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Article

Impact of hog farming on water quality of aquatic environments in North Carolina

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SUMMARY

North Carolina is the second largest hog producer in the nation and the large amounts of waste produced by hog farming can contaminate water bodies through runoff, leaching, and improper waste management. In this study, we collected samples from two water bodies near three hog farms and one aquatic environment that is not near a hog farm. We hypothesized that water bodies near the hog farms would have lower water quality with higher turbidity, total dissolved solids (TDS), and pH than the water body not in proximity to a hog farm because of water contamination with hog waste. To test this hypothesis, we built an inexpensive and portable water quality sensor using an Arduino UNO Rev3 microcontroller to measure the three aforementioned parameters. We collected water from four sublocations at each of the three experimental locations and two timepoints. The results showed that the turbidity was 4–6 times higher, TDS was 1.5–2 times higher, and pH was 3 units higher in the 2 experimental locations compared to the control location. This indicates that the water bodies near hog farms have lower water quality, which is not suitable for aquatic life and is likely to be negatively impacted by hog farming. This study and its findings are important for understanding the impact of hog farming on the proximal water bodies.

INTRODUCTION

Hog farming is one of the leading agricultural industries in North Carolina (NC). In 2019, a study conducted by North Carolina State University (NCSU) stated that the NC hog farming industry accounts for over $10 billion in the state economy and the creation of over 44,000 new jobs (1). As of September 2022, there were a total of 8.3 million hogs and pigs in NC (2). This increase in production has led to positive economic impacts, making NC the second largest hog producer in the United States, trailing behind Iowa (2). Multiple factors have led to the increase in hog production, such as modern technologies, environmental regulations, waste management systems, and lower costs to produce hogs (3). As the hog farming industry continues to expand in NC, the positive impact that it has on the economy increases as well. Currently, 50.5 pounds of pork are consumed annually by an average American, and by 2031 that amount is predicted to increase by 1.5 pounds per person (4). To accommodate the increasing demand for meat, hog production will have to increase as well. Despite the positive economic benefits of the increase in hog production, there has been an increase in the negative effects of hog farming on the environment. Nitrification and eutrophication are common downsides of hog production, and they occur due to excess nutrients that come from runoff (5).

Nitrification is the conversion of ammonia into nitrate in the soil, which can cause nitrate leaching and gaseous nitrous oxide (N_2O) production (6). This can lead to lower-quality soil, which can destabilize the environment and affect aquatic life through the nitrification cycle. Lower-quality soil tends to hold less water, which results in the increase of runoff into lakes and streams. The excess nutrients that the soil cannot hold are then cast into aquatic environments through runoff. In some cases, nitrification can have a positive impact on the growth of plant life, but when it is in the form of ammonia it can increase the toxicity in the water streams and pollute the environment. Eutrophication occurs when the excessive amount of nutrients from fertilizers in water causes the rapid growth of algae or phytoplankton, also known as algae blooms. These algae blooms create dead zones, which are areas with a reduced level of oxygen in the water. This reduced level of oxygen leads to a decrease in the population of aquatic life, which contributes to the instability of the environment. Eutrophication also leads to higher pH levels, increasing certain pollutants' toxicity (7).

Nitrification and eutrophication stem from improper waste management, which occurs when waste from hog farms is released into the environment rather than in secure locations. Lagoons are small water sectors separated from larger water bodies, which agricultural and livestock farms use to dispose of waste (8). In 2021, one million tons of hog waste entered NC waterways because there were two holes in a Jones County lagoon (9). All the waste from the hog farm leached into the Trent River of NC which supplied water to local communities in NC (9). Lagoons can also be damaged by natural disasters such as floods and earthquakes, which can spread waste into water bodies and create detrimental impacts on the environment (10).

Surface runoff from hog farms can carry nitrogen and phosphate fertilizers to water bodies, which can cause unrestricted nitrification (11). Excess nitrification stimulates eutrophication but can also influence changes in the long-term population of phytoplankton from desired species to invasive species (12). Non-native species that grow at rapid rates and dominate the native species are known as invasive species, which can cause harm to the native species.

The goal of this research study was to determine if the water quality of aquatic environments near hog farms is negatively impacted. We hypothesized that the experimental group, Beaverdam Creek and Neuse River, would have lower water quality with higher turbidity, total dissolved solids (TDS), and pH values when compared to the control group, Crabtree Lake values because of the proximity of Beaverdam Creek and Neuse River to hog farms. Other studies have measured microbial load to assess water quality and satellite imagery to determine the negative impact of hog farms on the environment. Our study specifically addresses the water quality near hog farms in NC using a self-built and portable Arduino UNO Rev3 (AUR3)-based water quality sensor to measure three parameters (pH, turbidity, and TDS) to determine water quality. We chose to test the turbidity, TDS, and pH because they are physical and chemical indicators of water quality. We found that all three parameters were significantly higher in the experimental group compared to the control group indicating that hog farming could potentially impact the water quality in NC water bodies.

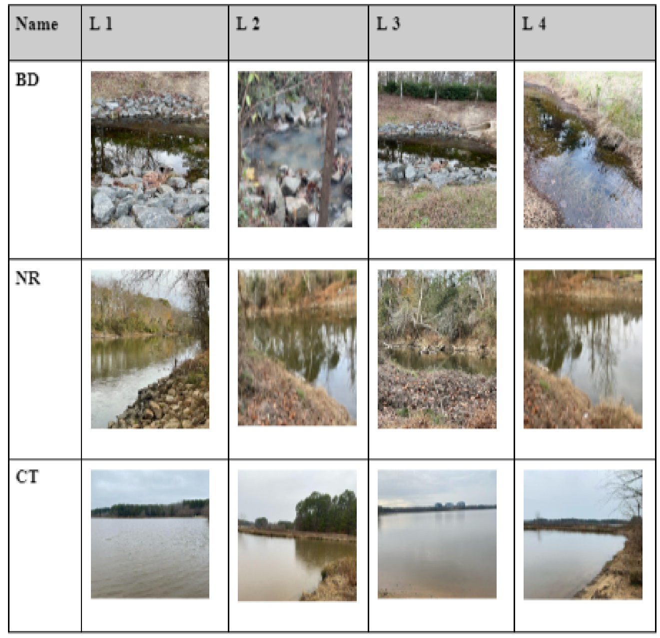

Figure 1. Images of sampling locations. We sampled three locations to determine water quality. For each site, we took 3 samples from 4 sublocations at each site for a total of 12 samples. Beaverdam Creek (BD) and Neuse River (NR) were close to hog farms (less than three miles) and served as our experimental groups, while Crabtree Lake (CT) was greater than three miles from a hog farm and served as our control.

RESULTS

To evaluate our hypothesis, we collected 50 ml of water at three locations, namely Beaverdam Creek, Neuse River, and Crabtree Lake (**Figure 1**). At each location, we used 4 sub-locations to collect water with 3 replicates each, resulting in 12 representative samples for each location. We took samples at 2 timepoints (November 12th and 19th, 2022) to account for any environmental impacts on the data collected, resulting in a total of 72 samples. We measured turbidity, pH, and TDS for each sample using the sensors connected to a laptop to record the raw values (**Figure 2**). To determine the statistical significance of the water quality values, we used the ANOVA followed by a post hoc Tukey HSD Test from an ANOVA-based statistical calculator.

Turbidity of water samples

Turbidity is the relative clarity of a liquid, and the turbidity sensor retrieves nephelometric turbidity units (NTU) through light transmittance in the water sample. The amount of light that passes through the water sample determines the turbidity of the sample. The average turbidity, in NTUs, when sampled on November 12th was 1374.88 ± 190.84 for Beaverdam Creek, 2017.02 ± 142.65 for Neuse River, and 335.30 ± 19.95 for Crabtree Lake (**Figure 3**). The average turbidity when sampled on November 19th was 1857.18 ± 177.53 NTU for Beaverdam Creek, 1930.14 ± 16.06 NTU for the Neuse River, and 335.31± 19.95 NTU for Crabtree Lake. We saw that the raw NTU values for the experimental group were 4–6 times higher than that of the control group.

The measurements collected from the sensor result in a range of turbidity values. To find the nearest NTU value that represents the turbidity of the water, a conversion using removal efficiency was required to account for the percent change from initial turbidity to the final turbidity of the water (13). After converting the NTU values, we found that the nearest NTU at experimental locations is 4–6 times more than the control location for both timepoints (n = 12, one-way ANOVA, $p < 0.0001$) (**Table 1**).

TDS of water samples

TDS is a measure of the total dissolved solids in the liquid sample and is measured in parts per million (ppm). The TDS sensor works by measuring the conductivity of the dissolved solids in a water sample, including that of minerals, salts, and other conductive materials. The average TDS value,

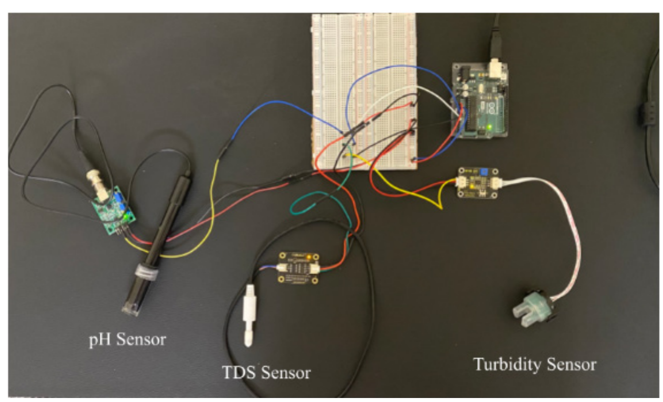

Figure 2. Aerial view of AUR3 Water Quality Monitoring System. We used the AUR3 water quality sensor which contains a pH, TDS, and turbidity sensor to determine the water quality in our samples. We generated the code for the AUR3 sensor using C++ in the Arduino IDE.

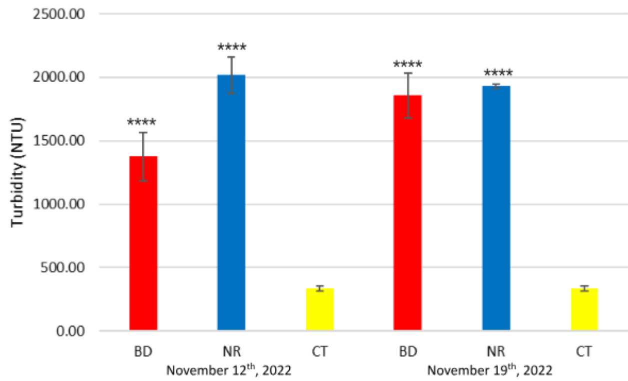

Figure 3. Turbidity is significantly higher in the experimental water bodies compared to the control water bodies (n = 12). Average turbidity (NTU) levels of each water body on November 12th, 2022, and November 19th, 2022. Error bars represent the standard error across all replicates from each sampling location and timepoint. We tested each replicate using the turbidity sensor from the AUR3 water quality sensor. ****p < 0.0001, ANOVA followed by post hoc Tukey HSD test for average NTU at Beaverdam Creek (BD) and Neuse River (NR) compared to Crabtree Lake (CT).

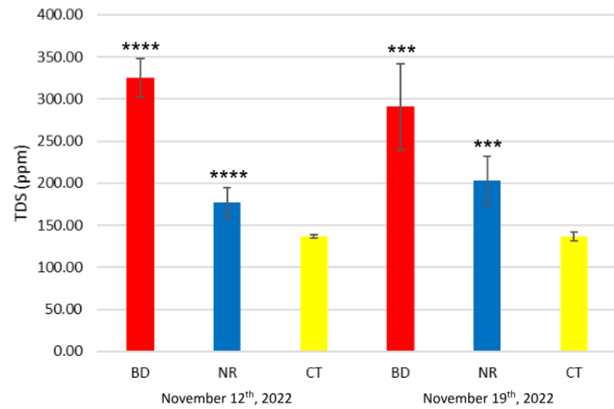

Figure 4. TDS is significantly higher in the experimental water bodies compared to the control water bodies (n = 12). Average TDS (ppm) levels of each water body on November 12th, 2022, and November 19th, 2022. Error bars represent the standard error across all replicates for each sampling location and timepoint. We tested each replicate using the TDS sensor from the AUR3 water quality sensor. ***p = 0.001 and ****p < 0.0001, ANOVA followed by post hoc Tukey HSD test for average TDS at Beaverdam Creek (BD) and Neuse River (NR) compared to Crabtree Lake (CT).

in ppm, on November 12th, 2022, was 325.03 ± 22.63 ppm for Beaverdam Creek, 176.55 ± 17.89 ppm for Neuse River, and 136.64 ± 1.67 ppm for Crabtree Lake. The average TDS value on November 19th, 2022, was 290.76 ± 51.16 ppm for Beaverdam Creek, 203.00 ± 28.76 ppm for Neuse River, and 136.64 ± 4.85 ppm for Crabtree Lake (**Figure 4**). The results indicate that TDS for Beaverdam Creek and Neuse River was 1.5–2 times higher than the TDS at the control location on November 12th, 2022 (n = 12, one-way ANOVA, p < 0.0001) and November 19th, 2022 (n = 12, one-way ANOVA, p = 0.001).

pH of water samples

The average pH on November 12th, 2022, was 12.17 ± 0.39 for Beaverdam Creek, 10.20 ± 0.98 for Neuse River, and 8.40 ± 0.26 for Crabtree Lake. The pH on November 19th, 2022, was 11.83 ± 0.45 for Beaverdam Creek, 10.32 ± 0.51 for Neuse River, and 8.40 ± 0.26 for Crabtree Lake (**Figure 5**). These results indicate that the pH in experimental locations was 2–3 units higher than the pH at the control location on November 12th, 2022 (n = 12, one-way ANOVA, p < 0.001) and on November 19th, 2022 (n = 12, one-way ANOVA, p < 0.0001).

DISCUSSION

Our results indicate that the turbidity, TDS, and pH are higher in water bodies near hog farms than in the control group that is not near a hog farm. This provides evidence that hog farming could negatively impact the aquatic environment in the localized region tested in NC. The turbidity at Beaverdam Creek and Neuse River was 1400–2000 NTU and Crabtree Lake was 300–400 NTU based on the conversions to the nearest NTU. For streams in NC, the recommended NTU range is 1–50 NTU, and for lakes and reservoirs, the recommended range is 1–25 NTU (14). Our measurements indicate that the NTU values are 56–100 times higher than the recommended range in the experimental group. General causative factors of high turbidity are usually suspended solids such as clay, silt, plankton, industrial waste, and sewage (14). The turbidity results indicated that the control location was above the normal range, but there were visible fish that could also stir up the bottom sediment during sample collection, suggesting that it could sustain certain aquatic life forms. However, Beaverdam Creek and Neuse River are not suitable for aquatic life since they exceed safe turbidity levels. Higher turbidity can lead to detrimental impacts on aquatic life as it reduces the amount of sunlight that can be accessed by plants underwater. This leads to lower levels of oxygen in the water bodies and results in an unsustainable environment for aquatic animals. Lower oxygen levels are also attributed to dead zones, which can be created by eutrophication. Eutrophication can contribute to higher turbidity levels as well, but in our samples, there were no apparent signs of eutrophication, so it may not have impacted the turbidity. High turbidity can also hinder a predator's ability to catch its prey in the water. Visually oriented animals need clear water to interact with their surroundings, and high NTU can be detrimental to their survival (15).

The TDS values were higher in Beaverdam Creek and Neuse River than in the Crabtree Lake sample. While we were testing the statistical significance of our results, the post hoc Tukey HSD test indicated that the November 19th, 2022, Neuse River and Crabtree Lake comparison was insignificant. This was our only comparison group that resulted in an insignificant test. This may have occurred due to high variance in the data resulting in a higher standard deviation. Some

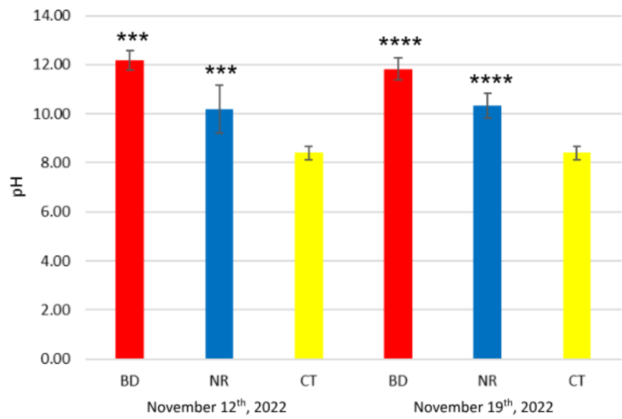

Figure 5. pH is significantly higher in the experimental water bodies compared to the control water bodies (n = 12). Average pH levels of each water body on November 12th, 2022, and November 19th, 2022. Error bars represent the standard error across all replicates for each sampling location and timepoint. We tested each replicate using the TDS sensor from the AUR3 water quality sensor. ***$p < 0.001$ ($p = 0.000155$) and ****$p < 0.0001$, ANOVA followed by post hoc Tukey HSD test for average pH at Beaverdam Creek (BD) and Neuse River (NR) compared to Crabtree Lake (CT).

Table 1. Raw average NTU values are converted to the nearest reported NTU values based on the EPA conversion table

Sample Date	Location	Raw Average (NTU)	Converted Average (NTU)
Nov. 12, 2022	Beaverdam Creek	1374.88	1400
	Neuse River	2017.02	2000
	Crabtree Lake	335.50	340
Nov. 19, 2022	Beaverdam Creek	1857	1900
	Neuse River	1930.14	1900
	Crabtree Lake	335.51	340

NOTE: Average turbidity (NTU) values from each water body on November 12th, 2022, and November 19th, 2022. The converted values indicate that the turbidity in the experimental group is 4–6 times higher compared to the control group.

of the factors affecting the TDS variability could have been the direction and speed of the water current and any human activity in the proximal land areas. Higher TDS indicates that there are more dissolved solids, such as minerals and salts, in the water. This could result in an imbalance in the level of minerals in an aquatic environment. This can cause negative impacts on the health of aquatic animals because an optimal amount of minerals is needed for the survival of these animals. Minerals in the water help aquatic life maintain osmotic pressure in their bodies (16). Osmotic pressure occurs during osmosis and is required to stop fluid movement during the process of separating a solution from pure water through a semipermeable membrane (17). High TDS also impacts the gills and kidneys of aquatic organisms, affecting their survival rate (18). To determine the composition of contributing solids for high TDS, further study will be needed. One way to find the type of minerals in the water sample is by evaporating the water until the dissolved solids are separated from the sample. High TDS can also indicate the level of salinity in the water. Salt levels can increase as fertilizers that are used in hog farms enter the water bodies through runoff. Higher salinity can lead to a decrease in aquatic life because it impacts the mineral content in the water which is crucial to the survival of various species. This change in TDS can cause unsuitable conditions for plant and animal life in water, which can have adverse impacts on the environment.

The pH level that is required for the sustainability of animal and plant life in water is in the range of 6.5–8.5 pH (19). If the pH levels increase above this range, this indicates that the water is alkaline. If it decreases below this range, it indicates that the water is acidic which can negatively impact aquatic life. The pH range in the control group from 8–9 pH indicates it is suitable for aquatic life, while the pH levels in Beaverdam Creek and Neuse River in the range of 10–12 pH are not suitable for the sustainability of aquatic animals. High pH values can increase the toxicity of ammonia, which is observed when nitrification occurs (20). Ammonia-nitrogen (NH_3-N) is known to have higher toxicity at higher pH levels and lower toxicity at lower pH levels. Beaverdam Creek and Neuse River samples could be impacted by the toxicity of increased ammonia, which is harmful to aquatic life. Higher toxicity due to ammonia can lead to a decrease in aquatic life because it is difficult for organisms to efficiently remove the substance. This can result in causing a buildup of ammonia in aquatic organisms over time (21).

One confounding variable in this experiment is the inherent difference between the control and experimental water bodies, one being a lake and the others being a river and stream. The types of factors impairing water quality in these bodies are different. A water study in Iowa indicated that the tendency of rivers and streams to be impaired for aquatic life is higher than that of lakes due to factors such as higher turbidity, large watersheds, and greater susceptibility to fish kills from pollution inputs (22). In our research, other factors such as the free-flowing nature of Beaverdam Creek and Neuse River compared to the stagnant nature of Crabtree Lake could impact the measurements. Human recreational activity is higher in Crabtree Lake than in Neuse River and Beaverdam Creek based on the proximity to the collection site; however, the volume of Beaverdam Creek and Neuse River is much higher than in Crabtree Lake. This indicates that while we do observe a lower water quality in the samples that are in proximity to hog farms, a direct correlation between hog farming and water quality cannot be established with certainty.

While the replication within this study provides statistical robustness, we could conduct a future study including more locations throughout the NC region. This would improve the significance of the findings and add more statistical power. We could add collection dates throughout the year to monitor changes in parameters over time and incorporate different distances of the collection locations from hog farms for future studies. We could observe how various weather patterns influence water quality levels. Rain is a factor that could augment runoff, which leads to an increase in pollutants in water bodies. To save data regarding the water quality in water bodies, we can connect the SD board and an RTC breakout board to the Arduino UNO microcontroller. The SD board will store the values of pH, turbidity, and TDS, and the RTC board will store the date that the sample was tested. Data from this could be combined with other parameters such as microbial quality measurements of concentrated animal feeding operations and the composition of minerals in the water to provide a comprehensive water quality analysis by integrating the datasets.

One reason hog farms are not using proper waste management systems is the economic cost that it entails (23). Without considering the environmental penalty, hog farms cause harm to the environment to reduce costs. Enforcing stricter regulations on hog farming could reduce improper waste management and hence reduce the negative impact hog farms have on the environment. Creating environmental protection zones for water bodies that are highly contaminated should also be enacted to ensure that the water body is not impacted further by hog farms.

This is the first study using an AUR3-based sensor system that measures turbidity, pH, and TDS in water bodies near hog farms. The portability of the sensor gives the flexibility of using it directly in the field at the site of collection for the end user. This research study is significant as it documents the lowered water quality based on turbidity, TDS, and pH measurements among water bodies that are near hog farms and provides some support for the consideration of water quality monitoring and proper waste management systems by hog farms.

MATERIALS AND METHODS

Water quality sensor setup

This research was conducted using an AUR3-based water quality monitoring system. The AUR3 is connected to a laptop to receive information regarding water quality through input/output (I/O) from the microcontroller. The setup for the AUR3 consisted of a USB cable that connects the microcontroller to the computer. The AUR3 connected the pH, turbidity, and TDS sensors through a breadboard, a solderless board that connected with AUR3 to the sensors with only jumper wires. The GND pin was used to obtain consistent input from the sensors that could be compared with relative values from the microcontroller. The voltage reference was 3.3–5.0 V.

The turbidity sensor has a potentiometer, which is typically used in calibration, but in the process of creating this water quality sensor, it was not required (**Figure 2**). The turbidity sensor retrieves nephelometric turbidity (NTU) values through light transmittance in the water sample. The amount of light that passes through the water sample determines the turbidity of the sample.

TDS is a measure of the total dissolved solids in the liquid sample and is measured in parts per million (ppm). It was measured through the conductivity of the dissolved solids as detected by the TDS sensor on the AUR3.

The pH sensor was calibrated using three standard buffer solutions at: 4.01 pH, 7.00 pH, and 10.00 pH. The calibration process took 30–60 min for each buffer solution to maintain consistent pH values.

Water sample collection

Water samples were collected from two water bodies, Beaverdam Creek and Neuse River. These locations were chosen because they were located within a three-mile radius of three hog farms. After a review of the literature, no previously determined distance indicated hog farming's impacts on water quality. A three-mile radius was determined as the cutoff because Beaverdam Creek and Neuse River were in a three-mile proximity of a hog farm and were in a zone with various hog farms in the proximal distance. Beaverdam Creek was 0.5 miles from a hog farm and because Beaverdam Creek flows into Neuse River, which is 2.5 miles from a hog farm, the 3-mile radius was established to understand the impacts of hog farming on water quality. At each location, water was collected from four sublocations (L1, L2, L3, L4) and three replicates from each sublocation to maintain accuracy and reproducibility. Each location was visited twice in a one-week interval. The first collection was on November 12th, 2022, and the second collection was on November 19th, 2022. For the control group, water collected from Crabtree Lake which is not located near a hog farm was tested. A total of 72 water samples were collected. 50 mL of water was collected from the surface of the shore at all locations to maintain consistency in depth at the collection site.

Water sample testing

To analyze the samples, the code for each sensor was generated in the Arduino IDE. The code reads in the raw inputs from each sensor, which are converted to the voltage values (3.3–5.0 V). For each sensor, the voltage values are then converted to the specified units. For the TDS and pH code, a buffer array was created to obtain accurate data. The buffer array reads 10 values from the sensor which is then sorted using a bubble-sort algorithm. By sorting the array, the values from positions 2 to 8 can be accessed, and the average of these values was used to find an accurate value for pH and TDS. The values were then output to the serial monitor and stored in Excel for future analysis. Three replicates for each sublocation were taken to compensate for any deviation while testing the water sample and reported an average of three replicate values for each. To maintain consistency, each location was tested in the same way.

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REFERENCES

1. Schuster, Dinah. “Partner Profile: North Carolina Pork Council.” *N.C. Plant Science Initiative*, 9 Feb. 2021. www.cals.ncsu.edu/psi/news/partner-nc-pork-council/. Accessed 15 Dec. 2022.
2. “September 2022 Hog Report.” *USDA*, 29 Sep. 2022. www.nass.usda.gov/Statistics_by_State/North_Carolina/Publications/Press_Releases/HogRelease09.pdf. Accessed 16 Dec. 2022.
3. Hurt, C. “Hog Production Booms In North Carolina: Why There? Why Now?” *Purdue University*, 16 Aug.1993. www.ag.purdue.edu/commercialag/home/paer-article/hog-production-booms-in-north-carolina-why-there-why-now/. Accessed 17 Dec. 2022.
4. Shahbandeh, M. “Per Capita Consumption of Pork in the United States from 2015 to 2031” *Statista*, 2 Mar. 2022. www.statista.com/statistics/183616/per-capita-consumption-of-pork-in-the-us-since-2000/. Accessed 15 Dec. 2022.
5. “Nutrients and Eutrophication.” *Water Resource Mission Area*, 3 Mar. 2019. www.usgs.gov/mission-areas/water-resources/science/nutrients-and-eutrophication. Accessed 17 Dec. 2022.
6. Beeckman, Fabian, *et al*. “Nitrification in agricultural soils: impact, actors, and mitigation.” *Current Opinion in Biotechnology,* vol. 50, pp. 166-173, Apr. 2018.
7. Chislock, M. F., *et al*. “Eutrophication: Causes, Consequences, and Controls in Aquatic Ecosystems.” *Nature Education Knowledge,* vol. 4, no. 10, 2013.
8. “What Is a Lagoon?” *NOAA*, 20 Jan. 2023. www.oceanservice.noaa.gov/facts/lagoon.html. Accessed 3 Feb. 2023.
9. Sorg, L. “Hog Farm That Spilled 1 million Gallons of Feces, Urine into Waterways Had Been Warned of Lagoon Problems.” *NC Newsline*, 12 Jan. 2021. www.ncnewsline.com/2021/01/12/hog-farm-that-spilled-1-million-gallons-of-feces-urine-into-waterways-had-been-warned-of-lagoon-problems/. Accessed 18 Dec. 2022.
10. Weesjes, Elke. “While Flood Water Recedes, Animal Waste Pollution Doesn’t.” *Natural Hazards Center*, 28 Oct. 2016. www.hazards.colorado.edu/article/hogs-and-hurricanes-while-flood-water-recedes-animal-waste-pollution-doesn-t. Accessed 20 Dec. 2022.
11. Mateo-Sagasta, J., *et al*. “Water pollution from agriculture: a global review.” *Food and Agriculture Organization of the United Nations*, www.fao.org/3/i7754e/i7754e.pdf. Accessed 18 Dec. 2022.
12. Burkholder, J., *et al*. “Impacts of Waste from Concentrated Animal Feeding Operations on Water Quality.” *Environmental Health Perspectives,* vol. 115, no. 2, Feb. 2007.
13. Aravind, A., Fai, C. M., & Hua, C. K. “Feasibility Study of Pollutant Removal in Ringlet Reservoir using Lily Canna.” *International Journal of Engineering & Technology*, vol. 4, pp. 499-508, Nov. 2018.
14. “SEDIMENT-Related Criteria for Surface Water Quality.” *US EPA*, 19 Jan. 2017. www.archive.epa.gov/epa/sites/production/files/2015-10/documents/sediment-appendix3.pdf. Accessed 17 Dec. 2022.
15. Ortega, J. C. G., *et al*. “Negative effect of turbidity on prey capture for both visual and non-visual aquatic predators.” *Journal of Animal Ecology*, vol. 89, pp. 2427–2439, Aug. 2020.
16. Lall SP and Kaushik SJ. “Nutrition and Metabolism of Minerals in Fish.” *Animals (Basel),* vol. 11, no. 9, pp. 2711, 16 Sep. 2021.
17. Feher, J. “2.7 - Osmosis and Osmotic Pressure.” *Quantitative Human Physiology (Second Edition)*, pp. 182-198, 2017.
18. Wright, Karie A. “Effects of increasing total dissolved solids on the Walker Lake, Nevada, fishery,” *Natural Resources and Environmental Issues*, vol. 15, no. 16, 2009.
19. “Indicators: Acidification.” *EPA*, www.epa.gov/national-aquatic-resource-surveys/indicators-acidification. Accessed 21 Dec. 2022.
20. “Ammonia.” *EPA*, www.epa.gov/caddis-vol2/ammonia. Accessed 21 Dec. 2022.
21. Wurts, William. “Daily pH Cycle and Ammonia Toxicity.” *World Aquaculture*, vol. 34, pp. 20-21, 2003.
22. “Difference in Water Quality Impairments: Lakes vs. Rivers.” *Iowa Department of Natural Resources*, Mar. 2010. www.iihr.uiowa.edu/igs/publications/uploads/wfs-2010-09INSERT.pdf. Accessed 22 Dec. 2022.
23. Stolark, Jessie. “Stink, Swine, and Nuisance: The North Carolina Hog Industry and Its Waste Management Woes.” *Environmental and Energy Study Institute*, 10 Aug. 2018. www.eesi.org/articles/view/stink-swine-and-nuisance-the-north-carolina-hog-industry-and-its-waste-mana. Accessed 23 Dec. 2022.