Assessing *Karenia brevis* on the West Florida Shelf using Remote Sensing and GIS Techniques

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Abstract

Harmful algal blooms (HABs) are a phenomenon that occur on Florida's coast when the dominant algae species overpopulate the area under certain conditions. In recent years, these HAB events have been increasing in frequency and extremity due to multiple factors that are explored in this study. The factors that determine HAB growth are nutrients, temperature, salinity, and flow rate. We focused on the algae species *Karenia brevis* which is commonly known to cause Florida's "red tide." This species is especially harmful because of its mixotrophic nature, size, and toxicity. *K. brevis* HABs on the West Florida Shelf (WFS) are the worst in the entire United States. The goal of this study is to dive into the factors that make WFS prone to so many *K. brevis* HABs for extended periods of time. One of the worst HABs in Florida was in 2005, which is our year of study. Satellite data from Aqua MODIS was analyzed to determine the area of the HAB, nutrient and river discharge rate data was used to show one way *K. brevis* gets nutrients, and ArcGIS Pro was used to plot nutrient pollution hot spots. Other sources such as multiple NOAA and U.S. military sites were used to look at the temperature, salinity, and flow rate. Our remote sensing results lined up spatially and temporally with the *in-situ* data and the percent frequency data is similar to other *K. brevis* bloom studies for 2005. Mapped point and non-point sources showed that the nutrient pollution hotspots are the streams flowing into and out of Lake Okeechobee along with the Tampa area. The intense hurricane season increased the precipitation which then led to more runoff and nutrient pollution in the ocean. A large, long-lasting HAB peak followed shortly after the hurricane season. By analyzing the other factors that influence HAB growth, we found that they are within the optimal range for *K. brevis* the majority of the year.

Introduction

Harmful Algal Blooms (HABs) occur when the dominant algae species grow out of control due to a list of factors. They are classified as harmful when they cause issues in the ecosystem and/or health conditions in humans. *Karenia brevis* is the dominant marine HAB species in Florida and it is known for causing the famous "Florida red tide" due to its red/brown color (Kirkpatrick et al., 2004). *K. brevis* HABs can cause the dissolved oxygen to decrease to anoxic levels when the blooms are at their worst. This process is called eutrophication. When the large amounts of HABs eventually die and sink below the pycnocline the heterotrophic bacteria in that area decompose the algae. Since these bacteria are heterotrophic, they use respiration which uses oxygen. The more HABs that grow, die, and sink the more organic material the heterotrophic bacteria need to decompose, which in turn uses more oxygen. This can cause hypoxic or anoxic conditions depending on the severity of the HAB. This process of eutrophication causes large-scale fish kills every year that they bloom, suffocating anything in the water that requires oxygen.

K. brevis also produces a toxin called brevetoxin which is a red toxin that causes multiple illnesses in marine organisms, and respiratory illness and Neurotoxic Shellfish Poisoning (NSP) in humans (Kirkpatrick et al., 2004). Since *K. brevis* is not protected by any kind of physical armor, it can easily burst in turbulent waters, releasing all of its brevetoxins at once. This can cause the level of brevetoxins to be extremely high where it can become airborne and cause respiratory illness for Florida residents. Shellfish like oysters, clams, and mussels are filter feeders that filter out the toxins in the water which accumulate in their bodies. When there are high levels of brevetoxins during a bloom, the shellfish in the area become toxic and can cause NSP if consumed (Kirkpatrick et al., 2004). Brevetoxins also cause illnesses in marine organisms on top of the low oxygen levels from eutrophication. These two factors can endanger important species like the Florida manatee and affect the aquaculture industry (Martin et al., 2017).

K. brevis is a mixotrophic dinoflagellate that blooms in the late summer and fall every year off the coasts of Florida. These blooms can last for months to years with the longest two ever recorded lasting 30 months (1994-1997) and 31 months (2001-2004) (Stumpf et al., 2022). *K. brevis* has a few advantages over the other algae species in the area, including its mobility and where/how it gets its nutrients.

One of these advantages is that it is a dinoflagellate that performs diel vertical migration (DVM) to maximize its influx of nutrients and sunlight. DVM is the process commonly seen in many species of dinoflagellates. Dinoflagellates specifically will stay at the surface during the day to be in the sunlight, then migrate deeper into the water column during the nighttime to consume nutrients that are at greater depths (Shaeffer et al., 2009). Some smaller, non-motile phytoplankton are not able to perform DVM, so they are restricted to the flow and movement of water within the water column to carry them to nutrients. If the water column is stratified and there is a strong pycnocline then those non-motile phytoplankton will not be able to reach the nutrient-dense water below the pycnocline. Warmer air and surface temperatures cause a more stratified ocean which strengthens the thermocline and therefore strengthens the pycnocline. Florida has a humid subtropical climate so the state experiences warm to hot temperatures year-round. This also causes the surface ocean temperature to be high, meaning that the ocean around Florida is usually stratified when no large mixing event, like a hurricane or tropical storm, occurs. The ability to perform DVM gives dinoflagellates, like *K. brevis*, the upper hand compared to other non-motile phytoplankton in the Florida area.

Another advantage is that *K. brevis* is a mixotrophic protist meaning that it is able to gain energy from multiple sources, including autotrophy and phagotrophy (Ok et al., 2023). *K. brevis* is naturally autotrophic, utilizing the sun to make energy, which is one form of energy uptake. An extra source of energy comes from the cyanobacterium *Synechococcus* which it consumes through phagotrophy (Glibert et al. 2009). This study provides evidence that the consumption of *Synechococcus* improves the growth rate of *K. brevis* in low nitrogen waters. *K. brevis* has the ability to adapt to consume the necessary nutrients in many different forms depending on the availability (Vargo, 2008). Two other common forms of nutrients that *K. brevis* utilizes are dissolved organic nitrogen (DON) from the cyanobacterium *Trichodesmium* blooms and urea from fertilizers (Burkholder et al., 2008). *Trichodesmium* bloom in the same area of the Gulf of Mexico that *K. brevis* does, when they bloom, they take in atmospheric nitrogen and regenerate it into ammonium and release it making to easier for other organisms, like *K. brevis*, to use for their nutrient needs (Mulholland et al., 2004). Urea is derived from ammonia and is a form of nitrogen that is commonly used in fertilizers. The use of urea has been increasing over the past few decades and supplies nutrients to HABs (Glibert et al., 2006). Since *K. brevis* has the ability to adapt to many different forms of nutrient uptake it gives it another advantage against competition in the same area who can only use one or two kinds of nutrient uptake.

In the past few decades, efforts have been made to detect *K. brevis* blooms using satellites and remote sensing. Many algorithms have been created to detect *K. brevis* as accurately as possible in comparison with *in-situ* measurements. Some algorithms are better depending on the season and location of the HABs. Accurate detection and analysis of HABs is important for monitoring their severity, which impacts both the human population and the ecosystems in Florida. One of the satellites used for this detection is NASA's Aqua which contains a Moderate

Resolution Imaging Spectroradiometer (MODIS) instrument. MODIS collects 36 spectral bands from 0.4-14.4 μm, two of which are Rrs555 (remote sensing reflectance band 555) and nFLH (normalized fluorescence line height) that are key to the algorithm used in this study (NASA, n.d.). Rrs555 is the remote sensing reflectance at 555 nm which is in the red part of the spectra. nFLH is the normalized fluorescence line height which is derived using MODIS bands 13-15 also in the red part of the spectra. One of the most accurate and successful algorithms tested by Soto et al. (2015a) subtracts the nFLH band from the Rrs555 band within a certain range.

In this study, we use satellite data from Aqua MODIS to apply the algorithm and use unsupervised classification to produce HAB maps of Florida in 2005. The HAB area is quantified by finding the percent frequency of the HAB area in the classified images. *In-situ* hydrology data is co-related to the percent frequency results from the satellite data. The frequency and path of hurricanes around and within the Gulf of Mexico are also used to analyze precipitation and mixing of coastal waters. Finally, we use ArcGIS tools to display *in-situ* HAB and nutrient data to relate the two spatially and temporally.

Methodology

MODIS Aqua 8-day average images of Florida for nFLH and Rrs555 for the year 2005 were downloaded from oceancolor.gsfc.nasa.gov/. They were downloaded mapped in 4 km resolution from the Level 3 and 4 data browsers. Level 4 data is data from the satellite that has had the greatest amount of processing and corrections made to it. This makes Level 4 products highly accurate. Since these images are Level 4 products, they have corrections like cloud cover already made to them, so no further corrections were necessary. The algorithm used to analyze these images is as follows:

$$\mathrm{Rrs555} - \mathrm{nFLH}$$

Where Rrs555 < 0.007 sr^{-1} and nFLH > 0.033 mW $\mathrm{cm}^{-2}\mu\mathrm{m}^{-1}\mathrm{sr}^{-1}$ (Soto et al., 2015)

This algorithm was developed by El-Habashi, Ioannou, Tomlinson, Stumpf, and Ahmed and further tested by them (El-Habashi et al., 2016). These criteria are implemented because they were found to have the highest F-measure, which is a statistical measure of predictive performance, when tested by Soto et al. (2015). The images were processed using SeaDAS software. First both the Rrs555 and nFLH were collocated together then the algorithm was performed using the Band Math tool. When using Band Math, it is important to deselect the box that only saves the expression, not the data. The spatial dimensions of this study are -84.2 W, 30 N, -79.5 E, and 24 S which was narrowed down from the world map by using the Specify Product Subset tool. To calculate the percent frequency taken up by the HAB, K-Means Cluster Analysis Unsupervised Classification is used. The classes that contain the HAB are changed to white while all of the other classes are changed to a light grey color. Both the image with the algorithm implemented and the classification are exported by right-clicking on the image in view and selecting Export View as Image.

The data set "Historic Harmful Algal Bloom Events 2000-2006" was downloaded from ArcGIS Online in Catalog from Florida Fish and Wildlife Conservation Commission. Since *Karenia brevis* blooms are considered to be harmful in concentrations of 1,000 cells/liter or more. A selection was made to select for all of the points greater than 1,000 cells/liter in 2005. Major river data, named lakes data, and nutrient sampling locations were input into the map. The nutrient sampling data was collected using the Water Quality Data Portal on the National Water Quality Monitoring Council site. The data query tool was used to find all of the nutrient data for streams and the ocean in the state of Florida during the year 2005. The monitoring site stations table was joined to the sample results table. According to the Environmental Protection Agency (EPA), the amount of nitrogen in the water that is polluting is 3 mg/L or above. The amount of phosphorous that is polluting is 1 mg/L. Two separate maps were created to make both a nitrogen and phosphorous map showing the sampling points that were above the pollution threshold. A heat map of all of the sampling stations with the densest region being the most polluted was created for both nitrogen and phosphorus separately. A frequency and statistics calculation were done to determine how many times a sampling location had a value over the pollution threshold in 2005 for both nitrogen and phosphorous combined. Another map was created using HAB data for 2005, major river data, and point and non-point source nutrient pollution data. The non-point sources were golf courses over 100 acres and the point sources were active wastewater treatment facilities.

In order to show the relationship between river discharge rate and nutrient pollution in 2005, both sets of data were collected and plotted together. The river discharge rate for the Caloosahatchee River at station S79 was collected from the U.S. Geological Survey. The nutrient pollution data was collected at station PI-14 in the form of Nitrate + Nitrite from the Coastal and Heartland National Estuary Partnership within the University of South Florida Water Institute. These data sets were plotted together on a combo graph in Microsoft Excel to show their relationship.

Results

Remote Sensing Detection

Percent frequency is the percent of pixels within the specified area of the image that represent a feature. In this case percent frequency is used as a proxy for total HAB area in the specified dimensions of the image. The spatial and temporal satellite data matches up with the *in-situ K. brevis* data collected from the Florida Fish and Wildlife Conservation Commission shown in Figures 5-10. One of the 8-day average images is shown in Figure 1, this image shows a large bloom on the WFS in the same areas as the *in-situ* data does. The percent frequency graph in Figure 2 also matches up with the *in-situ* data, the peak HAB area was in the months of August to October for both. This was determined by looking at the attribute table for the cells/liter count and date of the *in-situ* sampling data and comparing it to Figure 2.

The percent frequency of the final image in Figure 1 is calculated after the classification by adding together the percent area of the classes containing the HAB. This was done for each image and plotted in Figure 2, which highlights the peak of HAB area from August to October. Our Figure 2 graph lines up with other *K. brevis* bloom studies for 2005. For example, Figure 2 in Stumpf et al. (2022) shows the bloom severity index over many years including 2005. The peaks and dips of their graph match the one in this study. June-November is the typical hurricane season; in 2005 there was a record-breaking number of hurricanes, along with many tropical storms. Many of these extreme weather events passed over Florida and the Gulf of Mexico as shown in Figure 3. Outside of the hurricane season, 2005 did not receive above the normal amount of precipitation, but during the hurricane season, it received an extremely high amount of precipitation. This increase in precipitation also increased the runoff and discharge rate out of streams, which flowed into the ocean. This sudden influx of nutrients fueled the HABs to grow out of control about halfway through the hurricane season (Hu et al., 2006). High winds can also increase HABs through physical damage to the ecosystems which stirs up nutrients from other sources and introduces them into the water column (Phlips et al., 2020).

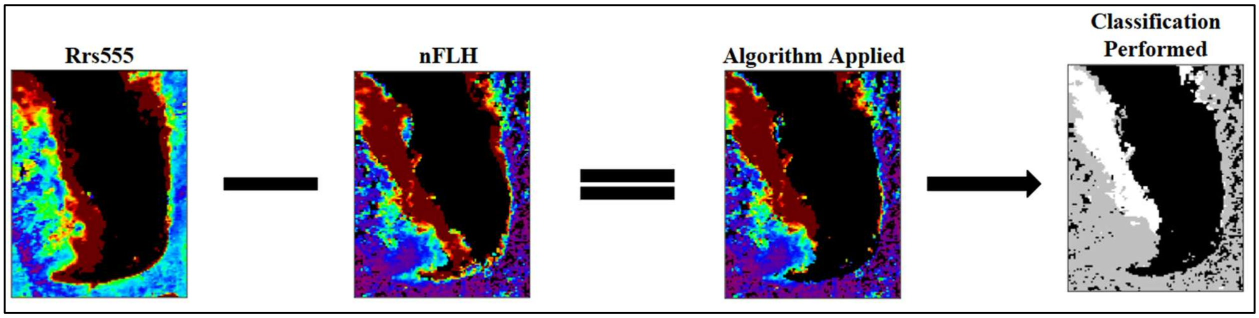

Figure 1. Visual representation of the algorithm and classification used in this study. The nFLH band greater than 0.033 mW $cm^{-2}\mu m^{-1}sr^{-1}$ is subtracted from the Rrs555 band less than 0.007 sr^{-1}. K-Means Cluster Analysis Unsupervised Classification is then used to make the final image. The white in the classified image shows the area of the HAB.

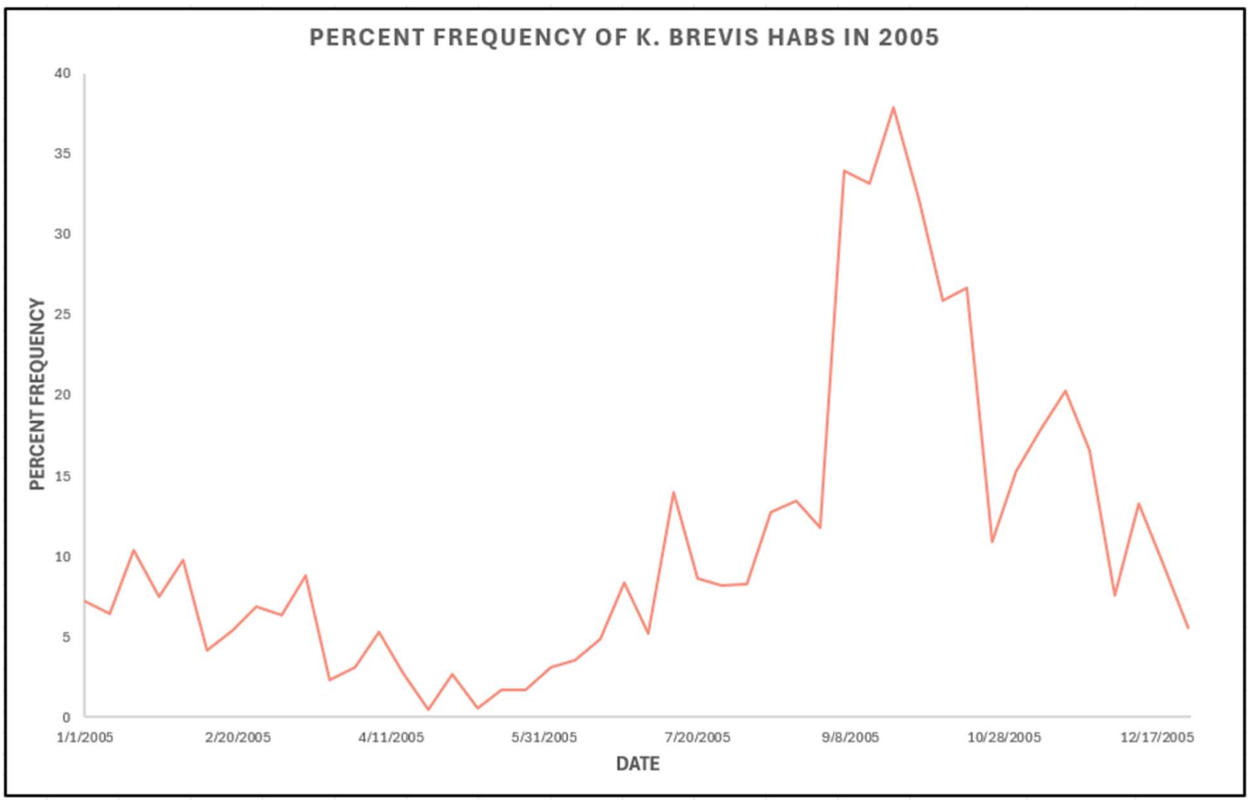

Figure 2. Percent frequency of the *Karenia brevis* blooms calculated using K-Means Cluster Analysis Unsupervised Classification on the applied algorithm images created in SeaDAS.

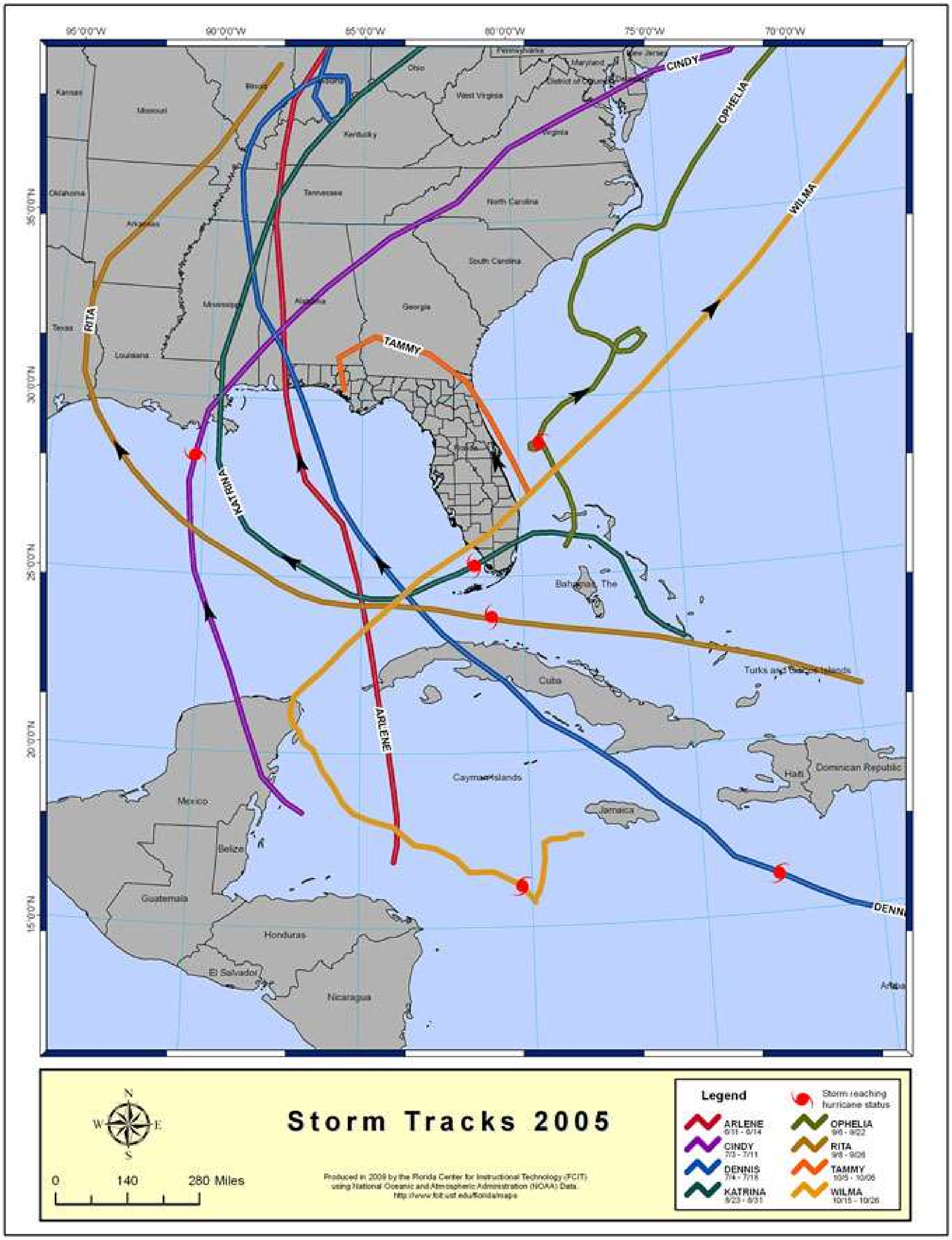

Figure 3. The 2005 hurricane season showing the tropical storm and hurricane paths through the Gulf of Mexico (Florida Center for Instructional Technology, n.d).

<u>Nutrients</u>

Nutrient pollution from nitrogen and phosphorous contributes greatly to HAB growth and maintenance. Typically, phytoplankton prefer a certain ratio of nutrients called the Redfield Ratio which is 106 carbon:16 nitrogen:1 phosphorous. However, *K. brevis* can actually thrive with a non-Redfield ratio of nutrients because it has many ways to take in nutrients due to its mixotrophy (Glibert and Burford, 2017). These nutrients can come from sources such as fertilizers that are used on farms, lawns, and golf courses; and also, from raw sewage and treated sewage released from wastewater treatment facilities (Howarth et al, 2002). When it rains, the nutrients run off into streams, lakes, and eventually into the ocean. There are other ways nutrient pollution can reach the ocean and fuel HABs such as submarine groundwater discharge (Hu et al., 2006). Submarine groundwater discharge, shown in Figure 4, is the process of groundwater flowing from land into the ocean, estuaries, or other coastal waters. It flows through sediments and rock formations beneath the seabed. Some of this water includes recirculated seawater and freshwater from land (Burnett et al., 2006). Submarine groundwater discharge is not the dominant source of nutrients, but Smith and Swarzenski (2012) suggest that it still plays a vital role in HAB formation.

Figure 5 is a map of two common point and non-point sources of nutrient pollution: golf courses and wastewater treatment facilities. These locations are congregated along the coasts and in central Florida. Figures 6 and 7 show the densest areas of nutrient sampling locations with a heat map. It is important to note that these maps are only showing the densest areas of sampling, there are more locations not shown because of the symbology. The sampling hotspots are rivers flowing into and out of Lake Okeechobee, including the Caloosahatchee River. Along with a hotspot near the Tampa area. Figures 8 and 9 are graduated color maps showing the sampling locations for nitrogen and phosphorous that are above the respective pollution thresholds. The pollution threshold for nitrogen is 3 mg/L and 1 mg/L for phosphorous according to the EPA. Figure 10 is a frequency map showing the number of samples taken at a sampling location that are above the pollution threshold. These figures show that the main hotspot locations of nutrient pollution are around Lake Okeechobee and in the Tampa area. Precipitation and runoff carries these nutrients out to the ocean where they are used by *K. brevis*.

The testing station locations for the nitrite + nitrite concentration and river discharge rate are shown in Figure 11. Uhlenbrock (2009) found that these station locations are the most ideal for showing the relationship between the two datasets. Figure 12 displays the nitrate + nitrite concentration and river discharge rate together over 2005. These two data sets are highly correlated. The increased precipitation of the hurricane season caused higher runoff which in turn increased river discharge rate. These factors contributed heavily to increased nutrient concentrations further downstream. This large influx of nutrients over three months then caused a peak in HAB area shortly after, shown in the graph in Figure 13. When the nitrite + nitrite concentration started to increase from the precipitation, *K. brevis* started to slowly bloom as well. It peaked in the late summer and early fall as it usually does, but the intensity of the bloom was influenced by the increased nutrient flow. Another way to show this relationship is by calculating mass loading which is the nutrient concentration (mg/m^3) multiplied by the river discharge rate (m^3/day) to get the final units of mg/day (Smith, 2021). Mass loading was calculated and plotted with the *K. brevis* percent frequency data in Figure 14. Similar to Figure 13, the peak of mass loading is between May to September due to the increase in precipitation.

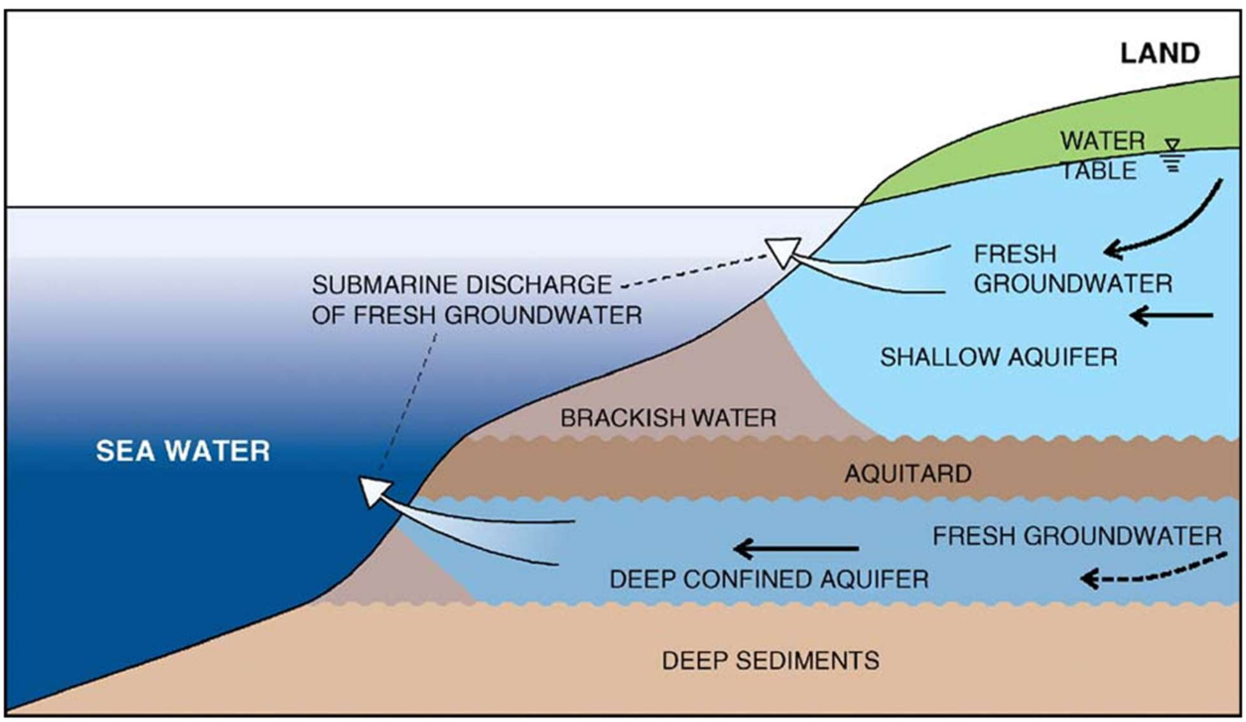

Figure 4. Submarine groundwater discharge diagram showing how the different sources flow into the ocean (Burnett et al., 2006).

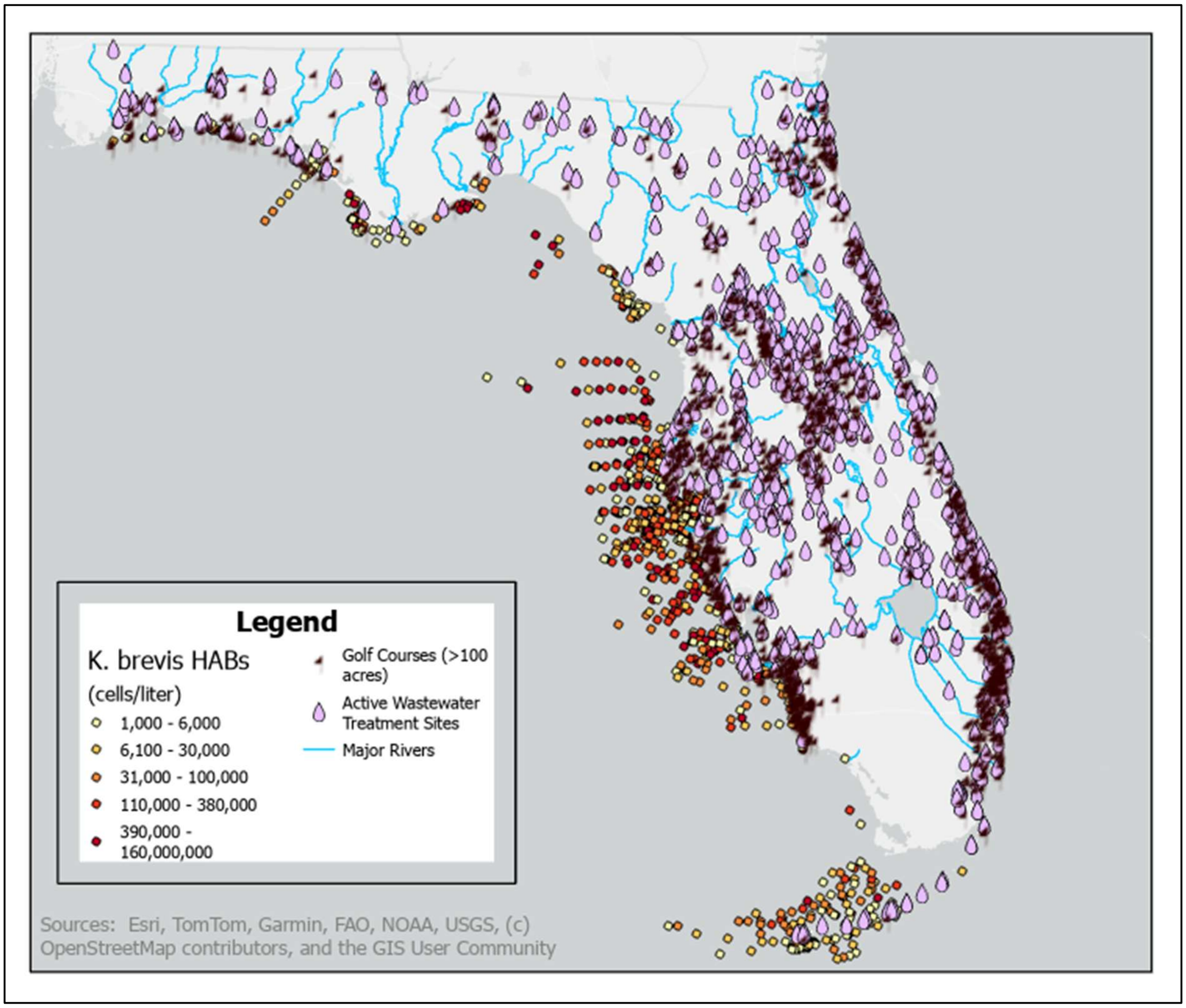

Figure 5. Map of point and non-point source pollution including golf courses greater than 100 acres and active wastewater treatment facilities. The *in-situ* data for *K. brevis* blooms in 2005 is also shown. Both pollution layers were filtered to only show locations in 2005 or before.

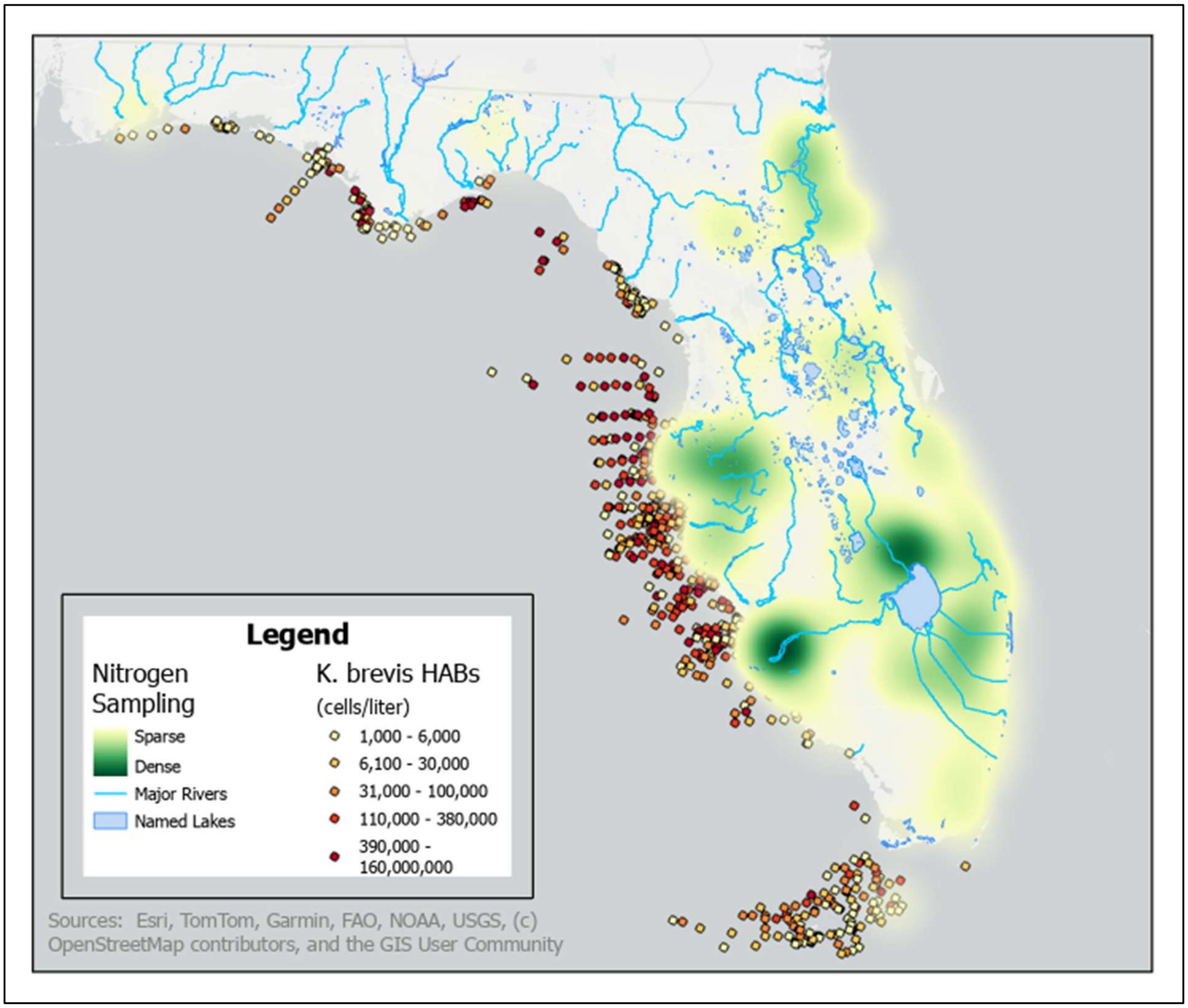

Figure 6. A heat map showing the location and density of nitrogen sampling sites in Florida in 2005. A darker green color is where there is a higher density of sampling sites. This is not related to the amount of pollution at these sites, only the location and density. Hydrology and *K. brevis* blooms in 2005 are shown as well.

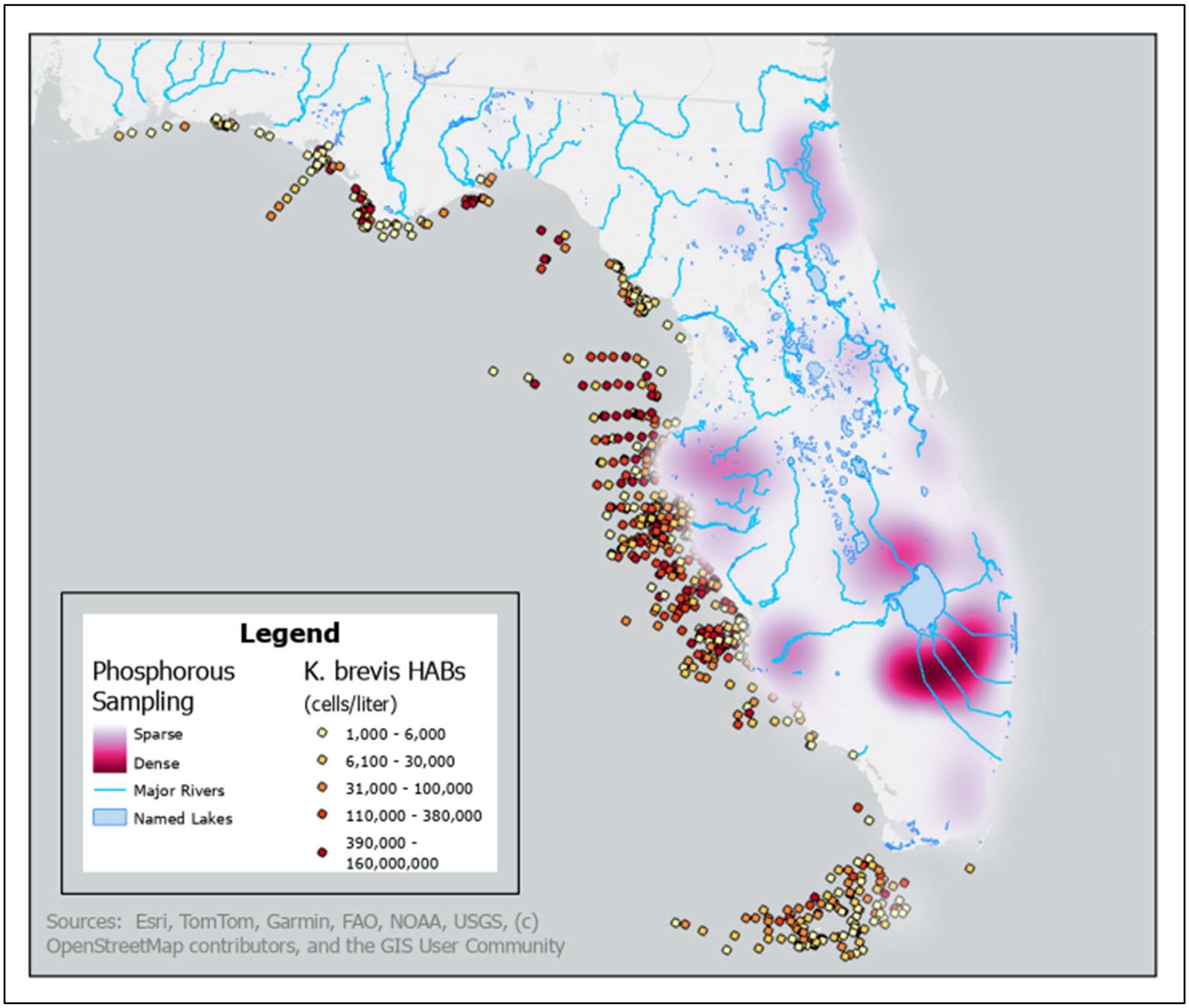

Figure 7. A heat map showing the location and density of phosphorous sampling sites in Florida in 2005. A darker pink color is where there is a higher density of sampling sites. This is not related to the amount of pollution at these sites, only the location and density. Hydrology and *K. brevis* blooms in 2005 are shown as well.

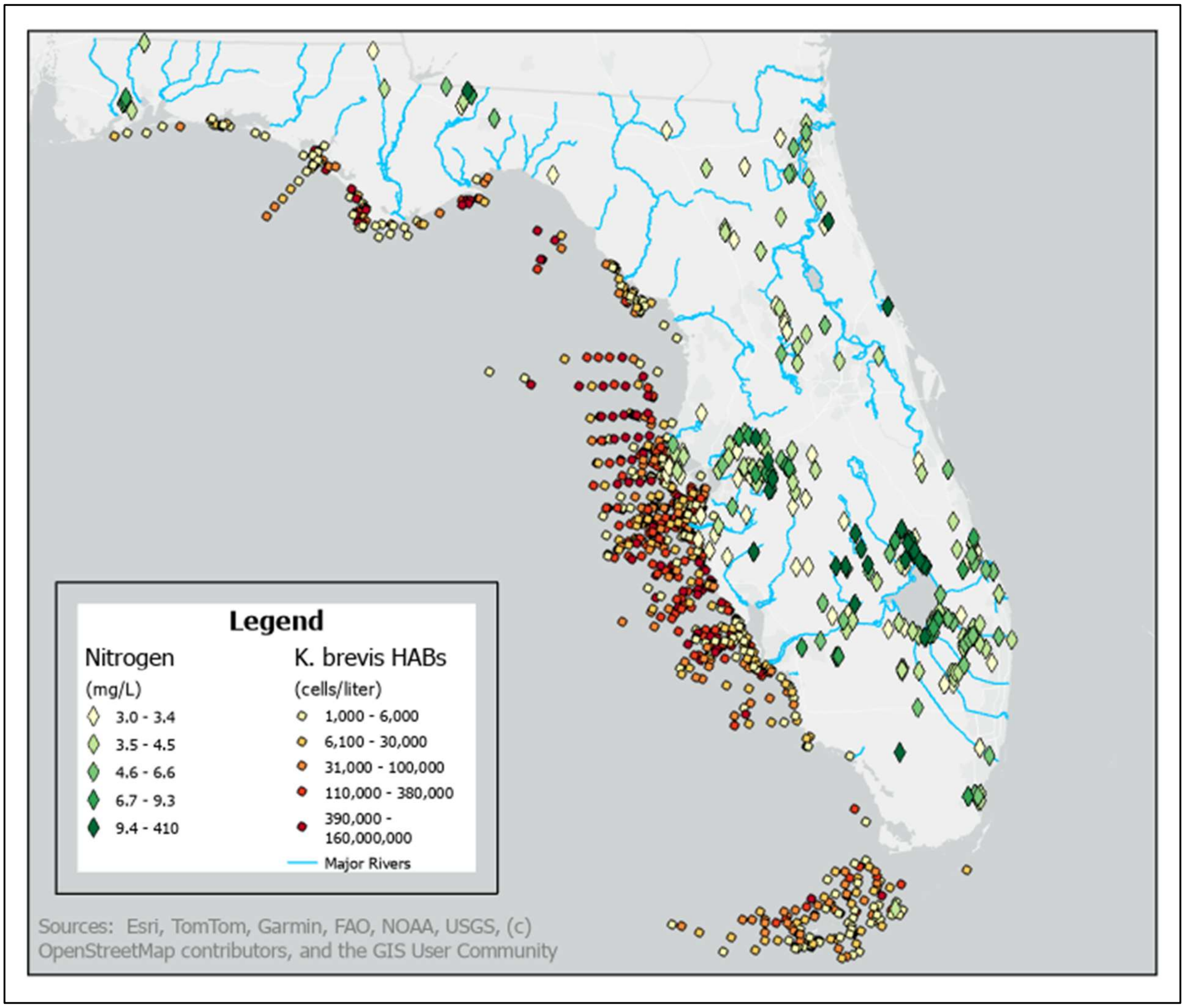

Figure 8. A map of nitrogen sampling sites where the value of nitrogen is greater than 3.0 mg/L. Any site over 3.0 mg/L is considered over the pollution threshold, according to the EPA guidelines. Hydrology and *K. brevis* blooms in 2005 are shown as well.

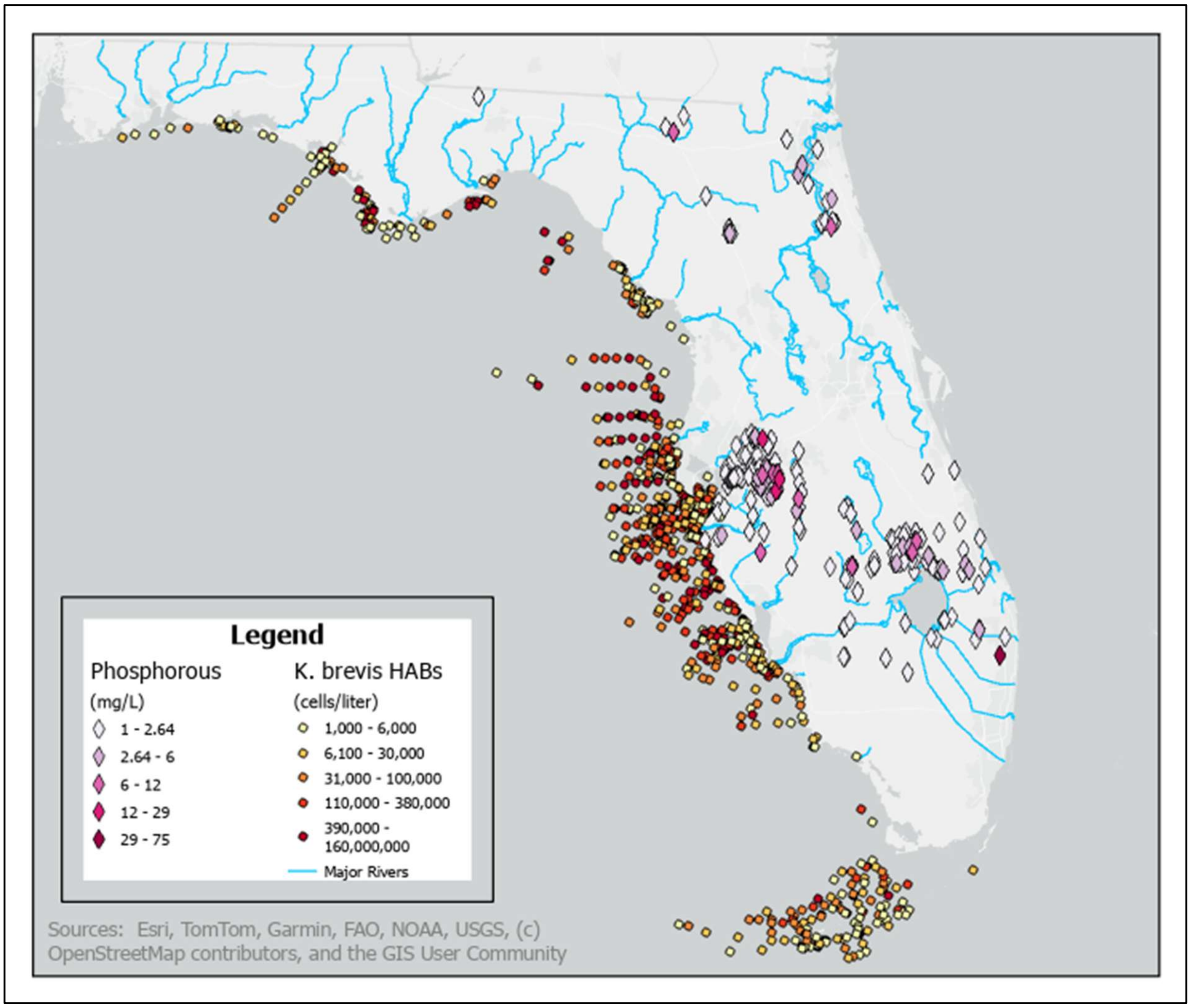

Figure 9. A map of phosphorous sampling sites where the value of phosphorous is greater than 1.0 mg/L. Any site over 1.0 mg/L is considered over the pollution threshold, according to the EPA guidelines. Hydrology and *K. brevis* blooms in 2005 are shown as well.

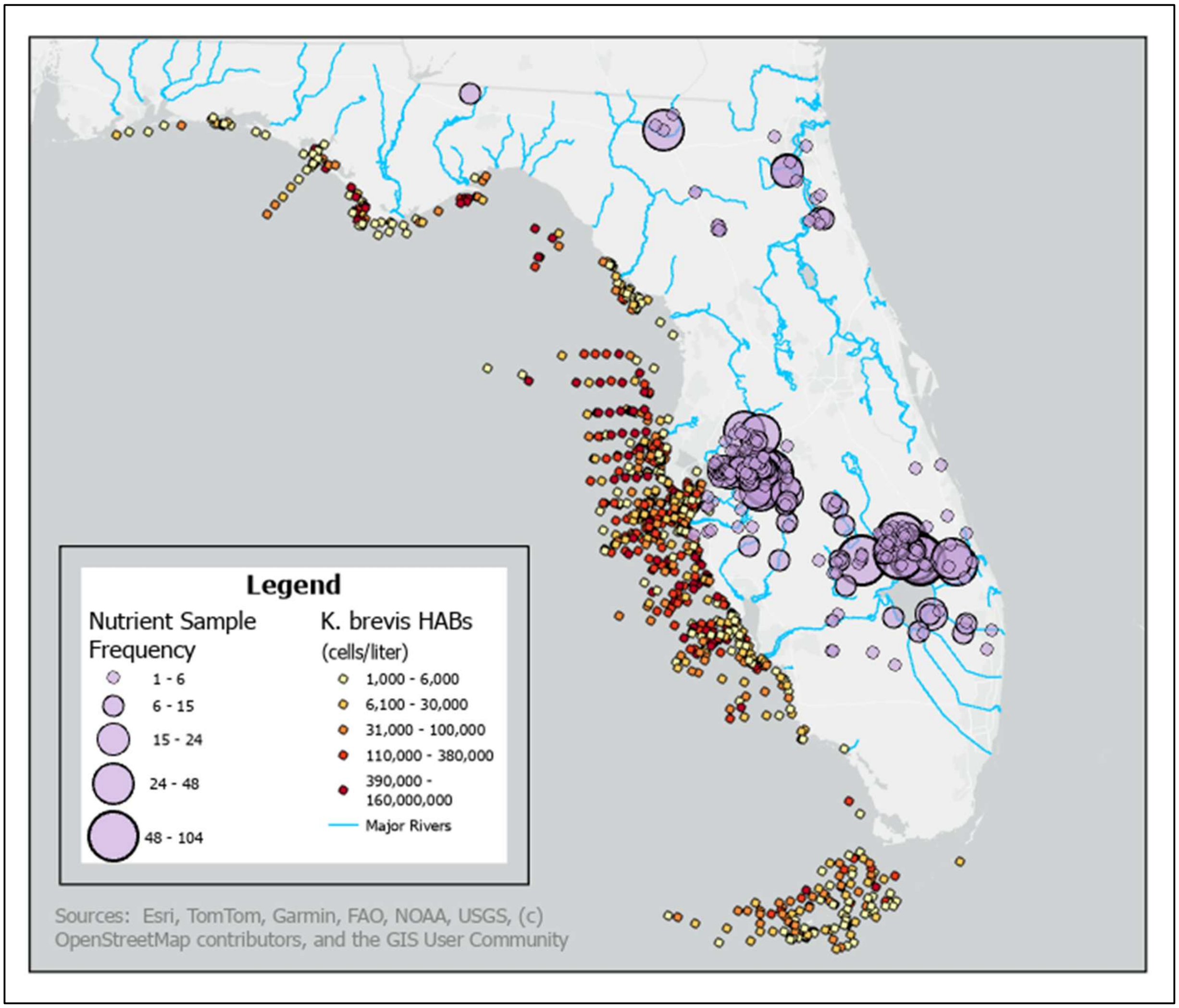

Figure 10. A frequency map showing the combined frequency of sampling sites that were over the nutrient (nitrogen and phosphorous) pollution threshold in 2005. The larger the purple circle the greater number of samples at that location that were over the pollution threshold. Hydrology and *K. brevis* blooms in 2005 are shown as well.

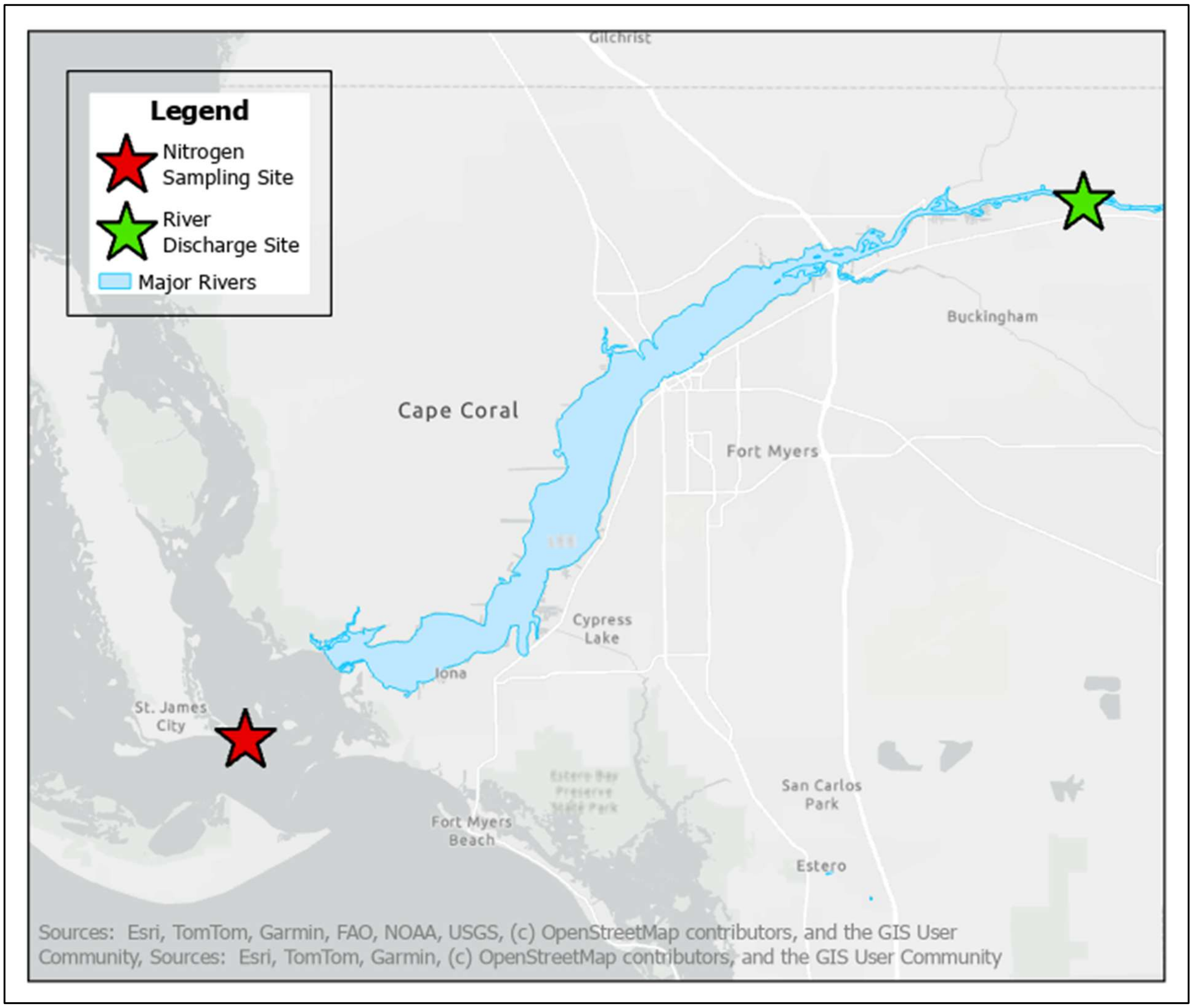

Figure 11. The locations of the nitrogen (nitrate + nitrite) sampling site and river discharge rate monitoring site for the data shown in Figure 12.

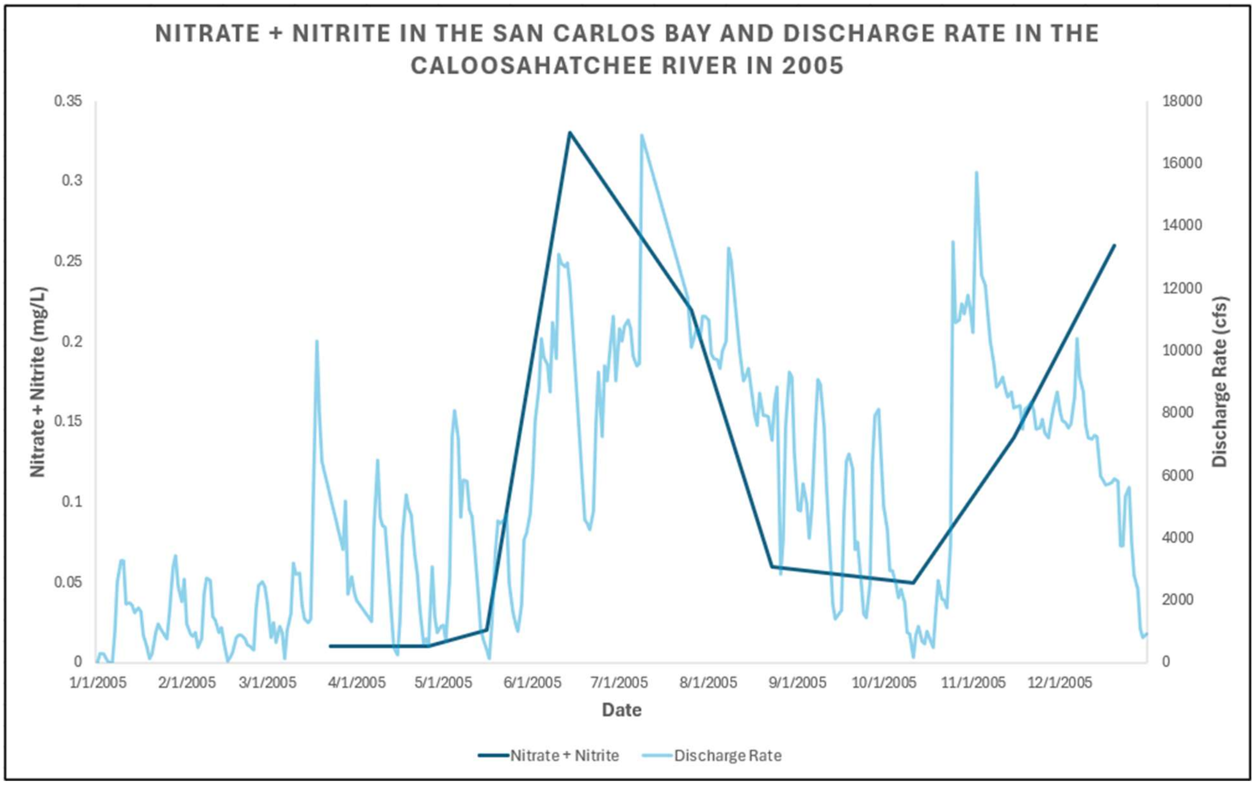

Figure 12. The nitrate + nitrite *in-situ* values collected from the PI-14 monitoring station in the San Carlos Bay plotted with the river discharge rate values collected from the S79 monitoring station in the Caloosahatchee River. The nitrate + nitrite values were collected monthly, with a few months missing with no data. The river discharge rate was collected daily, with a few days missing data. Nitrate + nitrite data was collected from the Coastal and Heartland National Estuary Partnership within the USF Water Institute. River discharge rate data was collected from the United States Geological Survey.

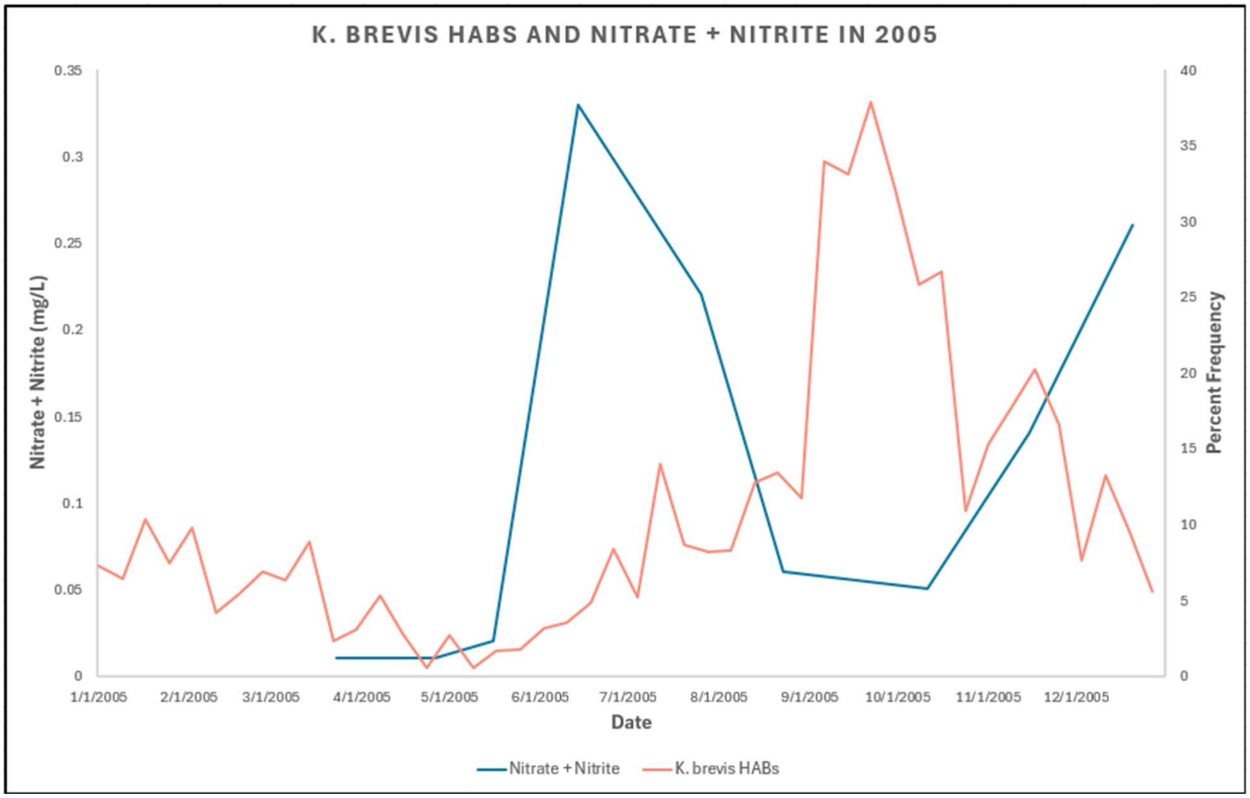

Figure 13. The nitrate + nitrite *in-situ* values from Figure 12 plotted with the percent frequency area of *K. brevis* from Figure 2. This shows the lag in *K. brevis* growth after the spike in nutrients during the hurricane season.

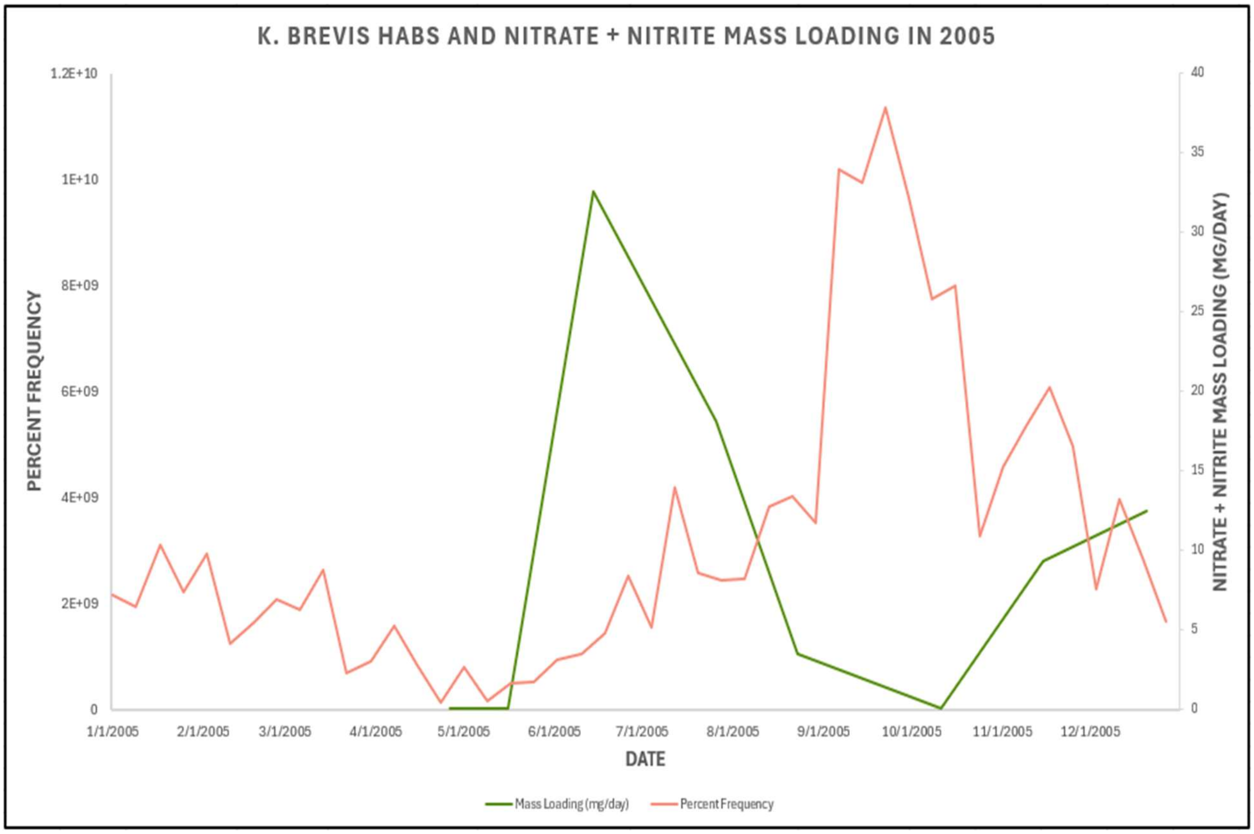

Figure 14. The nitrate + nitrite mass loading values calculated using the *in-situ* sampling data and river discharge rate data plotted with the percent frequency of *K. brevis* from Figure 2. The peaks and dips line up with the nitrate + nitrite *in-situ* values in Figure 12.

<u>Other Influencing Parameters</u>

K. brevis prefers warm temperatures between 15-30 degrees Celsius or 59-86 degrees Fahrenheit (Vargo, 2009). Depending on the exact location in Florida, the sea surface temperature will vary. At Naples Pier, for example, the temperature doesn't go below 20 degrees Celsius even in the coldest months, and it exceeds 25 degrees Celsius for more than half the year (*Naples Pier Water Temperature and Wetsuit Guide*, n.d.). These consistently warm conditions are what *K. brevis* prefers to grow into HABs. While the temperature will slightly vary along the coasts, the water is warm enough for *K. brevis* to grow into HABs for months and even sometimes years at a time.

The optimum salinity for growth is between 25-45 PPT discovered in the lab but in the field *K. brevis* has been found at a range from 8-40 PPT (Vargo, 2009). Data from the 1/12° Global HYCOM+CICE System model show that the salinity stays within the 32-38 PPT range which is in the optimal growth range for *K. brevis* (U.S. Military, 2022).

The Loop Current shown in Figure 15 is the main current that flows throughout the center of the Gulf of Mexico where it the curls around and flows right up against the East coast of Florida joining with the Gulf Stream. Data from the 1/12° Global HYCOM+CICE System show that the West coast doesn't experience the fast Loop Current flowing against the coastline very often, so it has a lower turbulence (U.S. Military, 2022). *K. brevis* prefers to be in low-turbulent waters in order to bloom enough to be considered a HAB (Brand et al., 2012).

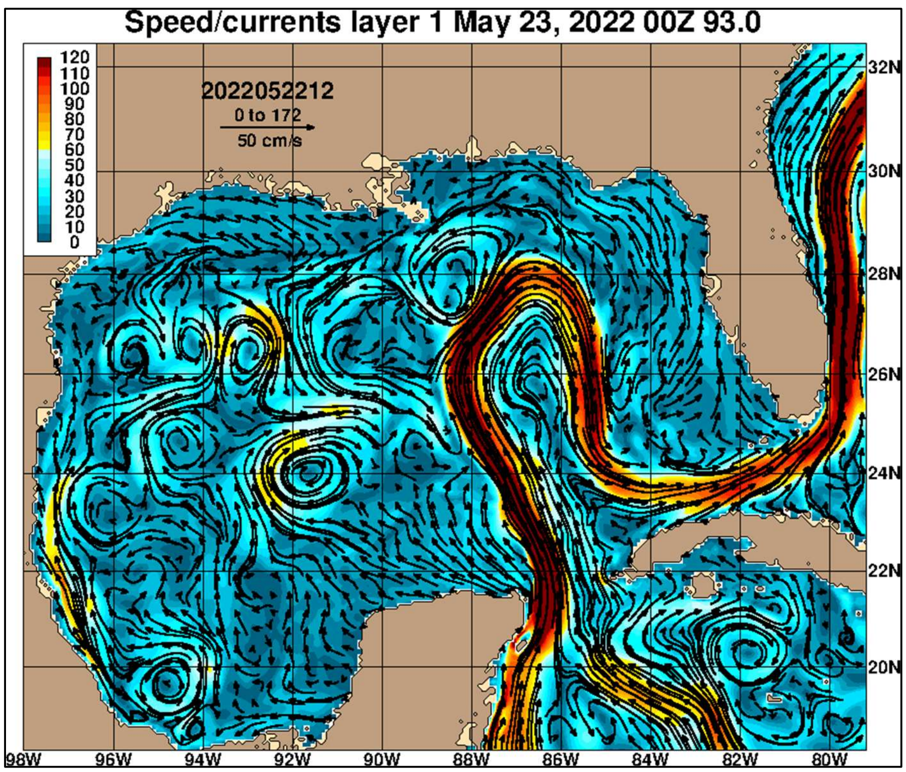

Figure 15. The Loop Current shown in red detected by the 1/12° Global HYCOM+CICE System (U.S. Military, 2022).

Discussion/Conclusion

In this study, we used satellite data from Aqua MODIS and analyzed it in SeaDAS to show the area and intensity of *Karenia brevis* HABs in 2005. The HABs peaked in late summer and early fall. Due to a high influx of nutrients from the runoff of the hurricane season, the HAB was intensified during that time period. *In-situ* nutrient data from water quality monitoring sites was collected from Florida STORET Public Access along with *in-situ K. brevis* data collected from the Florida Fish and Wildlife Conservation Commission. Point and non-point source nutrient pollution data was also collected from the Florida Department of Environmental Protection and the University of Florida. These data were used to show the hotspots of nutrient pollution in Florida using ArcGIS Pro. Nutrient pollution is prominent in the rivers flowing into and out of Lake Okeechobee, along the Caloosahatchee River, and in the Tampa area. Nitrate + nitrite and river discharge rate data were retrieved from the Coastal and Heartland National Estuary Partnership and the U.S. Geological Survey, respectively. These two data sets were plotted together on the same graph to show their correlation. Their peaks and dips are almost identical and show how runoff affects nutrient flow downstream. The nitrate + nitrite data was also plotted with the percent frequency data from the satellite image analysis. The HAB peak follows shortly after the nutrient peak, showing how this nutrient influx played a role in the HAB formation.

The biological advantages of *K. brevis*, nutrient pollution, warm temperatures, consistent salinity, and slow flow rate year-round make the WFS the perfect place for *K. brevis* HABs to accumulate. These biological advantages include the ability to move throughout the water column to perform DVM and being a mixotrophic organism that can make energy in multiple ways. Nutrient pollution comes from many different sources on land including agricultural areas, golf courses, urban areas, wastewater and sewage treatment facilities, and submarine groundwater discharge that pollute water sources that end up in the ocean. The temperature and salinity of the ocean are within the optimal range for *K. brevis* growth. The current does not flow right against the West coast, like it does for the East coast, allowing the HABs to be in their preferred low-turbulence conditions on the WFS. These HABs cause harm to the ecosystem and people by causing illnesses from their brevetoxin and eutrophication which creates hypoxic or anoxic conditions. Both marine organisms and humans can contract severe illnesses from brevetoxin that could be lethal. The future direction of this field should aim to find a way to mitigate and prevent these HABs from growing out of control.

Future Work

The submarine groundwater discharge has been analyzed in the literature; however, Hu et al. (2006) suggest that the next step would be to pinpoint the exact locations of the submarine springs on the WFS. With these exact locations, and using mapping software like ArcGIS, it can be cross referenced with the satellite data for 2005 from this study to further understand how it influences HABs. Another future area of study would be to look at *Trichodesmium* blooms using backscatter satellite data to see how those blooms coincide with the *K. brevis* blooms (Subramanian and Carpenter, 1994). Since *Trichodesmium* is a large source of nutrients for *K. brevis* it would provide a better understanding of how these blooms line up spatially and temporally.

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References

Brand, L., Campbell, L., Bresnan, E. (2012). *KARENIA*: The biology and ecology of a toxic genus. *Harmful algae*, *14*, 156–178. https://doi.org/10.1016/j.hal.2011.10.020

Burkholder, J. M., Glibert, P. M., & Skelton, H. M. (2008). Mixotrophy, a major mode of nutrition for harmful algal species in eutrophic waters. *Harmful Algae*, *8*(1), 77-93. https://doi.org/10.1016/j.hal.2008.08.010

Coastal & Heartland National Estuary Partnership. (n.d.). *Charlotte Harbor Water Atlas*. CHNEP Water Atlas. https://chnep.wateratlas.usf.edu/datadownload/disclaimer.aspx

El-Habashi, A., Ioannou, I., Tomlinson, M., Stumpf, R., & Ahmed, S. (2016). Satellite retrievals of *Karenia brevis* harmful algal blooms in the West Florida shelf using neural networks and comparisons with other techniques. *Remote Sensing*, *8*(5), 377. https://doi.org/10.3390/rs8050377

Florida Center for Instructional Technology. (n.d.). Storm tracks by year of hurricanes and tropical storms, 2005. https://fcit.usf.edu/florida/maps/pages/11600/f11629/f11629.htm

Glibert P., Burkholder J., Kana T., Alexander J., Skelton H., Shilling C. (2009). Grazing by *Karenia brevis* on *Synechococcus* enhances its growth rate and may help to sustain blooms. *Aquat Microb Ecol*, 55, 17-30. https://doi.org/10.3354/ame01279

Glibert, P. M., Harrison, J., Heil, C., & Seitzinger, S. (2006). Escalating Worldwide Use of Urea: A Global Change Contributing to Coastal Eutrophication. *Biogeochemistry*, *77*(3), 441–463. http://www.jstor.org/stable/20519793

Glibert, P.M., and M.A. Burford. (2017). Globally changing nutrient loads and harmful algal blooms: Recent advances, new paradigms, and continuing challenges. *Oceanography 30*(1), 58–69, https://doi.org/10.5670/oceanog.2017.110.

Hu, C., F. E. Muller-Karger, and P. W. Swarzenski (2006), Hurricanes, submarine groundwater discharge, and Florida's red tides, Geophys. Res. Lett., 33, L11601, doi:10.1029/2005GL025449
Burnett, W. C., Aggarwal, P. K., Aureli, A., Bokuniewicz, H., Cable, J. E., Charette, M. A., Kontar, E., Krupa, S., Kulkarni, K. M., Loveless, A., Moore, W. S., Oberdorfer, J. A., Oliveira, J., Ozyurt, N., Povinec, P., Privitera, A. M. G., Rajar, R., Ramessur, R. T., Scholten, J., … Turner, J.

V. (2006). Quantifying submarine groundwater discharge in the coastal zone via multiple methods. Science of The Total Environment, 367(2–3), 498–543. https://doi.org/10.1016/j.scitotenv.2006.05.009

Kirkpatrick, B., Fleming, L. E., Squicciarini, D., Backer, L. C., Clark, R., Abraham, W., Benson, J., Cheng, Y. S., Johnson, D., Pierce, R., Zaias, J., Bossart, G. D., & Baden, D. G. (2004). Literature Review of Florida Red Tide: Implications for Human Health Effects. *Harmful algae*, *3*(2), 99–115. https://doi.org/10.1016/j.hal.2003.08.005

Martin, J., Runge, M., Flewelling, L., Deutsch, C., and Landsberg, J. (2017). An expert elicitation process to project the frequency and magnitude of Florida manatee mortality events caused by red tide (*Karenia brevis*): *U.S. Geological Survey Open-File Report 2017–1132*, 17 p., https://doi.org/10.3133/ofr20171132

Mulholland, M., Heil, C., Bronk, D., O'Neil, J., Bernhardt, P. (2004). Does nitrogen regeneration from the N2 fixing cyanobacteria *Trichodesmium* spp. fuel *Karenia brevis* blooms in the Gulf of Mexico. *Harmful Algae 2002*. 59. 47-49.

Naples Pier Water Temperature and Wetsuit Guide. Surf Forecast Surf Report. (n.d.). https://www.surf-forecast.com/breaks/Naples-Pier/seatemp

NASA. (n.d.). *Modis web*. NASA. https://modis.gsfc.nasa.gov/about/design.php

Ok, J. H., Jeong, H. J., Lim, A. S., Kang, H. C., You, J. H., Park, S. A., & Eom, S. H. (2023). Lack of mixotrophy in three Karenia species and the prey spectrum of Karenia mikimotoi (Gymnodiniales, Dinophyceae). *Algae*. https://doi.org/10.4490/algae.2023.38.2.28

Phlips, E. J., Badylak, S., Nelson, N. G., & Havens, K. E. (2020). Hurricanes, El Niño and harmful algal blooms in two sub-tropical Florida estuaries: Direct and indirect impacts. *Scientific Reports*, *10*(1). https://doi.org/10.1038/s41598-020-58771-4

Schaeffer, B., Kamykowski, D., Sinclair, G., McKay, L., & Milligan, E. (2009). Diel vertical migration thresholds of *Karenia brevis* (Dinophyceae). *Harmful Algae*, *8*(5), 692-698. https://doi.org/10.1016/j.hal.2009.01.002

Smith, C. G., & Swarzenski, P. W. (2012). An investigation of submarine groundwater-borne nutrient fluxes to the West Florida shelf and recurrent harmful algal blooms. *Limnology and Oceanography*, *57*(2), 471–485. https://doi.org/10.4319/lo.2012.57.2.0471

Smith, L. (2021, March 23). *3.4 contaminant loading to the receiving environment*. Hydrogeology and Mineral Resource Development. https://books.gw-project.org/hydrogeology-and-mineral-resource-development/chapter/contaminant-loading-to-the-receiving-environment/

Soto, I. M., Cannizzaro, J., Muller-Karger, F. E., Hu, C., Wolny, J., & Goldgof, D. (2015). Evaluation and optimization of remote sensing techniques for detection of *Karenia brevis* blooms on the West Florida Shelf. *Remote Sensing of Environment*, *170*, 239–254. https://doi.org/10.1016/j.rse.2015.09.026

Stumpf, R. P., Li, Y., Kirkpatrick, B., Litaker, R. W., Hubbard, K. A., Currier, R. D., Harrison, K. K., & Tomlinson, M. C. (2022). Quantifying *Karenia brevis* bloom severity and respiratory irritation impact along the shoreline of Southwest Florida. *PloS one*, *17*(1), e0260755. https://doi.org/10.1371/journal.pone.0260755

Stumpf, R. P., Li, Y., Kirkpatrick, B., Litaker, R. W., Hubbard, K. A., Currier, R. D., Harrison, K. K., & Tomlinson, M. C. (2022). Quantifying *Karenia brevis* bloom severity and respiratory irritation impact along the shoreline of Southwest Florida. *PLOS ONE*, *17*(1). https://doi.org/10.1371/journal.pone.0260755

Subramanian, A., & Carpenter, E. J. (1994). An empirically derived protocol for the detection of blooms of the marine cyanobacterium trichodesmium using CZCS imagery. *International Journal of Remote Sensing*, *15*(8), 1559–1569. https://doi.org/10.1080/01431169408954191

Uhlenbrock, Kristan M., "Nutrient Distribution Effects from Freshwater Discharge at Franklin Lock and Dam (S-79) in 2005 and 2006 on the Caloosahatchee Estuary and San Carlos Bay, Fort Myers, Florida" (2009). Graduate Theses and Dissertations. https://scholarcommons.usf.edu/etd/60

USGS. (n.d.). *Caloosahatchee River at S-79*. USGS Water Data for the Nation. https://waterdata.usgs.gov/monitoring-location/02292900/#dataTypeId=daily-00060-0&startDT=2005-01-01&endDT=2005-12-31

Vargo, G. (2008). A brief summary of the physiology and ecology of *Karenia Brevis Davis* (G. Hansen and Moestrup Comb. Nov.) red tides on the West Florida shelf and of hypotheses posed for their initiation, growth, maintenance, and termination. *Harmful Algae*, *8*, 573-584. https://doi.org/10.1016/j.hal.2008.11.002

Geospatial Data

Florida Department of Environmental Protection. "Florida Lakes". [Feature Layer]. No scale given. "Florida Department of Environmental Protection Geospatial Open Data". April 2002. https://geodata.dep.state.fl.us/datasets/97b765ff2b70400d8bcab23fbe2a5e88_0/about.

Florida Department of Environmental Protection. "Wastewater Facility Regulation (WAFR) - Wastewater Sites". [Feature Layer]. No scale given. "FDEP Open Data Administrator". April 2006. https://geodata.dep.state.fl.us/datasets/FDEP::wastewater-facility-regulation-wafr-wastewater-sites/about

Florida Fish and Wildlife Conservation Commission. "Historic Harmful Algal Bloom Events 2000 – 2006". [Feature Layer]. No scale given. "FFWC GIS and Mapping Data Downloads". March 2017. https://atoll.floridamarine.org/arcgis/rest/services/FWC_GIS/OpenData_HAB/MapServer/12

Florida Fish and Wildlife Conservation Commission-Fish and Wildlife Research Institute. "Florida's Major Rivers (lines)". [Feature Layer]. No scale given. "ArcGIS Online". February 2015. Florida's Major River (Lines) - Overview (arcgis.com).

National Water Quality Monitoring Council. (n.d.). Water Quality Portal. https://www.waterqualitydata.us/#mimeType=csv&providers=NWIS&providers=STORET.

University of Florida GeoPlan Center. "GOLF COURSE FACILITIES IN FLORIDA – 2015" [Feature Layer]. No scale given. "FGDL Metadata Explorer: Search and Download Data." October 2015. https://www.fgdl.org/metadataexplorer/full_metadata.jsp?docId=%7BFFDF03E8-4EC3-4C94-BC78-A4372EF1B3F9%7D&loggedIn=false.