Hypoxia in the Guana Tolomato Matanzas National Estuarine Research Reserve

By Beth Robertson

INTRODUCTION

Hypoxia is a natural phenomenon that occurs when water becomes stratified, usually when denser, more saline layers sink to the bottom of a body of water while warmer, oxygenated water stays at the surface. Because the oxygenated surface water does not reach the sediment, oxygen becomes scarce, particularly when water becomes warmer and plant life is abundant (NOAA 2014). Areas of hypoxia are often called dead zones because many organisms cannot survive the low oxygen levels. Dead zones in coastal areas have been increasing for the last 50 years with more than 400 worldwide as of 2008 (Diaz & Rosenberg 2008). Between rising sea and air temperatures and eutrophication, this trend is unlikely to change anytime in the near future. Currently, half of all estuaries in the United States exhibit hypoxia each year (NOAA 2014).

The effects of hypoxia and anoxia on wildlife are varied, and occasionally counterintuitive. In a study of sediment organisms in Perdido Bay, researchers found that low dissolved oxygen was a significant factor in declining biodiversity of the communities (Flemer et al. 1999). However, in a study conducted in the York River found higher epifaunal recruitment after hypoxic periods (Sagasti et al. 2003). The effects of a long period of hypoxia may have no mortality for some species, yet wipe out all individuals from others, devastating a community (Riedel et al. 2012).

Just how low the oxygen level needs to be to have an observable effect also varies between species. Experiments by Goodman and Campbell in 2007 demonstrated that most organisms would have a lethal concentration 50% at less than 2mg L^{-1} of oxygen. Of those studied, only scaled sardines had an LC50 greater and they began dying at 2.72mg L^{-1} of oxygen for 24 hours. The effect of hypoxia on zooplankton is also dependent on the species with mortality ranging between 0.5ml l^{-1} and 1ml l^{-1} oxygen (Stalder and Marcus 1997).

Even within the same species, the results are not easily predictable. An experiment by Holman and Hand (2009) found that post-anoxia mortality rates of the ghost shrimp, *Lepidophthalmus louisianensis*, depended on the size of the shrimp: shrimp less than a gram had a median survival time twice as long as their brethren that were larger than two grams.

Although lowered dissolved oxygen may not kill all the individuals, it can still have an effect on growth, reproduction and behavior. Richmond et al. (2006) found in their experiments with *Acartia tonsa*, a copepod, that hypoxia increased maturation time after hatching and decreased egg production, survivorship, and the size of females. *Streblospio benedicti*, a polychaete that lives in estuaries, stopped eating and decreased burrowing in hypoxic conditions, though they could survive up to two weeks this way (Llanso 1991). The experiments of McNatt and Rice (2004) showed that hypoxia slowed the growth of fish *Brevoorita tyrannus* and *Leiostomus xanthurus*, two fish that live in estuaries as juveniles. An experiment on *Micropogonias undulates*, the Atlantic croaker, demonstrated that low dissolved oxygen decreases growth of the reproductive organs and disrupts endocrine function (Thomas et al. 2007).

The results on a species were not necessarily deleterious - female grass shrimp, *Palaemonetes pugio*, that are exposed to hypoxic conditions have higher fecundity and their larvae were able to survive starvation longer. However, the shrimp left under hypoxic conditions look longer to produce broods and the eggs hatch (Brouwer et al. 2007).

Some fish are able to acclimatize. A study of gulf killifish, *Fundulus grandis*, were able to do this with some success. Fish that were collected in the summer, and thus exposed to hypoxic conditions in the wild, could survive hypoxic conditions longer without aquatic surface respiration than fish collected at other times of the year (Love and Rees 2002). However, another group found that even diel hypoxia cause smaller reproductive organs in this same species (Cheek et al. 2009).

The purpose of this study was to determine if there were any causal links between hypoxia and other water quality parameters in the Guana Tolomato Matanzas National Estuarine Research Reserve in Florida. Hypoxia in this area could create significant economic as well as environmental impact given the high rate of tourism and its status as a Class II waterbody (62-302.400 F.A.C.). It was hypothesized that hypoxic conditions would be related among the selected sites and physical conditions such as temperature, as well as the overabundance of nutrients, would play a role in depleted dissolved oxygen.

METHODS

The Sites

The data were obtained by the National Oceanic and Atmospheric Administration's National Estuarine Research Reserve System (NERRS) Surface Water Monitoring Program

(SWaMP). Water quality data from three sites were analyzed: Fort Matanzas, Pellicer Creek, and Pine Island. Located within the Upper East Coast Watershed in the St. Johns Water Management District, much of the basin is publicly owned with 60,000 acres of forests, wetlands, and protected coastal habitats (NOAA 2014). According to 2004 Land Use imagery, forests and wetlands constitute just under 58% of the basin, while agriculture is less than 3% and urban just under 24% (FDEP 2008). The Tolomato River Basin drains about 53,802 acres and makes up the more northern part of the watershed. The Matanzas River Basin drains about 103,615 acres and is on the southern end of watershed. Both of these areas are tidally influenced from two inlets, the St. Augustine and the Matanzas (NOAA 2014).

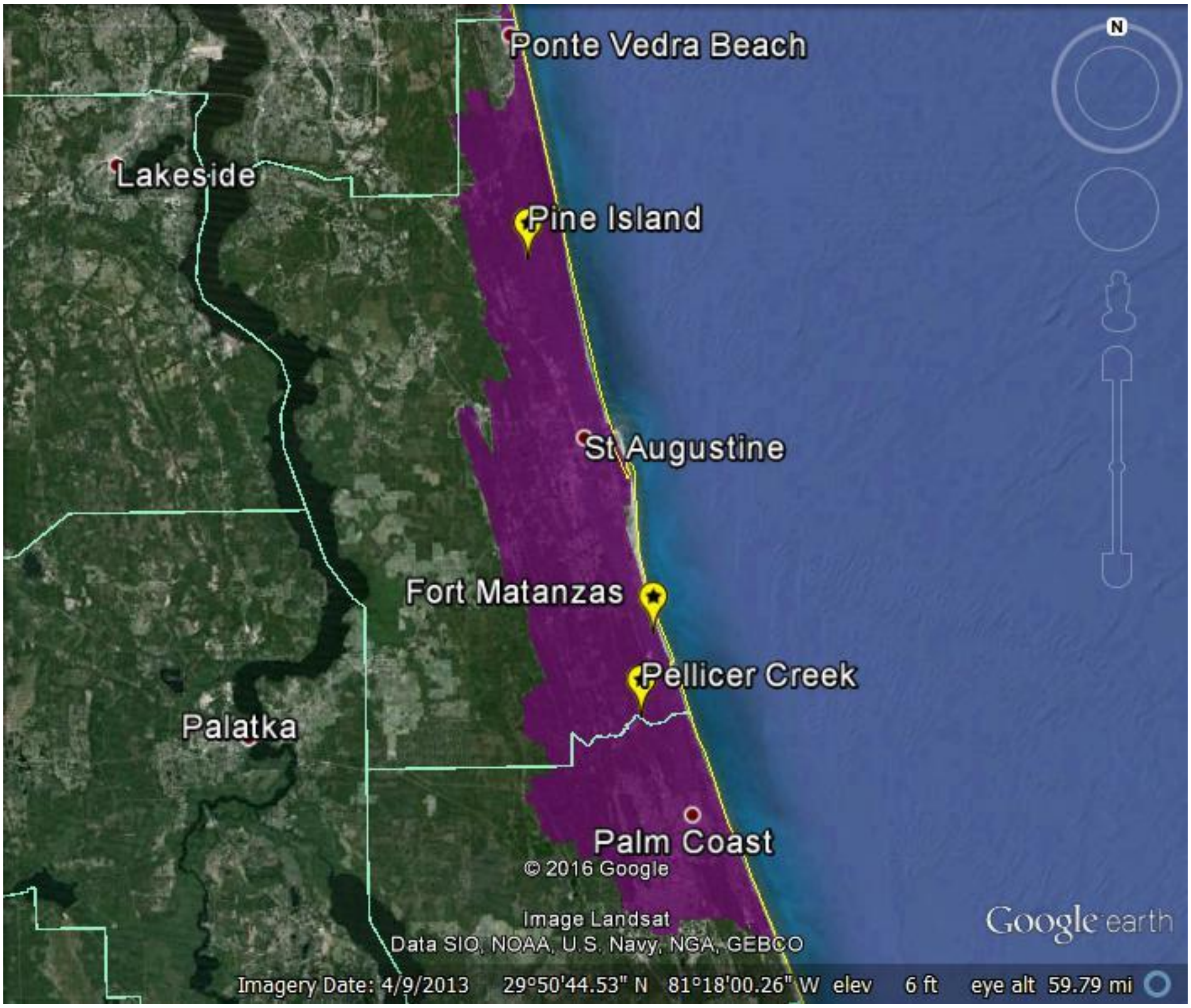


Figure 1. *Sources*: "Upper East Coast Watershed and Guana Tolomato Matanzas National Estuarine Research Reserve Stations." 29°50'44.53"N and 81°18'00.26"W. **Google Earth**. April 9, 2013. March 1, 2016.

These sites were selected because, although they are fairly near to each other, they are still distinct. The Pine Island site is positioned in the Tolomato River near Pine Island. It is located within an aquatic preserve and drains an area heavily influenced by silviculture. It is the deepest of the sites at around 3.8m and varies 1.6m with the tide. The Fort Matanzas station is in the Matanzas River approximately two miles NNW of Fort Matanzas National Monument. The depth at this site is around 3.6m and its tidal variation is 1.4m. The Pellicer Creek site is within the Pellicer Creek Aquatic Preserve at a dock in Faver-Dykes State Park. The creek is buffered by conservation lands and water depth at this station is about 2.3m and varies tidally 0.6m (NOAA 2014). Despite all of the sites being within 30 miles of one another, their water characteristics varied dramatically.

Data Analysis

Data were obtained from the NERRS SWaMP and covered the years 2007-2014. All data flagged as suspect, rejected, missing, or out of sensor range were removed. In addition, any data with quality control codes that indicated the data might be suspect such as biofouling and sensor malfunction were also dismissed. Water quality data were collected every fifteen minutes using YSI 6600 EDS datasondes, which comes out to over 800,000 readings. Nutrient data were collected via grab sample once a month at each location. In addition, diel sampling via an ISCO sampler was conducted monthly at the Pellicer Creek site.

Although not all agencies agree on the exact same figure, for the purposes of this paper, hypoxia was defined as an oxygen content less than 2mg/L. For this reason, a single low reading may not have any effects at all nor paint the most accurate picture. Oxygen concentrations can fluctuate rapidly and these readings were taken at 15-minute intervals. For the purposes of this study, hypoxia was not considered problematic until it had persisted for at least an hour.

RESULTS

Although all sites had some periods of hypoxia, its occurrence and average length of episode varied considerably among the three sites. For instance, Pine Island had the lowest number of recorded hypoxia readings at nine. Fort Matanzas was only slightly more at thirtythree, while Pellicer Creek had a staggering 4,168. In terms of sustained hypoxic conditions lasting more than one hour, Fort Matanzas only had two occurrences, once in 2009 and once in 2014. Pine Island did not have any sustained hypoxia in the whole eight year span.

Pellicer Creek, in contrast, had ongoing hour-plus-long hypoxic episodes over every year compiled, with the most in 2011. Defining these episodes of hypoxia is difficult because frequently the oxygen level would recover for a while before dipping back down. To try to make better sense of this, the number of times the oxygen level dipped below 2mgL^{-1} and stayed below for at least one hour was counted as well as the number of sequential days of hypoxia readings. Figured this way, there were 152 sustained periods of hypoxia. The length of time these lasted ranged from one to twenty-one days, meaning that for twenty-one days there was at least one oxygen reading below 2mgL^{-1}. For fourteen of those days, the hypoxia lasted at least one hour. The longest period of uninterrupted hypoxia was 10 hours.

As can be seen in Table 1, Pellicer Creek was the warmest of the three sites (23.3°C) and had a dramatically lower specific conductance (27.46 mS cm^{-1}), dissolved oxygen (5.5 mg L^{-1}), and pH (7.3) than the other two. Fort Matanzas had the lowest temperature (22.5°C) and turbidity (9 NTU), and the highest specific conductance (52.96 mS cm^{-1}), DO (5.5 mg L^{-1}), and pH (7.3). Pine Island remained between the two in those categories. The data were not normally distributed, so the nonparametric Kruskal-Wallis statistical test was used. Although there were obvious trends, none of the results were statistically significant.

Table 1. Mean water quality readings at each sample site from 2007-2014. Recorded errors are stand deviation.

Site	Temp. °C	Spec. cond. mS cm^{-1}	DO mg L^{-1}	pH	Turbidity NTU
Fort Matanzas	22.5 ± 5.2	52.96 ± 3.12	6.5 ± 1.2	8.0 ± 0.2	9 ± 14
Pellicer Creek	23.3 ± 5.8	27.46 ± 14.34	5.5 ± 1.7	7.3 ± 0.5	12 ± 14
Pine Island	23.0 ± 5.9	45.48 ± 10.06	6.1 ± 1.5	7.6 ± 0.2	12 ± 20

Regarding the nutrient data listed in Table 2, Pellicer Creek did have noticeably higher phosphorus (0.037 mg L^{-1}) and chlorophyll *a* (8.692 μg L^{-1}) than the other two sites (0.015 mg L^{-1} and 4.138 mg L^{-1} for Fort Matanzas and 0.23 mg L^{-1} and 5.681 mg L^{-1} for Pine Island respectively). Pine Island, on the other hand, had higher ammonium (0.054 mg L^{-1}) and nitrate/nitrite readings (0.030 mg L^{-1}) than Fort Matanzas (0.044 mg L^{-1} NH_4 and 0.015 mg L^{-1} NO_2/NO_3) and Pellicer Creek (0.046 mg L^{-1} NH_4 and 0.018 mg L^{-1} NO_2/NO_3). Fort Matanzas was lowest for all parameters. As before, these differences were not statistically significant.

Table 2. Mean nutrient concentrations at each sample site from 2007-2014. Recorded errors are standard deviation. Phosphate, ammonium, and nitrate/nitrite are reported in mgL^{-1} while chlorophyll *a* is reported in μg L^{-1}.

site	PO_4	NH_4	$NO_2 + NO_3$	chlorophyll *a*
Fort Matanzas	0.015 ± 0.007	0.044 ± 0.027	0.015 ± 0.012	4.138 ± 2.802
Pellicer Creek	0.037 ± 0.020	0.046 ± 0.035	0.018 ± 0.019	8.692 ± 6.367
Pine Island	0.023 ± 0.022	0.054 ± 0.043	0.030 ± 0.054	5.681 ± 2.830

For all three sites, the water temperature is notably warmer during periods of hypoxia, which is consistent with observations that hypoxia typically occurs during the summer (Table 3). The more surprising difference was the higher specific conductivity, especially at Pellicer Creek (27.46 mg L^{-1} vs. 34.39 mg L^{-1}). Also of note was the lower pH for Fort Matanzas (8.0 vs. 7.6) and Pine Island (7.6 vs. 7.4), but not much of any change for Pellicer Creek (7.3 vs. 7.2). Even under hypoxic conditions, turbidity is not a very consistent parameter with errors equal to the average at Pellicer Creek and greater than the average at Pine Island.

Table 3. Mean water quality parameters at each site while under hypoxic conditions. Error is standard deviation.

Site	Temp. °C	Spec. cond. mS cm^{-1}	DO Mg L^{-1}	pH	Turbidity NTU
Fort Matanzas	25.6 ± 3.2	55.50 ± 2.39	1.2 ± 0.4	7.6 ± 0.3	8 ± 4
Pellicer Creek	30.1 ± 2.1	34.39 ± 10.36	1.5 ± 0.4	7.2 ± 0.2	16 ± 16
Pine Island	29.8 ± 1.2	47.16 ± 8.67	1.7 ± 0.3	7.4 ± 0.2	18 ± 19

A causative agent could not be found for the hypoxic periods across sites because the timing was inconsistent. There were no sustained periods of hypoxia at Pine Island and the only readings occurred August and September spread across several years (Figure 2). Fort Matanzas, on the other hand, only had readings in May and July of 2009 and 2014.

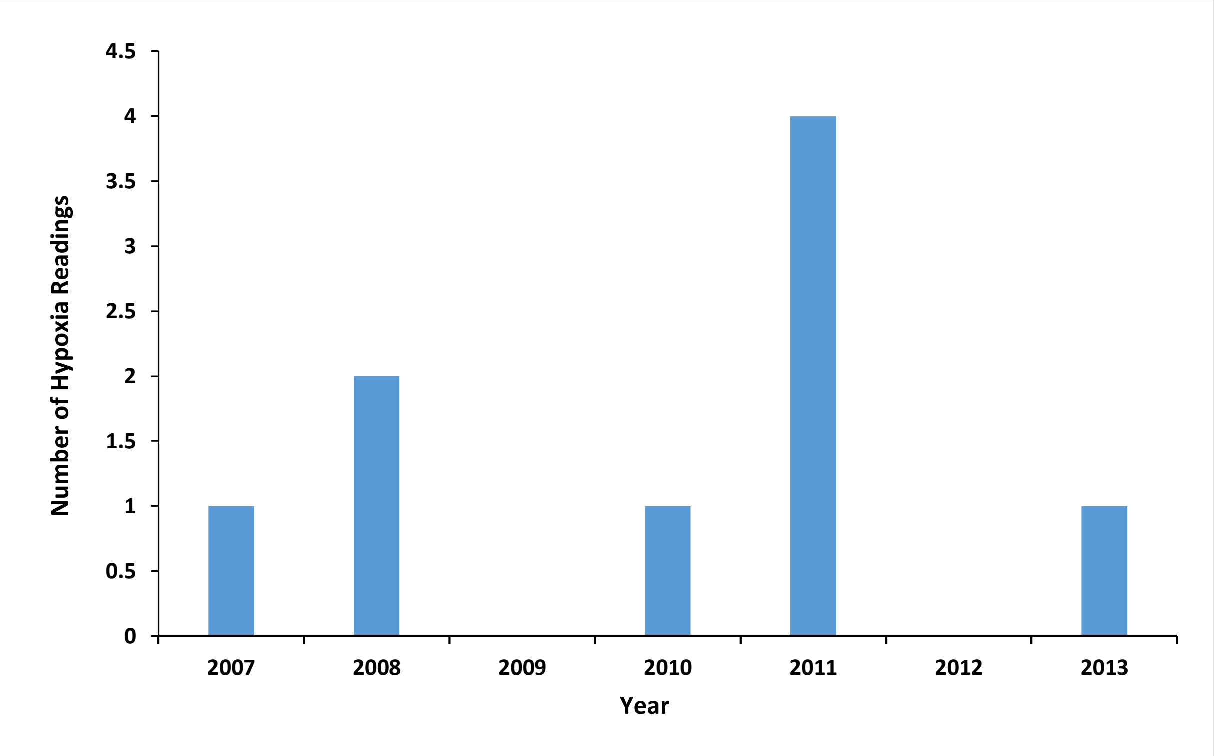


Figure 2. Number of hypoxia readings at Pine Island by year.

Pellicer Creek, in contrast, had ongoing hypoxia problems (Figure 3). Its worst hypoxic period was in 2011, when 43% of oxygen readings less than 2mg L^{-1} occurred. The best year was 2008 with 35 readings and only two instances of hypoxia lasting more than an hour. This does not correspond with any hypoxia problems with the nearby Fort Matanzas. The years

2009 and 2014, which were the only years Fort Matanzas experienced hypoxia, were very mild for Pellicer Creek.

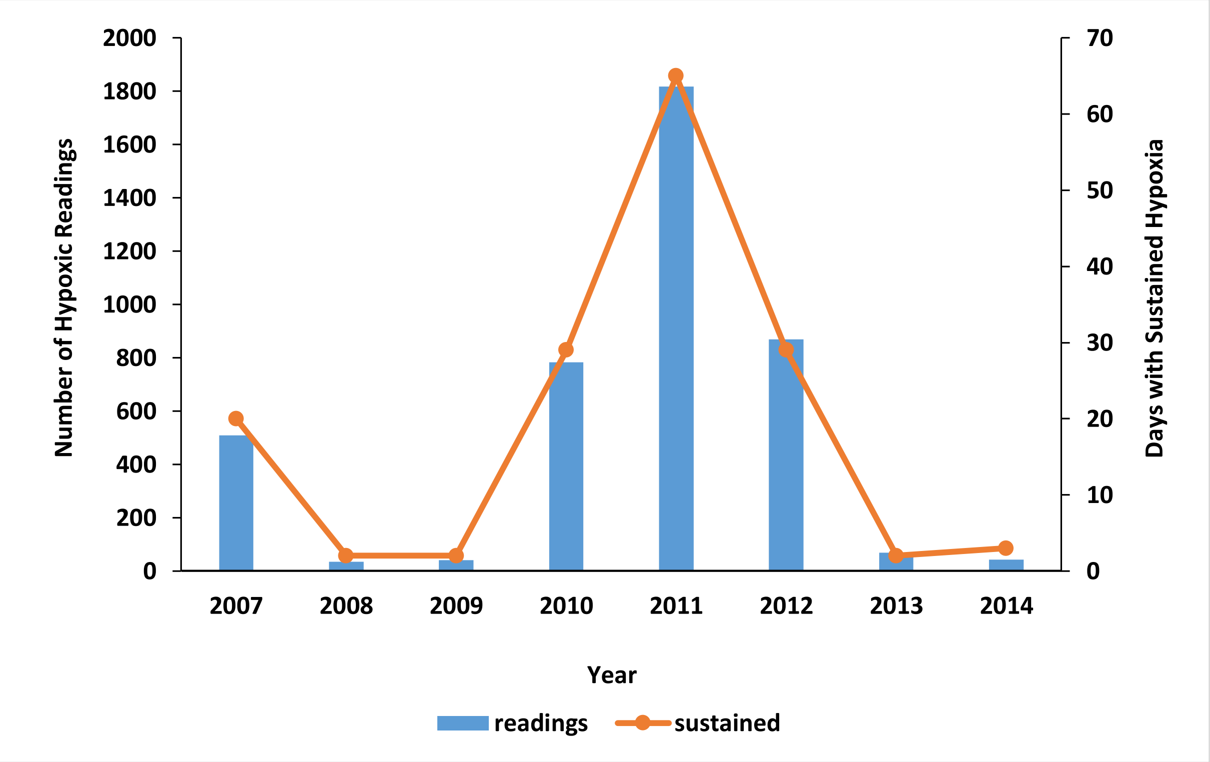


Figure 3. Number of hypoxic readings and days with sustained hypoxia at Pellicer Creek by year.

For Pellicer Creek, low oxygen concentration was most common in July, followed by August and June. The winter months, November through February, had no problems, which is consistent with typical seasonal hypoxia. It is notable that the months October, March, and April, which have cooler water temperatures, still had hypoxic conditions, meaning that temperature, although a major factor, cannot be the only cause.

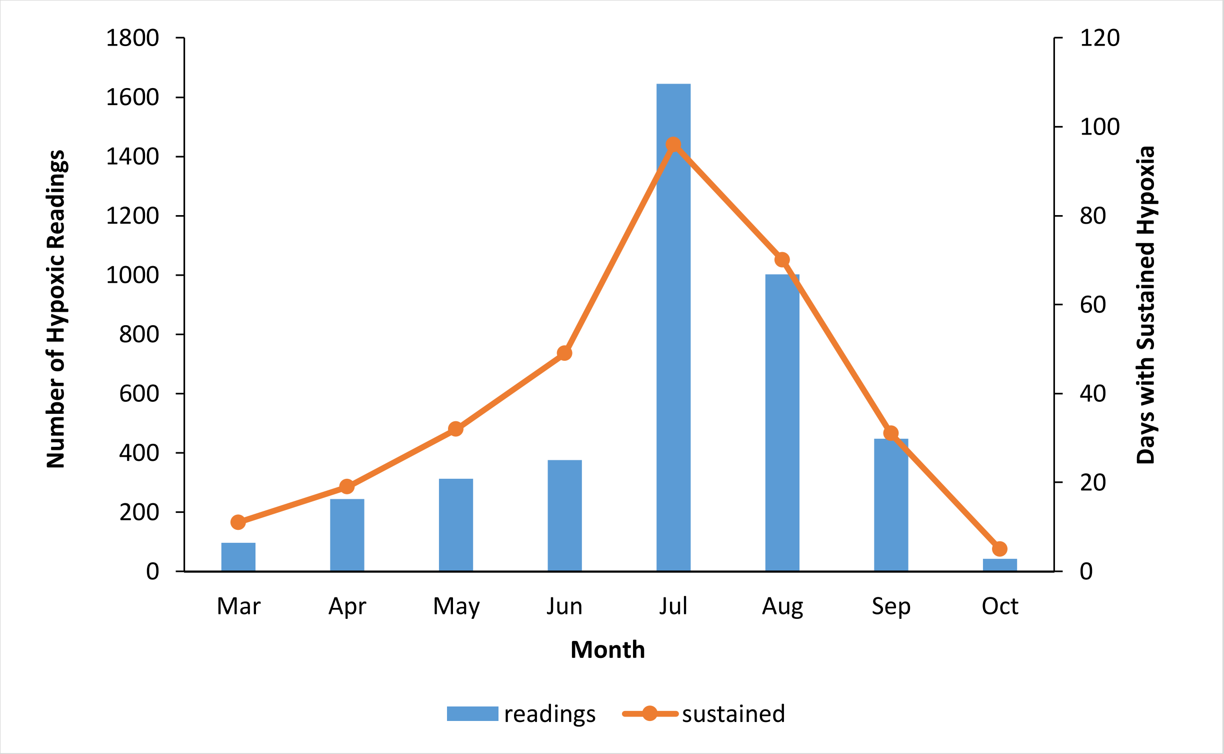


Figure 4. Number of hypoxic readings and days with sustained hypoxia at Pellicer Creek by month.

Typically, oxygen levels decline overnight as photosynthesis shuts down. Since oxygen is no longer being produced but still being consumed through respiration, the concentration declines. At Pellicer Creek, the dissolved oxygen trends did not always follow this pattern. As can be seen in Figure 6, the middle of the day is the most likely time to have low oxygen levels. The majority of hypoxic readings occurred during the day, with 66% from 8:00 to 17:00, despite this only being 42% of the day. The most common time for low oxygen was 11:00, followed closely by 9:00. Water temperatures, on the other hand, do not peak until later in the day, and so cannot be the main cause. Of the times the water temperature reached 33°C, the dissolved oxygen dipped below $2 mgL^{-1}$ only 9.6% of the time. There was even less correlation for the other temperatures and despite the fact the temperature reached 35°C 143 times over the eight years of the study, none of those times resulted in dramatically declined dissolved oxygen concentrations. The most common temperature for low oxygen was actually 30°C (Figure 6). It is possible that at beyond this temperature, the organisms responsible for depleting the oxygen were no longer at their ideal temperature and began to slow their respiration.

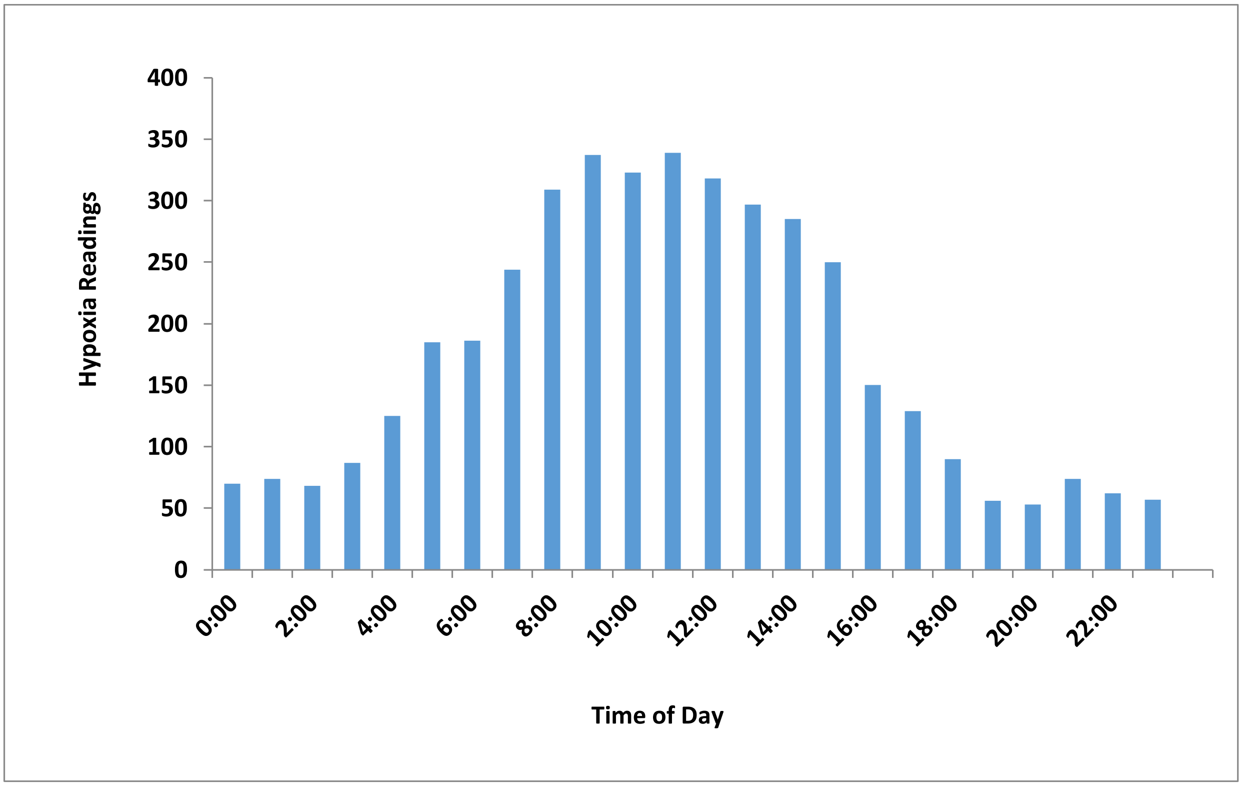


Figure 5. Number of hypoxia readings at Pellicer Creek by time of day.

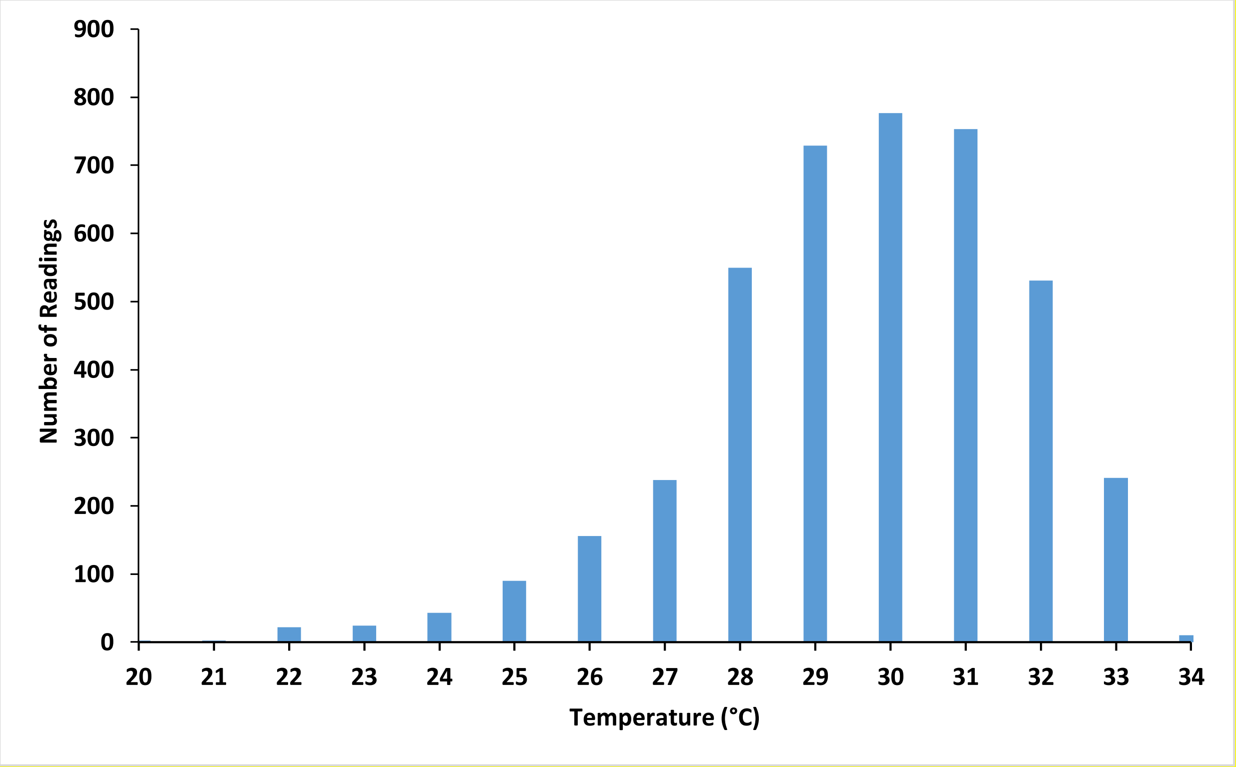


Figure 6. Temperature of water during hypoxic conditions at Pellicer Creek.

As can be expected, temperatures and dissolved oxygen are inversely related (Figure 7). How well the two are linked varies, particularly with time of year. For instance, overall, the r^2 value for the two components is 0.60. In January, $r^2 = 0.55$, but in July, the r^2 is less than 0.001. The relationship seems to fall apart in July most likely because that is when the bulk of the really high temperatures are as well as the really low dissolved oxygen numbers and the two are not always directly linked.

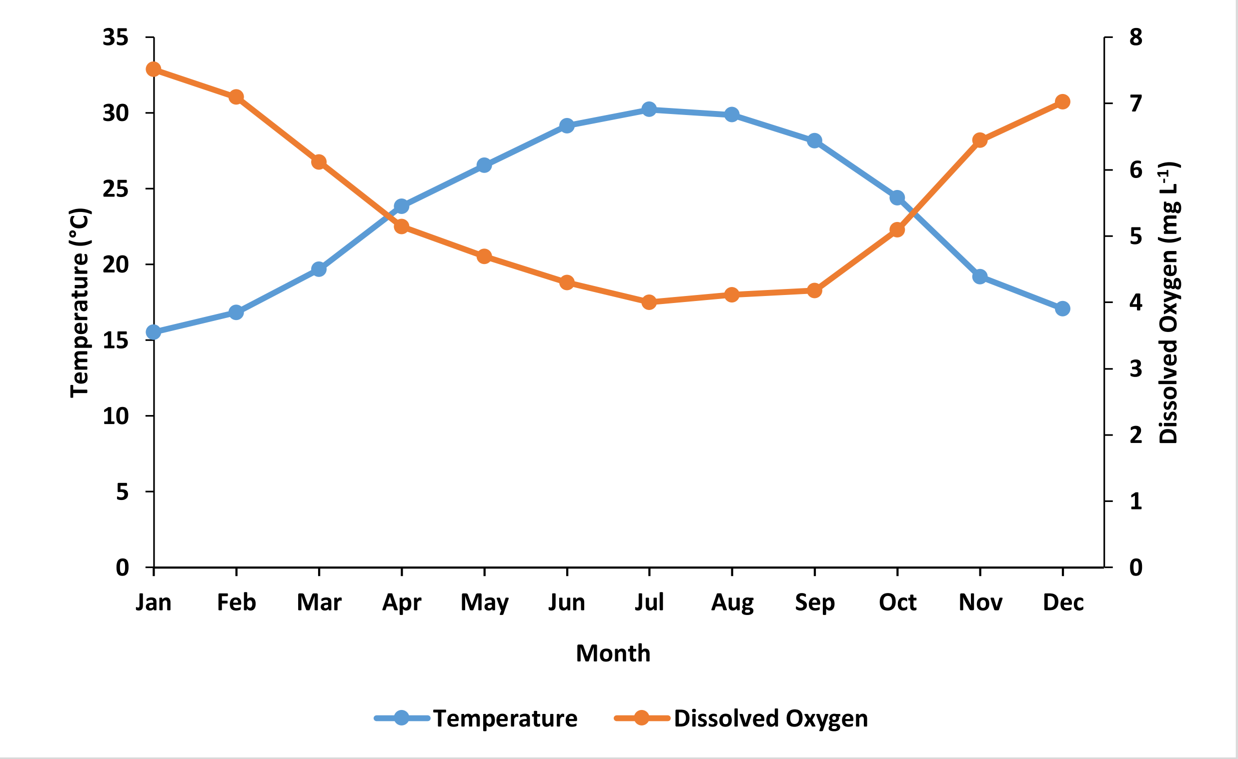


Figure 7. Mean temperature and dissolved oxygen each month at Pellicer Creek.

Diel relationships

Dissolved oxygen shows daily trends as well as seasonal ones. During the winter months, there does not appear to be any strong daily trends other than the dissolved oxygen, which follows the pattern of lowest in the morning and highest in the afternoon (Figure 8). However, when we look during the summer, there are more obvious daily trends (Figure 9). Dissolved oxygen, temperature, and pH all have a tendency to be lowest in the morning and highest in the afternoon. To determine if this was an isolated occurrence, the same comparisons were made for July 2011, the year of the worst hypoxic conditions. The diel trends seemed to be the same, only with the pH and dissolved oxygen shifted down while the temperature was shifted up. It is important to note that while these averages are highly correlated, the results from each individual day are not nearly so. Overall, the r^2 was only 0.20 for temperature and dissolved oxygen.

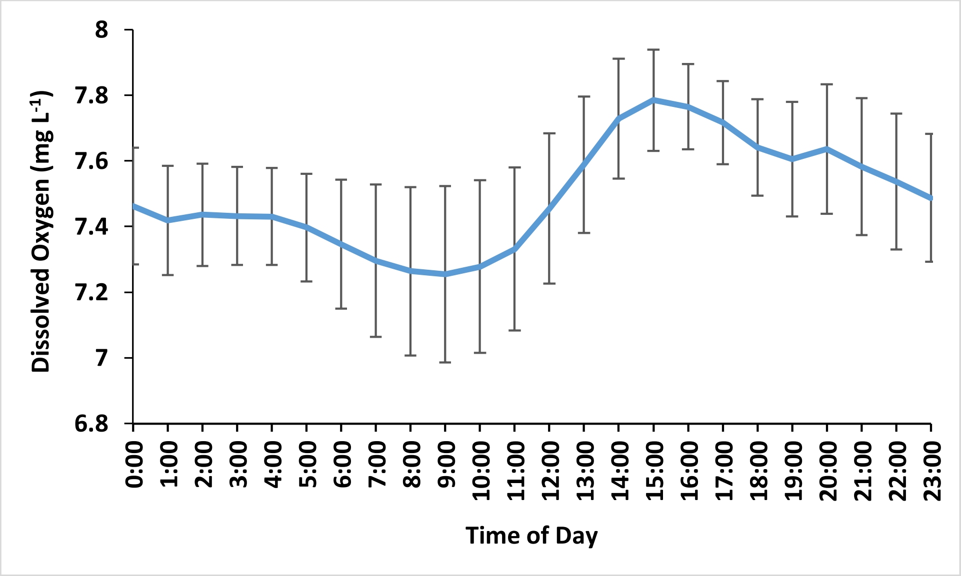
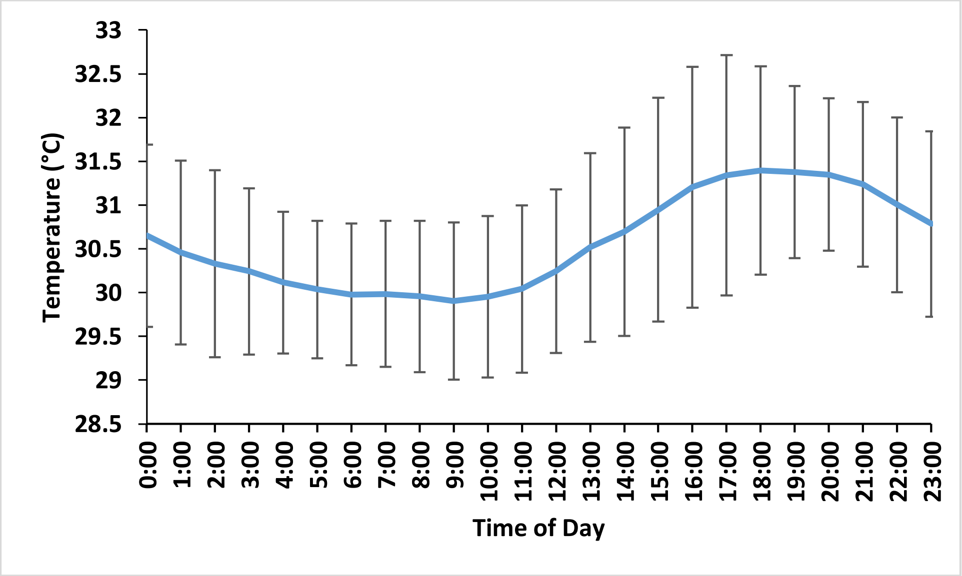


Figure 8. Mean dissolved oxygen over the course of the day during January 2008 at Pellicer Creek. Error bars reflect standard deviation.



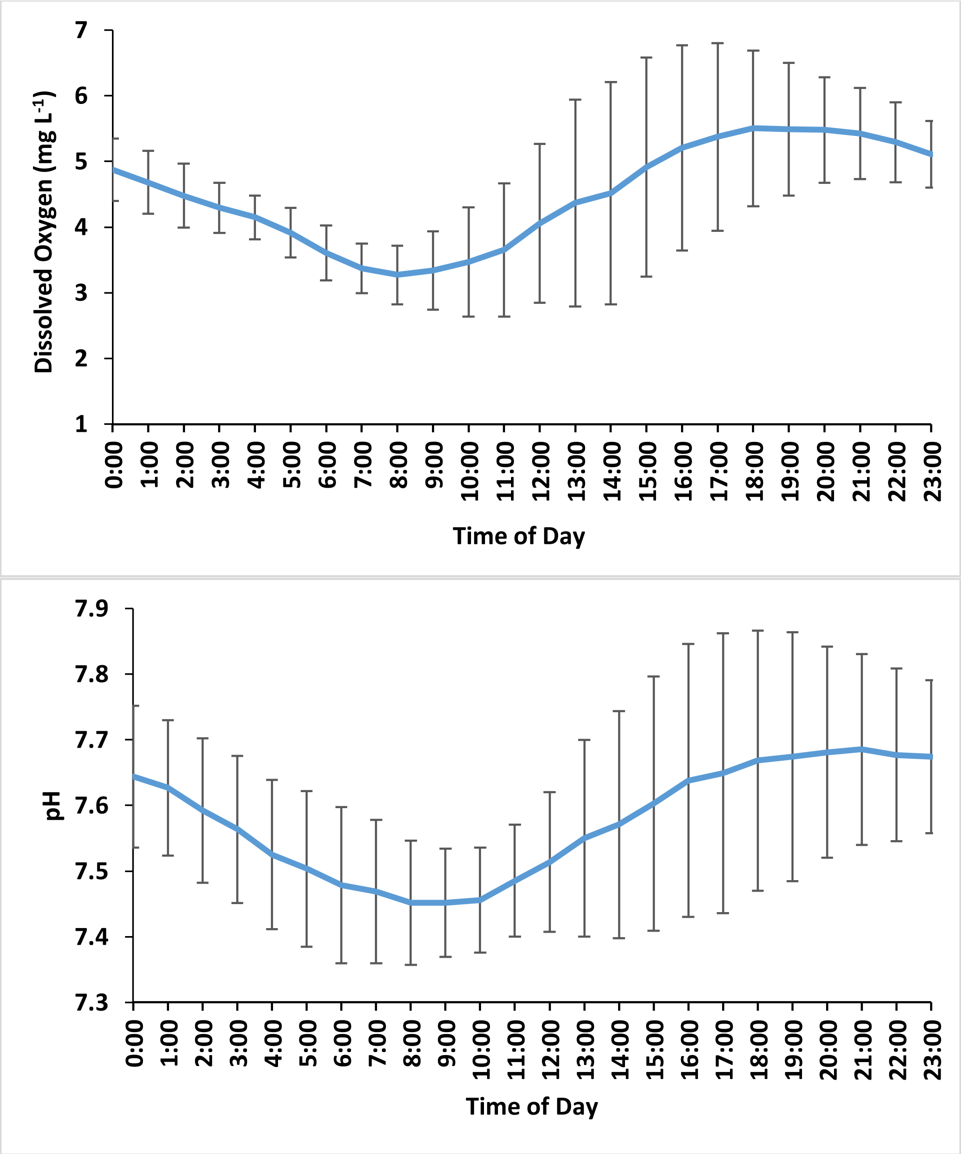


Figure 9. Mean diel temperature, dissolved oxygen, and pH at Pellicer Creek in July 2008. Error bars reflect standard deviation.

DISCUSSION

So why did Pellicer Creek suffer from hypoxia so much more than the other two? First, the largest predictor of dissolved oxygen content of water is temperature. Of the three sites, Pellicer Creek did have warmer average water temperature than Fort Matanzas or Pine Island. This does make sense considering that the Pellicer Creek monitoring site is in shallower water than the others, the samples were taken higher in the water column, and it is less tidally influenced. But the differences in temperature are very small, only about 0.3°C between Pine Island and Pellicer Creek even in the summer.

A second variable of dissolved oxygen is salinity. Salt water is able to hold less oxygen than freshwater, however, this does not seem to be an important factor between sites. The reported data included specific conductance and then salinity was mathematically derived from that number. For this reason, specific conductance is referenced in this paper. Fort Matanzas has a specific conductance twice that of Pellicer Creek, but only very rarely has hypoxia problems. It is also the most stable of the three groups with a standard deviation of 3.12. Pine Island is somewhere between the two, but has a standard deviation more than three times as high. Pellicer Creek had the lowest specific conductance, but had the highest variability. The pH varies among the sites in a similar way to specific conductance, most likely because seawater generally has a higher pH than freshwater.

Once we look at the nutrient data, we see there are other factors that come into play. Average ammonium and nitrate/nitrite are much higher in Pine Island than Pellicer Creek and Fort Matanzas. The proximity of Pellicer Creek to Fort Matanzas partially explains their very similar readings. On the other hand, average phosphorus is around twice as high for Pellicer Creek than Fort Matanzas, with Pine Island somewhere in the middle. In aquatic systems, phosphorus is sometimes the limiting factor, so the higher levels might be contributing to the higher chlorophyll *a* and more common hypoxia.

It is also worth noting that the chlorophyll *a* readings for Pellicer Creek violate the water quality standards set by DEP. On average, chlorophyll *a* should not exceed $4.3 \mu g L^{-1}$ (F.A.C. 62-

302.532), but the average for the study is about twice that at 8.7μg L^{-1}. And this is not just one year or summer throwing off the average. The mean for January is 5.9μgL^{-1}, while the lowest for the entire year is October at 5.2μg/L. So under normal circumstances this creek is above its benchmark. What's more, it is expressed as an AGM or annual geometric mean and shouldn't be exceeded more than once in a three year period (F.A.C. 62-302.532). The law also includes standards for total nitrogen and total phosphorus, however, since the data are in phosphate, ammonium, and nitrate/nitrate, the two cannot be directly compared.

It is difficult to determine exactly what is causing the hypoxia, particularly considering Pellicer Creek is in a refuge and thus should not have a constant influx of chemicals and nutrients washed in like other more urban water bodies. Near the creek, however, are tree farms, which would have some fertilizer application. In addition, several homes are in close proximity, as well as Faver-Dykes State Park. Because the area is so rural, all of these properties are on septic systems that inevitably leach small amounts of nutrients into the creek. Although septic systems are good at removing pathogens, all except the most advanced – and most expensive – retain most of their nutrients in their effluent. Experiments performed at Cape Hatteras National Seashore, also a protected area, lead researchers to believe that the algal blooms, BOD, and hypoxia were the result of excessive nutrients from septic systems (Mallin & McIver 2012).

Fort Matanzas, while also buffered by protected areas on some sides, has US Hwy 1 to the east. However, because of the highway, there is higher density, and nearly all of the properties would be on a sewer system. Sewer lines are by no means a foolproof way to keep waste from the river, but because it is so tidally influenced, much of what leached would be washed out to sea.

Pine Island is on the Tolomato River and wherever the river is not specifically preserved are housing developments. This is probably why the ammonium and nitrate/nitrite levels are highest here. Because of the density of the homes, some are on a city sewer system, while older and larger lots are on septic and certainly many of the homes fertilize their lawns. The other two sites are only slightly above surficial aquifer levels of nitrate/nitrite for this basin (FDEP 2012).

What about 2011 made it such a bad year for low oxygen concentrations at Pellicer Creek? Several factors contributed. First, it was a hot year. From February through September, monthly temperatures were higher than average (Figure 10). Second, specific conductance was higher than average the entire year (Figure 11). Third, the phosphate concentration was higher than average for the months of May through August (Figure 12). At its highest point in July of 2011, phosphorus reached an average of 0.101mg L^{-1}. Such levels would characterize it as highly eutrophic and high levels of algae could be expected (Minnesota Pollution Control Agency 2007). Unsurprisingly, the chlorophyll *a* concentration was higher than normal every month of 2011 except November and December, becoming more than twice the normal in July (Figure 13). The result was a DO that lagged behind normal from January through the rest of the year.

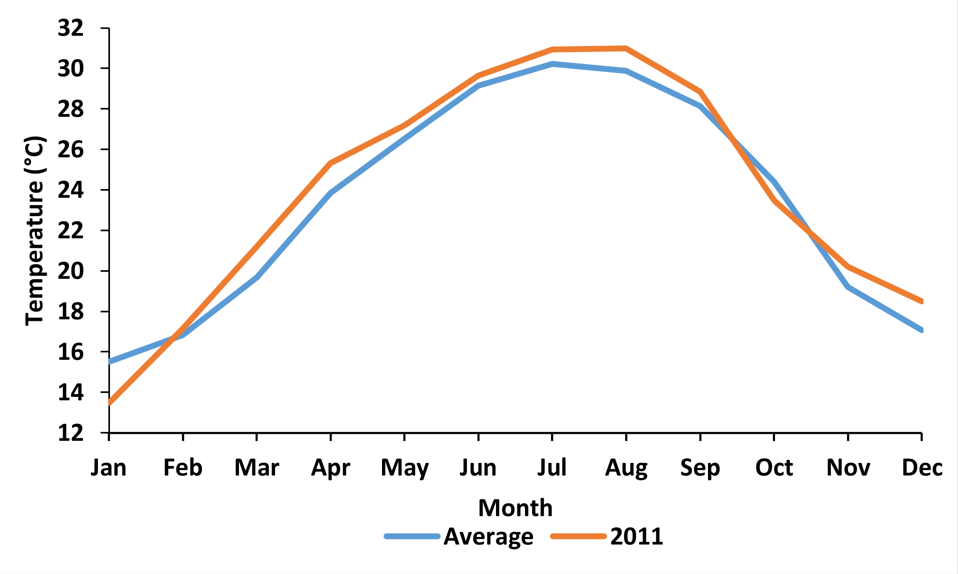


Figure 10. Mean temperature by month in 2011 and on average at Pellicer Creek.

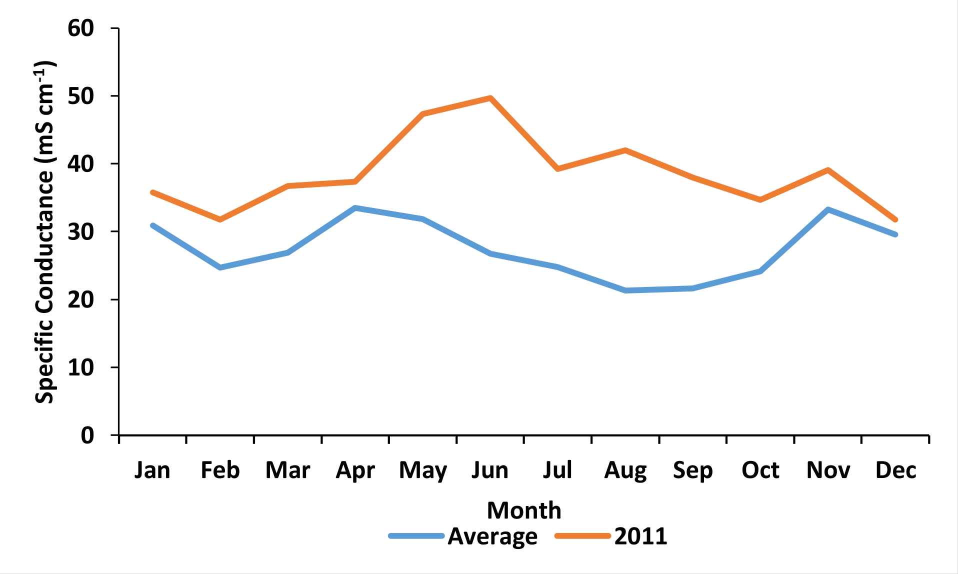


Figure 11. Mean specific conductance by month in 2011 and on average at Pellicer Creek.

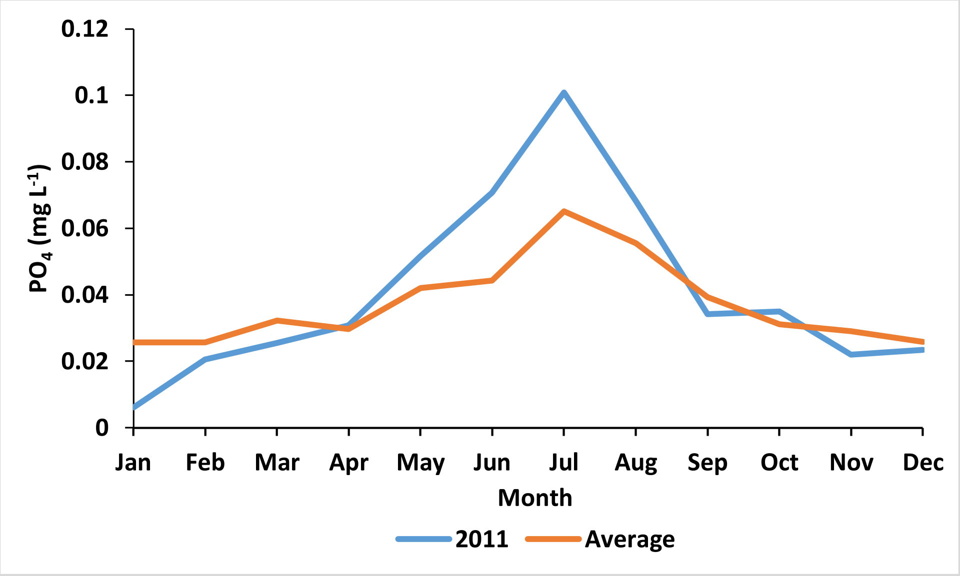


Figure 12. Mean phosphate in each month of 2011 and on average at Pellicer Creek.

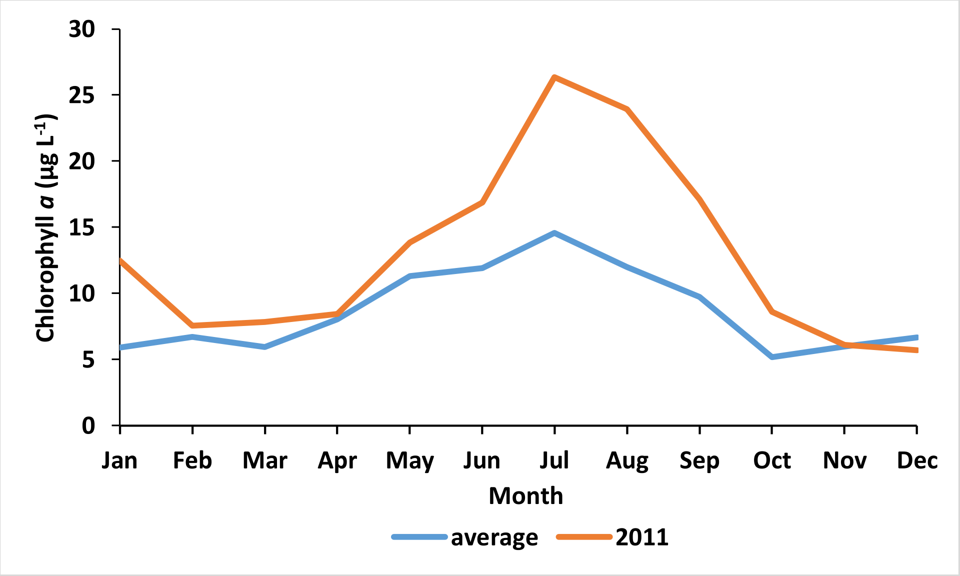


Figure 13. Mean chlorophyll *a* in each month of 2011 and on average at Pellicer Creek.

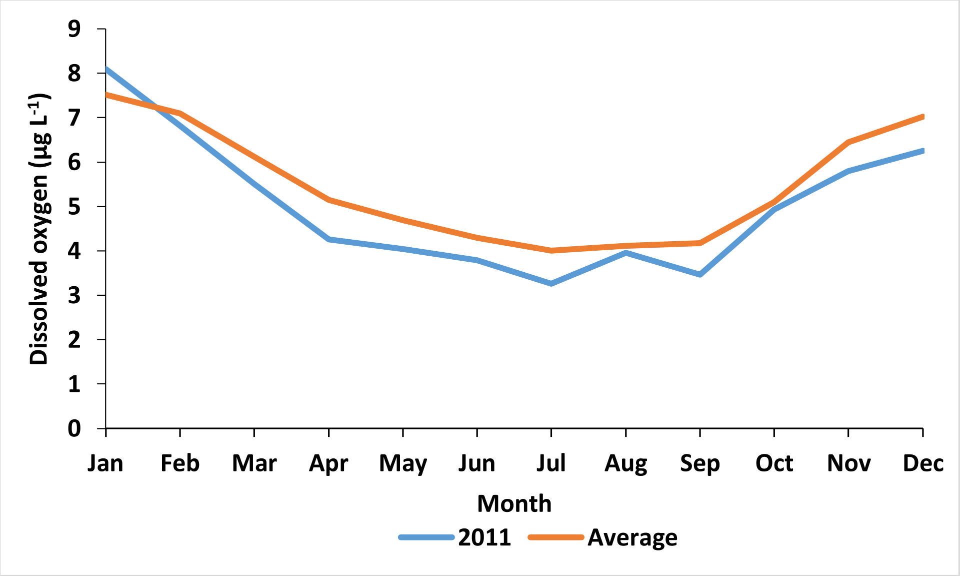


Figure 14. Mean dissolved oxygen by month in 2011 and on average at Pellicer Creek.

Additional studies may help determine the cause and extent of the hypoxia problem in the region. A shorter experiment in which nutrient data is collected more regularly could help us to determine the source of the pollution. An experiment performed near Big Pine Key was able to tie a preceding rainfall event to lower oxygen levels, and higher levels of ammonium, phosphorus, and chlorophyll *a*. This would indicate that the pollution is caused by stormwater (LaPointe & Matzie 1996). The researchers were only able to make those links because of their daily nutrient data compared to our limited, although still useful, monthly data. Future studies could look at other sites to see what might be common or compare water quality data with meteorological data to see if wind or precipitation might have any effects.

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