Enhancing Stormwater Sampling Methods with UAV Water Collection Module

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***Abstract*—Traditional water collection methods can be laborious, time-consuming and sometimes dangerous. They require researchers to physically access and manually sample sites during or shortly after hazardous weather conditions due to the temporal nature of stormwater runoff. This also requires delay between sampling and analysis which can compromise time-sensitive metrics. Drone-based water collection provides a fast, efficient alternative capable of operating in adverse weather, offsetting potential cost increases. In the Piedmont Region of North Carolina, storm water runoff is a major source of pollutants, like nitrogen and phosphorus, and collecting samples during storms would expand available data. This research develops and tests a water-collection module for an unmanned aerial vehicle (UAV) implemented on a SwellPro Fisherman FD3 drone.**

The design is divided into five subsystems: sampling mechanism, water collection, sensor integration, communications array, and propeller guard. Water is collected using a small diaphragm pump and a modified sampling bottle that enables system flushing in accordance with water collection standards. In the sampling and collection system, pump tubing is spooled when not in use to prevent tangling and sway, using a 15 kg-cm servo and custom 3D-printed mechanisms. The intake tube is housed in a sampling cage containing dissolved oxygen, temperature, and pH sensors, enabling simultaneous sample collection and in situ measurement. The system provides real-time readouts and records data for later laboratory analysis. In the communication system, controls and telemetry are managed by two ESP-32-S3 microcontrollers communicating via LoRa HF modules. This modular architecture supports expandability, transferability to other UAVs, and independent subsystem development. Isolation from the primary drone controller enables granular power management, improved error handling, and reduced integration constraints.

Subsystems were evaluated through flushing efficacy, three-point load bearing stress tests, cable strength, sensor accuracy benchmarked against laboratory instruments, communications range and delay, and an efficiency comparison between UAV-based and traditional hand sampling measuring collections within a one-hour window. Full system testing was conducted at the Haw River, NC. This work aims to improve stormwater monitoring and support pollutant identification and prevention efforts in North Carolina's Piedmont Region.

***Index Terms*—System design, stormwater runoff, UAV water collection, water quality assessment**

I. Introduction

Stormwater runoff is a major source of pollutants to surface water bodies in the Piedmont Region of North Carolina. A first step in mitigating contamination is identifying its source, which is complicated by event characteristics, variable source areas of runoff, and pollutant transport mechanisms. Current approaches require significant sampling over large spatial areas during small windows of time when runoff is occurring. Collecting stormwater samples with a remotely controlled unmanned aerial vehicle (UAV) will facilitate high spatial resolution maps necessary for identifying the contribution of contaminants from intermittent channels and outfalls within hot moments of pollutant transport. While this introduces complications of operating a drone during a storm event, the drone would overcome many of the present complications in stormwater sampling. Thus, the objective of this research is to develop and validate a prototype module for a UAV system for collecting stormwater samples from both surface water and stormwater outfalls during storm events. Deliverables include a functional prototype that is weatherproof and capable of collecting 100 mL samples and probe data from open water and stormwater outfalls, and an engineered report.

Fig. 1. Full drone system with propellor guards, water sampling mechanism, and sensor implementation on a SwellPro Fd3 Fishing Drone.

II. Background and Motivation

To identify sources of pollutants, researchers must collect water samples to monitor the health of the ecosystem in the area [1]–[3]. The samples are tested for temperature, pH, and dissolved oxygen DO_2 [4]. These are critical indicators of the health of an aquatic system showing if the water is able to provide for the ecosystem that relies on it [4]. Using sample data, unhealthy water is identified and, more importantly, its source can be located and addressed. Specifically, this research will be implemented in the Haw River, where the pollutants are caused by various sources like waste, drainage systems, and more [5]–[8].

The ease of managing the challenges of water collection is an entirely different issue. Many methods are dangerous, challenging, and limited [9]–[11]. Significant research has been conducted to demonstrate the use and value of implementing unmanned aerial vehicles (UAVs) [12]–[15]. In addition, the use of UAVs for water sampling and testing is a rapidly growing field in the commercial market even in the timeframe of this project [16]–[19]. These systems are often expensive, difficult to obtain, and challenging to integrate with existing systems or drones. However, the commercialization of this growing technology and method indicates the demand and importance within environmental water studies.

This research implements a fishing drone from SwellPro shown in Figure 1, which utilizes control algorithms for stable weight carrying, implements water proofing technologies for salt and fresh water, and allows for precise GPS position holding for easier sampling [20].

III. Methodology

This research aims to develop and implement of a water sampling system connected to a SwellPro Fisherman FD3 Fishing Drone. The water collection device must be under 2 kgs, collect a minimum of one sample of 100 ml of water, and take less time to collect the sample than the traditional by hand method. The design will implement an interface between the user and the drone, record sensor information, and provide intuitive controls to operate the added system. The design implements a pump rather than raising and lowering a more traditional Van Dorn water sampling method. Further objectives are outlined within the technical design requirements (TDRs) which provide quantitative benchmarks to measure success.

After defining the problem, each major component of the solution was broken down into a subsystem, so that each subsystem would be developed concurrently and then all integrated together after. The solution was broken down into the sampling mechanism, water collection device, sensor implementation, communications array, and propeller guard system. All developed support pieces will be 3D printed using fused deposition modeling (FDM). The designs are made from PETG due to the UV and water-resistant features as well as the general strength.

A. Water Collection Testing

To establish a functional water collection subsystem, three primary tests were conducted to evaluate performance, reliability, and system integrity: defining the timing necessary for sampling filling, establishing the validity of testing, and ensuring a leak-proof design. The sample collection timing was recorded with the drone fully set up and elevated at set distances to establish the proper pump head, and noting how long it took to collect a full sample bottle, roughly 125 mL. To prove the flushing mechanism was successful, combine 115 mL of tap water and 10 mL of blue dye to generate an initial sample solution. Set up the system with the UAV elevated, and time how long it takes for the blue dye to be fully flushed from the sample container. Finally, use clean water to fill the sample bottle and fly the assembled system for 2-3 minutes, measuring the leftover water to ensure the leakage is minimal.

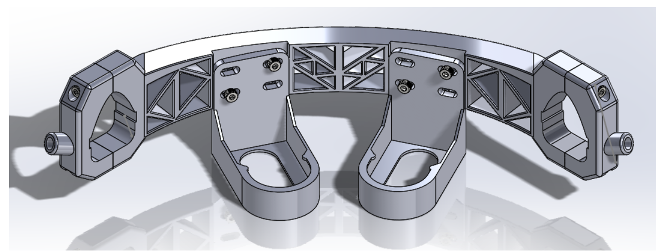

Fig. 2. A CAD assembly of the Water Collection Subsystem.

B. Spool Mechanism Testing

The spool mechanism subsystem was validated through a series of nine structured tests targeting servo torque capacity, encoder accuracy, structural integrity, operational durability, and failure behavior. Maximum torque was determined by securing the servo to a rigid fixture, attaching a 2.5 cm lever arm, and applying incremental force via a connected force sensor while commanding increasing power levels.

Encoder accuracy was assessed through video analysis using LoggerPro, in which a reference mark was placed on the spool and the servo was commanded through controlled rotations of 1, 5, and 10 revolutions; encoder counts were then compared against measured rotation to calculate percent error. Structural integrity of the spool mounts was evaluated using a three-point load test, in which simulated hose tension loads were applied incrementally up to twice the expected operating load while observing for deformation or cracking.

Operational durability was assessed by running the servo continuously under moderate load for one to two hours, after which gears, bearings, and mounts were inspected for wear or overheating. Material performance was examined by comparing deflection behavior under increasing load between a plastic and steel axle. Additional testing verified hose and wiring behavior across repeated spooling and unspooling cycles, hose swivel leak resistance under pressurization, full system behavior under loaded deployment conditions, and servo and mechanical response during an intentional stall event.

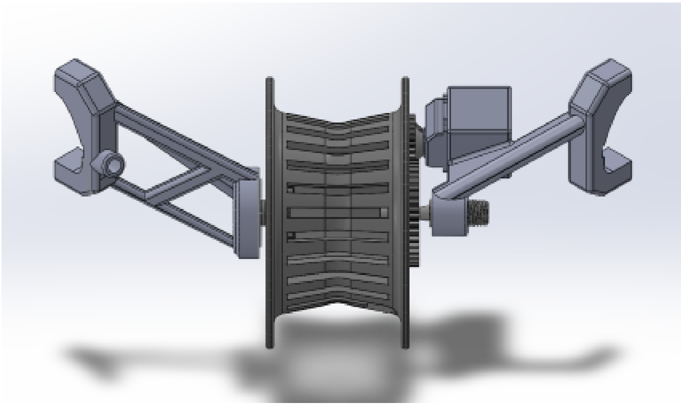

Fig. 3. A CAD assembly of the Spool Mechanism Subsystem.

C. Propellor Guard Testing

To evaluate the structural integrity of the propeller guard subsystem, a series of controlled compression tests were conducted using a Vernier Force Plate connected to a LabQuest Mini and Logger Pro Online for real-time data acquisition. Each test measured the maximum force sustained by different configurations of the propeller guard prior to failure. The testing process was divided into four stages to isolate the performance of individual components and connections. First, a single propeller guard segment was placed on the force plate with its arch facing upward, and a 0.454 kg hammer was used to apply downward force until fracture occurred; this test was repeated three times to ensure consistency. Next, two segments were assembled using their dovetail connection and tested by applying force directly at the joint interface. The third stage involved testing the fully assembled propeller guard, with force applied to the front face of the arch to simulate a realistic loading condition. Finally, the connection between the propeller guard and the joint attachment was tested by applying force directly at the interface. In all cases, force was gradually increased until structural failure occurred, and the peak force values were recorded and analyzed to compare the relative strengths of each configuration.

D. Sensor Integration Testing

The sensor cage subsystem was tested for accuracy and precision in working conditions in order to evaluate the capability of each sensor and the effectiveness of the sensor cage geometry. The temperature sensor was evaluated for accuracy against a lab thermometer with a standardized tolerance of ±0.15°C. Both probes were submerged in beakers of cool (11°C), room temp (22°C), and warm (36°C) water and 10 simultaneous readings from each were recorded at 30 second intervals. These three temperatures were used to cover the full potential working range of the sensor in the field. The mean absolute error (MAE) was then calculated using the simultaneous readings. The MAE calcuation is as follows:

$$\text{MAE} = \frac{1}{N}\Sigma|x_i - \text{mean}| \tag{1}$$

where N is the number of samples and x_i is a data point.

The pH sensor was evaluated for accuracy using three lab standardized buffer solutions at 4.00 pH, 7.00 pH, and 10.00 pH. These pH levels both ensure the sensor electrode functions across the pH scale, and the offset and gain derived from 2-point calibration are valid in the higher pH range since the two points used were only at 4.00 pH and 7.00 pH. The electrode was submerged in each buffer solution, and 10 readings were recorded at 30-second intervals. The MAE was then calculated using the readings and known buffer values.

The DO_2 sensor was evaluated for accuracy using 100 mL beakers of still and aerated water. The still water was carefully transferred to a beaker to avoid agitation, while the aerated sample was stirred for 10 minutes to ensure high levels of dissolved oxygen. These samples simulated low ($\leq 45\%$) and high ($\geq 70\%$) saturation environments in order to determine the accuracy of the DO_2 sensor in distinguishing the two. The sensor was submerged in each sample, and 10 readings were recorded at 30-second intervals while slowly stirring the electrode. The percentage of readings meeting the expected threshold for each sample was calculated.

The entire sensor cage was first tested for precision over various flow rates in running water. This test evaluates the capability of the sensors and effectiveness of the sensor cage geometry in simulated stormwater runoff conditions. The sensor cage was placed in front of a hose running water at a slow, medium, and then high flow rate. The 10 consecutive readings of all sensors were taken at 30-second intervals while maintaining a constant flow rate. The standard deviation between each sensor's readings were then calculated. The sensor cage was then tested for precision in polluted conditions with debris and organic matter using a large 2L sample from a nearby lake. This sample simulated potentially damaging conditions under which the sensors must operate, and the cage must protect them. The cage was submerged in the sample, and 10 consecutive readings of all sensors were recorded. The standard deviation between each of the sensor's readings was then calculated.

E. Communication Testing

The communications array consists of an ESP32-S3 micro-controller, a Core1121-XF LoRa module from Waveshare, and additional supporting components at both the receiving drone and controller ends. Requirements for the components attached to the drone include: waterproof (using IP67/IP68 guidelines), equal or greater range than the drone's internal controls, sufficient power and battery life for onboard devices, and successful integration with spool and sensor components. The schematic for the drone end of the system is shown in Figure 4. Waterproofing with IP68 guidelines includes submersion tests at depths greater than 1.5 m for no less than 30 min. Testing will be done to these standards in turbulent water to simulate volatile water conditions once final parts have arrived. Range as specified by the LoRa device is effective up to 5 km Line of Sight (LoS), which greatly exceeds the drone's specified range of 1.6 km. This will be confirmed with a range test, both LoS and obstructed, to confirm that the additional frequencies do not degrade the integrity of either communication band. Expected battery life and power delivery will be confirmed with the addition of a second battery in the available space gained by pending smaller components. Tests will be conducted to determine maximum, idle, and average current draw from the batteries in parallel, from which the duration of possible operation can be calculated using the batteries' rated capacity. Sensor and servo components of their respective subsystems are measured in binary success of achieving the desired outcome.

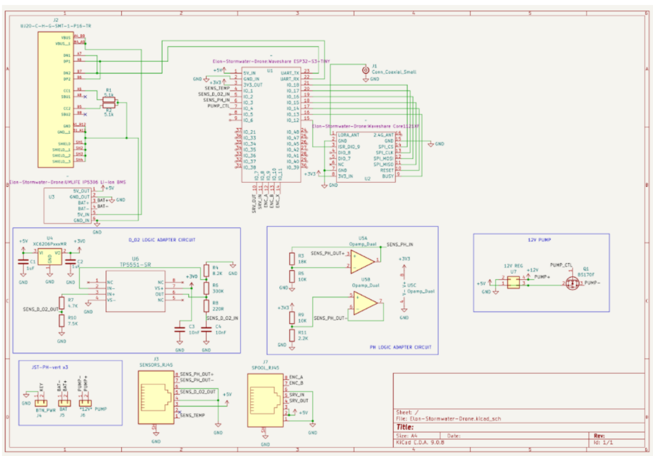

Fig. 4. Communication box on drone schematic

IV. Results

The results from the methodology above demonstrate subsystem effectiveness and integration.

A. *Water Collection Results*

From the testing on the water collection subsystem, the flushing method is an effective mechanism; there is negligible leakage for the time frame and water sampling goals, and it takes 10.5 seconds to fill an empty container to a 125 mL sample with 2.0 m of pump head. This data verifies the amount of time necessary to run the pump, and validates the design to the constraints given. The data collected is shown in Table I.

TABLE I
Data generated from verifying the water collection subsystem

Height	Power	Flush	Timing (s)
1.0 m	12V & 0.208A	1	45
1.0 m	12V & 0.208A	2	42
1.0 m	12V & 0.208A	3	46
1.5 m	12V & 0.230A	1	60
1.5 m	12V & 0.230A	2	63
1.5 m	12V & 0.230A	3	54
2.0 m	12V & 0.230A	1	77
2.0 m	12V & 0.230A	2	63
2.0 m	12V & 0.230A	3	62

B. *Spooling Mechanism Results*

All nine tests of the spooling mechanism yielded results within or exceeding acceptable performance thresholds. The maximum torque test recorded 4.8 kg of force at a 2.5 cm lever arm, confirming the servo's capacity under operational loads. The encoder accuracy remained within ±10% over 720° of rotation, sufficient for reliable positional feedback during spool deployment. The spool mounts withstood 6 kg of applied force without deformation or cracking, demonstrating structural robustness well beyond the expected operating load. After one hour of continuous operation, no significant wear was observed on the gears or bearings. Testing with a plastic axle confirmed the system operated successfully under load, validating that a steel axle provides a conservative safety margin. The hose swivel exhibited no leakage during pressurized rotation, and the system tolerated 1.6 kg of hose tension before a servo stall occurred. Critically, no mechanical damage or structural failure was observed under stall conditions, indicating a safe and predictable failure mode. These results collectively confirm that the spool mechanism meets the design requirements for strength, precision, and durability under operational and edge-case conditions.

C. *Propellor Guard Results*

The results of testing demonstrated that the propeller guard system provides meaningful structural protection while identifying areas for improvement. Compression testing revealed that the weakest point in the system was the front-most dovetail joint, which failed at approximately 300 N, whereas an individual guard segment without joints could withstand up to 700 N. Despite this, the guard system performed adequately for its intended purpose, as the forces experienced during typical drone operation and minor impacts are expected to be well below these failure thresholds. Additionally, the inclusion of the stainless steel mesh layer enhances functionality by acting as a barrier to debris such as leaves, and airborne particles that may be present in storm conditions. This helps prevent foreign objects from entering the propeller region, reducing the likelihood of jams or damage and improving overall system reliability during flight.

D. *Sensor Integration Results*

The sensor cage and all sensors performed within an acceptable range of tolerance for their application. Most importantly, the temperature sensor showed a maximum MAE of 0.140°C across each temperature sample demonstrating an acceptable error, particularly with consideration of the lab thermometer's standardized tolerance of ±0.15°C. During the simulated-condition precision tests the temperature sensor showed an impressive standard deviation of 0.00°C, demonstrating consistent and stable readouts at the sensor's reported resolution despite varying flow rates and water quality/debris conditions. This standard deviation also demonstrates the effectiveness of the sensor cage geometry, as the cage kept the sensor completely submerged and protected allowing for the consistent recordings. The additional water quality sensors, pH, and DO_2,

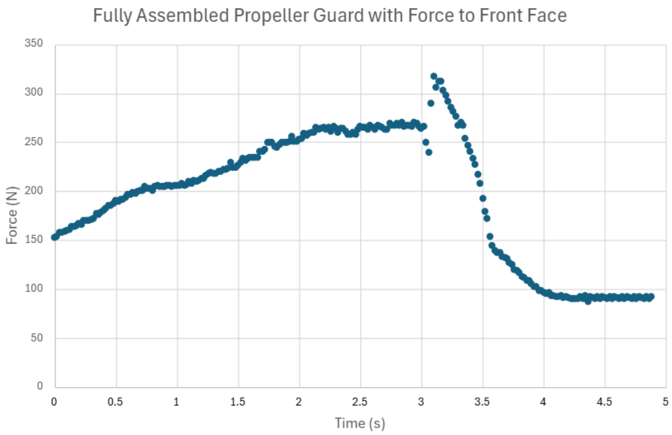

Fig. 5. Stage 3 of propeller guard testing, where the force is applied to the exterior wall of the assembled prop guard until structural failure occurs.

also performed within acceptable tolerances during accuracy and precision tests. The pH sensor showed a maximum MAE, across all buffer solutions, of 0.068 pH in the 10.00 pH buffer solution. This result is consistent with the EPA Region 4 field pH measurement tolerance of 0.2 S.U. for general ecological monitoring, the applicable regional standard in North Carolina [21]. The DO_2 sensor had a success rate of 100% in identifying low versus high oxygenated samples given the $\leq$45% and $\geq$70% thresholds. During the precision tests, the maximum standard deviation across all conditions was 0.010 pH for the pH sensor and 2.611% for the DO_2 sensor. The results of these tests are shown in Table II and III. These findings serve as a sufficient proof of concept that, alongside temperature monitoring and water sampling, multiple additional sensors can be implemented within the sensor cage subsystem in order to collect any desired water quality metrics - in this case pH and DO_2.

TABLE II
SENSOR CAGE ACCURACY

Temperature (°C)		pH		DO_2	
Sample	MAE	Buffer	MAE	Saturation	Accuracy
∼11 °C	0.122	4.00	0.037	low ($\leq$ 45%)	100%
∼22 °C	0.140	7.00	0.055	high ($\geq$ 70%)	100%
∼36 °C	0.128	10.00	0.068		

TABLE III
SENSOR CAGE PRECISION

Running Water Test			Lake Water Test	
Flow Rate	Sensor	Std. Dev.	Sensor	Std. Dev.
Slow	Temp (°C)	0.000	Temp (°C)	0.000
	pH	0.010	pH	0.005
	DO2 (%)	1.524	DO2 (%)	2.611
Moderate	Temp (°C)	0.000		
	pH	0.005		
	DO2 (%)	1.320		
High	Temp (°C)	0.000		
	pH	0.004		
	DO2 (%)	1.336		

E. Communication Array Results

Testing for the communication array demonstrates successful sensor data readout and collection. Additional testing and results will conclude when the necessary parts arrive and are assembled.

V. CONCLUSIONS

This work presents the design and validation of a UAV-based system for stormwater sampling and in situ data collection. Experimental results show that the system can reliably collect water samples within operational constraints while maintaining measurement accuracy across integrated sensors. Mechanical components demonstrated sufficient strength and durability under expected loading conditions, and system integration enabled coordinated operation of sampling, sensing, and communication functions during testing.

The results support the viability of UAV-assisted sampling as an effective alternative to traditional methods, particularly for accessing difficult or hazardous locations and capturing data during time-sensitive storm events. The ability to rapidly deploy and collect both physical samples and real-time measurements represents a meaningful improvement in spatial and temporal data resolution for water quality monitoring.

Several areas remain for further development. Improving control over the deployment mechanism would enhance consistency during operation, while reducing overall system weight could extend flight time and efficiency. Expanding compatibility with additional UAV platforms would also increase flexibility for broader use cases. Continued evaluation of communication performance under varied environmental conditions will be important for long-term reliability. The next major step is field testing during an actual event.

Overall, this system demonstrates a practical and scalable approach to UAV-based environmental sampling and provides a strong foundation for future refinement and field deployment.

ACKNOWLEDGMENTS

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REFERENCES

[1] U.S. Environmental Protection Agency, “Sources and solutions: Stormwater,” 2025, accessed: 2026-03-29. [Online]. Available: https://www.epa.gov/nutrientpollution/sources-and-solutions-stormwater

[2] C. Chen, W. Guo, and H. H. Ngo, “Pesticides in stormwater runoff—a mini review,” *Frontiers of Environmental Science & Engineering*, vol. 13, no. 5, p. 72, 2019. [Online]. Available: https://doi.org/10.1007/s11783-019-1150-3

[3] R. Hanlon, S. J. Jacquemin, J. A. Birbeck, J. A. Westrick, C. Harb, H. Gruszewski, A. P. Ault, D. Scott, H. Foroutan, S. D. Ross, J. GonzÃ¡lez-Rocha, C. Powers, L. Pratt, H. Looney, G. Baker, and D. G. Schmale, “Drone-based water sampling and characterization of three freshwater harmful algal blooms in the united states,” *Frontiers in Remote Sensing*, vol. Volume 3 - 2022, 2022. [Online]. Available: https://www.frontiersin.org/journals/remote-sensing/articles/10.3389/frsen.2022.949052

[4] North Carolina Department of Environmental Quality, “Water quality data assessment,” n.d., accessed: 2026-03-29. [Online]. Available: https://www.deq.nc.gov/about/divisions/water-resources/water-planning/modeling-assessment/water-quality-data-assessment

[5] Town of Haw River, "Stormwater," n.d., accessed: 2026-04-02. [Online]. Available: http://townofhawriver.com/Stormwater
[6] Piedmont Triad Regional Council, "Stormwater smart," n.d., accessed: 2026-04-02. [Online]. Available: https://www.ptrc.org/services/regional-planning/stormwater-smart
[7] North Carolina Department of Environmental Quality, "Final stormwater management plan (swmp) for permit ncs000404," 2025, accessed: 2026-04-02. [Online]. Available: https://www.deq.nc.gov/energy-mineral-and-land-resources/stormwater/public-notices/individual-permits/ncs000404final-swmp20250304/open
[8] Haw River Assembly, "Muddy water watch," 2026, accessed: 2026-04-02. [Online]. Available: https://www.hawriver.org/muddy-water-watch
[9] Interstate Technology & Regulatory Council (ITRC), "6. nonpassive grab sampling technologies," Passive Sampling Technology Update, Section6, 2024, accessed: 2026-03-29. [Online]. Available: https://psu-1.itrcweb.org/6-nonpassive-grab-sampling-technologies/
[10] F. H. Rainwater and L. L. Thatcher, "Methods for collection and analysis of water samples," U.S. Geological Survey, Water Supply Paper 1454, 1960, accessed: 2026-03-29. [Online]. Available: https://doi.org/10.3133/wsp1454
[11] Elsevier, "Water sampling," ScienceDirect Topics in Earth and Planetary Sciences, n.d., accessed: 2026-03-29. [Online]. Available: https://www.sciencedirect.com/topics/earth-and-planetary-sciences/water-sampling
[12] S. D. Shelare, K. R. Aglawe, S. N. Waghmare, and P. N. Belkhode, "Advances in water sample collections with a drone â€" a review," *Materials Today: Proceedings*, vol. 47, pp. 4490–4494, 2021, fRESMâ€™21. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2214785321039213
[13] H. Lally, I. O'Connor, O. Jensen, and C. Graham, "Can drones be used to conduct water sampling in aquatic environments? a review," *Science of The Total Environment*, vol. 670, pp. 569–575, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0048969719312446
[14] K. Ragib Ishraq Sanim, M. Kalaitzakis, B. Kosaraju, Z. Kitzhaber, C. English, N. Vitzilaios, M. Myrick, M. Hodgson, and T. Richardson, "Development of an aerial drone system for water analysis and sampling," in *2022 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2022, pp. 1601–1607.
[15] D. Castendyk, J. Voorhis, and B. Kucera, "A validated method for pit lake water sampling using aerial drones and sampling devices," *Mine Water and the Environment*, vol. 39, no. 3, pp. 440–454, 2020. [Online]. Available: https://doi.org/10.1007/s10230-020-00673-y
[16] DJI Enterprise, "Water sampling with drones," n.d., accessed: 2026-03-29. [Online]. Available: https://enterprise.dji.com/news/detail/water-sampling-with-drones
[17] SPH Engineering, "Drone-based water sampling systems," n.d., accessed: 2026-03-29. [Online]. Available: https://shop.sphengineering.com/collections/drone-based-water-sampling
[18] Fly4Future, "Waterproof drones for water sampling & quality monitoring," n.d., accessed: 2026-03-29. [Online]. Available: https://fly4future.com/development-and-prototyping/drones-for-water-quality/
[19] Aurelia Aerospace, "Drone water sampling system," n.d., accessed: 2026-03-29. [Online]. Available: https://aurelia-aerospace.com/products/water-sampling-system
[20] SwellPro, "Swellpro official website," n.d., accessed: 2026-03-29. [Online]. Available: https://www.swellpro.com/
[21] United States Environmental Protection Agency, "Field ph measurement," 2025, last updated June 24, 2025. Accessed: 2026-04-13. [Online]. Available: https://www.epa.gov/quality/field-ph-measurement