Green sturgeon habitat suitability varies in response to drought related flow regimes

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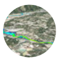

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Green sturgeon habitat suitability varies in response to drought related flow regimes

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Abstract A series of habitat suitability models were created based upon 2-dimensional tracking of Green Sturgeon and hydraulic simulations. This is an effort to better understand the relationship between the population decline, habitat suitability, and knowledge of the remaining post-dam era habitat available to Green Sturgeon. Records of the movements of Green Sturgeon were collected using a refined acoustic telemetry system (Vemco Ltd., Vemco Positioning System [VPS]) in three pools, the first at rkm 377.0 at the confluence with the Sacramento River of Antelope Creek, the second at rkm 407.5 at the confluence with Inks Creek, and the third at rkm 426.0 at the confluence with Paynes Creek near Red Bluff over a period of two years. The Flow and Sediment Transport with Morphologic Evolution of Channels (FaSTMECH) model was used to simulate depth and velocity. Previously developed habitat suitability curves for spawning Green Sturgeon within the study area were coupled to two-dimensional hydraulic simulations to estimate Weighted Usable Area (WUA), a metric of suitable habitat area within each of the studied reaches. The effect of changing river discharges on suitable spawning habitat for Green Sturgeon was examined over a six-year period, the first of which had normal rain conditions and the following years drought conditions. The peak amounts of spawning habitat in the pool on the Sacramento River at the rkm 377 was the same for all six years, roughly 8000 square meters. The constancy in the amount of WUA, in the face of decreasing rates of discharge may explain why these sites are occupied from year to year. The amount of spawning habitat in the pool at rkm 426, decreased during the four-year drought period, from 2012 to 2015. This may make it less favorable for occupation by Green Sturgeon.

Keywords Green sturgeon · Habitat suitability · Drought · Hydrology · Telemetry

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Introduction

The Green Sturgeon (*Acipenser mediorostris*) was listed during April 2006 as "threatened" according to the Endangered Species Act (National Marine Fisheries Service 2006). Criteria supporting the need for listing status can be summarized as follows: 1) the decrease in its historical habitat, 2) a precipitous decline in population numbers, 3) limited documentation of spawning outside of the main-stem Sacramento River, and 4) potential loss of quality habitat within the Sacramento River and Delta system (National Marine Fisheries Service 2006; Adams et al. 2007). Observational data from Klamath and Rogue River Green Sturgeon which have attempted to quantify the loss of available habitat would suggest that use of main-stem channel habitat is greater than that of smaller tributary streams (Mora et al. 2009). However, within the Sacramento – San Joaquin system, modelling would suggest that Green Sturgeon could distribute within several of the larger tributaries such as the Feather River, Pit, and the McCloud River (Mora et al. 2009).

The Green Sturgeon is an anadromous fish species that spend the majority of its adult life in the northeast Pacific Ocean along the western coast of North America (Moser and Lindley 2007; Moser et al. 2016; Lindley et al. 2008). Adults migrate northward over the coastal shelf during the fall, winter off the coast of Washington and Canada, and move southward during the spring to enter the bays and estuaries (Erickson and Webb 2007; Huff et al. 2011; Lindley et al. 2008, 2011; Moser and Lindley 2007). Mature adult Green Sturgeon migrate during late spring to the upper Sacramento River (Heublein et al. 2009; Wyman et al. 2017), where they spawn (Brown 2007; Poytress et al. 2015). They enter their river of origin approximately every two to six years with a peak interval of four years to spawn (Mora et al. 2017).

The population appears to be very vulnerable to changes in hydrology. For example, in April 2011, 24 Green Sturgeon were rescued from two flood diversions in the Sacramento River (Thomas et al. 2013). Coded acoustical beacons were placed on these stranded individuals and their migratory success and survival were determined with an array of autonomous receivers throughout the watershed. Seventeen of the 24 continued their upstream migration to their spawning grounds. A population viability analysis indicated that the population would decrease 50% below the baseline population level over 50 years in the absence of rescue. The size of the spawning run is not large, estimated to vary between 336 to 1236 between 2010 and 2015 by sampling with a Dual-Frequency Identification Sonar (DIDSON) (Mora et al. 2015). Hence, there is a need to know the extent of suitable habitat for spawning between years. The objective of this study was to compare the Weighted Usable Area (WUA), a metric of suitable habitat area, of three sites between wet and dry years to understand how drought impacts the quantity of habitat suitable to Green Sturgeon for spawning in the Sacramento River.

Methods

Wyman et al. (2017) provided a framework for evaluating behavioral preferences for physical habitat parameters on the microhabitat scale during the Green Sturgeon upstream migrations on the Sacramento River. This study builds on those results. A brief synopsis of the previous analysis is provided here, however, the reader is referred to Wyman et al. (2017) for details of the acoustic telemetry, hydraulic modeling, and habitat suitability values used here.

The movements of Green Sturgeon were recorded during 2011 and 2012 with an array of acoustical receivers (Vemco Ltd. VR-03) configured as a Vemco Positioning System (VPS) that tracked the movements of individuals in two dimensions. Tag detections from each receiver were post-processed by VEMCO to derive fish positions with an associated horizontal positioning error (HPE) estimate calculated for each position. HPE is a unitless estimate of error: lower HPE values correspond to smaller scatter of calculated positions (i.e., higher accuracy) (Smith 2013). Fish positions with HPE >8 m were removed from the data set to increase the accuracy of the fish positions used in subsequent analyses (see Scheel and Bisson 2012; Coates et al. 2013). These locations were pools at the confluences of Antelope (Site A) at rkm 377.0, Inkes (Site B) at rkm 407.5 and Paynes Creek (Site C) at rkm 426.0 of the Sacramento River. Wyman et al. (2017) used the positions of Green Sturgeon as recorded in the VPS and superposed those positions on two-dimensional hydraulic simulations of velocity and depth. In addition, the spatial distribution of grainsize composition of the channel bottom at each of the three sites was determined using a DIDSON acoustic camera (Wyman et al. 2017). The physical habitat parameters of interest: depth, velocity, and substrate, are hereafter referred collectively as the habitat parameters. At each fish location, the habitat parameters were determined by interpolating depth and velocity from the hydraulic simulations and grainsize from spatial maps of grainsize, for each recorded fish position. The resulting distributions of each habitat parameter were grouped by available and utilized habitat within the sampled footprint of the VPS system. The results indicated that at these three known locations, tagged Green Sturgeon generally occupied deeper and faster locations within the available or sampled habitat during the spawning season. In other words, the sturgeon occupied a selective or preferred subset of the available physical habitat. The measurements, on which habitat preference curves were based, are presented in Tables 1, 2, 3.

The goal of this study is to use these previously developed habitat preference curves to calculate weighted usable area (WUA) as a function of discharge through each of the three study sites between 2011 and 2016. As in the previous study a two-dimensional hydraulic simulation generates spatial and temporal values of depth and velocity through each study reach. To include substrate, surveyed substrate values were mapped to the hydraulic model grid. The result are daily gridded values of the habitat metrics. WUA, is then calculated as:

$$WUA = \sum_{i=1}^{n} F(f(D_i), f(V_i), f(S_i)) \times A_i,$$

where f(Di), f(Vi), and f(Si) are the simulated suitability values at each cell of the grid for depth, velocity and substrate. F is the geometric mean of the three gridded habitat parameters, and A is the area of each cell, and n is the number of cells in the grid. WUA is calculated on a daily basis and for each simulated period a function of WUA vs discharge is developed.

The positions of the receivers as well as the densities of fish detections within each site were determined during 2011 and 2012. Positions of the fish were then entered into model with measurements of environmental properties. The depths and flows were recorded using an Acoustical Doppler Current Profiler (ADCP), while the substrate type was determined using a DIDSON acoustical camera. The spatial distribution of the fish positions were then related to bathymetry, flow field, and extent of different substrate types. Habitat suitability curves were developed for depth, velocity, and substrate type within three known spawning locations over two years. An overall cumulative habitat suitability score was calculated that averaged the depth, velocity, and substrate scores over all fish, sites, and years. A weighted usable area (WUA) index was calculated throughout the sampling periods for each of the three sites. Cumulative results indicate that the microhabitat characteristics most preferred by Green Sturgeon in these three spawning locations were velocities between 1.0–1.1 m/s, depths of 8–9 m, and sand, gravel, and cobble substrate.

Table 1 Mean annual discharge, percent annual mean, and mean annual run-off for the Sacramento River and the state of California over a six-year period from 2011 to 2016, including four drought years from 2012 to 2015

Year	Mean Annual Discharge (m^3/s)	Percent of Annual Mean, Yrs 1964–2016	Total Annual Run-Off (ac-ft/year)
2011	390.7	110.8	9,994,964
2012	266.0	75.4	6,805,991
2013	273.0	77.4	6,983,438
2014	192.4	54.6	4,922,882
2015	201.0	57.0	5,143,061
2016	269.9	76.5	6,904,492

The objective of our study was to investigate, through similar modeling, the effect of reduced river discharges on suitable spawning habitat for Green Sturgeon during a period of drought. During the period of the drought, 2012 to 2016, the rate of discharge decreased from the mean annual discharge of 341.12 m^3/s from 1965 to 2016. It ranged from 80.0% in 2013 to 56.4% of the mean annual discharge in 2014. Our intent was to summarize drought related discharge, during the spawning season, for the dry years of 2012–2016 and compare them to the wet year of 2011. These discharges were run as inputs for the hydraulic modeling, and WUA was calculated for each of the five drought years within the three study sites. A comparison of WUA between dry and wet years was completed to investigate either the expansion or more likely the contraction of available suitable habitat within each of the three study sites during drought conditions (Fig. 1).

Results

The mean annual average discharge of water measured at the U.S. Geological Survey (USGS) gage Sacramento River above Bend Bridge near Red Bluff, CA (USGS gage# 11377100), based on daily measurements from 1 January to 31 December of each year, was 390.7 m^3/s in 2011 (Table 4). This was equivalent to a total annual run-off of 9,994,964 acre feet per year from the watershed above Bend Bridge. This is a unit of volume commonly used in the United States as a reference to large-scale water resources such as reservoirs,

Table 2 Weighted Habitat Suitability Indices (WHSI) for different depths

Depth (m)	0.0–0.9	1.0–1.9	2.0–2.9	3.0–3.9	4.0–4.9	5.0–5.9	6.0–6.9	7.0–7.9	8.0–8.9	9.0–9.9	10.0–10.9	11.0–11.9
Normalized Count	0.00	0.00	0.00	0.00	0.02	0.03	0.08	0.13	0.27	0.22	0.06	0.02
WHSI	0.01	0.00	0.01	0.09	0.13	0.29	0.49	0.54	1.00	0.82	0.20	0.08

aqueducts, canals, and river flows. It is defined by the volume of water necessary to cover one acre of surface area to a depth of one foot. We used this indicator, although not a metric unit, because it has a tangible meaning and is used widely among hydrologists, although it is equivalent to 1233.5E+10 cubic meters of water. The mean discharge during 2011 within the river was 110.8% of the average mean discharge, 341.12 m^3/s, recorded for years 1964 to 2016, the period record available. The mean annual discharge decreased during the following five years to a minimum of 192.4 m^3/s, or 56.4% of normal, during 2014 before rising slightly during 2015 and continuing to rise during 2016 to 269.9 m^3/s, or 76.5% of the average recorded discharge. The wet period followed by the extended drought is best shown in a graph (Fig. 2).

Site A, the pool on the Sacramento River at the confluence with Antelope Creek, appeared to be most resilient to extreme flows. The peak amount of suitable habitat was the same for all six years, roughly 8000 m^2 (see orange traces in Fig. 3). Although suitable habitat was low with the initial high level of flow during spring 2011 (see blue trace), the non-drought year, it increased to a peak of 8000 m^2 with the precipitous drop in flows during May of 2011. However, the amount of suitable habitat then decreased to 4800 m^2 with more gradually increasing flows to a minimum before increasing again to 7200 m^2 with decreasing flows during the first year. During the next two years, 2012 and 2013, the suitable habitat decreased with increasing flows. On the other hand, the amount of suitable habitat increased with increasing flows during the same period during the second three years, 2014–2016. The minimum amount of suitable habitat, excluding 2011, ranged from 5250 m^2 in 2015 to 7500 m^2 in 2016. The within-year range in suitable habitat ranged from 500 m^2 during 2016 to 2750 m^2 in 2015.

The maximum amount of suitable habitat at Site B was slightly less than that of Site A and much less than Site C. It ranged from 6500 m^2 during 2014 to just above 6000 m^2 during the non-drought year, 2011 (see orange traces in Fig. 5). It remained relatively constant from 2011 to 2016. Similar to Site A, the suitable habitat decreased during the non-drought year, 2011, and the first three years of the drought, 2012–2014. It remained relatively constant during the next two years characterized by small increases and decreases in the flow. The changes in flow were similar to those at Site A but much less than that occurring at Site C.

The maximum amount of suitable habitat at Site C was greater than at Sites A and B. It was roughly 13,000 m^2 during the non-drought year, 2011, and the first two years of the drought, 2012 and 2013 (see orange traces in Fig. 4). However, it was lower during the next three years, 12,000 m^2 during 2014, 10,000 m^2 during 2015, and 11,500 m^2 during 2016. Yet during each year the maximum amount of suitable habitat at Site C was greater than that at Sites A and C. The minimum amounts of suitable habitat at Site C exceeded those at Sites A and B during all of the drought years. Furthermore, the change in the amount of suitable habitat at Site C was greater than that at Sites A and B during each of the drought years. The decrease in suitable habitat during low flows ranged from 3500 m^2 during 2012 to roughly

Table 3 Weighted Habitat Suitability Indices (WHSI) for different water velocities

Velocity (ms^{-1})	0.00–0.09	0.10–0.19	0.20–0.29	0.30–0.39	0.40–0.49	0.50–0.59	0.60–0.69	0.70–0.79	0.80–0.89	0.90–0.99	1.00–1.09	1.10–1.19	1.20–1.29	1.30–1.39	1.40–1.49	1.50–1.59
Normalized Count	0.1	0.02	0.06	0.10	0.19	0.33	0.43	0.55	1.03	1.86	2.27	1.87	1.00	0.23	0.04	0.00
WHSI	0.01	0.01	0.03	0.05	0.08	0.15	0.19	0.24	0.46	0.82	1.00	0.83	0.44	0.10	0.02	0.00

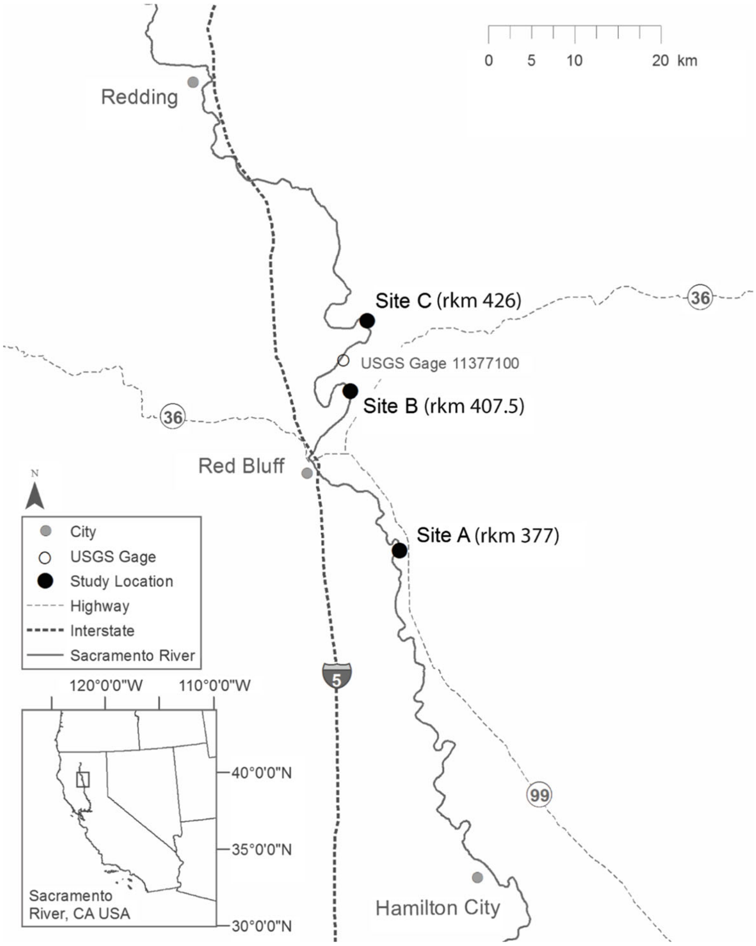


Fig. 1 The three sites where movements of green sturgeon were determined with VPS, Site A at 377 rkm, site B at 407.5 rkm, and site C at 426 rkm [modified from Fig. 1 in Wyman et al. (2018) with permission]

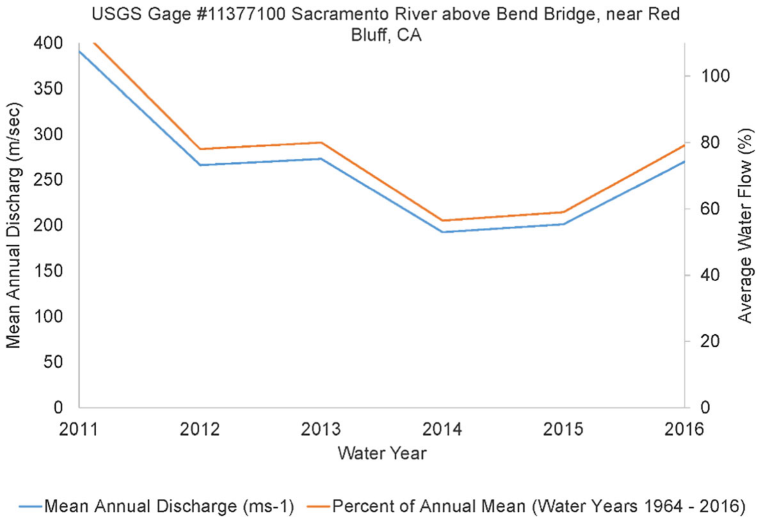
5000 m during 2014 and 2015. Hence, the low flows at Site B drastically decreased the amount of suitable habitat available there.

The WUA versus discharge can be compared between the sites. The WUA peaked at 750 m^2 at Site A (Antelope) with a discharge of roughly 275 m^3/s over the six-year period, the WUA peaked at 500 m^2 at Site B (Inks) at a discharge of 220 m^3/s, and the WUA at Site C (Paynes) peaked at nearly 4000 m^2 at a discharge of 350 m^3/s, (Fig. 6). The flows, measured at Bend Bridge near Red Bluff varied from 200 m^3/s in March 2016 (see 25th percentile in stippled square, right panel) to a little over 400 m^3/s at the end of June 2016, encompassing the period of spawning. Hence, it is interesting that sturgeon spawn at the time when the suitable habitat is maximum with discharge rates varying from a little below 200 m^3/s to a little above 400 m^3/s. The maximum amount of suitable habitat at Paynes (Site C) was generally greater than at Site A (Antelope) and B (Inkes) (see left panel in Fig. 5). Furthemore, the inter-annual change in amounts of suitable habitat at Site C was greater than at Sites A and B.

Table 4 Weighted Habitat Suitability Indices (WHSI) for different substrate types

Substrate Type	Sand	Gravel	Cobble	Boulder	Bedrock
Normalized Count	0.11	0.36	0.17	0.26	0.11
WHSI	0.29	1.00	0.45	0.71	0.29

Fig. 2 Mean annual discharge in $m^3 s^{-1}$ and percent of annual mean between 1964 and 2016 shown over a period of six years including four, 2012–2015, that constituted a drought



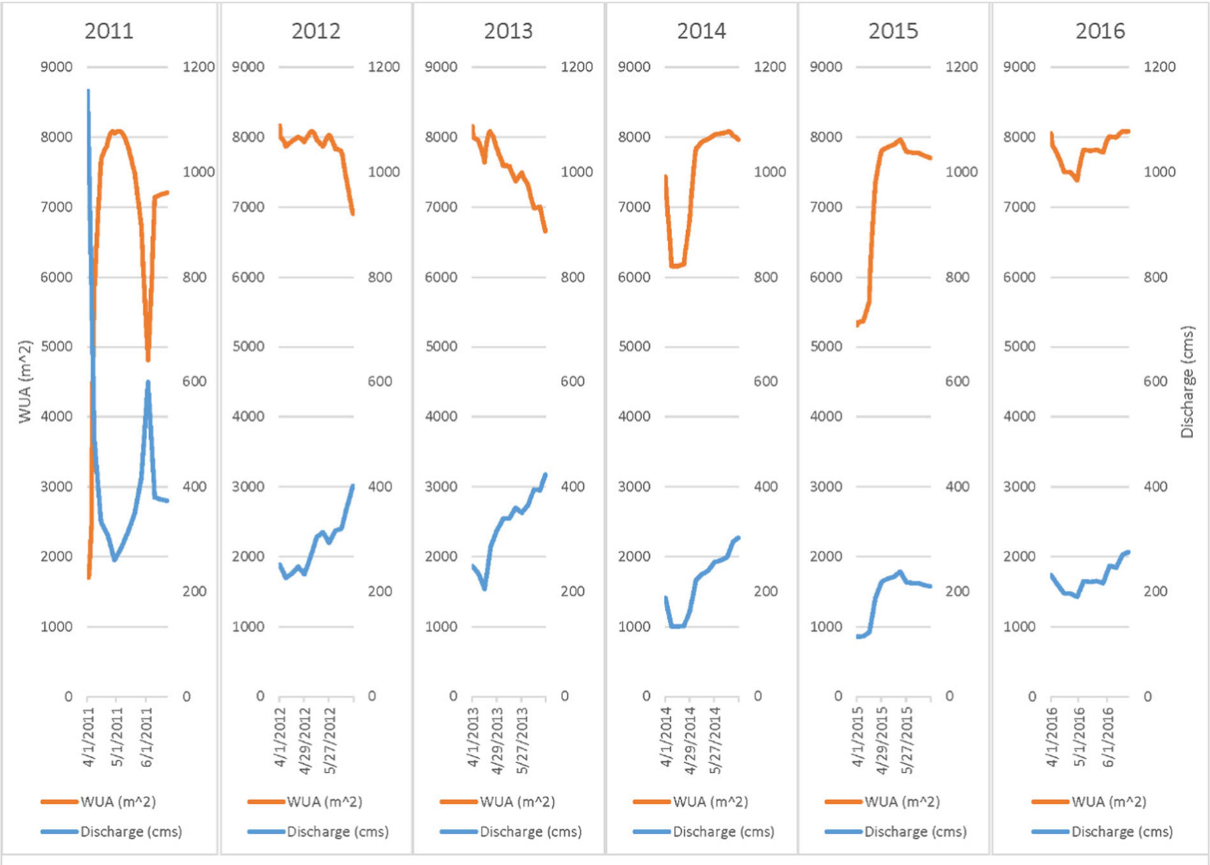


Fig. 3 The wetted useable area for green sturgeon in the presence of different rates of water discharge at the confluence of Site A during a six-year period from 2011 to 2016, including four drought years from 2012 to 2016. Note that the WUA remains relatively constant despite moderately decreasing levels of discharge. This may explain why green sturgeon favor this pool as a site suitable for spawning, i.e., there is constancy in the amount of spawning habitat present when averaged over the whole year

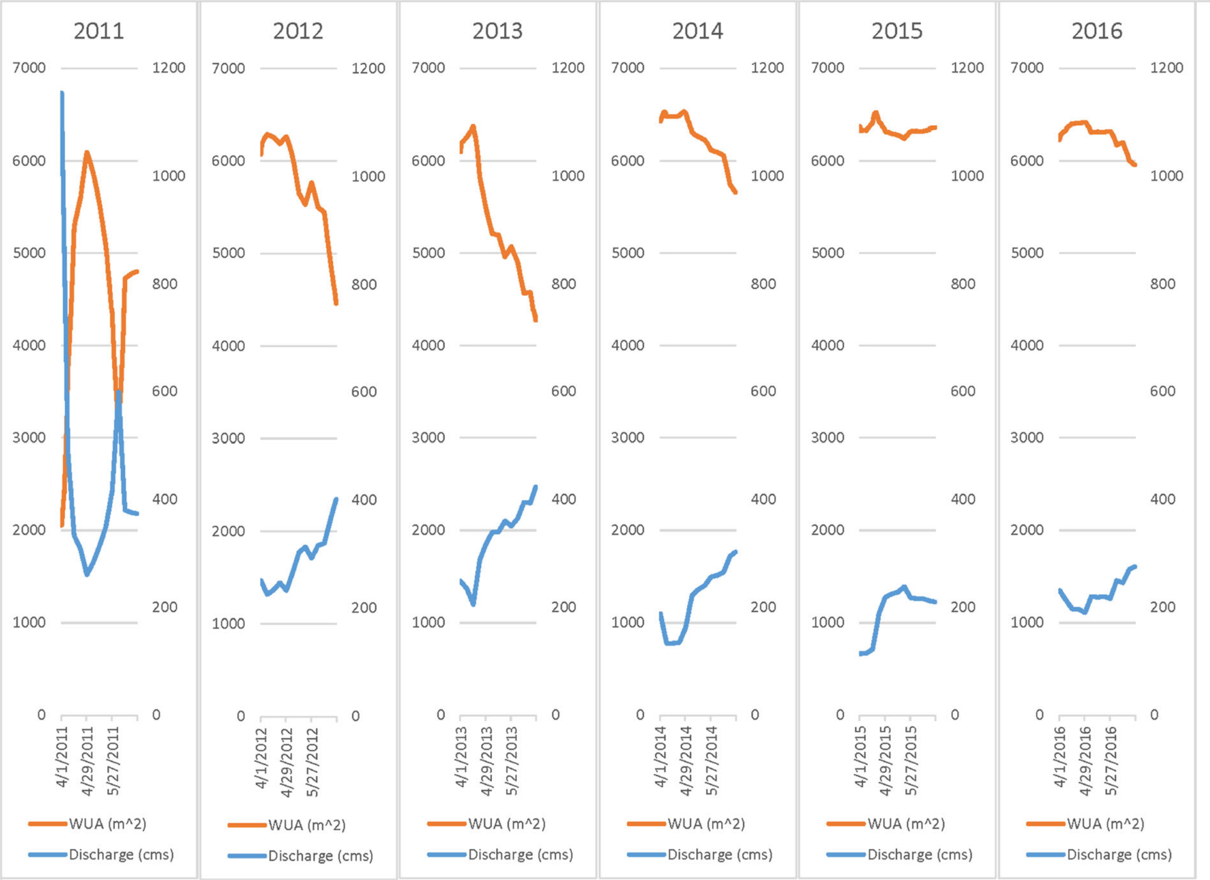


Fig. 4 The wetted useable area for green sturgeon in the presence of different rates of water discharge at the pool on the Sacramento River at Site B during a six-year period from 2011 to 2016, including four drought years from 2012 to 2016. Note that the maximum amount of WUA was similar to that of Site A as well as the change in flows during each year

Discussion

The distribution of Green Sturgeon tracked by an array of tag-detecting receivers in Sites A-C were related to environmental conditions determined using an acoustic doppler current profiler (ADCP) and a two-dimensional hydrodynamic model. The methodology is described in detail Wyman et al. (2017). An overall cumulative habitat suitability score was calculated that averaged the depth, velocity, and substrate scores over all fish, sites, and years. A weighted usable area index was calculated throughout the sampling periods for each of the three sites. Cumulative results indicate that the microhabitat characteristics most preferred by Green Sturgeon in these three spawning locations were velocities between 1.0 and 1.1 m/s, depths of 8–9 m, and gravel and sand substrate. Artificial substrate samplers were used to collect Green Sturgeon eggs at seven sites in the Sacramento River, including Sites A, B, and C (Poytress et al. 2015). The eggs were present on medium gravel substrates at sites with mean water column velocities of 0.8 m/s and at depths ranging from 0.6 to 11.3 m with a mean of 6.4 m. Fish may be selecting for depths which produce velocities in a more optimal range, given the discharge conditions at each location. Strong preferences for velocities over depths is are not observed in Gulf sturgeon (Flowers et al. 2009). Egg mat surveys reveal that the Gulf Sturgeon (*Acipenser oxyrinchus desotoi*) spawn over similar velocities and similar depths across years and between sites regardless of river conditions.

Changes in river discharge alter the spatial distribution of depth, velocity, and substrate composition. As such, the weighted usable area (WUA) of spawning sites, calculated based on the cumulative suitability index scores for these parameters, also fluctuates in

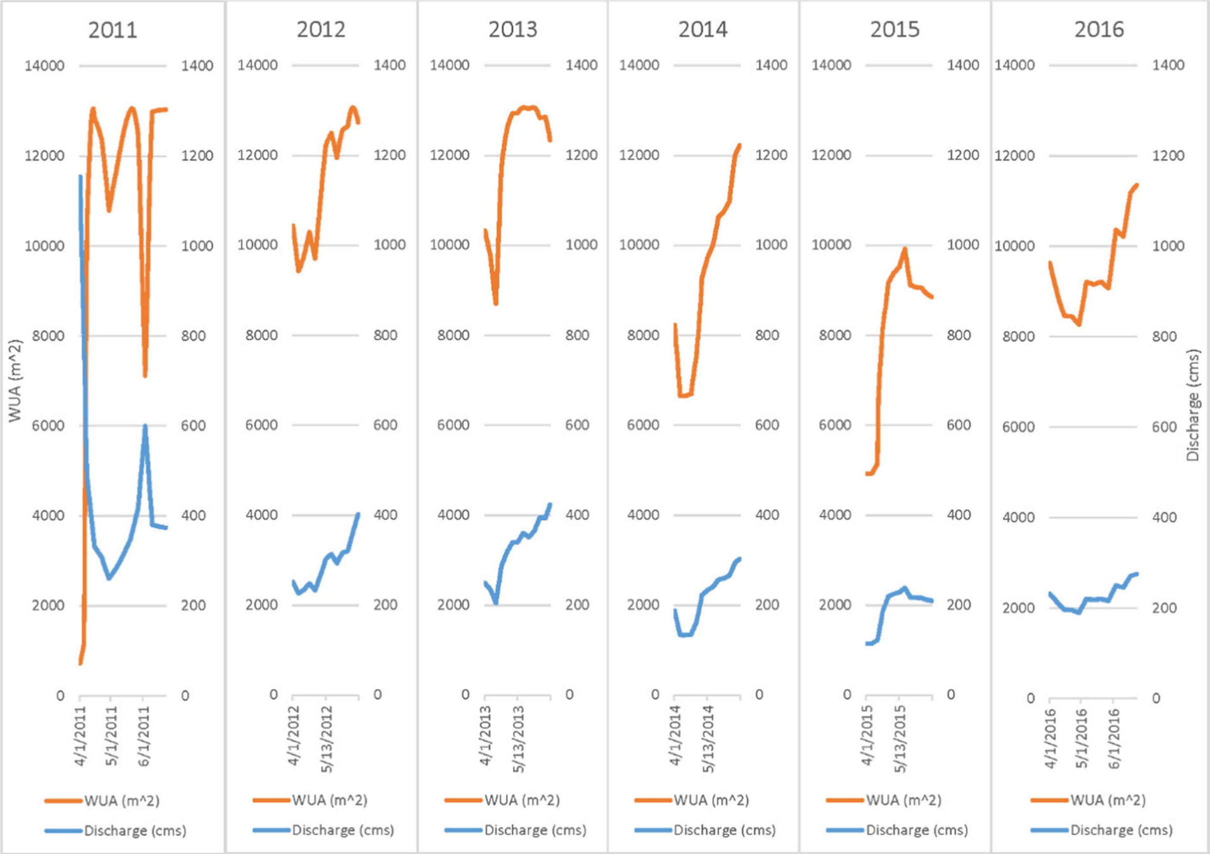


Fig. 5 The wetted useable area for green sturgeon in the presence of different rates of water discharge at the pool on the Sacramento River at Site C during a six-year period from 2011 to 2016, including four drought years from 2012 to 2016. Note that the maximum amount of WUA was greater than that of Site A, but the change in flows was more dramatic

relation to discharge. Alterations to discharge patterns due to drought can therefore have large impacts on the amount and quality of preferred spawning habitat (Gillenwater et al. 2006; Tonina et al. 2011). The shrinking of preferred spawning microhabitats would likely lead to decreases in sturgeon reproductive success through reduced survivorship of eggs and larvae, ultimately influencing recruitment and population dynamics within species (Flowers et al. 2009). These relationships highlight the importance of predicting the effects of discharge variation on preferred spawning habitat.

The amount of spawning habitat available during the drought varied with location. The maximum WUA remained relatively constant during the first wet year and five subsequent dry years at Sites A and B. The amount of suitable habitat either decreased or increased with increasing discharge over the period. The maximum amount of spawning habitat at Site C was greater as well as the minimum amount of habitat than Sites A and B. However, the degree of change in habitat was less at Sites A. and B. Hence, the latter locations encountered less dynamic changes in hydrology. It may be that pools with relatively constant WUAs between years and less dramatic changes in suitable habitat are favored more than those with high amounts of suitable habitat but greater interannual changes. The evidence for this hypothesis is mixed based on the CPU values for egg and larval retrieval at the sites (Poytress et al. 2015). Numbers of 29, 43, and 9 eggs and larvae were collected with CPUs of 0.151, 0.127, and 0.022 from 2008 to 2010 and numbers of 1, 9, and 16 with CPUs of 0. 003, 0.031, and 0.088 during 2010–2012 at Site A (see Table 1 in Poytress et al. 2015). Numbers of 1, 9, and 16 eggs and larvae were collected with CPUEs of 0.003, 0.031, and 0.088 during 2010–2012 at Site C. The number of estimated spawning events of 7, 10, and 3 at site A exceeded the 1, 3, and 2 estimated to occur at site C at rkm 426. However, only 2 and 1 larvae and

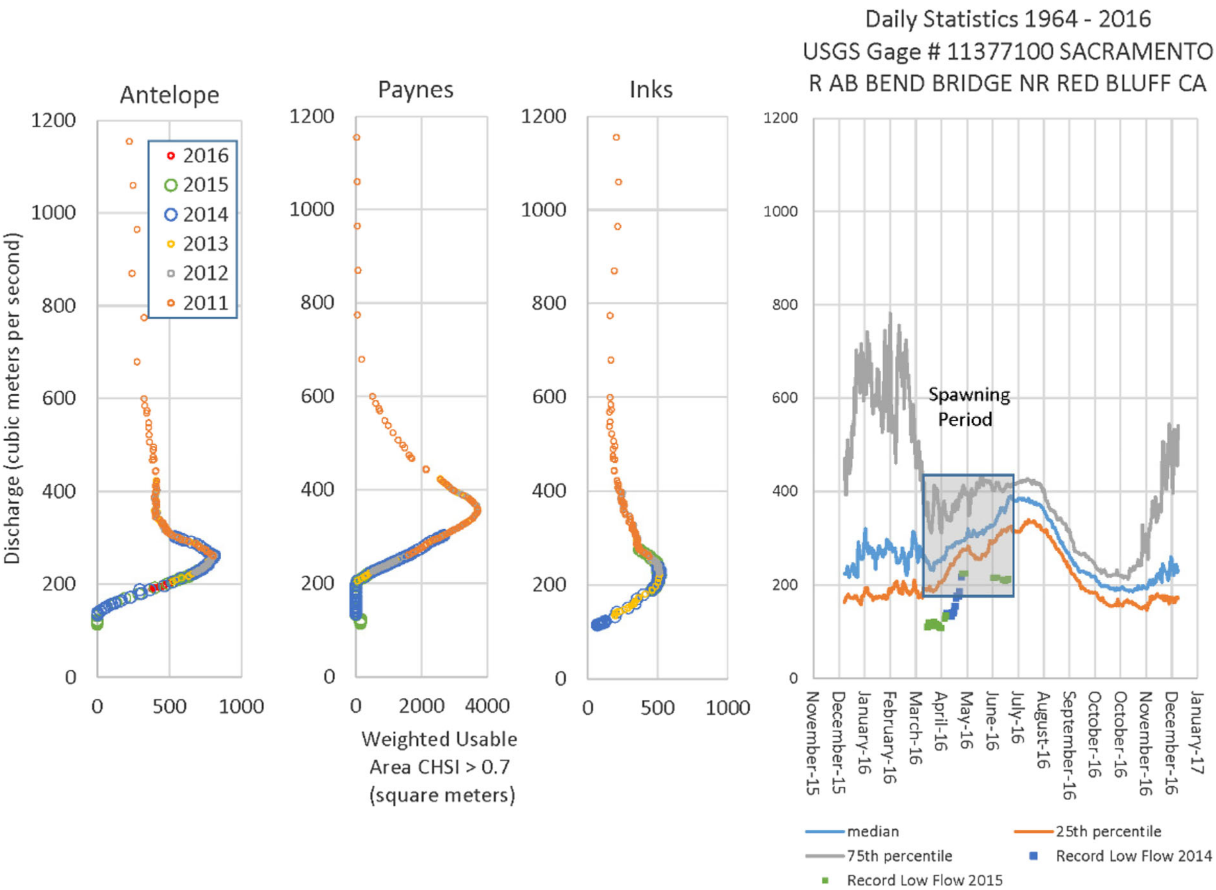


Fig. 6 The panels on the left indicate the WUA present during different discharge rates at three spawning locations, Sites A-C, based upon the collection of eggs and larvae. The right panel shows the discharge rates from November 2015 to January 2017. Note that the spawning period from 15 March to 15 June 2015 occurred at discharge rates varying from 200 to 400 m^2. The amounts of weighted useable area for spawning peaked in the presence of these discharge rates at all three sites on the Sacramento River

eggs were collected with CPUEs of 0.008 and 0.005 during 2009 and 2010 at Site B. These were attributed to 2 and 1 spawning events. Hence, the support for this hypothesis is mixed, and more egg and larval surveys will be necessary to either support or falsify this hypothesis. Adding further difficulty in answering this question is that sturgeon may now spawn more frequently above the Red Bluff Diversion Dam at rkm 391 once it was put in place a month later in 2009–2011 and removed during 2012–2013. The number of Green Sturgeon carrying coded acoustical beacons detected by autonomous monitors above the dam increased once the dam was operated later and increased more once it was decommissioned (Steel et al. 2018).

Habitat suitability index models have been utilized to examine riverine habitat suitability or selection in relation to resource management (Brown 2007; Vinagre et al. 2006), flow alternations (Zorn et al. 2012), climate change (Tonina et al. 2011), and dam removal and replacement (Gillenwater et al. 2006; Tomsic et al. 2007). We have used this approach to identify the range of available physical habitat variables within three Green Sturgeon spawning locations in the Sacramento River over a period of six years, of which five were considered to be drought conditions. As part of the designation of critical habitat for the sDPS Green Sturgeon, NMFS (2006) stated that suitable spawning sites should include deep pools with fast, complex flow regimes delivering currents sufficient to impede fungal growth, siltation, and suffocation of eggs. In general, Wyman et al. (2017) provided important methodologies for precise mapping of selected spawning habitat over a wide range of locations within the putative spawning grounds. This study utilized this approach to monitor the effect of a period of drought on the suitable area for spawning of green sturgeon in the Sacramento River. Indeed, the approach used here should be applied to much of the Sacramento River to quantify the amount of sturgeon spawning habitat that will remain in the future. The suitable area for spawning, based on the characterization of environmental properties, flow velocities, depths, and substrate composition, have been identified for three discrete locations, where evidence from the collection of eggs and larvae indicate that spawning has occurred within them. The next step will require a survey of the bathymetry of the upper Sacramento River so that the habitat suitability model can be used to indicate where suitable spawning habitat for the species occurs throughout the watershed over time in the future. With this knowledge, the river can be managed to sustain the vulnerable sDPS of Green Sturgeon in the future in light of a changing climate.

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