OPTICAL TRACKING OF A CHEMICAL PLUME IN THE SURFACE WATERS OF A SHALLOW WATER ESTUARINE SYSTEM USING A CUSTOM AUTONOMOUS SURFACE PLATFORM

Midshipman First Class Megan LaMendola, USN, Class of 2022; U.S. Naval Academy, Oceanography Department, Annapolis, MD , USA

Advisers: Dr. Joseph P. Smith and Mr. Benjamin Hickman

Background and Objectives

Custom autonomous surface vehicles (ASVs) have great potential for waterborne hazard plume mapping and tracking in shallow coastal systems. These platforms have the potential to be trained and programmed as 'smart' assets that could actively follow a waterborne chemical plume based on its optical or (radio-)chemical signature. This study will demonstrate the capability of tracing the optical signature of a chemical plume using a custom-built ASV in Carr Creek embayment, a shallow embayment at the of the Severn River in the Chesapeake Bay. The expected dispersion and transport of a conservative waterborne chemical hazard plume was compared with the actual dispersion and transport of chemical plumes from live releases of inert chemical proxy agents with known optical properties (dye release) as measured by the ASV. ***Results will be used as a first step in the development of a 'smart' autonomous surface platform with the capability to track the optical signature of a chemical plume that could be used in real-world applications for waterborne hazard fate and transport tracking in shallow water systems.***

Methods and Approach

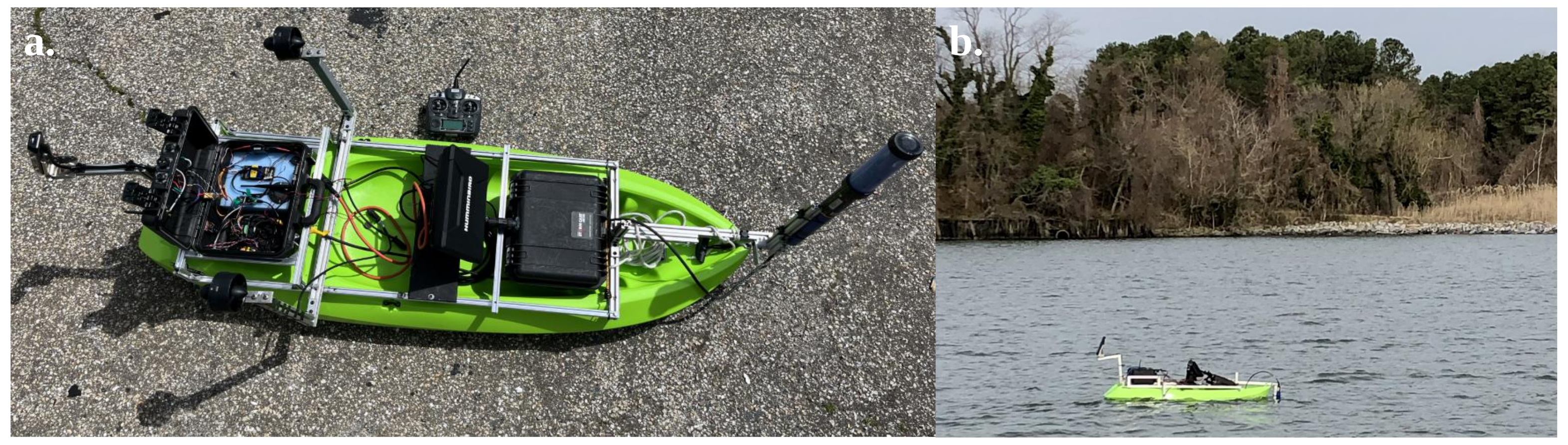


Figure 1. **(a)** The Custom-built, Coastal Kayak Autonomous Surface Vehicle (ASV) and **(b)** The Coastal Kayak ASV underway in Carr Creek embayment at the mouth of the Severn River in Chesapeake Bay.

The Coastal Kayak ASV is built upon a 6' ride-atop kayak with X-rail and 80/20 framing rail. It is an affordable, multi-use autonomous research platform that has the capacity to integrate a variety of instruments and sensor for applied research and can be used in shallow water systems (**Fig. 1a & b**). The ASV is powered 12 VDC marine battery and propulsion is achieved using two reversible Blue Robotics T-200 Thrusters (https://www.bluerobotics.com/). The ASV can be operated remotely through a R/C remote controller and or it can be programmed to run autonomously. Autonomous control is executed using the 3D Robotics Pixhawk 2.1 Blue Cube auto-controller. Programming and mission planning is accomplished using Mission Planner software (Ardupilot Development Team, 2016). The ASV is outfitted with a CubePilot Here 3 Precision GNSS Module and a RFD 900X-US ultra-long range radio modem for telemetry. For this study, the ASV was outfitted with a YSI EXO1 Multiparameter Water Quality Sonde that can be equipped with up to 5 sensors including rhodamine (https://www.ysi.com/exo1). A YSI DCP Signal Output Adapter was used to interpret sonde data for interface with the Teensy 3.5m 32 bit Arduino compatible microcontroller A Digi Xbee Transceiver Module was used to transmits sonde data back to an identical unit located at the command computer. The ASV was also equipped with a Humminbird SOLIX 10 CHIRP MSI+ G3 chart plotter & imaging sonar (https://humminbird.johnsonoutdoors.com).

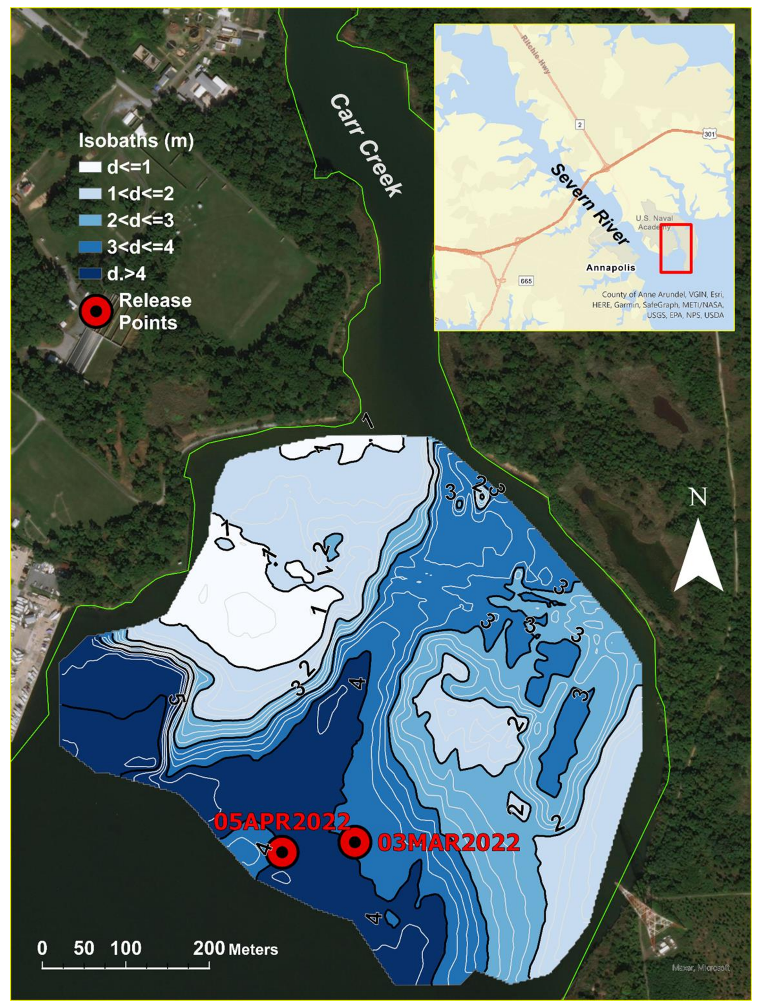


Figure 2. Map of the Carr Creek embayment study & testing area showing contoured bathymetry and the location of two separate rhodamine dye releases: 03 MAR 2022 and 05 APR 2022.

Carr Creek embayment is a shallow embayment fed by Carr Creek located at the mouth of the Severn River, a tidal-tributary of the mesohaline Chesapeake Bay (**Fig. 2**). This sheltered area provided an ideal location for controlled rhodamine dye releases and plume tracking testing using the Coastal Kayak ASV. Two separate tests were conducted: 1) a manual plume tracking mission (03 MAR 2022) and 2) an autonomous plume tracking mission (05 APR 2022). For each test, A 1 L, 2.5% rhodamine dye stock solution of was released in Carr Creek embayment (**Fig. 3a**) and tracked based on expected (predicted) plume dispersion and travel (**Fig. 3b**). Observed results were used to estimate plume direction, speed, and concentration after dispersion for comparison to predictions.

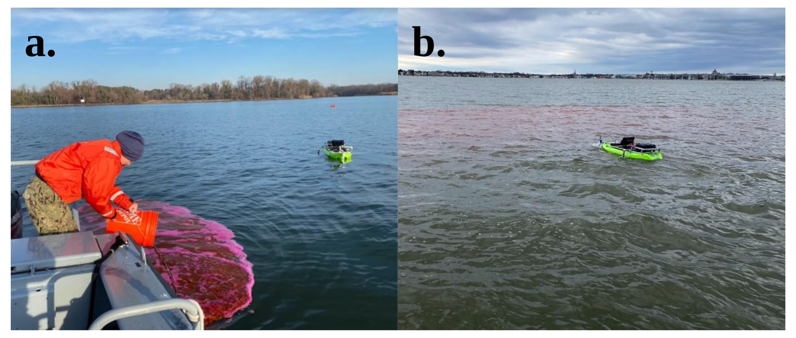


Figure 3. **(a.)** Midshipman 1/C Megan LaMendola releasing rhodamine dye and (**b**) the Coast Kayak ASV tracking a plume.

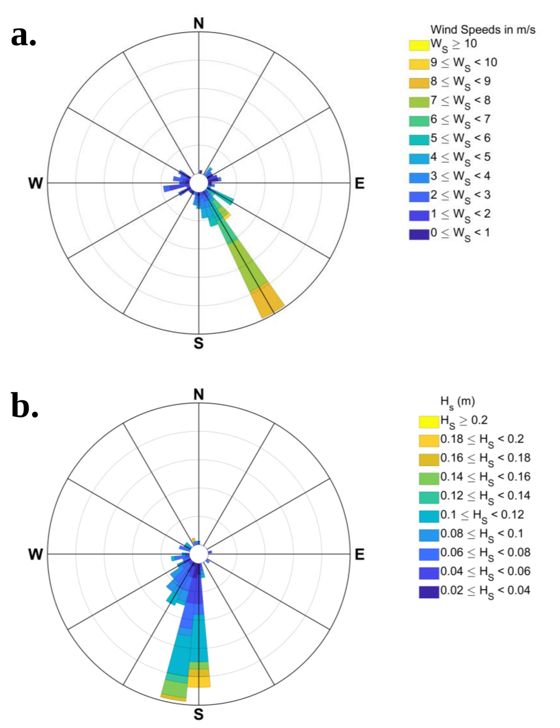


Figure 4. **(a)** Wind rose showing sustained wind speed and direction and (**b**) wave rose showing significant wave height (H_s) and mean wave direction 24 hours prior to the rhodamine release on 03 MAR 2022. Wind data is from NOAA NDBC Station TPLM2 at Thomas Point lighthouse ~ 9 km south of the release point. Wave data is from a Sofar ocean Spotter wave buoy moored in Carr Creek embayment (*Arnold, Bell, and Cyrus, 2022*).

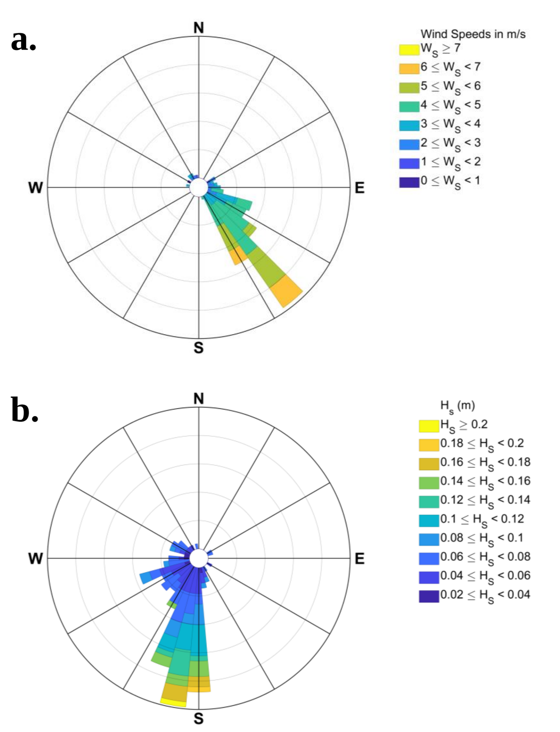


Figure 6. **(a)** Wind rose showing sustained wind speed and direction and (**b**) wave rose showing significant wave height (H_s) and mean wave direction 24 hours prior to the rhodamine release on 05 APR 2022. Wind data again is from NOAA NDBC Station TPLM2 at Thomas Point lighthouse and wave data is from a Sofar ocean Spotter wave buoy moored in Carr Creek embayment (*Arnold, Bell, and Cyrus, 2022*).

Manual Plume Tracking Mission, 03 MAR 2022

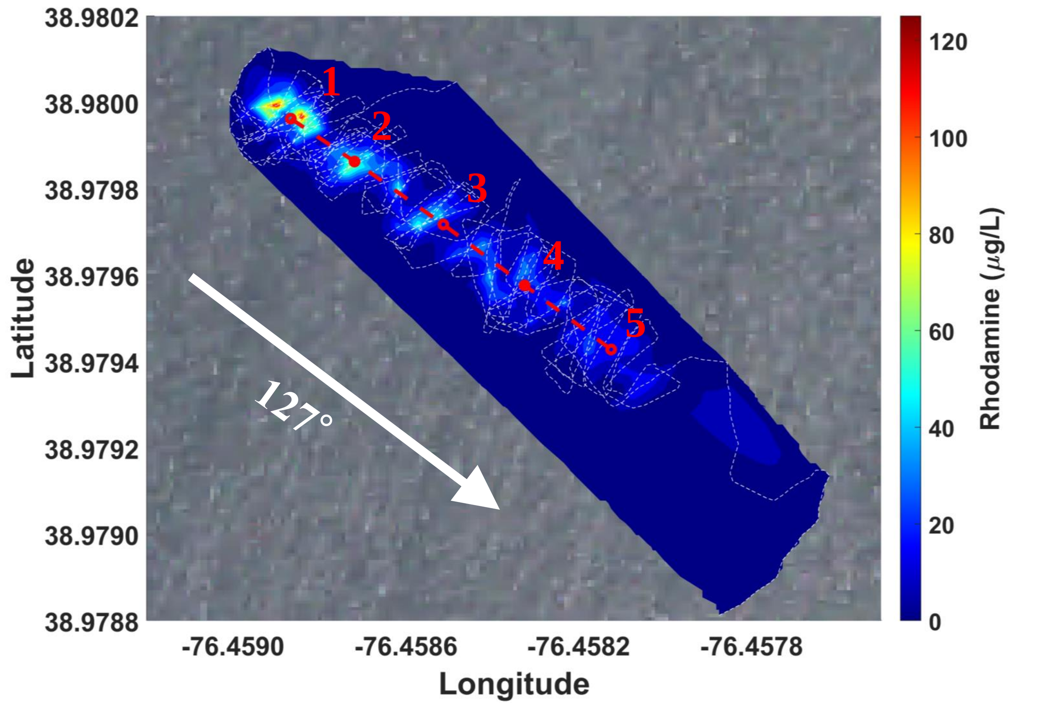


Figure 5. A contour plot of rhodamine concentrations in Carr Creek embayment measured using the Coastal Kayak ASV in manual (remote-controlled) mode to track a release of 1L of 2.5% (24000 mg/L) rhodamine dye solution on 03 MAR 2022. The ASV track is shown as a white dashed line. The estimated centroid for 5 distinct plume 'patches' are shown as red circles connected by a red dashed line. The time and distance between patch centroids was used to estimate the speed and direction of plume travel. Total rhodamine mass for each patch was estimated as the area around each centroid time x 0.5 m (assuming all rhodamine was in the upper 0.5 m of the water column) x the average patch rhodamine concentration (**Table 1**).

Table 1. Measured and derived data from tracking a release of rhodamine dye solution in Carr Creek embayment using the Coastal Kayak ASV in manual mode on 03 MAR 2022.

Plume Patch #	Patch Centroid Latitude	Patch Centroid Longitude	Est. Patch Area (m²)	Maximum Rhodamine Conc.(μg/L)	Average Rhodamine Conc. (μg/L)	Est. Rhodamine Mass (mg)	Patch Travel Distance (m)	Patch Travel Time (min)	Patch Travel Speed (m/s)
1	38.9800	-76.4589	440	122.9	17.3	3806	0	0	-
2	38.9799	-76.4587	480	69.4	12.4	2976	16.9	6.1	0.05
3	38.9797	-76.4585	550	52.1	11.4	3135	24.1	5.5	0.07
4	38.9796	-76.4583	660	41.92	10.8	5586	22.6	4.7	0.08
5	38.9794	-76.4581	890	30.1	7.5	3564	24.0	6.1	0.07
Average Travel Speed of Plume (m/s)									***0.07***

A 1 L solution of Bright Dyes rhodamine solution was release into the surface waters of Carr Creek embayment on 03 MAR 2022 (**Fig. 1**) in the morning near high slack water. Sustained winds 24 hour prior to the release were from the south-southeast at 5-10 m/s (**Fig. 4a**) and waves were from the south with H_s < 2 m (**Fig. 4b**). This rhodamine plume was tracked using the Coastal Kayak ASV in manual mode, with the operator having to visually location the rhodamine plume and adjust ASV course to track (**Fig. 5**). This method was inefficient but the operator was able to stay with the plume (~ 5-20% of the total mass) until it dispersed as was no longer visible as it traveled to the southeast at an average speed of 0.07 m/s (**Table 1**). Manual tracking did not allow for track uniformity and consistency. The direction of plume travel relative to the wind and wave field suggests a combination of tides and local-scale circulation Carr Creek embayment may be influencing plume direction and dispersion.

Autonomous Plume Tracking Mission, 05 APR 2022

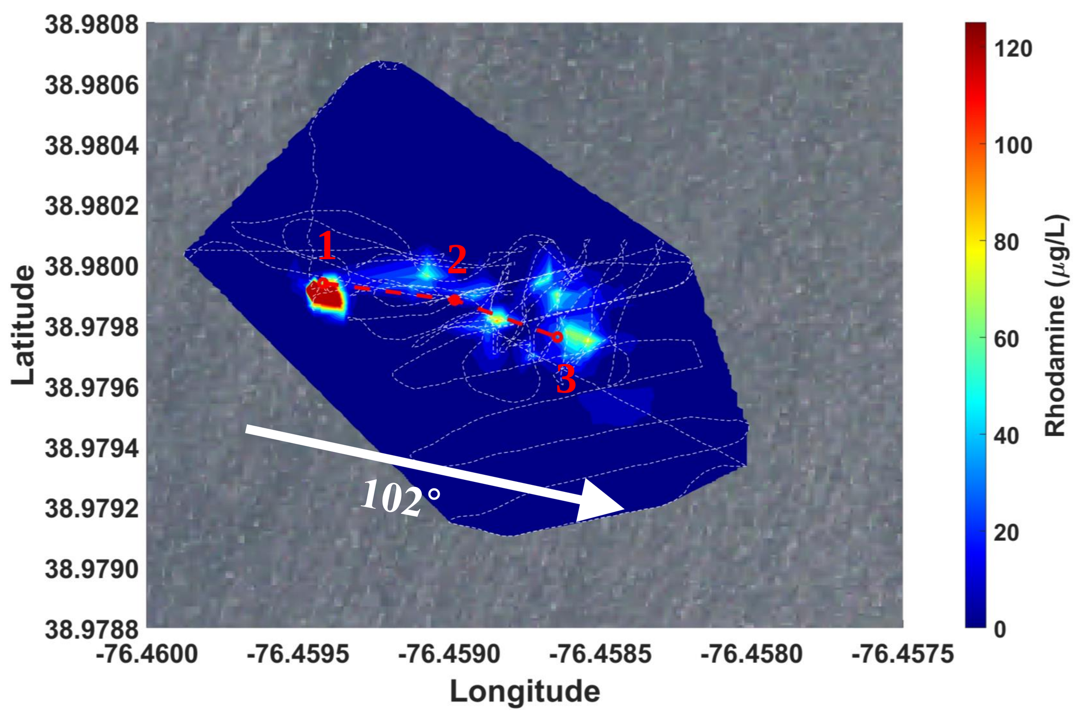


Figure 7. A contour plot of rhodamine concentrations in Carr Creek embayment measured using the Coastal Kayak ASV in autonomous mode to track a release of 1L of 2.5% (24000 mg/L) rhodamine dye solution on 05 APR 2022. The ASV track is shown as a white dashed line. The estimated centroid for 5 distinct plume 'patches' are shown as red circles connected by a red dashed line. Values in **Table 2** were calculated using the same assumptions as those in **Table 1**.

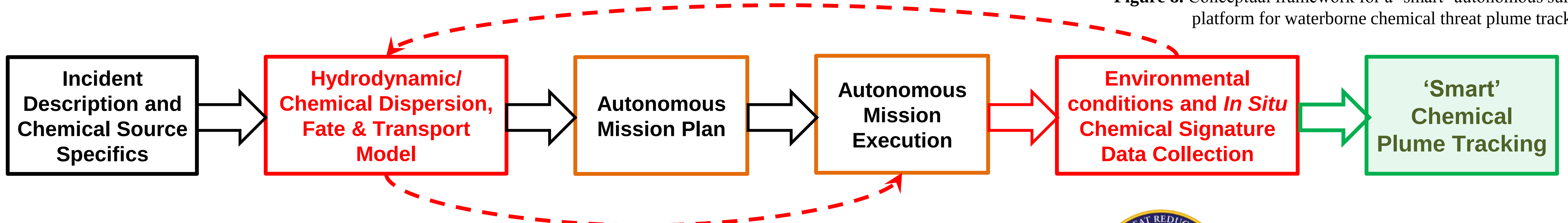
Table 1. Measured and derived data from tracking a release of rhodamine dye solution in Carr Creek embayment using the Coastal Kayak ASV in autonomous mode on 05 APR 2022.

Plume Patch #	Patch Centroid Latitude	Patch Centroid Longitude	Est. Patch Area (m²)	Maximum Rhodamine Conc.(μg/L)	Average Rhodamine Conc. (μg/L)	Est. Rhodamine Mass (mg)	Patch Travel Distance (m)	Patch Travel Time (min)	Patch Travel Speed (m/s)
1	38.9799	-76.4594	240	1216.0	72.4	8688	0	0	-
2	38.9799	-76.4590	1050	93.8	11.4	5985	38.2	4.3	0.15
3	38.9798	-76.4586	1430	75.7	6.9	4934	32.4	3.1	0.18
Average Travel Speed of Plume (m/s)									***0.16***

A second rhodamine dye release was conducted in Carr Creek embayment on 05 APR 2022 (**Fig. 1**) in the afternoon near high slack water. Sustained winds were from the southeast at 5-10 m/s (**Fig. 6a**) and waves were from the south at H_s < 2 m (**Fig. 6b**). This rhodamine plume was tracked using the Coastal Kayak ASV in autonomous mode with preprogrammed grid patterns. This method roved to be less effective than manually-tracking. As the plume was moving and dispersing, grid patterns had to be adjusted based on local forcing conditions and actual plume travel. Results suggest the plume was moving to the southeast at 0.16 m/s but these results are uncertain because each patch may not have been fully recorded as autonomous missions were adjusted on-the-fly (**Fig. 7**). These results and the results of the manual tracking test suggest the need to develop a 'smart' ASV system that can sense environmental conditions and use *in situ* data to continuously update an onboard model and adjust autonomous mission plans seamlessly in order to live-track chemical plumes (**Fig. 8**).

Conclusions and Future Work

Figure 8. Conceptual framework for a 'smart' autonomous surface platform for waterborne chemical threat plume tracking.



This work represents the first steps in the development of a 'smart' autonomous surface platform with the capability to live-track the signature of a chemical plume (Fig. 8). This capability could used in real-world applications for waterborne hazard fate and transport tracking in shallow water systems.

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