Environmental Disasters and Water Quality: A Multifaceted Look into the Effects of Anthropogenic and Natural Disasters on Water Quality Metrics in Coastal Louisiana

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Abstract

Water quality plays an important role in the ecological, societal, and economic well-being of all communities. Perhaps nowhere is this more important than coastal Louisiana, where many towns subsist primarily on maritime industry and are situated precariously along the Gulf of Mexico.[1] In every ecological disaster affecting these coastal regions some 2.6 million people, approximately half the population of the state, are at risk of losing their homes, livelihoods, or lives.[2] Keeping the importance of water quality to these communities in mind, the investigators set out to quantify and analyze the effects of two natural disasters (Hurricanes Rita and Harvey) and one anthropogenic ecological disaster (the BP Oil Spill) on salinity, pH, and dissolved oxygen (DO). These parameters are among the most important water quality metrics for sectors such as the seafood industry[3], which comprises a large portion of the economy in Southern Louisiana.[4] Using these metrics, the investigators found that hurricane activity was strongly linked to changes in salinity. However, the investigators were unable to definitively link hurricane activity with a statistically significant change in pH even though a minor reduction in overall pH was observed. Additionally, the anthropogenic ecological disaster investigated, the BP Oil Spill, was not linked to significant changes to either top or bottom layer dissolved oxygen, even though the chemical dispersant agents that were used have been linked to the lowering of DO levels.[5] It is posited that both of these finding relate to the distance between the respective locations of Hurricane Harvey and the BP Oil Spill and the Louisiana Universities Marine Consortium (LUMCON) Facility in Cocodrie, Louisiana (the site of water sampling). Further research about the more local effects of these events may reveal insights into their true environmental impacts.

Introduction

Students of the Fall 2020 Introduction to Cell and Molecular Biology Service Learning course at Tulane University partnered with LUMCON to measure and track changes in water quality with a particular emphasis on the effects of ecological disasters on such metrics. LUMCON, a research and educational institution focused on monitoring and sustaining marine environments in the Gulf of Mexico, runs Bayouside Classroom with the aim of collecting water samples and maintaining a database that tracks longitudinal changes in water quality. Water quality metrics, such as temperature, salinity, dissolved oxygen, pH, and turbidity, are important indicators of the health of an aquatic ecosystem.[6] Additionally, they allow scientists to deduce the effects of natural and man-made disasters on aquatic life. Recording these indicators helps environmental scientists detect and respond to threats to aquatic ecosystems while preserving water bodies. Since the semester was offered virtually due to the COVID-19 pandemic, the Service Learning program shifted to analyze the existing data on pH, DO, and salinity that was published in the LUMCON database. This paper reports the findings of the analyses of the data by three participating groups.

pH is a measure of the concentration of hydrogen ions in a solution and is affected by photosynthetic and respiratory rates, specifically by way of the consumption and accumulation of carbon dioxide, some of which is converted into carbonic acid in the water.[7] Thus, in times of high photosynthetic activity and relatively low respiration, a decrease in available carbon dioxide causes pH levels to rise. Conversely, in times of low photosynthetic activity and relatively high respiration, an increase in available carbon dioxide causes pH levels to drop, acidifying the body of water. While slight pH fluctuations in water bodies occur throughout the day, most aquatic organisms can tolerate minimal fluctuation within an ideal range of 7.5-8.4.[8] pH can also be significantly affected by anthropogenic factors, such as pollution and the burning of fossil fuels, which may produce acid rain.[7]

Salinity refers to the concentration of dissolved salt present in a sample of water. Salinity levels determine the flora and fauna that can live within a certain environment, with organisms that are accustomed to saltwater environments requiring higher salinity levels to survive and organisms adapted to freshwater environments requiring lower salinity levels.[9] While aquatic environments can tolerate minor fluctuations, they must maintain fairly steady salinity levels to sustain their delicately balanced ecosystems. However, large changes in salinity can occur as a result of human activity, such as irrigation runoff, as well as natural occurrences, like storm surges caused by hurricanes. Even in the context of an equal absolute change in salinity, the timeframe across which the changes take place may dramatically affect the severity of the impacts on aquatic organisms.[10]

Dissolved oxygen (DO) relates to the concentration of oxygen gas dissolved in water. The presence of DO within an aquatic ecosystem is affected by the changes in photosynthetic and respiratory rates resulting from slight fluctuations in temperature and salinity. DO is an important indicator of aquatic health as many aquatic organisms cannot survive in hypoxic conditions, defined as zones within which the oxygen concentration is at or below 3.0 mg per liter.[11]

GROUP 1 – Why so Salty: An Analysis of Hurricane Rita's Effects on Coastline Salinity in Louisiana

Introduction

The connection between climate change caused by anthropogenic factors, increased hurricane frequency, and severe weather activity has been well-studied and documented.[12] Separately, increased attention has been given to the link between spikes in salinity and increased marine wildlife mortality, especially in aquatic organisms living in freshwater and brackish regions.[10] This work will explore the connection between these seemingly independent phenomena, establishing a "chain of events" linking anthropogenic climate change and increased severe weather to spikes in salinity and increased marine wildlife mortality.

Hypothesis

The hypothesis had two parts: firstly, when hurricane activity occurs, there may be a statistically significant spike in salinity in bodies of water as a direct result, and secondly, the recovery to baseline salinity levels may occur over a timespan of approximately two years. There are two prominent observations that led to this prediction: the tendency for large storm surges to transport water with high salt concentrations upstream from downstream sources and the correlation between this phenomenon and the resulting wide-scale effects on fish populations. Salinity can have a significant impact on marine wildlife and learning more about this trend will allow LUMCON and other ecologists to further investigate potential impacts on Gulf Coast ecosystems.

Methods

In this project, water quality data was analyzed from two locations, LUMCON Front Pond and Bayou, which are both located in Cocodrie, Louisiana. These locations were chosen as primary points of focus because of the regular and consistent data available for analysis.

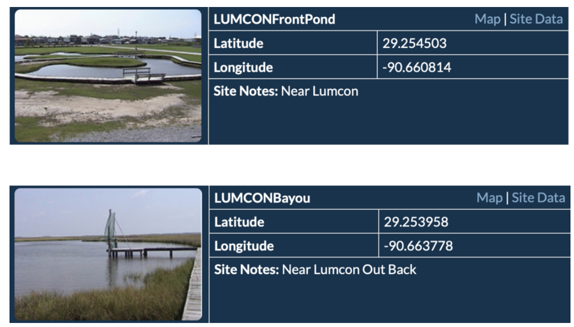


Figure 1: LUMCON Front Pond and Bayou Collection Site Location Data. Reprinted from LUMCON Bayouside Classroom[13]

Hurricane Rita made landfall in Louisiana's Cameron Parish as a Category 3 hurricane on September 24, 2005.[14] It was decided that Hurricane Rita would serve as the event of interest for analysis due to its strength as well as proximity to the LUMCON locations from which data was gathered. The data was split into three groups, with the pre-event and post-event data sets being defined as the two years preceding and succeeding the event, respectively, and the event being defined as the one-month period within which the hurricane occurred. Data from September 2003 to September 2005 (the pre-event period) was used to establish baseline salinity ranges for the testing sites prior to the hurricane. The data from September 2005 to October 2005 (the event period) was used to analyze the short-term changes in salinity immediately after the hurricane. Finally, the data from October 2005 to October 2017 (the post-event period) was used to assess the long-term changes and impacts.

Statistical Analysis

To determine the recovery time, two different methodologies were implemented: a p-value test, and a running average test. For the p-value test, a baseline salinity value for the location was first established by calculating the average salinity levels, for both the top and bottom salinity of a given location, from the pre-event period (September 2003 – September 2005). For the comparison group, all the data points in each month following Hurricane Rita were grouped into samples on a month-by-month basis. Treating the baseline as a sample as well allowed for a simple two-sample hypothesis test to be run, with the null hypothesis being that the baseline sample and the monthly sample are the same, and the alternative sample being that they are different. The threshold for significance was set at $p=0.20$, meaning that if a two-sample hypothesis test returns a p-value less than 0.20, the null hypothesis is rejected, and the test is carried out on the following month's data. By shifting the p-value required for rejecting the null hypothesis from the standard $p=0.05$ to $p=0.20$, there can be more confidence that the return to baseline has occurred only when salinity levels have greatly deviated from where there would be a statistically significant difference between baseline and current salinity levels. This imposes a more stringent requirement for determining lack of statistically significant difference, thus indicating a likely return to baseline when salinity levels more closely mirror the baseline values. Since data can be off the normal value but still insignificant, setting a higher cutoff increased the likelihood that that month's data reflected that of the baseline. This test was performed until $p>0.20$, meaning that there was a 20% or greater chance that the observed difference between the baseline and monthly salinity values occurred due to random chance alone if there was no statistically significant difference between these two salinities. The p-value test cannot be used to determine the likelihood that the null hypothesis is correct, but rather gives the probability of seeing a test statistic that is at least as extreme as what was observed given that there was no statistically significant difference between the baseline and monthly salinities. Using this methodology, the first monthly sample where this is true is demarcated as the end of the recovery period (or a "return to normalcy"). To validate this two-sample hypothesis test, it was supplemented with a running average test. For each data point, the average of it and the previous 19 data points were taken. If the running average for a given point fell below the established baseline, then the given date was marked as the end of the recovery period.

Results

Data Set	Baseline salinity level (parts per thousand (ppt))	Average Salinity after Hurricane Rita (ppt)	P-value Recovery Month	Running Average Recovery Month
Front Pond Top Salinity	7.43 ppt	22.83 ppt	Feb 2007	Feb 2007
Front Pond Bottom Salinity	7.77 ppt	23.16 ppt	Feb 2007	Feb 2007
Bayou Top Salinity	9.31 ppt	18.62 ppt	Jan 2007	Feb 2007
Bayou Bottom Salinity	9.17 ppt	19.65 ppt	Jan 2007	March 2007

Table 1: Salinity Levels Before and After Hurricane Rita (September 2005) and the Recovery Month. Data adapted from LUMCON Database [15]

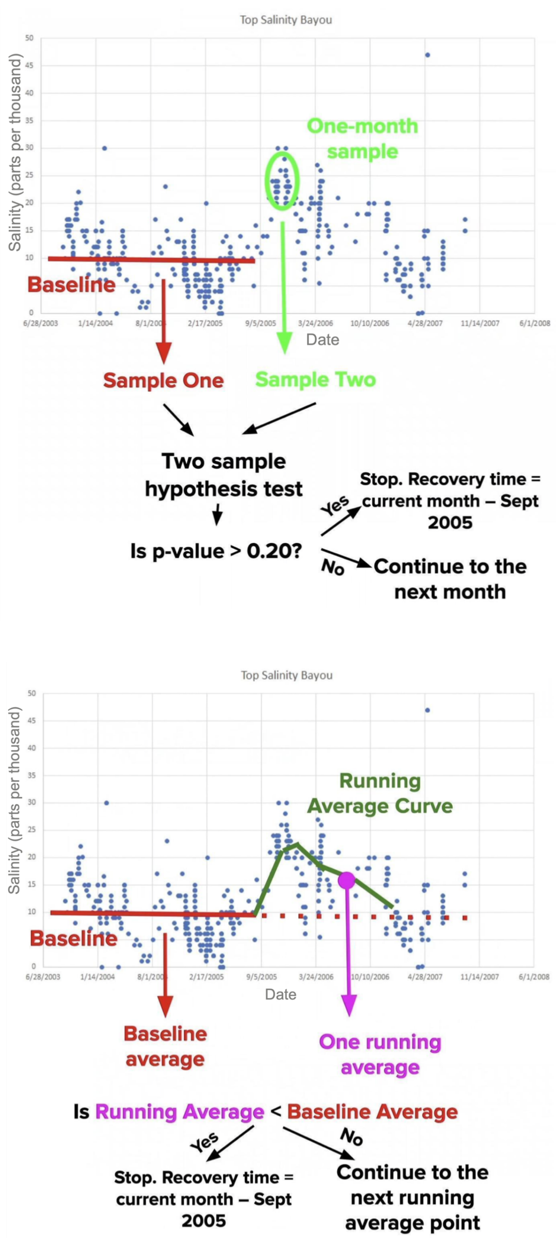


Figure 2: Surface Salinity Measurements from the LUMCON Bayou Location with P-test and Running Average Analysis Flow Charts Shown

Discussion

The data shows that there is a plausible link between Hurricane Rita and an increase in salinity levels of Front Pond and Bayou locations. In the Front Pond location, the baseline top and bottom salinity levels were approximately 7 parts per thousand, but after Hurricane Rita, the salinity levels of the Front Pond more than tripled in value to about 23 parts per thousand. Similarly, the Bayou location had a baseline top and bottom salinity of approximately 9 parts per thousand, and after Hurricane Rita, the top and bottom salinity more than doubled to about 19 parts per thousand. This sharp increase in salinity in both locations after Hurricane Rita is significant because most aquatic plants and animals are directly harmed by drastic, rapid changes in salinity.[10] The salinity levels of both the Front Pond and Bayou locations did not return to their baseline levels until 14-16 months after Hurricane Rita, meaning that these aquatic environments were not suitable for their native flora and fauna for over a year.

One potential source of error is the variability in the collection of the data. The salinity values were acquired by the work of a variety of school groups, so the collection of data was not uniform. Moreover, data points were not collected on a regular basis, so there were periods of time where there was no data available for the group to analyze.

A larger span of data points taken on a regular basis would be crucial to improve this statistical analysis. While no further data can be taken from the time of Hurricane Rita, this study could be applied to current and future hurricanes to reveal a similar phenomenon. Another way to improve this study on Hurricane Rita would be to incorporate data from locations outside the LUMCON system during the same time parameters.

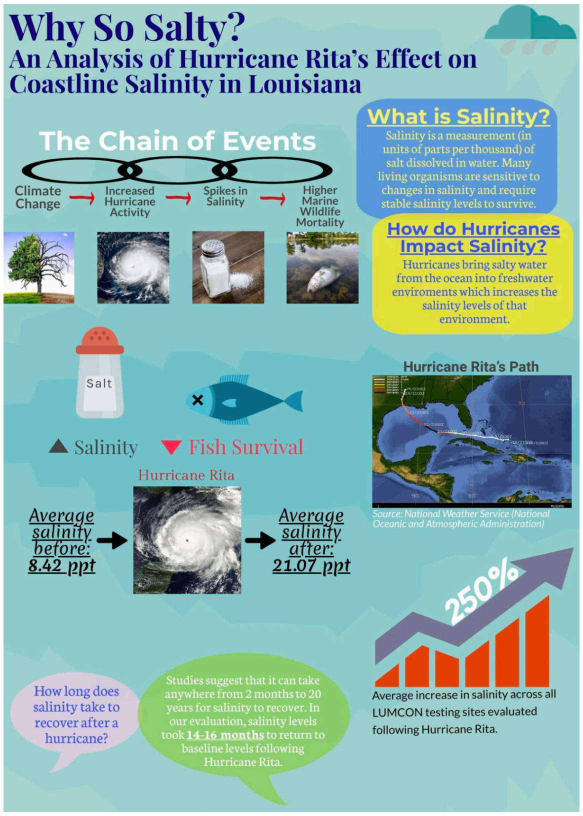


Figure 3: Group 1 Infographic for community members on the impacts of hurricanes on coastline salinity. For each group, infographics were part of the presentation, breaking down the scientific data into a more approachable format for community members to understand and apply in their own lives.

GROUP 2 – The Effect of Hurricane Harvey on pH in Audubon Park Water Bodies

Introduction

Hurricanes damage infrastructure and flood terrestrial environments, leading to increased runoff of toxins and pollution into the ocean. Extreme weather events such as hurricanes are becoming increasingly prevalent across the country, including in New Orleans, which means that monitoring water quality in affected areas is essential to the health of the humans and wildlife that depends on those water bodies.[16] The significance of maintaining ecological balance cannot be overstated, since human health and socioeconomic equity in Louisiana communities are both impacted.[6] The group decided to investigate the effect of Hurricane Harvey, a Category 4 hurricane that made landfall on the Texas coast on August 25th, 2017, because of the intensity of the storm and possible consequent effects. Southeast Texas was most affected by the hurricane, since it stalled in that area and caused heavy rain and flash flooding.[17] Louisiana also experienced widespread flooding, and New Orleans reported increased wind speed and rainfall.[18] However, the effect on the city was likely not as severe as the group expected and does not seem to have caused any significant or lasting change in water quality as measured by pH.

Hypothesis

The null hypothesis proposed was that there would be no significant change in pH of the water in the Audubon Bridge site after Hurricane Harvey. The alternative hypothesis proposed was that there would be a decrease in pH of the water in the Audubon Bridge site after Hurricane Harvey due to accumulation of waste and acid deposition caused by the high winds of the hurricane.

Methods

The group set out to determine which parameters would be relevant in evaluating water quality. The Audubon Bridge site (coordinates: 29.931109, -90.124156)[13] in Audubon Park was selected due to the proximity of the lagoon to the researchers' home campus. Through careful examination of data from pre-existing databases and research into the effects of pH, the group decided to focus on the pH variability in freshwater ecosystems because many organisms can only tolerate a narrow range of pH, making it an important measure of water quality.

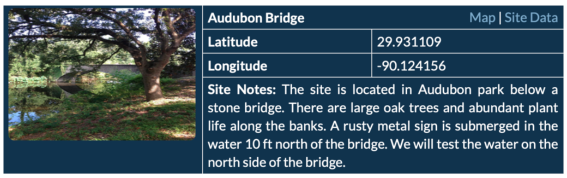


Figure 4: Audubon Bridge Collection Site Location Data. Reprinted from LUMCON Bayouside Classroom[13]

Data was extrapolated from August 1, 2016 to December 13, 2016 and July 31, 2018 to December 31, 2018. These dates were chosen because the group wanted to examine data from before and after Hurricane Harvey to see how the event impacted pH levels. Hurricane Harvey occurred in 2017, but the post-hurricane data is from 2018 because there was no data available from this site in 2017.

Statistical Analysis

Data was collected from the LUMCON Bayouside Classroom database. The data from each year, 2016 and 2018, was compared using analysis of average and t-test (two samples assuming unequal variance).

Results

From the documented field notes, the group noticed a trend that periods of heavy rain lowered the pH, which could be an indication of acid rain. Also, when large algal blooms were present on sunny days, pH was slightly lower than normal range. On bright and sunny days, the rate of photosynthesis increases and CO_2 is removed, which causes pH to rise. Photosynthesis can only take place in sunlight, thus the pH of the water will be highest during the middle of the afternoon and lowest just before sunrise.[8]

The average pH value for the data set that represents the timeframe before Hurricane Harvey was 7.670. After Hurricane Harvey, the average pH value was 7.398.[15] The average pH was lower after the hurricane, indicating that Hurricane Harvey and other natural disasters can increase the acidity of water. To further analyze the data, the group conducted a t-test for two samples assuming unequal variances. The p-value for the one-tailed hypothesis is 0.0654, and the alpha value is 0.05. Since the p-value is greater than the alpha value, the investigators fail to reject the null hypothesis, and thus conclude that there was no significant difference in pH level after Hurricane Harvey, even though the overall pH value decreased.

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	7.6733333	7.3975
Variance	0.4374667	0.0147587
Observations	15	24
Hypothesized Mean Difference	0	
df	15	
t Stat	1.5984124	
P(T<=t) one-tail	0.0653993	
t Critical one-tail	1.7530504	
P(T<=t) two-tail	0.1307986	
t Critical two-tail	2.1314495	

Table 2: Results of T-test

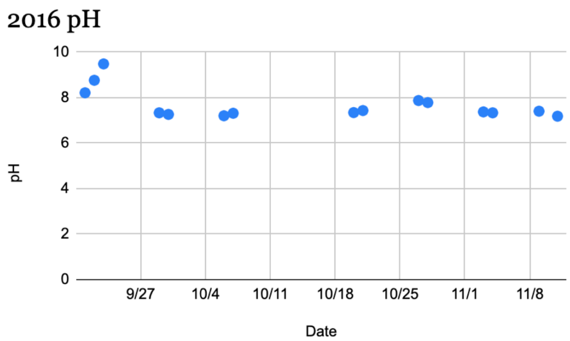


Figure 5: pH Levels August 1, 2016 – December 13, 2016

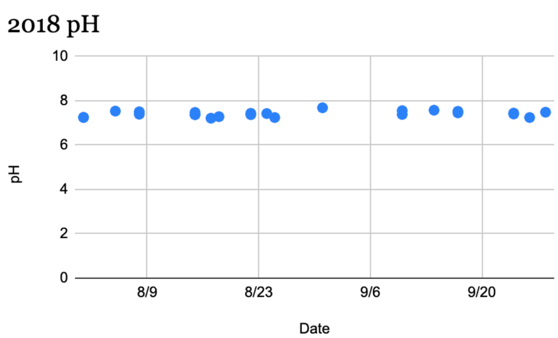


Figure 6: pH Levels July 31, 2018 – December 31, 2018

Discussion

It is evident that region-specific natural disasters such as hurricanes exacerbate negative environmental impacts. This can take many forms, such as accumulating pollutants from the air and depositing them as acid rain.[19] With this in mind, the group chose to focus on pH as a primary measure of water quality. This allowed the group to employ quantitative data analysis, performing T tests and averages, as well as using charts that track sample dates, times, and top pH values.

Although the results were relatively close to significance, significance was not achieved, and if it was, this likely would have been caused by outliers within the data set. This lack of significant results was likely due to several limitations of the project. For one, not many data points were available for analysis and there was no data from 2017 so it is possible that there was a return to normalcy from the hurricane before the 2018 data was collected. Finally, the storm chosen did not directly impact New Orleans and the Audubon Bridge site, which may have played a role in the severity of the effects seen at the data collection site.

If the students were to reproduce this study, it would be ideal to select a site with an abundance of data to analyze. This would allow the group to extrapolate data from outside of the Audubon Park area, and at locations such as LUMCON's collection sites. This also would have allowed the group to select a site in a location that was more affected by the hurricane. Along with reconsideration of collection sites, inclusion of temperature in the study's parameters would be another relevant factor to delve into, as water temperature is closely tied to many of the previously discussed environmental factors and conservation issues.

Even though the final results did not demonstrate statistical significance, there is still an abundance of research corroborating the finding that water conditions can be affected by natural disasters, which are worsening as a consequence of anthropogenic climate change.[20] Hurricane Harvey and its potential impacts on aquatic systems merely functioned as an example of an extreme event that could dramatically alter ecosystems in a short period of time.

Figure 7: Group 2 Infographic for community members on anthropogenic effects on aquatic pH

GROUP 3 – The Effect of the BP Oil Spill on Dissolved Oxygen

Introduction

The BP Oil Spill began on April 20, 2010 due to an explosion on the Deepwater Horizon oil drilling rig in the Gulf of Mexico, 40 miles off the Louisiana coastline. Over the course of 87 days, millions of barrels of oil were released into the Gulf of Mexico, prompting a massive cleanup effort.[21] Measures of water quality, such as DO, were constantly analyzed to gauge the ecological impact of the oil spill. Optimal DO levels fall between 9.5 and 12 mg/L; however, reports released by the Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA) showed DO levels had dropped by about 20 percent in regions affected by subsurface oil.[22] Scientists from agencies involved in the report attributed the lower DO concentration to the clean-up efforts of BP.[22] A notable example was the usage of chemical dispersants to consume oil particles in the Gulf of Mexico. Applying dispersants such as Corexit exposed animals living beneath the ocean surface to this toxic oil.[23] Additionally, oil-eating microbes absorb oxygen during respiration, lowering the concentration of DO within the environment. Thus, the top and bottom DO levels of water, proximal to the site of the Deepwater Horizon wellhead, were potential indicators of the health of surrounding aquatic ecosystems after the oil spill.

Hypothesis

After extensive research on the ecological effects of oil spills, the group wanted to determine the impact that the BP Oil Spill had on the top and bottom DO levels of bodies of water proximal to the site of the Deepwater Horizon wellhead. The investigators posited that if chemical dispersants, such as Corexit, lower DO, then the top and bottom DO levels of LUMCON Bayou would fall within hypoxic levels (2-3 mg/L) after April 20, 2010.

Methods

Sample sites that were adjacent to the Gulf of Mexico were analyzed as the group predicted the oil spill would have had a direct impact on nearby estuarine wildlife. The LUMCON Bayou site (coordinates: 29.253958, -90.663778)[13] is located about

140 miles away from the Deepwater Horizon wellhead. Compared to the other available collection sites, LUMCON Bayou also had the most consistent data from both before and after the spill, allowing the group to accurately compare DO levels across the two time intervals.

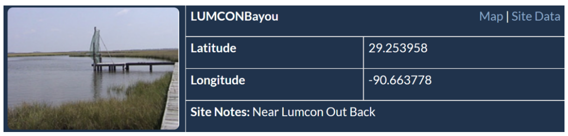


Figure 8: LUMCON Bayou Collection Site Location Data. Reprinted from LUMCON Bayouside Classroom[13]

Data was taken from the time periods of April 2001 to December 2005, prior to the oil spill, and January 2010 to December 2014, following the oil spill. By examining the data sets from both before and after the BP Oil Spill, any changes in DO levels would be observed.

Statistical Analysis

To analyze the data, a two-sample t-test was used to determine if the difference between the two data sets, collected from 2001-2005 and 2010-2014, is considered statistically significant or can be attributed to random chance.

Results

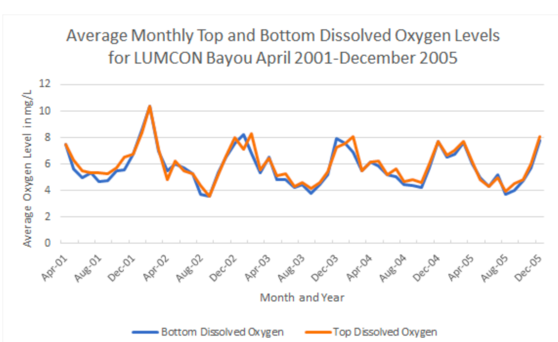


Figure 9: Changes in top and bottom dissolved oxygen (DO) levels from April 2001 – December 2005, before the BP Oil Spill

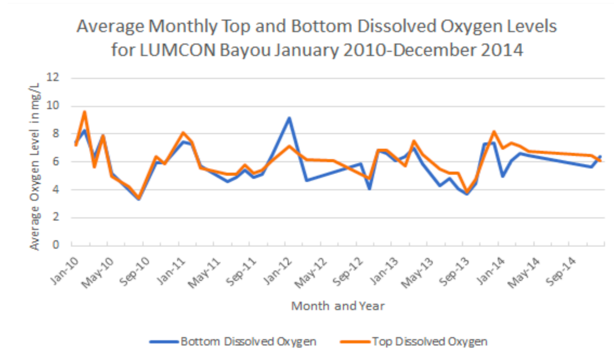
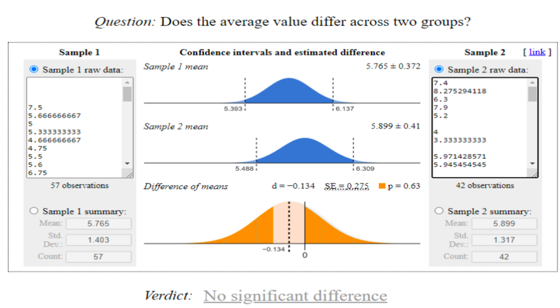


Figure 10: Changes in top and bottom dissolved oxygen (DO) levels from January 2010 – December 2014, after the BP Oil Spill

Although the recorded data for 2010 is limited compared to other collection times, the group was able to produce a comprehensive quantitative analysis from the provided data. The average monthly DO values fall at the end of April and continue to decline until August, reaching the lowest value of 3.6 mg/L of 2010.[15] However, this decline is temporary, and DO stabilizes in October and November with DO recordings of 6.4 mg/L and 5.9 mg/L respectively.[15]

The trends shown in 2010 onwards are similar to the trends in the 2001-2005 control group. August of 2010 has a slightly lower average compared to that same month in prior years, but September of 2002 has a comparable value across the time intervals. However, in October of 2010, the average for that month reached an all-time high compared to other years. Overall, the monthly averages following the oil spill are equivalent or slightly higher DO values when compared to the monthly averages from 2001-2005. Because each year follows similar seasonal trends with no obvious outliers, these graphs do not indicate any significant changes from before and after the oil spill.

A two-sample t-test compared the average monthly top and bottom DO values for 2001-2005 and 2010-2014. The threshold for significance was selected as p=.05, with the calculated p-values of 0.63 for bottom DO and 0.37 for top DO indicating the difference between two sample groups could be attributed to random chance. Using a confidence interval, the group is 95% confident that there is no statistically significant difference between the two samples. Thus, the group failed to detect any significant effect of the BP Oil Spill on either the top or bottom DO levels at the LUMCON Bayou site.



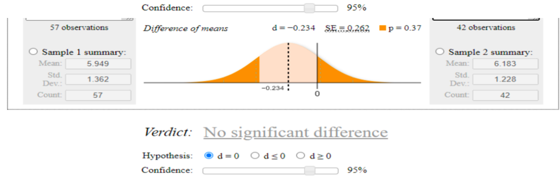


Figure 11: Comparison of Bottom DO Monthly Average Between Sample Groups (Sample 1: 2001 – 2005, Sample 2: 2010 – 2014)

Figure 12: Comparison of Top DO Monthly Averages Between Sample Groups (Sample 1: 2001 – 2005, Sample 2: 2010 – 2014)

Discussion

Following a review of the data, the group did not find a significant change in top or bottom DO levels of the LUMCON Bayou as a result of the BP Oil Spill. Although top DO dropped significantly in April of 2010, there is not a statistically significant correlation between the BP Oil Spill and hypoxic DO levels. Monthly top and bottom DO averages between 2001-2005 and 2010-2014 show similar seasonal trends in hypoxic and healthy DO levels. For example, the month of September is consistently characterized by DO concentrations at or below 4.0 mg/L, bordering on hypoxic levels.[15] This trend is observed throughout the 2001-2005 time period, which served as the experimental control, and the 2010-2014 time period that, according to the hypothesis, should have been most affected by the BP Oil Spill. Based on the data analysis, there was no statistically significant difference in the DO levels before and after the BP Oil Spill at the LUMCON Bayou site. The hypothesis, that the DO levels will decrease as a result of the oil spill, was not supported. However, there has been documented evidence that DO levels near the Deepwater Horizon wellhead have decreased as a result of the oil spill.[24] A possible explanation of this discrepancy could be the distance between the LUMCON Bayou site and the source of the oil spill.

The BP Oil Spill was an ecological disaster that affected aquatic and terrestrial wildlife; however, the extreme data points, measured as dissolved oxygen (DO) values between 0-4 mg/L (hypoxic levels) and above 13 mg/L, are not definitively related to the event. Significant reduction in DO values may be explained by the destruction of vegetation which reduces the shade and raises water temperature, thus decreasing the magnitude of gaseous particles and dissolved oxygen.[25] Other man-made processes, like the addition of nutrients to aquatic environments through runoff, can cause algal blooms that absorb DO from the water. Anoxic DO levels recorded after the BP Oil Spill may be explained by these events or extraneous variables, such as the weather. Finally, the LUMCON Bayou site is likely too far away from the Deepwater Horizon wellhead to observe any significant changes in DO levels. Future studies could improve on this by examining sites that were closer to the Deepwater Horizon wellhead and would therefore have been more heavily impacted by the oil spill.

Figure 13: Group 3 Infographic on the BP Oil Spill, also referred to as the Deepwater Horizon Oil Spill, and its impacts on aquatic ecosystems

Conclusion

The consequences human activities have on aquatic wildlife are observed daily throughout Louisiana and across the globe. Rising temperatures and extreme weather events, which have increased in intensity and frequency in recent years, are only a few examples of these effects. Human actions can impact aquatic ecosystems both directly, through accidents such as the BP Oil Spill, and indirectly, by contributing to climate change and exacerbating natural disasters. Various metrics of water quality can be applied to understand the implications of environmental disturbances on a micro- and macro-biological level. Each group analyzed a specific measure of water quality (salinity, pH, and dissolved oxygen) to determine how an ecosystem responds to dramatic change. Although results of these studies did not match the groups' initial expectations, the team learned that water quality is intrinsically tied to ecological homeostasis and biodiversity. Fluctuations in salinity, pH or DO can have a severely detrimental impact on aquatic organisms and the future habitability of aquatic ecosystems. Future studies may utilize the data set on LUMCON'S Bayouside classroom to analyze how climate change, and the subsequent warming of waters, has affected water quality. Studying these metrics may help ecologists develop strategies to combat man-made disasters or severe weather events. Immediate action must be taken to prevent ecological disasters, like the BP Oil Spill and Hurricanes Harvey and Rita, from harming Louisiana's aquatic ecosystems.

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