Life History Conceptual Model for White Sturgeon
(Acipenser transmontanus)

Prepared by

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Reviewed

PREFACE

This Conceptual Model is part of a suite of conceptual models which collectively articulate the current scientific understanding of important aspects of the Sacramento-San Joaquin River Delta ecosystem. The conceptual models are designed to aid in the identification and evaluation of ecosystem restoration actions in the Delta. These models are designed to structure scientific information such that it can be used to inform sound public policy.

The Delta Conceptual Models include both ecosystem element models (including process, habitat, and stressor models) and species life history models. The models were prepared by teams of experts using common guidance documents developed to promote consistency in the format and terminology of the models http://www.delta.dfg.ca.gov/erpdeltaplan/science_process.asp .

The Delta Conceptual Models are qualitative models which describe current understanding of how the system works. They are designed and intended to be used by experts to identify and evaluate potential restoration actions. They are not quantitative, numeric computer models that can be "run" to determine the effects of actions. Rather they are designed to facilitate informed discussions regarding expected outcomes resulting from restoration actions and the scientific basis for those expectations. The structure of many of the Delta Conceptual Models can serve as the basis for future development of quantitative models.

Each of the Delta Conceptual Models has been, or is currently being subject to a rigorous scientific peer review process. The peer review status of each model is indicated on the title page of the model.

The Delta Conceptual models will be updated and refined over time as new information is developed, and/or as the models are used and the need for further refinements or clarifications are identified.

CONTENTS

I. Introduction

The purpose of this report is to develop a conceptual life history model of white sturgeon (*Acipenser transmontanus*) and the factors that affect reproduction, growth, and survival in the Sacramento-San Joaquin Rivers and San Francisco bay-delta. This model can be used to organize, visualize, and evaluate how the complex life history of white sturgeon relates to the spatial and temporal variability of riverine and estuarine ecosystems and potential consequences of ecosystem restoration and water management alternatives. This model is compatible with the suite of environmental and species models developed by the Department of Fish and Game Ecosystem Restoration Program (ERP) to assess and prioritize proposed restoration actions for the delta. The model has a geographic emphasis on the Sacramento River and bay-delta regions, though the entire distribution of white sturgeon should be considered when population level responses are of concern, due to the migratory life history of this species.

The conceptual life history model incorporates information from numerous sources about white sturgeon, often relying upon life history information from populations outside California. While additional surrogate information from other North American sturgeons could have been used in the model, the distinctive diadromous and ecological characteristics of California white sturgeon limited the utility of these species' information, thus information from other diadromous sturgeon species is only occasionally considered. Due to the limits of quantitative information about white sturgeon, this model is presented in a qualitative narrative, though numerical information is provided when available. While it will not provide quantitative limits on species take relative to maintaining a stable population size, it could be further developed into a population forecasting model since it divides the life history into life history stages, transition probabilities, and factors whose effects on reproduction and survival could be quantified.

Life history stage transitions are visualized in a series of life stage submodels highlighting the processes and relationships among ecological factors influencing the transition between stages (Figures 1 and 2). A complex set of conditions and processes are necessary to determine whether an individual white sturgeon completes the transition from one life stage to the next. Our knowledge of how biotic and abiotic factors are critical for maintaining healthy populations is fairly basic. Thus, the importance, predictability, and understanding of each of these linkages are identified in the model. Lastly, a similar characterization of independent stressors is undertaken to describe potential factors affecting survival during each life history stage in a known geographic region. This model is dynamic and not intended to be a final version. As new data become available, the model should be refined so managers and biologists have the most current information available.

II. Biology (See Figure 2, 4; Table 1)

White sturgeon are long-lived, late-maturing diadromous fishes found in estuaries and major rivers along the west coast of North America. Early life stages of white sturgeon are highly sensitive to environmental variables such as water temperature, dissolved oxygen, sunlight, river flow, and salinity (Table 1). White sturgeon eggs are negatively buoyant and develop an adhesive gelatinous coat upon contact with water (Cherr and Clark 1985, Wang et al. 1985), which allows them to attach to the substrate very near where they were spawned. Hatching time is temperature-dependent and may range from 3 to 13 days (Wang et al. 1985). Optimal temperatures for white sturgeon hatching and development range from 14-16 ºC (Wang et al. 1985), with mortality observed below 8° C and above 20°C. White sturgeon fertilization and hatch rates in the laboratory can be as high as 95.4% and 82.1%, respectively (Deng et al. 2002); though it is likely that the fertilization and hatch rates for white sturgeon eggs in the natural environment are much lower. Abnormal development, fungal infection, predation, non-optimal water quality, or low river flows may all contribute to egg mortality in the wild (Parsley et al. 1993).

White sturgeon larvae (10.0 – 11.0 mm) are less developed than green sturgeon larvae at hatching (Deng et al. 2002). Fin development is incomplete and hatchling white sturgeon are poor swimmers, though immediately after hatching they initiate a brief, low intensity downstream dispersal along the bottom that lasts up to six days in the laboratory (Conte et al. 1988, Kynard and Parker 2005). After this brief river dispersal, embryos seek benthic cover until the initiation of exogenous feeding (Kynard and Parker 2005). Under optimal conditions (14-16 ºC; Wang et al. 1985), white sturgeon complete yolk sack absorption between 12 to 14 days post hatch (dph) and begin actively feeding nocturnally (Kynard and Parker 2005). Once white sturgeons are able to feed exogenously, they metamorphose into young of the year (YOY) after 20 to 30 dph.

White sturgeon YOY make a second, active downstream migration that widely disperses them to rearing habitat throughout the lower rivers and delta (McCabe and Tracey 1994; Kynard and Parker 2005). In the Columbia River below Bonneville Dam, larvae may disperse up to 150 km from their spawning site (McCabe and Tracey 1994). As YOY, white sturgeon become tolerant to brackish waters in the laboratory (15 ppt; McEnroe and Cech 1985), although few field studies have documented larval or YOY white sturgeon outside of freshwater habitats.

Laboratory studies indicate that YOY white sturgeon grow rapidly with body weight doubling with each two to three week period during the first four months of life (at 16° C; Brannon et al. 1984). While young white sturgeon growth is rapid, it gradually slows with age. If laboratory studies are valid, fish in the Sacramento River can attain sizes of 43-45 cm total length (TL) in their first year, then grow 2-6 cm per year after attaining a size of 102 cm TL (Kohlhorst et al. 1980b, Brennan and Cailliet 1989).

Juvenile sturgeon can use a broad range of habitats defined by their temperature, dissolved oxygen, and salinity tolerances; thus the distribution of juvenile habitat fluctuates seasonally (Niklitscheck and Secor 2005; See "Distribution" section; Table 1) in freshwater and brackish environments. Temperatures higher than 25 °C are not tolerated by juvenile white sturgeon, and stress is observed near 20 °C (Cech et al. 1984, Geist et al. 2005). Growth is reduced when individuals are exposed to reduced dissolved oxygen, presumably from reduced feeding activity, reduced energy expenditures and/or locomotory patterns (Cech et al. 1984). Crocker and Cech (1997) suggest this energetic pattern may increase survival during widespread or prolonged periods of low dissolved oxygen. Juvenile white sturgeons have higher salinity tolerance than YOY and can tolerate up to 25 ppt when acclimated in experiments (McEnroe and Cech 1985). However, stress observed at higher salinities (> 15 ppt) may influence growth and survival (Tashjian et al. 2007).

Adult and sexually mature white sturgeons spend most of their lives in brackish and seawater estuary habitats (Moyle 2002, Gleason et al 2007). Several observations of long-distance marine migrations suggest coastal habitats may also be utilized to some degree by these older life stages (Kohlhorst et al. 1991; DeVore et al. 1999; Welch et al. 2006). The ability to make marine migrations indicates that salinity tolerance in adult white sturgeon must increase to 35 ppt, at least in some individuals (Table 1). Adult and mature white sturgeons consume a variety of benthic prey species and feeding movements appear to be governed by tidal and/or diel cycles (Moyle 2002; Parsley et al. 2008). A study of movements of lower Columbia River white sturgeon found increased individual activity at night, suggesting nocturnal foraging (Parsley et al. 2008). This study also found that some adult white sturgeon individuals exhibited site fidelity, returning to the same location (or within meters of it) in the lower river after spawning upstream (Parsley et al. 2008).

Growth rates of Sacramento-San Joaquin River adult white sturgeon have been estimated by Pycha (1956) and Kohlhorst et al. (1980b) by counting annual rings in the pectoral fin ray, a method subsequently validated by Brennan and Cailliet (1991). The age-length relationship differs between the two studies, with higher apparent growth rates particularly for older sturgeon in the Pycha (1956) study. It is uncertain whether this discrepancy reflects a biological change in growth rate over time or is a reflection of the high degree of uncertainty surrounding this aging technique (Rien and Beamesderfer 1994). Sex-specific growth rates have not been determined (Brennan and Calliet 1989), 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. This suggests either a sex-specific difference in growth rate or lifespan.

Adult sturgeon reach sexual maturity at different ages/sizes in different river systems, but the smallest sexually mature female described the Sacramento–San Joaquin system was 95 cm fork length (FL; Chapman et al. 1996) and was estimated to be 9 years old using Brennan and Cailliet's (1989) Von Bertalannfy growth equation. The youngest reproductive male white sturgeon reported by Chapman et al. (1996) was 75 cm FL, which was estimated to be 6 years old. However, Moyle (2002) reports older ages at sexual maturity for white sturgeon, at ages 12 and 10 years for females and males, respectively. Uncertainty around age estimates derived from fin ray annulus counts (as utilized in developing Brennan and Caliett's (1989) relationship) may account for the disparity between these estimates (See "Future Research" section). Regardless, white sturgeon reach sexual maturity at a younger age in the Sacramento and San Joaquin River system compared to more northern populations such as in the lower Columbia River, where the median age of first sexual maturity for females was 24 years old (DeVore et al. 1995).

White sturgeons are iteroparous breeders with a spawning period in the Sacramento and San Joaquin Rivers between mid-February to late May, with peak activity during March and April (Kohlhorst 1976). Chapman et al. (1996) found that female white sturgeon on the Sacramento River produced on average 203,328 eggs. However, Skinner (1962) described a 9.2 ft (280 cm), 460 pound (206 kg) female white sturgeon that was estimated to yield 4.7 million eggs, a value that exceeded the expected upper limit of fecundity-weight relationship described by Chapman et al. (1996) by a factor of 2.7. Spawning periodicity is thought to be 2 to 4 years for females and 1-2 years for males (Chapman et al. 1996). This is considerably shorter than what was reported for the lower Fraser River and presumably other northern populations, where Semakula and Larkin (1968) estimated female spawning intervals to be 4 to 8 years. Tracking studies of reproductively mature adults suggest that upstream movements can be quite rapid, on the order of ~25 km/day (Schaffter 1997). Spawning behaviors of wild white sturgeon are not well characterized, although it is known that they are communal broadcast spawners where one female's eggs are fertilized by many males. Parsley et al. (1989) attributed surfacing and breaching (jumping) behaviors in the tailrace of The Dalles Dam tailrace on the Columbia River to spawning (cited in PSMFC 1992).

III.Distribution (Table 2, Figure 1)

A. Population Structure

White sturgeon historically ranged from Ensenada, Mexico to the Gulf of Alaska, and spawning populations are found in the Sacramento-San Joaquin, Columbia, Snake, and Fraser river systems (Moyle 2002). Little is known about the evolutionary relationships among white sturgeon populations across the species' range. Investigations of population structure have been limited by the polyploid nature of the white sturgeon nuclear genome. Mitochondrial DNA studies have elucidated some level of population structure within and among river systems (Brown et al. 1992, Smith et al. 2005), but low mutation rate and uniparental inheritance in this marker make it inappropriate for examining contemporary gene flow among populations. Preliminary studies using nuclear markers suggest that genetic structuring does exist between major river systems, but additional research is needed (Rodzen et al. 2004).

B. Eggs, Larvae, Young of Year

Early life stages of white sturgeon are found primarily in fresh water at or downstream of spawning sites. The majority of white sturgeon spawning is limited to the Sacramento River in a section between Colusa (rkm 231) downstream to Verona (rkm 160; Kohlhorst 1976; see below). A comprehensive survey of YOY and juvenile white sturgeon in the entire Sacramento-San Joaquin delta found a majority of individuals

(60%) in the Sacramento River, although they were captured through most of the delta year-round (Radtke 1966). Stevens and Miller (1970) captured 76 sturgeon larvae, most on the Sacramento River between Collinsville and Rio Vista, an area that can be seasonally brackish. Thirteen larvae were captured in Suisun Bay (Stevens and Miller 1970) and others were caught at Rio Vista and in Cache Slough (T. Farley, personal communication cited in Stevens and Miller 1970). Kohlhorst (1976) sampled for white sturgeon eggs and larvae and captured a total of nine eggs and 246 larvae at three sites, rkm 129 (near Verona), rkm 180 (north of Knights Landing) and rkm 233 (Colusa). Several authors have found sturgeon eggs or larvae in the San Joaquin River between April and May of 1964 and 1967, but little is known about white sturgeon spawning in this river (Radtke 1966; Stevens and Miller 1970). Sturgeon have been observed on the Mokelumne River and a YOY sturgeon was captured there and genetically identified as a white sturgeon (Radtke 1966; J. Israel, University of California Davis, unpublished data; See "Spawning Adults"). Stevens and Miller (1970) stated that white sturgeon larvae were flushed into the delta and Suisun Bay when high outflow occurs, but they are restricted to more interior locations in low outflow years.

It is still unknown what habitats are preferred for rearing by larval and YOY white sturgeon. White sturgeon from other Pacific northwestern river systems have demonstrated larval and YOY white sturgeon are associated with a variety of substrates, including mud, silt, sand, hard clay, gravel, cobble, boulder, and bedrock (Parsley et al. 1993, Bennett et al. 2007). A laboratory study by Bennett et al. (2007) suggested that larval white sturgeon avoided sandy substrates, and the ubiquity of sandy substrates in the degraded Kootenai River system is one hypothesis for the widespread recruitment failure in the white sturgeon population residing there (Paragamian et al. 2001). Regardless of substrate, research from the lower Columbia River has shown YOY white sturgeon preferred water greater than 12.5 m (McCabe and Tracey 1994). The presence of early life stages in riparian and floodplain habitats is very limited, though these habitats have been speculated to be important for spawning recruitment (Coutant 2004). Van der Leeuw et al. (2006) found early life stages of white sturgeon present in shallow seasonally flooded riparian habitat in the Columbia River downstream of Bonneville Dam.

C. Juveniles

Very little specific information is available on the distribution of juvenile white sturgeon in the Sacramento-San Joaquin system. A single study describing juvenile white sturgeon distribution indicates that the Sacramento River and most of the delta is utilized by this life stage (Radtke 1966). The majority of juveniles sampled were captured in the Sacramento River (Radtke 1966). YOY and subadult white sturgeon salinity tolerance increases with size, which would allow them to access greater quantities of habitat available in the north, central, and southern San Francisco Bay. In the past three years, the California Department of Fish and Game (CDFG) has sampled numerous white sturgeon under 90 cm TL in their annual white sturgeon adult population survey conducted in Suisun and San Pablo Bays from August to October (A. Drauch, University of California Davis, personal communication). This suggests that juvenile white sturgeons are present in the bay as well as the western delta.

D. Adults

When not undergoing spawning or ocean migrations, adult and subadult fish are usually most abundant on or near their feeding grounds in brackish portions of the San Francisco Bay-Delta (e.g., San Pablo Bay, Suisun Bay, and to a lesser extent in the mid-Bay and south Bay, California Department of Fish and Game, unpublished data). They occasionally are found in tidal riverine and estuarine habitats of larger tributary streams such as Coyote Creek and Guadalupe River in the South Bay and Napa and Petaluma Rivers and Sonoma Creek in the North Bay (Leidy 2007). These habitats consist primarily of shallow water habitats that provide opportunities for benthic feeding on opossum shrimp and amphipods. Foraging movements are presumably in response to salinity changes (Moyle 2002) associated with tides and seasonal outflow. In dry years, white sturgeon follow brackish waters upstream and the opposite occurs in wet years (Kohlhorst et al. 1991). Adults tend to concentrate in deep areas with soft bottoms and often move into intertidal or shallow subtidal areas to feed during high tides (Moyle 2002).

Landlocked populations of white sturgeon on the Sacramento River have also been noted. For example, white sturgeon were stocked into Lake Oroville in the 1980s and occasional recaptures of adults occur (E. See, Department of Water Resources, personal communication). In addition, a remnant population of white sturgeon is present in Shasta Lake where adults still persist and are sought by anglers (S. Baumgartner, California Department of Fish and Game, personal communication). This population historically spawned in the Pit River but impoundment of this system currently prevents reproduction.

Tagging studies suggest that most white sturgeon remain in the estuary and lower Sacramento and San Joaquin rivers year-round (Kohlhorst et al. 1991). However, white sturgeon tagged in California have been recaptured out of state, indicating that at least some adults utilize the marine environment for some part of their life. White sturgeon tagged in the San Francisco estuary have been recaptured in the Columbia River, Chehalis River, and Willapa Bay (Washington) as well as the Umqua River, Yaquina River, and Tillamook Bay, Oregon (Kohlhorst et al. 1991). A white sturgeon tagged in the Klamath River traveled 1000 km north to be recaptured in the Fraser River (Welch et al.2006).

E. Spawning Adults

In California, white sturgeon are known to spawn in the Sacramento and San Joaquin rivers in the Central Valley. Additionally, white sturgeon spawning is believed to occur regularly in other California rivers such as the Feather, Smith, Klamath, and Eel rivers. Sturgeon spawn on gravel or rock substrate in moderate to fast currents (Dees 1961, Nikolskii 1961, Berg 1962, Gard 1996), although white sturgeon are known to spawn in atypical habitats as well (reviewed in Anders 2002). In the Columbia River, McCabe and Tracy (1994) observe evidence of white sturgeon spawning at depths of 3-23 m and water velocities along the bottom of 0.6 – 2.4 m/sec. Parsley et al. (1993) observe spawning in the Columbia River in the swiftest water available (mean water column velocity 0.8-2.8 m/s) primarily over cobble, boulder, and bedrock. Kohlhorst and

Cech (2001) note that white sturgeon in the Sacramento River spawn in deep gravel riffles or rocky holes. However, in the Sacramento River, the substrata downstream of Colusa, which is near the uppermost reach of known spawning habitat, mainly consists of mud, sand, and gravel, with cobbles and larger rip-rap lining the banks in some areas (Kohlhorst 1976, Schaffter 1997).

The majority of white sturgeon in the San Francisco estuary appear to utilize the Sacramento River for reproduction. For example, tag returns by anglers indicate that over ten times as many fish spawn in the Sacramento River than the San Joaquin River (Kohlhorst et al. 1991). In the Sacramento River, adult white sturgeon begin moving into the lower river from the delta and estuary during late fall and winter (Miller 1972, Kohlhorst et al. 1991, Kohlhorst and Cech 2001). A subset of larger individuals (relative to fish found on the feeding grounds), presumably mature spawners, migrate upriver between mid-February and late May to an ~90 km section of river between Verona and several kilometers upstream of Colusa (Miller 1972, Kohlhorst 1976, Schaffter 1997). Based on the presence of suitable habitat characteristics, white sturgeon spawning may occur upstream of Colusa as well, although this has never been detected (Kohlhorst 1976; Schaffter 1997). The California Department of Fish and Game white sturgeon report card data provides additional evidence of presence above Colusa, and 41 large adult sturgeons were captured in the Sacramento River between Red Bluff and Colusa in the spring (Gleason et al. 2008). Historical white sturgeon spawning grounds exist even further upstream in the Sacramento River (e.g. the Pit River) but they are now inaccessible due to the placement of Shasta Dam (Kohlhorst 1976).

Less is known about spawning in the San Joaquin River or other tributaries (i.e. Feather, Mokelumne). It is strongly suspected that the San Joaquin River supported a larger spawning population than at present, prior to the upstream diversion of its flow for agricultural irrigation (Schaffter 1997). In the San Joaquin River, spawning adults have been captured between Mossdale and the Merced River confluence in late winter and early spring (Kohlhorst 1976). It also is suspected that the Feather River supported a larger spawning population than at present prior to construction of Oroville Dam in 1961. A comprehensive search for evidence of sturgeon in the lower Feather River during 2003 was not successful, although environmental parameters (e.g., temperature) were determined to be suitable (Seesholtz 2003). In 2006, adult white sturgeon were captured in the lower Feather River and breaching behaviors were observed below Shanghai Bend (A. Seesholtz, Department of Water Resources, personal communication). A total of sixteen white sturgeon were recorded (creel surveys and sightings during monitoring) during 2006 in the Feather River, and three white sturgeon of unknown size were captured in the Feather River by anglers in the spring of 2007 (A. Seesholtz, Department of Water Resources, personal communication; Gleason et al. 2008). One YOY white sturgeon (22 mm TL) was captured in the Mokelumne River, which may indicate that spawning occurs in this river as well (Radtke 1966; J. Israel, University of California Davis, unpublished data). However, because larval dispersal behavior is not well characterized and white sturgeon larvae are present throughout the delta (see above) these occurrences cannot be taken as solid proof that white sturgeon spawn in the Mokelumne River.

IV. Ecology (Figures 3-10)

A. Reproduction to embryonic development (Figure 5, Figure 9)

Optimal conditions for spawning are presumably found at many locations within the lower Sacramento River. Ovarian maturity, timing of spawning, and incubation success in white sturgeon are largely temperature dependent. Spring temperatures rapidly ascend in the spring months, and the length of white sturgeon incubation (4 to 13 days) is sensitive on water temperatures (Wang et al. 1985, Conte et al. 1988). Field studies have found eggs when water temperatures appear optimal for egg incubation on the Sacramento (14° -16°C, Kohlhorst 1976). In experiments, incubation temperatures above 17°C resulted in premature hatching with higher mortality and no hatching at temperatures above 20°C (Wang et al. 1985, 1987). Wang et al. (1987) speculate that 6-8 °C might represent the low temperature threshold for successful white sturgeon incubation, and this is typically the coolest river temperatures encountered annually during the early winter in the spawning ground river reach (6-8°C at Knights Landing, P. Klimley, University of California Davis, unpublished data).

Flow relationships for white sturgeon were examined by CDFG and greater flows during the late spawning and early life history stages between April and July resulted in greater YOY production (Kohlhorst et al. 1991). Recruitment was positively correlated with outflow in all months from April to July, but there was no correlation with mean daily volume of diversions. Kohlhorst et al. (1991) also found a recruitment pattern that seemed to be influenced by spawning stock abundance for white sturgeon, which mature at about 14 years of age, and it is likely spawning stock abundance and environmental factors both influence recruitment of sturgeon YOY. White sturgeon eggs require suspended sediments to allow for adhesion to substrate and to prevent clumping (Conte et al. 1988); however the biologically relevant level of turbidity is unknown. Sediment was shown to delay white sturgeon hatch timing and decrease mean larval length, and embryo survival was negatively correlated with duration of sediment cover on the Kootenai River (Kock et al. 2006).

B. Developing embryo to Feeding larvae (Figure 5)

Early life stages of white sturgeon require rearing and foraging habitats in the lower rivers and along migratory corridors in the delta. Kohlhorst (1976) sampled during a high flow year when recruitment should be high, but detected neither a flow threshold for spawning activity nor a large number of larvae in the delta, suggesting successful survival of these early stages are influenced by riverine rearing habitat. White sturgeons are sensitive to temperature at early life stages. Wang (1985) showed the size of a white sturgeon larva was inversely related to water temperature during egg incubation in experiments. If white sturgeon are similar to green sturgeon, dissolved oxygen is presumably important to yolk sac absorption and embryos subject to increased temperatures may require greater dissolved oxygen levels.

Kynard and Parker (2005) found that larvae completed their initial nocturnal dispersal in approximately two days, which was the shortest dispersal period of any sturgeon species they had examined, and then utilized rocky substrate for hiding. Newly hatched white sturgeon were observed to seek cover in the substrate during daylight hours and only moved into the water column when cover was unavailable or the light intensity was low (Loew and Sillman 1998). Braaten et al (2008) found that shovelnose (*Scaphirhynchus platorynchus*) and pallid sturgeon (*S. albus*) larvae drifted slower than the mean water column velocity, but still drifted very long distances (94-530km). While it is unknown how far the early life stages of white sturgeon drift in the river, embryos and larvae are intolerant of brackish water, and survival may be limited by saltwater intrusion into areas they are drifting. It is unknown if they use tidal reverse flows in the lower Sacramento River to maintain a distribution primarily in freshwater. White sturgeon larvae were observed to avoid sandy substrates and preferred a pea gravel substrate in the 12-22 mm size range (Bennett et al, 2007). Once finding a hiding spot, white sturgeon took approximately 10 days at 15.5-18.6^{o}C to digest their yolk sac and initiate exogenous feeding (Deng et al 2002). Larval white sturgeons are unique in that their digestive systems are nearly fully formed both physically and physiologically at this stage (Gawlicka et al. 1995).

Egg predation has not been quantified on white sturgeon in the Sacramento River, and its effects on mortality relative to temperature, dissolved oxygen, and substrate is unknown. Larvae develop sharp scutes as they grow, which probably provides some protection from predation (Parsley et al. 2002). However, Miller and Beckman (1996) recorded predation on white sturgeon eggs in the Columbia River by prickly sculpin *(Cottus asper)*, common carp (*Cyprinus carpio*), northern pikeminnow (*Ptychocheilus oregonensis*), and largescale sucker (*Catostomus macrocheilus*). Prickly sculpin and pikeminnow are native to the Sacramento River (McGinnis 1984) and likely consume many sturgeon eggs and yolk-sac larvae. Predation effects on sturgeon eggs may be mediated by water velocity, with lower current speeds and reduced turbidity levels facilitating predation (Parsley et al. 2002, Gadomski and Parsley 2005b). Predation by prickly sculpin on white sturgeon yolk sac larvae was documented in the Columbia River (Gadomski and Parsley 2005a) regardless of high turbidity (360 NTUs).

C. Feeding larvae to juvenile (Figure 6)

In experiments (Cech et al. 1984), young juvenile white sturgeon (0.5 to 0.6 g) grew significantly greater at 20°C than 15°C. No growth difference was observed between 20° and 25°C, though increased temperatures led to increased activity in juvenile white sturgeon (Cech et al. 1984). Temperatures in the lower Sacramento River and northern Delta are often in the range of 18°C to 25°C during the late spring and summer (P. Klimley, University of California Davis, unpublished data). White sturgeons were sensitive to hypoxia at temperatures between 15^{o} and 25^{o}C in experiments (Cech et al. 1984).

The recruitment of strong year-classes to the San Francisco estuary population of white sturgeon is related to the amount of freshwater outflow in the Sacramento River (Kohlhorst et al. 1991; M. Gingras and M. Fish, CDFG, unpublished data). A significant positive correlation was evident between the year-class index calculated from the number of YOY and subadult fish (up to age 5) captured in otter and midwater trawls from 1980–2007 and the sum of outflow from April through July for a given year. Larval white sturgeon were found to tolerate up to 11 ppt water, although even at this salinity many fish appeared to be stressed (Brannon et al. 1985). In experiments, McEnroe and Cech (1985) observed that larvae could survive salinity up to 16 ppt if acclimated by small increases in salinity over a period of 4 weeks.

Little is known about the diets of white sturgeon larvae in the wild, although laboratory studies suggested that they consist of benthos, periphyton, and possibly pelagic fry and zooplankton (Brannon et al. 1984, Buddington and Christofferson 1985). In the delta, YOY white sturgeon sampled in the late summer and fall consumed amphipods (*Corophium spinicorne*), shrimp (*Neomysis mercedis*), and larval and adult midges (*Tendipedidae*) (Schreiber 1960). Kynard and Parker (2005) reported activity of feeding white sturgeon larvae peaked at night whether fish were dispersing or foraging, which is presumably an evolutionary response to predation.

Feeding larvae are more vulnerable to prickly sculpin predation than eggs or yolk sac fry (Gadomski and Parsley 2005b). Prickly sculpin ingested more white sturgeon than alternate prey, regardless of size of the larvae or juvenile, or availability of other prey (Gadomski and Parley 2005a). Juvenile white sturgeon in the San Francisco bay-delta and its tributaries are probably consumed by a variety of predators, including birds and piscivorous fishes (Kohlhorst and Cech 2001). Predation of larval and juvenile white in the wild is a significant source of mortality and may be a factor limiting recruitment of young-of-the-year white sturgeon in some locations (Gadomski and Parsley 2005a).

D. Juvenile to spawning adults (Figure 7)

Our understanding of juvenile white sturgeon distribution in subtidal and intertidal habitats is limited though abiotic factors likely limit their mosaic of seasonally available habitats. On the Columbia River, white sturgeon were observed to move downstream in the spring and upstream in the fall, and individuals reoccupied habitats inhabited in previous years (Parsley et al. 2008). Temperature likely plays an important role in the distribution of juvenile white sturgeon in nursery habitat. Water temperatures at low depths (0-1 m) in the Sacramento-San Joaquin estuary averaged 20.5^{o}C during summer, the "growing season" for juvenile white sturgeon (Cech et al. 1984), which is the upper limit of their thermal optima. Cech et al. (1984) observed slow growth and some mortality in juvenile white sturgeon (<1 kg) held in water temperatures above 20^{o}C. Laboratory studies of larger juveniles (60-80 cm) found that white sturgeon show signs of stress above 19^{o}C, and oxygen consumption increases with swimming speed and was temperature dependent (Geist et al 2005). The upper temperature tolerance for white sturgeon is considered to be 25°C.

Salinity is also an important characteristic of juvenile white sturgeon habitat. White sturgeon appeared to show preference for freshwater over brackish water (Brannon et al. 1985), though juvenile white sturgeon have been observed in fresh and brackish waters in the Central Valley (Stevens and Miller 1970, Kohlhorst 1976). McEnroe and Cech (1985) found that all sizes of white sturgeon in their study (from 0.4 – 56g) were able to tolerate an abrupt transfer from freshwater (0 ppt) to 15 ppt water. YOY and juvenile mortality was 100% in abrupt transfers from freshwater to brackish (25 and 35ppt) water, and acclimation at an intermediate salinity (15 ppt) increased survival of these fishes at high salinity (25 ppt; McEnroe and Cech 1985). No juvenile sturgeon survived transfers to 35 ppt water (McEnroe and Cech (1985). While increasing salinity is likely representative of natural conditions in the delta, which allows juvenile white sturgeon to slowly acclimate to salinity changes as the migrate into the delta (Tashjian et al. 2007), salinities of 15-20 ppt are stressful for juvenile white sturgeon and may influence growth and survival (Tashjian et al. 2007). Tashjian et al. (2007) suggested 15 ppt as a low stress salinity and 20 ppt as high stress salinity for juvenile white sturgeon.

When juvenile white sturgeons migrate from the river into the estuary, their diet shifts to larger benthic food items, though they remain generalists and opportunists. Seasonally abundant drifting and benthic invertebrates have been shown to be the major food items of shovelnose and pallid sturgeon on the Missouri River (Wanner et al. 2007), lake sturgeon in the St. Lawrence River (Nilo et al. 2006), and white sturgeon in the lower Columbia River (Muir et al. 2000). These seasonally abundant insects included Diptera, Ephemeroptera, and Tricopteran pupae and larvae. The diversity of the prey of sturgeons in rivers may be an indication of competition with other riverine fish for drifting prey. If this is the case, there may be competition for food with other fish present in the Sacramento River such as Sacramento suckers, striped bass, and salmonids. In the delta, mysid shrimp and amphipods (*Corophium*) were observed to be the primary food items in juvenile (<39cm) white sturgeon stomachs (Radtke 1966).

Adult white sturgeon can tolerate brackish and seawater, but exhibit signs of stress at salinities >35 ppt (McEnroe and Cech 1985). Their ability to tolerate more saline environments allows adult white sturgeon to prey upon a broader set of food items. As white sturgeon juveniles grow, they are presumed to become more piscivorous, consuming herring and their eggs (*Clupea harengus pallasi*), American shad (*Alosa sapidissima*), starry flounder (*Platichthys stellatus*), and goby (Radtke 1966, McKechnie and Fenner 1971). Available benthic food items in the bay-delta estuary have changed in the recent past and invasive invertebrates have replaced native mollusks and shrimps. Kogut (2008) found that the invasive overbite clam (*Corbula amurensis*) was a major component of the white sturgeon diet, and unopened clams were able to pass through the digestive tract. It is possible that foraging on less edible non-native clams has caused dietary dilution, increased internal exposure to contaminants, and/or reduced growth of white sturgeon occupying the estuary, although no studies have evaluated white sturgeon diets since these ecological changes occurred. There is little information about whether intra- or interspecific competition or predator-prey dynamics influence white sturgeon abundance, distribution, or growth (Muir et al. 1988, Parsley et al. 1989, PSMFC 1992).

The CDFG tagging program has collected length-frequency information for white sturgeon caught in trammel nets during tagging operations since 1990. A time-series of length-frequency distributions compiled from these data shows the progression of discrete cohorts through time. The distributions in Schaffter and Kohlhorst (1999) illustrate the significant recruitment of year classes in 1982 and 1983, which was coincident with large outflows between April and July, entered the tagging operation's gear susceptibility in the early 1990s. More recently collected length data from tagging operations in 2001-2002 and 2005-2006 show the entry of a strong cohort from the wet, high outflow years between 1995-1998 (M. Gingras, CDFG, unpublished data).

E. Spawning adults to mature adults (Figure 8-10)

Adult white sturgeons appear to occupy the lower Sacramento River for a couple months prior to spawning. Upstream movements to spawn are triggered by photoperiod, increases in river flow, and preferred temperature. A minimum flow in the Sacramento River at Colusa of 150 m^3/s was identified as a potential threshold by Schaffter (1997). Water temperatures appear to play a role in the initiation of white sturgeon spawning behavior, and optimal spawning temperatures vary by river system (Kohlhorst 1976, McCabe and Tracy 1994, Paragamian and Kruse 2001). River temperature appears to be an important cue in spawning behavior, as the greatest activity seems to occur at water temperatures optimal for development. Kohlhorst (1976) found that Sacramento River water temperatures during the spawning period ranged from 7.8-17.8ºC, and the water temperature during peak activity was approximately 14.4ºC. Very little is known about adult white sturgeon habitat in the Sacramento River or bay-delta, though they are present throughout the river and delta during the spring, fall, and winter (Gleason et al. 2008). These large white sturgeon are most commonly captured in Suisun Bay, between Rio Vista and Chipps Island and Knights Landing, and Montezuma Slough (Gleason et al. 2008).

Natural predation on adult white sturgeon has not been well studied, and until recently was assumed to be negligible. However, over the past three years various anglers and agency biologists have reported that predation on white sturgeon by sea lions is no longer uncommon. In 2007, one or more sea lions were observed on white sturgeon spawning grounds near Knights Landing on the Sacramento River (K. Murphy, CDFG, pers. comm..). Sea lion predation on white sturgeon, primarily by Steller's sea lions, has also increased dramatically in the Columbia River below Bonneville Dam within the last three years and an estimated 400-600 super-legal sturgeon were killed by sea lions in 2006 (O. Langness, Washington Department of Fish and Wildlife, pers. comm.). Recent changes in the food web are influencing apex piscivores like killer whale, which rely upon healthy salmon populations for food (NMFS 2008). Sea lions are also piscivorous apex predators in the San Francisco bay delta, and it is possible their diet has also shifted due to changes in salmon abundance. Sea lions are capable of moving into brackish and fresher waters, and may be shifting their diets to exploit the Sacramento white sturgeon population, which is the largest fish in the delta. While white sturgeon are protected by scutes, the ability of sea lions to learn foraging and hunting patterns may allow some of them to learn how to ambush sedentary adult white sturgeon. It is uncertain what effect sea lion predation is having on the adult white sturgeon population.

Kogut (2008) found that C. *amurensis* is a major component of the white sturgeon diet, and can pass alive through the gut of a white sturgeon. Considering that one hypothesis for the "Pelagic Organism Decline" (POD) is a food-shortage for pelagic-feeding fishes, it should not be overlooked that this was coincident with a dramatic decline and sustained low abundance of legal-sized white sturgeon (CDFG, unpublished data). Bay shrimp and grass shrimp are effective baits for sturgeon in the recreational fishery, and presumably make up an important part of their natural diet. Fishes consumed during the juvenile stage are presumably consumed by adult also, and herring eggs are a white sturgeon food item when these fishes spawn in the bay during the winter (McKechnie and Fenner 1971).

V. Stressors by life-history stage (Table 3-6)

White sturgeons are long lived, and are subject to numerous environmental and anthropogenic stressors that may affect the probability that they reach reproductive maturity. Males are observed to reproduce as early as six years old, while females grow older prior to maturing as early as nine years old (Chapman et al 1996). Multiple environmental factors potentially limit white sturgeon survival during the earliest freshwater stages of their life cycle. This period is called the “critical age” in fishes due to its relevance in survival and recruitment of individuals into the adult population (Hardy and Litvak 2004). Recruitment failure during the earliest life history stages seem to be a significant bottleneck for other North American Acipenserids such as pallid sturgeon and the white sturgeon in upper Columbia and Kootenai rivers, and these populations have numerous reproductive adults, but recently have produced few surviving wild juveniles (Duke et al. 1999, Hildebrand et al. 1999, Korman and Walters 2001) .

There are many potential limiting factors during the freshwater and brackish early life history stages. They are the following: 1) insufficient flows, 2) lack of rearing habitat, 3) increased predation, 4) warm water temperatures, and 5) decreased dissolved oxygen. April to July mean monthly river outflow appeared positively correlated with the abundance index of YOY white sturgeon (Kohlhorst et al. 1991), and Stevens and Miller (1970) have observed that many larvae are found in the western delta during high-flow years. Sufficient outflows are important for dispersal of larvae into habitat in the bay and delta. Rearing habitat for larvae and YOY white sturgeon may be lacking due to channel and tidal marsh modification. These large river flows may also serve to disperse white sturgeon away from high predation in the river.

Predation by native species on white sturgeon appears to be significant in other basins (i.e., Columbia River, See “Ecology Sections a. and b.”), and additional mortality is likely caused by invasive predators. Warm water temperatures may not influence a significant portion of the spawning season, but its influence on early life history stage survival and habitat may reduce egg and larval survival. Presumably dissolved oxygen is an important character of early life history stages. Juvenile white sturgeon demonstrated reduced activity in hypoxia, and earlier life stages likely require higher dissolved oxygen (See “Ecology” section).

White sturgeons face anthropogenic threats at younger stages in the river and older stages in the estuary. Doroshov et al. (2007) found mortality and deformities of larval white sturgeon when the maternal female was exposed to levels of selenium found in bay waters, so it is possible that chemical toxicants play an important role in limiting the population's early life history stages. An active white sturgeon sport fishery has existed for about fifty years, with the most recent change in fishing regulations occurring in 2007 to reduce threats from this activity. As with most other sturgeon species, the life history characteristics of white sturgeon (e.g., late maturing, infrequent spawning) in concert with cyclic recruitment in the Sacramento River population make them susceptible to overexploitation, and the additional annual mortality due to harvest by sport anglers over and above natural mortality rates cannot be dismissed as a potential limiting factor of the white sturgeon population.

A. Entrainment

White sturgeon entrainment from agricultural operations, power plants, and the state and federal water project facilities causes direct mortality for down-migrating larvae, juvenile, and adult white sturgeon, though the magnitude of these stressors varies for life stages and location. Entrainment at agricultural and power plant diversions is not well documented, and likely is site specific. Nobriga et al. (2004) did not observe any sturgeon in their sampling of entrainment at agricultural diversions on the Sacramento River in the North Delta. Entrainment of larval fish by water diversions in the south delta was a source of mortality for white sturgeon during the high-flow years of 1982 and 1983. Estimated entrainment of YOY and subadult fish during these years exceeded 10,000 and 3,000 individuals, respectively, although there is uncertainty regarding the accuracy of these estimates (R. Gartz, CDFG, personal communication). White sturgeon entrainment at the state and federal pumps is quite variable and ranged from the above highs to records of zero for at least one of the facilities in nine years between 1981 and 2006. Larger juvenile sturgeons had lower entrainment with angled bar racks and louvers than sturgeon less than 200 mm (Amaral et al. 2002). Adult sturgeon have been impinged on the 'trash racks' at the state's Skinner Fish Facility in the south delta (R. Gartz, CDFG, personal communication).

B. Flow operations

Operational changes in river flow have led to significant ecological changes that influence white sturgeon at multiple life history stages. River flows influence white sturgeon spawning, habitat availability, and prey resources. River flows have been shown to be related to YOY abundance. Schaffter (1997) suggested flow increases above low base flows (>180m^3/s) may trigger spawning and he observed spawning occurring 1 to 3 days following a flow increase. The dispersal of larval white sturgeon is dependent on high spring river flows, which optimally consists of multiple large flow pulses and a relationship between the mean monthly outflow from April – July and white sturgeon YOY has been developed (Kohlhorst et al. 1991). Reduced seasonal flows or flows mismatched ecologically with sensitive early life stages may reduce dispersal of these life stages when they are most vulnerable to native and nonnative predation. Flow reductions may serve to reduce or eliminate YOY survival even if spawning was successful. Schaffter (1997) observed radio-tagged adult white sturgeon ceased their river migration and fish moved downstream when flows at Colusa were reduced to less than 150m^3/s.

A modification of flow rate has the potential to provide an unnatural cue for spawning which could result in lowered reproductive success. It is likely the changes in river flows and temperatures due to the operation of Oroville Dam and the Thermolito Afterbay had a relatively larger effect than reduction in spawning habitat on the Feather River (AFRP 1995). Reduced mainstem flows on the San Joaquin River have likely caused a constriction of spawning habitat in this portion of California, which would have represented the historic southern extent of white sturgeon distribution.

Operation of the Delta Cross Channel (DCC) in the lower Sacramento River has changed over time. White sturgeon larvae and adults are found in this area between January and June, while juveniles likely inhabit this reach year round. The current winter and spring closure of the DCC may limit larval and juvenile dispersal into the central delta, though larvae spawned late in the spring could be diverteds into this region subjecting them to increased risks of entrainment, increased predation, and increased stress due to warmer temperatures. Spawning adults may be delayed in reaching spawning grounds in the early winter due to misleading water flows through the south and central delta, and fish headed up the San Joaquin River may be confused due to the shifted Sacramento River flows entering the south delta via the DCC. Juvenile green sturgeon are observed in the south delta in the summer, and white sturgeon are presumed to be more abundant and evenly dispersed through the delta, though the impact of the South Delta Operable Gates on white sturgeon is unknown (J. Stuart. NMFS, pers. comm.). The closure of these operable gates in June may impact San Joaquin River white sturgeon larvae and YOY more than those in the Sacramento River due to its proximity, though this would vary greatly depending of productivity of the San Joaquin River population.

Outflow influences YOY, juvenile, and adult white sturgeon bay and delta habitats by influencing salinity. Tagging data demonstrate white sturgeon move upstream when saline waters encroach eastward in dry years, while white sturgeon expand use of bay habitat when brackish water is pushed westward in wet years (AFRP 1995). Modification of flows and salinity in the bay-delta has influenced the invasion by nonnative species and food productivity of the estuary, which could impact larval, juvenile, and adult white sturgeon, though little data exists to evaluate these effects. Kogut (2008) found that the invasive overbite clam, which is distributed in brackish portions of the bay-delta, is a major food source for white sturgeon.

C. Reservoir operations

Reservoir operations influence white sturgeon through two primary actions in the lower portions of the Sacramento, Feather, and San Joaquin rivers. First, reservoir operations impact spawning, incubating, and rearing habitat quality by modifying flow rate, magnitude, and timing (see “B. Flow Operation” above), which make river habitats less suitable during many years. Also, reservoir construction has restricted the upstream distribution of white sturgeon in these basins. White sturgeon were trapped above Shasta Dam in 1944, and the self-sustaining lake population was lost when Pit River dams blocked spawning of these fish (AFRP 1995). White sturgeon were also observed in the San Joaquin River at the face of the Mendota Dam in 1947 (Skinner 1962).

The reduction in spawning habitat due to physical barriers may limit spawning to sections of the river lower than preferred for larvae to develop necessary adaptations to salinity. If white sturgeon larvae require more time in freshwater than brackish or seawater environments, this downstream constriction of spawning habitat may reduce larval survival due to mismatch between the habitats and the physiological tolerances of white sturgeon.

D. Habitat loss

Managers do not know much about spatial and temporal distribution of white sturgeon in the San Francisco bay-delta prior to construction of floodplains, weirs, and gates; leveeing of delta islands; and redirection of flows into the south delta pumps. Assessments of historic habitat changes are based on our perception of what constituted optimal spawning, rearing, and foraging habitats. Dams on the Feather, Sacramento, and San Joaquin rivers have changed flow characteristics favorable to larval, juvenile, and adult white sturgeon, possibly limiting recruitment on these systems. These flood control and water conveyance structures influencing adult white sturgeon include the Fremont Weir, which traps adult white sturgeon in the Yolo Bypass, and Thermolito Outlet, which may restrict white sturgeon from reaching spawning habitat in the Feather River.

Static physical habitat changes are pervasive among significant portions of the freshwater and estuarine ecosystems used by white sturgeon in California. More than 95% of the historic tidal marshes in the San Francisco Bay estuary have been dyked and filled since 1850. Before 1850, the region sustained 1,400 square kilometers of freshwater wetlands and 800 square kilometers of salt marshes; today, only 125 square kilometers of undyked marshes remain of the original 2,200 square kilometers (USGS Fact Sheet 1994). Tidal marshes, particularly brackish marshes, presumably provide foraging resources for white sturgeon (see “Distribution” and “Ecology” section). While no studies have documented the relationship of tidal marsh food webs and white sturgeon, loss of these habitats presumably reduce nursery and foraging habitats for YOY through spawning adult life stages. It is unlikely that these changes influence individual white sturgeon, but cumulatively impact the population by possibly lowering the ecosystem’s carrying capacity.

Modification of the riverscape and estuary has likely resulted in the loss of habitat important for multiple white sturgeon life stages and functions. Larvae, juveniles, and adult life stages are all benthic in orientation and require deep habitats for dispersal, foraging, holding, and spawning. Larval dispersal, larval and juvenile predator avoidance, and adult spawning are likely affected by gravel and rock extraction and/or installation for bank protection. Levees restrict the natural meanderings of the river and serve to channelize the water, which increases water velocities. Schaffter (1997) speculated white sturgeon may spawn downstream of the Feather River on the numerous wing dams constructed of pilings and large rocks to reduce shoaling in the river between Verona and Sacramento. In the Sacramento River, the known spawning habitat for white sturgeon (approx. 90 km) between Verona and several kilometers upstream of Colusa (Miller 1972, Kohlhorst 1976, Schaffter 1997) is in the center of the Sacramento River Bank Protection Project Area and channelized by levees. In the bay-delta, channelization has likely had a negative impact on the amount of intertidal habitat available for juvenile and adult foraging. These areas are presumably important to juvenile growth and reproductive maturation of adults. Invasive plant species in the bay-delta have reduced the quality and quantity of shallow water habitat available for juveniles and adults, while increasing habitat for non-native predatory black basses. The alteration of the estuary food web due to invasive species has also likely shifted white sturgeon estuarine diets (Kogut 2008).

Creation of water diversion channels through the Yolo and Sutter Bypasses has also changed the natural course of the Sacramento River. River flow is diverted through these bypasses for flood control purposes during periods of high flow associated with winter storms. Flows are diverted back to the main channel from the bypasses when water levels subside, and the bypasses dry up. When these bypasses are closed, white sturgeon on their way to the spawning grounds are often stranded, leaving them vulnerable to poaching, desiccation, scavenging, and death unless they are rescued (Z. Matica, Department of Water Resources, pers. comm.). The Fremont Weir is a documented barrier to white sturgeon (Z. Matica, Department of Water Resources, pers. comm.), though a recent set of studies provide design and operational criteria for sturgeon passage (DWR 2007). Salinity is likely to influence larval, YOY, and subadult habitats in the delta, if salinity management strategies change or if a levee failure rapidly increases salinity in that region. White sturgeon feed extensively in the shallow habitats of San Pablo Bay, Suisun Bay, Grizzly Bay, and other shallow areas, and the extent to which these areas have been reduced (or augmented) has not been quantified to these authors' knowledge.

E. Water quality

Water quality is likely a stressor of habitat suitability in riverine and estuarine areas occupied by larval, juvenile, and adult white sturgeon. Low levels of dissolved oxygen result in reduced oxygen consumption rates, swimming abilities, and growth in white sturgeon (Crocker and Cech 1997, Cech et al. 1984). White sturgeon forage in subtidal and intertidal habitats in the western and southern delta, where low dissolved oxygen can occur seasonally. Sedimentation and the transport of sediment has been altered since the mid-1800s in the Central Valley, primarily due to hydraulic mining, land-use issues, dredging, and reduced tidal flushing due to restricted freshwater inflow, and turbidity is a critical character for predator avoidance of feeding larvae (Gadomski and Parsley 2005c) and presumably YOY. Climate change will affect water quality and quantity, and should influence egg incubation, larval and juvenile growth rates, and spawning migration periodicity. While green sturgeon spawning persists in a reach of the Sacramento River with potentially cold waters regulated via the Shasta Dam temperature control device, the management utility of this tool with a changing climate is uncertain.

F. Toxics

White sturgeon are long-lived, bottom-feeding fish at the top of the benthic food web, and as such are classic bioaccumulators of contaminants. Selenium impacts all life stages of white sturgeon in the San Francisco bay-delta and is found in high levels of their common prey items (Johns et al. 1988, White et al. 1988). *Corbula* is high in selenium, and this prey item is prominent in the diet of white sturgeon in San Francisco Bay (Urquhart and Regalado 1991), so it is not unexpected that selenium concentrations have remained high for this species (Greenfield et al. 2003). Doroshov et al. (2007) exposed gravid female white sturgeon to a selenium enriched diet, which resulted in selenium incorporation into the plasma vitellogenin and egg yolk proteins. The accumulation of selenium in egg yolk to a level $\geq 15\ \mu g\ g^{-1}$ resulted in severe deformities and mortalities of newly hatched larvae, and the amount of selenium measured in the ovaries of recently caught wild white sturgeon has approached or exceeded these levels (Doroshov et al. 2007). Dietary selenium increased osmoregulatory stress in juvenile white sturgeon, a concern relevant to the bay-delta system (Tashjian et al. 2007). Webb et al. (2006) found methylmercury accumulated in white sturgeon on the Columbia River, and its concentration in liver and gonads was negatively correlated with condition factor and relative weight suggesting it negatively effects their reproductive population.

Kruse and Scarnecchia (2002) show moderately increased mortality rates of white sturgeon embryos due to concentrations of trace metals and other contaminants found in the Kootenai River. Comprehensive study of toxic trace metals by the USGS has shown that contamination levels in San Francisco Bay accelerated during the 1950's (Cloern et al. 2006). Some Bay locations are among the most highly polluted coastal sites in the United States, with contamination by silver, cadmium, lead, and selenium being especially high (Cloern et al. 2006). Greenfield et al. (2003) tested white sturgeon from San Francisco Bay for a suite of toxins as part of an ongoing long-term monitoring program, and found that DDT and chlordane concentrations in the tissues of white sturgeon actually have declined since the 1980s, although selenium has remained at elevated levels.

G. Invasives

Invasive species influence the habitat, food resources, and predation risks of white sturgeon during multiple life stages. Invasive plants have modified shallow water habitats by reducing dissolved oxygen and circulation in the central delta. These habitats have become inhabited by nonnative predators of larval and YOY white sturgeon. The overbite clam, *Corbula* amurensis has become a major food item for white sturgeon, since its introduction into the estuary in 1986 (Moyle 2002). This clam has been observed to pass through the gut of white sturgeon undigested; suggesting consumption of this species may be causing dietary dilution and reduced growth of juvenile and adult white sturgeon (Kogut 2008).

H. Population

Harvest and poaching may be one of the greatest stressors for adult white sturgeon (and may affect subadults > 113 cm). The collapse of the commercial white sturgeon fishery in San Francisco bay-delta during a 10-15 year span in the late 1800's illustrates the vulnerability of this white sturgeon population to overexploitation of adult fishes. Legal harvest mortality rates were sporadically measured by CDFG between 1954 and 2005 and ranged from 1.4% to 11.5% (Schaffter and Kohlhorst 1999, CDFG, unpublished data). Maintaining levels of spawning stock biomass per recruit is critical to sturgeon conservation and Goodyear (1993) advised maintaining at least 20% of the adults, while Boreman et al. (1984) suggested a greater level of adult biomass (50%) was a target for rebuilding. For white sturgeon in the Columbia River, Boreman (1997) found that levels of fishing mortality similar to what are observed in the Sacramento population would maintain 30% to greater than 60% of the maximum lifetime egg production of the population. This suggests the Sacramento white sturgeon fishery mortality is low enough that the population is viable, but not always in a rebuilding dynamic.

Length-frequency distributions revealed a contemporary lack of individuals greater than 183 cm TL, which was the maximum size limit from 1990 through 2006 (Schaffter and Kohlhorst 1999, CDFG, unpublished data). While this observation may be biased due to lower gear susceptibility, it is a cause for concern because fish of this size are highly fecund and important to stability of the population (Donnellan and Gingras 2007, Boreman 1997). Changes to the fishing regulations in 2007 included a 3-fish annual bag limit, and the maximum size limit of a harvestable fish was reduced from 183 to 167cms. Between 2006 and 2008, the proportion of harvested catch went from 64% to 23% indicating new fishing regulations may be reducing harvest. It may be possible to evaluate whether this slot size reduction leads to conservation of remaining large, fecund fish (albeit not from poachers) by comparing CDFG sturgeon study length-frequency distributions in the future. Cohorts from good recruitment years of the mid- and late 1990s are reaching maturity and the new bag limits should be evaluated annually to confirm they are reducing harvest of these adults and assuring production of younger cohorts.

Illegal poaching of white sturgeon to supply the black market with caviar and sturgeon flesh is a serious and increasing threat to the population (M. Gingras, CDFG, personal communication). While the mortality rates and magnitude of this illegal activity are unquantifiable, they may be quite high. For example, the unusually low annual survival rates (~60% to 82%) during the 1990s (Schaffter and Kohlhorst 1999) may have been due in part to poaching. The eggs from a ripe 183 cm female fish (which was legally harvestable until March 1, 2007) are reported to fetch $3,000 on the black market, and this tremendous financial incentive exists for poachers to exploit this population. Several organized poaching rings have been exposed and prosecuted since 2000.

I. Other

Mortality of adult sturgeon due to impact by boat strikes and ship propellers has also been observed (D. Woodbury, NMFS, personal communication; K. Flowers, CDFG, personal communication), but it is unknown how commonly this occurs. These sources of mortality are apparently relatively minor, though they impact adult fish.

The prevalence of diseases in wild white sturgeon is unknown, although white sturgeon iridovirus is not uncommon in aquaculture facilities for this species (M. Adkinson, CDFG, personal communication), several of which are located in the Delta region. Wild adult white sturgeon were observed with skin lesions during sturgeon tagging operations in San Pablo Bay during 2007 (M. Donnellan, Oregon Department of Fish and Wildlife, personal communication), but the prevalence was low (< 0.5-1%).

VI. Future Research

A. Reproduction

One critical information gap is how often individual white sturgeon spawn. Chapman et al.'s (1996) work in the San Francisco bay-delta estuary suggested a 1-2 year spawning periodicity for males, and a 2-4 year periodicity for females. However, these estimates were based on the prevalence of developed gonads. Longitudinal studies of the same individuals (e.g., using implanted long-life acoustic transmitters) are easily adapted to the CDFG delta and bay tagging efforts which occur annually. Telemetric studies have been performed in the past to assess movements of individuals and have yielded useful data, but the generality of the results is questionable due to limitations in sample size (i.e. the number of fish fitted with transmitters). The California Fish Tracking Consortium is a good resource for developing and undertaking a telemetry project with white sturgeon of different ages and stages of reproductive maturity, but any telemetric study should be interdisciplinary and evaluate habitat and other unknown components of the species ecology. Sexing and identification of reproductive maturity can be undertaken efficiently using bioassays developed already for white sturgeon (Feist et al 2004, Webb et al 2002), and this type of research should be included initially to validate noninvasive methods of sex determination (Vescei et al. 2003).

Although research by CDFG and others have documented a positive correlation between river outflows and their year class index, little research has been conducted to evaluate the relationships between other environmental variables and reproductive success. One important relationship which has yet to be determined is that between the abundance of spawners and the CDFG year-class index. Because early life history stages have been suggested to be a critical limiting stage in a self-sustaining white sturgeon population in the San Francisco bay-delta (Kohlhorst et al. 1991), it is important to understand possible factors that may limit reproductive success and recruitment. Field studies involving early life history stages of white sturgeon in the lower Sacramento River are necessary to better document the correlation between river outflows and the CDFG year-class index. While this relationship has been observed in the bay-delta system, it is interesting that there seems to be many low recruitment years, a few high recruitment years, and no moderate recruitment years, although in many years there are normal outflows of these intermediate values.

B. Habitat and Migration

Limited sampling of reproductive adult, eggs, larvae, and juvenile white sturgeon has occurred in the lower Sacramento River, and even less is available for the Feather and San Joaquin rivers. It is essential that spawning, nursery, and rearing sites be identified and characterized for protection. Research that would serve to address some of the questions above involves telemetric studies, hydroacoustic surveys, and egg and larvae sampling. These types of studies are being undertaken in the upper Sacramento River by U.S. Fish and Wildlife Service (Poytress et al. 2009), U.S. Bureau of Reclamation, and University of California Davis (Israel et al. 2009) for green sturgeon. Developing similar interagency studies and using the California Fish Tagging Consortium database will provide significant new insights into white sturgeon habitat and migration. Remote sensing tools (e.g., multibeam bathymetry, sidescan sonar, LIDAR) could provide the needed information on (relatively) static riverine habitat, and in-stream monitoring stations for temperature and depth-specific water velocity measurements (e.g., Acoustic Doppler Current Profiler) would be useful in characterizing available habitat. A significant proportion of the presumed estuarine thermal refugia for juvenile anadromous Atlantic sturgeon in the Chesapeake Bay were found to be unsuitable during the summer due to persistent hypoxia and salinity (Niklitschek and Secor 2005), and similar research should be undertaken to evaluate water quality threats to juvenile habitat suitability.

The riverscape is critical for reproduction and rearing and future work should repeat upon the limited studies of Kohlhorst (1976) and Schaffter (1997) for comparison. Additional sampling effort is needed to verify the previously described locations and extent of spawning and rearing in all inhabited freshwater reaches used by white sturgeon. CDFG adult sturgeon population survey provides an excellent opportunity to mark adult and juveniles with acoustic tags. This information could be contextualized with the ongoing Sturgeon Report Card to evaluate the impacts of harvest and habitat modification and possibly estimate abundance. Egg and larval studies should be initiated using this adult movement data to guide evaluation of early life history habitats and characterization of these locations in the lower portions of the spawning rivers and sections of the delta. Field research aimed at sampling early life history stage and juvenile white sturgeon will be the only way to confirm the relationship between April through July mean monthly outflows and the CDFG year class index. Managers may also want to use movement data to reevaluate the initial determinations of how river flow changes influence white sturgeon and/or delay movement upriver. These types of multidisciplinary investigations need to lead to development of habitat suitability models to simulate changes to the spatial/temporal extent of habitats due to flow modifications.

C. Ecology

Increasing field research is necessary to develop a comprehensive understanding of the ecology of early and adult life history stages of Sacramento River white sturgeon and how stressors interact with its ecology. Several aspects of the feeding and community ecology of white sturgeon that have been addressed in the past should be updated to account for the bay-delta’s changing environment and ecology. The bay environment has changed radically in the 20-30 years since much of these data were collected (e.g., *Corbula* invasion, phytoplankton/ zooplankton decline, POD, food web alteration due to exotic species, greater human population in the Bay area and associated effects). A study addressing the bioenergetics of white sturgeon would also be useful in order to ascertain dietary requirements and estimate the impact of sturgeon on prey populations (e.g., *Corbula*). A study of the prevalence and extent of the emerging issue of predation on subadult and especially adult white sturgeon by California sea lions would be highly relevant in light of already depressed sturgeon abundance. Marine mammal predators can dramatically depress prey populations when exploiting a previously unexploited food source, as shown by the decimation of sea otters in Southwest Alaska by killer whales (e.g., Estes et al. 1998). Lastly, the age-length relationships of Kohlhorst et al. (1980) and Brennan and Cailliet (1989) should be reevaluated using either an OTC-validation study approach or otolith microchemistry.

Due to the duplicated nature of the white sturgeon genome, population genetic research has been limited to using mitochondrial or a small handful of nuclear markers (e.g. Anders 2002, Smith et al. 2005), and not provided enough resolution to understand current spatiotemporal connectivity of white sturgeon populations. Recently, new microsatellite markers and better analysis methods have been developed to allow higher resolution studies of current white sturgeon population structure (Rodzen and May 2002, Rodzen et al. 2004b, Börk et al. 2007, Drauch and May, unpublished data). The knowledge of population genetics can be directly applied to management. There is very limited information on white sturgeon dispersal between estuaries along the west coast of North America. Currently, the white sturgeon sport fishery in California is managed separately from sports and commercial fisheries in the Columbia River. If white sturgeon are dispersing regularly between California and out-of-state river systems, it may be of interest to develop an interjurisdictional management plan that protects the interest of all states utilizing the fishery.

D. Harvest

A data limitation in assessing the white sturgeon population is the accuracy of CDFG's population estimates. The accuracy of the estimates is directly related to the number of white sturgeon tagged and recaptured, and typical accuracy has been approximately +/- 50%. Accuracy of +/- 25% is a common target for management purposes, and power analysis should be performed to estimate the desired sample size (and associated cost) of achieving this level of accuracy. Further, tag shedding rates and post-release mortality due to tagging operations should be critically evaluated. The assumption that these factors are absent or negligible has the dangerous effect of overestimating population abundance. The accuracy of CDFG's harvest rate estimation from tagging studies will soon be directly testable, as anglers fishing for sturgeon are now required to complete and return a report card for all fish harvested (as of March 1, 2007). It is recommended that CDFG's white sturgeon monitoring program be continued on an annual basis, instead of the historic biennial occurrence of this program. Genetic data from west coast sturgeon populations can be used in investigations of illegal poaching of white sturgeon in California and elsewhere. DNA from confiscated poached materials can be used to identify the origin of the illegally harvested fish, allowing enforcement personnel to target hotspots of illegal activity.

E. Toxics

Research into toxin accumulation in white sturgeon, and the lethal and sublethal effects of toxicity should be expanded. The study of selenium toxicity in white sturgeon by Doroshov et al. (2007) was insightful, and this type of laboratory study should be extended to the field and to other contaminants (as well as the additive and synergistic effects of toxic contamination). It would then be useful to assess the prevalence of such toxic effects in the wild population.

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VIII. Tables

Table 1. Biological characteristics of white sturgeon.

	Habitat (*life stage*)	**Periodicity**	**Age (Dph)**	**Weight (g)**	**Total Length (cm)**	**Temperature Range (optima)**	**Salinity range[3]**	**Oxygen optima**	**Turbidity range**	**Typical stage survival & fecundity**
1	Lower rivers (*Egg/Embryo/ larvae*)	February - May	<10dph[1]	~0.15[1]	<1.7[1]	11-20°C, (14-16)[2]	0	>10 ppm[4]	UKN	s=UKN
2	Lower rivers (*Feeding Larvae)*	April - June	10-45dph[1]	~0.41[1]	1.7-6[1]	11-20°C, (14-16)[2]	5-10ppt	>80.0 mmHg[5]	UKN	s=UKN
3	Lower rivers *(Juveniles)*	year-round	45 dph - < 6 years old	>1.4g-2.5kg[1, 2]	6-45[1]	<20°C optimal[6]	10-15ppt	>80.0 mmHg[5]	UKN	s=UKN
4	Delta *(Juveniles)*	year-round	45 dph - <6 years old	2.5-15kg[2]	>30-75	<20°C optimal[6]	15 ppt	>80.0 mmHg[5]	UKN	s=UKN
5	Bay *(Juveniles)*	year-round	45 dph - <6 years old	2.5-15kg[2]	>30-75	<20°C optimal[6]	15-25ppt	>80.0 mmHg[5]	UKN	s=UKN
6	Lower rivers (P*re-spawn Adult*)	winter	male = >6-10 years, female = >9-12 years[2]	>15-125kg[7]	male = 75cm, female = 95cm[2]	<25°C optimal[6]	<35 ppt	UKN	UKN	s=0.67-0.82[7]
7	Lower rivers (*Spawner*)	November-May	male = 6-10 years, female = 9-12 years[2]	>15-125kg[7]	male = 75cm, female = 95cm[2]	<25°C optimal[6]	<35 ppt	UKN	UKN	s=0.67-0.82[8], Ave. f = 203,000[9]
8	Bay (*Mature Adult*)	year-round	Same as above	>15-125kg[7]	male = 75cm, female = 95cm[2]	<25°C optimal[6]	<35 ppt	UKN	UKN	s=0.67-0.82[8], Ave. f = 203,000[9]

1. Deng et al 2002; 2. Wang et al. 1987; 3. McEnroe and Cech 1985; 4. Brannon 1985; 5. Crocker and Cech 1997; 6. Cech et al 1984; 7. Pycha 1956; 8. CDFG, unpublished data; 9. Chapman et al. 1996

Table 2. White sturgeon life stage periodicity.

Egg/Embryo/Larvae

Sighting location	Jan		Feb		Mar		April		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
Colusa to Verona				■	■	■	■	■	■	■														

Juvenile

Sighting location	Jan		Feb		Mar		April		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
River	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Delta	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Suisun Bay	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

Spawning/Postspawning/Mature adult

Sighting location	Jan		Feb		Mar		April		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
Lower Sacramento River	■	■	■	■	■	■	■	■	■	■											■	■	■	■
Lower San Joaquin River	■	■	■	■	■	■	■	■	■	■											■	■	■	■
North Delta	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
South Delta	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
West Delta	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Suisun Bay	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
North Bay	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

Table 3. White sturgeon life stage matrix.

		A			B			C
	Habitat (*life stage*)	**Entrainment - small ag**	**Entrainment - power plant**	**Entrainment - SWP/CVP**	**Flow Operations - DCC**	**Flow Operations - Reduced seasonal flows**	**Flow Operations - S. Delta operable gates**	**Reservoir operation**
1	**Middle/ Lower rivers** *Egg/embryo*					Reduced flows could disrupt downstream dispersal		Impoundement could affect temp at spawning and nursery sites (Feather)
2	**Lower rivers** *Larvae*	Direct mortality			Could influence dispersal rate to estuary	Reduced flows could disrupt downstream dispersal	Could influence dispersal rate to estuary	Impoundment could modify temps at nursery sites
3	**Delta** *Juveniles*	See Delta Stressor Subtable	See Delta Stressor Subtable	See Delta Stressor Subtable	See Delta Stressor Subtable	See Delta Stressor Subtable	See Delta Stressor Subtable	
4	**Bay** *Juveniles*	See Bay Stressor Subtable				See Bay Stressor Subtable		
5	**Delta** *Pre -spawn Adult migration*		Direct take	Direct take	Alters summer and fall migration patterns	Reduced flow may not provide natural spawning cue	Affects migration rate	
6	**River** *Spawner*					Reduced flow may not provide natural spawning cue	Affects spawning location	Unable to access historical spawning sites in Sacramento and San Joaquin basins, impoundment could modify temps at spawning sites
7	**River** *Post -spawn*				Alter summer post spawning emigration	Reduced flow may not provide natural migration cues		
8	**Delta** *Post-spawn*			Exhausted adults sometimes impinged on trash racks at SSFF				

Table 3 continued. White sturgeon life stage stressor matrix.

	D			E		
	Habitat Loss - spawning	**Habitat Loss - Rearing**	**Habitat Loss - Migration**	**Water quality - Temperature**	**Water quality - DO**	**Water quality - Turbity**
1	Loss of substrate would increase predation risk	Loss of substrate would increase predation risk		< 8C and > 20C = lethal		Low suspended sediments could reduce adhesion to substrate and increase clumping
2	Loss of substrate would increase predation risk	Loss of substrate would increase predation risk		< 8C and > 20C = lethal	Cannot tolerate low DO	Increased turbity could alter diel behavior
3		See Delta Stressor Subtable		See Delta Stressor Subtable	See Delta Stressor Subtable	See Delta Stressor Subtable
4				See Bay Stressor Subtable	See Bay Stressor Subtable	See Bay Stressor Subtable
5	More difficult to find spawning habitats		Unable to access spawning sites, Fremont Weit	Abnormally high temps could provide inappropriate cue or atresia	May restrict migration into San Joaquin due to extremely low DO in south delta	
6	Levees and dredging reduce available spawning habitat		Unable to access historical spawning sites	Abnormally high temps could provide inappropriate cue or atresia		Influences spawning behavior
7						
8						

Table 3 continued. White sturgeon life stage stressor matrix.

		F	G	H	I
	Water quality - Salinity	**Toxics**	**Invasives**	**Population**	**Other**
1	Cannot tolerate brackish water	Maternal selenium exposure causes dev. abnormalities	Increased predation in river		
2	Cannot tolerate brackish water	Maternal selenium exposure causes dev. abnormalities	Could alter food supply and increase predation		
3		See Delta Stressor Subtable	See Delta Stressor Subtable		
4	See Bay Stressor Subtable	See Bay Stressor Subtable	See Bay Stressor Subtable		
5		Maternal exposure to selenium decreases fecundity		Direct harvest mortality	Boat strikes, hatchery disease
6		Maternal exposure to selenium decreases fecundity		Direct harvest mortality	Boat strikes, hatchery disease
7		Maternal exposure to selenium decreases fecundity		Direct mortality	
8		Maternal exposure to selenium decreases fecundity	Sedimentation and climate change may affect food availability; salinity regimes may also impact	Direct mortality	Boat strikes, hatchery disease

Table 4. Delta white sturgeon life history stressor submatrix.

		A			B			C	D		
	Habitat (*life stage*)	**Entrainment - small ag**	**Entrainment - power plant**	**Entrainment - SWP/CVP**	**Flow Operations - DCC**	**Flow Operations - Reduced seasonal flows**	**Flow Operations - S. Delta operable gates**	**Reservoir operations**	**Habitat Loss - spawning**	**Habitat Loss - Rearing**	**Habitat Loss - Migration**
3A	Delta - SD *Juveniles*	Direct take		Direct take		Reduced flows could disrupt downstream dispersal	Alter mgiration, possible mismatch of nursery and foraging habitat from Delta			Less rearing habitat available	
3B	Delta - MOK *Juveniles*	Direct take				Reduced flows could disrupt downstream dispersal				Less rearing habitat available	
3C	Delta - ND *Juveniles*	Direct take				Reduced flows could disrupt downstream dispersal				Less rearing habitat available	
3D	Delta - YB *Juveniles*					Reduced flows could disrupt downstream dispersal					
3E	Delta - WD *Juveniles*	Direct take	Direct take			Reduced flows could disrupt downstream dispersal				Less rearing habitat available	

Table 4 continued. Delta white sturgeon life history stressor submatrix.

		E				**F**	**G**	**H**
	Habitat (*life stage*)	**Water quality - Temperature**	**Water quality - DO**	**Water quality - Turbity**	**Water quality - Salinity**	**Toxics**	**Invasives**	**Population**
3A	Delta - SD *Juveniles*	Juveniles exhibit signs of stress >19°C	DO <56% saturation is stressful			High selenium in delta increases osmoregulatory stress	Could alter food supply	Harvest may include small number of juveniles greater than 113cm
3B	Delta - MOK *Juveniles*							
3C	Delta - ND *Juveniles*							Harvest may include small number of juveniles greater than 113cm
3D	Delta - YB *Juveniles*							
3E	Delta - WD *Juveniles*				Salinity affects stress survival			

Table 5. Bay white sturgeon life history stressor submatrix.

		B	D	E			F
	Habitat (*life stage*)	**Flow Operations - Reduced seasonal flows**	**Habitat Loss - Rearing**	**Water quality - Temperature**	**Water quality - DO**	**Water quality - Salinity**	**Toxics**
4A	Bay - NB *Juveniles*	Change in salinity regime may change food distribution	Reclamation of baylands has reduced rearing and foraging habitats	Juveniles exhibit signs of stress >19°C	DO <56% saturation is stressful	Will be stressed in areas 15-20 ppt	High selenium in bay increase osmoregulatory stress
4B	Bay - SB *Juveniles*			Juveniles exhibit signs of stress >19°C	DO <56% saturation is stressful	Will be stressed in areas 15-20 ppt	
4C	Bay - NB *Adult*						Endocrine disrupters, maternal exposure to selenium decreases fecundity
4D	Bay - SB *Adult*						

Table 5 continued. Bay white sturgeon life history stressor submatrix.

		G	H	I	
	Habitat (*life stage*)	**Invasive Spp**	**Population**	**Other**	
4A	Bay - NB *Juveniles*	Could alter food supply, dietary dilution	Direct mortality	Boat strikes; dredging. Direct mortality	
4B	Bay - SB *Juveniles*				
4C	Bay - NB *Adult*				
4D	Bay - SB *Adult*				

Table 6. White sturgeon life stage matrix with importance, understanding, and predictability scores.

		A	**B**	**C**	**D**	**E**	**F**	**H**	**Other**
	Habitat *(life stage)*	**Entrainment**	**Flow Operations**	**Reservoir operations**	**Habitat loss**	**Water quality**	**Toxics**	**Population**	
1	Lower/ Middle rivers *Egg/embryo*	I = 1 U = 2 P = 2	I = 4 U = 4 P = 3		I = 4 U = 3 P = 2	I = 4 U = 3 P = 2	I = 3 U = 3 P = 1		
2	Lower rivers *Larvae*	I = 2 U = 2 P = 2	I = 4 U = 4 P = 3		I = 3 U = 2 P = 2	I = 4 U = 4 P = 2	I = 2 U = 2 P = 1		
3	Delta *Juveniles*	I = 3 U = 1 P = 2	I = 2 U = 1 P = 2		I = 3 U = 1 P = 1	I = 3 U = 3 P = 1	I = 3 U = 1 P = 2	I = 3 U = 1 P = 1	I = U = P =
4	Bay *Juveniles*				I = 2 U = 1 P = 1		I = 3 U = 1 P = 2	I = 3 U = 1 P = 1	I = U = P =
5	Bay *Pre-spawn Adult migration*				I = 2 U = 1 P = 1		I = 1 U = 3 P = 1	I = 4 U = 4 P = 3	I = U = P =
6	River *Pre-spawn Adult migration*	I = 1 U = 3 P = 1	I = 4 U = 3 P = 3		I = 3 U = 2 P = 3	I = 1 U = 3 P = 3	I = 1 U = 3 P = 1	I = 4 U = 4 P = 4	I = U = P =
7	River *Spawner*	I = 1 U = 3 P = 1	I = 4 U = 3 P = 3		I = 3 U = 2 P = 3	I = 1 U = 3 P = 3	I = 1 U = 3 P = 1	I = 4 U = 4 P = 4	I = U = P =
8	River *Post-spawn*	I = 2 U = 2 P = 2			I = 2 U = 2 P = 3	I = 1 U = 3 P = 3	I = 1 U = 3 P = 1	I = 4 U = 4 P = 4	I = U = P =

Table 6. White Sturgeon Stressor Characterization Table Key

4 = High importance: expected sustained major population level effect, e.g., the outcome addresses a key limiting factor, or contributes substantially to a species population's natural productivity, abundance, spatial distribution and/or diversity (both genetic and life history diversity) or has a landscape scale habitat effect, including habitat quality, spatial configuration and/or dynamics.
3 = Medium importance: expected sustained minor population effect or effect on large area or multiple patches of habitat
2 = Low importance: expected sustained effect limited to small fraction of population, addresses productivity and diversity in a minor way, or limited spatial or temporal habitat effects
1 = Minimal or no importance: Conceptual model indicates little or no effect

4 = High predictability: Understanding is high and nature of outcome is largely unconstrained by variability in ecosystem dynamics, other external factors, or is expected to confer benefits under conditions or times when model indicates greatest importance.
3 = Medium predictability: Understanding is high but nature of outcome is dependent on other highly variable ecosystem processes or uncertain external factors.
OR
Understanding is medium and nature of outcome is largely unconstrained by variability in ecosystem dynamics or other external factors
2 = Low predictability: Understanding is medium and nature of outcome is greatly dependent on highly variable ecosystem processes or other external factors
OR
Understanding is low and nature of outcome is largely unconstrained by variability in ecosystem dynamics or other external factors
1 = Little or no predictability: Understanding is lacking

OR

Understanding is low and nature of outcome is greatly dependent on highly variable ecosystem processes or other external factors

4 = High understanding: Understanding is based on peer-reviewed studies from within system and scientific reasoning supported by most experts within system.
3 = Medium understanding: Understanding based on peer-reviewed studies from outside the system and corroborated by non peer-reviewed studies within the system.
2 = Low understanding: Understanding based on non peer-reviewed research within system or elsewhere.
1 = Little or no understanding: Lack of understanding. Scientific basis unknown or not widely accepted

IX. Figures

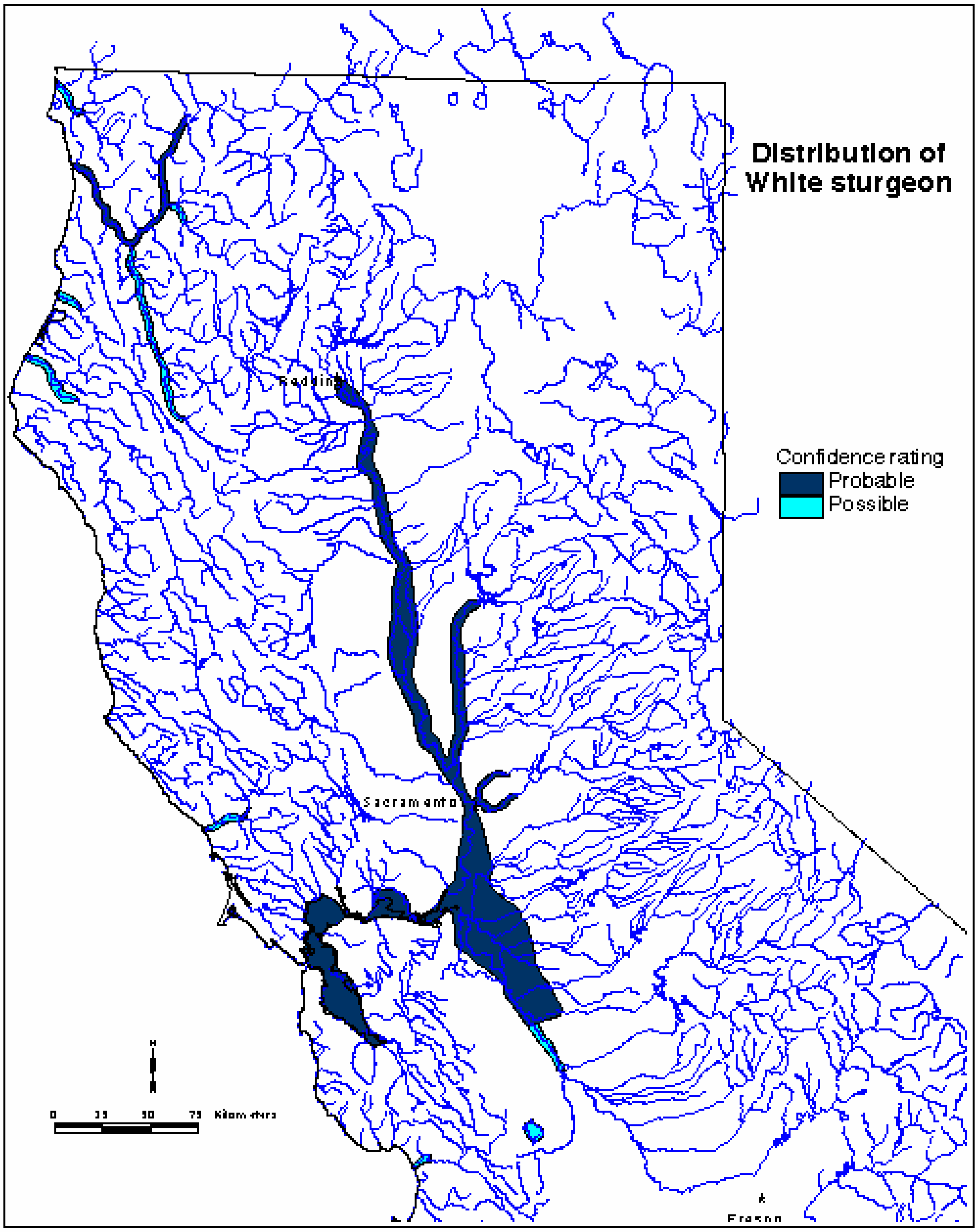

Figure 1.Distribution of white sturgeon in the Sacramento- San Joaquin Rivers and bay-delta. Blue areas denote probable and possible riverine and riparian habitats used by white sturgeon. Map from http://ice.ucdavis.edu/aquadiv/fishcovs/wst.gif.

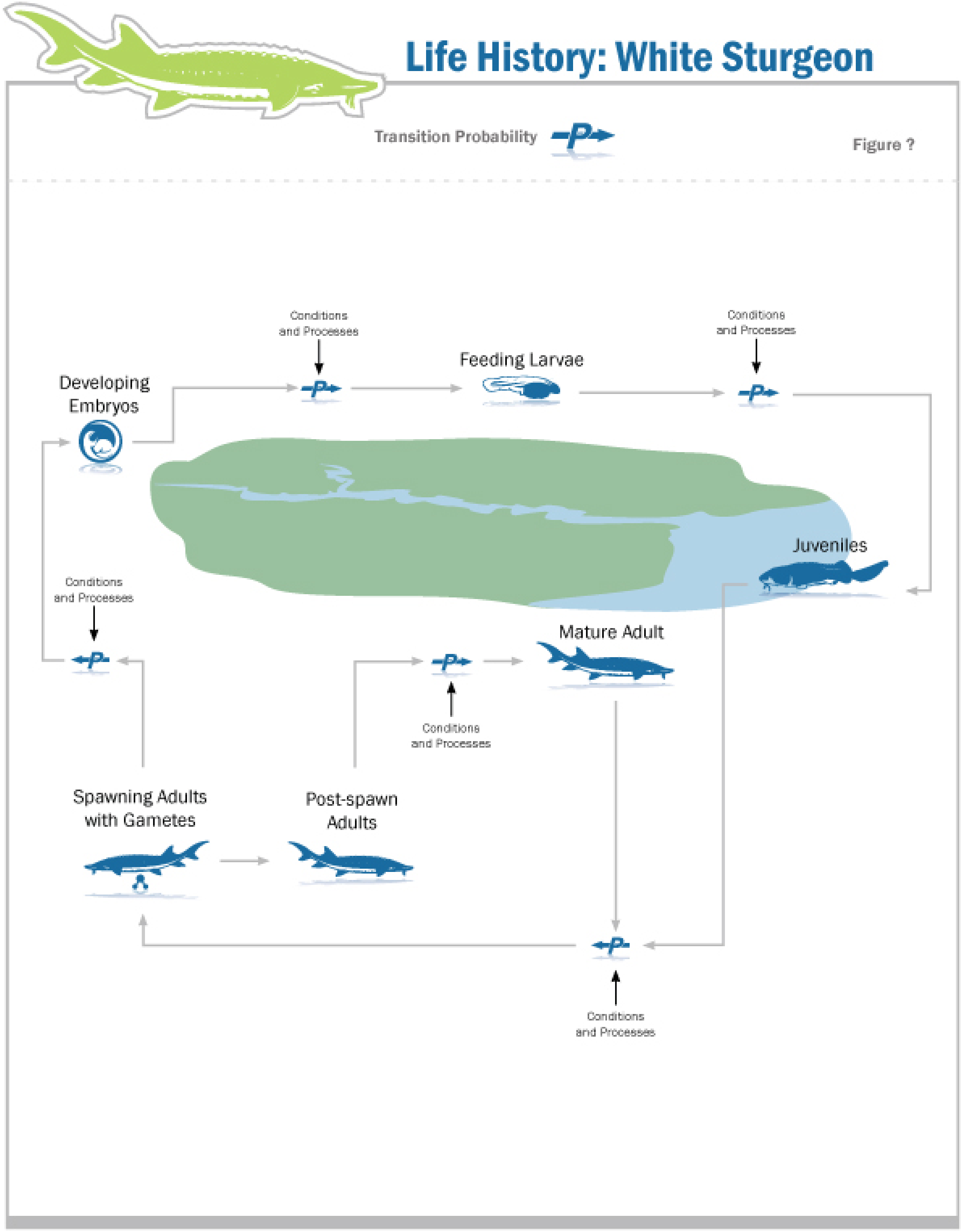

Figure 2. Conceptual life history model for white sturgeon.

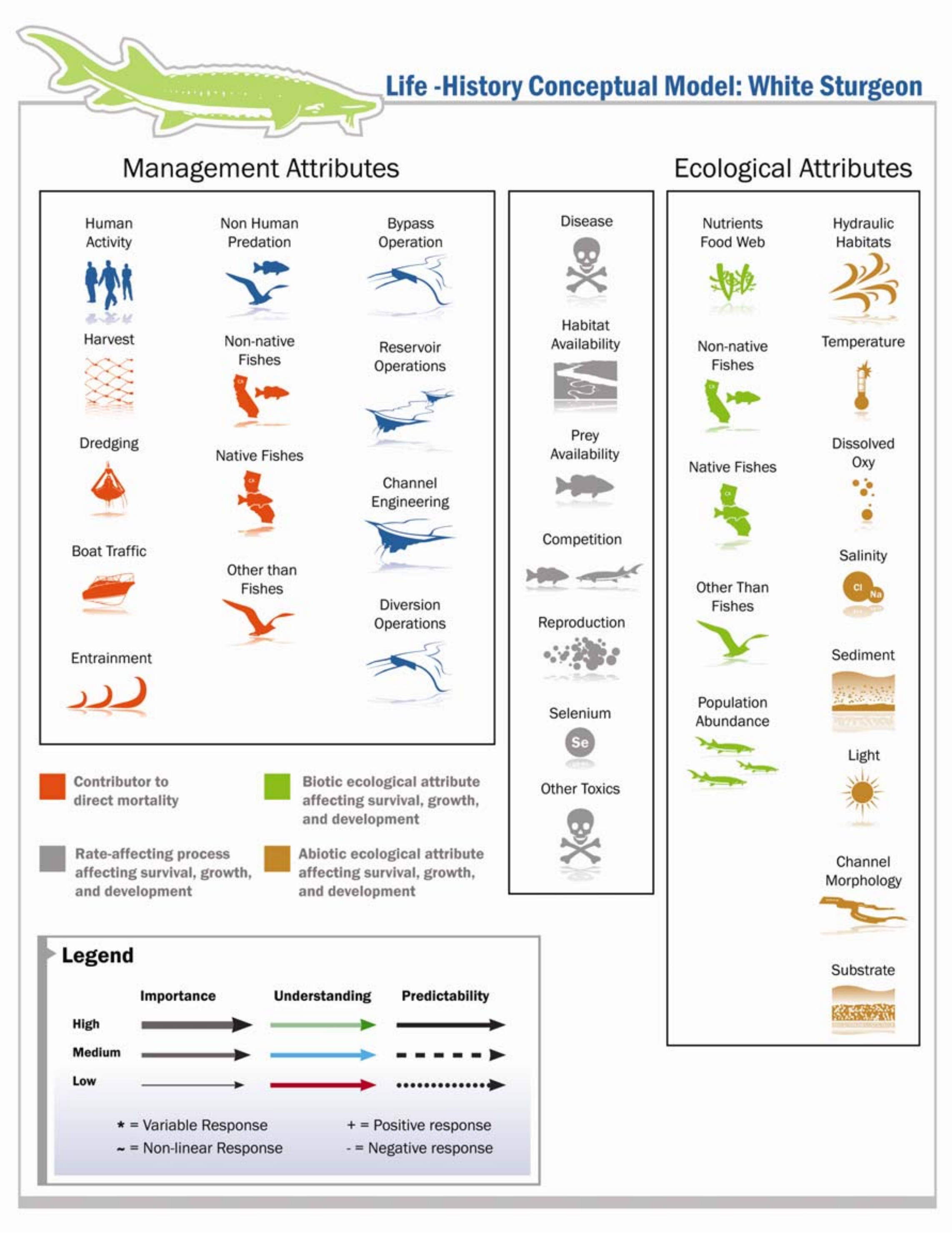

Figure 3. Abiotic and biotic factors influencing processes affecting the survival, growth, and development of white sturgeon (modified from Wildhaber et al. 2007).

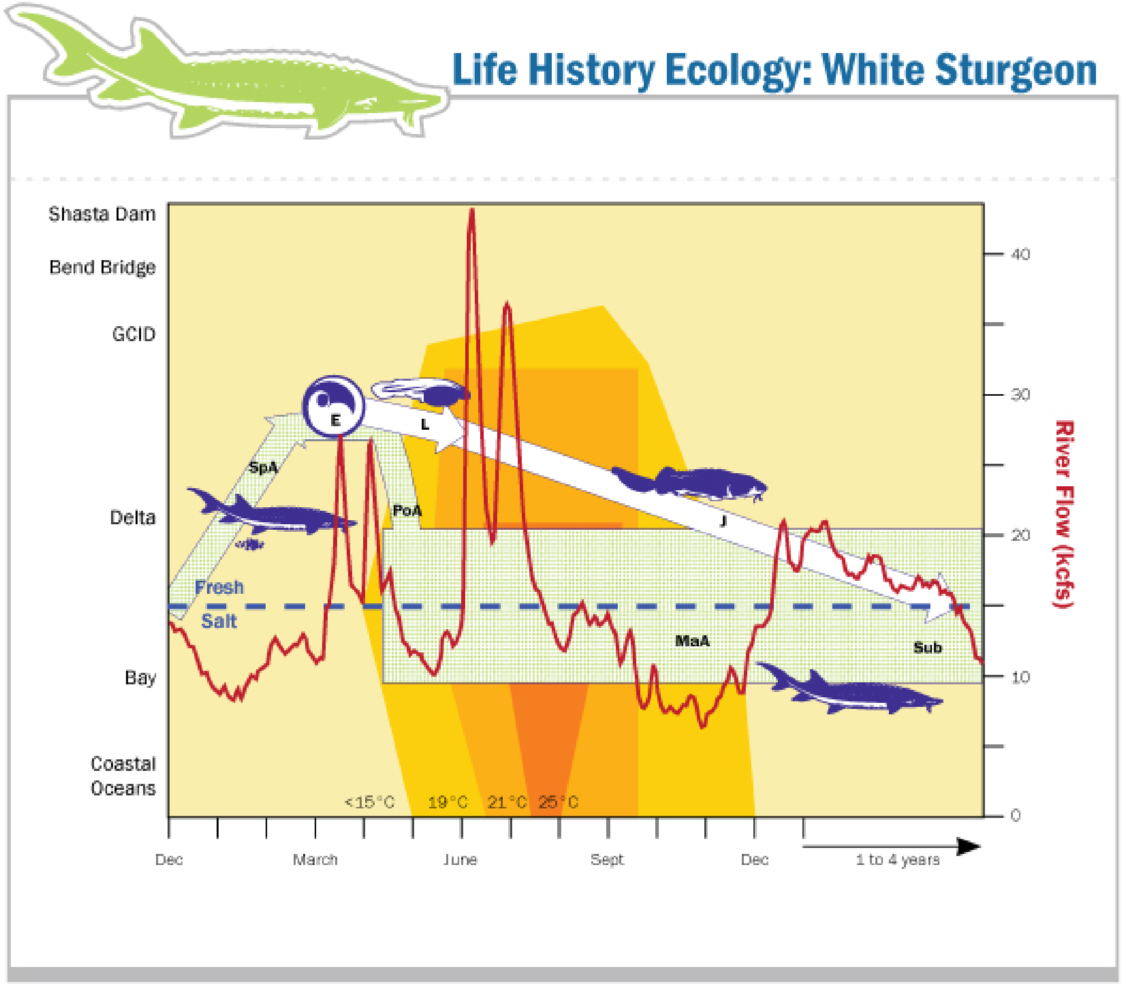

Figure 4. Conceptual life history ecological interaction model for white sturgeon in the Sacramento-San Joaquin Rivers and bay-delta. Spawning white sturgeon adults (SpA) enter the river in the winter to spawn and outmigrate quickly as post-spawners (PoA). Eggs (E) are broadcast spawned and mature into larvae (L), then enter and remain in the estuary at juveniles (J). Black line represents 2006 daily average flow at Vernalis (waterdata.usgs.gov). Temperature data are 2006 data from Bend Bridge, GCID, Bethel Island, Port Chicago, and Martinez (cdec.water.gov).

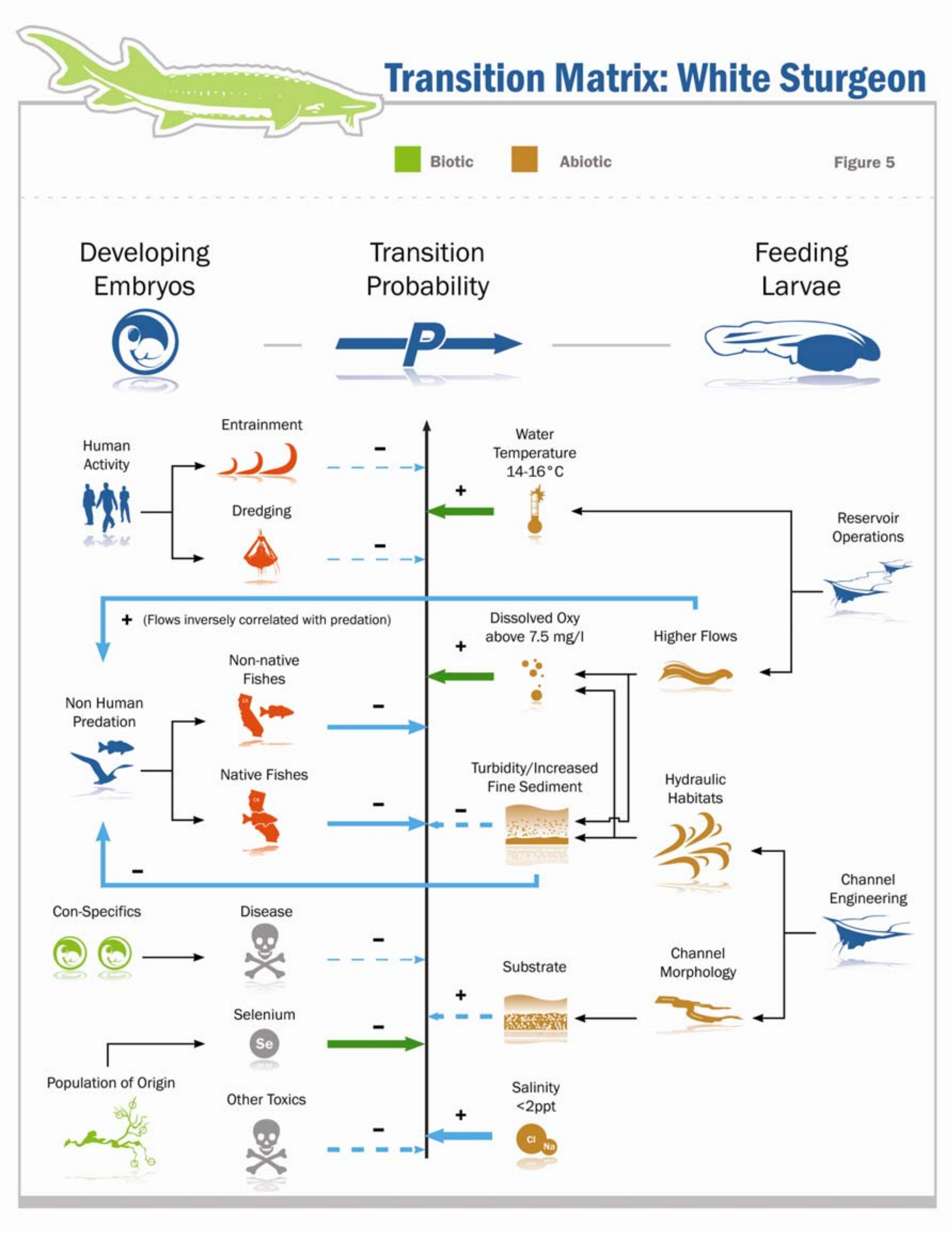

Figure 5. Riverine submodel for developing embryo to feeding larval stage of white sturgeon.

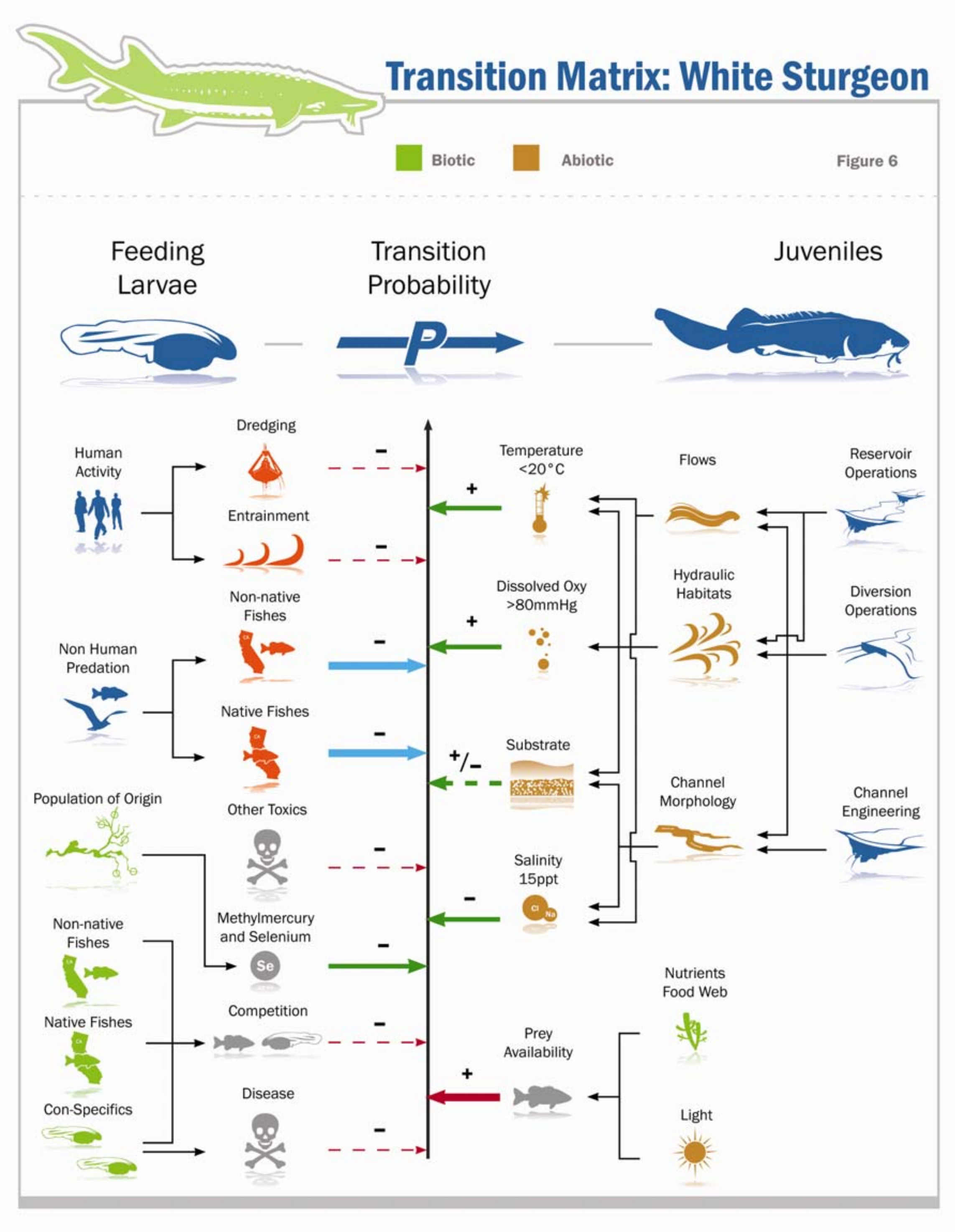

Figure 6. Riverine and bay-delta submodel of feeding larvae stage to juvenile white sturgeon.

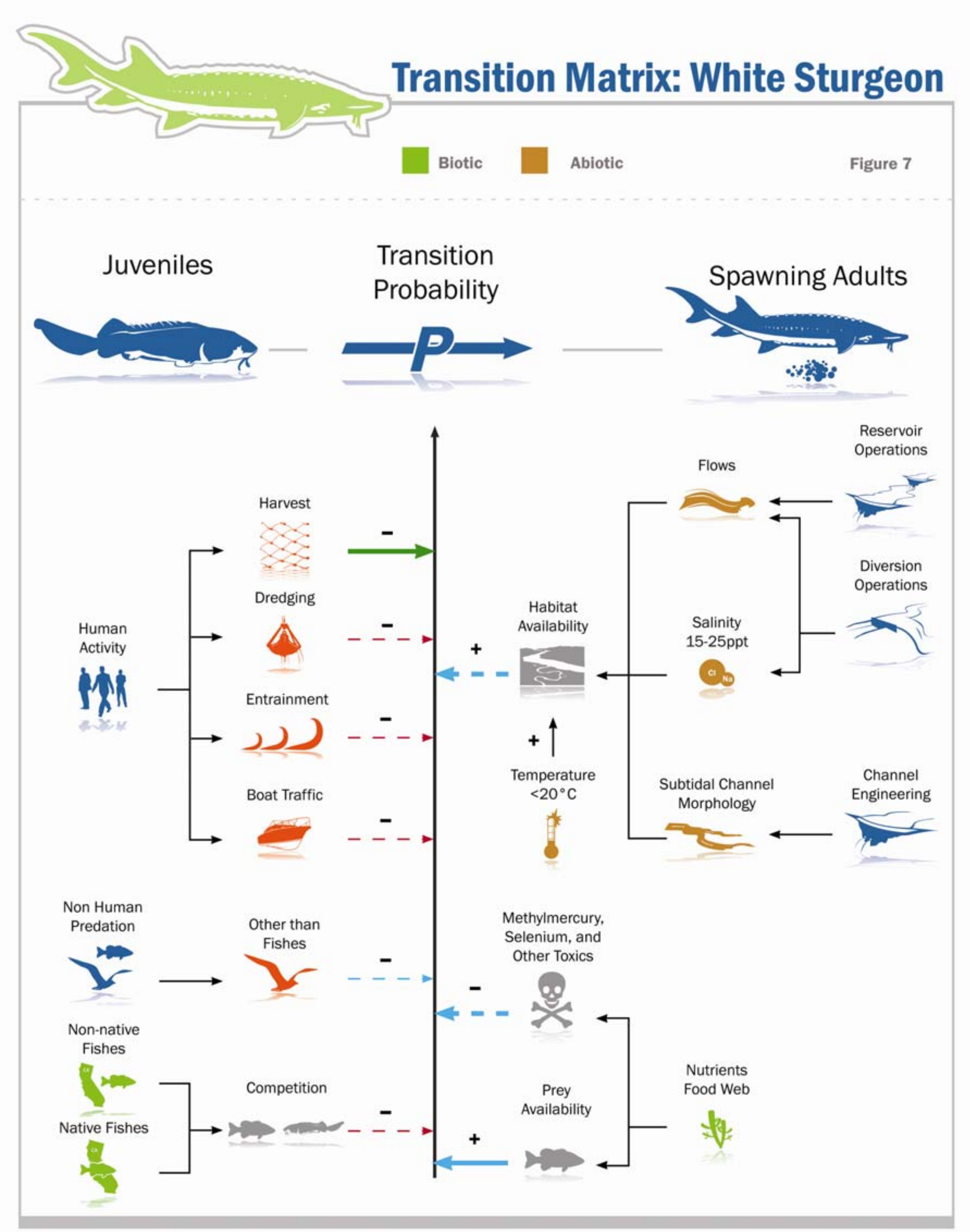

Figure 7. Bay-delta and marine submodel for juveniles to spawning adult white sturgeon.

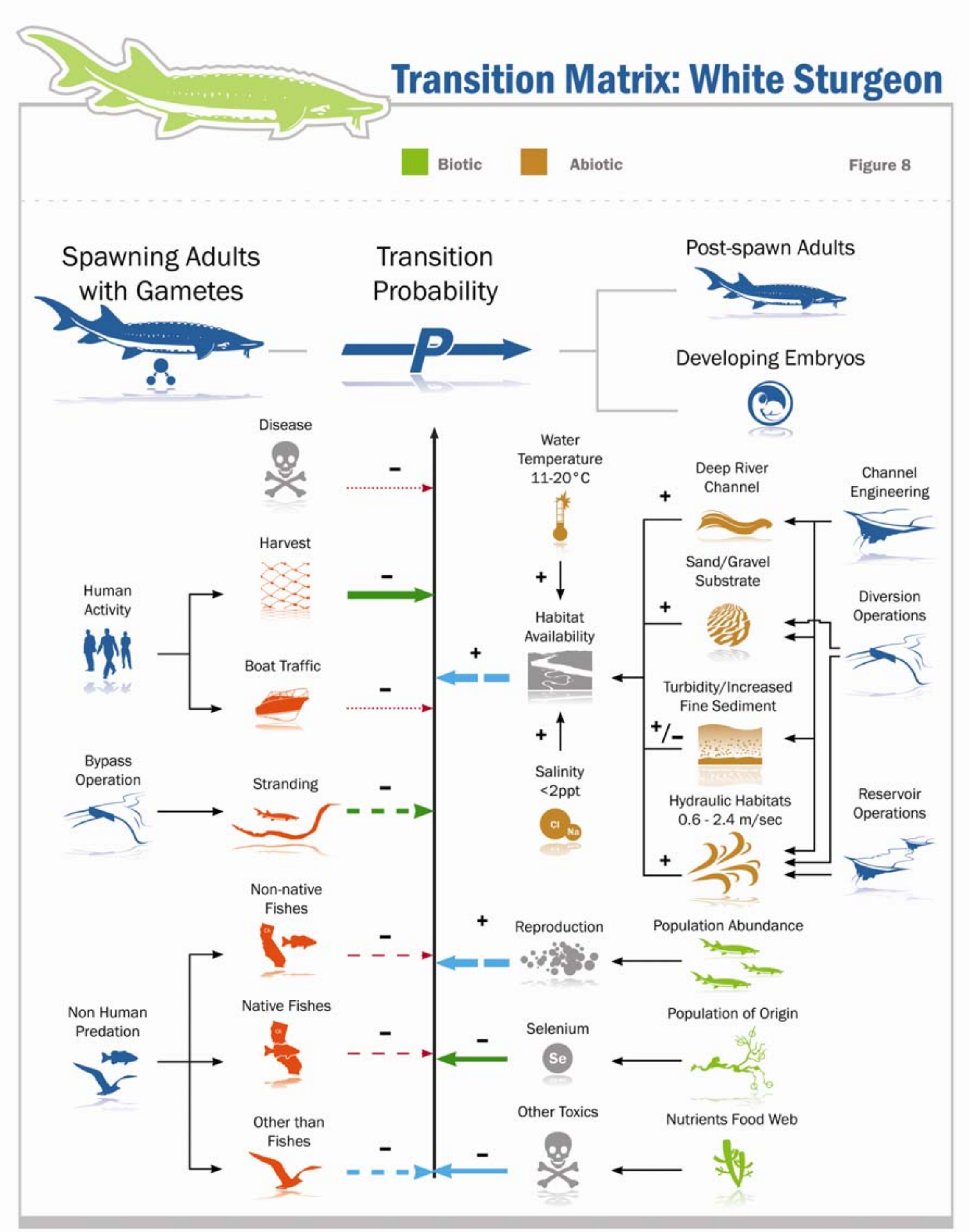

Figure 8. Riverine submodel for spawning adult to developing embryos for white sturgeon.

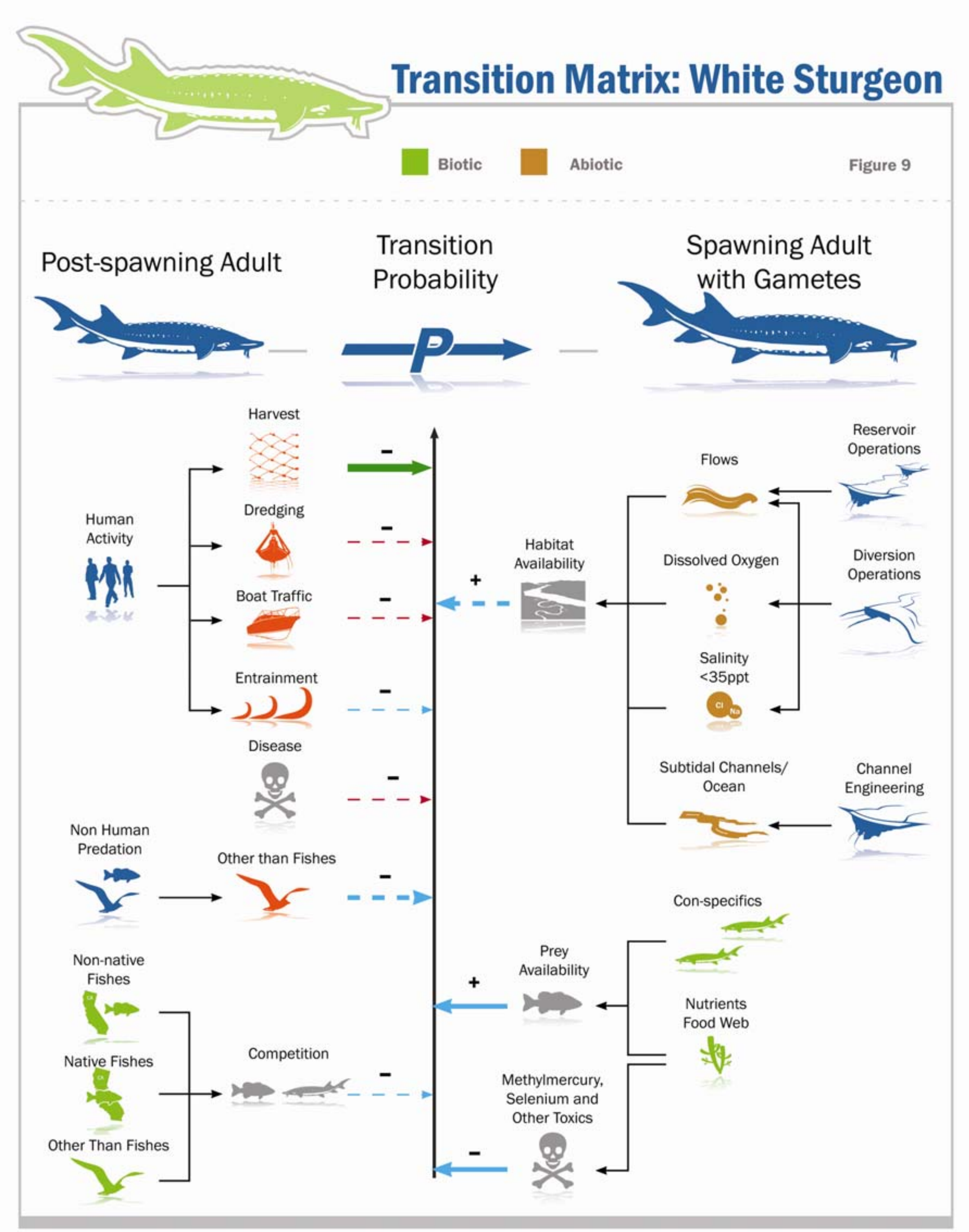

Figure 9. Riverine submodel for spawning adult to postspawn white sturgeon adult.

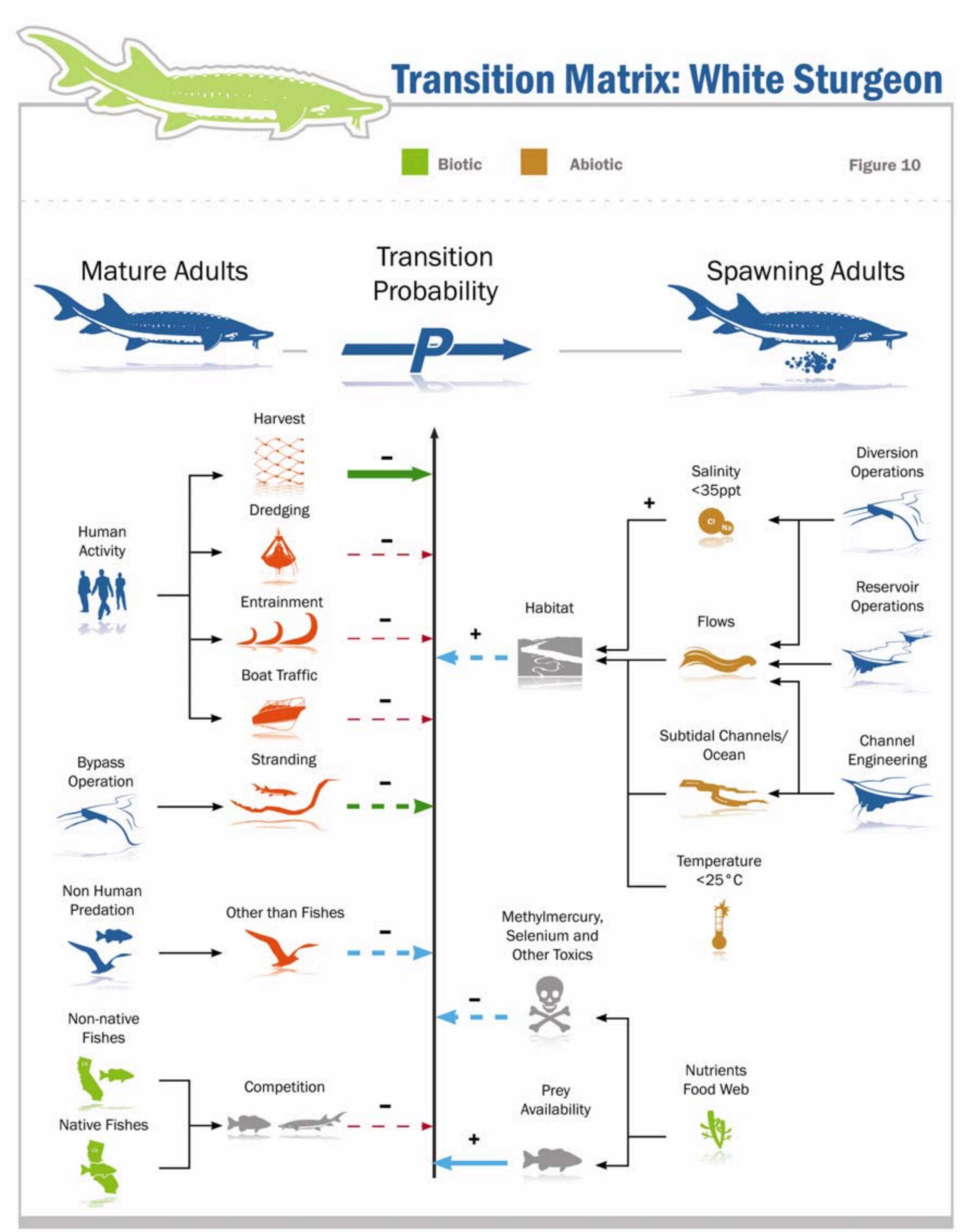

Figure 10. Bay-Delta and marine submodel for mature adults to spawning adult white sturgeon.