta (Mount and Twist 2005). An experimental program to determine the potential for flooded islands to support the two smelt species could consist of (a) modeling the likely environment that would occur once an island was flooded, (b) deliberate flooding of an island with gated breaches that allow control of water exchange and careful monitoring and (c) use of experimental mesocosms in flooded islands to determine rearing potential for smelt.

Currently, Twitchell Island is operated as a mitigation marsh, and includes habitat features that could support experimental rearing of Delta Smelt. The California Department of Water Resources owns and operates a series of mitigation habitats throughout the Delta that could be used to develop native fish refugia[10] (Figure 3). An action like this would also integrate many of the recommendations above, particularly for tidal wetland restoration, but would additionally simulate the natural flooding of intertidal habitats that would have occurred with a natural flow regime. Again, experimental rearing of cultured Delta Smelt could be implemented with tasks to test predictions related to predation effects on smelt larvae. Flooding islands could also reduce loading of ammonium through nitrogen recycling processes that naturally occur in tidal marshes.

We recommend integrating tidal marsh or managed wetland actions with experimental rearing of cultured fish to determine if providing novel habitats for declining smelt populations will provide meaningful benefits to their populations. Studies could also be conducted to determine if habitat restoration could be managed to facilitate the production and export phytoplankton and zooplankton to open water habitats.

CALIFORNIA WATERFIX

The California WaterFix is a proposal to improve water delivery to the South Delta pumping plants and to improve conditions in the Delta for Delta Smelt and other fishes. The proposed project entails burrowing one or two tunnels underneath the Delta to deliver Sacramento River water to the South Delta pumping plants. While the many details of tunnel construction and operation are lacking, we cautiously

10 *http://www.water.ca.gov/floodsafe/fessro/*

endorse the concept of providing additional points of diversion to provide operational flexibility for water delivery, and to minimize impacts to fish.

1. Assuming (as promised) the project does not take more water out of the system but makes delivery more reliable, it could be operated to increase connectivity in the North Delta Arc, supporting critical nursery habitat for smelt. Cross-Delta flows could be reduced resulting in fewer fish entering the Central-South Delta when otherwise they would move into Suisun Bay and Marsh.
2. In its present configuration, the Delta is highly susceptible to catastrophic levee failure. At some point, there will be large-scale levee collapse from earthquakes, high tides, storm flood flows, or all three. This would result in emergency implementation of alternative water conveyance with unknown impacts to the environment. The tunnels will reduce the likelihood of harmful large-scale emergency construction projects needed to move the water to consumers.
3. Entrainment of smelt could be reduced. Proposed intakes for the tunnel(s) will be located in the Sacramento River, upstream of current smelt habitat. If operated strategically to reduce entrainment of Delta Smelt in the South Delta, additional exports from this location could reduce immediate impacts on Delta Smelt.
4. California WaterFix should be accompanied by a flow regime including additional freshwater flows to the estuary, and large-scale restoration of marsh habitat (e.g., California EcoRestore).

There are many unknown aspects of the proposed tunnel project that make it difficult to assess the potential effects on Delta Smelt and Longfin Smelt. Given the high demand for freshwater in the state and the growing population, the likelihood that new water infrastructure will result in further reductions in flows to the estuary is concerning. An alternative water conveyance project could be designed to minimize the direct mortality incurred at points of water diversion. However, we cannot ignore the indirect effects of altered flow regimes on the Delta's ecosystem. A project of this scope will be needed if we continue to rely on the existing leveed Delta as the hub for our water supply.

CONCLUDING REMARKS

In our opinion, Delta Smelt and Longfin Smelt have a high likelihood of extinction from the estuary unless the novel approaches presented here are implemented quickly. In this essay we outline actions that could improve conditions for smelt in specific areas of the estuary, especially habitats along the North Delta Arc. The current status of smelt demands that we start taking risks in implementing large-scale actions, including projects on the scale of the California WaterFix. However, saving smelt will require overcoming bureaucratic and scientific inertia to implement new approaches. Many of our recommendations and those by the Delta Smelt Resiliency Strategy require substantial permitting, regulatory and legal approval. That alone can take years to complete. Unfortunately, time is too limited and the outlook for smelt too bleak to delay.

In the meantime, management actions and research should be focused around the actions provided by the Delta Smelt Resiliency Strategy and the actions we provide in this essay. The goals of the Smelt Symposium and this paper were to highlight the critical need for bold steps toward conservation of smelt in the estuary and provide a map for possible roads to recovery. We feel the scientific community contains enough scientific understanding of the species and the appropriate tools to implement adaptive management based experimentation to recover Delta Smelt and Longfin Smelt. The process will be challenging, and we will certainly make mistakes along the way, but given the vast knowledge we have garnered over the years studying smelt and the issues we face in the estuary, it would be unconscionable to allow these species to go extinct because of our inaction.

> *"Extinction may be inevitable if we fail to use our best information to manage for success."*
> —Jonathan Rosenfield, The Bay Institute

https://doi.org/10.15447/sfews.2017v15iss2art2

ACKNOWLEDGMENTS

We thank the Delta Stewardship Council for sponsoring the smelt extinction symposium and supporting this opinion piece (contract #888), and Shauna Oh and the Coastal and Marine Sciences Institute for organizing it. We freely stole ideas from the symposium participants, but take full responsibility for their presentation here, which often diverges from the ideas as presented. We thank Amber Manfree for use of her wonderful maps, thorough review by IEP members and the two anonymous reviewers who provided in-depth comments which greatly improved the manuscript. This work was supported by the USDA National Institute of Food and Agriculture, project #2098-H, to NAF.

REFERENCES

Archdeacon TP. 2016. Reduction in spring flow threatens Rio Grande Silvery Minnow: trends in abundance during river intermittency. Trans Am Fish Soc 145(4):754-765. *https://doi.org/10.1080/00028487.2016.1159611*

Baerwald MR, Schreier BM, Schumer G, May B. 2012. Detection of threatened Delta Smelt in the gut contents of the invasive Mississippi Silverside in the San Francisco Estuary using TaqMan assays. Trans Am Fish Soc 141(6):1600-1607. *https://doi.org/10.1080/00028487.2012.717521*

Baumstieger J, Moyle PB. 2017. Assessing extinction. Bioscience 67:357-366. *https://doi.org/10.1093/biosci/bix001*

Brown LR, Bennett WA, Wagner, RA, Morgan-King T, Knowles N, Feyrer F, Schoellhamer DH, Stacey MT, Dettinger M. 2013. Implications for future survival of Delta Smelt from four climate change scenarios for the Sacramento–San Joaquin Delta, California. Estuaries Coasts 36(4):754-774. *https://doi.org/10.1007/s12237-013-9585-4*

Brown LR, Komoroske LM, Wagner RA, Morgan-King T, May JT, Connon RE, Fangue NA. 2016. Coupled downscaled climate models and ecophysiological metrics forecast habitat compression for an endangered estuarine fish. PLoS One *https://doi.org/10.1371/journal.pone.0146724*

[CNRA] California Natural Resource Agency. 2016. Delta Smelt resiliency strategy. [Internet]. [accessed 2016 Sep 27]; Available from: *http://resources.ca.gov/docs/Delta-Smelt-Resiliency-Strategy-FINAL070816.pdf*

[CNRA] California Natural Resource Agency. 2017. Delta Smelt resiliency strategy. Progress update. [Internet]. [accessed 2017 Jul 17]; Available from: *http://resources.ca.gov/docs/Delta-Smelt-Resiliency-Strategy-Update.pdf*

Castillo G, Morinaka J, Lindberg J, Fujimura R, Baskerville-Bridges B, Hobbs J, Tigan G, Ellison, L. 2012. Pre-screen loss and fish facility efficiency for Delta Smelt at the south Delta's State Water Project, California. San Franc Estuary Watershed Sci 10(4). *https://doi.org/10.15447/sfews.2012v10iss4art4*

Cloern JE, Jassby AD. 2012. Drivers of change in estuarine-coastal ecosystems: Discoveries from four decades of study in San Francisco Bay. Rev of Geophysics [Internet]. [accessed 2016 Sep 27]; 50(4). Available from: *http://onlinelibrary.wiley.com/doi/10.1029/2012RG000397/full*

Connon RE, Geist J, Pfeiff J, Loguinov AV, D'Abronzo LS, Wintz H. 2009. Linking mechanistic and behavioral responses to sublethal esfenvalerate exposure in the endangered Delta Smelt; *Hypomesus transpacificus* (Fam. Osmeridae). BMC Genomics 10:608. *https://doi.org/10.1186/1471-2164-10-608*

Connon RE, Hasenbein M, Fritsch EB, Javidmehr A, Deanovic LA, Werner I. 2012. Refinement and application of novel molecular and biochemical biomarkers to determine sublethal contaminant exposure and effects in archived Delta Smelt samples. [Internet]. [accessed 2015 Oct 24]. Available from: *http://www.dfg.ca.gov/erp/biomarkers_planning.asp*

Dahm, CN, Parker, AE, Adelson AE, Christman MA. Bergamaschi BA. 2016. Nutrient dynamics of the Delta: effects on primary producers. San Franc Estuary Watershed Sci 14(4). *https://doi.org/10.15447/sfews.2016v14iss4art4*

Dugdale RC, Wilkerson FP, Hogue VE, Marchi A. 2007. The role of ammonium and nitrate in spring bloom development in San Francisco Bay. Estuar Coast Shelf Sci 73(1–2):17–29. *https://doi.org/10.1016/j.ecss.2006.12.008*

Dugdale RC, Wilkerson FP, Parker AE. 2013. A biogeochemical model phytoplankton productivity in an urban estuary: the importance of ammonium and freshwater flow. Ecol Model 263:291-307. https://doi.org/10.1016/j.ecolmodel.2013.05.015

[USDOI] U.S. Department of the Interior. 1978. Endagered Species Act amendments of 197. Public Law 95-632. 16 USC 1531. [Internet]. [accessed 2016 Sep 27];16 USC 1531. Available from: http://www.eswr.com/docs/lh/643-63.pdf

Fong S, Louie S, Werner I, Davis J, Connon RE. 2017. Contaminant effects on California Bay-Delta species and human health. San Franc Estuary Watershed Sci 14(4). https://doi.org/10.15447/sfews.2016v14iss4art5

Glibert PM, Dugdale RC, Wilkerson F, Parker AE, Alexander J, Antell E, Blaser S, Johnson A, Lee J, Lee T, Murasko S, Strong S. 2014. Major—but rare—spring blooms in 2014 in San Francisco Bay Delta, California, a result of the long-term drought, increased residence time, and altered nutrient loads and forms. J Exp Mar Biol Ecol 460:8-18. https://doi.org/10.1016/j.jembe.2014.06.001

Glibert PM, Fullerton D, Burkholder JM, Cornwell JC, Kana TM. 2011. Ecological stoichiometry, biogeochemical cycling, invasive species, and aquatic food webs: San Francisco Estuary and comparative systems. Rev in Fish Sci 19(4):358-417. https://doi.org/10.1080/10641262.2011.611916

Glibert PM, Wilkerson FP, Dugdale RC, Raven JA, Dupont CL, Leavitt PR, Parker AE, Burkholder JM, Kana TM. 2016. Pluses and minuses of ammonium and nitrate uptake and assimilation by phytoplankton and implications for productivity and community composition, with emphasis on nitrogen-enriched conditions. Limnol Oceanogr 61(1):165-197. https://doi.org/10.1002/lno.10203

Grossman GD. 2016. Predation on fishes in the Sacramento–San Joaquin Delta: current knowledge and future directions. San Franc Estuary Watershed Sci 14(2). https://doi.org/10.15447/sfews.2016v14iss2art8

Hammock BG, Hobbs JA, Slater SB, Acuña S, Teh SJ. 2015. Contaminant and food limitation stress in an endangered estuarine fish. Sci Tot Environ 532:316–326. https://doi.org/10.1016/j.scitotenv.2015.06.018

Hard JJ, Jones RP Jr, Delarm MR, and Waples RS. 1992. Pacific salmon and artificial propagation under the Endangered Species Act. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northwest Fisheries Science Center. NOAA Technical Memorandum NMFS-NWFSC-2 [Internet]. [accessed 2016 Sep 27]; 40 p. Available from: http://pavveor.krisweb.com/biblio/gen_nmfs_hardetal_1992_tm2.pdf

Hasenbein M, Werner I, Deanovic LA, Geist J, Fritsch EB, Javidmehr A. 2014. Transcriptomic profiling permits the identification of pollutant sources and effects in ambient water samples. Sci Tot Environ 468–469:688–98. https://doi.org/10.1016/j.scitotenv.2013.08.081

Herbold B, Baltz DM, Brown L, Grossinger R, Kimmerer W, Lehman P, Simenstad CS, Wilcox C, Nobriga M. 2014. The role of tidal marsh restoration in fish management in the San Francisco Estuary. San Franc Estuary Watershed Sci 12(1). https://doi.org/10.15447/sfews.2014v12iss1art1

[IEP-MAST] Interagency Ecological Program Management, Analysis, and Synthesis Team. 2015. An updated conceptual model of Delta Smelt biology: our evolving understanding of an estuarine fish. [Internet]. [accessed 2016 Sep 27]. Technical Report 90. Sacramento (CA): IEP-MAST. Available from: http://www.water.ca.gov/iep/docs/Delta_Smelt_MAST_Synthesis_Report_January%202015.pdf

Jeffries KM, Connon RE, Davis BE, Komoroske LM, Britton MT, Sommer T, Todgham AE, Fangue NA. 2016. Effects of high temperatures on threatened estuarine fishes during periods of extreme drought. J Exp Biol 219:1705-1716. https://doi.org/10.1242/jeb.134528

Jeffries KM, Komoroske LM, Truong J, Werner I, Hasenbein M, Hasenbein S. 2015. The transcriptome-wide effects of exposure to a pyrethroid pesticide on the critically endangered Delta Smelt *Hypomesus transpacificus*. Endanger Species Res 28:43-60. https://doi.org/10.3354/esr00679

Kirchhofer A., Müller DR. 2012. Conservation of endangered freshwater fish in Europe. Birkhäuser. [Internet]. [accessed 2016 Sep 27]; Available from: http://link.springer.com/book/10.1007%2F978-3-0348-9014-4

https://doi.org/10.15447/sfews.2017v15iss2art2

Komoroske LM., Connon RE, Lindberg J, Cheng BS, Castillo G, Hasenbein M, Fangue NA. 2014. Ontogeny influences sensitivity to climate change stressors in an endangered fish. Con Phys 2(1):cou008. *https://doi.org/10.1093/conphys/cou008*

Komoroske LM, Hasenbein M, Lindberg J, Connon RE, Fangue NA. 2013. Understanding climate change impacts on Delta Smelt. Int Compar Biol [Internet]. [accessed 2016 Sep 27]; 53:E115-E115. Available from: *https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4806739/*

LaCava M, Fisch K, Nagel M, Lindberg JC, May B, Finger AJ. 2015. Spawning Behavior of Cultured Delta Smelt in a Conservation Hatchery. N Am J Aqua 77(3):255-266. *https://doi.org/10.1080/15222055.2015.1007192*

Lehman PW, Boyer G, Satchwell M, Waller S. 2008. The influence of environmental conditions on the seasonal variation of Microcystis cell density and microcystins concentration in San Francisco Estuary. Hydrobiologia 600:187–204. *https://doi.org/10.1007/s10750-007-9231-x*

Lehman PW, Marr K, Boyer GL, Acuna S, Teh SJ. 2013. Long-term trends and causal factors associated with Microcystis abundance and toxicity in San Francisco Estuary and implications for climate change impacts. Hydrobiologia 718:141–158. *https://doi.org/10.1007/s10750-013-1612-8*

Lindberg JC, Tigan G, Ellison L, Rettinghouse T, Nagel MM, Fisch KM. 2013. Aquaculture methods for a genetically managed population of endangered Delta Smelt. N Am J Aquac 77(3):255-266. *https://doi.org/10.1080/15222055.2015.1007192*

Mahardja B, Ikemiyagi N, Schreier B. 2015. Evidence for increased utilization of the Yolo Bypass by Delta Smelt. IEP Newsletter [Internet]. [accessed 2016 Sep 27]; 28(1):13-18. Available from: *http://www.water.ca.gov/iep/docs/IEP%20Vol28_1.pdf*

Moyle PB, Brown LR, Durand JR, Hobbs JA. 2016a. Delta Smelt: life history and decline of a once abundant species in the San Francisco Estuary. San Franc Estuary and Watershed Sci 14(2). *https://doi.org/10.15447/sfews.2016v14iss2art6*

Moyle PB, Manfree AD, Fiedler PL, editors. 2016b. Suisun Marsh: ecological history and possible futures. Berkeley (CA): University of California Press.

Mount J, Twiss R. 2005 Subsidence, sea level rise, and seismicity in the Sacramento–San Joaquin Delta. San Franc Estuary Watershed Sci 3(1). *https://doi.org/10.15447/sfews.2005v3iss1art7*

Parker AE, Dugdale RC, Wilkerson FP. 2012a. Elevated ammonium concentrations from wastewater discharge depress primary productivity in the Sacramento River and the Northern San Francisco Estuary. Mar Poll Bull 64(3):574-586. *https://doi.org/10.1016/j.marpolbul.2011.12.016*

Parker AE, Hogue VE, Wilkerson FP, Dugdale RC. 2012b. The effect of inorganic nitrogen speciation on primary production in the San Francisco Estuary. Estuar Coast Shelf Sci 104:91-101. *https://doi.org/10.1016/j.ecss.2012.04.001*

Parker C, Hobbs J, Bisson M, Barros A. 2017. Do Longfin Smelt spawn in San Francisco Bay tributaries? IEP Newsletter 30(1). [Internet]. [accessed 2017 Jul 18]; Available from: *http://www.water.ca.gov/iep/products/newsletter.cfm*

Rose KA, Kimmerer WJ, Edwards KP, Bennett WA. 2013a. Individual-based modeling of Delta Smelt population dynamics in the Upper San Francisco Estuary. I. Model description and baseline results. Trans Am Fish Soc 142(5):1238-1259. *https://doi.org/10.1080/00028487.2013.799518*

Rose KA, Kimmerer WJ, Edwards KP, Bennett WA. 2013b. Individual-based modeling of Delta Smelt population dynamics in the Upper San Francisco Estuary. II. Alternative baselines and ood versus bad years. Trans Am Fish Soc 142(5):1260-1272. *https://doi.org/10.1080/00028487.2013.799519*

Schreier BM, Baerwald MR, Conrad JL, Schumer G, May B. 2016. Examination of predation on early life stage Delta Smelt in the San Francisco Estuary using DNA diet analysis. Trans Am Fish Soc 145(6):723-733. *https://doi.org/10.1080/00028487.2016.1152299*

Senn D, Novick E. 2014a. Scientific foundation for the San Francisco Bay nutrient management strategy. Richmond (CA): San Francisco Estuary Institute. [Internet]. [accessed 2016 Sep 27]; 157 p. Available from: *http://sfbaynutrients.sfei.org/sites/default/files/SFBNutrientConceptualModel_Draft_Final_Oct2014.pdf*

Senn D, Novick E. 2014b. Suisun Bay ammonium synthesis report. Richmond (CA): San Francisco Estuary Institute. [Internet]. [accessed 2016 Aug 15]; 191 p. Available from: *http://www.sfei.org/sites/default/files/SuisunSynthesisI_Final_March2014_0.pdf*

Sommer T, Harrell B, Nobriga M, Brown R, Moyle P, Kimmerer W, Schemel L. 2001a. California's Yolo Bypass: evidence that flood control can be compatible with fisheries, wetlands, wildlife, and agriculture. Fisheries 26(8):6-16. *https://doi.org/10.1577/1548-8446(2001)026<0006:CYB>2.0.CO;2*

Sommer TR, Harrell WC, Solger AM, Tom B, Kimmerer W. 2004. Effects of flow variation on channel and floodplain biota and habitats of the Sacramento River, California, USA. Aqua Con-Mar Freshwater Ecosystems 14(3):247-261. *https://doi.org/10.1002/aqc.620*

Sommer TR, Nobriga ML, Harrell WC, Batham W, Kimmerer WJ. 2001b. Floodplain rearing of juvenile chinook salmon: evidence of enhanced growth and survival. Can J Fish Aqua Sci 58(2):325-333. Available from: *http://www.nrcresearchpress.com/doi/abs/10.1139/f00-245#.WJIgzPkrKUk*

Sousa R, Novais A, Costa R, Strayer DL. 2014. Invasive bivalves in fresh waters: impacts from individuals to ecosystems and possible control strategies. Hydrobiol 735(1):233-251. *https://doi.org/10.1007/s10750-012-1409-1*

[SWRCB] State Water Resources Control Board. 2010. Transmittal of the 2010 Integrated Report [Clean Water Act Section 303(d) and Section 305(b)]. Letter to Alexis Strauss, USEPA, and four CDs of supporting materials, including the staff report, fact sheets, and responsiveness summary, dated October 11, 2010. [Internet]. [accessed 2015 October 24]. Available from: *https://www3.epa.gov/region9/water/tmdl/california.html*

Federal Register. 2012. Endangered and threatened wildlife and plants; 12-month finding on petition to list the San Francisco Bay-Delta population of Longfin Smelt as endangered or threatened. Fed Regist 77:63(2 April 212):19755-19797.

[USFWS] U.S. Fish and Wildlife Service. 2008. Formal Endangered Species Act consultation on the proposed coordinated operations of the Central Valley Project (CVP) and State Water Project (SWP). [Internet]. [accessed 2016 Mar 14]. Sacramento (CA): U.S. Fish and Wildlife Service. Available from: *http://deltacouncil.ca.gov/docs/background-materials-delta-science-program-ocap/formal-endangered-species-act-consultation*

Whipple A, Grossinger R, Rankin D, Stanford B, Askevold R. 2012. Sacramento-San Joaquin Delta historical ecology investigation: exploring pattern and process. Prepared for the California Department of Fish and Game and Ecosystem Restoration Program. A report of SFEI–ASC's Historical Ecology Program, Publication #672, [Internet]. [accessed 2016 Sep 27]; 225 p. Richmond (CA): San Francisco Estuary Institute–Aquatic Science Center. Available from: *http://www.sfei.org/sites/default/files/biblio_files/Delta_HistoricalEcologyStudy_SFEI_ASC_2012_lowres.pdf*

Wilkerson, FP, Dugdale RC. 2016. The ammonium paradox of an urban high-nutrient low-growth estuary. In: Glibert PM, Kana TM, editors. Aquatic microbial ecology and biogeochemistry: a dual perspective. Switzerland: Springer International. [Internet]. [accessed 2016 Sep 27] p. 117-126. *https://doi.org/10.1007/978-3-319-30259-1*

Wittmann ME, Chandra S. 2015. Implementation plan for the control of aquatic invasive Species within Lake Tahoe. Lake Tahoe AIS Coordination Committee, 2015 July 3; Reno, NV [Internet]. [accessed 2016 Sep 27]; 52 p. Available from: *http://www.trpa.org/wp-content/uploads/Implementation-Plan-AIS-Final-7_31_2015.pdf*

https://doi.org/10.15447/sfews.2017v15iss2art2