22nd January 2024

Aerial Dye and Drogue Release Report

Meil Bay

Summary

Cooke Aquaculture Scotland (CAS) undertook a dye and drogue release survey at the proposed Meil Bay site in July 2023. This study mapped the propagation of dye plumes and drogues to calculate a horizontal dispersion coefficient for use in future bath modelling applications.

Five releases of Rhodamine WT were conducted over 2 days at key points of the tide. For each release, dye plumes were mapped using georeferenced images taken from an Unmanned Aerial Vehicle (UAV). The horizontal dispersion coefficient was calculated using the mean squared displacement and time lag from the initial release. Results show an average horizontal dispersion coefficient of 0.12 m^2/s.

A second survey was conducted using five drogue releases, mapping longer-term particle fate and dispersion. Drogues were fitted with onboard GPS loggers, allowing area-based tracks to determine displacement and dispersion with time. The results recorded an average horizontal dispersion coefficient of 0.089 m^2/s.

It is recommended that the combined average of the two surveys is used in future particle tracking modelling. For the proposed Meil bay site, a horizontal dispersion coefficient of **0.105 m^2/s** should be used.

1. Introduction

The horizontal dispersion coefficient plays an important role in the dilution of the aqueous solutions discharged into the marine environment. To ensure high environmental standards are maintained, the measured dispersion coefficient can be used in numerical models to predict the distribution and concentration of a solution or particle released.

The horizontal dispersion coefficient accounts for the random turbulent particle motion that is not inherently incorporated within the primary hydrodynamic model. This is often impossible to include due to the resolution and associated computational resource required. The application of a horizontal dispersion coefficient provides a more computationally economical method of including these processes within a wider scale model. This enables particles to be tracked over a longer period and can determine particle fate on a much larger geographical scale.

The physical dispersion process is highly variable in time and space. In the coastal marine environment, the main contributors arise from tides, bathymetry, wind, waves and freshwater input. These factors introduce irregular motion within the water body, with turbulent length scale ranging from the micro (<1m) to the macro (>1km). The dye and drogue survey method combines these factors into a single value that best represents the mixing at the site, allowing the highly complex chaotic motion to be translated into representative particle motion.

1.1 Site description

The proposed development at Meil Bay expands and repositions the existing site. The proposed site will comprise of 16 x 100m circumference pens, arranged in a 2 x 8 formation within a 60m x 60m mooring grid. The expanded site is relocated 200m to the NW of the existing site in a deeper, less constrained location closer to the mouth of the bay (348439.6396E, 1012644.2477N). Benthic modelling using the SEPA default NewDepomod model revealed a maximum biomass of 1410 tonnes at the newly proposed site was compliant with all EQS rules. This provides a stocking density of 18.46kg/m^3 during peak biomass. Further information on the existing and proposed site infrastructure and pen layout is presented in Table 1.

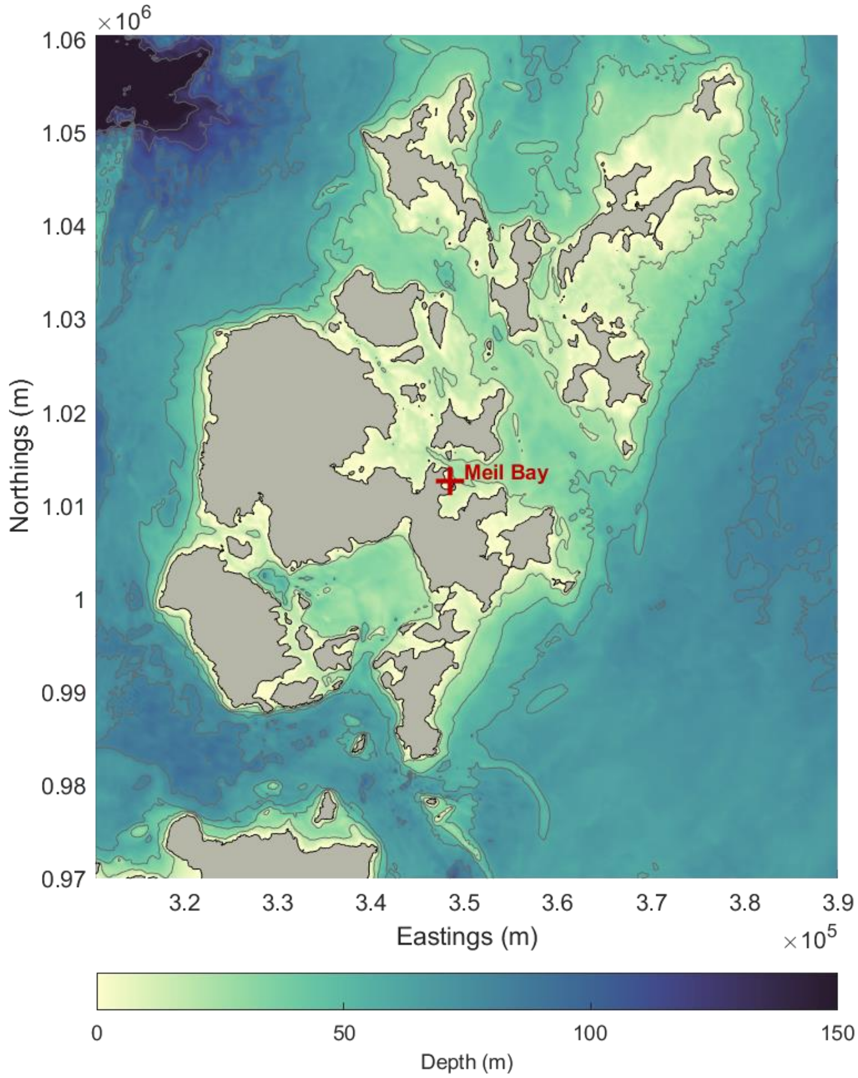

Figure 1. Site location (red cross) and bathymetry with depth contours at 20m intervals.

Table 1 – Site infrastructure and pen layout.

	Meil Bay (Existing)	Meil Bay (Proposed)
Consent number	CAR/L/1003888	CAR/L/1003888
Company	Cooke Aquaculture Scotland	Cooke Aquaculture Scotland
Receiving water	Shapinsay Sound	Shapinsay Sound
Site centre (OSGB36)	348452.07E, 1012342.29N	348439.6396 E, 1012644.2477N
Current meter location (OSGB36)/year of deployment	348378E, 1012552N/2018	348388E, 1012558N/2021

Distance to shore (km)	0.35	0.5
Average water depth (m)	9.6	12.1
Maximum biomass (t)	884	1410
Total number of pens	10	16
Number of pen groups	1	1
Formation	2 x 5	2 x 8
Pen group orientation (°)	23	36
Pen shape	Circular	Circular
Pen circumference (m)	100	100
Mooring grid (m)	60	60

2. Methodology

Dye Release

To measure and calculate the dispersion coefficient, 5 dye releases were performed on the 5th and 6th of July 2023. An Acoustic Doppler Current Profiler (ADCP) was deployed at 348425E, 1012650N for the duration of the survey and recorded tidal phase and surface current velocity. The details of the dye release time and track duration are shown in table 2. Dye releases performed on day 1 (05/07/2023), experienced shorter flight times and therefore shorter dye track due to partially discharged batteries. This was resolved for day 2, where full flight times were possible.

Table 2. Details of the individual dye release.

	Dye Release Time (BST)	**Plume track duration (mm:ss)**	**Number of aerial images**	**Tidal phase**
R1	05/07/2023 10:34:04	10:44	20	Peak flood
R2	05/07/2023 13:06:21	13:32	31	High water
R3	05/07/2023 14:19:58	17:48	27	Peak ebb

R4	06/07/2023 08:51:59	25:47	53	Low water
R5	06/07/2023 13:04:01	24:54	51	Peak flood (repeat)

Dye releases were coordinated with key moments in the tidal phase based on the tidal elevation. Due to complex flow patterns seen in surface velocity in figure 2, no obvious repeated flood/ebb current cycle are observed. The dye release times cover a diverse range of tidal conditions that are representative for the location.

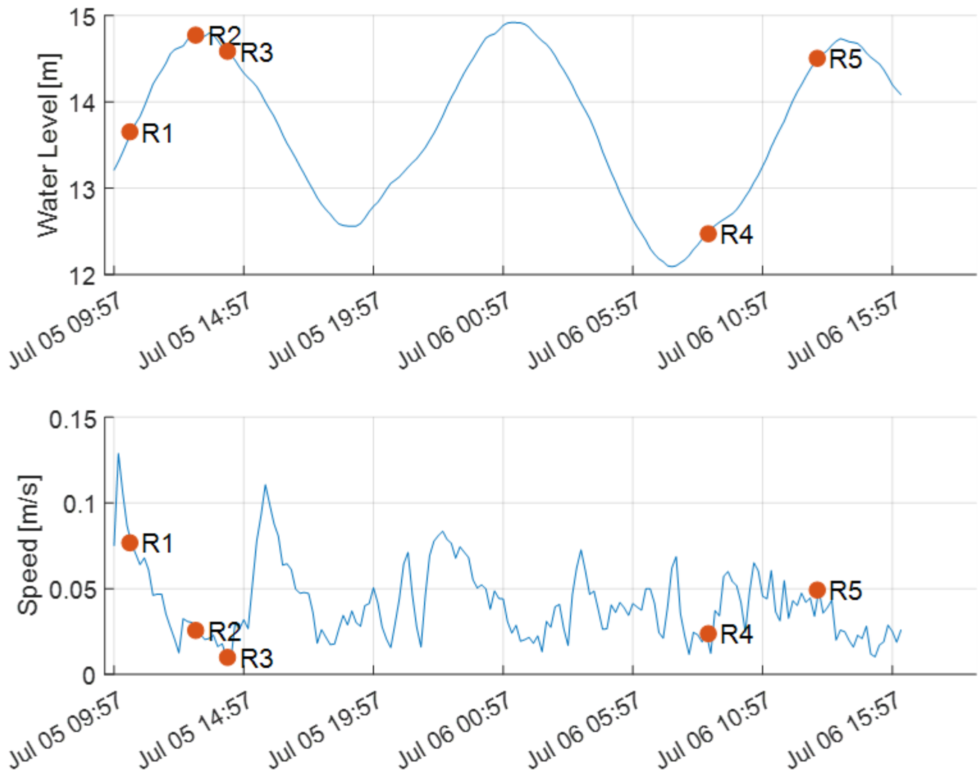

Figure 2. Tidal elevation and near-surface current velocity with the dye release times.

The dye, Rhodamine WT, was released at a single point at the site centre location. The advection and dispersion of the dye patch was monitored by a quadcopter UAV. Images were taken in a downward orientation approximately every 30 seconds for up to 26 minutes. Metadata from each image containing GPS, time and camera gimbal movement (yaw, pitch and roll) were used to geo-reference each pixel within the images.

Post-processing of the images used colour values to automatically identify the dye plume boundary. This allows the outer perimeter of the dye patch to be mapped in geographic space. An example of the image processing and dye plume identification is shown in figure 3. This shows the deployment of the dye and subsequent 5 images. During this early stage of the dye release, the dye plume is shown to be concentrated and the boundary indicated with a black line accurately maps the perimeter.

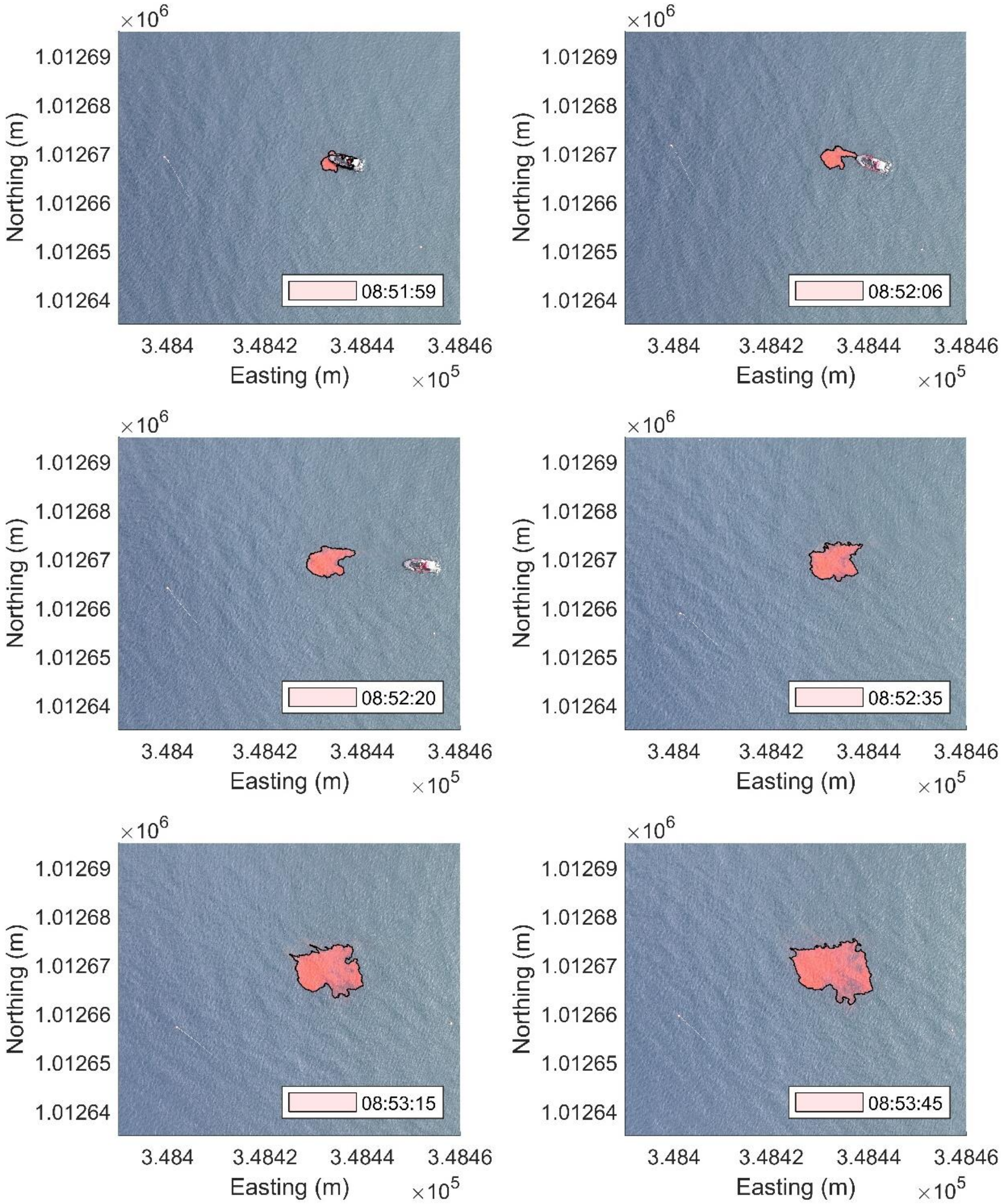

Figure 3. Georeferenced aerial image for the R4 release. The black line shows the extent of the measured dye plume with the image time (BST) located in the bottom right corner.

Einstein's theory to describe Brownian motion applies the mean squared displacement (MSD) to convert the 2-dimentional plume area to a displacement value from a central location. This central location used the centroid of the time dependent dye boundary.

$$MSD = \frac{1}{N}\sum_{i=0}^{N}\left|x^i(t) - x^i(0)\right|^2$$

$$K_h = \frac{1}{4}\,MSD/dt$$

where, N is the number of points in the boundary, $x^i(t)$ is the *i*-th points distance of the dye plume boundary and $x^i(0)$ is the centroid location of the plume. The dispersion coefficient (Kh) is then calculated using the synchronised time step (dt).

A linear fit is applied to the MSD and time interval data, where the dispersion coefficient (Kh) can also be calculated from the fit gradient.

Drogue Release

Five drogue releases were performed on the 12th of December 2023. An Acoustic Doppler Current Profiler (ADCP) was deployed at 348425E, 1012650N for the duration of the survey and recorded tidal phase and surface current velocity. The details of the drogue release time and track duration are shown in table 3 and figure 4.

Table 3. Details of the individual drogue releases.

	Drogue Release Time (GMT)	**Plume track duration (mm:ss)**	**Number of Drogues**	**Tidal phase**
R1	12/12/2023 09:56:00	45:00	5	High water flood
R2	12/12/2023 11:01:00	45:00	4	High water
R3	12/12/2023 12:41:00	50:00	5	High water ebb
R4	12/12/2023 13:56:00	45:00	5	Peak ebb
R5	12/12/2023 14:16:00	45:00	4	Low water

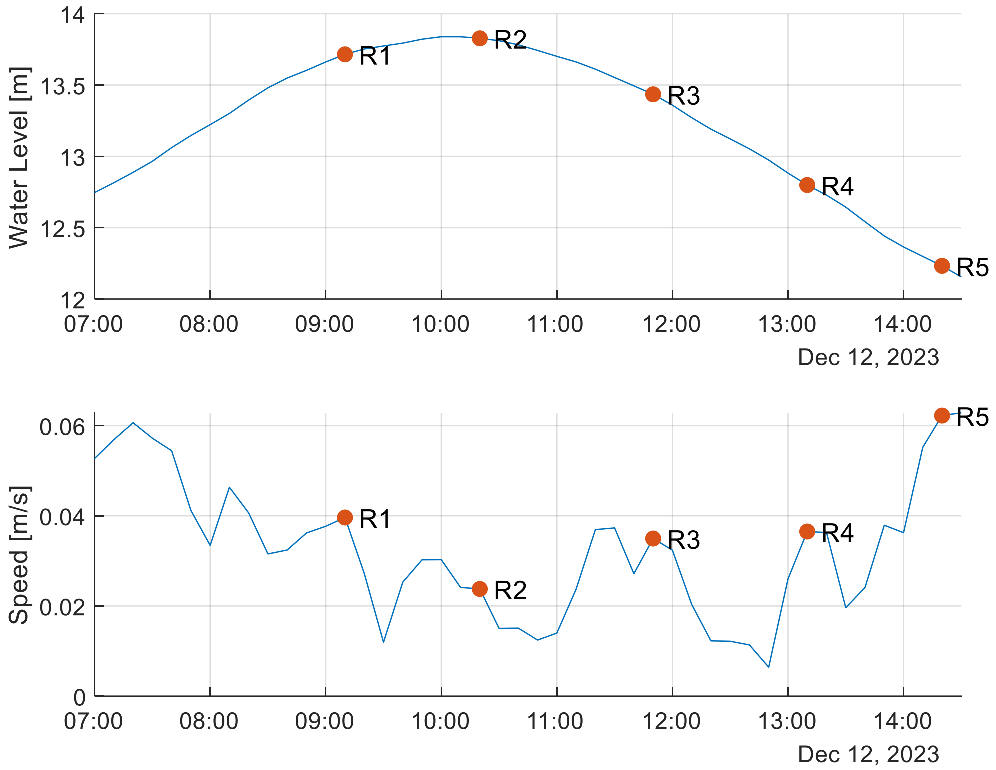

Figure 4. Tidal elevation and near surface current velocity with the drogue release times.

Drogues were released at a single point at the proposed site centre location. Each drogue consisted of a sub-surface sail similar to the CODE/DAVIS drifter and a surface buoy, housing the Iridium GPS system. Each release lasted approximately 1 hour with a sample interval of 5 minutes. A diagram of the drogue used is shown in figure 5. These drogues are reduced in size to improve performance in shallow coastal waters, these modifications also improved deployment, retrieval, and storage options once on the vessel. Due to the non-standardised sizing of the drogue, the drag area ratio was calculated to determine the drag between the surface and subsurface equipment. This calculation is shown in Table 4 where drag coefficient is estimated based on the profile shape of the equipment. The drogues are shown to have a drag ratio of 61.11. The Global Drifter Programme Barometer Drifter Design Reference (A. Sybrandy et al, 2009) states that the drifter should maintain a drag area ratio of more than 40. This criterion is comfortably achieved by the drogue used in this study.

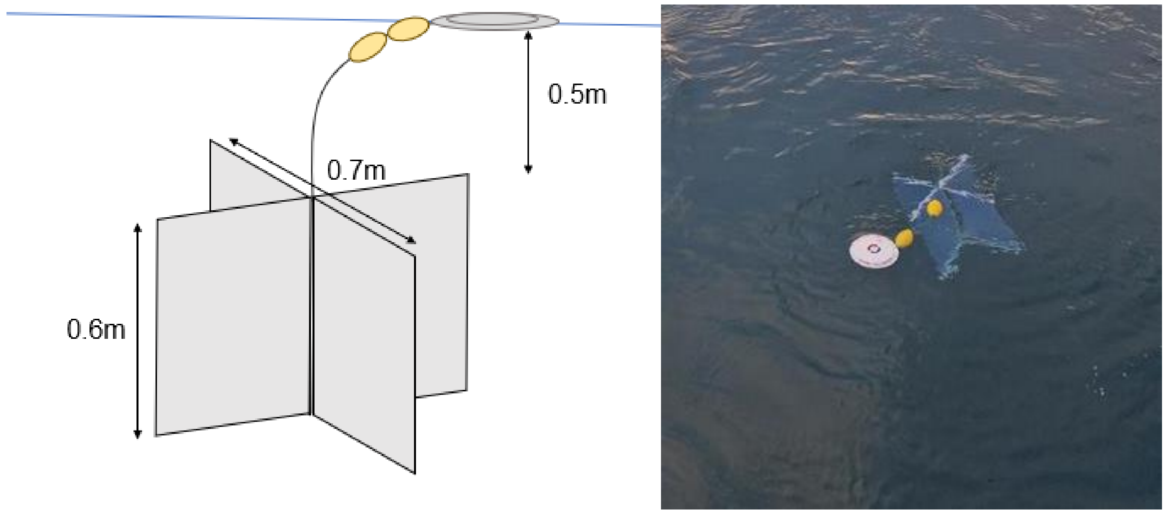

Figure 5. (left) Diagram of drogue with measurements. (right) Photo of drogue sinking immediately after deployment.

The effect of the wind on the drogue can be quantified using the wind slip equation parametrised in Lumpkin and Pazos (2007). This determines wind slip (U_{slip}) as the wind-induced velocity of the drogue. This relationship is shown as

$$|U_{slip}| = \frac{A}{R} U_{wind}$$

where R is the drag area ratio, A is a constant equal to 0.07 and U_{wind} is the wind speed.

The wind slip for a variety of operational wind speeds is shown in Table 4. This indicates low wind-induced velocities associated with the drogue, even in relatively strong winds. To ensure minimal wind effects on the drogues, wind slip should ideally be kept below 1 cm/s. For the drogues used in this study this equates a maximum wind speed of 8.7m/s (19.5mph).

Table 4 Drag area ratio and wind slip of drogues.

Sub-surface Equipment			
	Area (m^2)	Drag coefficient (C_d)	Drag Area (A x C_d)
Sails 0.35m x 0.6m	0.42	1.4	0.588
Mast 0.6m x 0.022m	0.015	1	0.015
Tether 0.5m x 0.004	0.002	1.17	0.002
Surface Equipment			

Buoy (x2) 0.075m x 0.12m	0.007		0.47	0.007
Drifter Sensor 0.25m x 0.035m	0.009		0.1	0.001
Drag Area Ratio				**61.11**
Wind Slip				
Wind Speed			**Wind induced slip (m/s)**	**Wind induced slip (cm/s)**
Beaufort Scale	**mph**	**m/s**		
2	7	3.1	0.0036	0.36
3	12	5.4	0.0062	0.63
4	18	8.0	0.0092	0.92
5	24	10.7	0.0123	1.23
6	31	13.9	0.0159	1.59

The post-processing of the drogue data synchronises all deployed drogues to the same time step. The MSD at each time interval is used to calculate the dispersion coefficient using the same calculation as used in the dye release section above.

3. Results

Dye Release

The dye boundary mapping is applied to all images for each dye release (R1 – R5). The dye boundaries are stored as stacked polygons for each release, an example of these stacked layers is shown in Figure 6. This shows 11 out of 51 timesteps plotted with the background image as the final true colour image in the sequence. This illustrates the expansion of the plume over time with the final time step showing the difficulty associated with drawing a boundary when the plume begins to dilute.

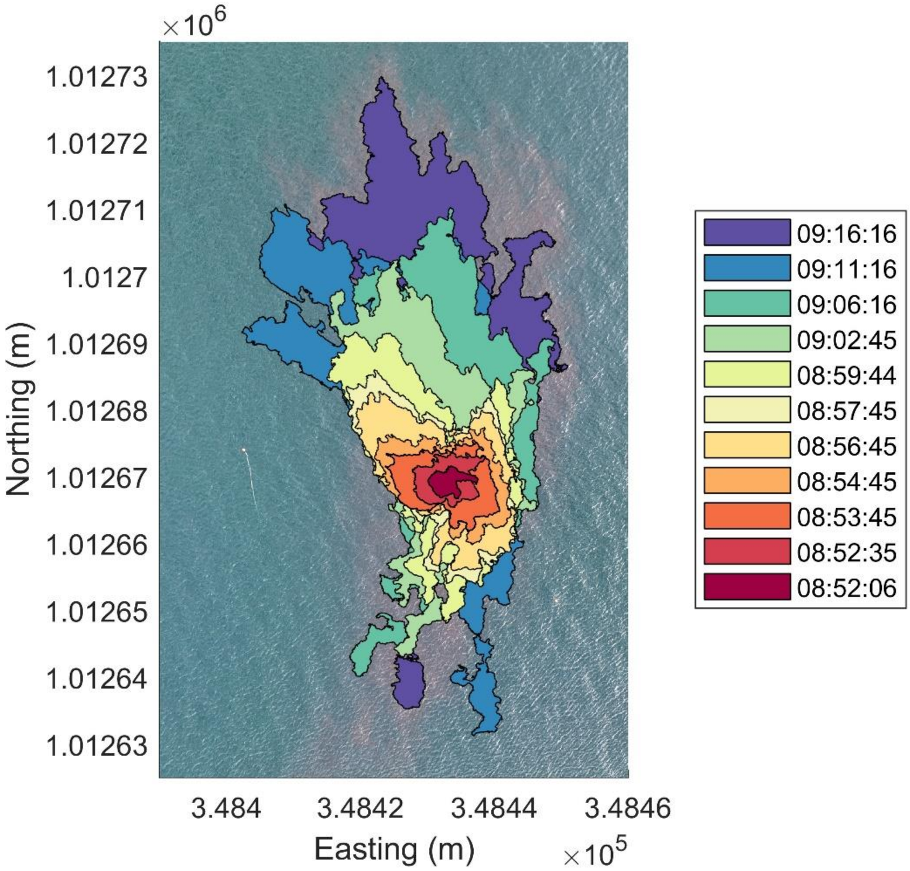

Figure 6. Extent of mapped dye plume boundary from a selection of timesteps from R4.

From the dye boundary data, the MSD is calculated (Figure 7), where each release shows an increase in MSD with lag time, indicating a continually growing plume area. The linear fit equation and the line gradient used to calculate the dispersion coefficient are provided in each subplot for the respective releases.

After approximately 20 minutes the dispersion of the dye plume lowers the visible concentration of the plume, making the detection of the outer boundary difficult. At this point, the size of the plume begins to shrink and fragment. This causes a reduction in the MSD that is not representative of the plume dispersion. Any data showing a continual reduction in plume area has been removed from the MSD analysis. This prevents any bias in the calculation of the final dispersion coefficient.

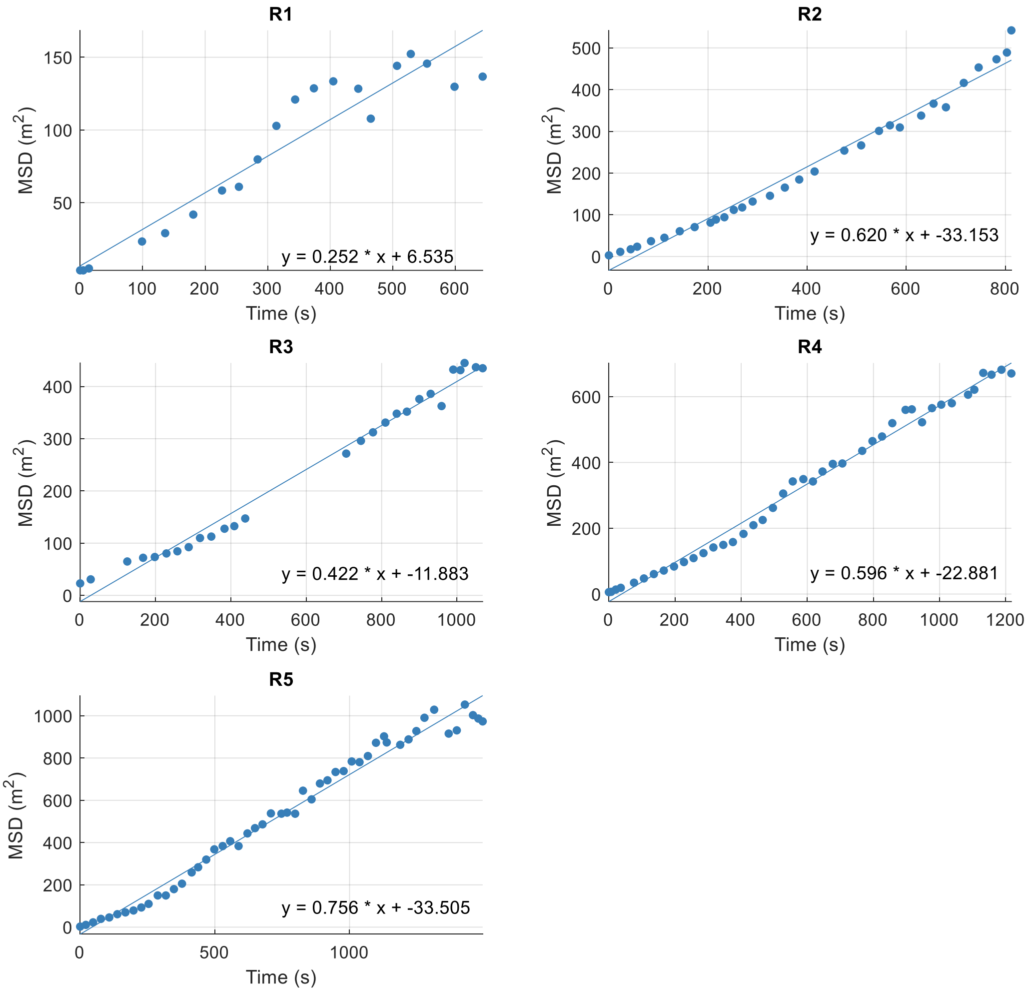

Figure 7. MSD over time with a linear fit line equation for dye releases 1 to 5.

The statistical parameters of the linear fit are provided in table 5. This shows high correlation and low errors associated with the processed data. R1 shows the highest NRMS values and lowest correlation coefficient, when compared to Figure 7, this indicates a larger variation in the rate of the plume spreading during the later part of the release. R4 shows the lowest relative error value, indicated by the clustering of data point along the fit line in Figure 7.

The results of the aerial dye plume tracking provide a range of values in the calculated dispersion coefficient. These values are all within the expected values and range from 0.074 to 0.164 m^2/s. An average horizontal dispersion coefficient of **0.12 m^2/s** is calculated from the measurements undertaken in this study.

Table 5. Line fitting statistics and dispersion coefficients for each release.

	R1	R2	R3	R4	R5
Pearson correlation coefficient	0.950	0.990	0.992	0.995	0.991
RMS Error	16.4	22.4	18.3	22.1	45.6
NRMSE	0.110	0.042	0.043	0.033	0.043
Fit gradient	0.252	0.620	0.422	0.596	0.756
Dispersion coefficient	**0.074**	**0.123**	**0.104**	**0.135**	**0.164**

Drogue Release

The time-synchronised drift tracks from all releases are shown in figure 8. Drogues are shown to predominantly travel in the West, North-West direction. As time from the release point increases the drogues are shown to separate. The net transport of the drogues ranges between 91 and 160m with average speeds ranging from 0.034 and 0.06m/s. This is consistent with the data collected by the ADCP. Due to shallow water and the presence of the existing farm, longer duration drogue releases were not possible.

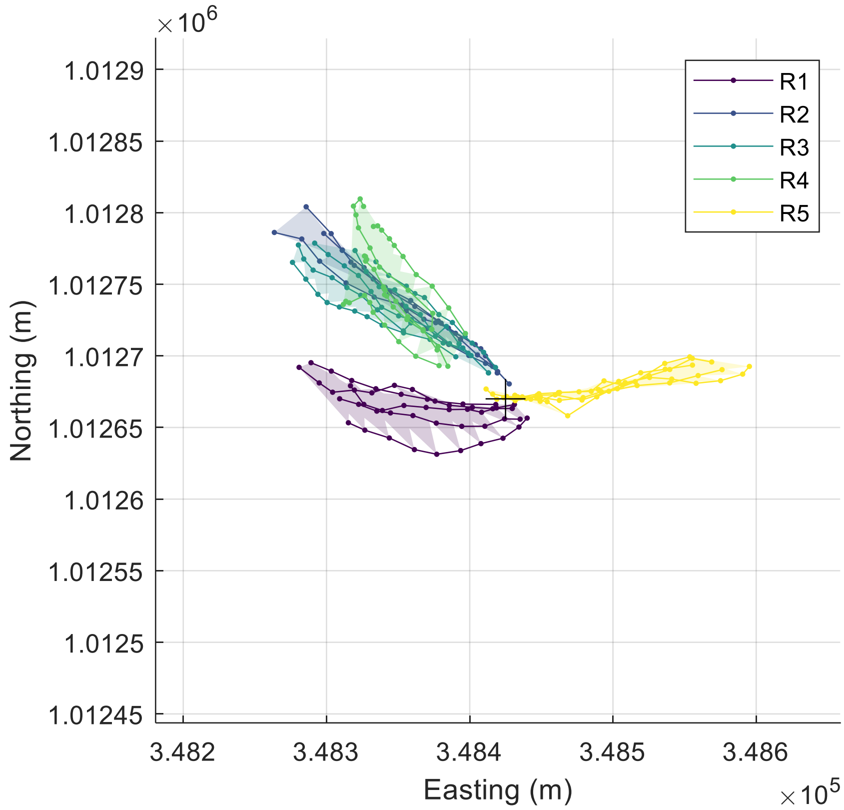

Figure 8. Time-synchronised drogue tracks for each release.

The calculated MSD of the drogue releases are shown in figure 9. A linear regression fit is applied to the data for each release. This shows while there is a continual increase in dispersion there remains a temporal variation with some instances of a reduction in the area coverage. The variation statistics, gradient and calculated dispersion coefficients are shown in table 6. Larger variations in spatial coverage of the drogues are shown in R1 and R3, and consistent dispersion is shown in R4.

The drogue calculated dispersion coefficient ranges from 0.071 to 0.101 m^2/s with an average dispersion coefficient of **0.089 m^2/s**. The largest value occurs during the Ebb tide where R3 and R4 record values 0.101 m^2/s. The lowest dispersion occurs during R2 (0.082 m^2/s) and R5 (0.071 m^2/s), these correspond with high and low water.

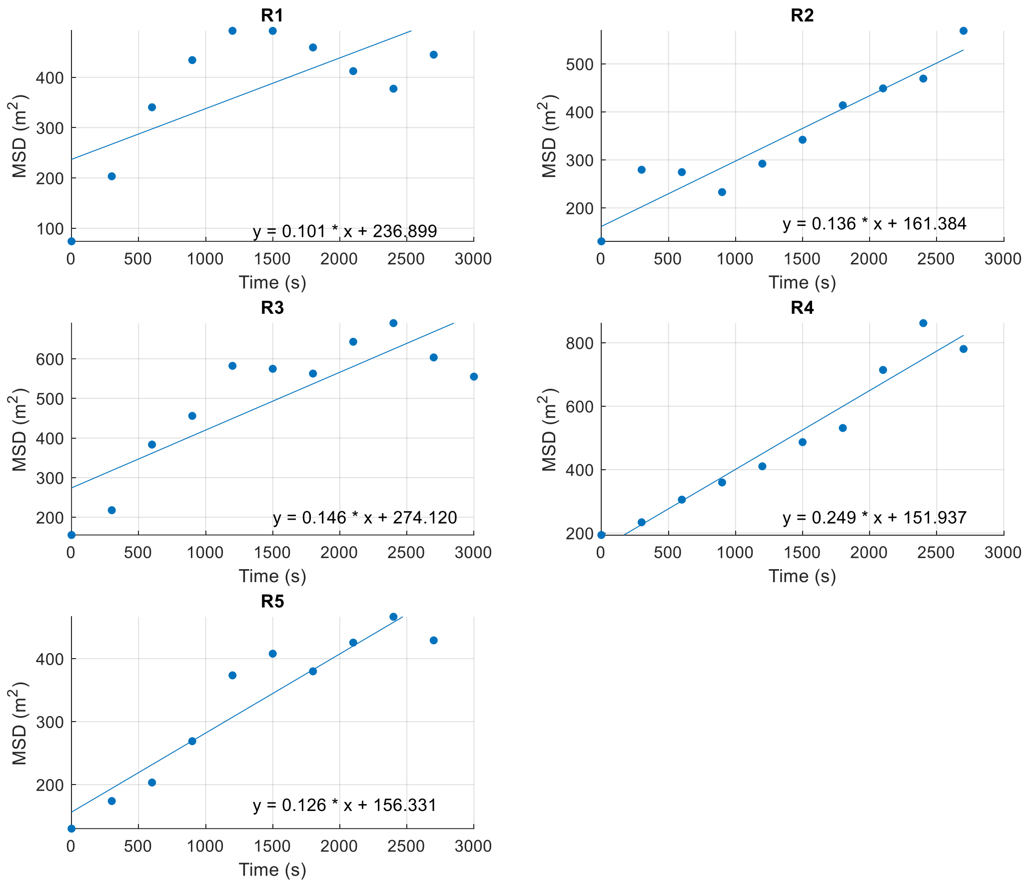

Figure 9. MSD over time with a linear fit line equation for drogue releases 1 to 5.

Table 6. Line fitting statistics and dispersion coefficients for each release.

	R1	**R2**	**R3**	**R4**	**R5**
Pearson correlation coefficient	0.675	0.952	0.838	0.973	0.942
RMS Error	95.0	37.6	90.1	51.1	38.5
NRMSE	0.227	0.086	0.168	0.076	0.114
Fit gradient	0.101	0.136	0.146	0.249	0.126
Dispersion coefficient	**0.090**	**0.082**	**0.101**	**0.101**	**0.071**

4. Conclusion

This report shows a new approach for calculating horizontal dispersion coefficients using Rhodamine WT dye. The use of aerial images allows dye plumes to be mapped in 2 dimensions using a non-invasive method. The use of Rhodamine and the red colour spectrum provides a clear plume that is easily distinguished using basic computational methods. The MSD of each dye plume and the respective lag time from release allow the calculation of a dispersion coefficient.

Additional results were collected using more conventional Lagrangian drogues. Five drogues were deployed and tracked for a longer duration determination of dispersion and particle fate.

The dye study measured horizontal dispersion coefficient ranging from 0.074 to 0.164 m^2/s with an average of 0.12 m^2/s. The drogue data showed a slightly more conservative dispersion range between 0.071 and 0.101 with a mean value of 0.09m^2/s. These survey results are not directly comparable as they were performed at different times. When compared with the default values used within NewDepomod and BathAuto of 0.1 m^2/s, these results are shown to be within a similar range.

The use of the aerial imagery to track dye plumes provides a vast improvement on the resolution of the shorter-term dispersion due to the large number of data points available and non-invasive survey method. Limitations of UAV dye surveys are optical detection and drone battery life. While these can be overcome by increasing release quantity and upgrading drone to more bespoke industrial models, only marginal gains in survey duration will be made. For longer duration (0.5 hr +) studies, traditional drogues offer a more efficient option.

It is recommended that the mean dispersion coefficient of both surveys is used for future bath treatment modelling. For Meil Bay a horizontal dispersion coefficient of **0.105 m^2/s** should be applied.

References

Lumpkin, R., and Pazos M. , (2007) *"Measuring surface currents with Surface Velocity Program drifters: The instrument, its data, and some recent results"* Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics, A. Griffa et al., Eds., Cambridge University Press, 39–67.

Sybrandy. A. L, P. P. Niiler, C. Martin, and W. Scuba, E. Charpentier, D. T. Meldrum (2009) *"Global Drifter Programme Barometer Drifter Design Reference"* Available at: https://www.ocean-ops.org/doc/DBCP/svpb_design_manual.pdf (Accessed December 2023)