Potential Impacts of Dissolved Oxygen, Salinity and Flow on the Successful Recruitment of Atlantic Sturgeon in the Delaware River

The Nature Conservancy

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Project Summary

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The Delaware River and Estuary were once home to the largest population of Atlantic sturgeon on the East Coast – today less than 1% of the historic spawning population remains.

Project Purpose:

The objective of this project is to synthesize available literature, data and models describing distribution and habitat suitability for Atlantic sturgeon and use that information as a foundation for recommending habitat conditions that are suitable to support successful Atlantic sturgeon recruitment in the Delaware River.

This project is framed by three broad study questions (on the right) and directed by three specific focal hypotheses that have been identified as potentially influencing recovery potential of this ancient species:

- The persistent dissolved oxygen (DO) sag near Philadelphia, PA, during summer months, may be causing mortality of early life stages of Atlantic sturgeon;
- Low flow events coupled with sea level rise may be reducing suitable freshwater spawning and rearing habitats; and
- Flow conditions may serve to mediate or exacerbate one, or both of these limitations.

Study questions:

For any given **location**, at any given **time** of year, what is the **most sensitive life stage** present;

what are **suitable habitat conditions** to support that life stage;

what current and future **factors influence suitability**?

Products include:

- A conceptual model of limitations to recruitment;
- Life history distribution tables and maps summarizing reaches of the river occupied at different times of year in relation to water quality zones and the salt front; and
- Recommended habitat conditions to support successful recruitment in the Delaware River.

Summary of recommended habitat conditions:

To support successful Atlantic sturgeon recruitment in the Delaware River, we recommend*;

- Instantaneous DO $\geq$ 5.0 mg/L
- Temperature < 28°C
- Salinity < 0.5 ppt, and
- Discharge > July Q85 (4,000 cfs @ Ben Franklin), when average daily DO < 5.5 mg/L

**Recommendations represent the minimum values required to support habitat suitable for recruitment based on best available literature, regional data and expert review. To address cumulative stressors present in the Delaware (e.g. dioxins), conservation measures should be more protective.*

Study conclusions:

- Sturgeon of all life stages occur throughout the freshwater portion of the river, with early life stages occurring year-round.
- Despite improvements in water quality over the last two decades, DO conditions in recent years likely inhibited successful development of early life stages.
- Improved water quality standards are needed to support suitable habitat conditions. Best available technologies could improve DO from lethal to suitable concentrations.
- Current low flow conditions influence salt front encroachment. In 2010, the availability of suitable freshwater habitat was reduced by between 10 and 20 miles throughout the summer, during egg, larval and young-of-year development. Under the drought of record, suitable freshwater habitat was reduced by up to 40 miles.
- Anticipated sea level rise is projected to permanently shift the average salt front upstream. Further, changing precipitation and evapotranspiration patterns may increase the extent of upstream migration in response to longer-duration low flow events.

For more information about this project please contact:

Tara Moberg, tmoberg@tnc.org
Mari-Beth DeLucia, mdelucia@tnc.org

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Acknowledgements

This project would not have been possible without substantial contributions from workgroup members. Over the course of the project, workgroup members shared telemetry and water quality data, refined scientific interpretation, and provided valuable insight on draft products. In particular, we would like to thank Dr. Dewayne Fox and Lori Brown (Delaware State University), Matthew Fisher, Lynn Lankshear (NOAA Fisheries), Dr. David Secor and Erin Markin (University of Maryland Center for Ecological Studies), Erik Silldorff (Delaware River Basin Commission), Michele DePhilip, Alison Bowden, Su Fanok, Sarah Johnson and Brian Boutin (The Nature Conservancy).

A complete list of workgroup participants is included in Appendix 5. The Nature Conservancy synthesized these findings based on research, data and input provided by workshop members. The report's collective set of recommendations and study conclusions are those of The Nature Conservancy and do not necessarily reflect all viewpoints of individual workshop members or the positions or policies of their organizations.

Corresponding authors:

Tara Moberg
Mari-Beth DeLucia
The Nature Conservancy
2101 N. Front Street, Bldg 1, Suite 200
Harrisburg, PA 17102
tmoberg@tnc.org

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Section 1. Introduction

1.1 Project purpose and approach

The Nature Conservancy was approached by regional sturgeon experts to examine the potential impacts of flow, dissolved oxygen (DO) and salt water encroachment on the successful recruitment of Atlantic sturgeon in the Delaware River. In order to examine where and how these factors may be limiting recruitment, we synthesized available literature, data and models on habitat suitability for Atlantic sturgeon. We used that information, framed by the study questions and methods in Box 1, to document current life stage distribution, assess focal hypotheses and to serve as the foundation for a set of recommended habitat conditions suitable for successful recruitment of Atlantic sturgeon in the Delaware River. Recommendations for estuarine habitats are outside of the scope of this report.

Box 1.

Study questions	Methods
For any given location and time of year, what is the most sensitive life stage present?	Section 2. Habitat use in the Delaware River Telemetry data (2005-2014) and regional literature, serve as the foundation for the location (river miles) and timing (season) of life stage occurrence in the Delaware River. These are documented in conceptual life history models and distribution maps for each life stage (Appendices 1 and 2).
What current and future factors influence habitat?	Section 3. Current and future factors influencing habitat Water quality and hydrology data were paired with distribution data to assess **three focal hypotheses**: • The persistent dissolved oxygen (DO) sag near Philadelphia, PA, during summer months, may be causing mortality of early life stages of Atlantic Sturgeon; • Low flow events coupled with sea level rise may be reducing freshwater spawning and rearing habitats; and • Flow conditions may serve to mediate one, or both of these limitations.
What are suitable habitat conditions to support each life stage?	Section 4. Recommended habitat conditions to support successful recruitment We summarized peer-reviewed and gray literature on habitat needs associated with dissolved oxygen, temperature and salinity. These needs are associated with a gradient of habitat suitability ranging from optimal to lethal conditions (Appendices 1 and 3). Building on this synthesis, we held a two-day workshop in June 2014 to review available information and develop a habitat recommendations framework. The workshop included regional Atlantic sturgeon experts from research institutions, federal and state fisheries management agencies in addition to water resource managers (Appendix 5).

1.2 Brief history of Atlantic sturgeon in the Delaware River

Atlantic sturgeon are an ancient fish that have been in existence for at least 70 million years. They rely on major coastal rivers, like the Delaware, for freshwater spawning and nursery habitat. The Delaware River and Estuary were once home to the largest population of Atlantic sturgeon on the East Coast with an estimated 180,000 adult females spawning in the river prior to 1890 (Cobb 1900, Secor and Waldman 1999, ASRT 2007). At this time, the river was considered the caviar capital of the world and overfishing was extensive. In addition to fishing pressure, beginning in the late 1800s and continuing through the 1900s, much of the lower Delaware River was anoxic during the summer and fall months (DRBC Task Force 1979, Albert 1988). This pollution created a barrier, blocking migration and access to spawning and rearing habitats. The combination of overfishing and pollution resulted in collapse of the population by the early-1900s. In 1991, the Delaware Division of Fish and Wildlife adopted a 7 foot minimum which essentially closed the fishery and in 1998, a coast wide moratorium eliminated any harvest of Atlantic sturgeon (ASMFC 1998). Sturgeon populations failed to show signs of recovery under the coast wide moratorium.

In 2009, a petition was filed with the National Marine Fisheries Service (NMFS) to list and protect Atlantic sturgeon as an endangered species under the Endangered Species Act (ESA). After scientific review of the critically low population estimates and documentation of pervasive threats, NMFS listed the Delaware River population (part of the New York Bight Distinct Population Segment), among others, as federally endangered (US OFR 2012). In this listing, factors identified as jeopardizing the population included habitat degradation (water quality and dredging), vessel strikes, entrainment and bycatch. In the Delaware River, the risk posed by each factor varies by life stage (Figure 1).

There have been no population surveys to estimate abundance of Atlantic sturgeon in the Delaware River. Based on Atlantic coast population estimates, it is presumed that the Delaware River currently supports less than 300 spawning adults per year, just 0.1% of the historical spawning population (ASRT 2007, Breece et al. 2013). In 2009, the first observation of successful spawning in over three decades was confirmed in the Delaware River, with subsequent observations occurring in 2011 and 2014 (DNREC-DFW 2015).

Remaining habitat for Atlantic sturgeon spawning and rearing in the Delaware River is found between Trenton, New Jersey and Wilmington, Delaware (Simpson and Fox 2007, ASRT 2007, Calvo et al. 2010, DNREC-DFW 2015). This reach of the mainstem is surrounded by one of the most heavily urbanized portions of the basin, including major cities, water intake structures and wastewater treatment plant discharges (DRBC Task Force 1979, Albert 1988, Sharp 2010). Major ports and shipping lanes have led to an increased frequency of ship strikes on spawning adults and blasting and dredging of channel bottom habitat. Sea level rise and increased frequency or duration of extreme low flow events will further threaten restricted habitat (DVRPC 2004, Ross et al. 2015). Of the many factors that pose risks to Atlantic sturgeon recruitment in the Delaware River , regional sturgeon experts hypothesize a few are acting as 'bottlenecks,' limiting the availability of suitable freshwater spawning and rearing habitats (Kahn and Fisher 2012, Breece et al. 2013, D. Fox, personal communication). Two conditions limiting spawning and rearing habitats are the focus of this project (Figure 1).

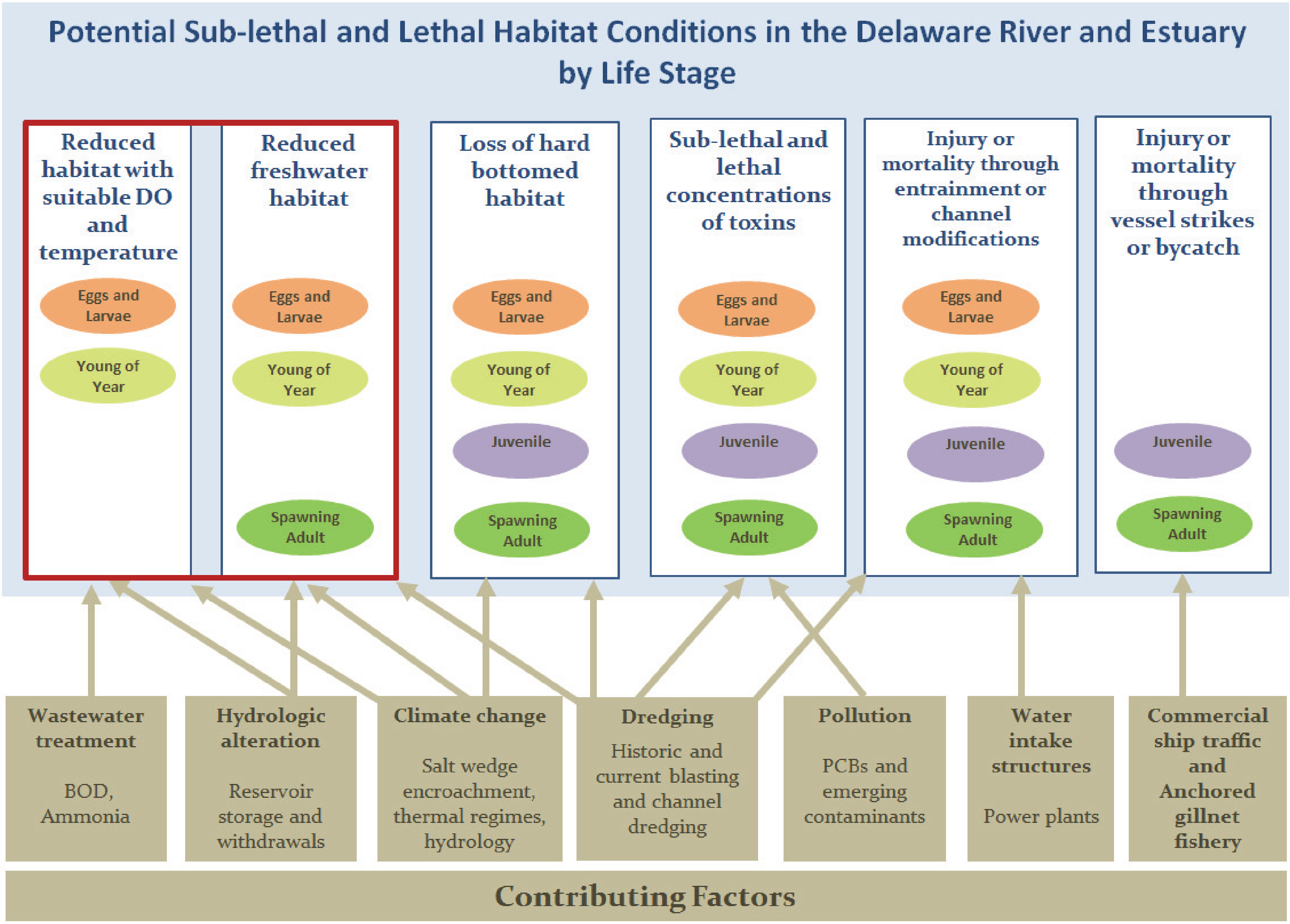

Figure 1. Conceptual model of factors limiting Atlantic sturgeon recruitment in the Delaware River and Estuary (Albert et al. 1988, US OFR 2012, Kahn and Fischer 2012, Kocik et al.. 2013). The **red highlighted box** includes the two limiting conditions that are the focus of this project.

Section 2. Habitat use in the Delaware River

Delaware River and Estuary habitats have supported all Atlantic sturgeon life stages, with the exception of adult growth, which occurs in marine environments (Lazzari et al. 1986, Gilbert 1989, Van Eenennaam et al. 1996, Stevenson and Secor 2000, ASRT 2007, Balazik et al. 2015, DNREC-DFW 2015, Appendix 1, Table 1). We used recent telemetry data (2009-2014) supplemented by regional literature to map the distribution of these life stages in the Delaware throughout the year (Appendix 2).

Spring and Summer (Appendix 2: Maps 1, 3 and 5). Reproductively mature adults begin migrating to their natal estuaries in the spring. As in most coastal rivers in the eastern U.S., the Delaware reaches peak annual flows during the spring months (Figure 2). It is this period of high flow conditions in combination with increasing temperature that cues adult sturgeon to migrate above the salt front to spawn in freshwater.

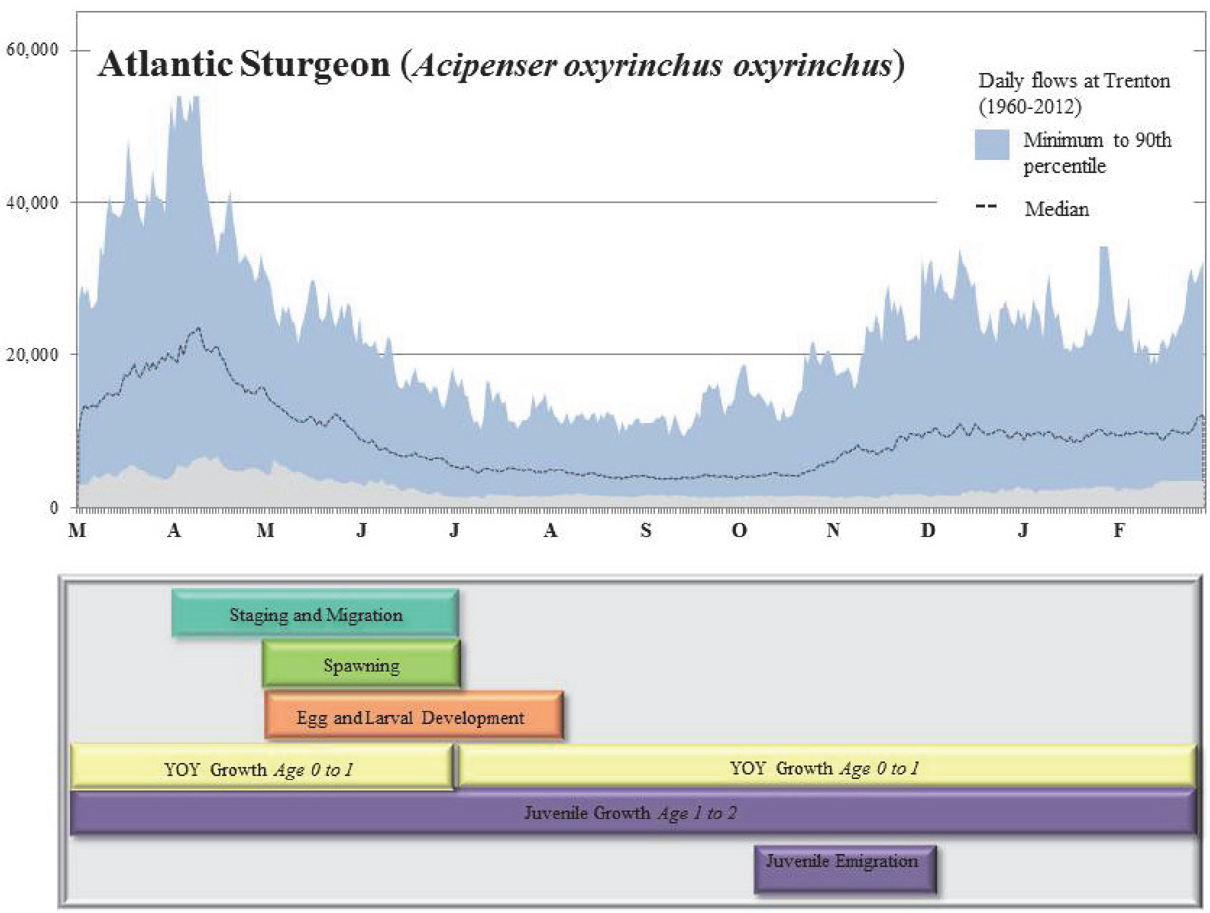

Figure 2. Flow-ecology diagram illustrating the relationship between annual hydrograph and timing of Atlantic sturgeon life stages specific to the Delaware River. It is hypothesized, but undocumented, that spawning may also occur in the fall (Balazik et al. 2015, DNREC-DFW 2015).

Spawning occurs over hard bottom substrate, including bedrock, cobble and gravel and is known to occur between May and June. On the Delaware, freshwater conditions underlain by hard bottom substrate occurs roughly between river miles (RM) 69 and 125 (Appendix 2, Table 1).

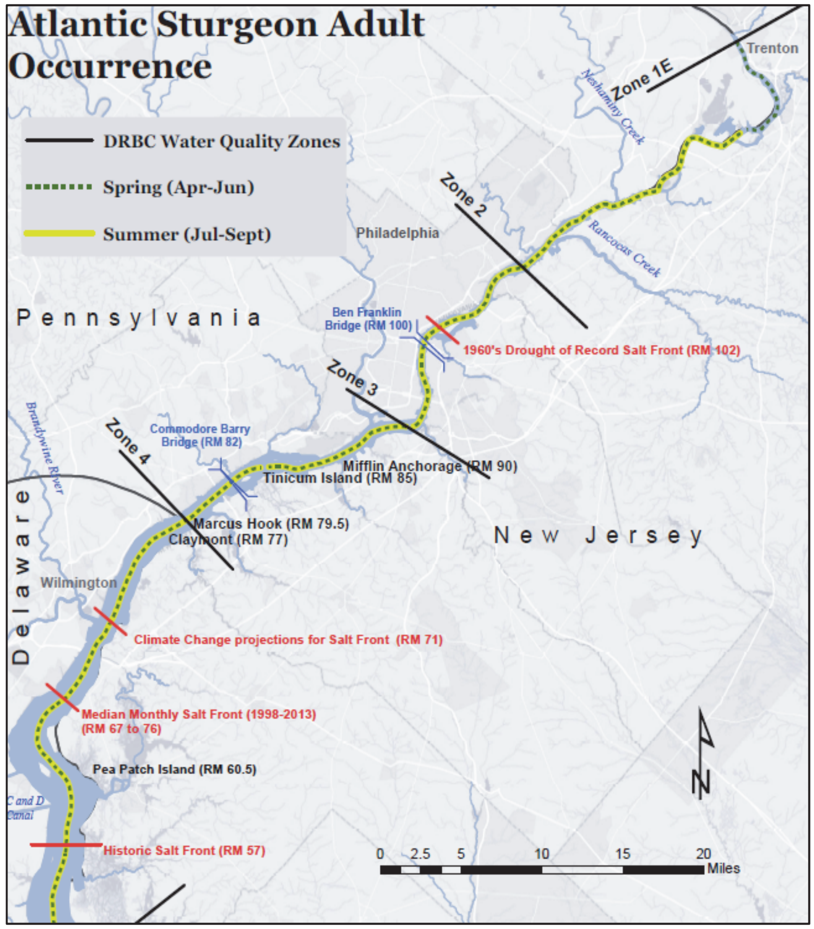

Figure 3. Example distribution map for Atlantic sturgeon adults during spring and summer in relation to Delaware River Basin Commission (DRBC) water quality zones, salt front locations and key river mile locations. A complete set of maps by life stage and season is included in Appendix 2.

Depending on the spawning date, egg and larval development can occur between May and July as high flows recede, stabilizing into summer base flows. Eggs are demersal, adhering to clean hard bottom, close to the location of spawning for about three to four days before hatching into larvae. Larvae develop close to spawning grounds over a four week period transitioning from a yolk sac diet to feeding on small benthic organisms. As early as July, larvae have developed into young-of-year, with improved swimming abilities. The summer is a time for rearing and growth for all early life stages.

Fall and Winter (Appendix 2, Maps 2, 4 and 6). The fall brings an increase in base flows and high flow pulses that cue juveniles to emigrate from freshwater nurseries to estuarine and marine habitats, usually during their second fall. Recently, during fall, adults have also been observed making an upstream migration (DNREC-DFW 2015). Currently, it is unknown whether this migration is associated with a second spawning event. Just south of the Delaware River, on tributaries to the Chesapeake, fall spawning has been verified (Balazik et al. 2012, Hager et al. 2014, Balazik et al. 2015). By the winter, adults have migrated out of the tidal river into marine habitats. Young-of-year and first-year juveniles overwinter between RM 125 (Roebling) and the salt front.

Section 3. Current and future factors impacting habitat suitability

This section summarizes factors that influence suitable freshwater spawning and rearing habitats, framed by the focal hypotheses about how DO, salinity, and flow conditions affect habitat suitability for various life stages.

3.1 Persistent dissolved oxygen sag

Beginning as early as the late 1800s and continuing through the 1900s, much of the Delaware River below Trenton (RM 124 to RM 56) was anoxic during the summer and fall months and unable to fully support the complement of species native to the Delaware River (Albert 1988, Sharp 2010).

Like many large rivers throughout the U.S., with the enactment and implementation of the Water Pollution Control Act and the Clean Water Act in the late 1960s and early 1970s, respectively, the severity and extent of the DO sag was reduced in the Delaware River, especially as major sewage treatment plants in the greater Philadelphia region were required to meet new water quality standards (Albert 1988). Between May and September when spawning, egg and larval development, and young of year development occur, mean monthly DO concentrations were well below 3.5 mg/L between 1966 and 1985, and below 5.0 mg/L through 2005 (Figure 4). In the mid-1970s, the estimated extent of the sag ranged from RM 62 (near New Castle) to RM 108 (near Burlington) (Sharp et al. 2010). From the 1960s through the early 2000s, there was a lack of spawning and recruitment documented between Philadelphia and Chester (Kahn and Fisher 2012).

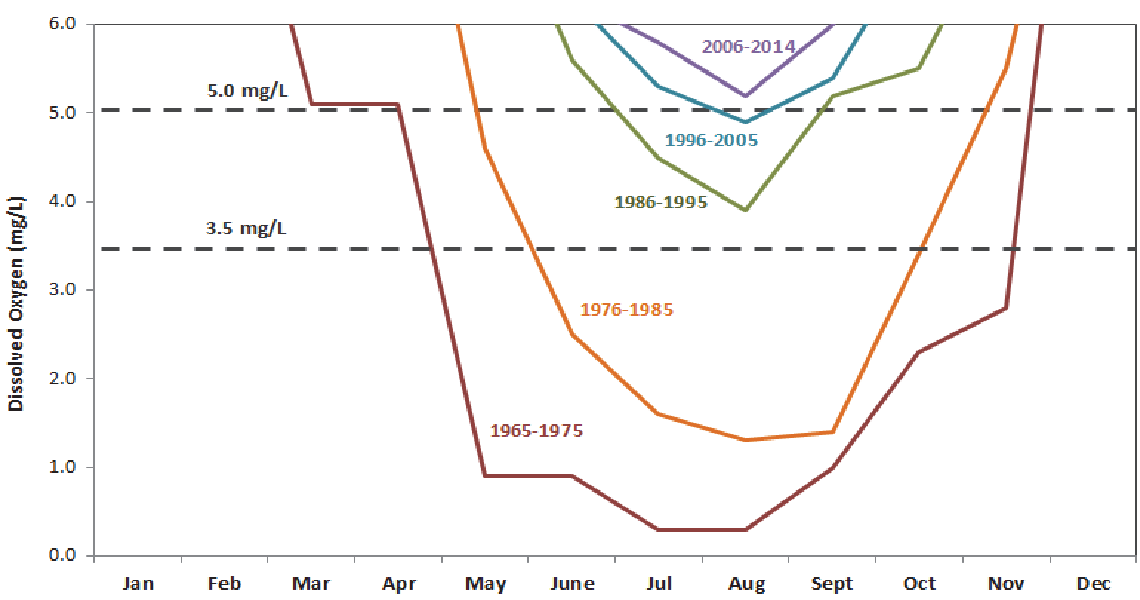

Figure 4. Mean monthly DO at Philadelphia (Ben Franklin Bridge) from 1965-2014.

In order to understand habitat conditions relative to recruitment observations, we used USGS DO, temperature, and flow data to assess two questions (Figures 5 and 6):

- What were DO, temperature and flow conditions during years that recruitment was observed (2009, 2011, 2014); and
- How does that compare to conditions during years when recruitment was not observed?

Atlantic sturgeon recruitment success is difficult to measure. For the purposes of this report, recruitment observations are defined as those years when more than one dozen young-of-year were observed through study capture, or those years that are linked to the year class of an equal or greater number of juveniles or sub-adults. Therefore, for the purposes of this report, we categorize 2009, 2011 and 2014 as years that recruitment was observed (DNREC-DFW 2015). Recruitment was not observed between 2005 - 2008, 2010, 2012 or 2013. For more information about sampling methods and intensity, please see DNREC-DFW 2015.

Relationship between recruitment observations and DO. During years when recruitment was observed, minimum daily DO was above 5.0 mg/L in 90% of the observations. Further, the median minimum daily DO during these years was > 6.0 mg/L during the spawning and egg and larval development periods (Figure 5). During years when recruitment was not observed, median minimum daily DO was between 4.0 and 5.0 mg/L, and conditions were frequently < 4.0 mg/L.

Relationship between temperature and DO. High water temperatures reduce the saturation of oxygen in the water, lowering DO and potentially leading to hypoxic conditions (Niklitshek et al. 2009). Figure 6 illustrates the relationship between increasing temperature and decreasing DO in the Delaware River. During observations in July and August 2005-2014, DO levels < 4.0 mg/L occurred when temperatures were > 25°C. DO levels < 5.0 mg/L occurred when temperatures were > 23°C.

Relationship between flow and DO. Factors influencing flow in the Delaware River include reservoir operations, water withdrawals and climatic variability. During the months of June through September of 2005-2014, all measurements taken when DO < 4.0 mg/L occurred under low flow conditions (< 8,000 cfs) (Figure 6). Analysis of long-term hydrology (1960-2014) at the USGS Ben Franklin Gage showed that the period of low dissolved oxygen during the summer of 2010 occurred during an extreme low flow event, with several weeks below 4,000 cfs (Figure 7). During this event, DO concentration were measured as low as 3.2 mg/L. Unfortunately, the USGS water quality station was down during this period, so continuous daily measurements are unavailable to develop regression analyses. Factors influencing flow in the Delaware River include reservoir operations, water withdrawals and climatic variability.

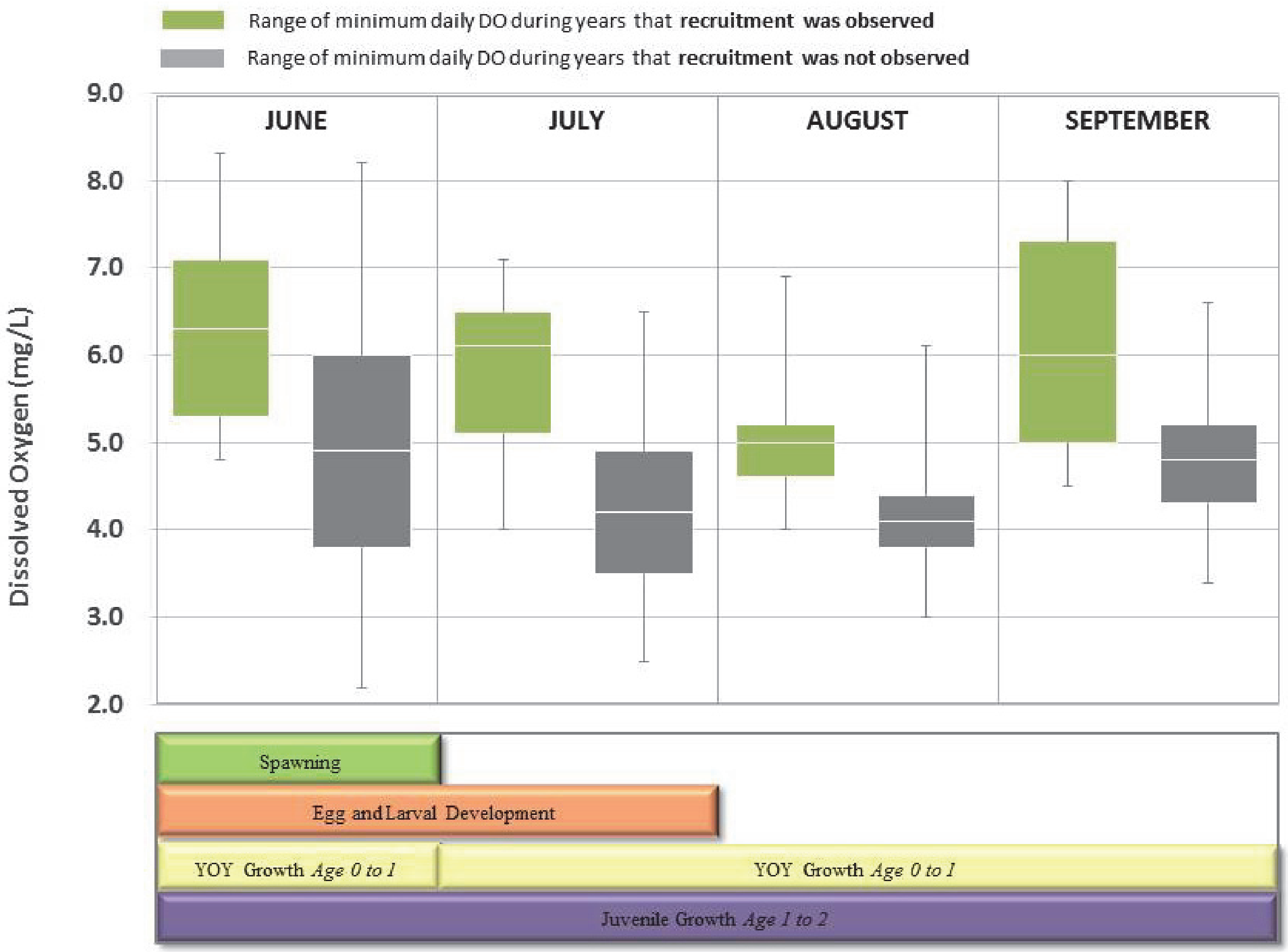

Figure 5. A comparison of the range of minimum daily DO concentrations at Ben Franklin Bridge (RM 100) between years when recruitment was observed (2009, 2011 and 2014) and years recruitment was not observed (2005-8, 2010, 2012, 2013). A box blot distribution represents the maximum and minimum values as represented by the upper and lowermost points, and the distribution of the 75th, 50th (median), and 25th percentiles as represented by the bottom, center and top of the box respectively.

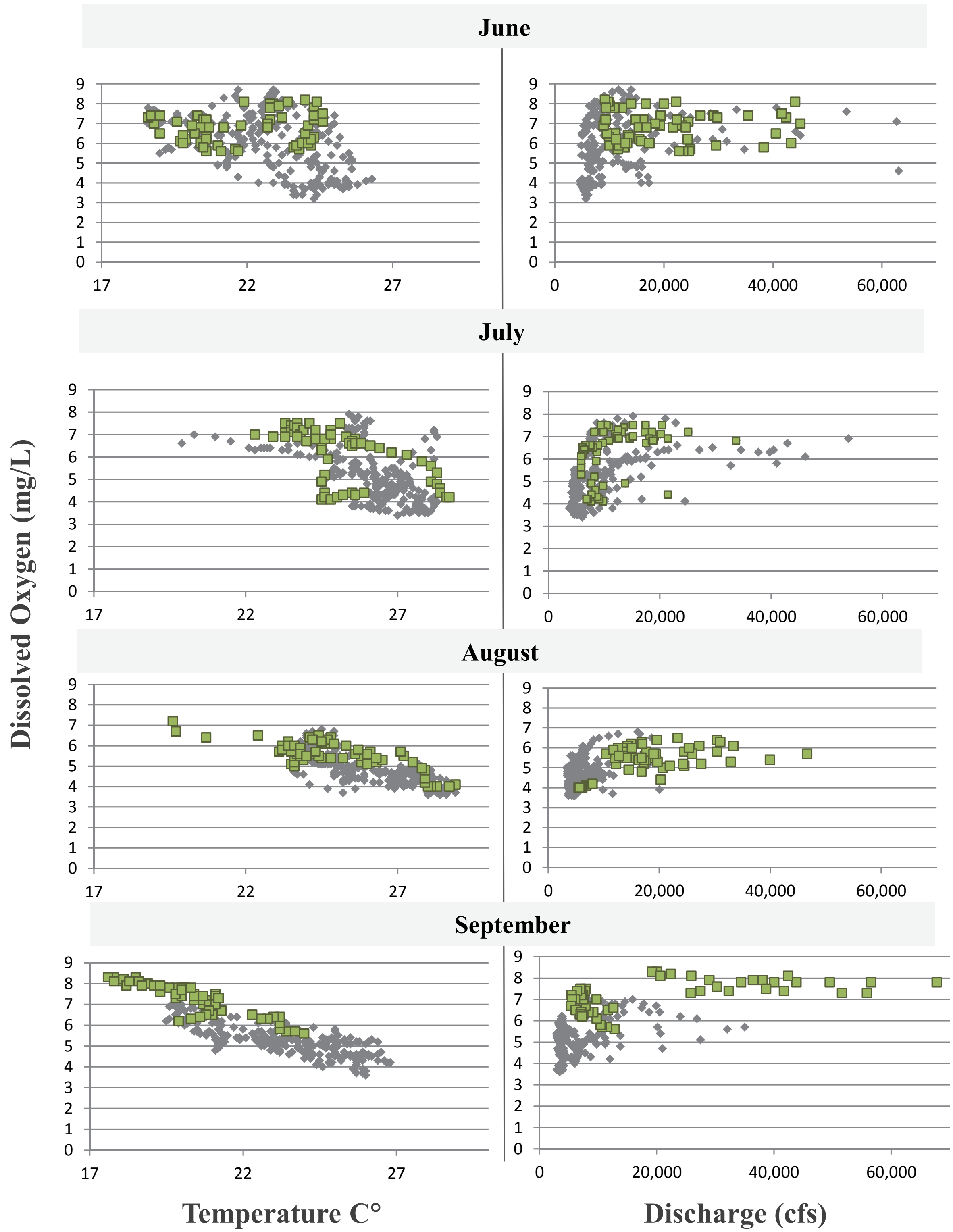

Figure 6. The relationship between DO, temperature and flow at the Ben Franklin bridge (RM 100) during years when recruitment was observed (**in green - 2009, 2011 and 2014**) and years when it was not (**in gray - 2005-2008, 2010, 2012, 13**). Not all 2010 data are reflected in these graphs due to lack of paired DO, temperature and flow data.

The Delaware River Basin Commission (DRBC) sets water quality standards for reaches of the river that were historically and are currently occupied by Atlantic sturgeon. Appendix 4, Table 1 lists the water quality standards for each reach including instantaneous (where applicable), 24-hr average and seasonal average standards. Standards vary by water quality zone and range from 3.5 mg/L to 6.0 mg/L in Zones 2-5c, which are currently occupied by spawning adults, young-of-year and juveniles (Appendix 4, Table 1). In 1979, a DRBC Ad Hoc Task Force recommended a minimum instantaneous standard be established. There are currently no standards for instantaneous DO concentrations downstream of Trenton, NJ. Biological oxygen demand (BOD) from upstream point source discharges contributes to lower DO (HydroQual 1998). A 1990's modeling study estimated that DO could be increased by up to 1 to 2 mg/L by reducing the ammonia content of wastewater discharges which account for an estimated 85 percent of total ammonia inputs (HydroQual 1998). This could be accomplished through best available technologies and practices (Cadmus 2009).

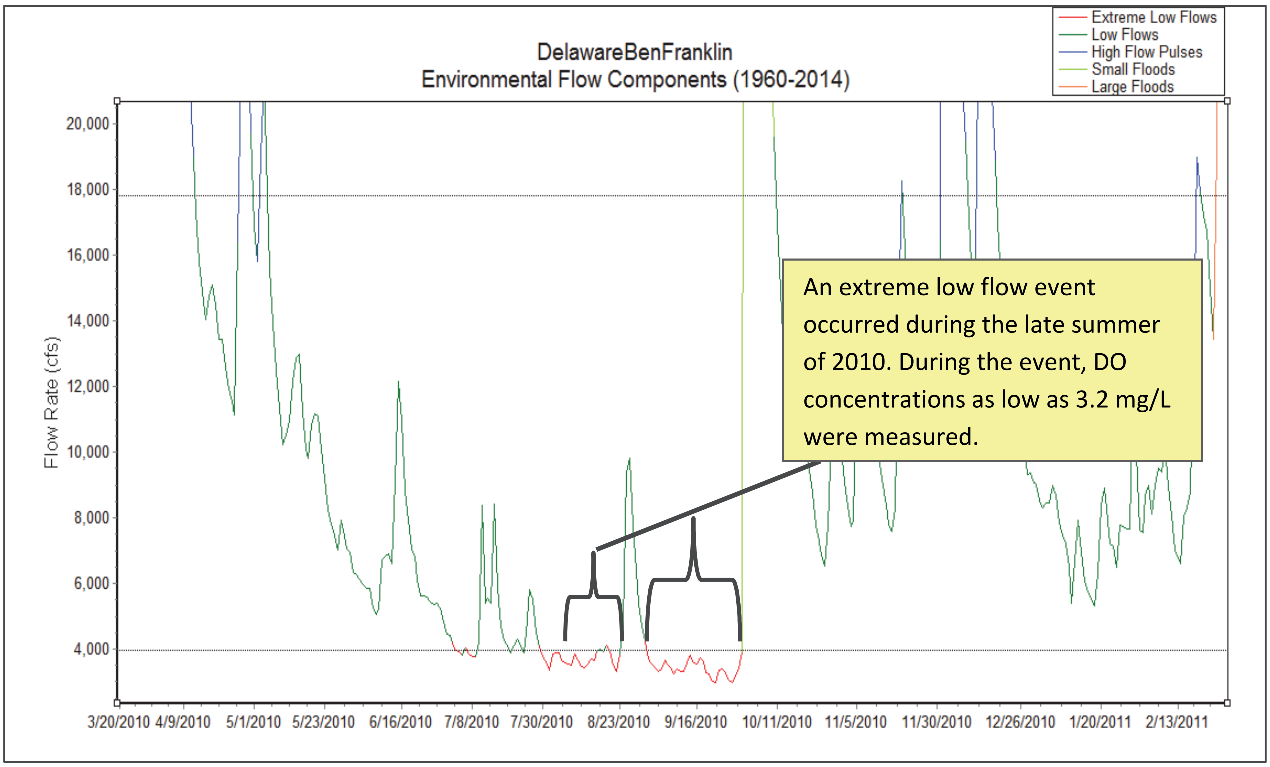

Figure 7. Analysis of long-term hydrology (1960-2014) shows that the period of low dissolved oxygen in 2010 occurred during an extreme low flow event. These events occurred during key months for egg and larval development and young-of-year growth. Extreme low flows (less than 4,000 cfs, **in red**) occurred for several weeks, separated by a small low flow event (in green).

3.2 Reduction in suitable freshwater spawning and rearing habitats

The location of the salt front influences the availability of suitable habitat for Atlantic sturgeon spawning and rearing habitats in the Delaware River. The salt front location, typically described by river mile (RM), is influenced by river flows, dredging, and a changing climate that includes both sea-level rise and changes in precipitation (Walters 1992, Kreeger et al. 2010, Ross et al. 2015).

Relationship between flow and salinity. High and average flow conditions keep the salt front further downstream. Conversely, low-flow or drought events have allowed the salt wedge to move upstream to Philadelphia, as was the case during the 1960's drought of record. During this drought, the salt front reached RM 102. In effect, at its maximum, the salt front was upstream of 40 miles of habitat for early life stage development. During most of this drought period, flows remained between 2,500 and 3,200 cfs (July-September). The 7-day minimum flow was 1,918 cfs which is equivalent to the July Q98[1].

More recently, during years when recruitment was observed, the maximum salt front occurred at RM 69.5 and 57.1 respectively (Appendix 4, Table 2). Spawning habitat occurs upstream of RM 69.5, and therefore freshwater conditions upstream of RM 69.5 likely supported early life stages throughout 2009 and 2011. During 2010, a year with no observed recruitment, the salt front migrated upstream to RM 86. This is above the reach of river identified as habitat for spawning and early life stages including Claymont (RM 77.5), Chester (RM 81.0) and Tinicum Island (RM 85.0) (Figure 8).

In July 2010, if there had been a successful spawning event, any eggs or larvae located between RM 70 and 75 (Zones 5 a and b) would have been enveloped by the salt front. In September, the salt front migrated to RM 86 and may have affected any young-of-year or juveniles in the intervening reaches.

Relationship between climate change and salinity. Under a climate change scenario, it is estimated that by the year 2100, the salt front could migrate upstream, potentially enveloping up to 7 miles (or an estimated 350 acres) of freshwater habitat in an average year (EPA 1986, Najjar et al. 2000, DVRPC 2004, Ross et al. 2015). For the mid-Atlantic region, most global climate models predict a substantial increase in the frequency of extreme precipitation events including heavy precipitation and the duration of low flow conditions (Kreeger et al. 2010). It is projected that even extreme rainfall events will not be sufficient to offset the predicted rise in sea level and migration in salt front (Ross et al. 2015). Low flow conditions may be exacerbated in the spring and summer months by projected increases in evapotranspiration which may decrease streamflow magnitudes by an additional 15 to 40% (Najjar et al. 2009).

[1] July Q98 refers to flow magnitude that was exceeded 98 percent of the time over the period of record, as another example, July Q50 would refer to a flow magnitude that was exceeded 50 percent of the time over the period of record. (i.e., median flow).

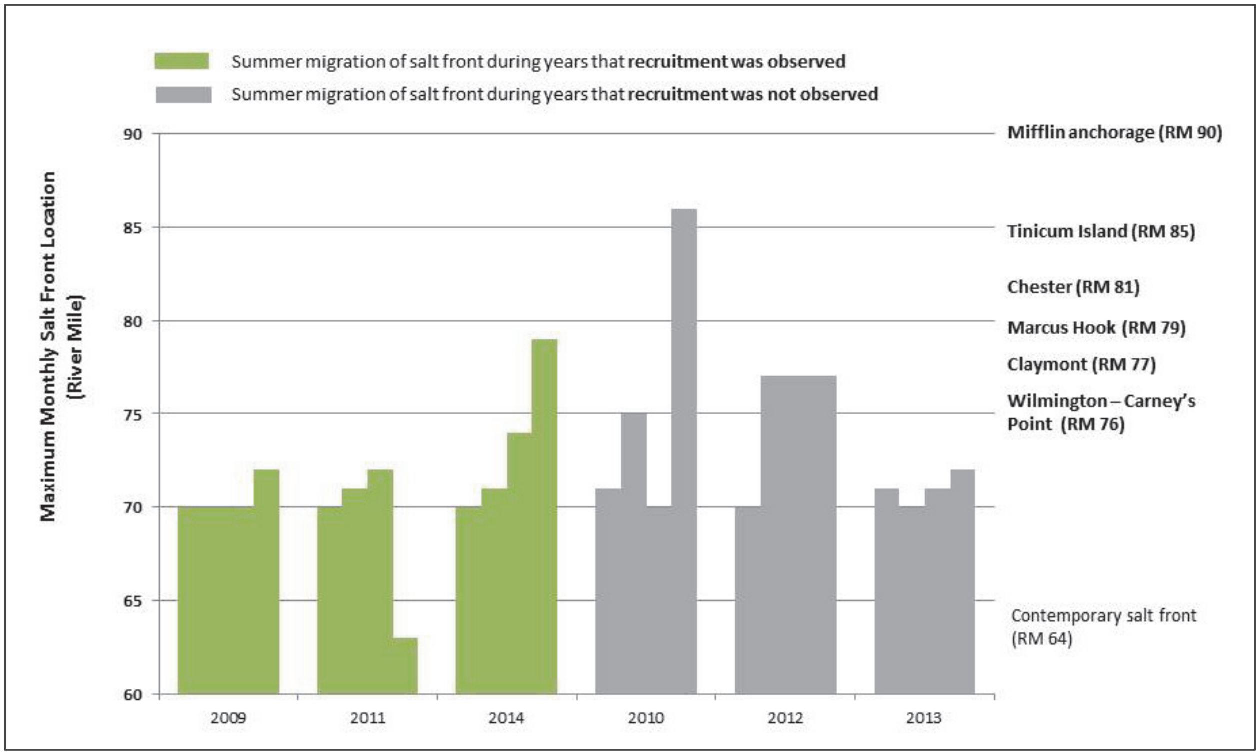

Figure 8. A comparison of the summer monthly salt front migration during June, July, August and September, respectively, between recent years when recruitment was observed (2009, 2011 and 2014) and when it was not (2010, 2012, and 2013).

Relationship between dredging and salinity. The Delaware River contains the largest freshwater port in the United States (Kaufmann et al. 2011). In addition to river flows, dredging to deepen the shipping channel changes the river's salinity and tidal dynamics and the location of the salt front (DiLorenzo et al. 1993, USACE 2009). Channel dredging continues to occur on the Delaware River from Philadelphia through the Estuary and has doubled channel depth from 17-24' during the 1800s to up to 45' under the most recent deepening project (Appendix 4, Table 3). In their Environmental Impact Statement for the most recent deepening project, the Army Corps of Engineers (Corps) documented that deepening the channel from 40-45' would further increase salinity concentrations upstream to Philadelphia (USACE SEIS 1997, Simpson and Fox 2008).

Both DRBC and the Corps are currently developing salinity models for the river to better understand the relationship between freshwater inflows and salinity in the river and estuary. The initial development and calibration of the Corps' salinity model is expected in 2016, with the opportunity for scenario modeling, including climate scenarios, in future years (USACE 2015).

Section 4. Recommended habitat conditions to support successful recruitment

In this section, we recommend habitat conditions suitable for recruitment of Atlantic sturgeon in the Delaware River, focusing on DO and salinity and the factors that influence them. The recommendations for each factor are summarized in Box 2, which is followed by an overview of support for recommendations. The following provides context for the recommendations:

- The recommendations are supported by best available science, including relevant literature and regional data, and are informed by expert review.
- They identify the minimum values that would be suitable to support growth and development and avoid risks to physiology and growth from non-lethal stresses (Figures 9 and 10).
- They are in the form of consensus statements and are as specific as available information supports. Supporting information is summarized and referenced below each statement. This is a rapidly developing field with vigorous ongoing research – therefore, habitat conservation and protection measures should be adaptive.

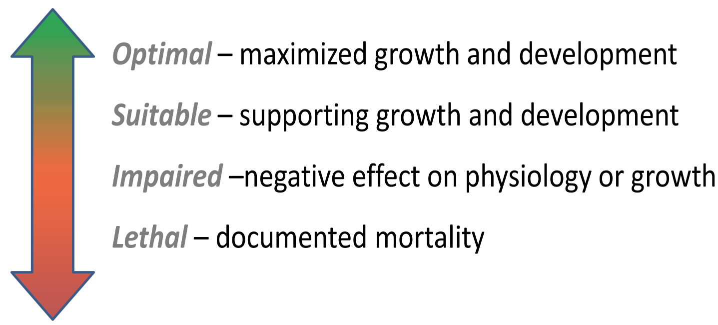

Figure 9. For the purposes of this study, literature and data were categorized along this continuum of suitability (Appendix 1).

- The cumulative risks of interactive stressors should be considered when taking conservation and protection measures. There are factors that are currently present in the environment (e.g., dioxins) that may interact with these stressors. These recommendations do not attempt to incorporate the risks of interactive stressors.

Box 2. Summary of recommended habitat conditions

In those reaches that include suitable benthic habitat, during relevant times of year, we recommend*:

- Instantaneous DO ≥ 5.0 mg/L
- Temperature < 28°C
- Salinity < 0.5 ppt
- Discharge > July Q85 (4,000 cfs @ Ben Franklin), when DO < 5.5 mg/L

*Recommendations represent the minimum values required to support habitat suitable for recruitment based on best available literature, regional data and expert review. To address cumulative stressors present in the Delaware (e.g. dioxins), conservation measures should be more protective.

Atlantic Sturgeon Young-of-Year Growth: Dissolved Oxygen

	DO (mg/l)	Support in literature	Context
Optimal	> 6.0	• In laboratory studies, YOY **growth rates were maximized** when dissolved oxygen concentration was above 70% (6 mg/L @ 25 C) (Niklitschek and Secor 2009). • **Optimal** DO for YOY life stage > 5 mg/L (Greene et al. 2009)	**Laboratory, Atlantic sturgeon**
Suitable	5.0	• Interpreting existing data and studies , a 60% saturation level, or 5 mg/L @ 25 C was determined to **protect sturgeon from nonlethal effects** in the Chesapeake (EPA 2003).	**Meta-analysis; Atlantic sturgeon**
	4.7 4.3	• YOY (30 to 200 days) experience **reduced metabolic and feeding rates** with less than 60 % oxygen saturation (4.3 to 4.7 mg/L @ 22C to 27 C)(Secor and Niklitschek 2001).	**Laboratory; Atlantic sturgeon**
Impaired	4.0	• Based on existing literature and preliminary data on habitat use and recruitment, **not likely support growth and survival** of Atlantic Sturgeon YOY (Kahn and Fisher 2012).	**Delaware River, Atlantic sturgeon**
Lethal	3.3	• **Mortality** observed during summer temperatures and DO < 3.3 mg/L (Secor and Niklitschek 2001).	**Laboratory, Atlantic sturgeon**
	3.0	• **Significant mortality** observed (85%) in YOY (90 days) held at 26 C and 3.0 mg/L for 10 days (Secor and Gunderson 1998). During the DO sag in the Delaware , YOY are younger (30 to 60 days) and more sensitive (Campell and Goodman 2004) to change. Also, river temperatures exceed those in the study (30 C in recent years Kahn and Fisher 2012)).	**Laboratory, Atlantic sturgeon**

Figure 10. From Appendix 1, examples of biological responses along a continuum of *habitat suitability* ranging from optimal to lethal. This example is specific to dissolved oxygen conditions for Young-of-Year.

Dissolved Oxygen

Young-of-Year and Juvenile growth and development are likely to be supported by DO concentrations with an instantaneous daily minimum ≥ 5.0 mg/L.

- On the Delaware River, during years when recruitment was observed (2009, 2011 and 2014), minimum daily DO remained above 5.0 mg/L in more than 95% of the observations, during young-of-year and juvenile growth life stages (Jan-Dec), and in all observations, daily minimum DO remained above 4.0 mg/L (Figure 5).
- Impaired conditions, including reduced metabolic and feeding rates have been documented at concentrations between 4.0 and 5.0 mg/L, and lethal conditions have been documented at concentrations less than 4.0 mg/L (Secor and Gunderson 1998, Secor and Niklitschek 2001, EPA 2003, Campbell and Goodman 2004, Greene et al. 2009, Niklitschek and Secor 2009, Niklitschek and Secor 2010, Kahn and Fisher 2012).
- Most studies on young-of-year and juvenile development stages were conducted in a laboratory setting. Control temperatures were generally 25 to 28°C. Recommendations should account for the influence of higher river temperatures (27 to 29°C) in the Delaware in recent years, , (Figure 6) (Kahn and Fisher 2012, USGS Unpublished data).
- On the Delaware River, in the summer of 2010, a DO sag occurred during the months of larval development. DO fell below 5.0 mg/L for more than two weeks in July and was as low as 3.2 mg/L (USGS unpublished data, PWD unpublished data). No young-of-year were observed during 2010 surveys (Kahn and Fisher 2012).

Egg and larval development is likely to be supported by DO concentrations with an instantaneous daily minimum ≥ 5.0 mg/L.

- On the Delaware River, during years when recruitment was observed, in more than 90 percent of the observations, minimum daily DO was above 5.0 mg/L during egg and larval development (June-July) , in all observations, minimum daily DO was above 4.0 mg/L (Figure 5).
- Larval Shortnose sturgeon (< 30 days old) were acutely exposed (for 6 hours) to a DO of 3.5 mg/L (22.5°C). At this concentration, 22% of the larvae experienced mortality (Jenkins et al. 1993). Shortnose sturgeon have been shown to be slightly more tolerant to poor water quality than Atlantic sturgeon.
- In laboratory studies, the egg and larval life stage was more sensitive to low DO concentrations than young-of year. Even short-term durations (hourly) of low DO, may stunt growth or cause mortality (Jenkins et al. 1993, Atlantic Sturgeon Workshop 2014).
- Until 2009, no recruitment had been documented between Philadelphia and Chester for decades (Albert 1988, Kahn and Fisher 2012). Minimum and average daily DO has been consistently below 5.0 mg/L during egg and larval development.

Migration and spawning is likely to be supported by DO concentrations that are ≥ 5.0 mg/L. Migrating adults would likely endure short-term, localized deviations below 5.0 mg/L.

- Migrating and spawning adults are the life stages that are least sensitive to DO concentrations. DO that protects egg and larval development, young-of-year and juveniles is expected to support of migration and spawning (EPA 2003, Campbell and Goodman 2004, Atlantic Sturgeon Workshop 2014).

Temperature

Egg and larval development is likely to be supported by late summer temperatures (July and August) < 28°C.

- On the Delaware, during years when recruitment was observed, maximum daily temperatures during the egg and larval development period (May-July) were 28°C (with DO of 4.4 mg/L). River temperatures were between 19.5 and 27.5 °C for 90% of the observations. (Figure 6).
- In a laboratory setting, Atlantic sturgeon eggs optimally hatched at temperatures between 18 and 20 °C (Theodore et al. 1980, Mohler 2003).
- On the Delaware River, eggs and larvae of Shortnose sturgeon were surveyed and present with temperatures ranging from 4.8 to 24.6°C (ERC 2008).

Young of Year and Juvenile development is likely to be supported by summer and late fall temperatures (July-Oct) of < 28°C

- During recent years when recruitment was observed, 95% of the observations during critical months of YOY and juvenile development had temperature <28°C (Figure 6).
- Juvenile sturgeon have been documented as exhibiting avoidance behaviors when water temperature was 24 to 28°C (Kiefer and Kynard 1993, Bain et al. 2000, Niklitschek and Secor 2009).
- Sub-lethal effects have been measured in juveniles at temperatures above 28°C (Secor and Gunderson 1998).

Cues for adult migration are likely to be supported by spring temperatures (April – June) between 6 and 13°C, with spawning being supported between 12.8 and 26°C.

- Upstream migration on the Delaware and Hudson Rivers occurred with temperatures between 6 and 13°C, with males migrating sooner, and under cooler temperatures (Dovel and Berggren 1983, Smith 1985).
- On the Delaware River, spawning was documented as occurring between 12.8 and 18.3°C (Ryder 1888, Scott and Crossman 1978).
- On the Hudson River (part of the same DPS), spawning occurred at a slightly higher temperature range, or from 14 to 26°C (Bain et al. 2000). Although the New York Bight DPS shares a population

between the Delaware and Hudson Rivers, comparisons are made cautiously, recognizing the preference for natal river conditions may be present.

Salinity

Egg and larval development is likely to be supported in habitat with salinity <0.5 parts per thousand (ppt)

- The egg and larval life stage has an extremely low salinity tolerance with suitable habitat typically occurring above the salt front (Van Eenennaam 1996). The salt front is defined as the location along the tidal Delaware River where the concentration of chloride exceeds 250 milligrams per liter and is estimated using a 7-day average (DRBC 2015).
- In a recent Delaware River survey for sturgeon eggs, all eggs were found in freshwater habitats (salinity < 0.5 ppt) (ERC 2008).
- In a laboratory setting, mortality has been documented at salinities as low as 5 to 10 ppt (Jenkins et al. 1993).

Young of year and juvenile life states are likely to be supported in habitat with salinity < 0.5 ppt

- In the Delaware, larval stages of Atlantic sturgeon were documented in habitats with salinity concentrations between 0 and 12 ppt (Shirey et al. 1999).
- Poor survival of young-of-year was documented in a bioenergetics study when salinities were > 8 ppt (Niklitschek 2001).

Adult spawning is likely to be supported in habitat with salinity <0.5 ppt

- Atlantic sturgeon spawn in freshwater (tidal and non-tidal) above the salt front (Dovel 1979, Bain et al. 2000, Atlantic Sturgeon Status Review 2007). Freshwater has a salinity < 0.5 ppt.
- In a recent Delaware River telemetry study, 95% of adults migrated well above the salt front, and the location of the salt front was the greatest explanatory variable predicting distribution (Breece et al. 2013).
- In the Hudson River, sturgeon in spawning condition were found 28 kilometers upstream of the salt front (Van Eenennaam et al. 1996).

Flow Conditions

Between June and September, impaired or lethal conditions of DO and salinity may be mitigated by low flow conditions of ≥ 4,000 cfs (at the Ben Franklin Bridge)

- During years when recruitment was observed, the 7-day minimum flow remained above 4,059 cfs (at the Ben Franklin bridge), and there were more than five summer high flow pulses (>18,000 cfs). Under these conditions, minimum daily DO was > 5.0 mg/L more than 90% of the time. Additionally, the salt front remained downstream of habitat for spawning and early life stage development.
- During the summer of 2010, when no recruitment was observed, the Delaware River experienced an extreme low flow pulse with several weeks below 4,000 cfs, and no summer high flow pulse events (>18,000 cfs). DO measurements were as low as 3.2 mg/L and the salt front enveloped and migrated upstream of habitat used for spawning and early life stage development.

Section 5. Conclusions

For decades, several factors including overfishing, habitat degradation (water quality and dredging), vessel strikes, entrainment and bycatch have limited successful recruitment of Atlantic sturgeon in the Delaware River. While further research is necessary to better understand the dynamics between compounding factors, from this synthesis we draw the following conclusions:

1. **Sturgeon of all life stages occur throughout the freshwater portion of the river, with early life stages occurring year-round.** While there are large gaps in understanding the population size and dynamics of Atlantic sturgeon in the Delaware River, telemetry data provide novel insight into the occurrence and distribution of sturgeon life stages. Early life stages, including eggs, larvae, and young-of-year sturgeon, are most sensitive to low DO concentrations and increased salinity. These life stages occur between Trenton, NJ and New Castle, DE, throughout the year, with the highest potential use occurring near Mifflin anchorage (RM 90), Tinicum Island (RM 85), Chester (RM 81), Marcus Hook (RM 79), Claymont (RM 77) and Carney's Point (RM 76). From telemetry data, we know that juvenile and adult sturgeon also use estuary habitats, but the estuary was not within the scope of this report or its recommendations.

2. **Despite improvements in water quality over the last two decades, DO conditions in recent years likely inhibited successful development of early life stages.** Between 2005 and 2014, DO concentrations were still frequently in ranges identified as impaired or lethal for early life stages of Atlantic sturgeon. DO concentrations above 6.0 mg/L are optimal, while DO concentrations below 5.0 mg/L may result in impaired conditions including avoidance behaviors and reduced metabolic and feeding rates. DO concentrations below 4.0 mg/L, even for a short duration, may result in mortality. Findings published in the literature have been corroborated by recruitment observations in the Delaware River. During recent years when recruitment was observed, minimum daily DO was above 5.0 mg/L in 90% of the observations. In these years, the median minimum daily DO was optimal (> 6.0 mg/L) during the spawning and egg and larval development periods. During years when recruitment was not observed, median minimum daily DO was < 5.0 mg/L, and conditions were frequently impaired or lethal (< 4.0 mg/L).

3. **Improved water quality standards are needed to support habitat conditions. Best available technologies could improve DO from lethal to suitable concentrations.** In the reaches where Atlantic sturgeon occur, current DO water quality standards range from 3.5 (lethal conditions) to 6.0 mg/L (optimal conditions), measured using a 24-hour average. As concluded by the 1979 Ad Hoc Task Force, 3.5 mg/L does not support fish propagation. Even if the concentration were designated at a suitable concentration, a 24-hour average standard is 'unacceptable' recognizing that lethal effects may occur in hours (DRBC Ad Hoc Water Quality Task Force 1979). The Ad Hoc Task Force recommended a minimum instantaneous standard be established and recent literature and data summarized through this study supports that recommendation. A 1990's modeling study estimated that DO could be increased by between 1 and 2 mg/L by reducing the ammonia content of wastewater discharge and therefore reducing nitrogen-based biological oxygen demand (HydroQual

1998). Similar reductions have been achieved using best available technologies and practices (Cadmus 2009). In recent years when recruitment was not observed, an increase of 2 mg/L could shift DO conditions from impaired and lethal to suitable and optimal.

4. **Current low flow conditions influence salt front encroachment. In 2010, the availability of suitable freshwater habitat was reduced by between 10 and 20 miles throughout the summer, during egg, larval and young-of-year development. Under the drought of record, suitable freshwater habitat was reduced by 40 miles.** Current low flow conditions influence the location of the salt front and availability of suitable freshwater habitats for early life stages. In the early summer of 2010, the salt front moved above key habitats near Claymont and Wilmington. Egg and larval development occurs during these months, and even short exposures to saline water may influence development success. In September of 2010, the salt front moved above Tinicum Island in September, influencing an estimated 20 miles of suitable freshwater habitat, which may have affected young-of-year. During the drought of record, suitable freshwater habitat was reduced by 40 miles.

5. **Anticipated sea level rise is projected to permanently shift the average salt front upstream. Further, changing precipitation and evapotranspiration patterns may increase the extent of upstream migration in response to longer-duration low flow events.** Under a changing climate, anticipated sea level rise and increased frequency and duration of drought conditions are expected to shift the salt front upstream. In an average year, it is estimated that this shift will permanently reduce the extent of suitable freshwater habitat in the lower river by an estimated 7 miles. In addition, it is estimated that a changing climate may result in longer-duration low flow events in the mid-Atlantic. Longer-duration low flow events may increase the extent of upstream migration in drought years as compared to historic fluctuations.

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Appendices

Appendix 1:	Life history stage definitions, conceptual models and habitat suitability diagrams
Appendix 2:	Adult, juvenile, and young-of-year seasonal distribution summary table and maps
Appendix 3:	Supporting literature, models and data
Appendix 4:	Supplementary tables
Appendix 5:	Workshop agenda, participants and outstanding research questions

Appendix 1:

Life history stage definitions, conceptual models and habitat suitability diagrams

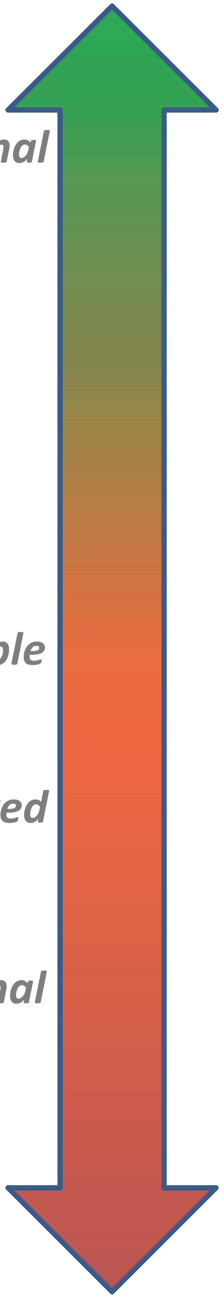
Table 1. Atlantic sturgeon life stages that occur in the Delaware River (definitions adapted from Lazzari et al. 1986, Gilbert 1989, Van Eenennaam et al. 1996, Stevenson and Secor 2000, Atlantic Sturgeon Review Team 2007, DNREC-DFW 2015, Balazik et al. 2015).

Life stage	Timing	Definition
Adult staging and migration	April-June	Reproductively mature individuals (Females 14-28 years, Males 5-22 years) transit through the estuary to their natal tidal river, wait for cues and begin upstream migration to a point above the estuarine turbidity maximum. Post-spawning, adults emigrate to estuarine and marine habitats.
	Sept-Oct	A second upstream migration behavior has been documented in the fall. It is unknown whether the migration is spawning related.
Spawning	May-June	Males fertilize eggs and females broadcast eggs above and upstream of suitable substrate.
	October	Unknown whether fall spawning occurs in the Delaware River. It has been recently documented in the James River and the Pamunkey River.
Egg and larval development	May-July	Eggs hatch in 4 to 6 days after deposition. The larval stage is considered to be between hatch and the age of 4 weeks.
Young of Year (YOY) growth	July-Feb	Starting at 4 weeks to 1 year.
	Mar-July	Move downstream from rearing habitats during the spring.
Juvenile growth	Year round	Between 1 and 2 years. The majority emigrate during their second fall at age 1.5 years.
Juvenile emigration	Oct-Nov	Juveniles emigrate from natal estuaries to marine habitats.

Life Stage	Key Ecological Attributes and Hypothesized Ecological Needs		Potential Limiting Factors in the Delaware River
Staging and migration (M) Spawning (S)	**Hydrology**	**M1:** A change to the timing or magnitude of seasonal flows may decouple **thermal and hydrologic cues** for upstream migration **S1:** A change to the timing or magnitude of seasonal flows may reduce suitable **habitat for spawning**	• Hydrologic alteration (Reservoir operations, water withdrawals, climat change) • Dredging
	Temperature	**M2, S2:** Temperature provides a primary cue for Atlantic Sturgeon upstream migration and spawning. Changes to thermal cues may reduce spawning success.	• Climate change - thermal regime • Hydrologic alteration
	Salinity	**M3,S3:** Atlantic sturgeon migrate to, and spawn in, freshwater. An increase in salinity may decrease longitudinal extent of suitable spawning habitat.	• Climate change - salt wedge encroachment • Hydrologic alteration • Dredging
	Benthic Substrate	**S4:** Atlantic sturgeon spawn over coarse grain substrates including bedrock, cobble and gravel. Changes to substrate composition may reduce spawning success.	• Dredging • Erosion and sedimentation • Hydrologic alteration

Figure 1.

Atlantic Sturgeon Migration and Spawning: Salinity



Optimal

Suitable

Impaired

Lethal

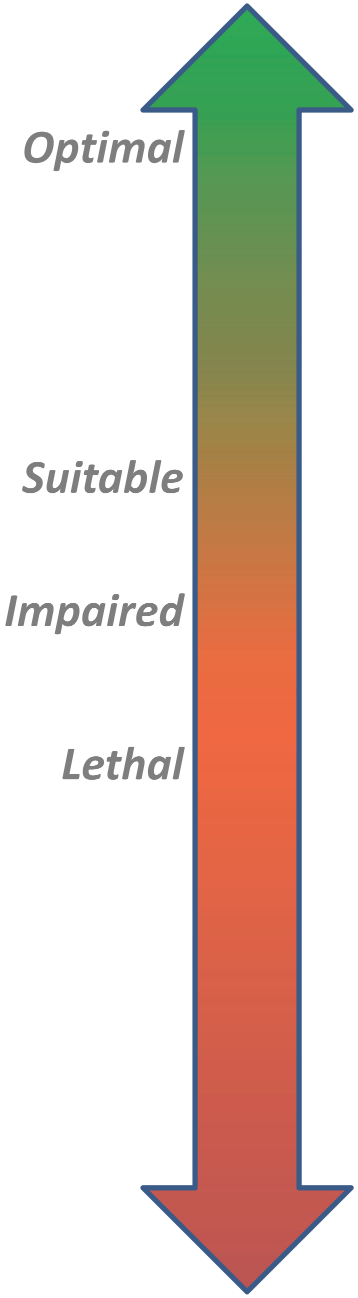
Salinity (ppt)	Support in literature	Context
< .5	• Atlantic sturgeon **spawn in freshwater** (tidal and nontidal) above estuaries (Dovel 1979, Bain et al. 2000). Freshwater has a salinity of <.5 ppt.	**Hudson River; Atlantic sturgeon**
	• In a recent Delaware River telemetry study, 95% of tagged **adults migrated well above the salt front** (15 to 98 rkm upstream of rkm 103). The majority of time (84%) was spent within 30 rkm of the salt front (between New Castle (rkm 99) and the Schuylkill River (rkm 148))(Breece et al. 2013).	**Delaware River; Atlantic sturgeon**
	• A model (MaxEnt) was developed to predict the distribution of adult Atlantic Sturgeon in the Delaware. The **location of the salt front was the greatest explanatory variable predicting distribution** (43%) (Breece et al. 2013).	**Delaware River; Atlantic sturgeon**
	• In the Hudson River system, Van Eenennaam et al. (1996) found **ovulating sturgeon upstream of the salt front** (28 rkm upstream).	**Hudson River; Atlantic sturgeon**

Figure 2.

Life Stage	Key Ecological Attributes and Hypothesized Ecological Needs		Potential Limiting Factors in the Delaware River
Egg and larval development (EL)	Hydrology	**EL1a:** A change to the timing or magnitude of seasonal flows may reduce suitable **hydraulic habitat for egg and larval development (d,v)** **EL1b:** Flow mediates DO and salinity. A decrease may lower DO and increase salinity.	Hydrologic alteration (Reservoir operations, water withdrawals, climate change) Dredging
	Temperature	**EL2a :** Temperature influences the rate of development . A decrease in temperature may decrease development rate. **EL2b :** Temperature mediates DO. An increase in temperature may decrease DO	Climate change - thermal regime Hydrologic alteration
	Dissolved Oxygen	**EL3:** Egg and larval development requires DO concentrations to occur within a range, variations outside that range, even short-term (hourly) may cause mortality.	BOD (e.g. ammonia, Nitrate, Nitrite) Hydrologic alteration
	Salinity	**EL4: Eggs and larvae are extremely sensitive to increased salinity.** An increase in salinity may delay development or cause mortality.	Sea level rise – salt wedge encroachment Hydrologic alteration
	Benthic Substrate	**EL5:** Egg and larval development requires coarse grain substrate including bedrock, cobble and gravel. Changes to substrate composition may reduce development success.	Dredging Erosion and sedimentation Hydrologic alteration

Figure 3.

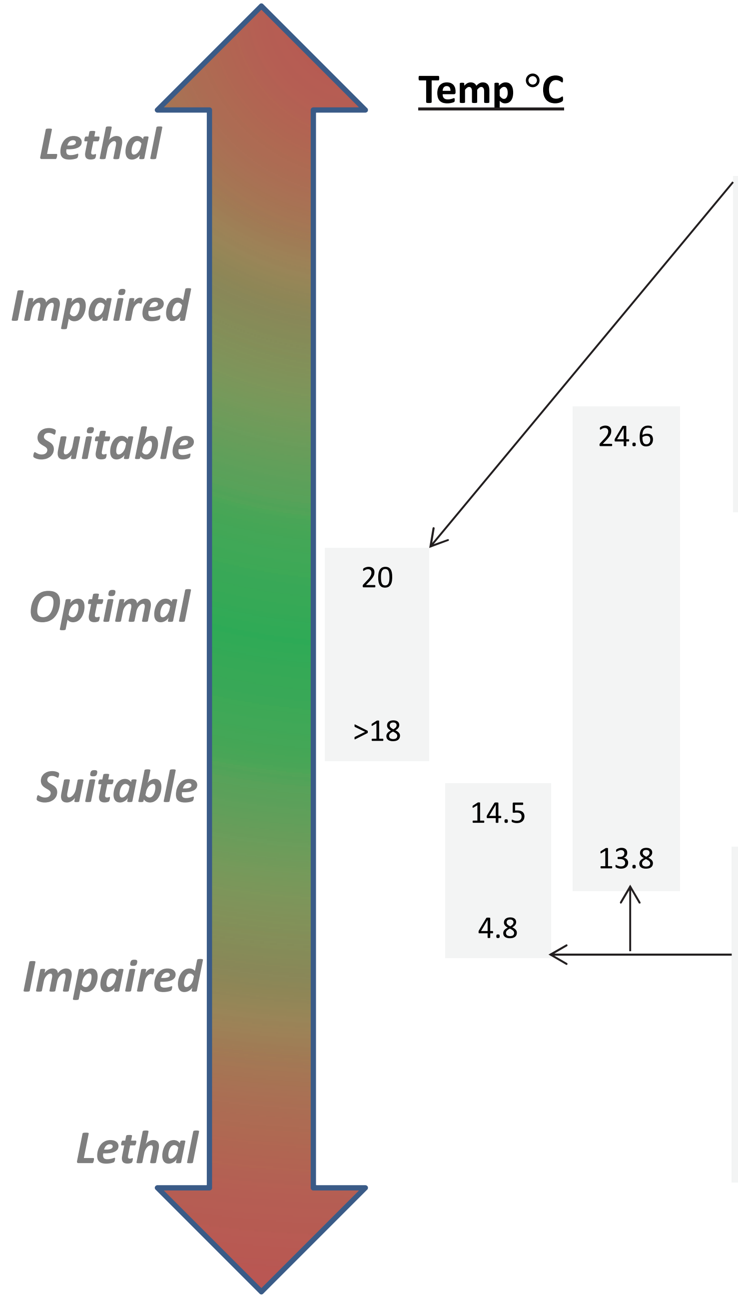
Atlantic Sturgeon Egg and Larval Development: Dissolved Oxygen



DO (mg/l)	Support in literature	Context
12.9 7.9	• On the Delaware River, eggs and larvae of shortnose sturgeon were **surveyed and present** 4 weeks after the spawning period. In the spring of 2007, DO ranged from 7.9 to 10.9 mg/L with temperatures of 13.8 to 24.6 C; in 2008 DO ranged from 11 to 12.9 mg/L with temperatures from 4.8 to 14.5 C (ERC 2008).	**Delaware River; Shortnose sturgeon**
3.5	• Larval shortnose sturgeon (19 days) held at 3.5 mg/L and 22.5 C had **22% mortality with acute exposure (6 hours).** Authors cautioned these findings as preliminary until more rigorous testing can be done, but strong evidence was presented that younger fish were more susceptible to low oxygen levels. compared to older juveniles (Jenkins et al. 1993).	**Laboratory; Shortnose sturgeon**

Figure 4.

Atlantic Sturgeon Egg and Larval Development: Temperature



Support in literature	Context
In a laboratory setting, Atlantic sturgeon eggs **optimally hatched** at temperatures between 18 and 20 °C (Smith et al. 1980).	**Laboratory; Atlantic sturgeon**
In a lab setting, Mohler (2003) found that temperatures **less than 18 °C can prolong hatch time** and increase risk of fungal development.	**Laboratory; Atlantic sturgeon**
On the Delaware River, eggs and larvae of shortnose sturgeon were **surveyed and present** 4 weeks after the spawning period. During May of 2007, DO ranged from 7.9 to 10.9 mg/L with temperatures of **13.8 to 24.6 °C**; in 2008 DO ranged from 11 to 12.9 mg/L with temperatures from **4.8 to 14.5 °C** (ERC 2008).	**Delaware River; Shortnose sturgeon**

Figure 5.

Atlantic Sturgeon Egg and Larval Development: Salinity

Salinity (ppt)	Support in literature	Context
0	• Suitable embryo habitat must be **well above the salt front** due to low salinity tolerance of this life stage (Van Eenennaam et al. 1996).	**Hudson River; Atlantic sturgeon**
	• In the Delaware, during a 2007 and 2008 survey **eggs were collected in freshwater habitats** (< .5 ppt) (ERC 2008).	**Delaware River; Atlantic sturgeon**
0 – 22	• In the Hudson, **eggs were collected** in salinities of 0 to 22 ppt (Bath et al. 1981).	**Hudson River; Atlantic sturgeon**
5 – 10	• In a laboratory setting, **mortality** has been documented at salinities as low as 5 to 10 ppt (Jenkins et al. 1993)	**Laboratory; Atlantic sturgeon**

Figure 6.

Life Stage	Key Ecological Attributes and Hypothesized Ecological Needs		Potential Limiting Factors in the Delaware River
YOY growth (Y)	**Hydrology**	**Y1a:** Year-round, a change to the timing or magnitude of seasonal flows may reduce suitable **habitat for YOY growth** **Y1b:** Year-round flows mediate DO and salinity and buffer extremes	Hydrologic alteration (Reservoir operations, water withdrawals, climate change) Dredging
	Temperature	**Y2a:** From June through October, YOY are extremely sensitive to increases in temperature and decreases in DO that couple to increase hypoxic conditions. These conditions may reduce benthic prey availability, growth or cause mortality.	Climate change - thermal regime Hydrologic alteration
	Dissolved Oxygen		BOD (e.g. ammonia) Hydrologic alteration
	Salinity	**Y3:** An increase in salinity may reduce the quantity of suitable habitat, delay development or cause mortality.	Sea level rise – salt wedge encroachment Hydrologic alteration
	Benthic Substrate	**Y4:** Prefer hard substrate including bedrock, cobble and gravel. Changes to substrate composition may reduce cover and foraging opportunities.	Dredging Erosion and sedimentation Hydrologic alteration

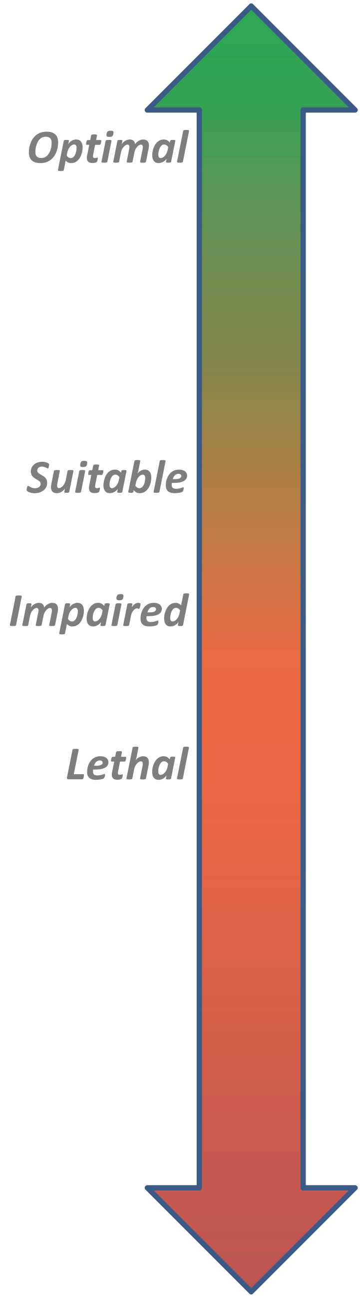
Figure 7

Atlantic Sturgeon Young-of-Year Growth: Dissolved Oxygen

	DO (mg/l)	Support in literature	Context
Optimal	> 6.0	• In laboratory studies, YOY **growth rates were maximized** when dissolved oxygen concentration was above 70% (6 mg/L @ 25 C) (Niklitschek and Secor 2009). • **Optimal** DO for YOY life stage > 5 mg/L (Greene et al. 2009)	**Laboratory, Atlantic sturgeon**
Suitable	5.0	• Interpreting existing data and studies , a 60% saturation level, or 5 mg/L @ 25 C was determined to **protect sturgeon from nonlethal effects** in the Chesapeake (EPA 2003).	**Meta-analysis; Atlantic sturgeon**
	4.7 4.3	• YOY (30 to 200 days) experience **reduced metabolic and feeding rates** with less than 60 % oxygen saturation (4.3 to 4.7 mg/L @ 22C to 27 C)(Secor and Niklitschek 2001).	**Laboratory; Atlantic sturgeon**
Impaired	4.0	• Based on existing literature and preliminary data on habitat use and recruitment, **not likely support growth and survival** of Atlantic Sturgeon YOY (Kahn and Fisher 2012).	**Delaware River, Atlantic sturgeon**
Lethal	3.3	• **Mortality** observed during summer temperatures and DO < 3.3 mg/L (Secor and Niklitschek 2001).	**Laboratory, Atlantic sturgeon**
	3.0	• **Significant mortality** observed (85%) in YOY (90 days) held at 26 C and 3.0 mg/L for 10 days (Secor and Gunderson 1998). During the DO sag in the Delaware , YOY are younger (30 to 60 days) and more sensitive (Campell and Goodman 2004) to change. Also, river temperatures exceed those in the study (30 C in recent years Kahn and Fisher 2012)).	**Laboratory, Atlantic sturgeon**

Figure 8.

Atlantic Sturgeon Young of Year Growth: Salinity



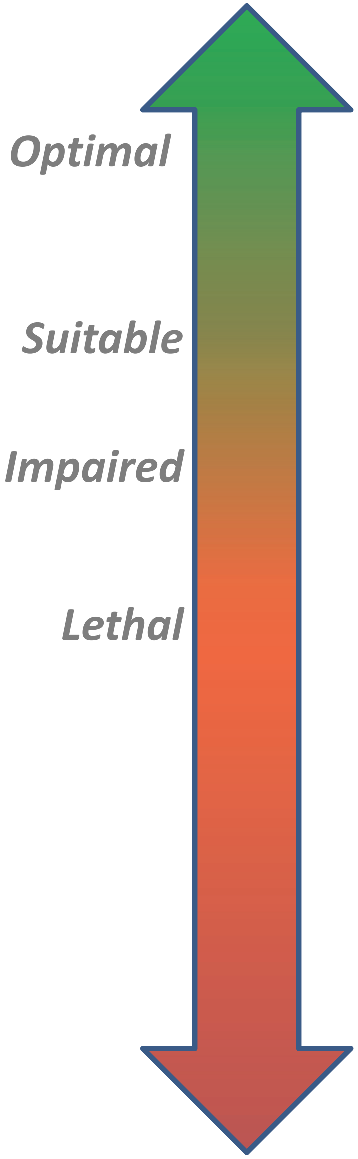
Salinity (ppt)	Support in literature	Context
0–12	• In the Delaware, egg and larval stages of Atlantic sturgeon were **documented in habitats** with salinity concentrations between 0 to 12 ppt (Shirey et al.1999)	**Delaware River; Atlantic sturgeon**
8	• In a bioenergetic study, Niklitschek (2001) found **poor survival of YOY** at salinities greater than 8 ppt.	**Laboratory; Atlantic sturgeon**

Figure 9.

Life Stage	Key Ecological Attributes and Hypothesized Ecological Needs		Potential Limiting Factors in the Delaware River
Juvenile growth (J)	**Hydrology**	**J1a:** Year-round, a change to the timing or magnitude of seasonal flows may reduce suitable **habitat for juvenile growth**	Hydrologic alteration (Reservoir operations, water withdrawals, climate change) Dredging
	Hydrology	**J1b:** During fall, a change to the timing or magnitude of seasonal flows may delay out-migrating juveniles	
	Temperature (Water Chemistry)	**J2:** From June through October, juveniles are extremely sensitive to increases in temperature and decreases in DO that couple to increase hypoxic conditions. These conditions may reduce benthic prey availability, growth or cause mortality.	Climate change - thermal regime Hydrologic alteration
	Dissolved Oxygen (Water Chemistry)	(J2)	BOD (e.g. ammonia) Hydrologic alteration
	Salinity (Water Chemistry)	**J3:** An increase in salinity may reduce the quantity of suitable habitat, delay development or cause mortality.	Sea level rise – salt wedge encroachment Hydrologic alteration
	Benthic Substrate	**J4:** Prefer coarse grain substrate including bedrock, cobble and gravel. Changes to substrate composition may reduce cover and foraging opportunities.	Dredging Erosion and sedimentation Hydrologic alteration

Figure 10.

Atlantic Sturgeon Juvenile Growth: Upper Thermal Limit



Temp (°C)	Support in literature	Context
24 28	• Juvenile sturgeon have been documented as tolerating an upper thermal limit of 24 to 28 °C in the Northeast (Kieffer and Kynard 1993, Bain et al. 2000).	**Connecticut and Hudson Rivers; Atlantic Sturgeon**
> 28	• **Sublethal effects** have been measured in juveniles at temperatures above 28 °C (Secor and Gunderson 1998).	**Laboratory; Atlantic Sturgeon**
	• Temperature is a key habitat parameter for structuring juvenile Atlantic Sturgeon summer habitat (Niklitschek and Secor 2005).	**Chesapeake Bay; Atlantic Sturgeon**
	• During their first two years of life, juveniles are restricted to lower saline waters, limiting their ability to seek refuge if high temperatures and low oxygen combine create hypoxic zones (Niklitschek 2001).	**Chesapeake Bay, Atlantic Sturgeon**

Figure 11.

Appendix 2:

Adult, young-of-year and juvenile distribution summary table and maps

Methods and Definitions: Adult, young-of-year and juvenile distribution table and maps

Interstate water quality zones, river miles, and salt Front information is provided by the Delaware River Basin Commission.

Interstate Water Quality Zones: Zones are designated based on usage of the river at particular locations; examples of usages include navigation, wildlife, fish, or other aquatic life, public water supply, agriculture, industry, and recreation. Zones 1A - 1E represent the non-tidal portion of the river, and zones 2 - 6 represent the tidal, or estuarine, portions of the river. This study focuses on Atlantic sturgeon habitat located in zones 2 – 5.

River Miles: The stream mileage system was published by DRBC staff in 1969 with revisions in 1988. The mileage system for the Delaware River and Bay consists of a line along which distances from the mouth of the Delaware Bay (mile zero) to the head of the main stem Delaware River (mile 330.7).

Salt Front: The salt front or salt line is defined as the 250 parts-per-million (or milligram-per-liter) chloride concentration. The salt front's location fluctuates along the Delaware River as streamflow increases or decreases in response to changing inflows, diluting or concentrating chlorides in the river.

Telemetry data: Atlantic sturgeon occurrence is represented using 2009-2014 telemetry data, generously shared by DNREC, Delaware State University, Tom Savoy, Hal Brundage and many others. Data for the Delaware River were made available through the Atlantic Cooperative Telemetry (ACT) Network database and generously organized by Lori Brown and Dewayne Fox. Telemetry data were assigned to each life stage using published fork lengths and linked to river mile (RM) using lat./long. coordinates. Occurrences were then sorted by month and aggregated into four seasons to map temporal distribution across RM.

Table 1. Summary of seasonal habitat use by young-of-year, juveniles and spawning adults.

Gray shading indicates occurrence of **Young-of-Year (Y), Juveniles (J) and Adults (A)** using 2009 - 2014 data[1]. The absence of gray shading indicates that the life stage was not observed in that location at that time of year.

Yellow shading indicates probability of spawning habitat[2] While egg and larval sampling has not occurred on the Delaware, it has been documented that demersal eggs attach to substrate and develop below spawning locations.

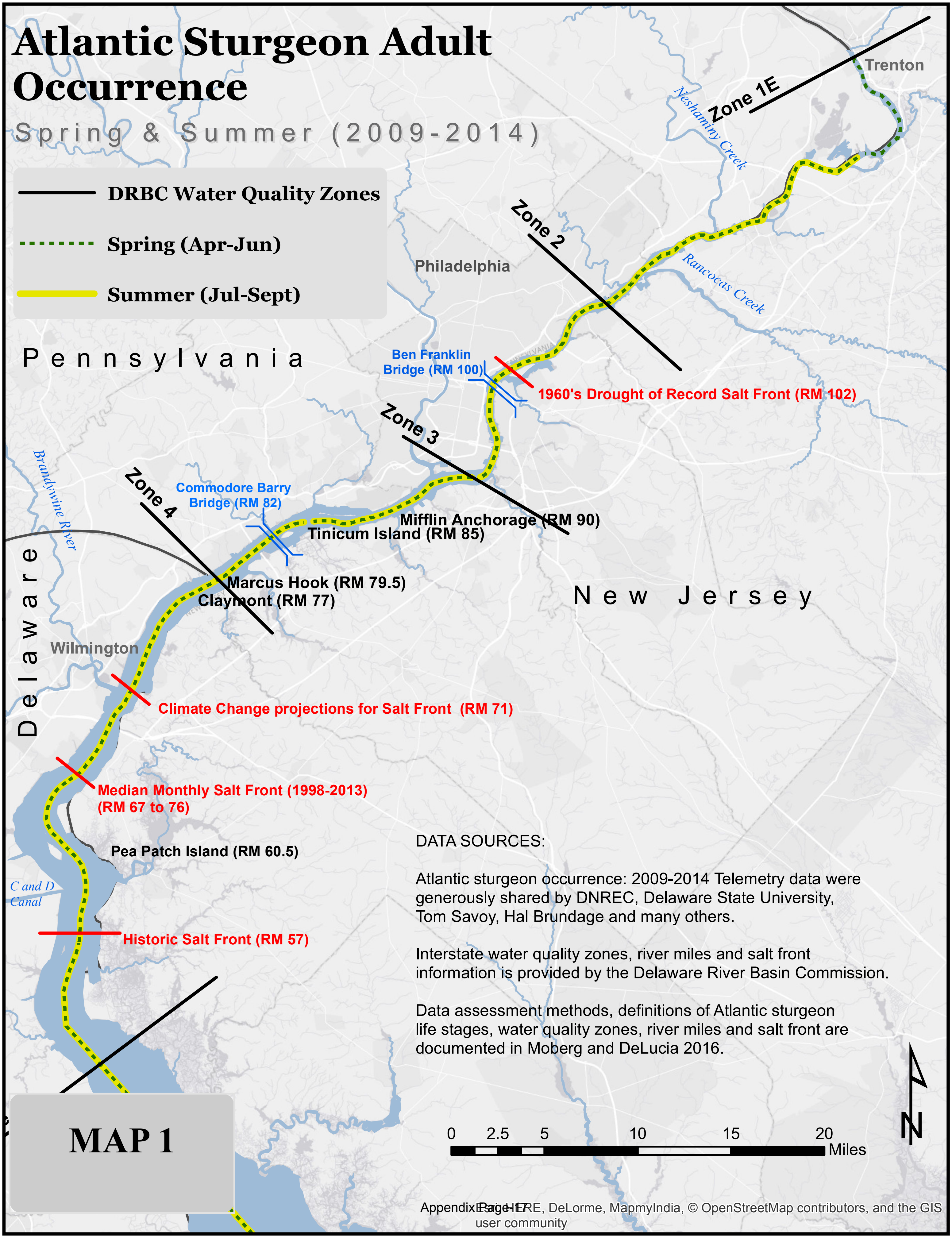
The **location of the salt front[3] under normal, drought and climate change conditions** is noted is red.

Delaware River Reaches			**Spring** (April - June)			**Summer** (July-Sept.)			**Fall** (Oct.-Nov.)			**Winter** (Dec.-Mar.)		
River Miles	**DRBC Zone**	**Reach Notes (River Mile)**												
139.0-133.5	Zone 1E	(134.5) Trenton												
133.4-125.5	Zone 2				A		J							
125.5-108.5		(125.0) Roebling (116.5) Burlington	Y	J	A	Y	J	A	Y			Y	J	
108.5-100.5	Zone 3	(101.0) Petty Island **(102) 1960's Drought salt front**	Y		A	Y	J	A	Y			Y	J	
100.5-95.0		(100) Ben Franklin Bridge (95) Philadelphia	Y	J	A	Y	J	A	Y			Y	J	
95.0-85.0	Zone 4	(91.8) Schuylkill River **(86.0) 2010 Drought salt front**	Y	J	A	Y	J	A	Y	J		Y	J	
85.0-78.5		(85.0) Tinicum Island (81.0) Chester	Y	J	A	Y	J	A	Y	J	A	Y	J	
78.5-69.5	Zone 5a	(77.5) Claymont (76.0) Wilmington **(71.0) Climate change salt front**	Y	J	A	Y	J	A	Y	J	A	Y	J	
69.5-60.5	Zone 5b	**(64) Contemporary salt front** (61.5) New Castle	Y	J	A	Y	J	A	Y	J	A	Y	J	
60.5-55.5	Zone 5c	(58.5) C&D canal (59.5) Delaware City (57.0) Historic salt front			A		J	A		J	A		J	

[1] Telemetry data collected by DNREC, NJDEP, Delaware State University, Tom Savoy, Hal Brundage.

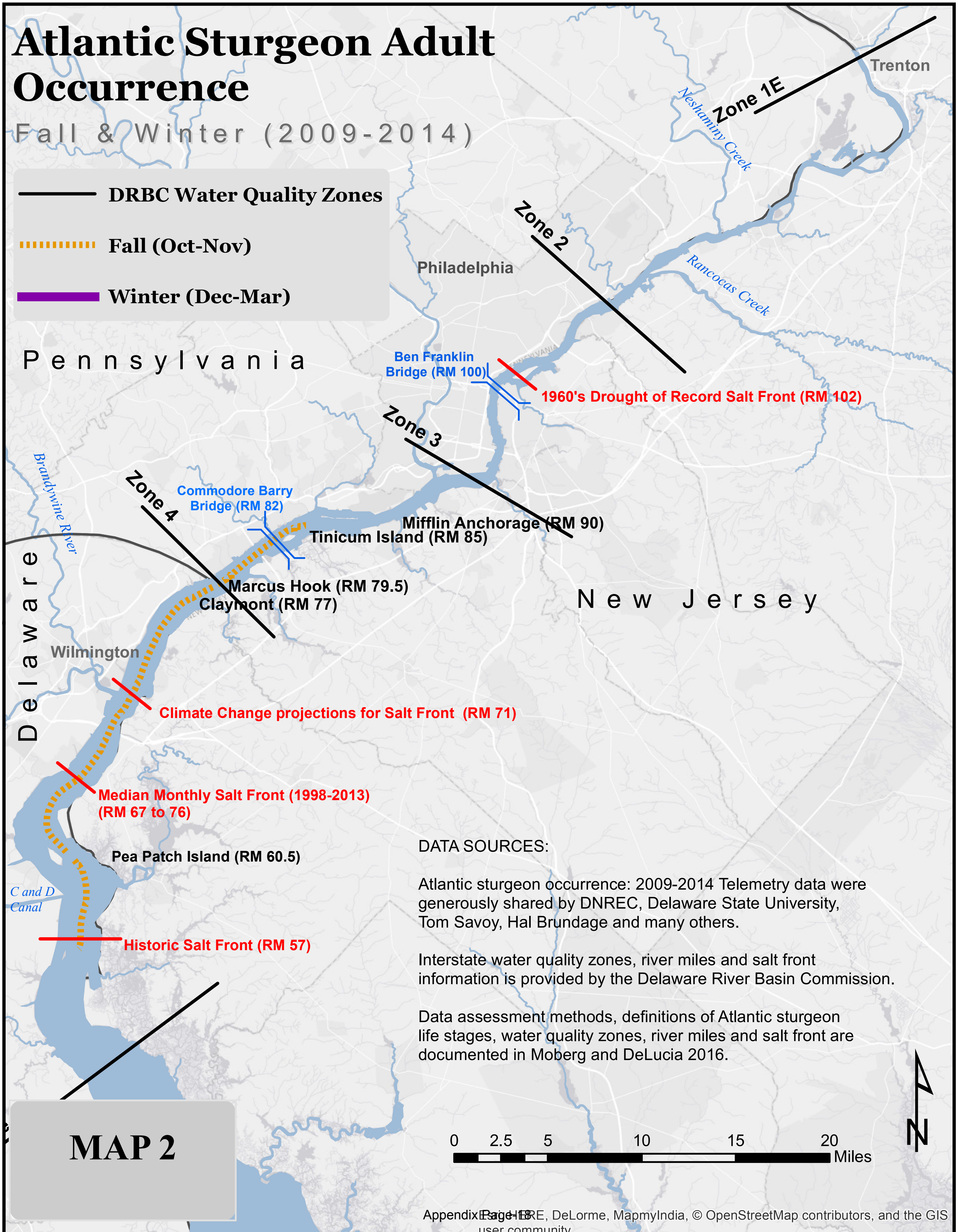
[2] Summarized using suitable substrate from Sommerfield and Madsen 2003, and river-specific literature from Simpson 2008, Breece et al. 2013, Calvo et al. 2010, DNREC-DNW 2015.

[3] The salt front is defined as the location along the tidal Delaware River where the concentration of chloride exceeds 250 milligrams per liter and is estimated using a 7-day average (DRBC 2015).


Atlantic Sturgeon Adult Occurrence
Spring & Summer (2009-2014)
DRBC Water Quality Zones
Spring (Apr-Jun)
Summer (Jul-Sept)
Pennsylvania
New Jersey
Delaware
Philadelphia
Trenton
Wilmington
Zone 1E
Zone 2
Zone 3
Zone 4
Neshaminy Creek
Rancocas Creek
Brandywine River
C and D Canal
Ben Franklin Bridge (RM 100)
1960's Drought of Record Salt Front (RM 102)
Commodore Barry Bridge (RM 82)
Mifflin Anchorage (RM 90)
Tinicum Island (RM 85)
Marcus Hook (RM 79.5)
Claymont (RM 77)
Climate Change projections for Salt Front (RM 71)
Median Monthly Salt Front (1998-2013) (RM 67 to 76)
Pea Patch Island (RM 60.5)
Historic Salt Front (RM 57)
DATA SOURCES:
Atlantic sturgeon occurrence: 2009-2014 Telemetry data were generously shared by DNREC, Delaware State University, Tom Savoy, Hal Brundage and many others.
Interstate water quality zones, river miles and salt front information is provided by the Delaware River Basin Commission.
Data assessment methods, definitions of Atlantic sturgeon life stages, water quality zones, river miles and salt front are documented in Moberg and DeLucia 2016.
0 2.5 5 10 15 20 Miles
N
MAP 1
Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community

Atlantic Sturgeon Adult Occurrence

Fall & Winter (2009-2014)



DATA SOURCES:

Atlantic sturgeon occurrence: 2009-2014 Telemetry data were generously shared by DNREC, Delaware State University, Tom Savoy, Hal Brundage and many others.

Interstate water quality zones, river miles and salt front information is provided by the Delaware River Basin Commission.

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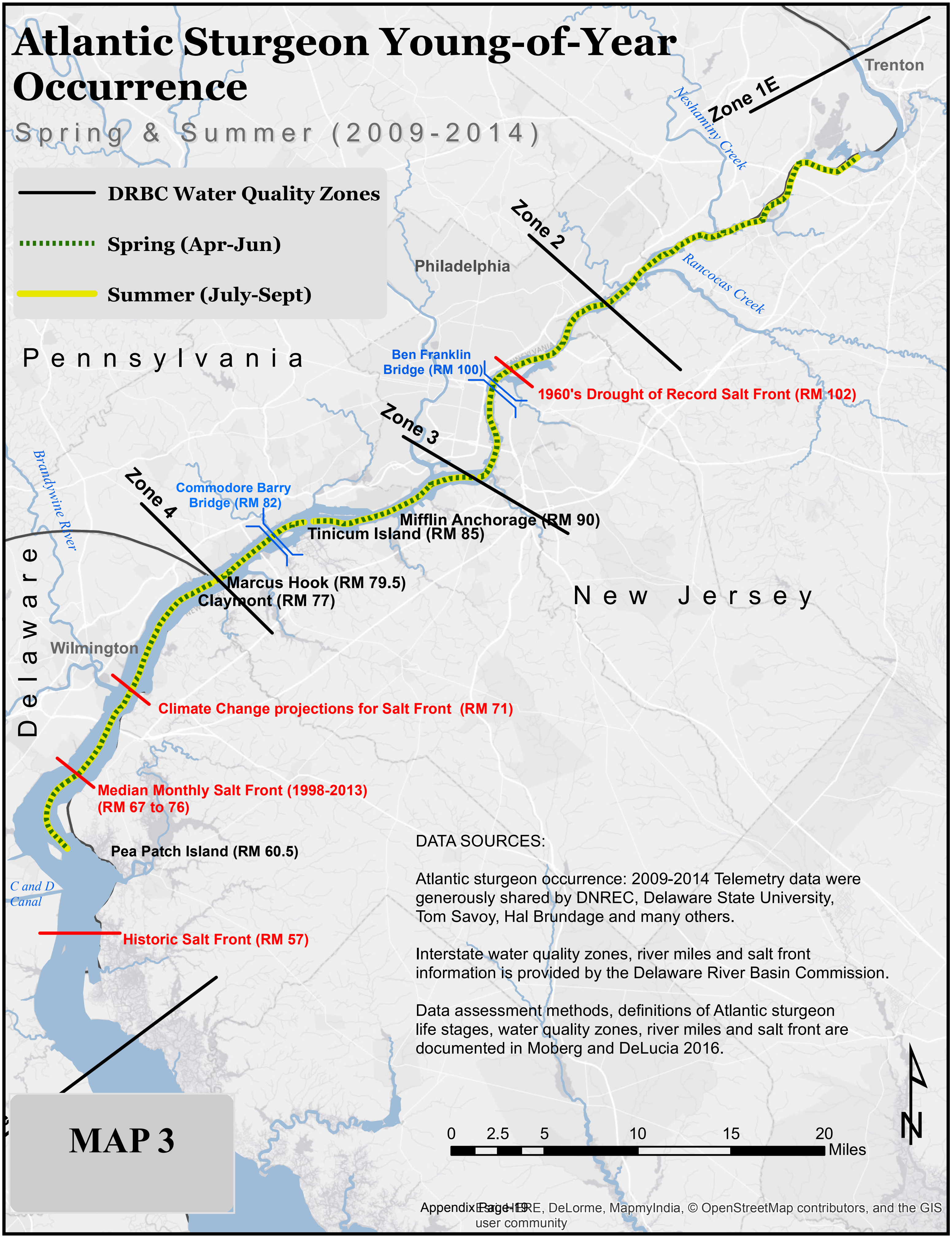
Atlantic Sturgeon Young-of-Year Occurrence
Spring & Summer (2009-2014)
DRBC Water Quality Zones
Spring (Apr-Jun)
Summer (July-Sept)
Trenton
Zone 1E
Neshaminy Creek
Zone 2
Philadelphia
Rancocas Creek
Pennsylvania
Ben Franklin Bridge (RM 100)
1960's Drought of Record Salt Front (RM 102)
Zone 3
Brandywine River
Zone 4
Commodore Barry Bridge (RM 82)
Mifflin Anchorage (RM 90)
Tinicum Island (RM 85)
Marcus Hook (RM 79.5)
Claymont (RM 77)
New Jersey
Delaware
Wilmington
Climate Change projections for Salt Front (RM 71)
Median Monthly Salt Front (1998-2013) (RM 67 to 76)
Pea Patch Island (RM 60.5)
C and D Canal
Historic Salt Front (RM 57)
DATA SOURCES:
Atlantic sturgeon occurrence: 2009-2014 Telemetry data were generously shared by DNREC, Delaware State University, Tom Savoy, Hal Brundage and many others.
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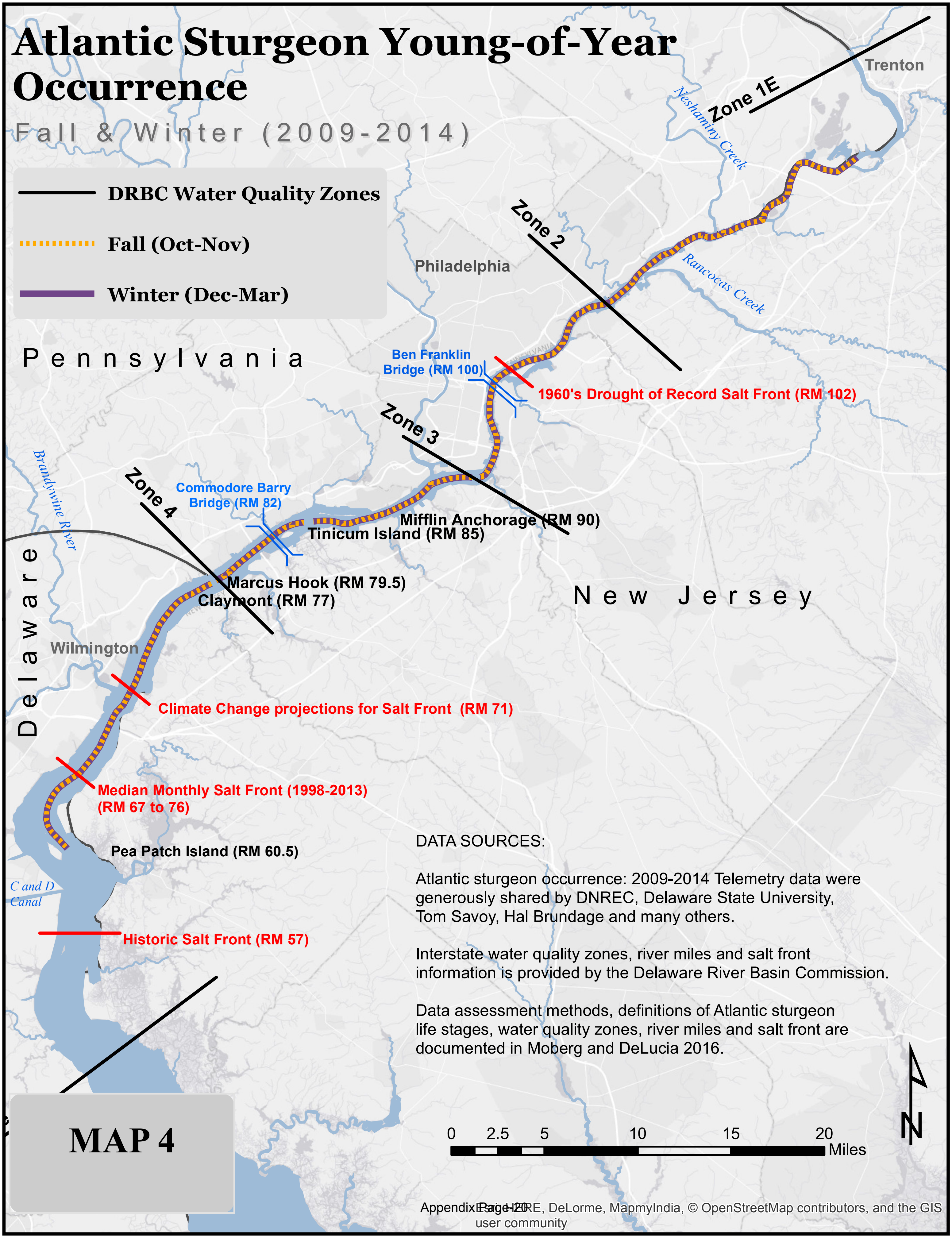
Data assessment methods, definitions of Atlantic sturgeon life stages, water quality zones, river miles and salt front are documented in Moberg and DeLucia 2016.
MAP 3
0 2.5 5 10 15 20 Miles
N
RE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community



Atlantic Sturgeon Young-of-Year Occurrence
Fall & Winter (2009-2014)
DRBC Water Quality Zones
Fall (Oct-Nov)
Winter (Dec-Mar)
Trenton
Zone 1E
Neshaminy Creek
Zone 2
Philadelphia
Rancocas Creek
Pennsylvania
Ben Franklin Bridge (RM 100)
1960's Drought of Record Salt Front (RM 102)
Zone 3
Brandywine River
Zone 4
Commodore Barry Bridge (RM 82)
Mifflin Anchorage (RM 90)
Tinicum Island (RM 85)
Marcus Hook (RM 79.5)
Claymont (RM 77)
New Jersey
Delaware
Wilmington
Climate Change projections for Salt Front (RM 71)
Median Monthly Salt Front (1998-2013) (RM 67 to 76)
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C and D Canal
Historic Salt Front (RM 57)
DATA SOURCES:
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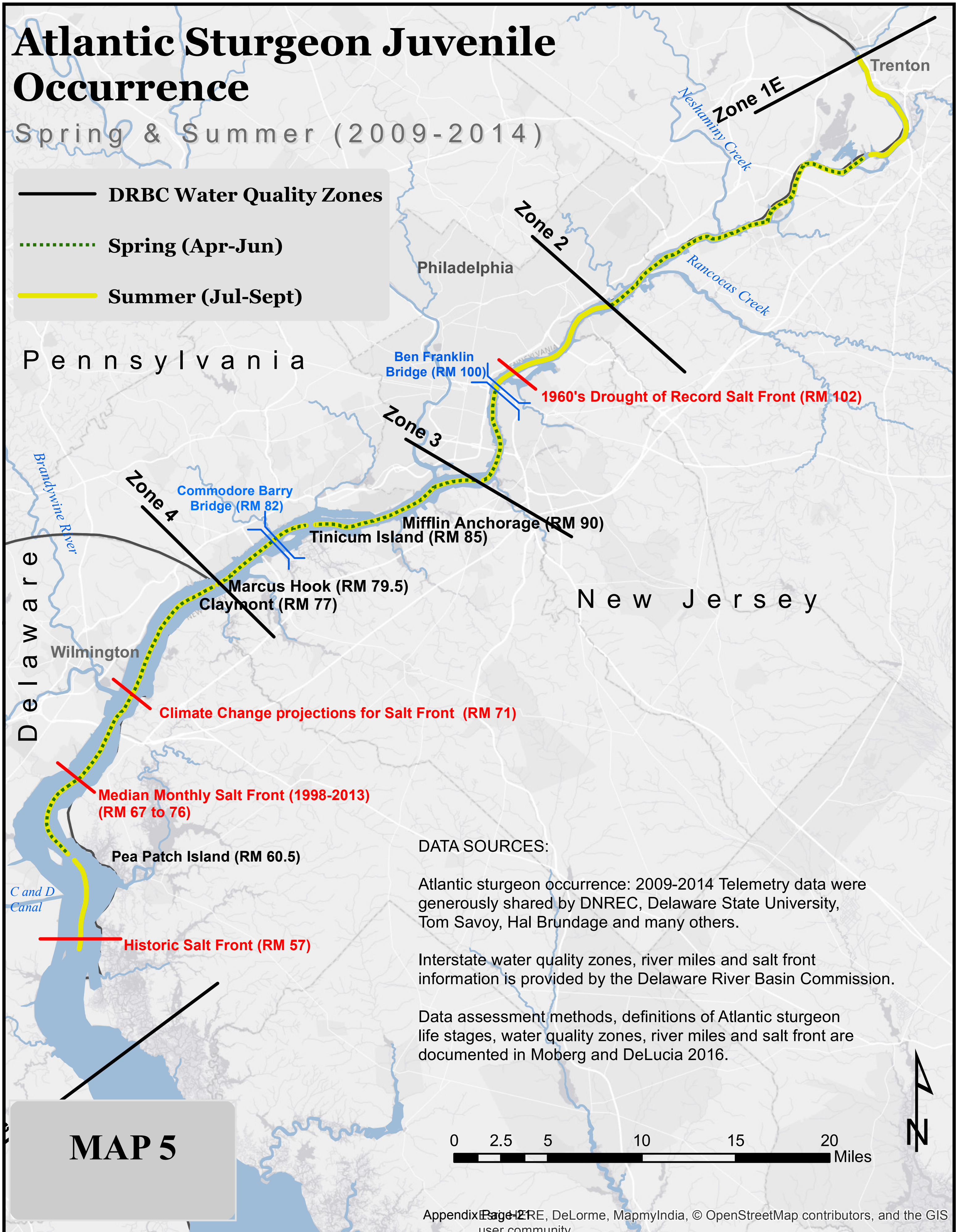
Interstate water quality zones, river miles and salt front information is provided by the Delaware River Basin Commission.
Data assessment methods, definitions of Atlantic sturgeon life stages, water quality zones, river miles and salt front are documented in Moberg and DeLucia 2016.
MAP 4
0 2.5 5 10 15 20 Miles
N
Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community


Atlantic Sturgeon Juvenile Occurrence
Spring & Summer (2009-2014)
DRBC Water Quality Zones
Spring (Apr-Jun)
Summer (Jul-Sept)
Trenton
Zone 1E
Neshaminy Creek
Zone 2
Philadelphia
Rancocas Creek
Pennsylvania
Ben Franklin Bridge (RM 100)
1960's Drought of Record Salt Front (RM 102)
Zone 3
Brandywine River
Zone 4
Commodore Barry Bridge (RM 82)
Mifflin Anchorage (RM 90)
Tinicum Island (RM 85)
Marcus Hook (RM 79.5)
Claymont (RM 77)
New Jersey
Delaware
Wilmington
Climate Change projections for Salt Front (RM 71)
Median Monthly Salt Front (1998-2013) (RM 67 to 76)
Pea Patch Island (RM 60.5)
C and D Canal
Historic Salt Front (RM 57)
DATA SOURCES:
Atlantic sturgeon occurrence: 2009-2014 Telemetry data were generously shared by DNREC, Delaware State University, Tom Savoy, Hal Brundage and many others.
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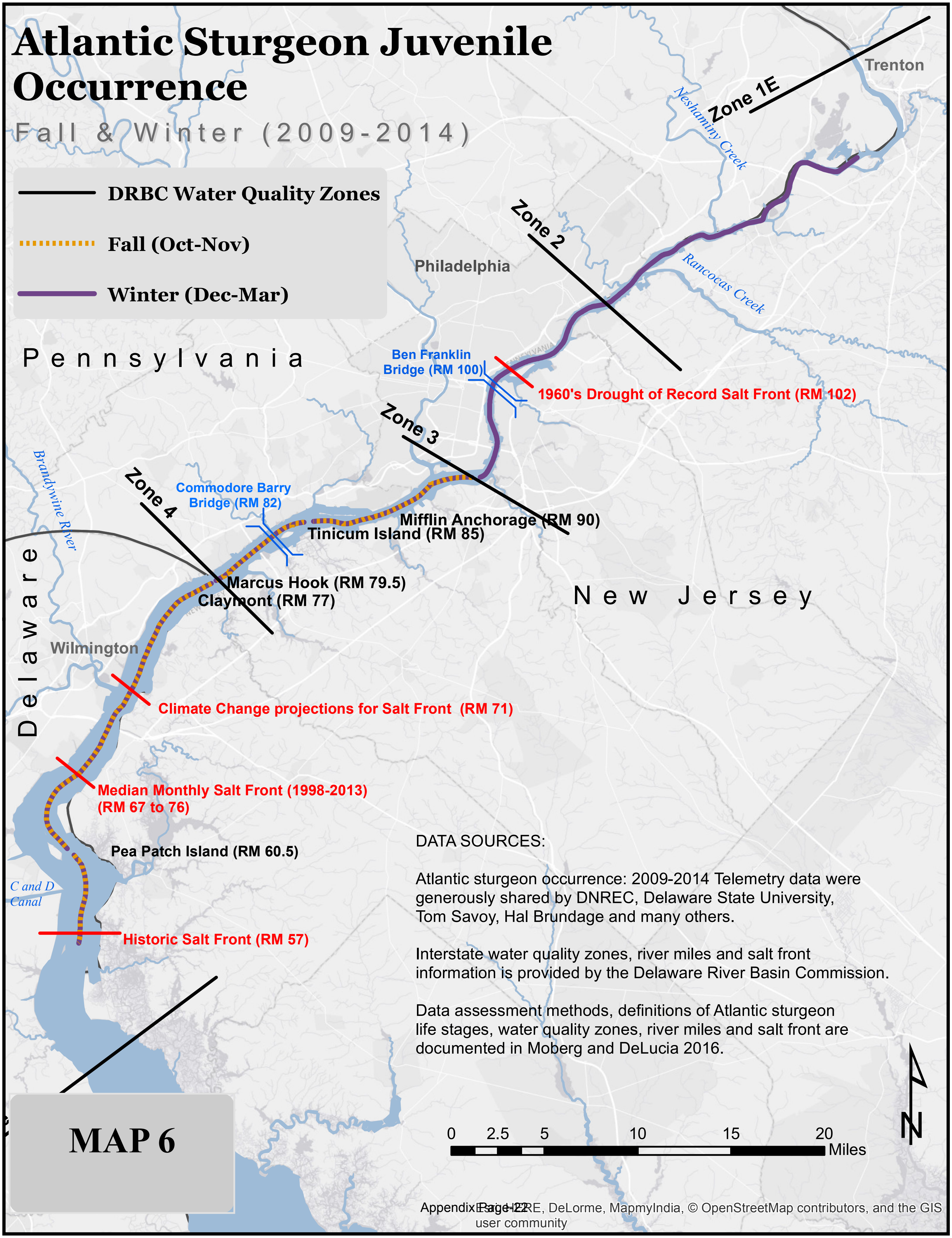
Data assessment methods, definitions of Atlantic sturgeon life stages, water quality zones, river miles and salt front are documented in Moberg and DeLucia 2016.
MAP 5
0 2.5 5 10 15 20 Miles
N
Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community

Atlantic Sturgeon Juvenile Occurrence

Fall & Winter (2009-2014)



Appendix 3:

Supporting literature, models and data

Table 1. Literature, models and data reviewed to describe distribution and suitable habitat conditions for Atlantic sturgeon in the Delaware River. In order to track the relevance of a given source, species, life stage and river information were tracked. A '1' value indicates that the source documents information relevant to the given life stage. Similarly literature that documents specific habiat conditions are noted in the final column. Please feel free to contact the authors for an electronic copy of this table or embedded information.

Reference	Sturgeon species	River basin	Staging and Upstream Migration	Spawning	Egg and larval development	YOY	Juvenile Growth	Juvenile emigration	Habitat Component
Ad Hoc Task Force. 1979. Dissolved oxygen requirments of a fishable Delaware river estuary. Delaware River Basin Commission, Trenton, New Jersey.	Atlantic	Delaware	1	1	1	1	1	1	WQ, DO
Albert, R.C. 1988. The historical context of water quality management for the Delaware estuary. Estuaries 11:99-107.	NA	Delaware							WQ
(**ASSRT) Atlantic Sturgeon Status Review Team 2007.** STATUS REVIEW OF ATLANTIC STURGEON (Acipenser oxyrinchus oxyrinchus),	Atlantic	General	1	1	1	1	1	1	
ASMFC 1998. Atlantic States Marine Fisheries Council 1998. Amendment 1 to the Interstate fishery management plan for Atlantic sturgeon. Fishery Management Report No. 31 of the ASMFC.	Atlantic	General							
Bain et al. 2000, Harvest habitats of Atlantic sturgeon in the Hudson River estuary. Lessons for sturgeon conservation	Atlantic	Hudson							
Balazik, M.T. et al., 2012. Empirical Evidence of Fall Spawning by Atlantic Sturgeon in the James River, Virginia. Transactions of the American Fisheries Society, 141(6), pp.1465–1471.	Atlantic	James	1	1	0	0	0	0	
Balazik, M.T., G. McIninch, G. Garman, R. Latrour. 2013. Age and Growth of Atlantic Sturgeon in the James River, Virginia, 1997–2011. Transactions of the American Fisheries Society 141(4):1074–1080.	Atlantic	James	0	0	0	0	1	0	
Balazik, M.T. and J.A. Musick. 2015. Dual annual spawning races in Atlantic sturgeon. PLoS ONE 10: e0128234. doi:10.1371/journal.pone.0128234	Atlantic	James, Pamunkey	1	1					
Borodin, N. 1925. Biological observations on the Atlantic sturgeon (Acipenser sturios). Transactions of the American Fisheries Society 55:184-190.	Atlantic	Delaware	1	1					

Reference	Sturgeon species	River basin	Staging and Upstream Migration	Spawning	Egg and larval development	YOY	Juvenile Growth	Juvenile emigration	Habitat Component
Breece, M.W., M.J. Oliver, M.A. Cimino and D.A. Fox. 2013. Shifting distributions of adult Atlantic sturgeon post-industrialization and future impacts in the Delaware River: a maximum entropy approach. PLOS One. 8:11 pp1-12 e-18321	Atlantic	Delaware	1	1					
Brownell, P.H. S. Bolden and B. Kynard. 2001. Spawning habitat suitability index models for shortnose and Atlantic sturgeon. Draft report. National marine Fisheries Service, Southeast Region.	Atlantic	NA	0	1	0	0	0	0	WQ, DO, Physical, Chemical
Campbell, J.G. and L.R. Goodman. 2004. Acute sensitivity of juvenile shortnose sturgeon to low dissolved oxygen concentrations. Transactions of the American Fisheries Society 133:772-776.	Shortnose	NA	0	0	0	0	1	0	WQ, DO
Calvo, L., H.M. Brundage, D. Haidvogel, D. Kreeger, R. Thomas, J.C. O'Herron, A. O'Herron, E.N. Powell. 2010. Effect of low dynamics, salinity and water quality on the Atlantic sturgeon, the shortnose sturgeon and the eastern oyster in the oligohaline zone of the Delaware estuary. Final Report Project Year 2008-2009 Submitted to the U.S. Army Corps of Engineers, Philadelphia District. 106 pp.	Atlantic, Shortnose	Delaware							Salinity, flow, water quality
Cobb, J. 1899. The Sturgeon Fishery of the Delaware River and Bay. Report to the State (Penna.) Commissioners of Fisheries for the years 1892, 1893, 1894. pgs 257-392.	Atlantic, Shortnose	Delaware							Distribution
Collins, M.R., S.J. Smith, W.C. Post and O. Pashuk. 2000. Habitat Utilization and Biological Characteristics of Adult Atlantic Sturgeon in Two South Carolina Rivers. Transactions of the American Fisheries Society 129:982–988.		Southeast (Combahee and Edisto)							
Desmond Kand, M.F., Young-of-year Atlantic sturgeon oxygen requirments and recent oxygen levels in the river - too close for comfort.	Atlantic	Delaware				1			WQ, DO
DNREC-DFW Delaware Department of Natural Resources and Environmental Control and Division of Fish and Wildlife. 2015. Sturgeons in the Mid-Atlantic region: a multi-state collaboration of research and conservation. Final report under Section 6 Species Recovery Grants Program. 204 pp.	Atlantic, Shortnose		1	1		1	1		
Delaware Valley Regional Planning Commission 2004. Sea level rise impacts in the Delaware estuary of Pennsylvania. Prepared for Pennsylvania Coastal Zone Management Program. CZM Project Number: 2002-PD.20. Philadelphia, PA.	NA	Delaware							Salinity
DiLorenzo, J.L., P. Huang, M.L. Thatcher, T.O. Najarian. 1993. Effects of historic dredging activitites and water diversions on the tidal regime and salinity distribution of the Delaware Estuary. Final report submitted to Delaware River Basin Commission. 124 pp.	NA	Delaware							Salinity

Reference	Sturgeon species	River basin	Staging and Upstream Migration	Spawning	Egg and larval development	YOY	Juvenile Growth	Juvenile emigration	Habitat Component
EPA 2003. Ambient water quality criteria for dissolved oxygen, water clarity and chlorophyll a for the Chesapeake Bay and its tidal tributaries. Washington, D.C.	Atlantic	Chesapeake Bay	1		1	1	1		Dissolved Oxygen
Environmental Research and Consulting, Inc. 2008. Final report of investigations of shortnose sturgeon early life states in the Delaware river spring 2007 and 2008. A report to the NJ Division of Fish and Wildlife Endangered and Nongame Species Program. Kennett Square, PA. 40 pp.	Shortnose	Delaware	0	1	1	1	0	0	Physical
Everly, A.W. & Boreman, J., 1999. Habitat Use and Requirements of Important Fish Species Inhabiting the Hudson River Estuary : Availability of Information. NOAA Technical Memorandum NMFS-NE-121,	Atlantic	Hudson	0	1	1	1	1	0	General
Eyler, S. M. Mangold and S. Minkkinen. 2004. Atlantic Coast sturgeon tagging database. Summary report perpared by US Fish and Wildlfie Service, Maryland Fishery Resource Office, Annapolis, Maryland.									Distribution
Fernandes, S.J., G. Zydlewski, J. Zydlewski, G. Wippelhauser, M. Kinnison. 2011. Seasonal distribution and movements of Shortnose sturgeon and Atlantic sturgeon in the Penobscot River Estuary, Maine.	Atlantic, Shortnose	Penobscot	1	0	0	0	1	1	
Flowers, H.J., Iii, W.E.P. & Dutterer, A.C., 2011. Spawning site selection and potential implications of modified flow regimes on viability of gulf sturgeon populations. Transactions of the American Fisheries Society, (October 2012), pp.1266–1284.	Gulf	ACF	0	1	1	0	0	0	Flow
Greene, K.E., J.L. Zimmerman, R.W. Laney and J.C. Thomas-Blate. 2009. Atlantic States Marine Fish Habitat : A Review of Utilization , Threats , Recommendations for Conservation , and Research Needs. Atlantic States Marine Fisheries Commission Habitat Management Series No. 9, Washington, D.C. 484 pp.	Atlantic	Delaware	1	1	1	1	1	1	WQ, Physical, Hydraulic
Haley, N.J. 1999. Habitat charactersitics and resource use patterns of sympatric sturgeons in the Hudson River estuary. Master's thesis. University of Massachusetts, Amherst.	Atlantic	Hudson							
Gilbert, C.R. 1989. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Mid-Atlantic Bight) – Atlantic and shortnose sturgeons. U.S. Fish and Wildlife Service Biological Report. 82(11.122).	Atlantic		1	1	1	1	1	1	General
Hager, C., Kahn, J., Watterson, C., Russo, J. and Hartman, K., 2014. Evidence of Atlantic sturgeon spawning in the York River system. Transactions of the American Fisheries Society 143: 1217-1219.	Atlantic	York	1	1					

Reference	Sturgeon species	River basin	Staging and Upstream Migration	Spawning	Egg and larval development	YOY	Juvenile Growth	Juvenile emigration	Habitat Component
Hatin, D., J. Munro, F. Caron and R.D. Simons. 2007. Movements, home range size, habitat use and selection of early juvenile Atlantic surgeon in the St. Lawrence estuarine transition zone. Pages 129-155	Atlantic	St. Lawrence				1	1		
HydroQual, I., 1988. Development of a Hydrodynamic and Water Quality Model for the Delaware River. , p.7.	NA	Delaware							WQ, BOD, Ammonia, Nutrients, DO, Point source
Jenkins, W.E., W.I.E. Smith and L.D. Hewared. 1993. Tolerance of shortnose sturgeon, Acipenser brevirostrum, juveniles to different salinity and dissolved oxygen concentrations. Pp 476-484 in Proceedings of the Annual Conference of southeast Association of Fish and Wildlife Agencies.	Shortnose	NA				1	1		WQ, Salinity, DO
Kahn, D.M., Fisher, M. & Delaware, D., 2012. Endangered Atlantic Sturgeon in the Delaware River Require Higher Standards for Dissolved Oxygen Delaware Division of Fish and Wildlife, Dover.	Atlantic	Delaware			1	1			WQ, DO, Ammonia
Kieffer, M.C and B. Kynard. 1993. Annual movements of shortnose and Atlantic sturgeons in the Marrimack River, Massachusetts. Transactions of the American Fisheries Society 122: 1088-1103.	Atlantic	Merrimack	1	1					
Kocik, J., C. Lipsky, T. Miller, P. Rago, and G. Shepherd. 2013. An Atlantic sturgeon population index for ESA management analysis. US Department of Commerce, Northeastern Fisheries Science Center Reference Document 13-06:36. Woods Hole, MA.	Atlantic	NA							
Kreeger, D., J. Adkins, P. Cole, R. Najjar, D. Velinsky, P. Conolly and J. Kraeuter. 2010. Climate change and the Delaware Estuary: Three case studies in vulnerability assessment and adaptation planning. Partnership fo the Delaware Estuary Report No. 10-01. 117 pp.	NA	Delaware							Salinity, climate change
Kynard, B. P. Bronzi and H. Rosenthal, eds. 2012. Life history and behavior of Connecticut River shortnose and other sturgeons. Special Publication no. 4. World Sturgeon Conservation Society, Norderstedt, Germany.	Shortnose, Atlantic	Connecticut	1	1	1	1	1	1	
Kynard, B., M. Horgan, M. Kieffer and D. Seibel. 2000. Habitat used by shortnose sturgeon in two Massachusetts rivers, with notes on estuarine Atlantic sturgeon: a hierarchical approach. Transactions fo the American Fisheries Society 129: 487-503.	Shortnose	Connecticut, Merrimack							Hydraulic
Kynard, B., M. Horgan. 2002. Otogenetic behavior and migration of Atlantic sturgeon, Acipenser oxyrinchus oxyrinchus and shortnose sturgeon, Acipenser brevirostru, with notes on social behavior. Environmental Biology of Fishes 63: 137-150.	Atlantic		1					1	

Reference	Sturgeon species	River basin	Staging and Upstream Migration	Spawning	Egg and larval development	YOY	Juvenile Growth	Juvenile emigration	Habitat Component
Laney, R.W., J.E. Hightower, B.R. Versak, M.F. Mangold, W.W. Cale Jr., and S.E. Winslow. 2007 Distribution, habitat use, and size of Atlantic sturgeon capture during cooperative winter tagging cruises, 1988-2006. Pages 167-182 in J. Munro, D. Hatin, J.E. Higtower, K.A. McKown, K.J. Sulak, A.W. Kahnle, and F. Caron, editors. Anadromous sturgeons: habitats, threats, and management. American Fisheries Society, Symposium 56, Bethesda, Maryland.	Atlantic	St. Lawrence							
Lazzari, M.A., J.C. O'Herron and R.W. Hastings. 1986. Occurrence of juvenile Atlantic sturgeon, Acipenser oxyrynchus, in the Upper Tidal Delaware River. Estuaries 9: 356-361.	Atlantic	Delaware					1	1	
Mohler, J.W. 2003. Culture manual for the Atlantic sturgeon Acipenser oxyrinchus oxyrinchus. U.S. Fish and Wildlife Service Region 5. Hadley, MA.	Atlantic	NA			1	1			
Munro, J., D. Hatin, J.E. Hightown, K. McKown, K.J. sulak, A.W. Kahnle and F. Caron, editors. 2007. Anadromous sturgeons: habitats, threats and management. American fisheris Society, Symposium 56, Bethesda MD.	Atlantic	Delaware, St. Lawrence, Gulf of Mexico, Neuse River,							
Najjar, R.G., H.A. Walker, P.J. Anderson, E.J. Barron, R.J. Bord, J.R. Gibson, V.S. Kennedy, C.G. Knight, J.P. Megonigal, R.E. O'Connor, C.D. Polsky, N.P. Psuty, B.A. Richards, L.G. Sorenson, E.M. Steele and R.S. Swanson. 2009. The potential impacts of climate change on the mid-Atlantic coastal region. Climate Research. 14:219-233.	NA	mid-Atlantic							Salinity, Climate Change
Nellis, P., J. Munro, D. Hatin, G. Desrosiers, R.D. Simons, and F. Guilbard. 2007. Macrobenthos assemblages in the St. Lawrence estuarine transition zone and their potential as food for Atlantic sturgeon and lake sturgeon. Pages 105-128 in J. Munro, D. Hatin, J.E. Higtower, K.A. McKown, K.J. Sulak, A.W. Kahnle, and F. Caron, editors. Anadromous sturgeons: habitats, threats, and management. American Fisheries Society, Symposium 56, Bethesda, Maryland.	Atlantic	St. Lawrence					1		
Niklitschek, E.J. and D.H. Secor 2009a. Dissolved oxygen, temperature and salinity effects on the ecophysiology and survival of juvenile Atlantic sturgeon in estuarine waters: 1. Laboratory results. Journal of Experimental Marine Biology and Ecology 381: S150-S160.	Atlantic	Chesapeake Bay					1		DO, temperature, salinity

Reference	Sturgeon species	River basin	Staging and Upstream Migration	Spawning	Egg and larval development	YOY	Juvenile Growth	Juvenile emigration	Habitat Component
Niklitschek, Edwin J. & Secor, David H., 2005. Modeling spatial and temporal variation of suitable nursery habitats for Atlantic sturgeon in the Chesapeake Bay. Estuarine, Coastal and Shelf Science, 64(1), pp.135–148. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0272771405000454 [Accessed May 26, 2012].	Atlantic	Chesapeake Bay			1	1	1		WQ, DO, temperature
Niklitschek, E.J. and D.H. Sector 2009b. Dissolved oxygen, temperature and salinity effects on the ecophysiology and survival of juvenile Atlantic sturgeon in estuarine waters: II. Model development and testing. Journal of Experimental and Marine Biology and Ecology 381: S161-S172.	Atlantic	Chesapeake Bay					1		DO, temperature, salinity
Niklitchek, E.J. and D.H. Secor 2010. Experimental and field evidence of behavioural habitat selection by juvenile Atlantic Acipenser oxyrinchus oxyrinchus and shortnose Acipenser brevirostrum sturgeons. Journal of Fish Biology 77:1293-1308.	Atlantic	Chesapeake Bay							
Randall, M., and J.J. Sulak 2007. Relationship between recruitment of gulf sturgeon and water flow in the Suwannee River, Florida. An article in Munro et al. 2007.	Gulf	Suwannee River			1	1	1		Flow
Ross, A.C., R.G. Najjar, M. Li, M.E. Mann, S.E. Ford, B. Katz. 2015. Sea-level rise and other influences on decadal-scale salinity variability in a coastal plain estuary. Estuarine, Coastal and Shelf Science 157:79-92.	NA	Delaware							Salinity, climate change
Ryder, R.A. 1888. The sturgeon and sturgeon industries of the eastern coast of the United States, with an account of experiments bearing upon sturgeon culture. Bulletin of the U.S. Fisheries Commission 8: 231-328.	Atlantic, Shortnose	NA			0				
Savoy, T. & Pacileo, D., 2003. Movements and Important Habitats of Subadult Atlantic Sturgeon in Connecticut Waters. Transactions of the American Fisheries Society, 132, pp.1–8.	Atlantic	Long Island Sound, Connecticut					1	1	
Scott, W.B. and E.J. Crossman 1973. Freshwater fishes of Canada, Fisheries Research Board of Canada Bulletin 184. Ottawa, Canada.	NA	NA							
Secor, D.H. & Niklitschek, E.J., 2001a. Hypoxia and Sturgeons: Report to the Chesapeake Bay Program Dissolved Oxygen Criteria Team, Solomons.	Atlantic	Chesapeake Bay		1	1	1	1		WQ, DO
Secor, D.H. & Niklitschek, E.J., 2001b. Sensitivity of sturgeons to environmental hypoxia: a review of physiological and ecological evidence. In R. V. Thurston, ed. Fish Physiology, Toxicology, and Water Quality. La Paz, Mexico, 22-26 Jan. 2001, pp. 61–78. Available at: http://aquaticcommons.org/4821/ [Accessed May 26, 2012].	Atlantic, Shortnose	Chesapeake Bay			1	1	1		WQ, DO, temperature
Secor, D.H.; Gunderson, T.E., 1998. Effects of hypoxia and temperature on survival, growth and respiration of juvenile Atlantic sturgeon, Acipencer oxyrinchus. Fishery Bulletin, pp.603–613.	Atlantic						1		WQ, DO, temperature
Secor, D.H. & JR Waldman. 1999. Historical abundance of Delaware Bay Atlantic Sturgeon and potential rate of recovery. American Fisheries Society Symposium 23: 203-216.	Atlantic	Delaware		1					
Sharp, J.H. 2010. Estuarine oxygen dynamics: what can we learn about hypoxia from long-time records in the Delaware estuary? Limnology and Oceanography 55:535-548.	NA	Delaware							WQ, DO

Reference	Sturgeon species	River basin	Staging and Upstream Migration	Spawning	Egg and larval development	YOY	Juvenile Growth	Juvenile emigration	Habitat Component
Shirey, C. A., C. C. Martin, and E. J. Stetzar. 1999. Atlantic sturgeon abundance and movement in the lower Delaware River. Final Report. NOAA Project No. AGC-9N. Grant No. A86FAO315. Delaware Division of Fish and Wildlife.	Atlantic	Delaware	1	1					
Sildorff, E. 2012. Upgrading dissolved oxygen water quality standards in the context of the Delaware River Basin Commission's nutrient standards. Presentation to the Science and Technical Advisory Committee.	NA	Delaware							WQ, DO, Ammonia
Simpson, P. and D. Fox. 2007. Atlantic Sturgeon in the Delaware River: Contemporary Population Status and Identification of Spawning Areas. University of Delaware, Dover. 41 pp.	Atlantic	Delaware		1					WQ, temperature, DO, salinity, Physical, substrate,
Smith, T.I.J. 1985. The fishery, biology and management of Atlantic sturgeon, Acipenser oxyrinchus, in North America. Environmental biology of fishes 14: 61-72.	Atlantic								
Sommerfield, C.K. and J.A. Madsen 2003. Sedimentological and geophysical survey of the Upper Delaware Estuary. Final Report ot the Delaware River Basin Commission. University of Delaware, Newark, DE. 127 pp.	NA	Delaware							Benthic
Stein, A.B., K.D. Friedland and M. Sutherland. 2004. Sturgeon marine distribution and habitat use along the northeast coast of the United States. Transaction of the American Fisheries Society 133: 527-537.	Atlantic	Northeastern US	1						Marine
USACOE 2009. DRAFT Delaware River main stem and channel deepening project: Essential fish habitat evaluation. Philadelphia, PA. 83 pp.	Atlantic	Delaware		1	1	1	1		Benthic, Hydraulic
Waldman, J.R. et al., 2013. Stock Origins of Subadult and Adult Atlantic Sturgeon , Acipenser oxyrinchus , in a Non-natal Estuary , Long Island Sound. Estuaries and Coasts, 36, pp.257–267.	Atlantic	Long Island Sound	1	1	1	1	1	1	Distribution
(US OFR) United States Office of the Federal Register. 2012. Endangered and threatened wildlife and plants; threatened and endangered status for distinct population segments of Atlantic sturgeon in the northeast region. Federal Register 77:5880-5912.	Atlantic	NA							Listing
Van Eenennaam, J.P., S.I. Doroshov, G.P. Moberg, J.G. Watson, D.S. Moore and J. Linares. 1996. Reproductive conditions of the Atlantic sturgeon (Acipenser oxyrinchus) in the Hudson River. Estuaries 19: 769-777.	Atlantic	Hudson	1	1					
Walters, R.A. 1992. A three-dimensional, finite element model for coast and estuarine circulation. Continental shelf research 12: 83-102.	NA	Delaware							Salinity, climate

Appendix 4:

Supplementary tables

Table 1. Delaware River Basin Commission water quality zones and water quality regulations for dissolved oxygen as defined in 18 CFR Part 410 (instantaneous, 24-hour average and seasonal average (4/1-6/15 and 9/16-12/31)). The extent of the historic DO sag is documented in Sharp 2010.

Delaware River Reaches		**Dissolved Oxygen Standards**			**Historic DO sag**	**Atlantic sturgeon life stages occurring in reach (2005-2014)**
DRBC Zone	**River Miles**	**Instantaneous**	**24-hr average**	**Seasonal average**		
Zone 1E	139.0-133.5	4.0 mg/L	5.0 mg/L	None	No	None
Zone 2	133.4-108.4	None	5.0 mg/L	6.5 mg/L	Yes	Young-of-Year, Juvenile, Spawning Adults
Zone 3	108.4-95.0	None	3.5 mg/L	6.5 mg/L	Yes	Young-of-Year, Juvenile, Spawning Adults
Zone 4	95.0-78.8	None	3.5 mg/L	6.5 mg/L	Yes	Young-of-Year, Juvenile, Spawning Adults
Zone 5 a	78.8-70.0	None	3.5 mg/L	6.5 mg/L	Yes	Young-of-Year, Juvenile, Spawning Adults
Zone 5 b	70.0-59.5	None	4.5 mg/L	6.5 mg/L	Yes	Young-of-Year, Juvenile, Spawning Adults
Zone 5 c	59.5-48.2	None	6.0 mg/L	6.5 mg/L	Yes	Juvenile, Migrating Adults

Table 2. A comparison of the location of salt front and flow conditions during years when recruitment was observed and a recent drought year with no observed recruitment.

	Year	Summer high pulse events (>18,000 cfs)	7-day minimum flow[4] (cfs)	Extreme low flow days (< 4,000 cfs)	Salt front location (RM)
No observed recruitment	2010	0	3,161	61	86.0
Successful recruitment observed	2009	5	4,059	0	69.5
	2011	9	6,070	0	57.1
	2014	2	4,470	10	79.0

Table 3. Depth of the Delaware River from Philadelphia through the Estuary, 1800 to present (Adapted from USACE 2015).

Authorization	**Depth**	**Width**	**Year completed**
Natural conditions (pre-1885)	***17'-24'***	***175-600'***	***NA***
January 1885 Board of Engineers	26'	600'	1898
March 1899 Improvement Plan	30'	600'	1905
June 1910 River and Harbor Act	35'	800'	1934
June 1938 River and Harbor Act	40'	800-1000'	1942
Water Resources Development Act of 1992	45'	400-1000'	Ongoing (2017)

[4] The exceedance values for 7-day minimum flows were July Q93 (2010), July Q83 (2009) and July Q50 (2011).

Appendix 5:

Workshop agenda, participants and outstanding research questions

The Nature Conservancy synthesized findings based on research, data and input provided by workshop members. The report's collective set of recommendations and study conclusions are those of The Nature Conservancy and do not necessarily reflect all viewpoints of individual workshop members or the positions or policies of their organizations.

Workshop Agenda

June 3 and 4, 2014

DoubleTree Hotel Downtown Wilmington Legal District
700 N. King Street
Wilmington, DE 19801
http://www.wilmingtondehotel.com/

Objectives:

- Review existing literature, data and models and their applicability to At. Sturgeon in the Delaware
- Develop a framework for habitat suitability recommendations and draft conclusions
- Identify information gaps and short- and long-term analytical opportunities
- Discuss other factors that may be influencing recruitment

Day 1 – June 3rd

11:00 -12:30	Project overview ▪ Review project scope and outcomes ▪ Workshop agenda and objectives ▪ Expert team introductions ▪ Orient to workshop packet - draft synthesis of available information on habitat suitability and life stage distribution
12:30 - 1:30	Lunch
1:30 - 3:00	Session 1: Egg and larval development, YOY, Juveniles
3:00 - 3:15	Break
3:15 - 4:15	Session 2: Spawning, in-migration and out-migration
4:15 - 4:30	Wrap up and adjourn

Day 2- June 4th

9:00 - 10:00	Review previous day's conclusions
10:00 - 11:00	Existing data collection efforts and model development – capabilities and limitations
11:00 - 11:15	Break

11:30 - 12:30	Products and next steps ▪ Short-term and long-term opportunities to address data gaps ▪ Additional threats to recruitment and research needs
12:30	Lunch and depart

Experts Consulted and Workshop Participants

Participant	Affiliation
Dewayne Fox*	Delaware State University
Lori Brown	Delaware State University
Matthew Breece*	University of Delaware
David Secor*	UMCES Chesapeake Biological Lab
Erin Markin*	UMCES Chesapeake Biological Lab, Graduate Student
Bill Pine	University of Florida
Isaac Wirgin*	Associate Professor, NYU
Heather Corbett*	New Jersey Department of Environmental Protection
Erik Silldorff*	Delaware River Basin Commission
Namsoo Suk	Delaware River Basin Commission
Lynn Lankshear*	National Marine Fisheries Service
Chris Chambers*	National Marine Fisheries Service
Barbara Conlin	U.S. Army Corps of Engineers
Matt Fisher*	Regional sturgeon expert
Joe Perillo*	Philadelphia Water Department
Hal Brundange	Environmental Research and Consulting, Inc.
Mari-Beth Delucia*	The Nature Conservancy
Tara Moberg*	The Nature Conservancy
Michele DePhilip*	The Nature Conservancy
Brian Boutin*	The Nature Conservancy

*Individuals denoted with an asterisk were in attendance at the two day workshop. Individuals without an asterisk assisted in the preparation of workshop materials.

Remaining research questions - The following research questions were identified as priorities during workshop and through follow-up discussions.

1. **Adaptively managing the resource**
   - The Delaware River is lacking a recent population estimate for Atlantic sturgeon. The current estimate of less than 300 spawning sturgeon relies on population estimates that were conducted in other mid-Atlantic rivers. A better understanding of the population is necessary for effective conservation and adaptive management.
   - There are several factors that are influencing the survival and successful recruitment of Atlantic sturgeon in the Delaware River. A quantitative life history model may help to characterize the relative importance of influential factors for research investments.
   - The pace of research and development in this field is rapid. Building off of the model and successes of the sturgeon Atlantic Coast Telemetry (ACT) Network, a centralized library cataloging past, emerging and recently published research related to Atlantic sturgeon recruitment could help to systematically build the knowledge base.
   - Any resulting conservation practices or measures should be flexible, and able to adjust to account for new information.

2. **Habitat conditions**
   - How do we account for interactive factors to success of egg and larval development in the Delaware River system (e.g. dioxins)? Does pH have an interactive affect in this system?
   - To better understand reach specific habitat conditions and the migration of the salt front under climate change scenarios, it is important to develop models that simulate the complex dynamics of the Delaware River and Estuary (DRBC and ACOE have models in development).
     - Once a model has been calibrated, scenarios may be developed to predict a range of expected conditions under a changing climate. Scenarios can also be developed to test a range of potential short and long-term solutions including drought management opportunities (e.g. reservoir releases and water withdrawal management).

3. **Critical reaches, habitat features and timing of occurrence**
   - There is a need to continue to refine understanding of distribution and use of habitats for young-of-year, juvenile and spawning adults. While the 2009-2014 telemetry data provide an excellent resource to document the extent of the distribution of each life stage, continued monitoring support is needed to understand the location and frequency of use of critical habitat features.
   - Currently, there is little known about the habitats used for egg and larval development. Eggs and larvae are not currently collected in this system.
   - While a fall upstream migration has been documented through recent telemetry data, it is unknown whether the migration is associated with a fall spawning event. If it is associated with a spawning event, then eggs and larvae would be present in the river during the fall and early winter.