https://doi.org/10.7289/V5/TM-SWFSC-589

NOAA Technical Memorandum NMFS

SEPTEMBER 2017

LIFE HISTORY AND CURRENT MONITORING INVENTORY OF SAN FRANCISCO ESTUARY STURGEON

Joseph Heublein, Russ Bellmer, Robert D. Chase, Phaedra Doukakis,
Marty Gingras, Douglas Hampton, Joshua A. Israel, Zachary J. Jackson,
Rachel C. Johnson, Olaf P. Langness, Sean Luis, Ethan Mora, Mary L. Moser,
Larissa Rohrbach, Alicia M. Seesholtz, Ted Sommer, and Jeffrey S. Stuart

NOAA-TM-NMFS-SWFSC-589

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

NOAA Technical Memorandum NMFS

https://doi.org/10.7289/V5/TM-SWFSC-589

NOAA Technical Memorandum NMFS
This TM series is used for documentation and timely communication of preliminary results, interim reports, or special purpose information. The TMs have not received complete formal review, editorial control, or detailed editing.

SEPTEMBER 2017

LIFE HISTORY AND CURRENT MONITORING INVENTORY OF SAN FRANCISCO ESTUARY STURGEON

Joseph Heublein, Russ Bellmer, Robert D. Chase, Phaedra Doukakis,
Marty Gingras, Douglas Hampton, Joshua A. Israel, Zachary J. Jackson,
Rachel C. Johnson, Olaf P. Langness, Sean Luis, Ethan Mora, Mary L. Moser,
Larissa Rohrbach, Alicia M. Seesholtz, Ted Sommer, and Jeffrey S. Stuart

Published by:
NOAA National Marine Fisheries Service
SWFSC Fisheries Ecology Division
110 McAllister Way
Santa Cruz, CA 95060

NOAA-TM-NMFS-SWFSC-589

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

Life History and Current Monitoring Inventory of San Francisco Estuary Sturgeon

Joseph Heublein[1*], Russ Bellmer[2], Robert D. Chase[3], Phaedra Doukakis[1], Marty Gingras[4], Douglas Hampton[1], Joshua A. Israel[5], Zachary J. Jackson[6], Rachel C. Johnson[7], Olaf P. Langness[8], Sean Luis[1], Ethan Mora[9], Mary L. Moser[10], Larissa Rohrbach[11], Alicia M. Seesholtz[12], Ted Sommer[12], and Jeffrey S. Stuart[1]

[1]West Coast Region, California Central Valley Office, NOAA Fisheries, Sacramento, CA 95814 USA (*corresponding author: joe.heublein@noaa.gov)

[2]California Department of Fish and Wildlife, Sacramento, CA 95811 USA

[3]U.S. Army Corps of Engineers, Redding, CA 96002 USA

[4]California Department of Fish and Wildlife, Stockton, CA 95206 USA

[5]U.S. Bureau of Reclamation, Sacramento, CA 95814 USA

[6]U.S. Fish and Wildlife Service, Pinetop, AZ 85935 USA

[7]Fisheries Ecology Division, Southwest Fisheries Science Center, NOAA Fisheries, Santa Cruz, CA 95060 USA and Department of Animal Sciences & Center for Watershed Sciences, University of California Davis, Davis, CA 95618 USA

[8]Washington Department of Fish and Wildlife, Vancouver, WA 98661 USA

[9]Fisheries Ecology Division, Southwest Fisheries Science Center, NOAA Fisheries and Cooperative Institute for Marine Ecosystems and Climate, University of California Santa Cruz, Santa Cruz CA 95060 USA

[10]Northwest Fisheries Science Center, NOAA Fisheries, Seattle, WA 98112 USA

[11]Anchor QEA, LLC, Wenatchee, WA 98801 USA

[12]California Department of Water Resources, West Sacramento, CA 95691 USA

Note: The findings and conclusions in this article are those of the author(s) and do not necessarily represent the views of the U.S. Fish and Wildlife Service.

Acknowledgements
We would like to thank David Woodbury, Bill Poytress, Yong-Woo Lee, Jake Hughes, and Ray Beamesderfer for contributing relevant and thoughtful presentations and input to our synthesis effort. We thank members of the Interagency Ecological Program (IEP) Sturgeon Project Work Team and Science Management Team for reviews of early drafts. Discussions and comments from two anonymous reviewers, Shawn Acuna, Josh Gruber, Bruce Herbold, Peter Klimley, Steve Lindley, Matt Manuel, Jamilynn Poletto, and Andrea Schreier greatly improved the manuscript. Many thanks to Bryan Begun (NOAA Corps) for his review of green sturgeon physiological information and development of an initial draft of Table 3. We appreciate the support of the IEP agency directors in initiating this effort and in their commitment towards improving core monitoring to increase our knowledge and management of these valuable resources.

Preface

This document describes life history and current monitoring of the two endemic sturgeon species of the San Francisco Estuary watershed: the southern Distinct Population Segment (sDPS) of North American green sturgeon green sturgeon and the Sacramento-San Joaquin River white sturgeon. It serves as background information used in the development of the conceptual models in Heublein et al. (2017). This document as well as Heublein et al. (2017) are fundamental in identifying existing and expanded monitoring needs necessary to track the status, trend, and viability of sDPS green sturgeon identified in National Marine Fisheries Service recovery planning efforts. Finally, this synthesized information is relevant in the development of future quantitative life cycle models for both sturgeon species. A comparative life history and a monitoring inventory are summarized below to relate areas where management actions and monitoring opportunities overlap for the two species and identify factors that may be unique to each species. More detailed life history descriptions and monitoring inventories follow; these are organized by species life stage.

Table of Contents

List of Figures and Tables

Comparative Life History and Monitoring of SFE Sturgeon

The spawning distribution of southern Distinct Population Segment (sDPS) green sturgeon and Sacramento-San Joaquin River or San Francisco Estuary (SFE) white sturgeon do not typically overlap (geographic regions of the SFE watershed are illustrated in Figure 1 of Heublein et al. [2017]). The majority of spawning for both species occurs in the mainstem Sacramento River; however, the downstream extent of sDPS green sturgeon spawning is approximately 80 kilometers (km) upstream of the typical spawning range of white sturgeon (Schaffter 1997; Poytress et al. 2015). Most sturgeon spawning in the SFE watershed occurs in spring, although white sturgeon can spawn earlier in winter, and green sturgeon spawning extends into early summer with periodic late summer and fall spawning (CDFG 2002; W. Poytress, USFWS, 2017a, unpublished data, see "Notes"). Spawning by both species typically occurs in areas that are deep and turbulent, but white sturgeon eggs occur in lower gradient reaches where channelized river habitat and fine substrate are common. There is no long-term monitoring of sturgeon spawning events (i.e., sampling for sturgeon eggs) on the Sacramento River. Recently, however, sturgeon egg sampling has occurred with some consistency in secondary spawning rivers (Feather and San Joaquin rivers).

With many of California's native fish subject to elevated and unsuitable water temperatures green sturgeon spawning in the upper Sacramento River is somewhat unique. Managed reservoir releases from Shasta Lake typically generate relatively low temperatures in the upper reaches of green sturgeon spawning and incubation habitat on the Sacramento River, and maintain suitable temperatures even in extreme drought conditions. In contrast, water temperatures that are suitable for normal egg development do not persist through the entire spawning and incubation period for white sturgeon in the San Joaquin River. Conditions on the Feather River in late spring and summer are also not appropriate for green sturgeon spawning and incubation in most years. This limitation to spawning habitat may become a more prominent issue if water temperatures continue to increase. Notably, spawning habitat in the upper reaches of the Sacramento River may provide sDPS green sturgeon resilience to climate change under a future scenario where most SFE sturgeon spawning habitats exceed optimal temperature ranges.

Coupling river conditions during sturgeon spawning and incubation with habitat requirements for egg and larval survival is a clear management consideration for both species. In laboratory studies, embryos of northern Distinct Population Segment (nDPS) green sturgeon and SFE white sturgeon have similar temperature optima and tolerances (see Fertilization to Hatch sections in this document for specific temperature ranges by species; Wang et al. 1985; Van Eenennaam et al. 2005). In this regard, management targets for spawning and incubation temperature may be similar for both species. In addition, river flows (which also influence water temperature) are heavily manipulated throughout the spawning ranges of both species. The direct effect of river flow magnitude and timing on spawning and incubation for both species remains uncertain. There is an outstanding management need for a complete understanding of the effects of managed and unmanaged flow and temperature on SFE sturgeon spawning and incubation.

General patterns of larval dispersal and habitat occupancy are different for green and white sturgeon. Although there is temporal overlap in the larval distributions of the two species, green sturgeon larvae in the Sacramento River have been collected from early spring through summer and white sturgeon larvae are typically collected from late winter through spring. In the Sacramento River, green sturgeon larvae are consistently collected near spawning reaches (Poytress et al. 2009, 2010, 2011, 2012, 2013). White sturgeon larvae, however, disperse from hatching areas and are collected throughout the freshwater estuary (CDFW, 2016a, unpublished data, see "Notes"). In the San Joaquin River, white sturgeon larvae appear to disperse less broadly than their Sacramento River counterparts (Z. Jackson, USFWS, 2017, unpublished data, see "Notes").

There is no intentional long-term monitoring of larval sturgeon in the SFE but larvae of both sturgeon species are captured incidentally in studies targeting other fish. Larval green sturgeon are captured annually in salmonid monitoring at Red Bluff Diversion Dam (RBDD) with rotary screw traps, and larval white sturgeon are captured episodically in the California Department of Fish and Wildlife (CDFW) "20mm Survey," which uses a rigid-opening trawl net constructed of 1,600-micrometer mesh to monitor delta smelt in the SFE. Data from these surveys represent an incomplete picture of larval sturgeon distribution, but some general patterns emerge. White sturgeon larvae may move into the freshwater estuary in spring and, as a result, would have access in some years to freshwater estuarine habitat and seasonally inundated wetlands. In contrast, sDPS green sturgeon larvae remain in riverine habitats until juvenile metamorphosis. This difference in larval distributions between species poses unique considerations for management of environmental conditions in their distinct habitats. Larval green sturgeon habitat in the upper Sacramento River is relatively stable due to flow and temperature management through operation of upstream dams and reservoirs. However, larval white sturgeon potentially utilize lower river and estuarine areas where conditions are more variable.

As described above, green sturgeon likely rear in spawning habitat on the Sacramento River for a few months or more before migrating to the estuary as juveniles (W. Poytress, USFWS, 2017a, unpublished data, see "Notes"), whereas white sturgeon may enter the estuary as larvae or early stage juveniles. Juveniles of both sturgeon species have been found throughout the Delta. There is likely significant overlap in distribution at the juvenile life stage, but green sturgeon appear to utilize brackish and seawater portions of the SFE more readily than white sturgeon (Thomas and Klimley 2015; M. Holm 2016, personal communication, see "Notes"). Catch of small juvenile sturgeon of both species in the estuary is episodic with year-class successes likely occurring during wet years with elevated flow (CDFW, unpublished data, 2015, 2016d, see "Notes"; Fish 2010). In laboratory studies using nDPS green sturgeon and SFE white sturgeon, exogenous larvae and juveniles reared with ample food show rapid growth rates in water temperatures at or above 19 degrees Celsius (°C; Cech et al. 1984; Mayfield and Cech 2004; Allen et al. 2006).

Juvenile green and white sturgeon are rarely caught in estuarine monitoring surveys; in many years, juvenile sDPS green sturgeon are absent from all monitoring. Data from juvenile white sturgeon sampling in the estuary is used to generate a coarse recruitment index and forecast of adult cohort abundance (Fish 2010). Although increasing juvenile collection of both species may be challenging, these potential data are critical to understanding environmental factors influencing juvenile sturgeon recruitment and establishing necessary early life stage abundance measures for sDPS green sturgeon.

Adult white sturgeon are found throughout the year in brackish areas of the SFE, and individuals tagged in the SFE are rarely detected or recaptured in marine areas or non-natal estuaries (Kohlhorst et al. 1991). The SFE appears to be exclusively occupied by sDPS green sturgeon with subadult and adult life stages more common in summer and fall compared to other seasons (Israel et al. 2009; National Marine Fisheries Service [NMFS] 2015). A mixture of nDPS and sDPS subadult and adult green sturgeon also occupy estuaries and nearshore marine areas in summer and early fall in Oregon and Washington (Lindley et al. 2011). Green sturgeon in the SFE may comprise a small proportion of the subadult and adult sDPS based on population analysis of non-natal estuarine aggregations of green sturgeon (NMFS 2015; Schreier et al. 2016). As a result, sDPS green sturgeon have been studied extensively through sampling of these mixed distinct population segment aggregations in non-natal estuaries. Additionally, green sturgeon are encountered with some regularity as bycatch in ocean commercial fisheries, allowing opportunities for commercial fishery-dependent monitoring.

White sturgeon are the more common and abundant sturgeon species in the SFE and support a large sport fishery. Thus, directed sturgeon sampling studies and fishery-dependent monitoring in the SFE watershed are focused predominantly on white sturgeon. While disproportionate catch may suggest habitat segregation between species in the SFE, directed sampling of adult green sturgeon in the SFE has almost always involved catch of both species (M. Holm 2016, personal communication, see "Notes"). In this regard, green and white sturgeon most likely occupy similar areas within the SFE. As described above, juvenile SFE sturgeon are rarely encountered, and larval SFE sturgeon are only collected incidentally in studies directed at other species and are typically too small for non-lethal tissue analyses. Ongoing monitoring of adult sturgeon in the SFE and associated studies (e.g., population modeling, tagging, analysis of genetics and contaminants) presents an opportunity to increase understanding of both species.

Spawning sDPS green sturgeon enter the SFE from the ocean from late winter to spring and ascend the Sacramento River with minimal staging and feeding in the estuary (Heublein et al. 2009). Adult white sturgeon spend the majority of their lives in the SFE and can initiate upstream migration in the late fall through spring (Kohlhorst and Cech 2001). Thus, consumption of contaminated food in the SFE may have a greater effect on white sturgeon vitellogenesis and eggs compared to sDPS green sturgeon. Both green and white sturgeon are susceptible to stranding at the Sutter and Yolo Bypass Weirs during the same hydrologic conditions and timing. The observed spawning habitat partitioning on the Sacramento River most likely indicates different preferences for spawning substrate or other habitat attributes between species (e.g., channel gradient and velocity). Both species show a variety of post-spawn migration and holding behaviors, but it is more common for post-spawn green sturgeon to hold for a few months or more in freshwater habitats and for white sturgeon to return to the SFE immediately after spawning (Heublein et al. 2009; Klimley et al. 2015).

The sDPS green sturgeon spawning run on the Sacramento River has been estimated annually using dual-frequency identification sonar (DIDSON) survey data since 2010 (Mora 2016). There is no directed monitoring of the white sturgeon spawning run on the Sacramento River beyond angler catch reporting in spawning reaches. Recently, directed study of spawning sturgeon has occurred on the San Joaquin River (white sturgeon) and, to lesser extent, the Feather River (primarily green sturgeon). White and green sturgeon migrating to spawning habitat in the Sacramento and Feather rivers are periodically sampled at the Sutter and Yolo Bypass Weirs, and white sturgeon are collected in general fish community monitoring in the Yolo Bypass. Annual spawning measures (e.g., annual run-size, spawning distribution, verification of successful spawning) are fundamental metrics necessary for management of both sturgeon species. Monitoring of spawning sturgeon should be expanded such that these metrics are uniformly available throughout the spawning ranges of both species.

Specific Life History Descriptions and Monitoring by Life Stage

Prior to developing the comparative life history and monitoring of SFE sturgeon (above), the following inventory of monitoring (summarized in Tables 1 and 2) and specific life history descriptions by life stage were established.

Table 1. Green sturgeon monitoring inventory.
Four general categories are used to organize the discussion of monitoring: life stage—surveys; collection or survey of fish; tissue analyses—analysis of fish tissue samples to estimate age, sex, reproductive condition, migratory histories, etc.; telemetry—monitoring of fish movement and behavior through implantation of active or passive tags and subsequent tag detection; and population modeling and synthesis—modeling or synthesis of survey, tissue analysis, and/or telemetry data to estimate demographics, population trends, movement patterns, etc. Study leads are provided in parentheses.

Green Sturgeon	Eggs	Larvae	Juveniles	Subadults/Adults	Spawning Adults
Life stage surveys	• Sacramento River rotary screw trap collections at RBDD (2016, 2017; USFWS) • intermittent egg mat surveys on the Feather River (DWR) • habitat mapping of past egg collection sites and putative spawning areas on the Sacramento River (USFWS; NMFS)	• Sacramento River rotary screw trap collections at RBDD (USFWS) and GCID (GCID) • intermittent larval D-netting on Sacramento River (USFWS) and Feather River (DWR)	• benthic trawl surveys near RBDD (USFWS) • Sturgeon Fishing Report Cards (location and length; CDFW) • intermittent collection in Bay Study (Delta; CDFW) intermittent salvage at the federal and state Delta pumping facilities (DWR; BOR)	• Sturgeon Study (trammel netting in Bay), Sturgeon Fishing Report Cards, boat logs, creel surveys (CDFW) • bycatch in California halibut trawl fishery (NMFS; CDFW) • intermittent sampling in San Pablo Bay, Columbia River, Grays Harbor, and Willapa Bay (UCD; WDFW; NMFS)	• DIDSON surveys in spawning habitat NMFS; CDFW; DWR) • hook and line sampling in Feather River (DWR) • Sturgeon Fishing Report Cards, creel surveys (CDFW) • Yolo Bypass and Knights Landing fyke traps, stranding at Fremont and Tisdale weirs (DWR; CDFW)
Tissue analyses		• analysis of larval development (spawn timing; UCD)	• genetic analysis of benthic trawl samples (NMFS)	• fin ray analysis from Sturgeon Study (age; USFWS) • genetic analysis of California halibut fishery bycatch (NMFS)	• reproductive stage of sturgeon stranded at Fremont and Tisdale weirs (CDFW; UCD)
Telemetry			• lower Sacramento River monitoring (primarily gill-netting) for acoustic tag implantation (CDFW; UCD) • acoustic tagging of juveniles captured in benthic trawls near RBDD (USFWS; UCD)	• satellite tagging of bycatch in California halibut trawl fishery (NMFS; CDFW); • detection of previously tagged fish in existing acoustic arrays (UCD; NMFS)	• detection of previously tagged adults in acoustic array (NMFS; WDFW; UCD; DWR) • acoustic tagging of sturgeon stranded a Fremont and Tisdale weirs (CDFW; UCD) • acoustic tagging of hook and line capture of adults in Feather River (DWR)
Population modeling and synthesis		• comparison of RBDD larval timing and abundance and environmental conditions (USFWS)	• hind-cast of recruitment success through estimated age of collected and reported juveniles (CDFW)		• modeling of run size using DIDSON and acoustic detection data, expansion of run size estimates to adult abundance estimates with spawning periodicity (NMFS)

Notes:
Study leads are provided in parentheses in table (RBDD: Red Bluff Diversion Dam; USFWS: U.S. Fish and Wildlife Service; NMFS: National Marine Fisheries Service; DWR: California Department of Water Resources; GCID: Glenn Colusa Irrigation District; UCD: University of California, Davis; CDFW: California Department of Fish and Wildlife; BOR: Bureau of Reclamation; WDFW: Washington Department of Fish and Wildlife)

Table 2. White sturgeon monitoring inventory.

White Sturgeon	Eggs	Larvae	Juveniles	Adults	Spawning Adults
Life stage surveys	• egg mat surveys, habitat mapping (San Joaquin River; USFWS)	• larval D-netting (San Joaquin River; USFWS) • 20mm Survey (CDFW) • salvage at the federal and state Delta pumping facilities (BOR; DWR)	• Bay Study (Delta; CDFW) • salvage at the federal and state Delta pumping facilities (BOR; DWR)	• Sturgeon Study (trammel netting in Bay), Sturgeon Fishing Report Cards, boat logs, creel surveys (CDFW) • salvage at the federal and state Delta pumping facilities (BOR; DWR)	• Sturgeon Study (post-spawn), Sturgeon Fishing Report Cards, creel surveys (CDFW) • Yolo Bypass and Knights Landing fyke traps (DWR;) • stranding at Fremont and Tisdale weirs (DWR; CDFW) • gill and trammel netting in San Joaquin River spawning areas (USFWS)
Tissue analyses	• development (spawn timing; UCD) • preliminary genetic analysis of eggs (UCD; Cramer Fish Sciences)	• development analysis of larvae (spawn timing; UCD; BOR)	• juvenile age at length (CDFW)	• fin ray analysis from Sturgeon Study (age and growth), tissue analysis from fishing derbies (age and contaminants), preliminary fin microchemistry analysis (USFWS)	• fin ray, reproductive condition, and genetic analysis of sturgeon captured in San Joaquin River spawning habitat (USFWS; UCD)
Telemetry			• lower Sacramento River monitoring (primarily gill-netting) for acoustic tag implantation (CDFW; UCD)	• detection of previously tagged fish in existing array (DWR; UCD)	• tagging of adults from fykes, bypass stranding, and San Joaquin River spawning habitat and detection of current and previously tagged adults in acoustic array (DWR; USFWS; UCD)
Population modeling and synthesis			• ongoing analysis of YCI and hind-cast relative brood year abundance (CDFW)	• ongoing estimates of harvest and adult abundance with Sturgeon Study and Sturgeon Fishing Report Card data (CDFW)	• analyses of recapture rates of externally tagged sturgeon in spawning habitat (CDFW)

Notes:
Monitoring category descriptions provided in Table 1. Study leads are provided in parentheses in table (USFWS: U.S. Fish and Wildlife Service; UCD: University of California, Davis; CDFW: California Department of Fish and Wildlife; BOR: Bureau of Reclamation; DWR: California Department of Water Resources)

Fertilization to Hatch

Green sturgeon eggs. Southern DPS green sturgeon spawn during the spring and summer in the middle and upper mainstem Sacramento River. Spawning has been documented on the Feather River in only two years, 2011 and 2017 (Seesholtz et al. 2015; M. Manuel, PSMFC, 2017, personal communication, see “Notes”). Late summer and fall spawning on the Sacramento River has also been documented in four years by larval collections at RBDD (2016; W. Poytress, USFWS, 2017a, unpublished data, see “Notes”) and Glenn-Colusa Irrigation District (GCID) oxbow (1997, 1999, and 2000; CDFG 2002).

A time range for fertilization can be estimated using information on egg and larval development and growth from laboratory studies, observed length or development stage at capture, and river water temperatures (Dettlaff et al. 1993; Poytress et al. 2015). Coarse spatial distribution of fertilized eggs or spawning can be generated by combining estimated time ranges of fertilization with corresponding adult detections in spawning habitat. Poytress et al. (2009, 2010, 2011, 2012, 2013) sampled eggs directly in the upper and middle Sacramento River between 2008 and 2012 (summarized in Poytress et al. 2015). The authors confirmed that spawning occurred at seven locations by egg matt sampling along the Sacramento River between the GCID oxbow (river kilometer [rkm] 332.5 from the confluence of the Sacramento and San Joaquin rivers) and Inks Creek (rkm 426). Eggs were collected at depths from 0.6 to 11.3 meters (m), with water temperatures ranging from 9.8 to 17.1°C. Based on the observed egg development stages and temperatures, spawning had occurred from April through July (Poytress et al. 2015). Notably, green sturgeon eggs were collected in rotary screw traps at RBDD (rkm 391) for the first time in 2016 (W. Poytress, USFWS, unpublished data, see “Notes”).

Sturgeon early life history sampling has been conducted in the Feather River since 2011 with egg mats and intermittent D-net sampling (Seesholtz et al. 2015; A. Seesholtz, DWR, 2017, unpublished data, see “Notes”). Sturgeon have never been collected in rotary screw traps in the Feather River. Spawning on the Feather River has been confirmed in only two locations: below Fish Barrier Dam, which is a barrier to anadromous fish passage, and 13 km downstream at the outlet of the Thermalito Afterbay (Thermalito Outlet). Seesholtz et al. (2015) estimated that spawning at the Thermalito Outlet occurred from June 12 through 19, 2011, when water temperatures were 16 to 17°C, whereas spawning occurred in substantially cooler temperatures at FishFish Barrier Dam (approximately 11°C) in late May or early June 2017 (M. Manuel, PSMFC, 2017, personal communication, see “Notes”).

Direct observation or DIDSON detection of sturgeon suggests that sDPS green sturgeon may spawn in other areas of the Feather River watershed. Anglers reported catch of numerous green sturgeon about 5-km downstream from Fish Barrier Dam in 2006 (A. Seesholtz, DWR, 2017, unpublished data, see “Notes”). Green sturgeon aggregations have been detected with DIDSON surveys much lower in the Feather River near Shanghai Bend (69-km downstream of Fish Barrier Dam) in habitats that appear suitable for spawning (e.g., suitable depth, water velocity, substrate; A. Seesholtz, DWR, 2017, unpublished data, see “Notes”). Adult green sturgeon have also been observed in spring and summer at Daguerre Point Dam on the Yuba

River (a large tributary to the Feather River) in 2011, 2016, and 2017 (Bergman et al. 2011; M. Beccio, CDFW, 2017, personal communication, see "Notes").

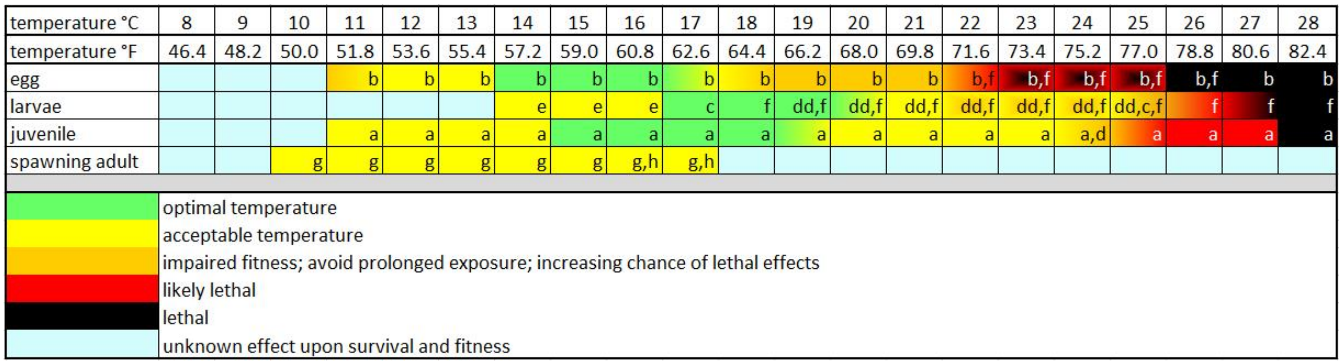
There are no long-term surveys that sample green sturgeon eggs, and locations of egg collection from short-term surveys are unlikely to represent the entire egg distribution. Adult detections in potential spawning habitat during spring and early summer can be used to infer a broader egg distribution. Adults have been detected in spring and summer in approximately 21 areas with suitable spawning habitat in the Sacramento River from above the GCID to the confluence of the Sacramento River and Cow Creek (rkm 451; Heublein et al. 2009; Klimley et al. 2015). Based on these observed adult distributions, contemporary egg distribution on the Sacramento River can range from the GCID oxbow in the middle Sacramento River to Cow Creek in the upper Sacramento River basin.

Nearly all laboratory-based data on green sturgeon physiology (e.g., growth rates, metabolism, swimming performance) involve the nDPS. With the overlap in estuarine and marine habitat between the population segments, and with similarities of adjacent historical natal freshwater habitats (e.g., watersheds of the Sacramento and upper Klamath rivers), it is assumed that physiology of the two distinct population segments is similar. However, the nDPS is an "untested surrogate" for the laboratory-based physiology of the sDPS because laboratory-based data for the sDPS do not exist for comparison. In areas or life stages where field-based information on habitat optima or preference is unavailable for sDPS, laboratory-based nDPS data should be cautiously applied because it is generated in a controlled setting and involves a latitudinally distinct population segment.

The following early life stage physiology information was collected in laboratory study of nDPS green sturgeon. Eggs sampled from a single nDPS Klamath River female hatched after 144 to 192 hours of incubation at 15.7 ± 0.02°C and were an average of 4.44 ± 0.15 millimeter (mm) in diameter (Deng et al. 2002). Van Eenennaam et al. (2005) exposed the fertilized eggs of one nDPS female to six temperature regimes (11, 14, 17, 20, 23, and 26°C). Egg survival to hatch was highest in the 14°C and 17°C treatments (39% and 36%, respectively), with total mortality at temperatures of 23°C and above (Van Eenennaam et al. 2005). Van Eenennaam et al. (2005) also found a decreased hatching rate in the 11°C treatment compared to 14°C, but the lower temperature limit for embryo survival was not determined. Elevated water temperature can cause deformities in embryos. The proportion of hatched embryos with deformities was relatively high at 17°C and 20°C (10.3% and 51.6%, respectively) and low at 11°C and 14°C treatments (3.7% and 1.2%, respectively; Van Eenennaam et al. 2005). Based on this information, Van Eenennaam et al. (2005) concluded temperatures less than 17.5°C are optimal for normal development of embryos (results summarized in Table 3).

Table 3. Green sturgeon temperature tolerances by life stage.

Laboratory studies involving nDPS green sturgeon from Klamath River broodstock (a, b, c, d, dd, f) were used to rate water temperatures for the eggs, larvae, and juveniles. Water temperatures recorded during sDPS green sturgeon egg and larvae collection on the upper Sacramento and Feather rivers (e, g, and h) were used to establish "acceptable temperature" for spawning adults and larvae. Categorization of temperature tolerance is not directly comparable at upper and lower levels in this table because "impaired fitness" may be related to both indirect sources of mortality (e.g., reduced growth rate) and direct sources of mortality (e.g., increased rate of deformities). a = Mayfield and Cech 2004; b = Van Eenennaam et al. 2005; c = Werner et al. 2007; d = Allen et al. 2006; e = Poytress et al. 2012; f = Linares-Casenave et al. 2013; g = Poytress et al. 2015; h = Seesholtz et al. 2015; and dd = Allen et al. 2006b.



temperature °C	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
temperature °F	46.4	48.2	50.0	51.8	53.6	55.4	57.2	59.0	60.8	62.6	64.4	66.2	68.0	69.8	71.6	73.4	75.2	77.0	78.8	80.6	82.4
egg				b	b	b	b	b	b	b	b	b	b	b	b,f	b,f	b,f	b,f	b,f	b	b
larvae							e	e	e	c	f	dd,f	dd,f	dd,f	dd,f	dd,f	dd,f	dd,c,f	f	f	f
juvenile				a	a	a	a	a	a	a	a	a	a	a	a	a	a,d	a	a	a	a
spawning adult			g	g	g	g	g	g	g,h	g,h											

🟩	optimal temperature
🟨	acceptable temperature
🟧	impaired fitness; avoid prolonged exposure; increasing chance of lethal effects
🟥	likely lethal
⬛	lethal
⬜	unknown effect upon survival and fitness

The following general discussion of water temperature in sDPS green sturgeon egg habitat involves coarse gauge data reported by the DWR California Data Exchange Center (CDEC; Sacramento River gauges at Keswick Dam – rkm 488, Bend Bridge – rkm 415, RBDD – rkm 391, and Wilkins Slough – rkm 190, see hyperlinks for historical and current CDEC gauge data, DWR, 2017a, in "Notes") and more-specific temperature information from unpublished agency monitoring and modeling efforts. In late spring and summer, flow and temperature on the Sacramento River are manipulated in part for agricultural diversion (GCID - rkm 332.5, and RBDD are the largest diversion facilities on the Sacramento River) and maintenance of a 13.3°C (56° Fahrenheit) water temperature "compliance point" for Sacramento River winter-run Chinook salmon (SRWC; *Oncorhynchus tshawytscha*) spawning and incubation. The compliance point typically ranges from rkm 415 to rkm 444, and water temperatures upstream of rkm 444 are progressively cooler up to Keswick Dam, where Shasta Lake reservoir release temperatures typically range from 10 to 12°C. As a result, optimal temperatures for sturgeon egg incubation (below 17°C) extend downstream to RBDD in spring and summer of most years, but typically remain below laboratory-based optima for egg incubation upstream of existing spawning and egg incubation areas (closer to Keswick Dam). In downstream areas closer to GCID, water temperatures are typically suboptimal for incubation in the late spring and summer (above 17.5°C). During periods of extremely low reservoir storage and outflow, incubation temperatures may be suboptimal in the late spring and summer near RBDD and approach potentially lethal temperatures (above 20°C) in areas closer to GCID.

Fish Barrier Dam on the Feather River creates a small impoundment below Oroville Reservoir called the Thermalito Diversion Pool. Water from the Thermalito Diversion Pool is either released to the river at Fish Barrier Dam or routed through the shallow Thermalito Afterbay, thereby bypassing a short tailwater and warming for crop irrigation. Warmer water is then diverted directly from the Thermalito Afterbay or released back into the Feather River at the Thermalito Outlet. Water management downstream of the Thermalito Outlet may have a variable effect on green sturgeon spawning habitat depending on the time of the year and operations. Peak winter and spring flows on the Feather River are typically captured in upstream reservoirs. Summer base flows can then be augmented by releases from the Thermalito Outlet, and flow augmentation may also decrease summer water temperatures. Water released from the Thermalito Outlet is warmer than the potential cold water pool released into the Feather River at Fish Barrier Dam. Hence, suitable conditions for normal egg incubation (water temperatures below 17.5°C) typically only persist into May downstream of the Thermalito Outlet.

White sturgeon eggs. The SFE white sturgeon spawn primarily in the mainstem Sacramento River and to a lesser extent in the San Joaquin River in late winter and spring. Based on collection of gravid adults, spawning also periodically occurs in other rivers (e.g., the Feather and Bear rivers) in the Sacramento River basin. There is no long-term monitoring of white sturgeon eggs in the Sacramento River, but egg distribution is likely similar to the putative spawning reach, which typically ranges from just upstream of Colusa (rkm 252) to near Verona (rkm 129; Kohlhorst 1976; Schaffter 1997). Adult white sturgeon have been reported by anglers near the confluence of the Sacramento River and Deer Creek (rkm 354) and have been observed and collected during summer and early fall near the GCID oxbow (rkm 332.5; Bergman 2011; M. Manuel, PSMFC, 2016, personal communication, see “Notes”). Juvenile white sturgeon have been collected in the rotary screw traps at GCID and reported by anglers in the area (M. Manuel, PSMFC, 2016, personal communication, see “Notes”). Given those observations, spawning white sturgeon and eggs presumably occur upstream from the GCID oxbow in some years. Egg distribution upstream of GCID requires verification by egg or larval collections because juveniles collected in the GCID trap may have moved there from downstream.

Sturgeon egg sampling is underway in the San Joaquin and Feather rivers in years when adult sturgeon are detected in spawning habitats. However, no white sturgeon eggs have been identified in samples from the Feather River. As described above, sturgeon egg distribution can also be inferred from ongoing acoustic detections of tagged adults in spawning habitat, reports of adults in spawning habitat gathered from the Sturgeon Fishing Report Cards, and from incidental bycatch of larvae and early stage juveniles in other monitoring or research studies.

In the Sacramento River, white sturgeon typically spawn between February and June. Tagged adult white sturgeon move from the SFE to spawning reaches of the Sacramento River between mid-February and early June (Miller 1972; Schaffter 1997; E. Miller UCD Biotelemetry Laboratory, 2017, unpublished data, see “Notes”). Kohlhorst (1976) used D-nets to collect white sturgeon eggs and larvae as early as mid-February, with the majority (93%) collected in March and April. Schaffter (1997) collected eggs in the Sacramento River on artificial substrates from March through May. Angler reporting of tagged adults in spawning habitat coincident with early season flow events also indicates migration and possibly spawning occur in December and January in some years (CDFW, 2016b, unpublished data, see “Notes”). In the San Joaquin River basin, fertilized eggs were collected downstream of Grayson at rkm 138 (measured from the Sacramento River confluence) in late April 2011 and downstream of Vernalis between rkm 115 and 140 from late March through mid-May in 2012 (Jackson et al. 2016). In March and April 2016, fertilized eggs were collected between rkm 115 and 140, though collection of a single larvae approximately 1 day post-hatch (dph) at rkm 101 indicates that spawning occurs further downstream than previously known (Z. Jackson, USFWS, 2017, unpublished data, see “Notes”).

Benthic substrate in white sturgeon spawning habitat is variable. Substrate in the Sacramento River ranges from fine sand to coarse sand near Verona and Wilkins Slough (rkm 189.5), fine gravel to medium gravel farther upstream near Colusa, and gravel and cobble in spawning sites just upstream from Colusa where the river gradient is higher. Schaffter (1997) found eggs in water depths of 1.5 to 4.6 m, with water velocities greater than 1.0 meter per second. Eggs were also collected in San Joaquin River spawning areas at depths of 1.6 to 10.5 m (Jackson et al. 2016). The river bottom in egg-collection areas of the San Joaquin River was dominated by silt and sand substrates, though patches of hardpan clay and fine gravels were present near several sites (Jackson et al. 2016). Fine substrate and lack of interstitial space in spawning habitat can decrease survival of white sturgeon eggs (Hildebrand et al. 2016). Thus, substrate in SFE white sturgeon spawning habitats, especially on the San Joaquin River, may limit recruitment to the larval or juvenile life stage.

Wang et al. (1985) found that development and survival of white sturgeon embryos were temperature-dependent. Optimal survival to hatching was observed when water temperatures during incubation in the hatchery were between 14°C (88.6% ± 2.2% survival) and 17°C (83.6% ± 1.9% survival). Embryo mortality increased as water temperatures increased to 20°C (49.1% ± 3.2% survival), and water temperatures of more than 20°C were lethal to developing embryos. Water temperatures in spawning habitat on the Sacramento River typically remain below this level, but median daily water temperatures in excess of 20°C were recorded in Sacramento River incubation habitat during drought conditions in April 2015 (CDEC Sacramento River gauges at Wilkins Slough, DWR, 2017a, see "Notes"). Spring water temperatures regularly reach or exceed suitable levels for egg incubation in the San Joaquin River, but viable white sturgeon embryos have been collected in water temperatures above 20°C (Jackson et al. 2016). The time necessary for white sturgeon eggs to hatch is also temperature-dependent (Wang et al. 1985; Deng et al. 2002). Under an optimal incubation water temperature of 15.7 ± 0.2°C, Deng et al. (2002) found that development time to hatching ranged from 152 to 200 hours and averaged 176 hours. Hatch time is an important consideration for managers if there are potentially variable habitat conditions (e.g., inundation levels, temperature) during egg development.

Hatch through Metamorphosis

Larval green sturgeon. Metamorphosis of nDPS green sturgeon (to juveniles) occurs at approximately 45 dph and an approximate length of 75 mm (Deng et al. 2002). Growth begins to increase as larvae transition from endogenous to exogenous feeding, which occurs at approximately 15 dph (Gisbert et al. 2001). Laboratory studies have shown that nDPS larvae possess limited swimming ability and generally seek refuge at 0 to 18 dph, suggesting that complex habitat with interstitial space for refuge (e.g., large cobble substrate) is critical at this life stage (Kynard et al. 2005). Under laboratory conditions, nDPS individuals 18 to 45 dph demonstrated initiation of diel downstream migration, favoring nighttime migratory movements (Kynard et al. 2005). Based on egg mat and rotary screw trap sampling at RBDD, Poytress et al. (2011) found similar results in field study of sDPS larvae compared to the laboratory investigations of nDPS larvae described above; larval dispersal was initiated at 18 dph, it peaked at 23 to 24 dph, and complete dispersion from hatching areas occurred by 35 dph.

Historically, larval sturgeon collected in the Sacramento and San Joaquin river systems were not routinely identified to species. However, green sturgeon larvae were identified in RBDD rotary screw trap samples when the study was initiated in 1995, which confirmed green sturgeon spawning at or above this location (Poytress et al. 2009). Larvae have been consistently collected in rotary screw traps in spring and summer at RBDD and GCID as part of a long-term monitoring program in the Sacramento River focused on juvenile salmonids. Data from rotary screw traps at RBDD have shown a similar temporal distribution data for larvae in the Upper Sacramento River compared to D-net sampling data (W. Poytress, USFWS, 2015a, unpublished data, see "Notes"). Larval catch numbers at GCID rotary screw traps are typically lower than

RBDD rotary screw traps (CDFG 2002), and appear to be less representative of temporal spawning downstream of RBDD.

Brown (2007) discovered larvae in the upper Sacramento River at Bend Bridge (rkm 415), and spawning has been confirmed as far downstream as the GCID facility (Poytress et al. 2015), suggesting that larvae occupy over 100 km of the Sacramento River. Due to the limited number of larval collections, the upstream egg distribution described above (Sacramento River to Cow Creek and Feather River to Fish Barrier Dam) is also applied to larvae. Larval sturgeon distribution may range well downstream from spawning habitat. Larval white sturgeon and unidentified larval sturgeon have been collected more than 100-km downstream from known white or sDPS green sturgeon spawning areas during the 20mm Survey and in salvage at the Tracy Fish Collection Facility and John E. Skinner Fish Protection Facility near federal and state Delta pumping facilities (CDFW, 2016a, unpublished data, see "Notes"). Thus, larval distribution is estimated to extend at least 100-km downstream from spawning habitats on the Sacramento and Feather rivers in high flow years. This estimated downstream distribution corresponds with the Colusa area on the Sacramento River (rkm 252) and the confluence of the Sacramento and Feather rivers near Verona (rkm 129) for larvae originating in the Sacramento River and Feather River, respectively.

Larval abundance and distribution may be influenced by spring and summer outflow. There appears to be a positive relationship between annual outflow and larval abundance in the RBDD rotary screw traps; RBDD rotary screw trap collections of larval green sturgeon were far greater in the three most recent wet years[1] (2011, 2016, and 2017) since the monitoring began in 1995 (W. Poytress, USFWS, 2015a, unpublished data, see "Notes"). Moreover, green sturgeon eggs and larvae were only collected during wet years (2011 and 2017) on the Feather River (Seesholtz et al. 2015; M. Manuel, PSFMC, 2017, personal communication, see "Notes").

In laboratory-based studies with abundant food and oxygen, larval nDPS green sturgeon (35 dph) growth was significantly greater at 24°C than 19°C or cycling 19 to 24°C (Allen et al. 2006b). Furthermore, larval nDPS green sturgeon reared at 11 and 13°C under normal food conditions had significantly reduced growth rates compared to larvae reared at 16 and 19°C, but temperature had no significant effect on size or growth rate when larvae were food-limited (J. Poletto, 2016, unpublished data, see "Notes"). Green sturgeon eggs, larvae, and juveniles co-occur in the middle and upper Sacramento River due to the protracted spawning period of sDPS green sturgeon. Spawning of critically endangered SRWC also occurs closer to Keswick Dam during sDPS spawning. Laboratory-based optima for larval and juvenile green sturgeon growth exceed suitable temperatures for green sturgeon spawning and embryo development (Table 3), and are well above suitable temperatures for Chinook salmon spawning and incubation. Thus,

---

[1] With the exception of 2016, the "wet year" phrase is based on resource agency water-year type or classification (CDEC water year classification, DWR, 2017b, see "Notes"). The 2016 water year for the Sacramento and San Joaquin valleys was classified as below normal and dry, respectively. However, 2016 is qualitatively described in this document as a wet year because above-average precipitation was recorded in most of the SFE watershed and spawning and migratory conditions typically associated with wet years occurred (e.g., elevated winter or spring flows, extended periods of bypass inundation).

water temperature in the middle and upper Sacramento River may have different effects on specific green sturgeon life stages and SRWC. Potentially optimal water temperatures for larval growth near RBDD could correspond to low concurrent spawning production and egg survival. Furthermore, warmer water temperatures near RBDD could be associated with poor survival of early life stages of green sturgeon in lower reaches of Sacramento River spawning habitat and SRWC closer to Keswick Dam.

Larval white sturgeon. In a laboratory study, metamorphosis of larval white sturgeon to juveniles occurred at approximately 45 dph (Deng et al. 2002). Larval white sturgeon are not specifically monitored, except for pilot efforts in 2013, 2015, and 2016 on the lower San Joaquin River (Faukner and Jackson 2014; Jackson et al. 2016) and a more directed effort begun in 2017 (Z. Jackson, USFWS, 2017, unpublished data, see "Notes"). White sturgeon larvae are also periodically collected in various locations throughout the Delta in general larval fish monitoring (e.g., 20mm Survey) in late winter and spring and in salvage at federal and state Delta pumping facilities.

Upstream larval distribution in the Sacramento River can be extrapolated from adult monitoring in spawning habitat (e.g., in-river sportfishing catch data, adult telemetry studies). Periodic aggregations of gravid white sturgeon or telemetry data in the Feather River, Yolo Bypass, and Bear River indicate spawning and larval distribution may also extend to those upstream areas. Based on this information, larval distribution ranges from downriver of spawning habitats (primarily in the Sacramento and San Joaquin rivers) to the approximate downstream extent of the Delta at Chipps Island.

Kynard and Parker (2005) report that Sacramento River white sturgeon larvae use benthic habitat following brief post-hatch dispersal and availability of interstitial benthic space may increase larval survival through multiple mechanisms (i.e., reduction in metabolic demand, stress, and predation; Hildebrand et al. 2016). Laboratory studies indicate exogenous larval white sturgeon are tolerant of salinities up to 16 parts per thousand (ppt) and have relatively high growth rates in 20°C water (Cech et al. 1984; McEnroe and Cech 1985). However, suitable temperatures for white sturgeon larvae outside of controlled laboratory conditions and for early stage larvae may be lower (less than 16°C; Hildebrand et al. 2016). A positive relationship exists between relative larval abundance and wet years based on data from long-term collection of white sturgeon larvae in the 20mm Survey (CDFW, 2016a, unpublished data, see "Notes"). Furthermore, larvae were only collected in San Joaquin River spawning habitats in 2016 (relatively cool conditions) and 2017 (during flooding conditions; Z. Jackson, USFWS, 2017, unpublished data, see "Notes").

Complete Metamorphosis to Ocean Migration or 75 Centimeters Fork Length

Juvenile green sturgeon. It is unknown how long juvenile sDPS green sturgeon remain in upriver rearing habitats after metamorphosis. Juveniles captured in the Delta by Radtke (1966) ranged in size from 200 to 580 mm fork length (FL), suggesting that juveniles remain upriver for several months before entering the Delta. The lack of juveniles smaller than 200 mm FL in Delta capture records further supports extended upriver rearing of sDPS juveniles before entering the estuary (CDFG 2002). The first successful study of juveniles in the Sacramento River occurred in 2015 in the Red Bluff area, where approximately 40 large age-0 green sturgeon (60 to 320 mm total length [TL]) were captured using benthic trawls throughout the summer (W. Poytress, USFWS, 2015b, unpublished data, see "Notes"). Based on those studies, it is likely that juveniles rear near spawning habitat for a few months or more before migrating to the Delta.

Duration of juvenile estuary rearing prior to ocean entry and subadult transition is also unknown. Small juvenile green sturgeon (age-0 and presumably age-1) have been incidentally captured in the following general fish community monitoring efforts and commercial fisheries during all months of the year: the CDFW San Francisco Bay Study trawl survey (hereafter referred to as the Bay Study), which has occurred throughout the SFE since 1980; salvage at the federal and state Delta pumping facilities; the USFWS Delta Juvenile Fish Monitoring Program; the San Francisco Bay herring gillnet fishery (M. Holm, 2016, personal communication, see "Notes"); and the San Francisco Bay shrimp trawl fishery (juvenile Acipenseridae, not identified to species). Larger juveniles are periodically captured in the following sampling studies targeting sturgeon: CDFW Sturgeon Population Study (hereafter referred to as the Sturgeon Study) trammel netting in San Pablo Bay and Suisun Bay (hyperlink to annual CDFW study summary in "Notes"); Sturgeon Fishing Report Card capture records from throughout the SFE (hyperlink to annual CDFW study summary, 2017, in "Notes"); and the historical CDFW juvenile sturgeon set-line study in the SFE (Dubois et al. 2010).

Thomas and Klimley (2015) reported juvenile sDPS green sturgeon movement in the SFE in a study that involved capturing larval green sturgeon at RBDD, rearing the fish in the laboratory for several months, and releasing those fish as tagged juveniles to the Delta. The tagged juveniles showed a broad range of movement patterns, from remaining in the Delta for several months to entering the ocean within a few months of release (Thomas and Klimley 2015). Results from Thomas and Klimley (2015) suggest that some individuals in the sDPS may enter the ocean and transition to the subadult life stage in their first year.

Juvenile growth in the nDPS is rapid as they move downstream, reaching up to 300-mm TL in the first year and more than 600-mm TL in years 2 and 3 (Nakamoto et al. 1995). Juveniles in the sDPS may grow considerably faster, with some having reached approximately 300-mm TL in 6 months or less (W. Poytress, USFWS, 2015b, 2017b, unpublished data, see "Notes"). Northern DPS juveniles tested under laboratory conditions have optimal bioenergetic performance (growth, metabolic rate, temperature preference, and swimming performance) at 15 to 19°C (Mayfield and Cech 2004) and are highly tolerant to changes in salinity during their first 6 months (Allen et al. 2011). Although green sturgeon have the ability to enter seawater well before 1 year of age (Allen et al. 2011), the typical length of fish encountered in the ocean (greater than 600 mm TL) suggests ocean entry occurs at a later age. However, length distributions of green sturgeon captured in the ocean may be biased high because most of those records are from commercial fisheries targeting relatively large fish species.

A pilot effort is underway by the UCD Biotelemetry Laboratory and CDFW to implant acoustic transmitters in juvenile green and white sturgeon captured in the Sacramento River and

Delta. Results from this study are likely to improve understanding of juvenile sturgeon habitat use in the SFE. California fishing regulations since 2007 have required sturgeon anglers to complete a Sturgeon Fishing Report Card, and juvenile green sturgeon capture date and length have been reported by this program. A preliminary recruitment time series by CDFW—using lengths of juvenile sDPS green sturgeon and nDPS age-length data—suggests recruitment was highest in the two most recent wet years[2] (M. Gingras, CDFW, 2016, unpublished data, see "Notes"). The recent implementation of the Sturgeon Fishing Report Card and refinement of age-length keys also provide managers with an early qualitative indicator of recruitment or cohort success using reported lengths of juvenile sDPS green sturgeon and records in the Sturgeon Study.

From scant collections of small sDPS green sturgeon in the Bay Study, nearly all recruitment appears to have occurred in wet years (M. Gingras, CDFW, 2016, unpublished data, see "Notes"). Furthermore, at federal and state Delta pumping facilities the highest juvenile green sturgeon collection on record and the highest estimated salvage since 1985 occurred in a wet year (2006; Gartz 2007). Based on lengths of salvaged green sturgeon reported in Gartz (2007), it is likely that the majority of juveniles salvaged in 2006 hatched in the same year. All of those findings are consistent with white sturgeon and the relationship between recruitment to age-0 and wet years (CDFG 1992; Fish 2010).

Juvenile green sturgeon entrainment in the presence of unscreened water diversions (Mussen et al. 2014) and diversions with fish protection devices (Poletto et al. 2014a, 2014b, 2015) have been studied extensively in the laboratory. These studies suggest juvenile green sturgeon are at high risk of entrainment in unscreened diversions and impingement on screened diversions. Furthermore, Vogel (2013) captured four green sturgeon and one white sturgeon during evaluation of fish entrainment at 12 unscreened diversions in the middle Sacramento River. Verhille et al. (2014) reported larval and juvenile green sturgeon swimming performance and flow velocity recommendations for diversions by life stage; however, fish screen design criteria specifically for larval sturgeon have not been developed.

Juvenile white sturgeon. The typical white sturgeon life history does not involve extensive marine migration, and an obvious limit to the juvenile life stage (e.g., first ocean entry in sDPS green sturgeon) is not known for the species. Chapman et al. (1996) estimated 75- and 95-centimeter (cm) FL as minimum sizes of maturity for male and female white sturgeon, respectively. Based on this estimate, 75-cm FL was selected as the upper size limit of the juvenile life stage.

Juvenile white sturgeon are believed to initiate a secondary dispersal (the primary dispersal occurring at the larval stage) in spring by actively swimming downstream during the night (Kynard and Parker 2005). Dispersal duration is unknown, but observed swimming intensity and duration in laboratory studies indicate dispersal likely lasts several days and over many kilometers (Kynard and Parker 2005).

---

[2] This refers to juveniles from brood years 2006 and 2011. At the time of writing, juvenile samples from brood year 2016 have not been analyzed.

Radtke (1966) indicated that juvenile white sturgeon are found in the Sacramento River and Delta, with the majority of juveniles captured in the Sacramento River. Numerous juvenile and larval white sturgeon have been sampled from the lower San Joaquin River, but those fish are presumed to have entered the system from the Sacramento River through the lower Mokelumne River, Georgiana Slough, or Three Mile Slough (Stevens and Miller 1970). However, spawning has been documented in the San Joaquin River, such that small juvenile white sturgeon collected in San Joaquin River spawning areas (upstream of the Delta) are almost certainly of San Joaquin River origin.

Small juvenile white sturgeon are collected sporadically in various tributaries of the SFE, and the following are some notable examples: one juvenile white sturgeon was captured in a rotary screw trap on the lower Mokelumne River over the past 15 years of monitoring (Workman 2003); one juvenile white sturgeon (possibly two) was detected in the Feather River about 2- to 3-km downstream of Thermalito Afterbay Outlet in May 2000 (Schaffter and Kohlhorst 2001); juvenile white sturgeon have been sampled in the Yolo Bypass during fisheries surveys (B. Schreier, DWR, 2015, personal communication, see “Notes”); and one juvenile white sturgeon was captured in a rotary screw trap located in the American River during February 2015 (C. McKibbin, CDFW, 2015, personal communication, see “Notes”). Juvenile white sturgeon are typically salvaged in low numbers at the federal and state Delta pumping facilities, but a relationship between salvage numbers at the state facility and year-class abundance is lacking (Gingras et al. 2013).

Managers have an early indication of cohort strength and can relate general environmental conditions associated with cohort success. The only index of age-0 production comes from general fish community sampling throughout the SFE in the Bay Study and the index is typically influenced heavily by catch in the lower Sacramento River in the Rio Vista area before May. Indices of recruitment, or year-class index (YCI) have been generated by otter trawl catch of age-0 and age-1 white sturgeon in the Bay Study since 1980. Recruitment trends in the YCI are supported by back-calculation of recruitment with direct or assigned estimates of age (e.g., age analysis of pectoral fin rays or use of age-length keys) from collections of white sturgeon by various monitoring studies. CDFW and USFWS continue to develop those recruitment-modeling techniques by refining estimates of age at length, gear selectivity, and mortality rates.

A positive relationship between high outflow and white sturgeon recruitment in the SFE is supported by juvenile surveys (CDFG 1992; Fish 2010) and hind-cast estimates of relative brood-year abundance from adult monitoring studies (Shirley 1987; M. Gingras, CDFW, 2015a, unpublished data, see “Notes”). Recent investigations show a Delta outflow-recruitment threshold at about 1,416 cubic meters per second (m^3/s; 50,000 cubic feet per second), such that the juvenile YCI is generally strong when flows are above that level (Fish 2010). Cohort abundance information since 1938 shows a boom-and-bust pattern that appears to be related to those high outflow periods (Shirley 1987; CDFG 1992; Fish 2010). Large white sturgeon cohorts have only been detected twice in the last 20 years—in 1998 and 2006—and both years were classified as wet (CDFW, 2016b, unpublished data, see "Notes"). It should be noted, however, that the primary white sturgeon recruitment survey (Bay Study) was incomplete in 2016 and 2017; indexes have not been generated since 2015.

Small juvenile white sturgeon are likely preyed upon by a variety of native and invasive piscivores (Hildebrand et al. 2016). A mark-recapture study involving small juvenile hatchery white sturgeon (approximately 200 mm FL) was recently conducted to estimate the efficiency of louvers intended to prevent entrainment of fish at the Tracy Fish Collection Facility (Karp and Bridges 2015). Karp and Bridges (2015) found white sturgeon in the stomachs of striped bass collected at the facility during this study. The application of an underwater noise device increased recapture of white sturgeon and louver efficiency estimates from 32.2% to 74.0%, and the increases were attributed to a disruption in predation (Karp and Bridges 2015).

Poor water quality and consumption of contaminated prey species in the SFE watershed may affect juvenile white sturgeon growth and survival. For example, juvenile white sturgeon grew quickly in laboratory studies with ample food at 20 and 25°C but growth was negatively affected by reductions in dissolved oxygen (DO) at all temperature treatments (15, 20, and 25°C; Cech et al. 1984). In laboratory studies, juvenile white sturgeon were able to tolerate abrupt transfer from freshwater (0-ppt salinity) to 15-ppt-salinity water for up to 5 days but experienced high mortality rates in abrupt transfers from freshwater to 25-ppt and 35-ppt-salinity water (McEnroe and Cech 1985; Amiri et al. 2009). Methyl mercury and selenomethionine (two ubiquitous contaminants in the SFE) added to food of juvenile white sturgeon reduced growth and increased mortality (Lee et al. 2011; De Riu et al. 2014). Furthermore, juvenile white sturgeon mortality increased in salinities of 15 to 20 ppt when they were previously exposed to dietary selenium (Tashjian et al. 2007).

Size rather than age appears to provide an osmoregulatory advantage (Amiri et al. 2009), such that larger juvenile white sturgeon are more common in brackish estuarine areas. White sturgeon sampled in CDFW setline surveys in Suisun and San Pablo bays had an average length of 86-cm TL (DuBois et al. 2010). Larger juvenile white sturgeon are also presumed to become more piscivorous, and are known to consume herring (*Clupea harengus pallasi*) and their eggs, American shad (*Alosa sapidissima*), starry flounder (*Platichthys stellatus*), and unidentified gobies (Radtke 1966; McKechnie and Fenner 1971).

Ocean Migration and Maturity

Subadult and adult green sturgeon. The subadult life stage begins at the first entry to the Pacific Ocean and extends to sexual maturation. Adults are mature fish that are not engaged in spawning or spawning migratory behavior. Subadults and adults inhabit marine and estuarine waters along the west coast of North America from Baja California (Rosales-Casian and Almeda-Juaregui 2009) to the Bering Sea (Colway and Stevenson 2007). When not in rivers for spawning, adults and subadults migrate seasonally along the coast and congregate at specific sites in nearshore marine waters (Lindley et al. 2008; Lindley et al. 2011). Subadults and adults enter estuaries and bays during early spring to summer months (presumably for feeding; Dumbauld et al. 2008) and return to the ocean during summer and fall (Moser and Lindley 2007;

Lindley et al. 2011). Southern DPS green sturgeon concurrently occupy several estuaries along the west coast during summer and fall months, primarily San Francisco Bay, Willapa Bay, Grays Harbor, and the Columbia River Estuary. The lack of angler reports or acoustic detection of tagged subadult-sized fish (roughly 60- to 100-cm TL) upstream of the Delta suggest subadults do not use freshwater riverine habitats.

Only a small number (typically, less than 100) of sDPS subadult and adult green sturgeon are collected annually in all monitoring studies in California, and consistent capture occurs only in the long-term (more than 40 years) Sturgeon Study. Data from the Sturgeon Study have been occasionally used to estimate sDPS abundance, but estimates have been imprecise because surveys and associated analyses are primarily designed to study white sturgeon, and because the mark and recapture rates of sDPS green sturgeon has typically been low. Catch of subadult and adult sturgeon is reported by recreational anglers in the SFE and tributaries through the Sturgeon Fishing Report Card program. Some reporting also occurs in the lower Columbia River and bays of Oregon and Washington. Creel surveys of California recreational fisheries and commercial passenger fishing vessels report sturgeon catch; however, prior to 2011, that catch was rarely identified to species. Thus, it is difficult to generate fishery-dependent sDPS green sturgeon harvest and abundance estimates in the SFE from those data beyond applying a rough assumption of the percentage of sDPS green sturgeon in the overall sturgeon population. A major challenge in estimating abundance and overall harvest of sDPS green sturgeon has been mixed aggregations of nDPS and sDPS green sturgeon in Oregon and Washington estuaries and historical harvest in commercial and recreational fisheries in those estuaries.

The Oregon Department of Fish and Wildlife (ODFW) and Washington Department of Fish and Wildlife (WDFW) conducted a large-scale (approximately 1,500 green sturgeon tagged) mark-recapture study to estimate the population size of subadult and adult green sturgeon (described in NMFS 2015). That study generated a wide range of population estimates for adult and subadult green sturgeon (approximately 4,000 to 65,000 fish) in Oregon and Washington estuaries; the authors of that study concluded that an estimate of 40,000 fish was reasonable (NMFS 2015). Genetic analysis by Schreier et al. (2016) revealed 60% of sturgeon tissues collected in this study were from sDPS green sturgeon. Using estimates of annual run-size and spawning periodicity, Mora (2016) estimated the number of sDPS adults to be 1,990 (95% confidence interval [CI] is equivalent to 1,172 to 2,808 adults). Mora (2016) also applied a conceptual demographic structure to that adult population estimate and estimated a sDPS subadult population of 10,450 (95% CI is equivalent to 6,155 to 14,745). The population dynamics inferred in these studies—along with relatively low collection numbers of green sturgeon in SFE surveys—suggest the majority of the sDPS subadult and adult population occupies non-natal estuaries during summer months.

Sport and commercial harvest of green sturgeon has been prohibited since 2006, but past harvest of green sturgeon in California, Washington, and Oregon may have had a significant effect on sDPS green sturgeon abundance (Figure 1). Green sturgeon commercial harvest in the Columbia River Estuary over the last 20 years of record (1983 to 2002) averaged approximately

1,850 individuals per year (ODFW and WDFW 2002). Based on the distinct population segment composition study of green sturgeon in the Columbia River Estuary described in Schreier et al. (2016), the average annual harvest of sDPS green sturgeon in the Columbia River Estuary during this period was more than 1,100 individuals. It is highly plausible that the harvest of subadult and adult sDPS green sturgeon in other commercial and sport fisheries equaled or exceeded harvest in the Columbia River Estuary over this period. The USFWS (1996) estimated the total harvest of adult green sturgeon in Oregon and Washington fisheries at 5,000 to 10,000 individuals per year. The abundance of subadult and adult sDPS green sturgeon prior to Endangered Species Act listing is unknown, but if abundance has remained relatively stable (e.g., 12,440 individuals; Mora 2016), past harvest involved a large portion of the population in some years.

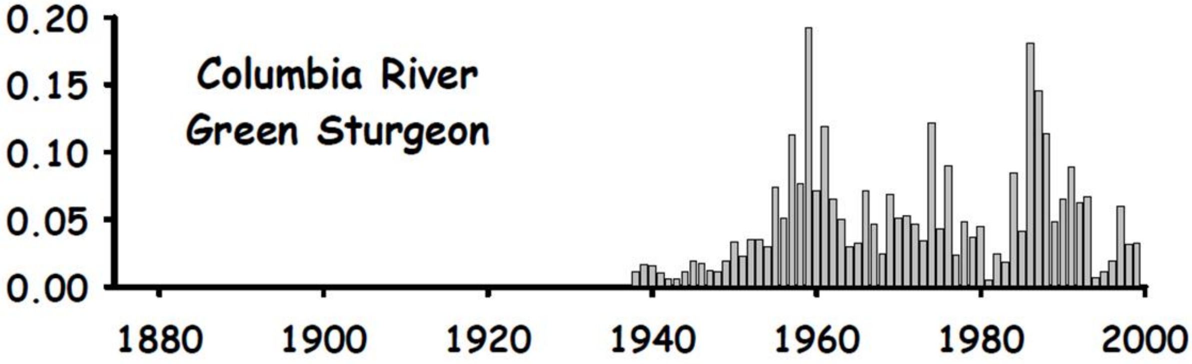


Figure 1. Historical yield of green sturgeon in Columbia River commercial fisheries in millions of pounds from Beamesdorfer et al. (2005).

Green sturgeon have been detected in a relatively narrow range of depths and temperatures while in the marine coastal environment. Adults and subadults were typically detected in depths from 20 to 70 m and temperatures from 7.3 to 16.0°C by Erickson and Hightower (2007) and Huff et al. (2011). In the estuarine environment, green sturgeon are exposed to varying water temperature, salinity, and DO. For example, green sturgeon in coastal estuaries have been detected in water temperatures ranging 11.9 to 21.9°C, salinities ranging from 8.8 to 32.1 ppt, and DO ranging from 6.54 to 8.98 milligrams of oxygen per liter (Kelly et al. 2007; Moser and Lindley 2007).

Limited numbers of green sturgeon have been encountered recently in white sturgeon stock assessments in the lower Columbia River, and recapture data from the Oregon and Washington estuary study described above have not been analyzed beyond 2012 due to poor recovery of tagged fish (O. Langness, WDFW, 2015, unpublished data, see "Notes"). Several studies have involved tagging subadult and adult fish with acoustic transmitters, but most tags were implanted before 2012 and will stop transmitting when they exceed the 5- to 10-year battery life. Movement by tagged fish in the SFE and Washington estuaries is monitored with receiver arrays maintained by the UCD Biotelemetry Laboratory and NMFS, respectively, while nearshore marine areas are monitored with compatible receiver arrays associated with other groups. Subadult and adult nDPS and sDPS green sturgeon are occasionally reported as bycatch in federally managed ground fisheries (Lee et al. 2015; Anderson et al. 2017). The number of sDPS green sturgeon observed in the California halibut fishery (primarily sDPS) exceeded 100 individuals in 2006 and 2015 (Lee et al. 2015; NMFS, 2016, unpublished data, see "Notes") and the only targeted monitoring of subadults and adults in the ocean involves this fishery. Some sDPS green sturgeon caught incidentally by the California halibut fishery operating out of Half Moon Bay and San Francisco since 2015 have been tagged with satellite transponders. This program aims to understand post-release mortality, but also can provide information on movement for up to three weeks after release.

Adult white sturgeon. Tagging studies show that when not migrating, adult white sturgeon are usually found in brackish and estuarine habitat (Kohlhorst et al. 1991; Gleason et al. 2008), including most tidal tributaries to the SFE (Leidy 2007). Several observations of long-distance marine migrations suggest coastal habitats may also be utilized to some degree by those older life stages (Kohlhorst et al. 1991; DeVore et al. 1999; Welch et al. 2006; Ruiz-Campos et al. 2011; E. Miller, UCD Biotelemetry Laboratory, 2017, unpublished data, see "Notes"). For example, white sturgeon tagged in the SFE have been recaptured in the Columbia River, Chehalis River, and Willapa Bay, Washington, as well as the Umpqua River, Yaquina River, and Tillamook Bay, Oregon (Kohlhorst et al. 1991). Furthermore, one adult white sturgeon tagged in the Klamath River entered the ocean and traveled approximately 1,000 km north to be recaptured in the Fraser River (Welch et al. 2006), and an adult white sturgeon was caught by gillnet near Todos Santos Bay in Baja California (Ruiz-Campos et al. 2011).

Daily and seasonal movement of adult white sturgeon may be influenced by salinity and tides. Kohlhorst et al. (1991) found that white sturgeon followed brackish waters upstream in dry years and remained downstream in the SFE in wet years. Foraging movements of white sturgeon in the Columbia River Estuary were also influenced by diel cycles and salinity changes associated with tides (Parsley et al. 2008).

Growth rates of Sacramento-San Joaquin River adult white sturgeon have been estimated by Pycha (1956) and Kohlhorst et al. (1980) by counting annuli in pectoral fin ray sections and fitting von Bertalanffy growth models to the resulting age-length data. The age-length relationship differs between the two studies, with higher apparent growth rates—particularly for older white sturgeon—in the Pycha (1956) study. It is uncertain whether this discrepancy reflects a biological change in growth rate over time or a reflection of the high degree of uncertainty attributable to use of this ageing technique (Rien and Beamesderfer 1994). Growth rates of male and female white sturgeon from the SFE do not appear to be significantly different (Kohlhorst et al. 1980), but a study by Chapman et al. (1996) noted that the smaller individuals they sampled tended to be males while the sex ratio in their sample of larger individuals was skewed towards females.

Sediments in the SFE are heavily contaminated with a variety of toxins. Much of the research on contaminants and fish in the SFE has focused on selenium and mercury, but a suite of other toxins are also present at high levels in sediment throughout the estuary. Some of the highest levels of toxic trace metals in the coastal United States were recorded in SFE (Cloern et al. 2006). As long-lived, bottom-feeding fish that spend the majority of their lives in the SFE, white sturgeon are highly susceptible to bioaccumulation of those contaminants. Tissues were analyzed from recently sampled adult white sturgeon in the SFE, and selenium and mercury were measured at levels known to impair condition factor (Gundersen et al. 2017). Gundersen et al. (2017) correlated organic contaminant and selenium levels in SFE white sturgeon with altered liver and gonad physiology and plasma hormone levels. Selenium levels in SFE white sturgeon appear to be a longstanding issue. High concentrations of selenium were found in white sturgeon tissue sampled in the SFE from 1970 to 2000 (Greenfield et al. 2003).

Available benthic food items in the SFE have changed in the recent past, and invasive invertebrates have replaced native mollusks and shrimps (Cohen and Carlton 1998). High levels of selenium have been found in common white sturgeon food items (Johns and Luoma 1988; White et al. 1988). Zeug et al. (2014) documented a predominance of invasive overbite clams (*Potamocorbula amurensis*)—a potential vector of bioaccumulation of toxic contaminants—in white sturgeon diets in the SFE. Sturgeon consume, but do not always digest, large quantities of the invasive overbite clam (Kogut 2008; Zeug et al. 2014); consuming indigestible clams may impair digestion of other items and affect sturgeon growth. Furthermore, bivalves have potentially higher levels of contaminants than other prey items in the SFE, and digested overbite clams may be a source of internal exposure to contaminants.

The recreational harvest of white sturgeon in California has remained relatively high in spite of a diminished population, such that monitoring of recreational capture and harvest is a primary management priority. Advances in recreational fishing techniques (e.g., use of shrimp as bait) since 1964 resulted in a rapid reduction in an initially large white sturgeon population (due to harvest prohibitions in the first half of 20th century) and continuous depletion of the few strong subsequent year classes. This is illustrated by commercial passenger fishing vessel log books data summarized by the Sturgeon Study, which shows a severe decline in catch and catch-per-unit effort (CPUE) during the first decade that shrimp were widely used as sturgeon bait (CDFW, 2016e, unpublished data, see "Notes"). This time series also shows a distinct increase in catch and CPUE in the early 1990s attributable to recruitment of the large, early-1980s year classes.

Actual harvest data along with estimates of harvest rate suggest that white sturgeon populations in the SFE may be limited in-part by overfishing. These data are generated by the use of an age-length key, Sturgeon Fishing Report Card data, and mark-recapture data (reward tags) by the Sturgeon Study. Based on ongoing study of age at length, white sturgeon aged 13 to 15 years fall mainly within the current slot limit of 40 to 60 inches FL. Thus, strong mid- to late-1990s year classes were heavily fished over the last 10 years and reduced to a population of fewer than 20,000 fish (Gingras et al. 2014). As part of the Sturgeon Study, reward tags with multiple values are applied to adult white sturgeon. Disproportionately high redemption of $100 tags relative to $20 tags and $50 tags indicates that much of the sturgeon harvest in the SFE goes unreported such that abundance estimates have likely been biased high.

Predation by native species on sub-adult and adult white sturgeon is not well documented. The CDFW has noted an increase in the incidence of California sea lions taking white sturgeon from trammel nets in the annual Sturgeon Study and the occasional presence of damaged or dead white sturgeon from apparent predation by California sea lions. Predation by marine mammals is a significant issue in the Columbia River. The estimated consumption of white sturgeon by pinnipeds in the Bonneville Dam tailrace ranged from approximately 150 to 3,000 individuals annually between 2006 and 2014 (Stansell et al. 2012, 2013, 2014).

Spawning

Spawning green sturgeon. Adults mature at about age 15 and spawn during spring and summer every 2 to 6 years thereafter (NMFS 2015). The putative spawning reach on the Sacramento River extends from above the GCID oxbow to the confluence of the Sacramento River and Cow Creek (Heublein et al. 2009; Klimley et al. 2015). Only two spawning events have been documented outside of the Sacramento River (2011 and 2017) and both occurred in the Feather River (Fish Barrier Dam and the Thermalito Outlet). The Sunset Pumps Weir (33-km downstream of Thermalito Outlet) limits sturgeon passage in certain flows. Modifications of the Sunset Pumps Weir are being designed in hopes that their implementation would improve migration conditions for sturgeon. There are also periodic reports of adult green sturgeon at the base of Daguerre Point Dam on the Yuba River (a tributary to the Feather River), but spawning in the Yuba River has never been documented.

Green sturgeon enter the Sacramento River from late winter through early summer to spawn. Stranding of green sturgeon at migration barriers in the Yolo and Sutter bypasses has only been documented in spring 2011, 2016, and 2017 (wet years). Stranding in 2011 involved at least 24 adults at stilling basins below the Yolo and Sutter Bypass Weirs (Fremont and Tisdale Weirs; Thomas et al. 2013). Entrainment and stranding of adult white sturgeon and salmonids in bypasses is fairly common when bypasses flood, but it is uncertain how bypass channels (e.g., Toe Drain, Tule Canal) affect sturgeon spawning migration during low-flow years. Gravid adult white sturgeon are collected in the Toe Drain in low-flow years when passage barriers prevent access to spawning habitat (DWR 2015). In this regard, route selection may affect inter-annual spawning success as adult sturgeon entrained in bypass channels may not reach spawning habitat within an appropriate time. Records of catch in migratory and spawning habitats are collected through CDFW creel surveys (i.e., Central Valley Angler Survey, California Recreational Fisheries Survey), Sturgeon Fishing Report Cards, and state-mandated commercial passenger fishing vessel log books. A small number of post-spawn fish are periodically collected in San Pablo and Suisun bays during late summer and early fall by the Sturgeon Study.

With the exception of small-scale tagging in the Feather River and at bypass weirs, there is no program tagging adult green sturgeon for acoustic telemetry in the Sacramento River system. An acoustic receiver network is in place throughout the California Central Valley and SFE that is operated and maintained by the UCD Biotelemetry Laboratory along with state and federal agencies. Tagged adults have been detected in spawning habitat in the Sacramento River since 2004, and the majority were tagged outside of California in Pacific Northwest coastal estuaries. Detections in this array provide information on migration timing and routes, spawning distribution and periodicity, and model inputs for run-size estimates from DIDSON surveys. Efforts are also underway by USFWS, UCD Biotelemetry Laboratory, and NMFS to map habitat in spawning and adult aggregation sites on the Sacramento River. The DWR monitors adult sturgeon in the Feather River, in part through telemetry that began in 2011 and DIDSON surveys that began in 2010. VEMCO VR2 acoustic receivers have been in place throughout the Feather River since 2008 and have detected approximately 15 green sturgeon that were tagged outside the Feather River (primarily in 2017; M. Manuel, PSMFC, 2017, personal communication, see "Notes").

DIDSON survey and telemetry data have been used to estimate green sturgeon run-size in the Sacramento River since 2010 (Mora 2016). Data and modeling from those surveys has greatly improved understanding of adult abundance. However, due to late maturation and variability in maturation age and spawning periodicity, it is challenging to relate trends in green sturgeon run-size to historical conditions that may have affected specific cohorts. Unlike with shorter-lived semelparous species, trends in spawner abundance and historical conditions associated with early life stage success—conditions that may have occurred decades before the observed trend—are intractable without accurate abundance modeling and ageing.

During seasonal RBDD gate closures before 2012, biologists periodically observed aggregations of adult green sturgeon directly below the gates in the spring and early summer. Spawning in this area has been verified several times by the collection of eggs (Poytress et al. 2015). Historical gate operations presumably influenced downstream hydrology, spawning, and holding at RBDD because aggregations have not been observed there since 2012. Although this spawning site was lost when gates were permanently raised in 2012, a new spawning site in an area historically inundated by the impoundment above RBDD was documented with the collection of eggs in RBDD rotary screw traps in 2016 and 2017 (W. Poytress, USFWS, 2017a, unpublished data, see "Notes").

The permanent raising of RBDD gates has the potential to affect multiple life stages of green sturgeon. Historically, adult green sturgeon arriving to RBDD after gate closure were relegated to a warmer reach of the Sacramento River for spawning. In extreme low flows, spawning areas below RBDD may be unsuitable for green sturgeon spawning in early summer. However, temperature above RBDD was suitable for spawning in early summer even in the recent historic drought. Thus, raising the gates at RBDD expanded the accessible spawning range for green sturgeon and—in what may be a key element of green sturgeon life history diversity—facilitated temporal and spatial variation in spawning distribution (A. Steel et al., UCD Biotelemetry Laboratory, 2017, unpublished data, see "Notes"). Furthermore, multiple dead adult green sturgeon have been documented below RBDD after gate closure. Those mortalities were attributed to injuries sustained during attempted downstream migration through a narrow opening below the closed RBDD gates. With gates permanently raised, that source of mortality no longer exists. Finally, the diversion facility at RBDD was recently upgraded. Although sturgeon entrainment at the RBDD facility has not been directly studied, entrainment risk for larval green sturgeon has presumably been reduced by both raising dam gates and potentially improved hydraulics associated with modern fish screens.

After spawning, green sturgeon hold in-river for varying periods of time but most commonly leave the system the following fall (Benson et al. 2007; Heublein et al. 2009). Early outmigration in late spring or summer may be related to elevated flows (Benson et al. 2007; Heublein et al. 2009). For adults that over-summer in spawning or holding habitats, outmigration occurs in the late fall or (rarely) in winter after spending more than a year in freshwater (R. Chase, USACE, 2015, unpublished data, see "Notes"). Extended occupancy of those spawning and holding habitats may be related to hydrologic cues or food availability, but it is uncertain why occupancy sometimes lasts more than a year. Normal outmigration patterns for adults in the Feather River are unknown because of flow management and the passage barrier at Sunset Pumps Weir. However, the behavior of tagged fish in the Feather River suggests that adult outmigration there is similar to adult outmigration in the Sacramento River (i.e., both spring and summer outmigration and over-summer holding behavior; DWR, 2017b, unpublished data, see "Notes").

Post-spawn outmigration through the SFE is also variable. Adults have been detected migrating to the Pacific Ocean rather quickly (2 to 10 days) and remaining in the SFE for a number of months after leaving upstream holding habitats (R. Chase, USACE, 2015, unpublished data, see "Notes"). Movement between river habitat and the SFE has only been related to spawning, and adults do not appear to migrate upstream from the SFE to forage (R. Chase, USACE, 2015, unpublished data, see "Notes").

Spawning white sturgeon. Chapman et al. (1996) estimated that SFE white sturgeon females reach maturity at 95- to 135-cm FL and white sturgeon males reach maturity at 75- to 105-cm FL. The smallest sexually mature female described in the SFE watershed was 104-cm FL (Chapman et al. 1996) and was estimated to be 9 years old using the von Bertalanffy growth equation from Brennan and Cailliet (1989). Female white sturgeon in the SFE are estimated to first spawn between 10 and 30 years old, and spawn every 2 to 4 years thereafter (Chapman et al. 1996).

White sturgeon in the SFE spawn in freshwater between mid-February and early June (Miller 1972; Kohlhorst 1976; Schaffter 1997; Jackson et al. 2016). Based on recent acoustic detections of tagged adults, white sturgeon may stage in the Delta or begin upstream migration to spawning habitat in fall or early winter (DWR 2015; Klimley et al. 2015). Spawning is known to occur in the San Joaquin River, the Sacramento River, some Sacramento River tributaries, and some watersheds on the northern California coast (Miller 1972; Kohlhorst 1976; Schaffter 1997; Jackson et al. 2016). However, long-term monitoring of adult and juvenile distribution indicates that most SFE white sturgeon originate from the Sacramento River. Spawning locations on the Sacramento River currently appear to be located from Colusa to the Verona area (Kohlhorst 1976; Schaffter 1997), although spawning likely occurs many kilometers upriver in some years (described above in the Fertilization to Hatch section). A relic population of white sturgeon persisted in Shasta Reservoir following construction of Shasta Dam (1940 to 1945), suggesting historical spawning in upper Sacramento River tributaries such as the Pit River (Schaffter 1997; Moyle 2002). However, historical stocking records for sturgeon are poor, so it is unclear if white sturgeon in Shasta Reservoir were entirely of natural origin. Periodic aggregations of gravid white sturgeon and telemetry data in the Yolo Bypass and Bear River indicate spawning may extend to those areas in some years.

Fishery-independent monitoring of white sturgeon has occurred since the early 1950s and has persisted at low intensity until it became a CDFW emphasis in 2006 with Federal Endangered Species Act listing of sDPS green sturgeon. Adult white sturgeon abundance, relative abundance, harvest rate, and survival rate are estimated annually in the Sturgeon Study, which uses data from commercial passenger fishing vessels, various creel surveys, and mark-recapture data from annual trammel net sampling in San Pablo Bay and Suisun Bay. Based on those data, trends in adult white sturgeon abundance and juvenile recruitment have been developed. However, current life stage monitoring is insufficient to develop mechanisms for episodic recruitment success or to address bias in abundance estimates and harvest rates associated with angler reporting.

Some directed sampling or incidental capture of adult white sturgeon occurs in spawning and migratory habitats. This includes sampling with fyke traps in the Yolo Bypass and Sacramento River, stranding at bypass weirs, and gill and trammel netting in San Joaquin River spawning habitat. Recapture of externally tagged fish (tagged in the Sturgeon Study) by the recreational fishery and data from Sturgeon Fishing Report Cards include information on sturgeon in migratory and spawning habitat. Other information on spawning adult behavior comes primarily from telemetry studies conducted by multiple groups (e.g., UCD, DWR, USFWS) throughout the SFE and spawning tributaries. Tissue from recreational harvest of white sturgeon (40- to 60-inches FL) in SFE fishing derbies was also analyzed in a recent directed study of contaminants (Gundersen et al. 2017).

Migration barriers and stranding have been documented in the Yolo Bypass, Sutter Bypass, and Bear River since the mid-1980s. Those stranding events were associated with poaching and intensive legal harvest that has since been prohibited. The most recent documented events occurred in spring 2011, 2016, and 2017 (wet years) and involved stranding of adult green and white sturgeon in stilling basins below the Fremont and Tisdale Bypass Weirs. It is uncertain how bypass channels affect sturgeon spawning migration and success during low-flow years. For example, adult white sturgeon were captured in relatively high numbers from 2012 to 2014 (dry years) in a fyke trap deployed in the Yolo Bypass Toe Drain (DWR 2015). Delays in upstream sturgeon migration due to the complexity in fish passage at various bypass barriers (e.g., Lisbon and Fremont Weirs) may reduce spawning success. Stranding of adult white sturgeon in the Bear River may occur in normal or dry years. The last documented stranding event on the Bear River was in spring 2012, the first year of the recent drought. Winter and spring flow and water surface elevation on the Bear River can be highly variable even in relatively dry years. These flashy hydrograph conditions are thought to attract spawning white sturgeon to the Bear River, then subject those fish to high stranding risk.

The direct effects of consumption of contaminated prey species are briefly described above, but white sturgeon egg and larval survival may also be impacted through maternal transfer of contaminants. Exposure of gravid female white sturgeon to a diet enriched in selenium resulted in selenium incorporation to plasma vitellogenin and egg yolk proteins (Doroshov et al. 2007). Selenium has been measured in liver and gonad tissues of white sturgeon collected in the SFE at levels known to cause reproductive toxicity (Linares-Casanave et al. 2015) and exceeded concentrations associated with severe deformity and high mortality in the egg yolks of larvae (15 milligrams per gram; Doroshov et al. 2007).

Increasing streamflow is believed to be an important cue for migration and spawning of white sturgeon across their range (Schaffter 1997; Hildebrand et al. 1999; Paragamian and Wakkinen 2011; Jackson et al. 2016). During a drought year, Schaffter (1997) documented white sturgeon spawning in the Sacramento River following 40 m^3/s increases in streamflow, which would correspond to an increase in outflow or runoff of approximately 3,456,000 m^3 or 2,800 acre-feet per day. Similarly, white sturgeon spawning was observed at all four San Joaquin River sampling locations following short-duration streamflow pulses (approximately 18 to 40 m^3/s) during otherwise low streamflow conditions in 2012 (Jackson et al. 2016) and again in 2016 (Z. Jackson, USFWS, 2017, unpublished data, see "Notes").

There is little quantitative information on spawning site habitat requirements. In the Sacramento and San Joaquin watersheds, white sturgeon spawning habitat has substrate ranging from silt-and-sand to gravel-and-cobble and water velocities ranging from low to high (Kohlhorst 1976; Schaffter 1997; Jackson et al. 2016). As indicated by the presence of eggs or larvae, white sturgeon have been observed to spawn at water temperatures of 8 to 23°C, with peak spawning occurring around 14°C (8 to 19°C, peak 14°C, Moyle 2002; 7.8 to 17.8°C, peak 14.4°C, Kohlhorst 1976; and 12 to 16°C, Schaffter 1997). Spawning in the San Joaquin River has occurred at higher temperatures (14.2 to 26.7°C, Jackson et al. 2016), although viability of larvae at the upper end of this range is unlikely. White sturgeon in the SFE typically return promptly to the estuary after spawning. However, adult holding through summer in freshwater spawning habitat has been documented on the Sacramento and San Joaquin rivers (Klimley et al. 2015; M. Manuel, PSMFC, 2016, personal communication unreferenced, see "Notes").

References

Allen, P. J., B. Hodge, I. Werner, and J. J. Cech. 2006. Effects of ontogeny, season, and temperature on the swimming performance of juvenile green sturgeon (*Acipenser medirostris*). Canadian Journal of Fisheries and Aquatic Sciences 63(6):1360-1369.

Allen, P. J., M. Nicholl, S. Cole, A. Vlazny, and J. J. Cech. 2006b. Growth of larval to juvenile green sturgeon in elevated temperature regimes. Trans Am Fish Soc 135:89-96.

Allen, P. J., M. McEnroe, T. Forostyan, S. Cole, M. M. Nicholl, B. Hodge, and J. J. Cech. 2011. Ontogeny of salinity tolerance and evidence for seawater-entry preparation in juvenile green sturgeon, *Acipenser medirostris*. J Comp Physiol B 181(8):1045-1062.

Amiri, M., D. W. Baker, D. Morgan, and C. J. Brauner. 2009. Size dependent early salinity tolerance in two sizes of juvenile White Sturgeon, *Acipenser transmontanus*. Aquaculture 286:121-126.

Anderson, E. C., T. C. Ng, E. D. Crandall, and J. C. Carlos. 2017. Genetic and individual assignment of tetraploid green sturgeon with SNP assay data. Conserv Genet DOI 10.1007/s10592-017-0963-5.

Beamesderfer, R. C. P., G. Kopp, D. Demko. 2005. Review of the distribution, life history and population dynamics of green sturgeon with reference to California's Central Valley. Gresham (OR): S.P. Cramer and Associates, Inc. General technical review. 39 p. Available from: http://www.fishsciences.net/reports/2005/Beamesderfer_2005_Review_of_the_distribution.pdf.

Benson, R. L., S. Turo, and B. W. J. McCovey. 2007. Migration and movement patterns of green sturgeon (*Acipenser medirostris*) in the Klamath and Trinity rivers, California, USA. Environ Biol Fishes 79:269-279.

Bergman, P. 2011. Videography monitoring of adult sturgeon in the Feather River basin, CA. Report to Anadromous Fish Restoration Program. Gresham, (OR): Cramer Fish Sciences. 22 p. Available from: https://www.fws.gov/lodi/anadromous_fish_restoration/documents/Feather_Sturgeon_Report_022811.pdf

Bergman, P.S., J. Merz, and B. Rook. 2011. Memo: Green Sturgeon Observations at Daguerre Point Dam, Yuba River, CA. Memo to Anadromous Fish Restoration Program. Gresham, (OR): Cramer Fish Sciences. 6 p. Available from: https://www.fws.gov/lodi/anadromous_fish_restoration/documents/Yuba_River_Sturgeon_Memo.pdf

Brennan, J. S., and G. M. Cailliet. 1989. Comparative age determination techniques for White Sturgeon in California. Trans Am Fish Soc 118:296-310.

Brown, K. 2007. Evidence of spawning by green sturgeon, *Acipenser medirostris*, in the upper Sacramento River, California. Environ Biol Fishes 79(3-4):297-303.

CDFG (California Department of Fish and Game). 1992. Sturgeon in relation to water development in the Sacramento-San Joaquin estuary; Entered by the California Department of Fish and Game for the State Water Resources Control Board 1992 water rights phase of the Bay-Delta Estuary proceedings. WRINT-DFG-Exhibit 28

CDFG. 2002. California Department of Fish and Game comments to NMFS regarding green sturgeon listing. Available from: http://www.swrcb.ca.gov/waterrights/water_issues/programs/bay_delta/deltaflow/docs/exhibits/nmfs/spprt_docs/nmfs_exh4_dfg_2002.pdf

Cech, J. J., S. J. Mitchell, and T. E. Wragg. 1984. Comparative growth of juvenile White Sturgeon and Striped Bass: effects of temperature and hypoxia. Estuaries 7:12-18.

Chapman, F. A., J. P. Van Eenennaam, and S. I. Doroshov. 1996. The reproductive conditions of White Sturgeon, *Acipenser transmontanus*, in San Francisco Bay, California. Fish Bull 94:628-634.

Cloern, J. E., S. N. Luoma, and F. H. Nichols. 2006. Managing Coastal Resources of the US. USGS. Available from: http://sfbay.wr.usgs.gov/general_factsheets/coastal_resources.html

Cohen, A. N., and J. T. Carlton. 1998. Accelerating Invasion Rate in a Highly Invaded Estuary. Science. 279:555-558.

Colway, C., and D. E. Stevenson. 2007. Confirmed records of two green sturgeon from the Bering Sea and Gulf of Alaska. Northwest Nat 88(3):188-192.

De Riu, N., J. W. Lee, S. S. Y. Huang, G. Moniello, and S. S. O. Hung. 2014. Effect of dietary selenomethionine on growth performance, tissue burden, and histopathology in Green and White Sturgeon. Aquat Toxicol 148:65-73.

Deng, X., J. P. Van Eenennaam, and S. I. Doroshov. 2002. Comparison of early life stages and growth of green and white sturgeon. In: Van Winkle W et al., editors. 2002. Biology, management, and protection of North American sturgeon. AFS Symposium 28:237-248.

Dettlaff, T.A., A. S. Ginsburg, and O. I. Schmalhausen. 1993. Sturgeon fishes: developmental biology and aquaculture. Springer-Verlag, New York.

DeVore, J., B. James, and R. Beamesderfer. 1999. Lower Columbia River White Sturgeon current stock status and management implications. Oregon Department of Fish and Wildlife and Washington Department of Fish and Wildlife, Olympia, Washington.

Doroshov, S. I., J. P. Van Eenennaam, J. Linares, and R. G. Linville. 2007. Potential environmental impacts on reproduction of green and white sturgeons. Oral presentation at Calfed 2007.

DuBois, J., E. Gleason, and M. Gingras. 2010. Review of juvenile sturgeon setline survey. IEP Newsletter 23(3):25-33.

Dumbauld, B. R., D. L. Holden, and O. P. Langness. 2008. Do sturgeon limit burrowing shrimp populations in Pacific Northwest estuaries? Environ Biol Fishes 83:283-296.

DWR (California Department of Water Resources). 2015. Fisheries evaluation of floodplain rearing and migration in the Yolo Bypass floodplain. Prepared by DWR Division of Environmental Services, Aquatic Ecology Section for California Department of Fish and Wildlife Ecosystem Restoration Program. January 2015. 102 p.

Erickson, D. L., and J. E. Hightower. 2007. 2007. Oceanic distribution and behavior of green sturgeon (*Acipenser medirostris*). In: Munro, J, et al., editors. 2007. Anadromous sturgeons: habitats, threats, and management. AFS Symposium 56:197-211.

Faukner, J. R., and Z. J. Jackson. 2014. 2013 San Joaquin River sturgeon spawning survey. Stockton Fish and Wildlife Office, Anadromous Fish Restoration Program, U.S. Fish and Wildlife Service, Lodi, California.

Fabrizio, M. C., and R. A. Richards. 1996. Commercial Fisheries Surveys. In: Murphy, B.R., and D. W. Willis, editors. 1996. Fisheries Techniques, Second Edition. American Fisheries Society, Maryland, U.S.A. p. 625-650.

Fish, M. A. 2010. A white sturgeon year-class index for the San Francisco estuary and its relation to delta outflow. IEP Newsletter 23(2):80-84.

Gartz, R. G. 2007. 2006 Fish Salvage at the Tracy Fish Collection Facility. March 21, 2007. California Department of Fish and Game Bay-Delta Region Fish Facilities Research and Operations Monitoring Unit 4001 North Wilson Way Stockton, CA 95205. Available from: ftp://ftp.dfg.ca.gov/salvage/Annual%20Salvage%20Reports/2006%20TFCF%20Annual%20Salvage%20Report.pdf

Gadomski, D., and M. Parsley. 2005. Effects of turbidity, light level, and cover on predation of white sturgeon larvae by prickly sculpins. Trans Am Fish Soc 134:369-374.

Gingras, M., and J. DuBois. 2013. Monitoring progress toward a CVPIA recovery objective: estimating white sturgeon abundance by age. Interagency Ecological Program for the San Francisco Estuary Newsletter 26(4):6-9.

Gingras, M., J. DuBois, and M. Fish. 2013. Further Investigations into San Francisco Estuary White Sturgeon (*Acipenser transmontanus*) Year-Class Strength. Interagency Ecological Program for the San Francisco Estuary Newsletter 26(4):10-12.

Gingras, M., J. DuBois, and M. Fish. 2014. Presentation: Impact of Water Operations and Overfishing on White Sturgeon, Interagency Ecological Program Annual Conference. 2014. California Department of Fish and Wildlife

Gisbert, E., J. J. Cech, and S. I. Doroshov. 2001. Routine metabolism of larval green sturgeon (*Acipenser medirostris*). Fish Physiology and Biochemistry 25:195-200

Gleason, E., M. Gingras, and J. DuBois. 2008. 2007 sturgeon fishing: preliminary data report. California Department of Fish and Game, Stockton, California.

Greenfield, B. K., J. A. Davis, R. Fairey, C. Roberts, D. B. Crane, G. Ichikawa, and M. Petreas. 2003. Contaminant Concentrations in Fish from San Francisco Bay, 2000. RMP Technical Report: SFEI Contribution 77. San Francisco Estuary Institute, Oakland, California.

Gundersen, D. T., J. Zachary, R. B. Bringolf, J. Merz, S. C. Zeug, and M. A. H. Web. 2017. Tissue contaminant burdens in San Francisco Estuary white sturgeon (*Acipenser transmontanus*) and dietary items: implications for population recovery. Arch Environ Contam Toxicol. DOI 10.1007/s00244-017-0378-9

Heublein, J. C., J. T. Kelly, C. E. Crocker, A. P. Klimley, and S. T. Lindley. 2009. Migration of green sturgeon, *Acipenser medirostris*, in the Sacramento River. Environ Biol Fishes 84:245-258.

Heublein, J., R. Bellmer, R. D. Chase, P. Doukakis, M. Gingras, D. Hampton, J. A. Israel, Z. J. Jackson, R. C. Johnson, O. P. Langness, S. Luis, E. Mora, M. L. Moser, L. Rohrbach, A. M. Seesholtz, and T. Sommer. 2017. Improved Fisheries Management Through Life

Stage Monitoring: the Case for the Southern Distinct Population Segment of North American Green Sturgeon and the Sacramento-San Joaquin River White Sturgeon. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-SWFSC-588.

Hildebrand, L., C. McLeod, and S. McKenzie. 1999. Status and management of white sturgeon in the Columbia River in British Columbia, Canada: an overview. J Applied Ichthyol 15:164-172.

Hildebrand, L. R., A. Drauch Schreier, K. Lepla, S. O. McAdam, J. McLellan, M. J. Parsley, V. L. Paragamian, and S. P. Young. 2016. Status of White Sturgeon (*Acipenser transmontanus*, Richardson, 1863) throughout the species range, threats to survival, and prognosis for the future. J Appl Ichthyol 32(Suppl. 1):261‑312

Huff, D. D., S. T. Lindley, P. S. Rankin, and E. A. Mora. 2011. Green sturgeon physical habitat use in the coastal Pacific Ocean. PLoS ONE 6(9):e25156. doi:10.1371/journal.pone.0025156.

Israel, J.A., K. J. Bando, E. C. Anderson, and B. May. 2009. Polyploid microsatellite data reveal stock complexity among estuarine north American green sturgeon (*Acipenser medirostris*). Can J Fish Aquat Sci 66:1491–1504. doi:10.1139/F09-091

Jackson, Z. J., J. J. Gruber, and J. P. Van Eenennaam. 2016. White sturgeon spawning in the San Joaquin River, California and effects of water management. Journal of Fish and Wildlife Management 7(1):171-180.

Johns C., and S. N. Luoma. 1988. Selenium accumulation in benthic bivalves and fine sediments of San Francisco Bay, the Sacramento-San Joaquin delta, and selected tributaries. Estuar Coast Shelf Sci 27:381-396.

Karp, C., and B. Bridges. 2015. White Sturgeon salvage efficiency at the Tracy Fish Collection Facility. Tracy Technical Bulletin 2015-3. U.S. Department of the Interior, Bureau of Reclamation, Mid-Pacific Region and the Technical Service Center.

Kelly, J. T., A. P. Klimley, and C. E. Crocker. 2007. Movements of green sturgeon, *Acipenser medirostris*, in the San Francisco Bay Estuary, California. Environ Biol Fishes 79:281-295.

Klimley, A. P., E. D. Chapman, J. J. Cech, D. E. Cocherell, N. A. Fangue, M. Gingras, Z. Jackson, E. A. Miller, E. Mora, and J. B. Poletto. 2015. Sturgeon in the Sacramento-San Joaquin Watershed: new insights to support conservation and management. 2015. San Francisco Estuary and Watershed Science 13(4).

Kogut, N. J. 2008. Overbite clams, *Corbula amurensis*, defecated alive by white sturgeon, *Acipenser transmontanus*. Calif Fish Game 94(3):143−149

Kohlhorst, D. W. 1976. Sturgeon spawning in the Sacramento River in 1973, as determined by distribution of larvae. Calif Fish Game 62(1):32-40.

Kohlhorst, D. W., L. W. Miller, and J. J. Orsi. 1980. Age and growth of White Sturgeon collected in the Sacramento - San Joaquin estuary, California: 1965-1970 and 1973-1976. Calif Fish Game 66:83-95.

Kohlhorst, D. W., L. W. Botsford, J. S. Brennan, and G. M. Caillet. 1991. Aspects of the structure and dynamics of an exploited central California population of White Sturgeon (*Acipenser transmontanus*). In: Williott, P., editor. 1991. Acipenser. Cemagref Publishers, Bordeaux, France. p. 277-293.

Kohlhorst, D. W., and J. Cech. 2001. White Sturgeon. In: California's Living Marine Resources: A Status Report. California Department of Fish and Game. p. 467-469.

Kynard, B., and E. Parker. 2005. Ontogenetic behavior and dispersal of Sacramento River White Sturgeon, *Acipenser transmontanus*, with a note on body color. Environ Biol Fish 74:19-30.

Kynard, B., E. Parker, and T. Parker. 2005. Behavior of early life intervals of Klamath River green sturgeon, *Acipenser medirostris*, with a note on body color. Environ Biol Fishes 72(1):85-97.

Lee, J-W, N. De Riu, S. Lee, S. C. Bai, G. Moniello, and S. S. O. Hung. 2011. Effects of dietary methylmercury on growth performance and tissue burden in juvenile Green (*Acipenser medirostris*) and White Sturgeon (*A. transmontanus*). Aqua Toxicol 105:227-234.

Lee, Y-W, R. Gustafson, J. Jannot, J. McVeigh, N. Riley, K. Somers, V. Tuttle, S. Wang, and E. Ward. 2015. Observed and estimated bycatch of green sturgeon in 2002-2013 U.S. West Coast groundfish fisheries. West Coast Groundfish Observer Program. National Marine Fisheries Service. Available from: http://www.pcouncil.org/wp-content/uploads/2015/06/D4_Sup_Att4_GreenSturgeonBiOpBycatchRpt_E-ONLY_JUN2015BB.pdf

Leidy, R. A. 2007. Ecology, Assemblage Structure, Distribution, and Status of Fishes in Streams Tributary to the San Francisco Estuary, California. San Francisco Estuary Institute. April 2007. Contribution No. 530.

Linares-Casenave, J., I. Werner, J. P. Van Eenennaam, and S. I. Doroshov. 2013. Temperature stress induces notochord abnormalities and heat shock proteins expression in larval green sturgeon (*Acipenser medirostris*, Ayres, 1854). J Appl Ichthyol 29: 958–967.

Linares-Casanave, J., R. Linville, J. P. Van Eenennaam, J. B. Muguet, and S. I. Doroshov. 2015. Selenium tissue burden compartmentalization in resident White Sturgeon (*Acipenser transmontanus*) of the San Francisco SFE Estuary. Environ Toxicol Chem 34(1):152-160.

Lindley, S. T., M. L. Moser, D. L. Erickson, M. Belchik, D. W. Welch, E. Rechisky, J. T. Kelly, J. C. Heublein, and A. P. Klimley. 2008. Marine migration of North American green sturgeon. Trans Am Fish Soc 137:182-194.

Lindley, S. T., D. L. Erickson, M. L. Moser, G. Williams, O. P. Langness, B. W. McCovey, M. Belchik, D. Vogel, W. Pinnix, J. T. Kelly, J. C. Heublein, and A. P. Klimley. 2011. Electronic tagging of green sturgeon reveals population structure and movement among estuaries. Trans Am Fish Soc 140:108-122.

Mayfield, R. B., and J. J. Cech. 2004. Temperature effects on green sturgeon bioenergetics. Trans Am Fish Soc 133(4):961-970.

McEnroe, M., and J. J. Cech Jr. 1985. Osmoregulation in juvenile and adult White Sturgeon, *Acipenser transmontanus*. Environ Biol Fishes 14:2330.

McKechnie, R. J., and R. B. Fenner. 1971. Food habits of white sturgeon, *Acipenser transmontanus*, in San Pablo and Suisun Bays, California. Calif Fish Game, 57:209-212.

Miller, L. W. 1972. Migrations of sturgeon tagged in the Sacramento-San Joaquin Estuary. Calif Fish Game 58(2):102-106.

Mora, E. A. 2016. A Confluence of Sturgeon Migration: Adult Abundance and Juvenile Survival. PhD Dissertation, Univ. Calif., Davis.

Moser, M. L., and S. T. Lindley. 2007. Use of Washington estuaries by subadult and adult green sturgeon. Environ Biol Fishes 79:243-253.

Moyle, P. B. 2002. Inland fishes of California. Berkeley: University of California Press. p. 109-113.

Mussen, T. D., D. E. Cocherell, J. B. Poletto, J. S. Reardon, Z. Hockett, A. Ercan, H. Bandeh, M. L. Kavvas, J. J. Cech Jr., and N. A. Fangue. 2014. Unscreened water-diversion pipes pose an entrainment risk to the threatened green sturgeon, *Acipenser medirostris*. PLoS ONE 9, e86321 doi: http://dx.doi.org/10.1371/journal. pone.0086321

Nakamoto, R. J., T. T. Kisanuki, and G. H. Goldsmith. 1995. Age and growth of Klamath River green sturgeon (*Acipenser Medirostris*). USFWS Project # 93-FP-13. January 31, 1995. 27 p.

NMFS (National Marine Fisheries Service). 2015. Southern Distinct Population Segment of the North American Green Sturgeon (*Acipenser medirostris*); 5-Year Review. West Coast Region, Long Beach, CA. Available from: http://www.nmfs.noaa.gov/pr/listing/southern_dps_green_sturgeon_5-year_review_2015__2_.pdf

ODFW and WDFW (Oregon Department of Fish and Wildlife and Washington Department of Fish and Wildlife). 2002. Status report Columbia River fish runs and fisheries 1938-2002, Tables only. 180p. Available from: http://www.dfw.state.or.us/fish/OSCRP/CRM/reports/status_report/2002_status_tables.pdf

ODFW and WDFW. 2014. Study of green sturgeon on the West coast of the United States. Project Completion Report. Prepared for the National Oceanic and Atmospheric Association for NOAA Fisheries Protected Species Conservation and Recovery Grant No.: NA10NMF4720037. 191 p.

Paragamian, V. L., and V. D. Wakkinen. 2011. White sturgeon spawning and discharge augmentation. Fish Manag Ecol 18:314-321.

Parsley, M. J., S. D. Duke, T. J. Underwood, and L. G. Beckman. 1989. Report C in A.A. Nigro, editor. Status and habitat requirements of White Sturgeon populations in the Columbia River downstream from McNary Dam. Annual Progress Report. Bonneville Power Authority, Contract DE-AI79-86BP63584. Portland, Oregon.

Parsley, M. J., N. D. Popoff, C. D. Wright, and B. K. van der Leeuw. 2008. Seasonal and Diel Movements of White Sturgeon in the Lower Columbia River. Transactions of the American Fisheries Society. 137(4):1007-1017.

Poletto, J. B., D. E. Cocherell, N. Ho, J. J. Cech Jr, A. P. Klimley, and N. A. Fangue. 2014a. Juvenile green sturgeon (*Acipenser medirostris*) and white sturgeon (*Acipenser transmontanus*) behavior near water diversion fish screens: experiments in a laboratory swimming flume. Can J Fish Aquat Sci 71:1030- 1038. doi: http://dx.doi.org/10.1139/cjfas-2013-0556

Poletto, J. B., D. E. Cocherell, T. D. Mussen, A. Ercan, H. Bandeh, M. Kavvas, J. J. Cech Jr., and N. A. Fangue. 2014b. Efficacy of a sensory deterrent and pipe modifications in decreasing unscreened water diversions. Conserv Physiol 2(1):cou056. doi: http://dx.doi.org/10.1093/ conphys/cou056

Poletto, J. B., D. E. Cocherell, T. D. Mussen, A. Ercan, H. Bandeh, M. Kavvas, J. J. Cech Jr., and N. A. Fangue. 2015. Fish protection devices at unscreened water diversions can reduce entrainment: evidence from behavioral laboratory investigations. Conserv Physiol 3(1):cov040. doi: http://dx.doi.org/10.1093/conphys/ cov040.

Poytress, W. R., J. J. Gruber, D. Trachtenbarg, and J. P. Van Eenennaam. 2009. 2008 Upper Sacramento River green sturgeon spawning habitat and larval migration surveys. Annual Report of U.S. Fish and Wildlife Service to U.S. Bureau of Reclamation, Red Bluff, CA.

Poytress, W. R., J. J. Gruber, and J. P. Van Eenennaam. 2010. 2009 Upper Sacramento River green sturgeon spawning habitat and larval migration surveys. Annual Report of U.S. Fish and Wildlife Service to U.S. Bureau of Reclamation, Red Bluff, CA.

Poytress, W. R., J. J. Gruber, and J. P. Van Eenennaam. 2011. 2010 Upper Sacramento River green sturgeon spawning habitat and larval migration surveys. Annual Report of U.S. Fish and Wildlife Service to U.S. Bureau of Reclamation, Red Bluff, CA.

Poytress, W. R., J. J. Gruber, and J. P. Van Eenennaam. 2012. 2011 Upper Sacramento River green sturgeon spawning habitat and larval migration surveys. Annual Report of U.S. Fish and Wildlife Service to U.S. Bureau of Reclamation, Red Bluff, CA.

Poytress, W. R., J. J. Gruber, C. Praetorius, and J. P. Van Eenennaam. 2013. 2012 Upper Sacramento River green sturgeon spawning habitat and young-of-the-year migration surveys. Annual Report of U.S. Fish and Wildlife Service to U.S. Bureau of Reclamation, Red Bluff, CA.

Poytress, W. R., J. J. Gruber, J. P. Van Eenennaam, and M. Gard. 2015. Spatial and temporal distribution of spawning events and habitat characteristics of Sacramento River green sturgeon. Trans Am Fish Soc 144(6):1129-1142.

Pycha, R.L. 1956. Progress report on White Sturgeon studies. Calif Fish Game 42:23-35.

Quist MC, Pegg MA, DeVries DR. 2012. Age and Growth, pp. 677–731. In: Fisheries Techniques (Zale, A., D. Parrish, and T. Sutton, Eds.), 3rd Edn. Bethesda, MD: American Fisheries Society.

Radtke, L. D. 1966. Distribution of smelt, juvenile sturgeon, and starry flounder in the Sacramento-San Joaquin Delta with observations on food of sturgeon. In J.L. Turner and D.W. Kelly (Comp.) Ecological Studies of the Sacramento-San Joaquin Delta. Part 2 Fishes of the Delta. California Department of Fish and Game Fish Bulletin 136:115-129.

Rien, T. A., and R. C. Beamesderfer. 1994. Accuracy and precision of White Sturgeon age estimates from pectoral fin rays. Trans Am Fish Soc 123:255-265.

Rosales-Casian, J. R., and C. Almeda-Juaregui. 2009. Unusual occurrence of a green sturgeon (*Acipenser medirostris*) at El Socorro Bay, Baja California, Mexico. CalCoFI Rep 50:169-171.

Ruiz-Campos, G., J. L. Castro-Aguirre, and F. J. Garcia-De Leon. 2011. First specimen of the white sturgeon (*Acipenser transmontanus* Richardson, 1836) in coastal waters of Mexico with data on its genetic identity. California Fish and Game 97(1):36-42.

Schaffter, R. G. 1997. White Sturgeon spawning migrations and location of spawning habitat in the Sacramento River, California. Calif Fish Game 83(1):1-20.

Schaffter, R. G, and D. W. Kohlhorst. 2001. Final report for phase 2, Task 5: determination of Green Sturgeon spawning habitats and their environmental conditions. Final report submitted to CALFED, Sacramento, California.

Schreier, A., B. Mahardja, and B. May. 2013. Patterns of population structure vary across the range of the White Sturgeon. Trans Am Fish Soc 142:1273-1286.

Schreier, A., O. P. Langness, J. A. Israel, and E. Van Dyke. 2016. Further investigation of green sturgeon (*Acipenser medirostris*) distinct population segment composition in non-natal estuaries and preliminary evidence of Columbia River spawning. Environ Biol Fish 99:1021 10.1007/s10641-016-0538-1.

Seesholtz, A. M., M. J. Manuel, and J. P. Van Eenennaam. 2015. First documented spawning and associated habitat conditions for green sturgeon in the Feather River, California. Environ Biol Fishes 98(3):905-912.

Shirley, D. E. 1987. Age distribution of white sturgeon (*Acipenser transmontanus*) in the Sacramento-San Joaquin Bay-Delta. M.S. Thesis, Univ. Calif., Davis.

Stansell, R. J., K. M. Gibbons, W. T. Nagy, and B. K. van der Leeuw. 2012. Evaluation of pinniped predation on adult salmonids and other fish in the Bonneville Dam tailrace, 2012. USACE. October 4, 2012.

Stansell, R. J., B. K. van der Leeuw, K. M. Gibbons, and W. T. Nagy. 2013. Evaluation of pinniped predation on adult salmonids and other fish in the Bonneville Dam tailrace, 2013. USACE. October 30, 2013.

Stansell, R. J., B. K. van der Leeuw, K. M. Gibbons, and W. T. Nagy. 2014. Evaluation of pinniped predation on adult salmonids and other fish in the Bonneville Dam tailrace, 2104. USACE. September 16, 2014.

Stevens, D. E., and L. W. Miller. 1970. Distribution of sturgeon larvae in the Sacramento-San Joaquin river system. Calif Fish Game 56(2):80-86.

Tashjian, D., J. Cech Jr., and S. S. O. Hung. 2007. Influence of dietary l-selenomethionine exposure on the survival and osmoregulatory capacity of white sturgeon in fresh and brackish water. Fish Physiol Biochem 33: 109–119.

Thomas, M. J., M. L. Peterson, N. Friedenberg, J. P. Van Eenennaam, J. R. Johnson, J. J. Hoover, and A. P. Klimley. 2013. Stranding of Spawning Run Green Sturgeon in the Sacramento River: Post-Rescue Movements and Potential Population-Level Effects. North American Journal of Fisheries Management 33(2):287-297.

Thomas, M. J., and A. P. Klimley. 2015. Juvenile green sturgeon movements and identification of critical rearing habitat. In: Klimley AP, Doroshov SI, Fangue NA, May BP. 2015. Sacramento river green sturgeon migration and population assessment. Sacramento (CA): U.S. Bureau of Reclamation.

USFWS (United States Fish and Wildlife Service). 1996. Recovery plan for the Sacramento-San Joaquin Delta native fishes. U. S. Department of the Interior Fish and Wildlife Service Region 1, Portland, Oregon. p. 83-94.

Van Eenennaam, J. P., J. Linares-Casenave, X. Deng, and S. I. Doroshov. 2005. Effect of incubation temperature on green sturgeon embryos, *Acipenser medirostris*. Environ Biol Fishes 72:145-154.

Verhille, C. E., J. B. Poletto, D. E. Cocherell, B. DeCourten, S. Baird, J. J. Cech Jr., and N. A. Fangue. 2014. Larval green and white sturgeon swimming performance in relation to water-diversion flows. Conserv Physiol 2: doi:10.1093/conphys/cou031.

Vogel, D. 2013. Evaluation of fish entrainment in 12 unscreened Sacramento River diversions. Final Report July 2013. Prepared for: CVPIA Anadromous Fish Screen Program (USFWS and BOR) and Ecosystem Restoration Program (CDFW, USFWS, and NMFS). Natural Resource Scientists, Inc. P.O. Box 1210 Red Bluff, CA 96080. 153 p.

Wang, Y. L., F. P. Binkowski, and S. I. Doroshov. 1985. Effect of temperature on early development of White and Lake sturgeon, *Acipenser transmontanus* and *A. fulvescens*. Environ Biol Fishes 14:43-50.

Welch, D. W., S. Turo, and S. D. Batten. 2006. Large-scale marine and freshwater movements of white sturgeon. Trans Am Fish Soc 135: 386-389.

Werner, I., J. Linares-Casenave, J. P. Van Eenennaam, and S. I. Doroshov. 2007. The effect if temperature stress on development and heat-shock protein expression in larval green sturgeon (*Acipenser medirostris*). Environ Biol Fishes 79:191-200.

White, J. R., P. S. Hoffman, D. Hammond, and S. Baumgartner. 1988. Selenium Verification Study: 1986-1987. Water Resources Control Report. State Water Resources Control Board, Sacramento, California.

Workman, M. L. 2003. Downstream migration monitoring at Woodbridge Dam on the Lower Mokelumne River, CA, December 2002 through July 2003. Report to the East Bay Municipal Utility District, Lodi, California.

Zeug, S. C., A. Brodsky, N. Kogut, A. R. Stewart, and J. E. Merz. 2014. Ancient fish and recent invaders: white sturgeon *Acipenser transmontanus* diet response to invasive-species-mediated changes in a benthic prey assemblage. Mar Ecol Prog Ser 514:163-174.

Notes

Beccio M. CDFW (California Department of Fish and Wildlife). 2017. In-person conversation between M. Beccio and J. Heublein regarding observations of green sturgeon below Daguerre Point Dam on the Yuba River.

CDFW. 2015. Unpublished data. [Historical catch of green sturgeon in Sturgeon Population Study]. Accessed. http://www.dfg.ca.gov/delta/data/sturgeon/bibliography.asp

CDFW. 2016a. Unpublished data. [Larval sturgeon records in the 20mm Survey]. Accessed. https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentId=133706

CDFW. 2016b. Unpublished data. [White sturgeon tag returns in relation to river flow]. Accessed 5-4-2016. https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentId=75740

CDFW 2016c. Unpublished data. [Distribution of adult sturgeon in the San Francisco Bay].

CDFW 2016d. Unpublished data. [Index of Annual Age-0 White Sturgeon Abundance, 1980-2015]. Accessed 4-19-2016. https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentId=69133

CDFW 2016e. Unpublished data. [Harvest and CPUE for Sturgeon by CPFVs in SF Bay and Delta, 1964-2015]. Accessed 7-30-2016. https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentId=34816

CDFW 2017. [Annual CDFW Sturgeon Fishing Report Card and Adult Sturgeon Population Study summaries]. Accessed. http://www.dfg.ca.gov/delta/data/sturgeon/bibliography.asp

Chase, R. USACE (U.S. Army Corps of Engineers). 2015. Unpublished data. [Movement of green sturgeon tagged in the Sacramento River].

DWR (California Department of Water Resources). California Data Exchange Center (CDEC). 2017a. [Sacramento River water temperature gauge data.] Accessed. http://cdec.water.ca.gov/index.html.

DWR 2017b. [Chronological reconstructed Sacramento and San Joaquin Valley water year hydrologic classification indices.] Accessed. http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST.

Gingras, M. CDFW. 2015a. Unpublished data. [Age distribution of white sturgeon catch in CDFW monitoring and back-calculated recruitment estimates].

Gingras, M. CDFW. 2015b. Unpublished data. [CDFW Bay Study catch of juvenile green sturgeon].

Gingras, M. CDFW. 2016. Unpublished data. [Compilation of green sturgeon catch data and back-calculated recruitment estimates (2000 to 2016)].

Holm, M. 2016. Telephone conversation with J. Heublein regarding bycatch of green sturgeon in commercial herring fishery and composition of sturgeon species in directed gill-net sampling in San Pablo Bay.

Jackson, Z. USFWS. 2017. Unpublished data. [White sturgeon egg and larval collections on the San Joaquin River].

Langness, O. WDFW (Washington Department of Fish and Wildlife). 2015. Unpublished data. [Recovery of tagged green sturgeon in Pacific Northwest estuaries and lower Columbia River white sturgeon monitoring].

Langness, O. WDFW. 2016. Unpublished data. [Preliminary contaminant analysis of nDPS and sDPS green sturgeon tissue collected in the lower Columbia River].

Manuel, M. PSMFC (Pacific States Marine Fisheries Commission). 2016. In-person and telephone conversation with J. Heublein regarding catch of white sturgeon in rotary screw traps and with hook at line at GCID.

Manuel, M. PSMFC. 2017. Telephone conversation with J. Heublein regarding catch of egg and larval green sturgeon below Fish Barrier Dam on Feather River in June 2017.

McKibbin, C. CDFW. 2015. In-person conversation between C. McKibbin and A. Seesholtz regarding catch of juvenile sturgeon in American River rotary screw trap.

Miller, E. UCD (University of California, Davis) Biotelemetry Laboratory. 2017. Manuscript in preparation. [White sturgeon estuarine and coastal movements using telemetric monitoring data].

NMFS (National Marine Fisheries Service). 2016. Unpublished data. [Green sturgeon observations in the California halibut trawl Fishery].

Poletto, J. UCD. 2016. Unpublished data. [Northern DPS larval green sturgeon growth at 11, 13, 16, and 19°C and under multiple ration treatments]

Poytress, W. USFWS. 2015a. Unpublished data. [Relationship between annual Sacramento River outflow and larval green sturgeon catch numbers at RBDD rotary screw traps].

Poytress, W. USFWS. 2015b. Unpublished data. [Juvenile green sturgeon catch number and size in benthic trawl surveys].

Poytress, W. USFWS. 2017a. Unpublished data. [Egg, larval, and small juvenile green sturgeon catch in RBDD rotary screw traps in 2016 and 2017].

Poytress, W. USFWS. 2017b. Unpublished data. [Juvenile green sturgeon catch and JSATS tag implantation in benthic trawl surveys in Fall 2016].

Seesholtz, A. DWR. 2017. Unpublished data. [DIDSON surveys, acoustic detection of tagged adults, and early life stage sampling of green sturgeon on the Feather River].

Steel A, et al. UCD Biotelemetry Laboratory. 2017. Manuscript in preparation. [Telemetric data show a greater proportion of adult green sturgeon moving upstream of RBDD after gates were permanently raised]

Thomas, M., M. Pagel, A. P. Klimley, and R. Bellmer. UCD Biotelemetry Laboratory and CDFW. 2017. Report in preparation. [Telemetric monitoring data show movements of juvenile white and green sturgeon in the SFE].