Water Quality and Autonomous Surface Vessel Technology in the Ala Wai Canal

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ABSTRACT

Algal blooms are increasing in frequency in marine and freshwater ecosystems worldwide. Algal blooms can be detrimental to ecosystems as well as pose a public health risk to humans. The Ala Wai Canal, a drainage system that surrounds the tourist destination Waikiki Beach, has been contaminated by the harmful bacteria *Vibrio vulnificus* and sewage spills. *Vibrio vulnificus* has been shown to increase in growth and survival during algal blooms, and sewage spills can cause Waikiki Beach to close. Therefore, it is important to understand how water moves through and away from the canal. I examined data from February 2019 to determine the effects rainfall has on chlorophyll a and turbidity, and developed qualifications to determine the feasibility of deploying an autonomous surface vessel, specifically a Wave Glider, to aid in data collection and monitoring of this at-risk area. I found that rainfall led to two peaks occurring in both chlorophyll a and turbidity values, but found that chlorophyll a did not cause the peaks in turbidity to occur. I also found no distinguishable patterns between how large the peaks were, how long it took for the peaks to occur, and how much rain had fallen when the peaks occurred, which highlights the need for more advanced monitoring. I determined that a Wave Glider deployment is feasible if the vessel is properly monitored. A deployment could assist researchers and public health officials by providing data in real time and tracking variables of interest.

KEYWORDS

chlorophyll a, turbidity, rainfall, harmful algal blooms, public health

INTRODUCTION

Algal blooms occur in freshwater and marine ecosystems worldwide and are increasing in frequency (Hallegraeff 1993). Algal blooms are naturally occurring phenomena that form under conditions of excess sunlight, high levels of nutrients, and slow-moving water (Fraga et al. 1988). However, their formation can be anthropogenically induced by fertilizer application, agriculture, urban runoff, or other sources that contribute to excessive nutrient loading (Glibert et al. 2005). The blooms are classified as Harmful Algal Blooms (HABs) when they become detrimental in one of two ways: (1) when their presence impacts other organisms and food web dynamics; or (2) when they increase production of toxins in the water (Anderson et al. 2002).

HABs impact other organisms by altering the abiotic factors of an environment. The density of the bloom can decrease visibility for other organisms as well as block sunlight from penetrating beyond the surface of the water (Glibert et al. 2005). With less sunlight, plants lower in the water column can no longer photosynthesize, which decreases the oxygen available for other organisms. As the bloom begins to die off and is decomposed by microorganisms via respiration, the oxygen in the water decreases further. These hypoxic conditions stress ecosystems and may result in “dead zones” where many organisms have left or died (Joyce 2000).

HABs can also increase toxins in the water by production from the algae (Carmichael 1994). For example, different species of cyanobacteria produce various toxins in both marine and freshwater environments that can poison organisms (Sivenson 1990). Toxic red tide-causing dinoflagellates produce brevetoxin or saxitoxin, which can kill marine mammals (Trainer and Baden 1999). Diatoms produce the neurotoxin domoic acid which accumulates in shellfish and causes seizures in shellfish-consuming organisms (Legebvre et al. 1999). Furthermore, algal blooms may enhance toxic bacteria growth and survival. Recently, the bacteria *Vibrio vulnificus* has been shown to have enhanced growth and survival rates in the presence of algal blooms (Greenfield et al. 2017). *Vibrio vulnificus* may cause death in humans if ingested via contaminated shellfish or via contact with an open wound (Jackson et al. 2017, Bross et al. 2007).

The Ala Wai Canal on Oahu has historically been contaminated by *Vibrio vulnificus* and sewage spills. The Ala Wai Canal was built in 1928 as part of a drainage system (“Ala Wai

Canal" 2014). It borders the northern and western edges of Waikiki beach, a major tourist destination. In 2006, a man died from *Vibrio vulnificus*-related complications after swimming in the water outside of the canal with an open wound (Venzon 2007). There have also been sewage spills in the canal on multiple occasions; in one case, 48,000,000 gallons were released due to inadequate drainage infrastructure (City and County of Honolulu 2006). Repeated contamination events could impact the state's economy as tourism-related activities on Waikiki Beach alone can contribute 8% of the state's Gross State Product (Department of Business 2003). Thus, it is important to understand how rainfall affects phytoplankton blooms, and in turn water quality, to reduce public health hazards in this at-risk area.

Unfortunately, monitoring and mapping algal blooms in the area is difficult without advanced technology. The State of Hawai'i Department of Health routinely checks popular beaches to ensure that the water quality meets public health standards, but frequent fluctuations in the water may result in contamination between checks (Clean Water Branch 2017). Autonomous surface vessel technology, such as the Wave Glider by Liquid Robotics, may provide valuable insight into the fluctuations of phytoplankton blooms and other water quality parameters. In this study, I examine water quality fluctuations in the Ala Wai Canal, asking the following questions: (1) how does rainfall affect water quality, specifically chlorophyll a and turbidity, in the Ala Wai Canal? (2) how feasible is deploying an autonomous surface vessel near the Ala Wai Canal and how could it aid in monitoring public health risks? This research provides insight for future studies in modeling algal blooms and harmful bacteria and sheds light on the necessity for investment in more advanced technology.

METHODS

Study site

The study site for this research is the Ala Wai Canal, located at 21.2871° N, 157.8312° W. The Ala Wai Canal borders Waikiki Beach, a major tourist destination, in Honolulu, Hawaii (Figure 1). The surrounding watershed drains in to the Ala Wai Canal, and the canal diverts the water from Waikiki Beach.

Figure 1. Study site. The Ala Wai Canal surrounds Waikiki Beach.

Water quality

Data collection

I analyzed rainfall, chlorophyll a, and turbidity data for the month of February because it allowed me to examine periods with and without rainfall. I used February 2019 hourly rainfall data from the Honolulu International Airport Sensor monitored by the National Oceanic and Atmospheric Administration. I used the February chlorophyll a and turbidity measurements from a fluorescent dissolved organic matter (FDOM) sensor located at the Hawaii Yacht Club at the mouth of the Ala Wai Canal. The sensor is submerged approximately half a meter in the water and collects data approximately every 6 minutes. I accessed this open-source coastal observation data at smartcoastlines.org (University of Hawai'i 2019).

Data analysis

To analyze my data, I first converted the date and time codes into Coordinated Universal Time for uniformity. Next, I broke the data down into rainfall events. I set the start of a rainfall event at 12:00am on a day that rainfall occurred. I set the end of the event at 11:59pm of the day that rainfall occurred, given that there was no rainfall for at least 24 hours after. Then for each rainfall event, I plotted each of the variables against each other: rainfall and turbidity; rainfall and chlorophyll a; and turbidity and chlorophyll a in Excel. I then qualitatively analyzed the relationships between rainfall and chlorophyll a, rainfall and turbidity, and chlorophyll a and turbidity. I also counted how many peaks in turbidity and chlorophyll a occurred after the rain started, how large those peaks were, how long it took for those peaks to occur, and how much rain had fallen when the peaks occurred. Finally, I computed simple statistics such as average, minimum, maximum, and standard deviation values for each event.

Autonomous surface vessel deployment feasibility

Wave Glider tool

A Wave Glider is an autonomous surface vessel created by Liquid Robotics (Figure 2). It consists of a surfboard-sized platform and towable submarine connected via an umbilical cord either four or eight meters in length. The submarine has fins, and the Wave Glider propels itself by adjusting the fins according to the phase of the water wave. On the platform, there is a solar panel that can power multiple sensors and probes, and a computer to store the data. The Wave Glider can avoid other ships via the ship Automatic Identification System (AIS).

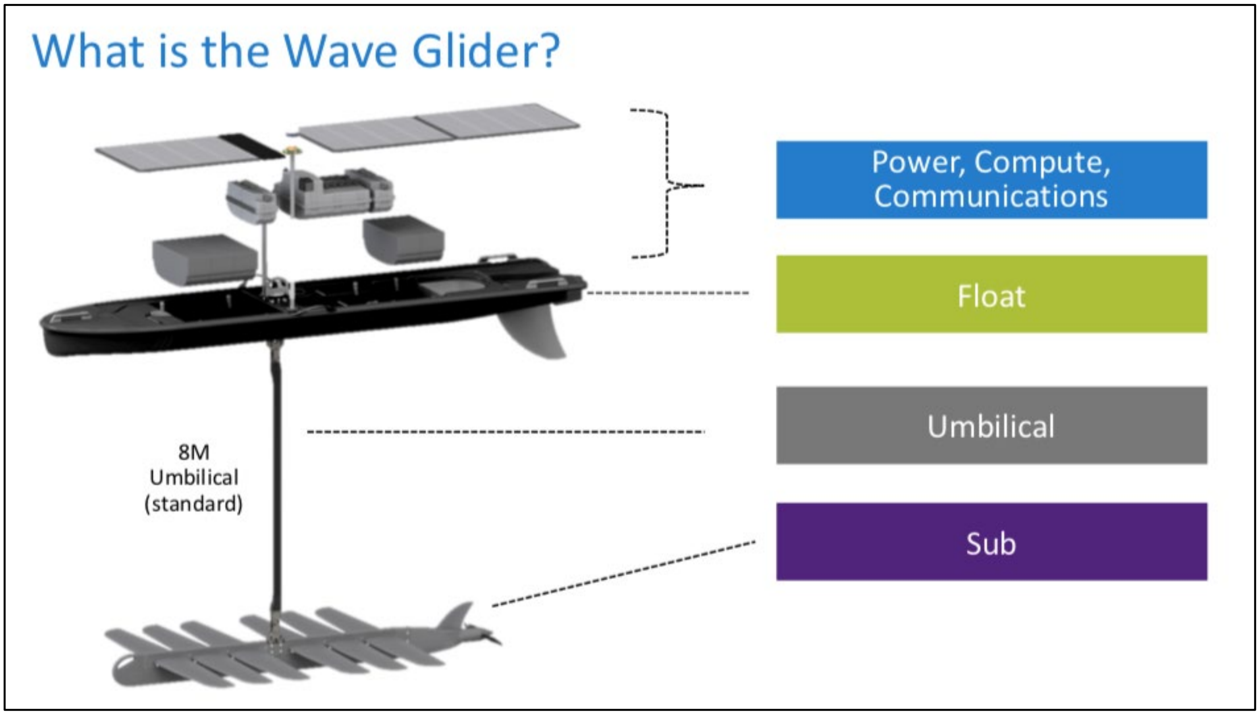

Figure 2. Wave Glider and parts. Source: Liquid Robotics.

Qualifications

To determine the feasibility of deploying a Wave Glider in my study area, I developed the following four criteria after interviewing Florybeth La Valle, a postdoctoral researcher who has previously attended Wave Glider deployment trainings from Liquid Robotics and previously deployed a Wave Glider (Table 1).

Table 1. Wave Glider Deployment Feasibility Qualifications.

Qualification	Considerations	Additional Notes
Bathymetry	Does the depth of the study area allow for the Wave Glider and the submarine to safely navigate?	If using the four meter or eight meter umbilical cord, the depth must be at least five meters and nine meters, respectively.
Vegetation	Does the geographic location and trophic state of the water indicate that there could be vegetation that could entangle the submarine? Does local knowledge indicate the presence of vegetaion or outcroppings on the seafloor that could entangle with the submarine?	
Proximity to Land	Will rough seas or a rogue wave potentially run the vessel aground? Will the distance hinder easy tracking and pickup were something to go wrong?	
Proximity to Recreational Areas	Is the Wave Glider in danger of hitting people or other boats not connected to AIS?	

Collectively, these four qualifications can inform a decision on if the determined study area is a viable place to deploy the Wave Glider.

With these qualifications, I aim to determine how a Wave Glider can contribute to ongoing research by the University of Hawai'i in and around the canal. Currently, researchers manually take monthly measurements at 18 way points (Figure 3).

Figure 3. Current research waypoints. Each yellow dot represents a waypoint.

Data analysis

To address Qualification 1 (Bathymetry), I used the Wave Glider Management Software to examine the depths of the proposed study area. To address Qualification 2 (Vegetation), I used local knowledge and analyzed the geographic location of the study area to determine the trophic state of the waters. To address Qualification 3 (Proximity to land), I examined a detailed map of the area on Google Earth. To address Qualification 4 (Recreational area), I researched how the surrounding area is used by the public.

RESULTS

Water quality

There were five rainfall events for the month of February ranging from one to five days (Table 2).

Table 2. Rainfall event durations.

Rainfall Event	Dates	Duration (days)
1	February 7	1
2	February 10 – February 11	2
3	February 13 – February 17	5
4	February 19 – February 20	2
5	February 25 – February 27	3

The data indicate that chlorophyll a fluctuates with rainfall, although rainfall is not the cause of all the fluctuations. This is most evident in the flucuations that occurred between February 21 and February 24 when no rainfall occurred (Figure 4).

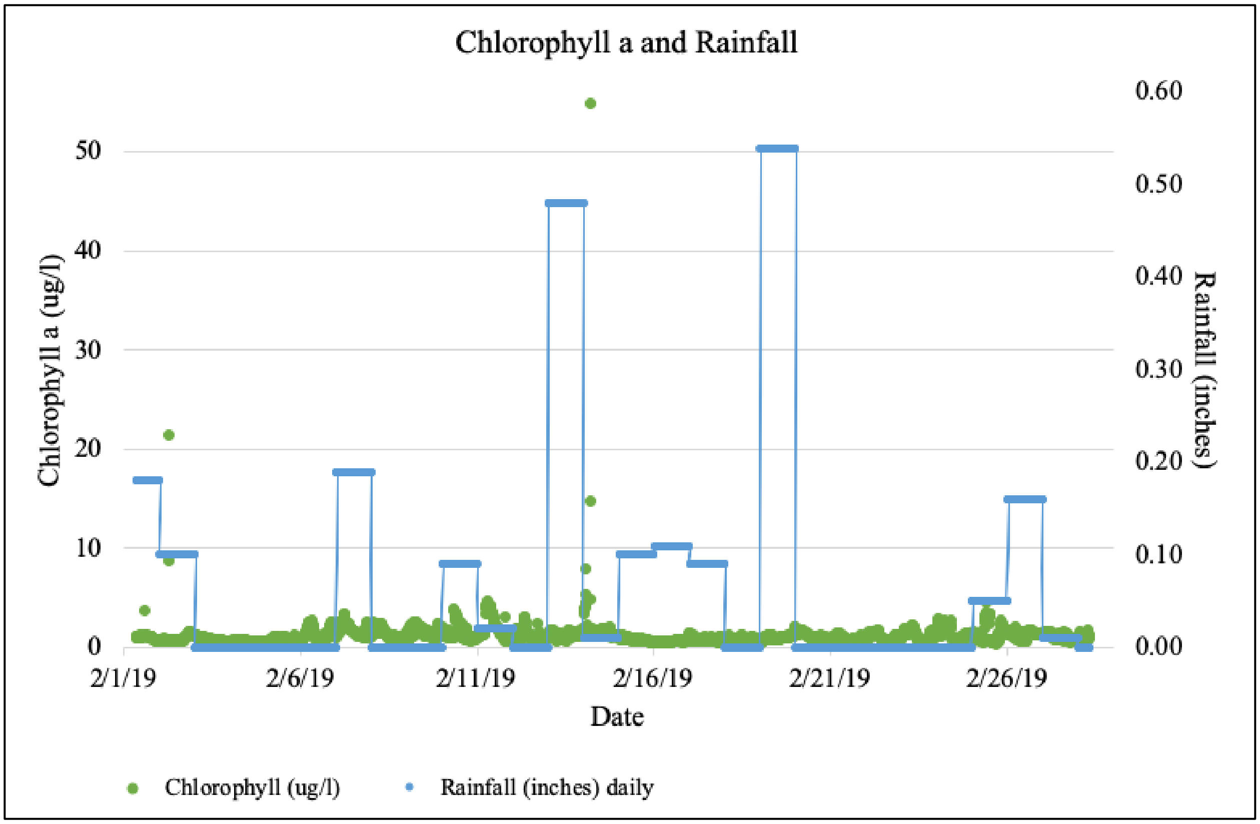

Figure 4. Chlorophyll a and rainfall throughout February.

The data indicate that turbidity fluctuates with rainfall as noticeable peaks occur during or slightly after rainfall occurs. However, the turbidity does not fluctuate in predictable manner. A noticeable example of this is a turbidity peak of approximately 350 NTU after 0.5 inches of rainfall on February 13 and a peak of less than 10 NTU after 0.54 inches of rainfall on February 19 (Figure 5).

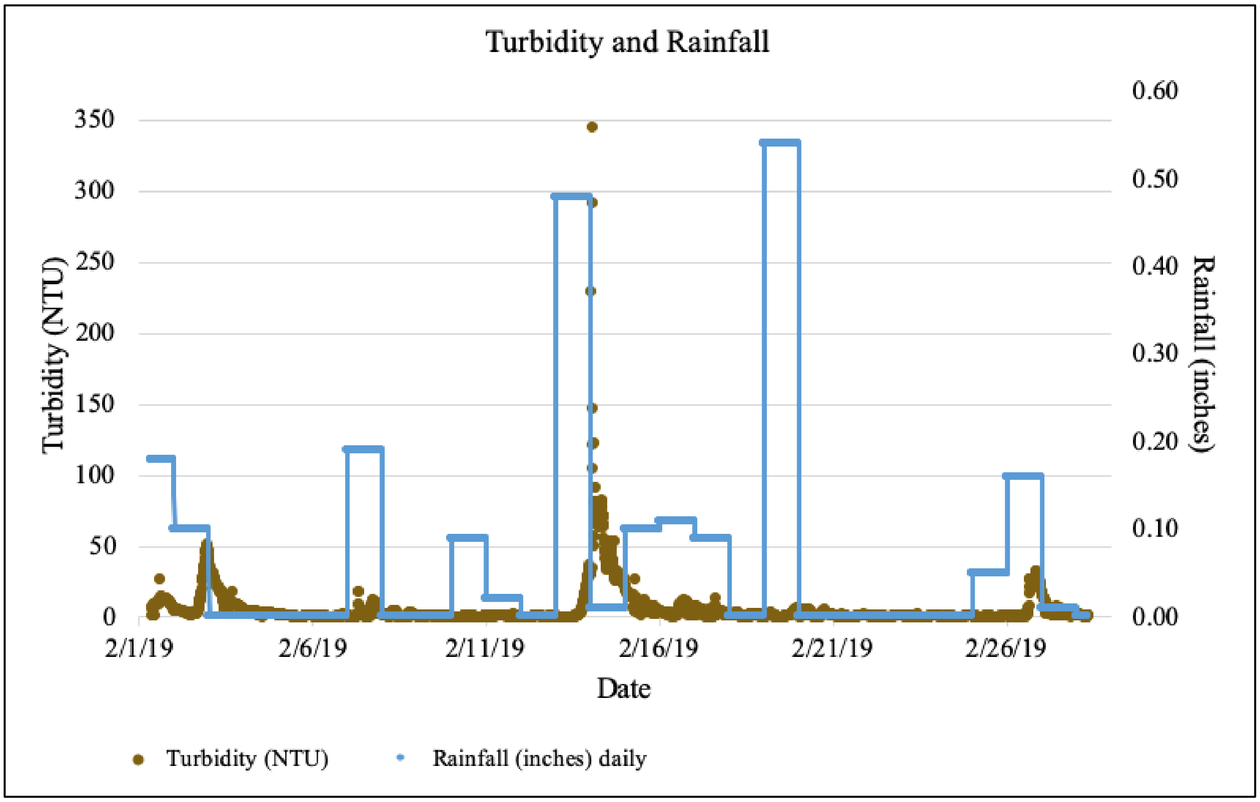

Figure 5. Turbidity and rainfall throughout February.

The data indicate that sometimes chlorophyll a and turbidity do correlate, but often they do not; chlorophyll a has much more variation throughout the month than turbidity. Additionally, when turbidity fluctuates, it is delayed when compared to chlorophyll a (Figure 6).

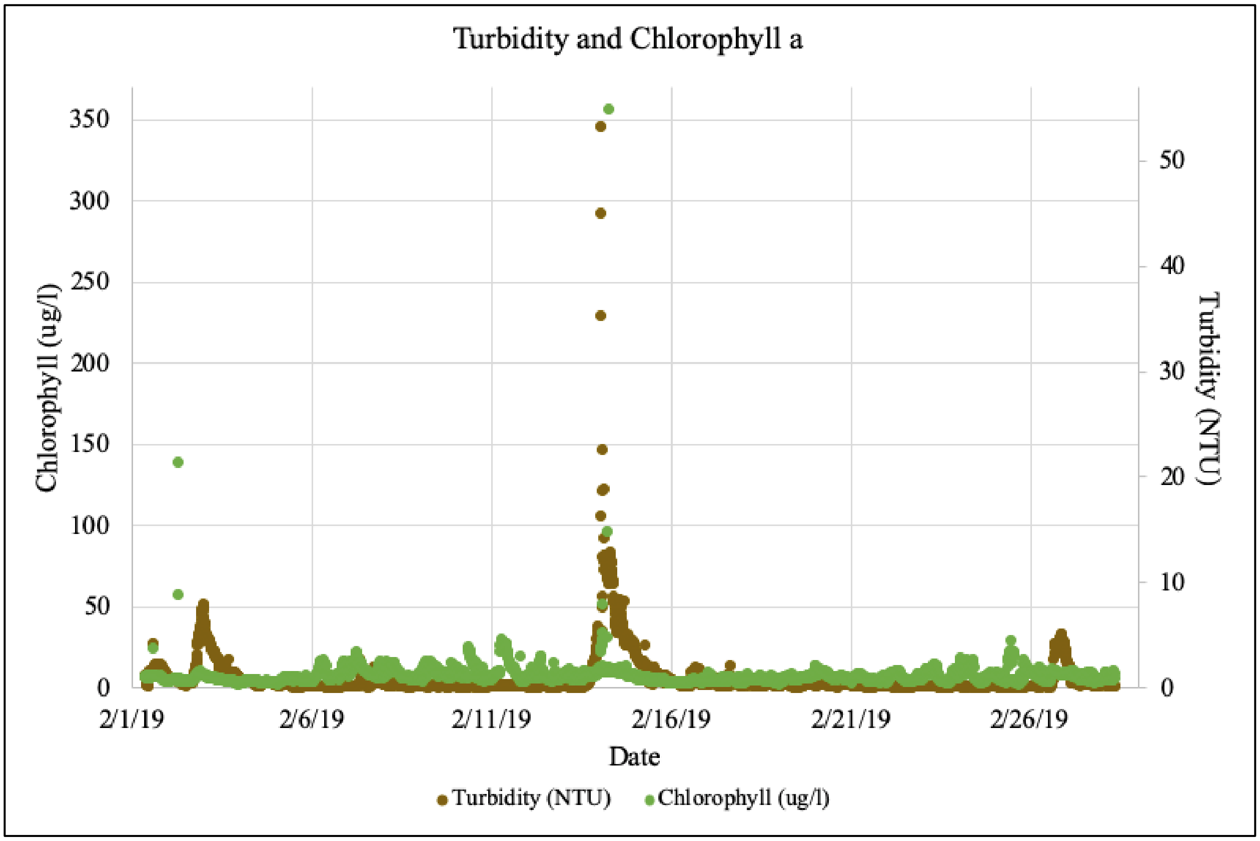

Figure 6. Chlorophyll a and turbidity throughout February.

I was able to discern two peaks each in both chlorophyll a and turbidity for each rainfall event. Table 1 shows the maximum values of the discernable peaks for each rain event, the time between first rainfall and peaks in chlorophyll a and turbidity, and the amount of rain that had fallen when the peaks in chlorophyll a and turbidity occurred. The maximum values for chlorophyll a and turbidity for the first peak of the third rainfall event show that the values are much higher than other maximum values during other events. Apart from two peaks per value per event, there were no other clear and observable patterns within the data as indicated by relatively large standard deviations.

Table 3. Results for each rainfall event. Maximum values for each category are indicated in green; minimum values for each category are indicated in orange.

Event	Chlorophyll a (ug/l)	Peak After (hour)	Cumulative Rain (inch)	Turbidity (NTU)	Peak After (hour)	Cumulative Rain (inch)
1	3.40	0.3	0.10	17.98	1.30	0.17
1	2.45	0.8	0.17	12.72	4.80	0.17
2	4.62	5.3	0.10	2.20	1.70	0.09
2	3.09	6.4	0.11	2.04	0.60	0.10
3	54.90	5.8	0.49	345.98	3.40	0.48
3	1.49	7.2	0.70	11.79	3.40	0.69
4	2.08	3.8	0.54	6.70	2.90	0.54
4	2.08	5.0	0.54	6.28	2.20	0.54
5	2.69	1.5	0.04	33.17	1.80	0.21
5	1.65	5.7	0.21	27.81	2.30	0.21
Average	7.85	4.18	0.34	44.67	2.44	0.32
Standard Deviation	15.71	2.34	0.23	100.26	1.16	0.21

Autonomous surface vessel deployment feasibility

Bathymetry

Only three of the current waypoints used for monthly sampling are accessible as the canal itself is too shallow to deploy a Wave Glider (Figure 7). However, there is opportunity to add more points outside of the canal and to track different blooms once outside of the canal.

Figure 7. A map of feasible waypoints for Wave Glider sampling. The yellow dots are currently sampled waypoints and the orange circles indicate feasible waypoints.

Vegetation

Oahu is located in oligotrophic waters, so I do not expect there to be kelp beds or other vegetation in the waters.

Proximity to land

I conclude that the Wave Glider will need to be monitored because the area outside the canal is within a few meters of land.

Recreational area

I conclude that the Wave Glider will need to be monitored because Waikiki beach is a few meters away from the area outside the canal.

Feasibility

Overall, it is possible to deploy a Wave Glider in this area with proper monitoring.

DISCUSSION

Although these results provide some insight into how rainfall affects and increases chlorophyll a and turbidity near the Ala Wai Canal, the vague patterns indicate the need for more research. Deploying an autonomous surface vessel has the potential to add significant value to public health water quality monitoring by recording how water leaving the canal travels out and away from the system. The Wave Glider could also provide detailed information on any other variables of interest researchers or public health officials may be interested in such as pH, refined fuels, temperature, and salinity if they invest in the proper sensor technology.

Water Quality

Rainfall, chlorophyll a, and turbidity

Rainfall did impact and increase chlorophyll a and turbidity as demonstrated by the peak in each variable that occurred after the start of a rainfall event. This result confirms expectations from the literature (Amraoui et al. 2009, Ahn et al. 2002). However, the relationship between turbidity and chlorophyll a is less clear. Turbidity often peaked after the chlorophyll a peaked, which contradicts the conceptual understanding of the two variables. Chlorophyll a and turbidity should peak at the same time as an increase in phytoplankton would cause the water to be less clear (indicating higher turbidity). Instead, only one of the events had peaks that occurred almost at the same times. Thus, although rainfall increases turbidity, the increase in turbidity is likely not caused by the increase in chlorophyll a.

Rainfall and chlorophyll a

Nine out of ten peak chlorophyll a values were within approximately 3 ug/l of each other. However, the first peak of the third rainfall event is a significant exception to this pattern – the value is approximately 340 ug/l higher than the other values. It is difficult to conclude what caused this extremely high measurement, but it does not appear to be a glitch as the surrounding data points were similar in value. A likely explanation is that because the third rainfall event had the most rainfall, more nutrients entered the water via runoff and more phytoplankton grew. It is of interest, though, that even though this value was much larger than other peak values, it was far from the 30,000 ng/l value indicating a phytoplankton density large enough to be classified as an algal bloom (Mallin et al. 2008).

Rainfall and turbidity

The magnitude of the turbidity fluctuations between the peak values was larger than the corresponding fluctuations for chlorophyll a. Because I determined that the peaks in turbidity were not due to increases in chlorophyll a, the turbidity measurements in this study are difficult to analyze. Because turbidity is simply a measure of light scattering by suspended particles, it is impossible to determine what directly caused the fluctuations without further analysis of nutrients and sediment in the water.

Autonomous surface vessel deployment feasibility

My development of qualifications for a feasible Wave Glider deployment is the first of its kind. Because the Wave Glider deployment near the Ala Wai Canal proved feasible, it is important to consider what kind of benefits a deployment could provide beyond more frequent water quality measurements of the contents of the canal. Currently, beaches are checked routinely by public health officials (Clean Water Branch 2017). A Wave Glider could provide frequent and real time insight at a variety of sampling points. In the event of a sewage leak, the Wave Glider could aid in determining exactly what sections of recreational beach areas are contaminated, as well as track the leak to monitor where any contaminants go and how they disperse in the water (Seegers et al. 2017). If a beach has to close, it has the potential to affect many of the five million visitors that Oahu entertains each year (Murar 2017). Although the Wave Glider has a steep initial cost of approximately $300,000 not including the sensors, the possibility for multi-year use and keeping sections of beaches open that would normally automatically close in a contamination event provide economic incentive for the purchase (Takahashi 2018). Additionally, there are few other alternatives to gather data this frequently in a mobile way. Buoys only cover small areas and can be expensive. High tech research vessels can cost up to $20,000 per day, meaning the cost would be equal to that of a Wave Glider after fifteen deployment days (Liquid Robotics 2017). Wave Gliders are durable and can be deployed for about a year at a time, then deployed again after cleaning, making them the best option for gathering frequent data in a mobile way.

Limitations and future directions

Although my study design answered the questions I set out to answer, there are some limitations. First, my water quality analysis was limited to just one month due to time constraints, so it is difficult to provide extensive evidence for the conclusions I drew. Possible next steps are to look at other months between the wet and dry seasons, and compare to other data gathered on the island, such as in Kaneohe Bay (Mallin et al. 2008). Additionally, if the sensor used remains at its post for multiple years, a comparison of year to year data could be conducted. Finally, more intensive time series analysis could be done on the data to account for daily, seasonal, and yearly fluctuations, via methods such as Shapiro-Wilks test for normality in the variables, correlation analyses between variables, and comparing means and maximums between seasons and years (Devi and Sarangi 2017, Mallin et al. 2008).

Another consideration is that I did not include dissolved oxygen in my analysis as the sensor did not have the capacity to measure it. If I had the data, it would have been a beneficial addition as dissolved oxygen is another important indicator of water quality. Although the manual monthly measurements by the University of Hawai'i do measure for dissolved oxygen, I could not analyze or draw conclusions from the singular data point for the month of February.

Broader implications

As algal blooms continue to increase in frequency worldwide, it is important to understand the factors contributing to their formation (Hallegraeff 1993). This study was an important step in analyzing these factors for a specific watershed. However, the base of the time series analysis and the qualifications for Wave Glider feasibility can be applied to any watershed, and any tourist beach area. Furthermore, by connecting sensors for temperature and pH in the long term, there is a possibility to contribute valuable data to monitoring climate change by determining the extent of warming and ocean acidification. Marine and freshwater ecosystems are and will continue to be in constant flux. To understand the role humans play and how we are impacted, collecting data to understand these ecosystem changes is the first step.

ACKNOWLEDGEMENTS

Writing a thesis takes a village, especially when things go wrong. Thank you to Florybeth la Valle and Thomas Azwell for accepting me into their research project and mentoring me throughout this process. Thank you to the ESPM 175 team, especially Ellen Plane, for assisting me in any and all struggles as well as sitting through many sessions of office hours. Thank you to Dr. Brian Glazer at the University of Hawaii for access to open-source coastal observing data via smartcoastlines.org, supported by the NSF (OCE1737357) and Schmidt Marine Technology Partners. Thank you to Dr. Craig Nelson and Jessica Bullington, also at the University of Hawaii, for their assistance and support. Finally, thank you to my family and friends for still loving me even though I only talked about this for a year!

REFERENCES

Ahn, C.Y., A.S. Chung, and H.M. Oh. 2002. Rainfall, phycocyanin, and N:P ratios related to cyanobacterial blooms in a Korean large reservoir. Hydrobiologia 474:117–124.

Ala Wai Canal (Waikiki Drainage Canal). 2014. Historic Hawaii Foundation. https://historichawaii.org/2014/02/19/ala-wai-canal-waikiki-drainage-canal/. Accessed 03/27/2019

Amraoui, F., M. Razack, and L. Bouchaou. 2009. Turbidity dynamics in karstic systems. Example of Ribaa and Bittit springs in the Middle Atlas (Morocco). Hydrological Sciences Journal 48:971–984.

Anderson, D. M., P. M. Glibert, and J. M. Burkholder. 2002. Harmful algal blooms and eutrophication: Nutrient sources, composition, and consequences. Estuaries 25:704–726.

Bross, M. H., K. Soch, R. Morales, and R. B. Mitchell. 2007. Vibrio vulnificus infection: diagnosis and treatment. American Academy of Family Physicians 76:539–544.

Carmichael, W. W. 1994. The toxins of cyanobaceria. Scientific American 270:78–84.

City and County of Honolulu. 2006. Crack found in beachwalk force main; sewage diverted to emergency bypass. City and County of Honolulu.

Clean Water Branch. 2017. Hawai'i's beach monitoring program. Hawai'i Department of Health. Hawai'i.

Department of Business, Economic Development & Tourism. 2003. The Economic Contribution of Waikiki. Department of Business, Economic Development & Tourism. Hawai'i.

Devi, K. N., and R. K. Sarangi. 2017. Time-series analysis of chlorophyll-a, sea surface temperature, and sea surface height anomalies during 2003–2014 with special reference to El Niño, La Niña, and Indian Ocean Dipole (IOD) Years. International Journal of Remote Sensing 38:5626–5639.

Fraga, S., D. M. Anderson, I. Bravo, B. Reguera, K. A. Steidinger, and C. M. Yentsch. 1988. Influence of upwelling relaxation on dinoflagellates and shellfish toxicity in Ria de Vigo, Spain. Estuarine, Coastal and Shelf Science 27:349–361.

Glibert, P., D. Anderson, P. Gentien, E. Granéli, and K. Sellner. 2005. The Global, Complex Phenomena of Harmful Algal Blooms. Oceanography 18:136–147.

Greenfield, D. I., J. G. Moore, J. R. Stewart, E. D. Hilborn, B. J. George, Q. Li, J. Dickerson, C. K. Keppler, and P. A. Sandifer. 2017. Temporal and Environmental Factors Driving Vibrio Vulnificus and V. Parahaemolyticus Populations and Their Associations With Harmful Algal Blooms in South Carolina Detention Ponds and Receiving Tidal Creeks. GeoHealth 1:306–317.

Hallegraeff, G. M. 1993. A review of harmful algal blooms and their apparent global increase. Phycologia 32:79–99.

Jackson, J. K., R. L. Murphree, and M. L. Tamplin. 1997. Evidence that mortality from Vibrio vulnificus infection results from single strains among heterogeneous populations in shellfish. Journal of Clinical Microbiology 35:2098-2101.

Joyce, S. 2000. The Dead Zones: Oxygen-Starved Coastal Waters. Environmental Health Perspectives 108:120–125.

La Valle, F. April 1, 2019. Personal interview.

Lefebvre, K. A., C. L. Powell, M. Busman, G. J. Doucette, P. D. R. Moeller, J. B. Silver, P. E. Miller, M. P. Hughes, S. Singaram, M. W. Silver, and R. S. Tjeerdema. 1999. Detection of domoic acid in northern anchovies and california sea lions associated with an unusual mortality event. Natural Toxins 7:85–92.

Liquid Robotics. 2017. The New Economics of Marine Environmental Monitoring. Liquid Robotics: A Boeing Company. Sunnyvale, CA.

Mallin, M. A., V. L. Johnson, and S. H. Ensign. 2008. Comparative impacts of stormwater runoff on water quality of an urban, a suburban, and a rural stream. Environmental Monitoring and Assessment 159:475–491.

Murar, K. 2017, January 30. Hawaii visitor arrivals near 9M, spending hits new high of $15.6B in 2016. American City Business Journals. https://www.bizjournals.com/pacific/news/2017/01/30/hawaii-visitor-arrivals-near-9m-spending-hits-new.html.

National Oceanic and Atmospheric Administration. (2019). Local Climatological Data Daily Summary February 2019 [Table]. Retrieved from https://www.ncdc.noaa.gov/cdo-web/datasets/LCD/stations/WBAN:22521/detail

Seegers, B. N., E. N. Teel, R. M. Kudela, D. A. Caron, and B. H. Jones. 2017. Glider and remote sensing observations of the upper ocean response to an extended shallow coastal diversion of wastewater effluent. Estuarine, Coastal and Shelf Science 186:198–208.

Sivonen, K., S. I. Niemelä, R. M. Niemi, L. Lepistö, T. H. Luoma, and L. A. Räsänen. 1990. Toxic cyanobacteria (blue-green algae) in Finnish fresh and coastal waters. Hydrobiologia 190:267–275.

Takahashi, D. 2018, December 12. Liquid Robotics launches new generation of wave glider ocean robots. VentureBeat. https://venturebeat.com/2013/04/08/liquid-robotics-launches-new-generation-of-wave-glider-ocean-robots/.

Trainer, V. L., and D. G. Baden. 1999. High affinity binding of red tide neurotoxins to marine mammal brain. Aquatic Toxicology 46:139–148.

University of Hawai'i at Manoa School of Ocean and Earth Science and Technology. (2019). Chlorophyll (EX/EM: 470/695nm) [Table]. Retrieved from http://grogdata.soest.hawaii.edu/smart/dataportal/node-116/C/

University of Hawai'i at Manoa School of Ocean and Earth Science and Technology. (2019). Turbidity (700nm) [Table]. Retrieved from http://grogdata.soest.hawaii.edu/smart/dataportal/node-116/N/

Venzon, N. C. 2007. Massive Discharge of Untreated Sewage into the Ala Wai Canal (Oahu, Hawaii): A Threat to Waikiki's Waters? Journal of Environmental Health 70:25–31.