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Article

A low-cost, Arduino-based system for real-time abiotic monitoring of a local watershed

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SUMMARY
The Chesapeake Bay faces serious challenges, like pollution, from human activity. However, local data on its tributaries, like the Little Paint Branch Stream in Montgomery County, Maryland, are often outdated or incomplete. For example, existing data for Little Paint Branch is limited to biotic indicators (Index of Biotic Integrity), with the most recent data collected in 2016. Including recent, continuous abiotic measurements would improve our understanding of water quality changes on daily to seasonal timescales. To address this gap, we assessed the Little Paint Branch watershed's condition in 2021 using abiotic measurements and examined how water quality varies over time. We hypothesized that the watershed would be in poor condition due to local construction and deforestation and that water quality shows daily and seasonal variation. To test this, a solar-powered, field-deployable Arduino-based prototype was built that measured turbidity, temperature, and pH four times daily in summer and winter, with three replicates per time point. The device featured internet connectivity for real-time monitoring and rapid response. Contrary to our hypothesis, abiotic data showed the watershed was in generally good condition. Our results showed that water temperature remained stable after 2 p.m. and closely followed air temperature; turbidity peaked at 2 p.m. on weekends and was higher on weekdays in winter, possibly due to runoff or human activity; and pH rose throughout the day, especially on weekends, which may affect aquatic life locally and downstream. This low-cost system shows how accessible technology can allow residents to monitor their environment, increase awareness, and preserve watersheds.

INTRODUCTION
The Chesapeake Bay is the largest estuary in the United States (1). It supports diverse ecosystems, provides jobs through industries like fishing and tourism, and serves as a recreational and cultural source for the approximately 18 million people living within its watershed, which spans six states and the District of Columbia (1). However, due to human activities, the Bay faces serious problems that need to be addressed. Some of the main environmental issues affecting the Chesapeake Bay include pollution from agriculture, urban development, and industrial activities (2). For example, excess nutrients and sediment from farms can cause harmful algal blooms that deplete oxygen in the water, creating dead zones that threaten fish and shellfish populations, which is a direct hit to the region's fishing industry (2). Similarly, polluted runoff from cities and towns carry oil, trash, and toxic chemicals into the Bay, degrading water quality and making popular swimming, boating, and recreation areas unsafe, which negatively affects tourism (3). Industrial waste products can introduce heavy metals and other contaminants into the ecosystem, endangering both wildlife and human health (4). These threats not only damage the Bay's natural balance but also jeopardize the economic and cultural benefits it provides to the 18 million people living in its watershed.

The Chesapeake Bay Foundation (CBF) has current recommendations for fixing environmental problems (2). Agriculture contributes excess nitrogen, phosphorus, and sediment, leading to harmful algal blooms and dead zones, or low-oxygen areas in the water where few organisms can survive (3). The CBF recommends implementing best management practices like cover crops, riparian buffers, and regenerative farming to mitigate these effects by reducing runoff and improving soil and water quality (2). Urban and suburban development further exacerbate pollution through stormwater runoff carrying fertilizers, pesticides, and oil into waterways (2). Green infrastructure solutions such as rain gardens, permeable pavements, and green roofs can address this issue by slowing and filtering runoff, reducing the volume of pollutants entering streams, and promoting natural infiltration (2). Industrial activities introduce toxic chemicals and heavy metals into the bay, and CBF also emphasized the need for stricter discharge regulations and cleaner production technologies to reduce this contamination (2). In addition to CBF's advocacy and outreach efforts, the Chesapeake Bay Program is a regional partnership of federal and state agencies, nonprofits, academic institutions, and citizens that takes a science-based, collaborative approach to restoring the Bay (4). Unlike CBF, which is a private nonprofit focused on advocacy and education, the Chesapeake Bay Program coordinates data collection, policy implementation, and monitoring across jurisdictions (2, 4). The Chesapeake Bay Program also offers practical tips for individuals, such as reducing fertilizer use, conserving water, and planting native species, to help protect the Bay (4). Together, both efforts aim to reduce pollution and restore the Bay's ecosystem for future generations.

Although these actions can directly and indirectly help the Chesapeake Bay, it would be difficult to make a large change as individuals. However, to truly keep the bay as clean as possible, people can start at the root of the problem: the local watersheds that drain into the bay. If small communities can work together to keep their local streams clean, then little by little, the quality of the Chesapeake Bay will improve as well. Thus, our goal was to assess the quality of Little Paint Branch, a watershed in Montgomery County, using abiotic factors to better understand the influence of our community's

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waterway to water quality in the Chesapeake Bay (**Figure 1**, **2A**). Little Paint Branch is a watershed assigned connected to Paint Branch, which is assigned to 53,659 people and flows into the Northeast Branch of the Anacostia River (and onward to the Chesapeake Bay) (5). It is a good example of a Chesapeake Bay watershed because it allows us to evaluate how local actions and environmental conditions may contribute to broader impacts on the Bay's ecosystem health, given its proximity to recreational parks and transportation. Although Little Paint Branch was marked as in "Fair" condition (out of "Excellent", "Good", "Fair", and "Poor") using the Index of Biotic Integrity (IBI), this data was from 2016, and therefore out of date and limited in scope (6).

The IBI is based on biotic factors, such as the presence and diversity of aquatic organisms, which reflect overall stream health but are not easily monitored in real-time (7). In contrast, abiotic factors (temperature, pH, dissolved oxygen, and turbidity) can be measured continuously and offer more immediate insights into environmental changes (7). For this reason, we aimed to update the quality assessment of Little Paint Branch in 2021 using abiotic indicators to provide a more current and responsive picture of watershed health. Although these factors are periodically measured through physical testing, given the ever-changing environment of the Chesapeake Bay, it would be beneficial to continuously monitor the local streams draining into the bay in order to identify any problems early and correct them as quickly as possible.

Low-cost, sensor-based monitoring systems have been successfully used in other watershed studies. A previous study developed an Arduino-based platform to track pH and turbidity in agricultural areas, and their results showed that these measurements could detect pollution spikes and long-term degradation trends (11).

In addition to being low-cost and accessible for community science, abiotic factors like turbidity, pH, and temperature are standard indicators of water quality used in environmental research and governmental monitoring programs. For example, studies by the U.S. Geological Survey (USGS) and Environmental Protection Agency (EPA) routinely rely on both abiotic and biotic metrics to assess watershed health, detect pollution sources, and guide restoration efforts (12). Similar studies have demonstrated that abiotic factors like temperature, pH, and turbidity are effective indicators of stream health. A previous study monitored urban streams and found that turbidity and pH strongly correlated with nearby construction and stormwater runoff, supporting the idea that real-time abiotic data can reflect environmental impacts (13). Turbidity reflects the amount of suspended sediment in the water and often increases due to stormwater runoff, construction, or agricultural activity, and elevated turbidity can reduce light penetration, disrupt aquatic habitats, and transport attached pollutants, negatively affecting biodiversity (9). pH indicates the acidity or alkalinity of the water, and values outside the typical freshwater range can stress or kill aquatic organisms and increase the toxicity of certain contaminants, often because of industrial and agricultural waste products (10, 14). Water temperature influences metabolic rates and dissolved oxygen availability, and elevated temperatures which are commonly associated with urbanization can lower oxygen levels and exceed the tolerance of sensitive species, leading to reduced aquatic diversity (15, 16). Stream quality is classified as "Good" if turbidity was below 10 Nephelometric Turbidity Units (NTU), pH ranged between 6.5 and 8.5, and temperature remained under 20°C (8–10).

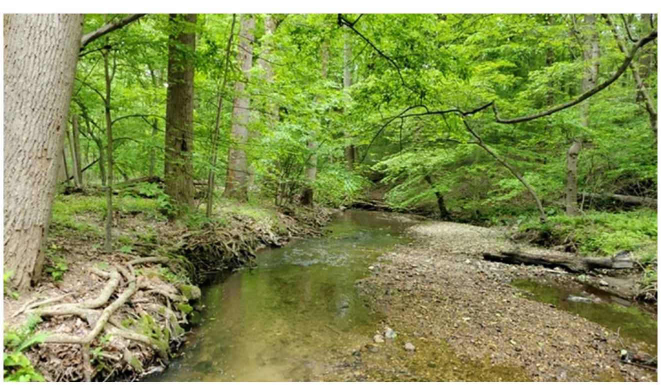

Figure 1: Little Paint Branch Stream. Photo of Little Paint Branch Stream where the water was collected for testing.

Watersheds, such as Little Paint Branch, are crucial to the health of the Chesapeake Bay. We created an inexpensive water monitoring device using an open-source Arduino electronics board to measure turbidity, temperature, and pH of the Little Paint Branch Stream to monitor its health. We hypothesized that the local watershed is not in good condition when evaluated using abiotic factors, due to increased construction and deforestation in the area. We also predicted that there would be both short-term (during the day) and long-term variability (seasonal) in water quality over time. First, we sought to find out the quality of the water in Little Paint Branch stream, which is our closest stream. Secondly, we compared the water quality changes during weekdays and weekends due to pollutants from factories, and if changes were evident due to seasonal (winter vs. summer) effects as well.

When small communities protect and restore their local streams, the collective impact can significantly improve the Bay's water quality over time. For example, in our study, we observed that water temperature remained stable after 2 p.m. and closely followed air temperature, while turbidity peaked at 2 p.m. on weekends and was higher on weekdays in winter, likely due to runoff or human activity. pH levels increased throughout the day, particularly on weekends, which could affect aquatic life locally and downstream. These patterns show how real-time data captures both natural variability and human impacts on watershed health. As climate change intensifies extreme weather and shifts seasonal patterns, continuous monitoring is important for early detection of issues like runoff, erosion, or pollution. By monitoring these conditions, communities can take proactive steps to protect local waterways and support the long-term health of the Chesapeake Bay.

RESULTS

A low-cost homemade water quality monitoring device using an Arduino Uno and a few sensors was made to measure water turbidity, temperature and pH to assess the more recent water quality of our local stream and monitor short- and long-term variability in water quality due to human, environmental, or seasonal interactions. The electronic components of the device were enclosed in a water-tight plastic container glued to a foam board and powered it with a rechargeable battery

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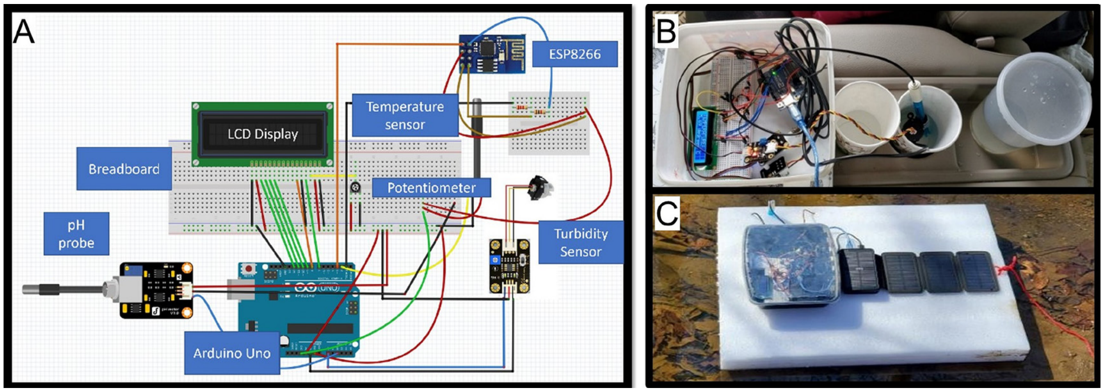

Figure 2. Water quality monitoring device. A) Circuit diagram, **B)** Prototype device for testing water quality inside a car, and **C)** Modified field-deployable, solar-powered, floating device that connects to the internet.

and solar panels to make it suitable for field deployment (**Figure 2A–C**). Data were collected from 10:00 AM to 4:00 PM on each measurement day, with sampling conducted on one weekend day and one weekday in winter and on two weekend days and two weekdays in summer for every two hours. Separate analysis of variance tests (ANOVAs) with Tukey-adjusted pairwise comparisons were used to assess differences at different times of day and in different seasons for each response variable (temperature, turbidity, and pH).

Water temperature increased throughout the day for both weekends and weekdays in both winter and summer, following a pattern similar to outside air temperature (**Figure 3**). This trend was especially evident in winter (**Figure 3C**). A significant increase of temperature in consecutive time points was seen from 10 am to 12 pm and from 12 pm to 2 pm on weekends (Tukey's pairwise comparison, $F(3, 8) = 112.8$, $p<0.05$, **Figure 3A**, **4**). In the summer, the temperature remained very similar on both weekends and weekdays but was also highly dependent on the outdoor air temperature (**Figure 3D**). It was only significantly increased between 10 am to 2 pm on weekends (pairwise, $F(3, 20) = 3.540$, $p<0.05$, **Figure 3B, 4**). During the winter, water turbidity changed throughout the day (on both weekdays and weekends) with significant increase at 2 pm on weekends compared to 12 pm (pairwise, $F(3, 8) = 4.295$, $p<0.05$), and the levels were generally higher on weekdays at each time point (pairwise, $F(3, 8) = 2.594$, $p<0.05$, **Figure 5A**, **6**).

During the summer, turbidity changed throughout the day, with a significant decrease on weekends compared to weekdays at 12 pm and 4 pm (multiple t-tests, $p<0.05$). It also increased significantly on weekends from 12 pm to 2 pm (pairwise, $F(3, 20) = 7.033$, $p<0.05$, **Figure 5B, 6**). In

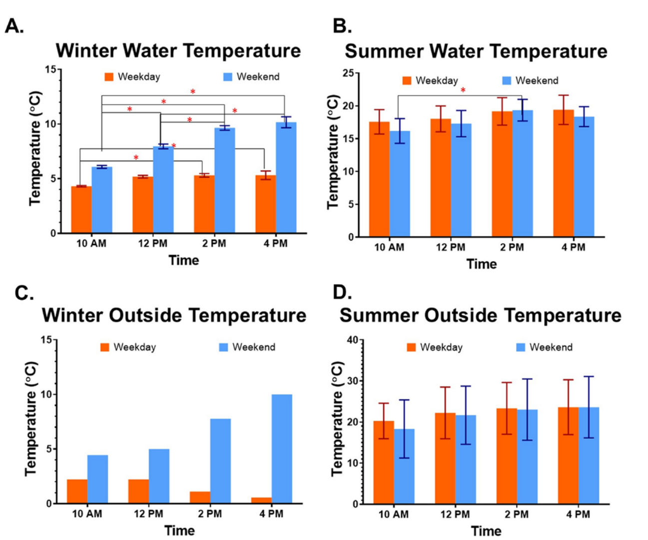

Figure 3. Water and air temperature readings during weekdays and weekends. One-way ANOVA with Tukey's multiple comparison tests were performed. Significant changes in water temperature ($p<0.05$) marked with horizontal lines and red asterisks. **A)** Winter water temperature (mean ± SEM, n=3, one independent experiment). **B)** Summer water temperature (mean ± SEM, n=6, two independent experiments). **C)** Winter outside temperature (n=1). **D)** Summer outside temperature (mean ± SEM, n=2, two independent experiments).

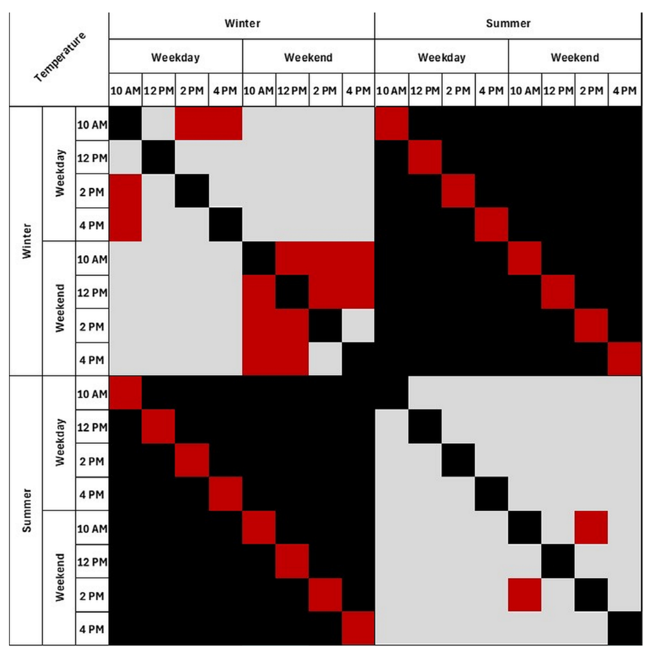

Figure 4. Composite figure of significant changes in water temperature. Red blocks identify significant comparisons ($p<0.05$), gray blocks identify non-significant comparisons, and black blocks identify no comparisons. Significance calculated with one-way ANOVA with Tukey's multiple comparison tests.

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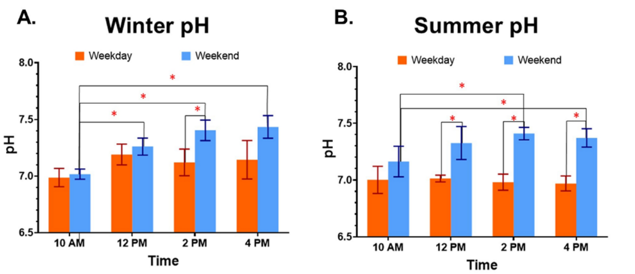

Figure 5. Water pH readings during weekdays and weekends. One-way ANOVA with Tukey's multiple comparison tests were performed. Significant changes in water pH (p<0.05) marked with horizontal lines and red asterisks. **A)** Winter water pH (mean ± SEM, n=3, one independent experiment). **B)** Summer water pH (mean ± SEM, n=6, two independent experiments).

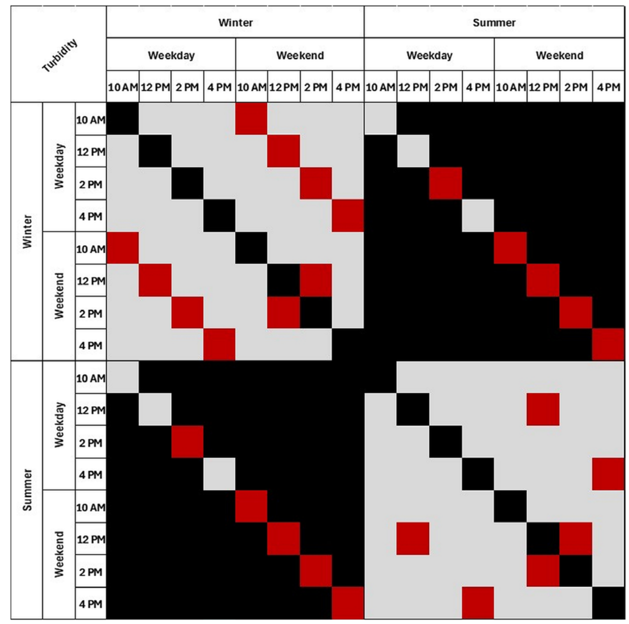

Figure 6. Composite figure of significant changes in water turbidity. Red blocks identify significant comparisons (p<0.05), gray blocks identify non-significant comparisons, and black blocks identify no comparisons. Significance calculated with one-way ANOVA with Tukey's multiple comparison tests.

the winter, the pH changed very little during the day with significant increase between morning and afternoon pH on weekends (pairwise, F (3, 8) = 16.69, p<0.05). The greatest difference between weekend and weekday pH was for the 2 pm measurements (multiple t-tests, p<0.05, **Figure 7A, 8**).

In the summer, the pH was significantly higher on weekend afternoons compared to weekdays and at 2 pm and 4 pm on weekends compared to morning (pairwise, F (3, 20) = 5.804, p<0.05, **Figure 7B, 8**). In summary, water temperature stabilized after 2 p.m. and mirrored air temperature trends; turbidity reached its highest levels at 2 p.m. on weekends and was generally greater on winter weekdays, likely due to runoff or human activity; and pH increased steadily over the day, particularly on weekends, which could influence aquatic ecosystems locally and downstream.

As expected, when comparing water quality data between winter and summer, a statistically significant difference was observed in water temperature readings at all timepoints indicating that water temperature was consistently higher in summer, likely due to elevated air temperatures (multiple t-tests, p<0.05, **Figure 4**). Turbidity levels also showed seasonal variation: on weekdays, turbidity was significantly lower in winter compared to summer only at 2 pm, while on weekends, turbidity was significantly higher in summer at all four timepoints, suggesting greater particulate matter or sediment disturbance in summer (multiple t-tests, p<0.05, **Figure 6**). In contrast, pH values did not show any statistically significant difference in seasonal variation at any timepoint (**Figure 8**).

DISCUSSION

We hypothesized that the watershed would be in poor condition due to human activity and that water quality shows daily and seasonal variation. Contrary to our hypothesis, the findings suggest that our local watershed is in relatively good condition based on abiotic measurements. Stream quality is classified as "Good" if turbidity was below 10 NTU, pH ranged between 6.5 and 8.5, and temperature remained under 20°C (8–10). In both winter and summer, the turbidity of our local stream hovered around 10 NTU, while pH values remained within 6.9 to 7.4. During winter, the water temperature stayed below 11°C, and in summer it reached a maximum of 19.4°C. These results indicate good water quality across both seasons and highlight a natural seasonal variation. However, this does not necessarily indicate an improvement in water quality between our data collected in 2021 and the data from 2016 provided by the Department of Environmental Protection, as a comprehensive assessment would require measurements of both biotic and abiotic factors, and neither the 2016 data nor our 2021 data include both (6).

Our second hypothesis that water quality changes throughout the day and differs between weekdays and weekends due to potential industrial pollutants was supported by the data. Water temperature increased in the morning and stabilized around 2 pm, correlating with ambient air temperature. Turbidity spiked at 2 pm on weekends and was notably higher on weekdays during winter (p<0.05). Similarly, pH increased throughout the day and was significantly higher in the afternoons, especially on weekends (p<0.05), suggesting potential anthropogenic influences. These patterns may be explained by specific human activities. Increased industrial waste flowing into rivers during weekdays, particularly from facilities such as wastewater treatment plants or manufacturing sites, can elevate levels of suspended solids which in turn affect both turbidity and pH. For example, a study of the Kłodnica River in Poland linked higher concentrations of total suspended solids, chloride, sulfate, and elevated pH directly to industrial and municipal discharges (14). On weekends, land-based recreational activities such as hiking or biking can result in soil compaction, vegetation loss, and erosion, all of which can introduce sediments into nearby streams and raise turbidity levels (15).

Despite these insights, several limitations may have impacted the results. The small sample size, particularly during winter (n = 3 samples collected at four different times throughout the day) reduces confidence in broader conclusions. Additionally, the study only spanned two seasons, winter and summer, which misses transitional

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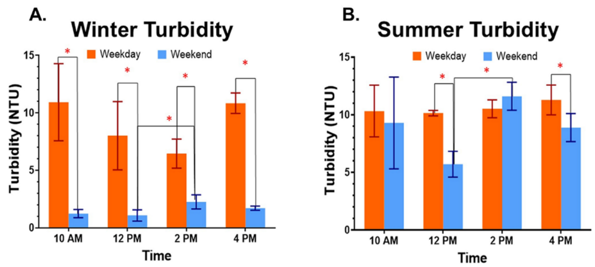

Figure 7. Water turbidity readings during weekdays and weekends. One-way ANOVA with Tukey's multiple comparison tests were performed. Significant changes in water turbidity ($p<0.05$) marked with horizontal lines and red asterisks. **A)** Winter water turbidity (mean ± SEM, n=3, one independent experiment). **B)** Summer water turbidity (mean ± SEM, n=6, two independent experiments). NTU: Nephelometric turbidity units.

periods such as spring and fall or events like post-rainfall runoff, which can greatly affect stream quality.

One notable exclusion from the project is the measurement of dissolved oxygen, which is a key indicator of stream health (16). This measurement requires an expensive sensor and therefore less available for communities. However, using it in future studies would provide a more complete picture of aquatic conditions. Further improvements could also involve tracking additional parameters such as surrounding vegetation, rainfall, and biotic indicators like macroinvertebrate populations. These would help bridge abiotic and biotic observations and better identify sources of variation in water quality.

The affordability and self-sufficiency of the device, powered by solar panels but requiring supplemental charging every 8–10 days, makes it a useful and promising tool that can used by many communities. Given its low cost and ease of deployment, this device could be adopted by citizen science programs or local schools as a hands-on tool for environmental monitoring, where community involvement and feedback could lead to more improvements and expand data collection efforts. Overall, this study demonstrates that low-cost, community-deployable sensors can capture meaningful daily and seasonal variation in abiotic water quality. These findings support accessible, real-time monitoring as a scalable tool for community engagement and early detection of environmental change relevant to watershed and Chesapeake Bay management.

MATERIALS AND METHODS

Device specifications

The water quality monitoring device was built using an Arduino Uno microcontroller board with sensors to measure water turbidity, temperature and pH. First, each sensor was tested individually and programed with the Arduino language. Second, each sensor was calibrated. Bottled water and whole milk were used to calibrate the turbidity sensor. The pH sensor was calibrated with pH 4.0 and pH 7.0 buffer solutions, white vinegar (pH ~2.5), and saturated solution of baking soda (pH ~8.5). The temperature sensor was calibrated using warm tap water at different temperatures and cold refrigerated water, with temperatures verified using a commercial thermometer. All three sensors were then attached together, calibration was fine-tuned, and the circuit diagram drawn using Fritzing software (18) (**Figure 2A-B**). The device was waterproofed using water-tight plastic container and hot glue and mounted to a foam board to be floatable. A Wi-Fi module and mobile hotspot were used to connect to the internet, and rechargeable batteries and solar panels were used to power the device (**Figure 2C**). Thus, the floating, solar-powered device was field-deployable and connected to the internet, which can be easily used by the communities to monitor water quality of local streams (Little Paint Branch stream in our case) in real time, thereby helping in early detection and rapid response (**Figure 1**).

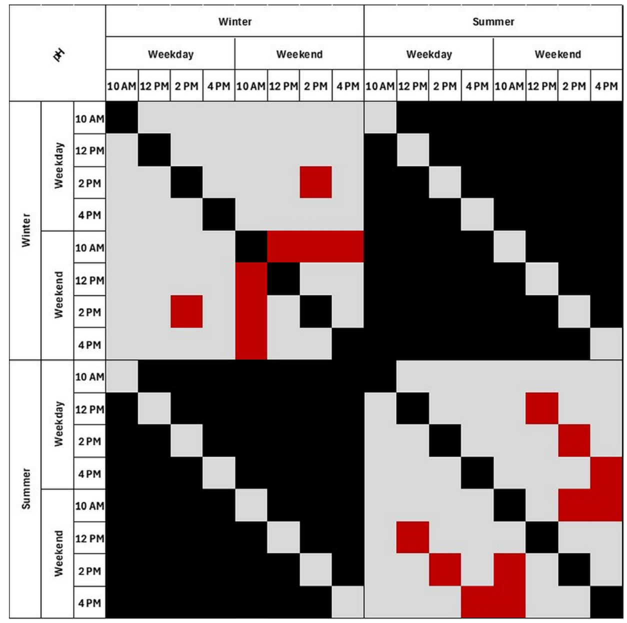

Figure 8. Composite figure of significant changes in water pH. Red blocks identify significant comparisons ($p<0.05$), gray blocks identify non-significant comparisons, and black blocks identify no comparisons. Significance calculated with one-way ANOVA with Tukey's multiple comparison tests.

Data collection

Samples were collected at four time points (10:00 AM, 12:00 PM, 2:00 PM, and 4:00 PM) on both weekends and weekdays during winter and summer, with three replicate samples collected at each time point. During winter, sampling was conducted on one weekend day and one weekday (n = 3 replicates per time point). During summer, sampling was conducted on two weekend days and two weekdays (n = 3 replicates per time point per day). A clean and dry, transparent plastic container with a lid was used to carry the water from the stream to a car parked nearby and the tests were run as soon as possible, with the car doors and windows open and AC off, to avoid affecting the temperature of the stream water. During summer experiments, the water was filtered to remove sand using a piece of folded cotton fabric. To ensure accurate readings from the turbidity sensor, the sensor was attached to the lid of an opaque plastic container to prevent light entering from outside. All sensors were calibrated for each measurement, and bottled water was used as a control for turbidity measurement. Outside temperature was also recorded from AccuWeather to see if the air temperature correlates with the water temperature.

Data analysis

To analyze the data, a one-way ANOVA was used to compare measurements taken at different times of day. Separate ANOVAs were used, one for each sensor's measurements. When the ANOVA showed a significant difference, Tukey's post-hoc test was used to identify the specific group differences. Multiple t-tests were performed between each time point for weekdays and weekends during winter and summer. Microsoft Excel and GraphPad Prism were used to analyze the data and to generate the plots (18).

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