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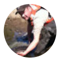

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White Sturgeon Spawning in the San Joaquin River, California, and Effects of Water Management

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Abstract

Inadequate recruitment is a hallmark of declining sturgeon populations throughout the world. Efforts to understand and address the processes that regulate recruitment are of foremost importance for successful management and recovery. Fish biologists previously only knew San Francisco Estuary white sturgeon (*Acipenser transmontanus*) to spawn in the Sacramento River, California. We assessed potential white sturgeon spawning locations by deploying artificial substrate samplers during late winter and spring of 2011 and 2012 from river kilometers 115.2 to 145.3 of the San Joaquin River. Collections of fertilized eggs, coupled with hydrology data, confirm that white sturgeon spawned within one and four sites in the San Joaquin River during wet (2011; $n = 23$) and dry (2012; $n = 65$) water-year conditions. Small pulse flow augmentations intended to benefit juvenile salmonids appear to have triggered white sturgeon spawning within this system. Understanding the effects of water management on spawning and subsequent recruitment is necessary to increase white sturgeon recruitment to the San Francisco Estuary.

Keywords: white sturgeon; egg sampling; spawning habitat; recruitment; San Joaquin River; San Francisco Estuary; water management

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Introduction

White sturgeon (*Acipenser transmontanus*) are the largest freshwater fish species in North America and are integral to the ecosystem and cultural heritage of the Sacramento–San Joaquin (San Francisco Estuary population), Columbia, and Fraser river systems. Within the San Francisco Estuary, the presence and spawning of both white sturgeon and green sturgeon (*Acipenser medirostris*) have been well documented by researchers in the Sacramento River (Kohlhorst 1976; Schaffter 1997; DuBois et al. 2014; Poytress et al. 2015). Although researchers have sampled larval and juvenile green and white sturgeons within the lower San Joaquin River, studies have attributed these observations to movements of sturgeons from the known spawning populations within the Sacramento River (Radtke 1966; Stevens and Miller 1970; Beamesderfer et al. 2004). While several researchers have speculated that sturgeons may spawn within the San Joaquin River during high streamflow conditions (Kohlhorst 1976; Beamesderfer et al. 2004), spawning has not been confirmed through any direct sampling activities and researchers know little about the spatial and temporal distribution of sturgeons within the San Joaquin River system.

The San Joaquin River has the nickname of the "hardest working water in the world" due to an extensive system of dams, diversions, and engineering (Kaneshiro et al. 2007). Water management in the San Joaquin River system is primarily focused on water storage for agricultural and municipal use, flood control, and power generation. These goals are fundamentally incompatible with maintaining the natural conditions under which native fishes, including white sturgeon, evolved. Intense water management has altered natural environmental conditions, including streamflow, sediment transport, water temperature, floodplain connectivity, and access to upstream habitats. Diversions in the basin inherently reduce water quantity and generally alter quality (e.g., temperature), which affects sturgeon habitat. Water diversions in the main stem and throughout the San Francisco Estuary may also entrain biologically significant portions of annual juvenile production (Mussen et al. 2014). The natural hydrology of the San Joaquin River system has been altered by humans such that the timing and magnitude of peak runoff has shifted and resulted in a decrease of annual water yield of more than 70% (Cain et al. 2003). Highest monthly unimpaired flow (i.e., natural runoff) in the San Joaquin River during the 1984–2009 period was most commonly in May (73%), followed by April (12%) and June (8%), whereas highest observed flow (i.e., reservoir discharge plus runoff from the watershed below dams) was most common in March (31%), followed by May (27%), February (15%), October (12%), and January (8%; SWRCB 2012).

White sturgeon year-class strength is heavily influenced by survival at early life stages (Kohlhorst et al. 1991; Hildebrand et al. 1999; Secor et al. 2002) and recruitment failure is common in most populations (Coutant 2004). Jager et al. (2002) describe many factors influencing white sturgeon recruitment, including discharge and temperatures during egg incubation and the downstream export of larvae following hatching. Therefore, gathering information on in-river physical characteristics and environmental conditions that influence white sturgeon recruitment is critical for management of the species. The objectives of this study were to determine if white sturgeon reproduce in the San Joaquin River, and if so, to characterize habitat conditions (e.g., temperature, depth, streamflow) where spawning occurred and describe the spatial and temporal distribution of spawning. Identifying suitable spawning habitat for white sturgeon will help inform future water management decisions and habitat protection and restoration actions needed to maintain or increase the white sturgeon population within the San Joaquin River and San Francisco Estuary.

Study Area

The San Joaquin River originates from the central Sierra Nevada and drains parts of the Sierra Nevada and Diablo Range of California. The river flows through 531 km of California, first west toward the floor of the Central Valley, then north toward the San Francisco Bay estuary, eventually reaching the Pacific Ocean (Figure 1A). Friant Dam, at river kilometer (rkm) 431 of the San Joaquin River (measuring from rkm 0 at its confluence with the Sacramento River), forms a complete barrier to upstream anadromous fish passage. However, a number of physical migration barriers (e.g., dry riverbed, diversion dams, seasonally installed weir) exist between the Merced River confluence (rkm 187.6) and Friant Dam due to the current state of water management on the San Joaquin River.

Methods

We sampled from rkm 115.2 to 145.3 (Figure 1B) and selected sites based on presence of at least two of the following attributes: pool habitat, areas of accelerating velocities, and reported observations of adult-sized sturgeon by anglers and wardens. We used artificial substrate samplers (i.e., egg mats) to sample for the presence of white sturgeon eggs from April 18 to May 16, 2011, and February 16 to June 1, 2012. The timing of sampling during 2011 was delayed and abbreviated due to a combination of logistic issues (e.g., travel restrictions, permitting). We constructed egg mats from two 89- × 65-cm rectangular sections of furnace filter material secured back to back within a welded steel framework (McCabe and Beckman 1990; Schaffter 1997; Poytress et al. 2015). The orientation of the furnace filter material allowed either side of the egg mat to collect eggs. Egg mats were held in position by a 2.0-kg anchor attached to the upstream end with two 76-cm lengths of 9.5-mm–diameter braided polypropylene line. We attached a labeled float to the downstream end of the egg mat with a 9.5-mm–diameter braided polypropylene line. Float line length varied depending on water depth and velocity. We set egg mats in pairs and predominantly deployed them in areas of accelerating velocity (i.e., areas flanking the deepest portions of pools). During 2011, we placed paired egg mats in eight locations between rkm 115.2 and 145.3 (Figure 1). We ceased sampling after limited effort at the rkm 115.2, 120.4, 126.4, 140.8, and 143.7 sites due to sampling difficulty associated with high streamflow conditions. In 2012, we placed paired egg mats in four locations between rkm 115.2 and 139.8 (Figure 1).

We recorded environmental and sample effort data during both the deployment and retrieval of egg mats (Table S1, *Supplemental Material*). We recorded depth and GPS coordinates using a Lowrance depth finder (Model StructureScan HDS 10-m). We obtained hourly streamflow and water temperature data from the U.S. Geological Survey gaging station near Vernalis (rkm 111.8) for the rkm 115.2 site, and from the California Data Exchange Center gaging stations at Maze Road Bridge

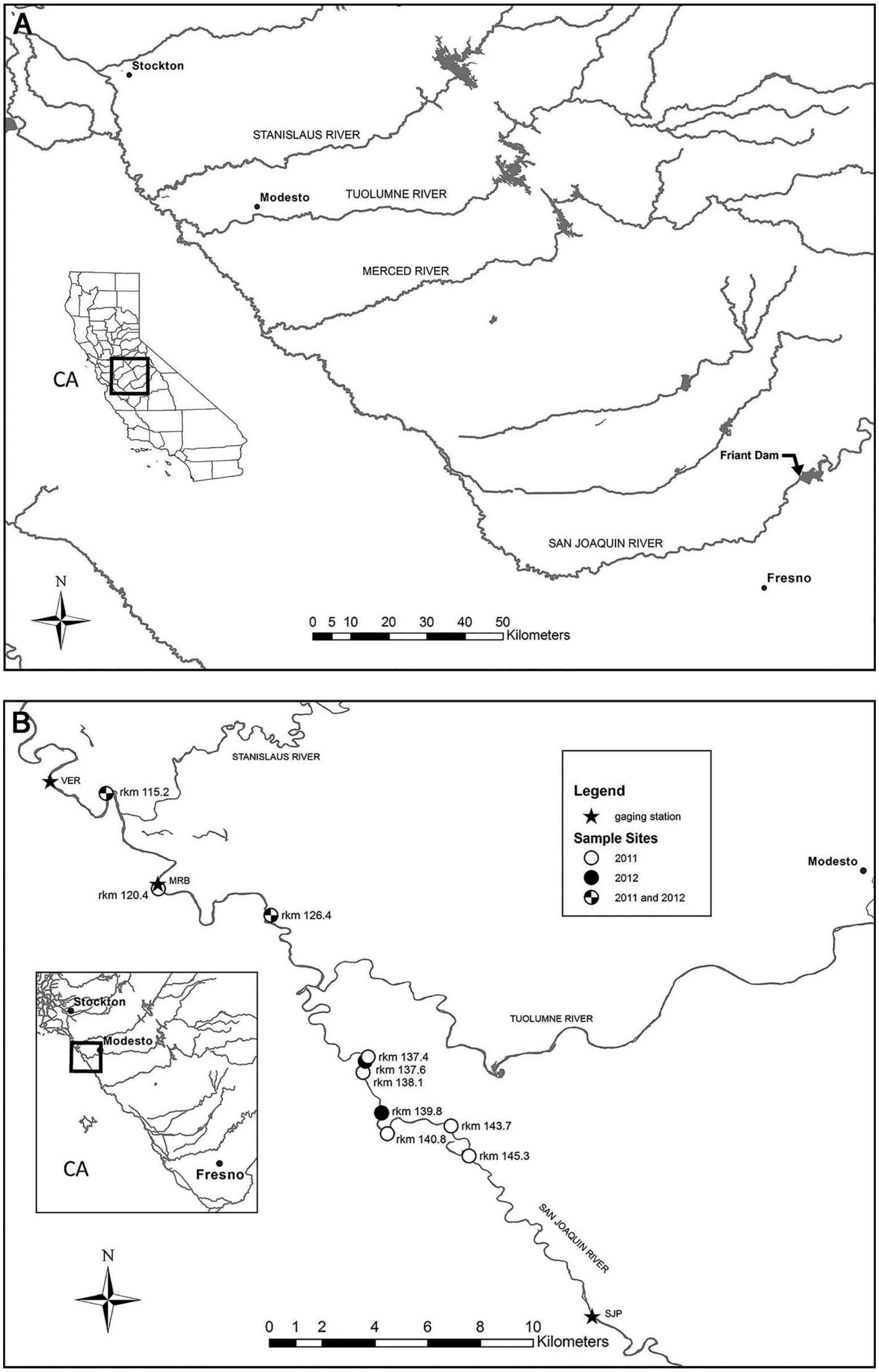

Figure 1. Panel A shows the northern San Joaquin Valley of California and the main tributaries to the San Joaquin River. Panel B depicts the white sturgeon (*Acipenser transmontanus*) spawning study area, sampling locations, and associated river gaging stations (U.S. Geological Survey gaging station at Vernalis, California [VER; USGS 11303500] and California Data Exchange Center gaging stations at Maze Road Bridge [MRB] and San Joaquin near Patterson, California [SJP]).

(rkm 120.2) for the rkm 120.4 and 126.4 sites and the San Joaquin near Patterson (rkm 154.9) for the rkm 137.4–145.3 sites (Figure 1). Sample effort consisted of the time between gear deployment and retrieval and is standardized into wetted mat days (wmd; i.e., one egg mat set for 24 h).

We visually inspected egg mats for eggs at least twice per week at each site during each sample season. To achieve this, crews retrieved mats, placed them on the deck of the boat in a custom-made mat carrier, and at least two field crew members initially inspected them on both sides. They rinsed mats to remove debris and then inspected them again. Crews filtered rinse water and debris with a removable 3.2-mm mesh net placed within the mat carrier below each mat to capture any dislodged eggs. After a second inspection of the egg mats, mesh nets, and rinsate, crews redeployed the egg mats.

Crews identified eggs down to family in the field. They placed suspected sturgeon and unidentified eggs in vials of 95% ethanol for species confirmation and evaluation of developmental stage and viability in the laboratory (Table S2, *Supplemental Material*). In the laboratory, we identified eggs as white sturgeon based upon coloration, size, and chorion thickness, as they are darker, smaller, and have a thicker chorion than green sturgeon eggs (Van Eenennaam et al. 2008). We based egg development stage on Dettlaff et al. (1993). We classified eggs as "not viable" if they were crushed during collection and handling, covered in fungus or algae, or had mottled pigmentation with white streaks. We measured the length and width of white sturgeon eggs (±0.001 mm, rounded to 0.01) using a dissecting scope (Wild M5-A) with camera lucida and a digital-image–analyzing tablet (Nikon Microplan II). We back-calculated spawn date and time for each egg using an exponential function based on water temperature and stage of embryonic development described for white sturgeon (Wang et al. 1985, 1987). We based minimum number of spawn events on rkm, date of egg collections, calculated fertilization time, and the assumption that it takes up to 21 h to complete oviposition (Van Eenennaam et al. 2012) following the methods described in Poytress et al. (2015). We defined a spawning event as any viable fertilized eggs collected within a 10-km distance and within a 21-h oviposition period. We defined incubation period as the time between the estimated time of spawning through egg collection. We report the data as a minimum number of spawning events, as it is possible that more than one female was spawning in an area at the same time and location.

Results

2011

We deployed egg mats at river depths ranging from 4.3 to 12.3 m for a total of 183.2 wmd among eight sample sites (Table 1). High river flows and limited staff availability focused our sampling efforts (68.6%; n=125.6 wmd) at three (rkm 137.4, 138.1, and 145.3) of the seven sample sites (Table 1). We collected 23 white sturgeon eggs from mats deployed at depths ranging from 8.2 to 10.5 m (Table 1). We collected all eggs, likely representing a single spawning event, at rkm 138.1 over a 4-d period (April 25–April 28, 2011; Figure 2; Table 2). We lost one egg during field handling; it was not included in Table 2. We classified 86% ($n = 19$) of the eggs as viable; mean egg length and width ranged from 3.26–3.57 mm and 3.02–3.34 mm, respectively (Table 2). San Joaquin River streamflow and water temperature ranged from 154.5 to 767.4 m^3/s and 13.9 to 18.2°C, respectively, throughout the 2011 sample period (Table 1; Figure 2). Streamflow and water temperature averaged 346.7 m^3/s and 15.3°C, respectively, at rkm 138.1 during the incubation period in 2011 (Table 1).

2012

We deployed egg mats at river depths ranging from 0.4 to 9.3 m for a total of 670.9 wmd among four sites (Table 1). We expended 82% (552.3 of 670.8 wmd) of the total sampling effort uniformly across three of the four sample sites (rkm 115.2, rkm 126.4, and rkm 137.6; Table 1). We added mats at rkm 139.8 during the sixth week of sampling due to observations of sturgeon in the area, accounting for 17.7% of total effort (118.5 wmd; Table 1). We collected 65 white sturgeon eggs among all sampling sites from egg mats deployed at depths ranging from 1.6 to 9.1 m between March 22 and May 14, 2012, representing at least six spawning events (Table 1; Table 2). Forty-six eggs (71%) were viable and determined to be in various stages of postfertilization embryonic development (Table 2). We collected eight eggs on April 2, 2012, from the upper sites (rkm 137.6 and 139.8); however, due to missing site discrimination data, it is not possible to tell which eggs and how many were collected at each site. Nineteen eggs (29%) were not viable; many of these were covered in fungus. We could not determine if the nonviable eggs were fertilized eggs that died during embryogenesis or were unfertilized eggs. Mean egg length and width ranged from 3.46–3.64 mm and 3.34–3.46 mm, respectively (Table 2). San Joaquin River streamflow and water temperature ranged from 12.7 to 127.4 m^3/s and 10.4 to 26.7°C, respectively, throughout the 2012 sample period (Table 1; Figure 2). Streamflow and water temperature during the incubation period ranged from 19.2 to 127.4 m^3/s and 14.2 to 26.7°C (Table 1; Figure 2). Hourly temperatures during the incubation period of egg collections on April 19 (rkm 137.6) and May 10 (rkm 137.4; rkm 139.8) ranged from 18.6 to 20.9°C and 19.9 to 22.1°C, respectively (Figure 2).

Discussion

Schaffter (1997) stated "identification and protection of spawning habitat is vital for the maintenance of the [white sturgeon] population and the sport fishery." While our study did set out to identify spawning locations and habitat characteristics (e.g., water temperature, streamflow) in the San Joaquin River, we are unaware of any actions implemented since 1997 with a stated purpose of

Table 1. Summary of white sturgeon (*Acipenser transmontanus*) spawning survey sampling effort and corresponding environmental conditions on the San Joaquin River, California, during the 2011 and 2012 sampling seasons. Data include sampling location given as river kilometer (rkm), dates, effort by site (wetted mat days and percentage of total annual effort), river depth, streamflow, and temperature. Range and mean values are displayed for the sampling and incubation (i.e., estimated spawn timing until time of collection; in parentheses) periods.

		Sample effort		River depth (m)		Streamflow (m^3/s)		Temperature (°C)	
Location	Sampling dates	Wetted mat days	% Effort	Range	Mean	Range	Mean	Range	Mean
2011									
rkm 115.2	April 18–25	10.5	5.8%	9.2–12.3 (—)	10.3 (—)	620.1–767.4 (—)	690.3 (—)	15.2–17.3 (—)	16.3 (—)
rkm 120.4	April 18–25	13.6	7.4%	6.3–10.1 (—)	8.1 (—)	584.1–713.4 (—)	640.7 (—)	15.0–17.3 (—)	16.2 (—)
rkm 126.4	April 18–25	13.7	7.5%	5.5–10.1 (—)	7.1 (—)	584.1–713.4 (—)	640.7 (—)	15.0–17.3 (—)	16.2 (—)
rkm 137.4	April 18–May 16	37.2	20.3%	4.6–9.2 (—)	7.3 (—)	154.5–420.6 (—)	283.2 (—)	13.9–18.2 (—)	15.9 (—)
rkm 138.1	April 21–May 16	48.7	26.6%	4.8–11.1 (8.2–10.5)	8.2 (9.6)	154.5–385.3 (325.2–367.2)	270.3 (346.7)	13.9–18.2 (14.6–15.8)	16.0 (15.3)
rkm 140.8	April 21–25	14.2	7.7%	5.4–7.8 (—)	6.0 (—)	154.5–385.3 (—)	270.3 (—)	13.9–18.2 (—)	16.0 (—)
rkm 143.7	April 25–28	5.5	3.0%	6.6–7.4 (—)	7.0 (—)	325.2–359.6 (—)	341.0 (—)	13.9–18.2 (—)	16.0 (—)
rkm 145.3	April 25–May 16	39.7	21.7%	4.3–12.2 (—)	7.1 (—)	154.5–359.6 (—)	250.7 (—)	13.9–18.2 (—)	16.0 (—)
2012									
rkm 115.2	February 16–June 1	188.6	28.1%	1.3–9.3 (5.8–9.1)	5.5 (7.1)	33.7–127.4 (125.2–127.4)	63.6 (126.4)	10.4–22.0 (17.1–18.6)	15.8 (17.8)
rkm 126.4	February 16–June 1	181.7	27.1%	0.9–9.0 (4.2–4.2)	4.5 (4.2)	25.9–99.1 (96.1–99.1)	45.5 (98.1)	10.9–26.0 (17.6–18.7)	17.4 (18.2)
rkm 137.6	February 16–June 1	182.0	27.1%	1.1–3.9 (1.6–3.8)	2.7 (2.6)	12.7–44.3 (19.2–44.3)	21.7 (25.1)	10.5–26.7 (14.2–26.7)	17.7 (18.7)
rkm 139.8	Mar 22–June 1	118.5	17.7%	0.4–2.1 (1.6–1.6)	1.4 (1.6)	12.7–44.3 (19.2–44.3)	21.7 (24.5)	14.9–26.7 (14.9–26.7)	19.9 (19.3)

protecting spawning habitat. The collection of white sturgeon eggs in 2011 and 2012 provided the first evidence of white sturgeon spawning in the San Joaquin River. The eggs collected were likely part of at least seven separate spawning events based upon capture location, date of capture, water temperature, stage of development, and the estimation that it takes a female up to 21 h to complete oviposition (Van Eenennaam et al. 2012). Our estimation of the number of spawning events is likely conservative as the recovery of eggs from a single spawning event was quite rare in this study. Until genetic analyses can be completed on individual eggs, it remains unknown whether multiple eggs collected during a single sampling event could have been from more than one female. The fecundity of a female white sturgeon ranges from 64,000 to 469,000 (Chapman et. al. 1996), yet we collected only 3–5 eggs from half of the 2012 spawning events. Sampling gear efficiency, insufficient numbers of deployed egg mats, losses during retrieval, and predation of eggs are probably leading factors contributing to the scarcity of eggs collected. Additionally, the extent of the time between the occurrence of a spawning event and egg mat retrieval likely resulted in increased egg loss. Caroffino et. al (2010) replaced mats with all lake sturgeon (*Acipenser fulvescens*) eggs attached after counting, and then recovered and recounted them 24 h later and reported that egg loss rate varied 20–100%. At 24 h postdeposition for Gulf sturgeon (*Acipenser oxyrinchus desotoi*) eggs, Sulak and Clugston (1998) reported nearly 100% loss of eggs. Although we likely experienced egg loss before mat retrieval, our results provide critical evidence of spawning activity in an area thought to be rarely, if ever, used.

Researchers (e.g., Kohlhorst 1976; Schaffter 1997) have speculated that the presence of white sturgeon in the San Joaquin River was a result of fish on a spawning migration during years with high runoff (i.e., wet water-year types). Spawning surveys in 2011 and 2012 occurred during two drastically different water-year types. Mean daily streamflow in the San Joaquin River during early 2011 was as much as four times higher than mean daily streamflow for water years 1993 to 2012 (Figure 3). As speculated, streamflow levels of this magnitude may have triggered white sturgeon to enter and spawn within the San Joaquin River. However, streamflow levels in 2012 were generally half or less than the 20-y average. Despite much lower than average streamflow during early 2012, we observed at least six spawning events, demonstrating that spawning also occurs in dry years.

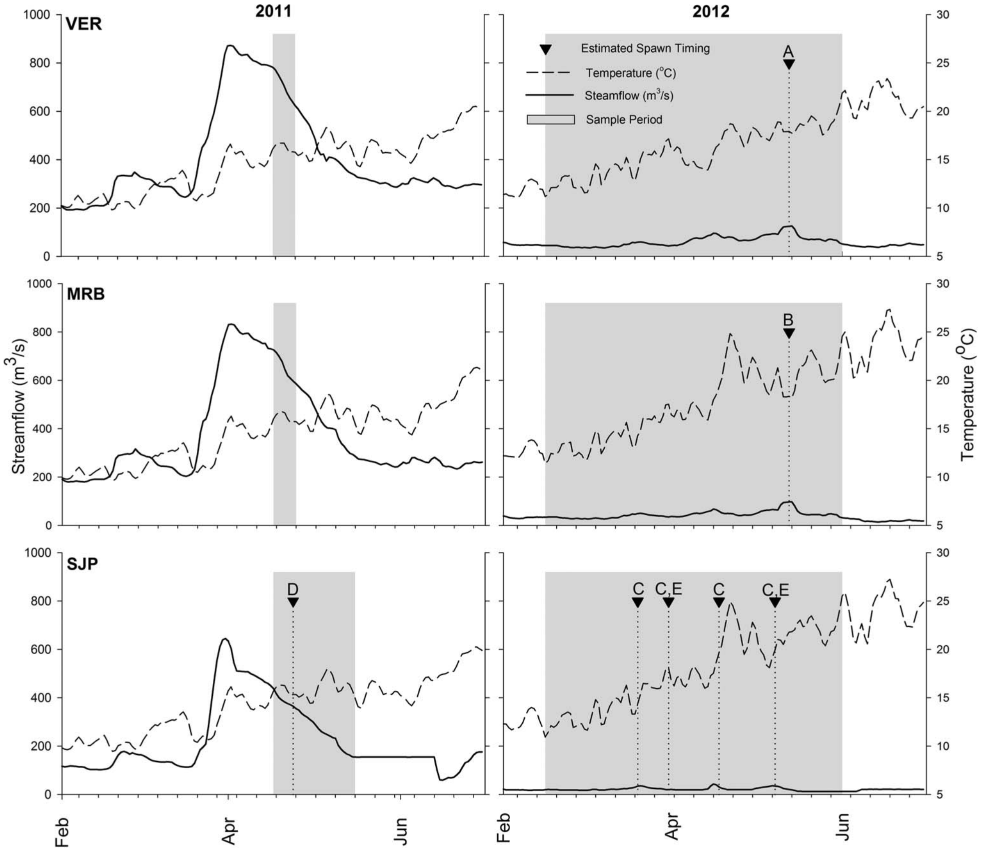

Figure 2. Mean daily average streamflow (m^3/s) and water temperature (°C) observed from February 1–July 1, 2011 and 2012, on the San Joaquin River, California, at the white sturgeon (*Acipenser transmontanus*) spawning survey sampling sites: (top panels) downstream of the Stanislaus River (river kilometer [rkm] 115.2); (middle panels) between the Stanislaus and Tuolumne rivers (rkms 120.4 and 126.4 in 2011 and rkm 126.4 in 2012); and (bottom panels) upstream from the Tuolumne River (rkms 137.4, 138.1, 140.8, 143.7, and 145.3 in 2011 and rkms 137.6 and 139.8 in 2012). Streamflow and water temperature data were obtained from the U.S. Geological Survey gaging station at Vernalis, California (VER; USGS 11303500) and California Data Exchange Center gaging stations at Maze Road Bridge (MRB) and San Joaquin near Patterson, California (SJP). Shaded areas represent the timing of sampling activities for each respective sampling area. Triangles represent estimated spawn timing and are coded by sample location (A = rkm 115.2; B = rkm 126.4; C = rkm 137.6; D = rkm 138.1; E = rkm 139.8).

An increase in streamflow is believed to be an important cue for migration and spawning of white sturgeon within various watersheds (Hildebrand et al. 1999; Paragamian and Wakkinen 2011). During the drought year of 1991, Schaffter (1997) documented white sturgeon spawning in the Sacramento River 1–3 d after an increase in streamflow of approximately 40 m^3/s. Auer (1996) observed increases in spawning activity of lake sturgeon concomitant with a change in water management operations on the Sturgeon River, Michigan, from a peaking operation to releasing near–run-of-river flows. The change in operations resulted in, among other things, 74% more fish observed and an estimated 68% increase in the number of females present (Auer 1996). In the present study, we documented white sturgeon spawning in the San Joaquin River in 2011 as flood flows receded. However, it remains unknown if spawning had occurred during the peak in streamflow at the end of March, since sampling did not commence until April 18. In comparison, white sturgeon spawning was observed at all four sampling locations in association with short-duration streamflow pulses during low streamflow conditions of 2012. Two March and early-April streamflow pulses (~18 to 25 m^3/s) were the result of rainfall, whereas one streamflow pulse (mid-May) was the result of reservoir releases on the Tuolumne and Merced rivers. Both rivers are tributaries to the San Joaquin River in the vicinity of the study area, and the reservoir releases were intended to increase survival of emigrating juvenile salmonids. Such flow augmentations appear to be providing unintended benefit to white sturgeon.

We collected 23 eggs over a 4-d period at rkm 142 in 2011. Water temperatures during the incubation period ranged from 14.6 to 15.8°C and were consistent with optimal white sturgeon spawning temperatures observed on the Columbia and Sacramento rivers, 10 to 18°C and 14 to16°C, respectively (Kohlhorst 1976; Parsley et al. 1993; McCabe and Tracy 1994). However, mean daily water temperatures in our study area during 2012 began to surpass 18.0°C in mid-April. Egg collections on April 19 (rkm 137.6) and May 10 (rkm 137.4; rkm 139.8)

Table 2. White sturgeon (*Acipenser transmontanus*) egg data from 2011 and 2012 San Joaquin River spawning survey collections. Sample date and location (river kilometer [rkm]), the number of collected eggs, percentage of collected eggs that were viable upon collection, length (mean ± SD) and width (mean ± SD) of eggs, number of spawning events, estimated timing of fertilization, and developmental stages represented by each egg collection are presented. We based developmental stage Dettlaff et al. (1993), and estimated time of fertilization was back-calculated using mean daily water temperatures and developmental stage. Minimum number of spawn events was based on rkm, date egg mats were retrieved, calculated fertilization time, and the assumption it takes up to 21 h to complete oviposition (Van Eenennaam et al. 2012) following the methods of Poytress et al. (2015).

Sample date	Rkm	No. of eggs	% Viable	Egg diameters (mm) Length	Width	Spawning events	Estimated timing of fertilization	Developmental stage
April 25, 2011		15	100%	3.26 ± 0.18	3.02 ± 0.18	1		
April 27, 2011	138.1[a]	3	100%	3.34 ± 0.18	3.21 ± 0.05		April 24, 1300 hours–April 25, 0300 hours	9–27
April 28, 2011		4	25%	3.57 ± 0.02	3.34 ± 0.01			
Mar 22, 2012	137.6	26	62%	3.56 ± 0.12	3.44 ± 0.12	1	March 20,1800 hours–March 21, 0100 hours	18–19
April 2, 2012	137.6, 139.8[b]	8	63%	3.51 ± 0.12	3.44 ± 0.12	1	March 31	22
April 19, 2012	137.6	5	60%	3.46 ± 0.02	3.34 ± 0.16	1	April 18, 0300 hours	22
May 10, 2012	137.6	3	100%	3.64 ± 0.10	3.42 ± 0.05	1[c]	May 8, 1900 hours	26
May 10, 2012	139.8	13	69%	3.55 ± 0.10	3.46 ± 0.11		May 8, 1300 hours	28
May 14, 2012	126.4	5	100%	3.58 ± 0.09	3.42 ± 0.07	1	May 13, 0600 hours	18
May 14, 2012	115.2	5	100%	3.46 ± 0.05	3.35 ± 0.08	1	May 13, 1500 hours–May 14, 0800 hours	4–14

[a] Based on developmental stage and estimated time of fertilization, these eggs could be from one female spawning over at least 14 h.

[b] We pooled eggs collected at the rkm 137.6 and 139.8 sites on April 2, 2012, due to missing site discrimination data.

[c] The May 10 spawning event could be one female that moved between rkm 137.6 and 139.8 within that approximate 6-h time period, or it could be from multiple females.

occurred when recorded hourly water temperatures during the incubation period were 18.6 to 20.9°C and 19.9 to 22.1°C, respectively. Wang et al. (1985) reported white sturgeon hatching rates decrease at 20°C and complete arrest of embryonic development at 23°C in laboratory experiments. Although embryos were exposed to unfavorable temperatures during the spawning and incubation period in 2012, we observed no obvious signs of deformities at the stages of embryonic development in any viable eggs that were collected. One may question whether the observed nonviable eggs could be related to the elevated temperatures; however, most of these nonviable eggs were found early in the spawning season when temperatures were within the optimal range, and 75% of the collected eggs were viable. A number of factors other than temperature may be causing or contributing to embryo mortality, including contaminants, sampling-related damage, and substrate type (Lemly 1996; Kock et al. 2006; Parsley and Kofoot 2013). Additionally, nonviable eggs may simply not have been fertilized. Considering the high fecundity of white sturgeon it is conceivable that some eggs might not be fertilized and we sampled too few eggs to make any definitive conclusions regarding the effect of elevated temperatures.

Sturgeon spawning habitat is generally associated with depths greater than 4 m (Parsley and Beckman 1994; Chapman and Jones 2010; Paragamian 2012). Deep pool habitat is limited on the San Joaquin River during most years. Flood conditions during 2011 resulted in elevated river stage and we collected egg samples at depths varying from 8.2 to 10.5 m. In contrast, in 2012 we collected eggs at depths varying from 1.6 to 9.1 m, and 43.9% of eggs were collected at depths less than 2.0 m (25 of the 57 eggs of known origin). Paragamian (2012) suggested that white sturgeon spawn in areas of highest available velocities and depth. The limited availability of sites with depths greater than 4 m and adequate velocities (Z.J. Jackson, unpublished) may be influencing fish to select shallow spawning sites with suitable velocities over deeper sites lacking adequate velocities.

Both rain events and San Joaquin River basin water management decisions resulting in increased streamflows preceded documentation of white sturgeon spawning. In wet years, this may take the form of elevated streamflow managed for flood control purposes and in dry years, small-magnitude, short-duration in-

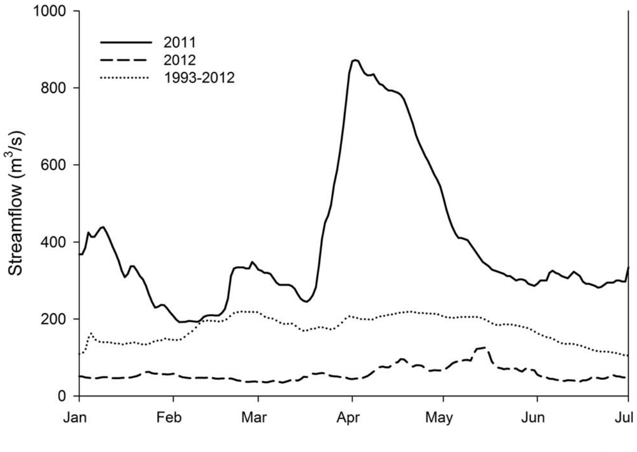

Figure 3. San Joaquin River mean daily streamflow (m^3/s) during January–June, 1993–2012, measured at the U.S. Geological Survey gaging station at Vernalis, California (USGS 11303500). These data are presented to demonstrate streamflow conditions observed during the 2011 and 2012 San Joaquin River white sturgeon (*Acipenser transmontanus*) spawning surveys with average streamflow conditions observed over a 20-y period ending in 2012.

creases in streamflow appeared to initiate spawning. Continued efforts should be made to restore a natural hydrologic regime and provide sturgeon spawning flows (streamflow increases $\geq$40 m^3/s) within the San Joaquin River during March–May. Ongoing regulatory and management processes (e.g., restoration of flow and habitat in the main stem river by the San Joaquin River Restoration Program, minimum flow requirements mandated by the Federal Energy Regulatory Commission and State Water Resources Control Board) may result in the desired hydrology and temperature needed to increase white sturgeon recruitment in the San Joaquin River. Future research should be implemented to evaluate the results of new management actions.

Current monitoring efforts include describing available habitat (e.g., depth, substrate, velocity) within the San Joaquin River (Z.J. Jackson, unpublished). Our research suggests that increases in streamflow during the March–May period are important drivers of spawning activity, perhaps more so than other important habitat features. However, additional research is needed to refine our understanding of the relationship between streamflow, velocity, water temperature, depth, and substrate on spawning initiation and success throughout the range of the species. Additional and more intensive egg sampling (i.e., more mats and more frequent mat retrieval), in conjunction with acoustic tracking of adults should also focus on further evaluating the effects of salmonid-focused flow augmentations on white sturgeon spawning and recruitment. Larval sampling should be conducted in various water-year types and across various water management scenarios in order to inform evaluation of the quantity and suitability of available spawning and rearing habitat and verify hatching success. Demonstrating additional benefit from spring flow augmentations may result in added support for continuing efforts to partially mimic natural hydrologic conditions. Additionally, salmonid-focused habitat restoration actions should consider white sturgeon spawning and rearing habitat needs to improve instream habitat for both important resources. Documentation of environmental conditions associated with successful recruitment of white sturgeon is of utmost importance for informing future water management actions in California and throughout their range.

Supplemental Material

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Table S1. Table of sampling location (river kilometers [rkm]), sampler identification number (float no.), sampler deployment and retrieval dates, times, and river depths (m), and the presence (eggs) and number of eggs (total eggs) collected during 2011 and 2012 San Joaquin River white sturgeon (*Acipenser transmontanus*) spawning surveys on the San Joaquin River, California.

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Table S2. Data for identified white sturgeon (*Acipenser transmontanus*) eggs collected during 2011 and 2012 San Joaquin River spawning surveys, California. Data include sampling date and location (river kilometer [rkm]), minimum (min) and maximum (max) egg diameter measurements, calculated spawning date and time (hour), the estimated number of spawning events (events), and egg developmental stage assignments.

Found at DOI: http://dx.doi.org/10.3996/092015-JFWM-092.S2 (18 KB PDF).

Reference S1. Beamesderfer R, Simpson M, Kopp G, Inman J, Fuller A, Demko D. 2004. Historical and current information on green sturgeon occurrence in the Sacramento and San Joaquin rivers and tributaries. Report by S.P. Cramer & Associates to State Water Contractors, Sacramento, California.

Found at DOI: http://dx.doi.org/10.3996/092015-JFWM-092.S3 (8722 KB PDF).

Reference S2. Cain JR, Walkling RP, Beamish S, Cheng E, Cutter E, Wickland M. 2003. San Joaquin Basin ecological flow analysis. Berkeley, California: Natural Heritage Institute.

Found at DOI: http://dx.doi.org/10.3996/092015-JFWM-092.S4 (7161 KB PDF).

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Found at DOI: http://dx.doi.org/10.3996/092015-JFWM-092.S7 (1932 KB PDF).

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