ANDERSON MARINE SURVEYS

Report To: Scottish Sea Farms

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Shapinsay, Orkney
Dye dispersion study

Introduction

Site-specific quantification of dispersion is important for the proper use of the particle tracking and dispersion models used in assessment of the environmental effects of cage aquaculture. Discharges to a water body, either as a single patch or a continuous plume, are transported and dispersed by a mixture of advective flow (e.g. tidal movement) and non-advective mixing. Non-advective dispersion has both horizontal and vertical components, and the models AutoDepomod, NewDepomod and BathAuto incorporate a standard nominal value of the horizontal component, K, of 0.1 m^2/s. However, typical reported values of K measured using dye patch dispersion in coastal waters range widely (e.g. from 0.02 – 2.17 m^2/s; Elliott et al 1997; Morales et al 1997). Significantly higher values of dispersion have also been reported using alternative methods; e.g. SAMS drifters (14.8 m^2/s in the Sound of Mull; Cromey et al 2001).

The principal mechanisms of dispersion vary with physical and time scales; from molecular diffusion at small scales, to turbulence and advective shear at intermediate scales (1-1000m) and oceanic processes at very large scales. Many of the intermediate and large-scale processes will be influenced by site-specific topographic and hydrodynamic characteristics; and therefore variability of K between and within model domains, and over time, may be significant.

Long-term (2h – 1 month), and large-scale (30m – 100km) dispersion is classically illustrated as an "Okubo diffusion plot" (or "oceanic diffusion diagram"), Figure 1, of variance vs time on logarithmic scales. Various field data indicate a consistent increase in variance[1], which corresponds to diffusivity increasing over time, and dispersion over timescales of a tidal cycle or more (>12.5h) considerably greater than the nominal 0.1 m^2/s.

Site-specific quantification of dispersion over relevant spatial and timescales is therefore an important component of validating models used to predict environmental effects of cage aquaculture. This report describes dispersion measurement at the

[1] The relationship between variance and diffusivity for a Gaussian representation of plume or patch processes is described below

Shapinsay cage site (Figure 2), carried out together with the adjacent Puldrite site (8.1km to the west).

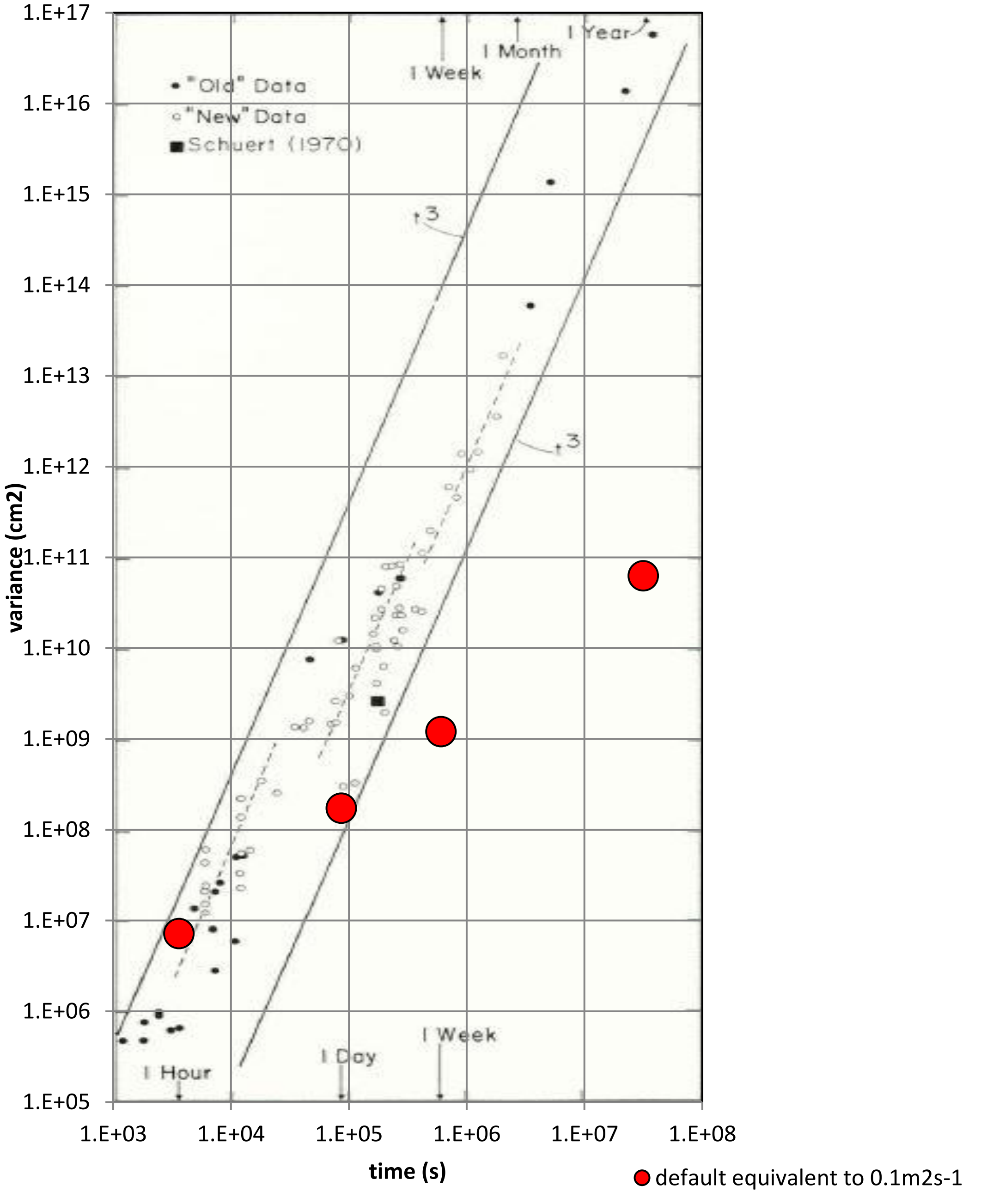

Diagram from Okubo (1974) SOME SPECULATIONS ON OCEANIC DIFFUSION DIAGRAMS
Rapp. P.-v. Réun. Cons. int. Explor. Mer, 167: 77-85. Decembre 1974.

Figure 1. Okubo diffusion plot. Nominal variance for 0.1 m^2/s diffusivity also shown.

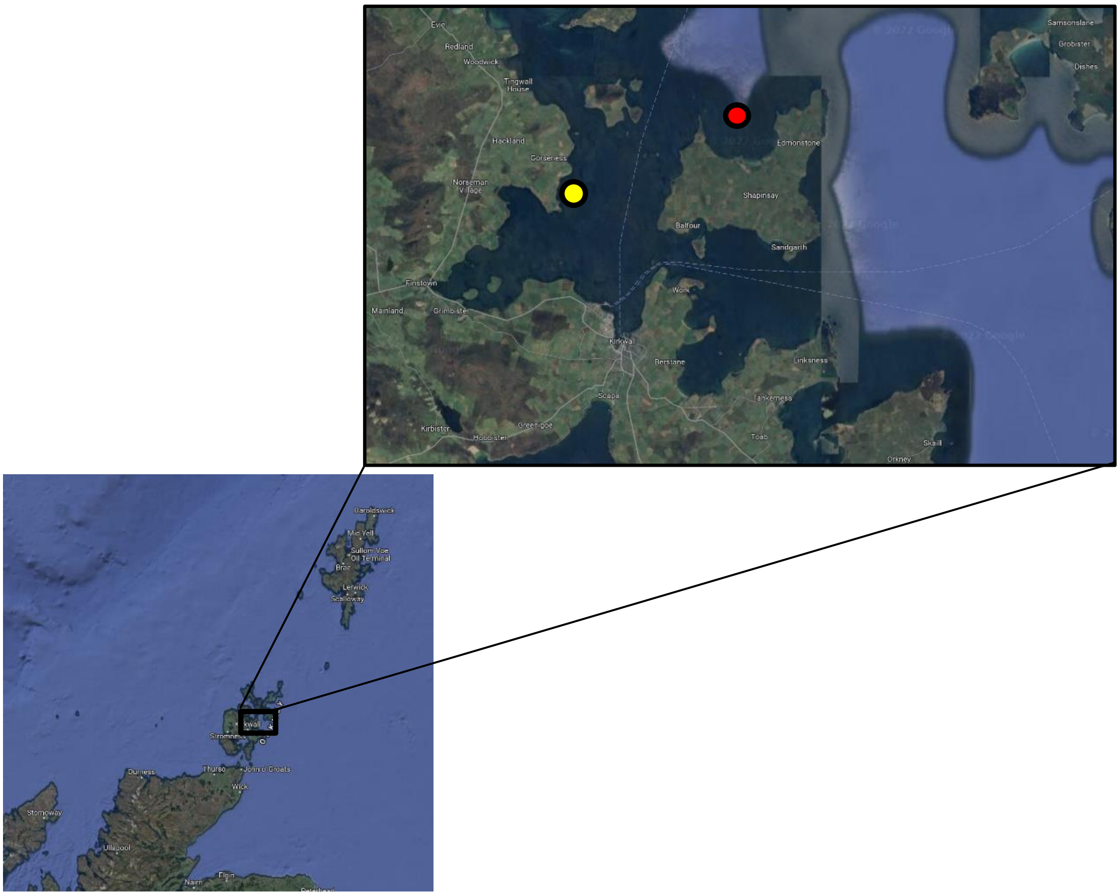

Figure 2. Shapinsay general location (red); also Puldrite study site (yellow)

Survey methods

The field survey programme was carried out on 05 and 07 July 2022, with dye releases covering a tidal cycle (Figure 3) over the two dates. A series of five dye releases to the sea surface were made.

Following each release, dye concentration in surface water (approximately 50cm depth) was measured with a Unilux fluorometer mounted on a rigid over-side pole, logging to PC.

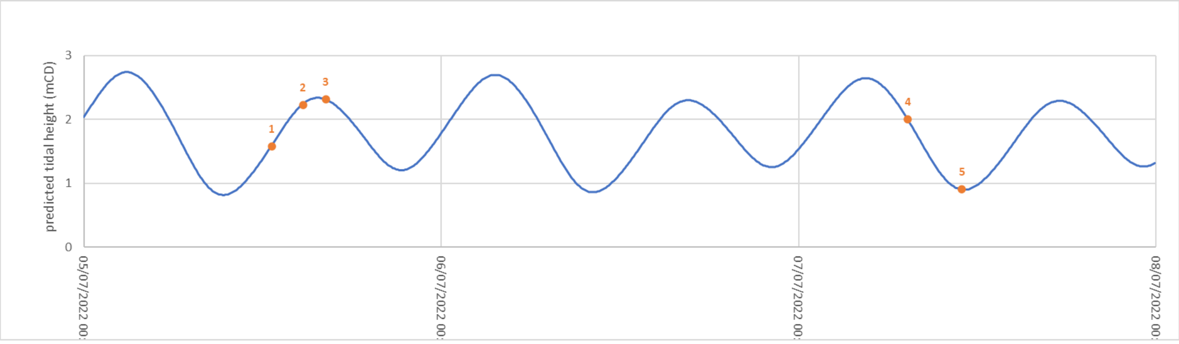

Figure 3. Timing of dye releases in relation to tidal cycle

Positioning was provided by a Simrad NSS7 evo2 echosounder/chart plotter (vertical resolution 0.1m), logging directly to PC at 1s intervals. Previous calibration indicates that the single fix accuracy of this instrument is consistently <2m.

An RDI Workhorse 600kHz ADCP (SN 24538) was deployed adjacent to the site for the period of the releases; in a gimballed bed frame. An appropriate sub-surface depth bin was selected for subsequent analysis. The meter was equipped with a pressure transducer to measure tidal height. Mooring location and depths are shown below:

	latitude	longitude	OSGB36 E	OSGB36 N	recorded deployment depth mCD
05 July 2022	59ºN 07.747'	002ºW 52.349'	350161	1027249	19.9

Declination for the survey location and date was 1.47ºW; grid convergence -0.75º and Grid Magnetic Angle[2] -0.72º.

Drogue releases were also carried out simultaneous to the dye releases, using standard-pattern drogues with reduced sail depth (≈1m, due to relatively shallow water depths), fitted with GlobalSat GPS dataloggers recording at 10min intervals.

[2] From http://www.geomag.bgs.ac.uk/navigation.html

Data analysis

Following discussions of similar survey programmes with SEPA, dye concentration contour plots are not considered to be the most appropriate approach to data analysis; since this requires multiple transects of the patch in different directions which increases disturbance of the patch, introduces errors associated with the elapsed time of the transects (during which the patch size, shape and position will change), and is frequently not possible due to constraints of water depth (especially in marginal weather conditions). For these reasons, analyses of dye patch releases have been carried out with the following objectives:

- Direct observation of plume width, direction and rate of plume advection

- Estimation of horizontal dispersion coefficient for use in quantitative modelling

The derivation of dispersion (or diffusivity) parameters, from either dye or drogue studies, is generally based on a Gaussian representation of plume or patch processes (Lewis 1997) which assumes constant mass in an increasing volume, resulting in concentration distribution in a given direction approximating to a Gaussian function in which spread can be quantified as variance. Variance (σ2) over time of either peak concentration in the patch, or more usually patch width estimated from a single transect across the patch, can be related to a time-dependent “instantaneous” Fickian diffusivity (K, m^2/s):

K = σ2 / 2t (Elliott et al 1997)

Where, σ2 is estimated from Gaussian parameters and t = elapsed time between dye release and start of transect (s).

These analyses can be made from single transects (elapsed time around 1-2 minutes) and minimise experimental errors.

A subset of data from transects selected as representative over the separate patch releases have been selected as representative. For each selected transect, the transect track was plotted to check for reasonable linearity, the concentration profile plotted to check for baseline drift and approximation to a normal curve, the X-Y location of peak concentration identified, and cumulative along-track distance from start of the transect calculated. The variance of fluorescence along the transect, σ^2 (m^2), was calculated at distances corresponding to a 1s measurement interval for each transect using an Excel spreadsheet as:

$$\sigma^2 = \frac{\Sigma c x^2}{\Sigma c} - \left(\frac{\Sigma c x}{\Sigma c}\right)^2$$

Where, c = fluorescence
x = along-transect distance (m)

Time-dependent “instantaneous” Fickian diffusivity (K, m^2/s) was then calculated as described above.

Results

Individual patches were recorded over elapsed times varying from 00:02:23 to 01:58:20 hours, and distances up to 1079m from the release point. Observed wind conditions were 2.1 – 4.4 NW on 05 July and 2.5 – 4.8 m/s W on 07 July. This is consistent with wind observations for the survey period at Kirkwall airport (Figure 4).

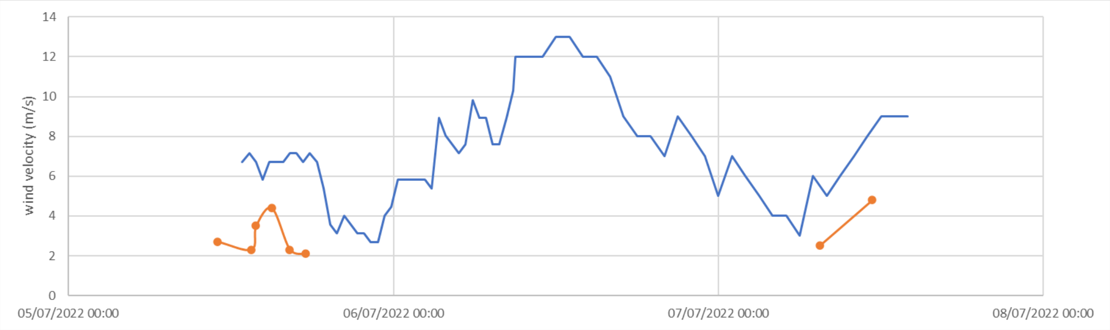

Figure 4. 30-min-averaged wind velocity at Kirkwall Airport, 05 – 07 July 2022; boat-based field observations also shown (orange)

Current velocities, averaged over twenty minutes, recorded during each dye release are shown in Figure 5. A range of velocities was recorded for each release: generally between 0.05 and 0.15 m/s although velocities following release 1 (mid-flood) and release 4 (mid-ebb) were higher, up to 0.222 m/s.

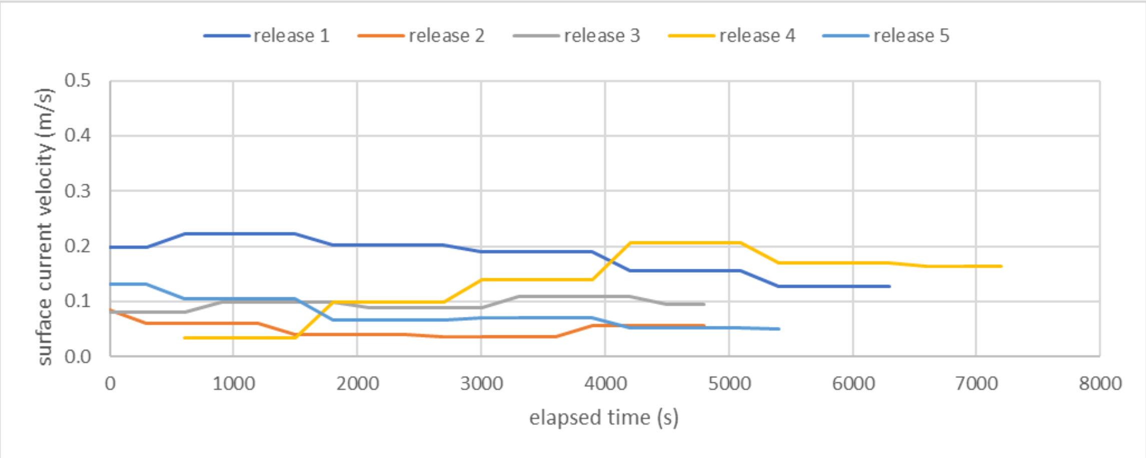

Figure 5. Sub-surface current velocity time series recorded during each dye release

Cumulative flow vectors calculated for the duration of each release are shown in Figure 6; flow vectors were relatively weak at HW (release 2) and LW (release 5), but stronger during flood to the SE (release 1) and ebb to the NW (release 3).

Advection paths of dye patch centres (Figure 6) tracked generally consistent with tidal vectors.

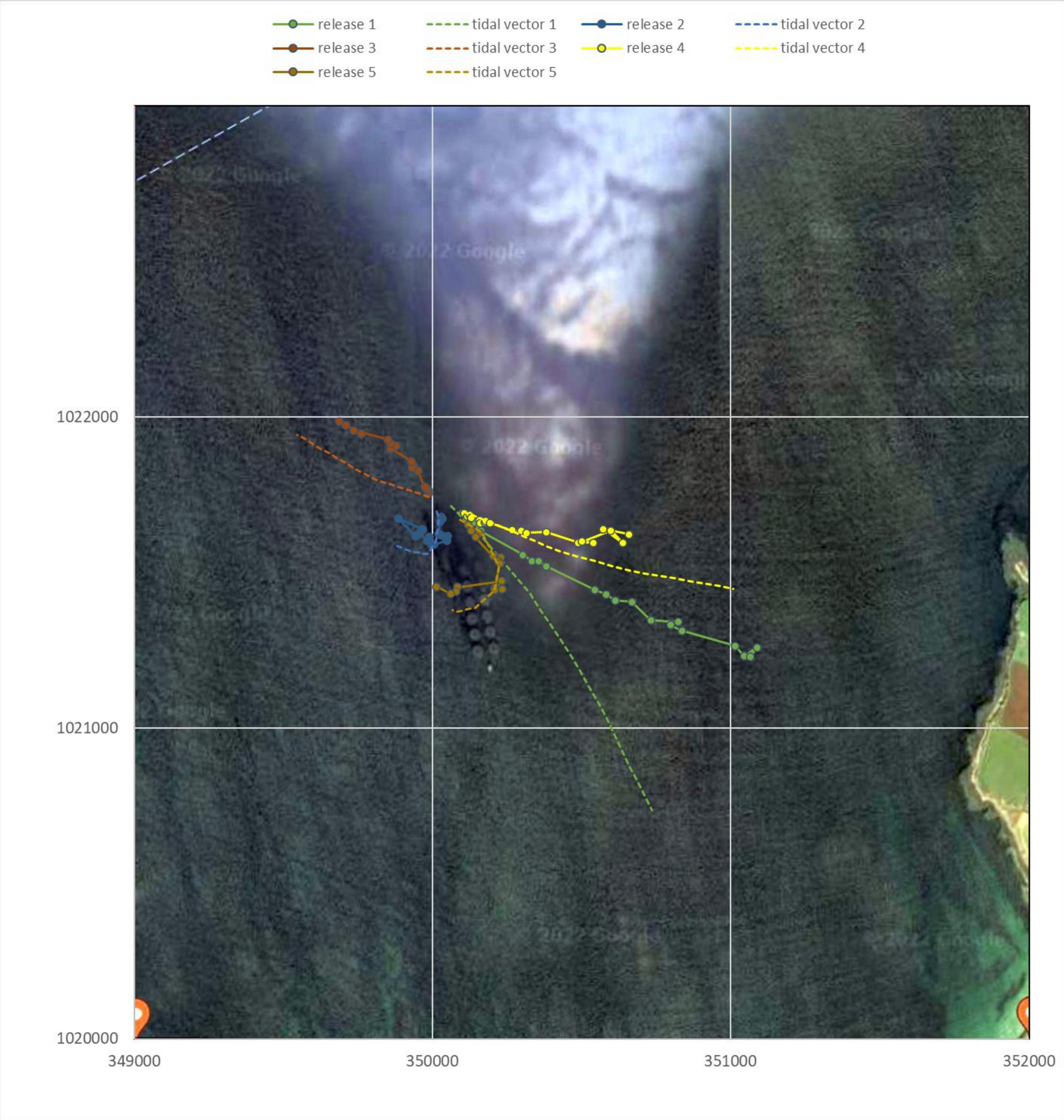

Figure 6. Advection paths of dye patch centres and tidal vectors over release periods

Recorded width (quantified as length scale, 2√3 σ (m)) of individual dye patches generally increased consistently over time following release (Figure 7); occasional outlier values result from fragmentation of the patch or from difficulties in locating the patch centre at longer elapsed times.

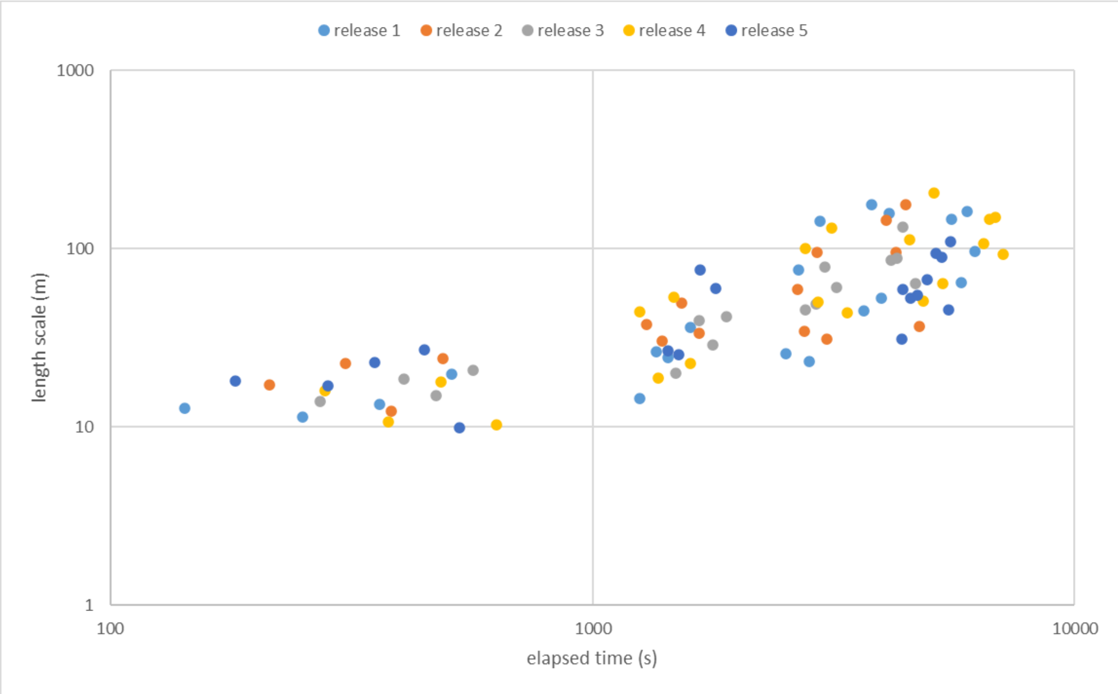

Figure 7. Dye patch width as a function of elapsed time

From a total of 90 transects over the five releases, measured Fickian diffusivity varied from 0.00696-0.345 m^2/s; mean 0.070 m^2/s, median 0.038 m^2/s (Figure 8). The best-fit regression curve for all data points was $K=0.006\ t^{0.2611}$, $r^2=0.11$.

In general, diffusivity reflected expected patterns of variability and was comparable between individual dye patch releases. Fickian diffusivity increased over the duration of an individual release. There was little evidence of any systematic variation in relation to recorded current velocity or tidal cycle.

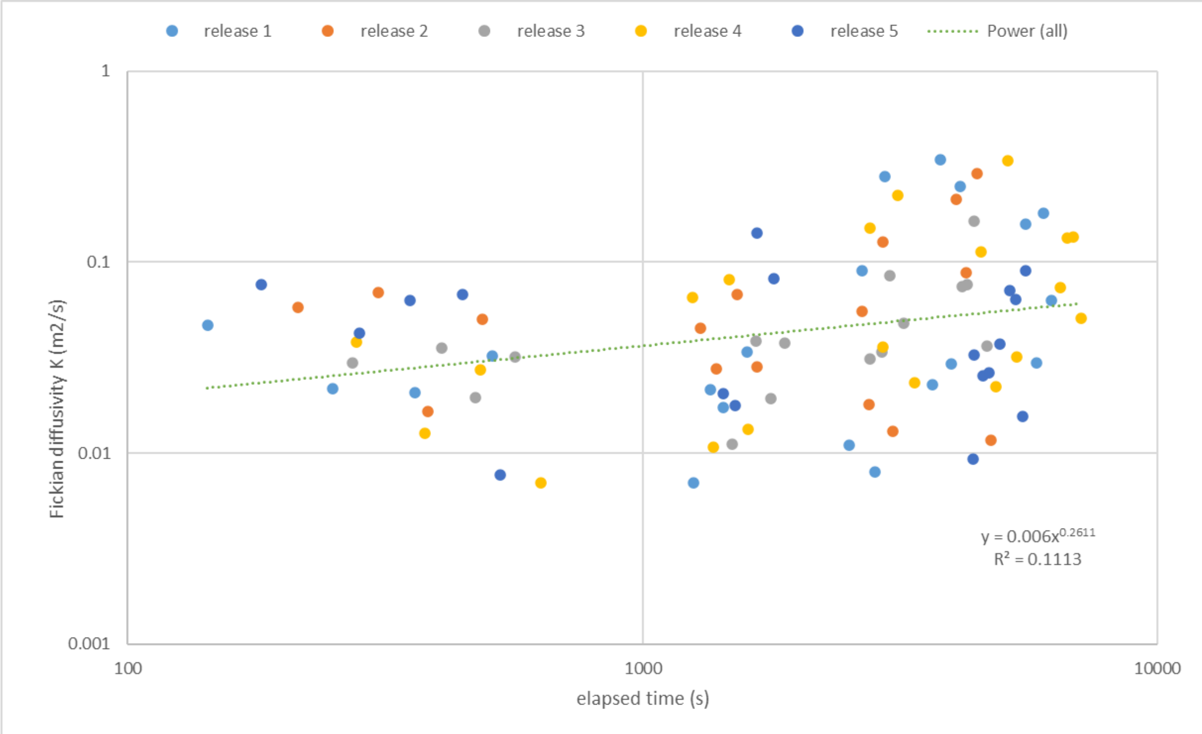

Figure 8. Fickian diffusion as a function of time (all patch transects)

Drogue tracks (Figure 9) were consistent with advection paths of dye patch centres and tidal vectors.

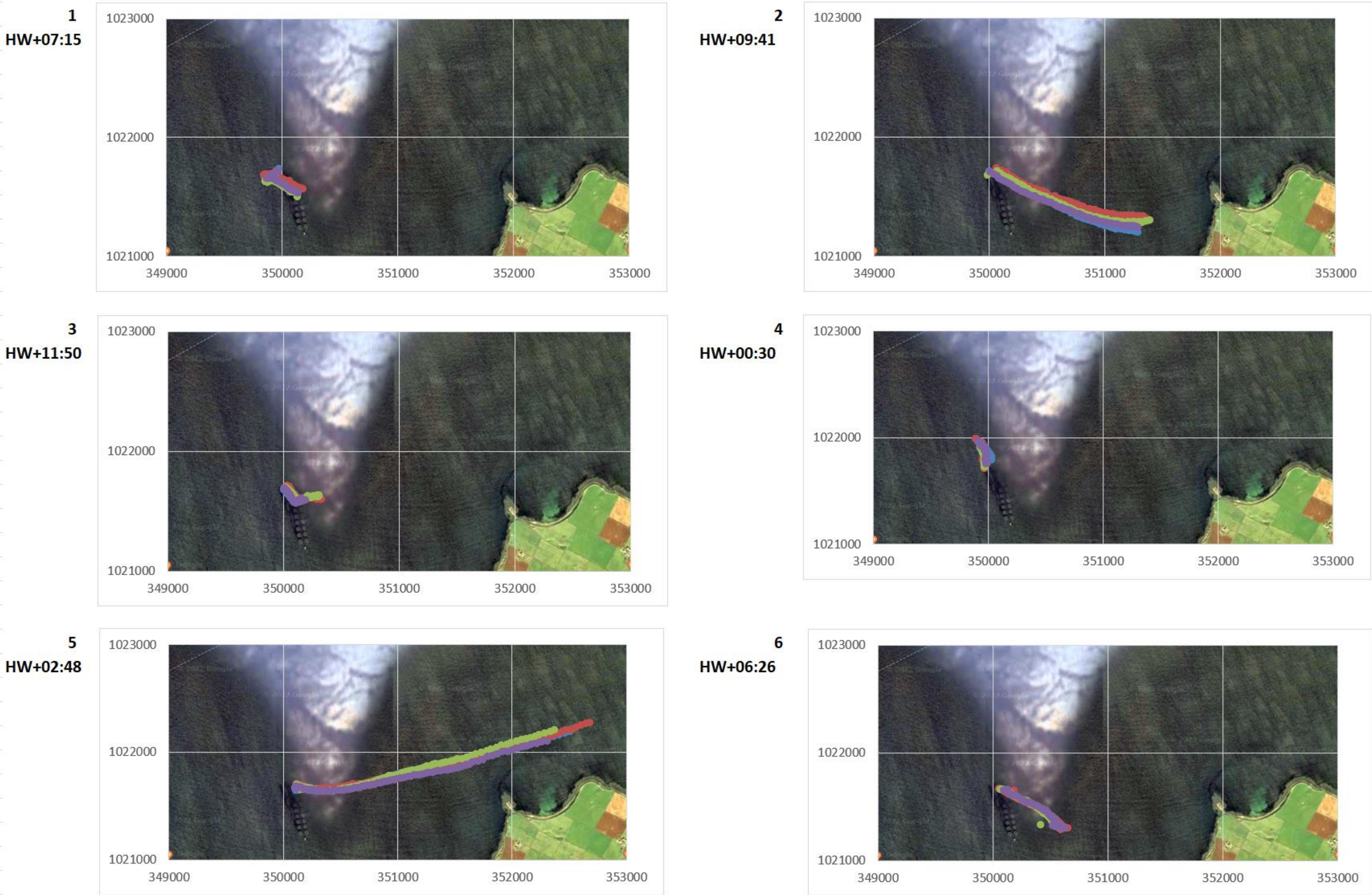

Figure 9. Drogue tracks

Discussion

Overall, dispersion characteristics of the site are typical of a relatively exposed site with moderate tidal energy, influenced by the major tidal flows through Eynhallow Sound. The major tidal axis (NW-SE) is rotated around 60º relative to the major tidal axis and residual flow directions recorded by a hydrographic survey carried out east of the site (July-Oct 2019; sub-surface mean velocity 0.181 m/s, residual direction 091°M). Mean current velocity in this study (0.112 m/s) is similar given that the dye studies were carried out during neap tides.

The magnitude of measured horizontal diffusivity, K, is generally consistent with the default value of 0.1 m^2/s (mean 0.070m^2/s, median 0.038 m^2/s, range 0.007-0.345 m^2/s). 17.8% of measured values exceeded 0.1 m^2/s; 82.2% were below this default value. The magnitude is also consistent with AMSL unpublished data from 1435 transects at eight representative sites (upper Loch Fyne, inner Moray Firth, exposed coastal Orkney, Sound of Gigha, Loch Ryan, North Channel, outer Loch Carron, Stornoway harbour) in the range 0.0003 – 0.903 m^2/s, overall mean 0.035 m^2/s.

As noted above, there was little evidence of any systematic variation in relation to recorded current velocity or tidal cycle.

Values of K vary with time; as also observed at other sites (approximately an order of magnitude over the duration for which releases were tracked, around 2h). This is illustrated on an Okubo plot (Figure 10), which demonstrates that extrapolation of the measured trends over time durations relevant to modelling (e.g. 12.5h tidal cycle; 72h duration of BathAuto for azamethiphos) predicts values of K comparable to the default equivalent to 0.1m^2/s.

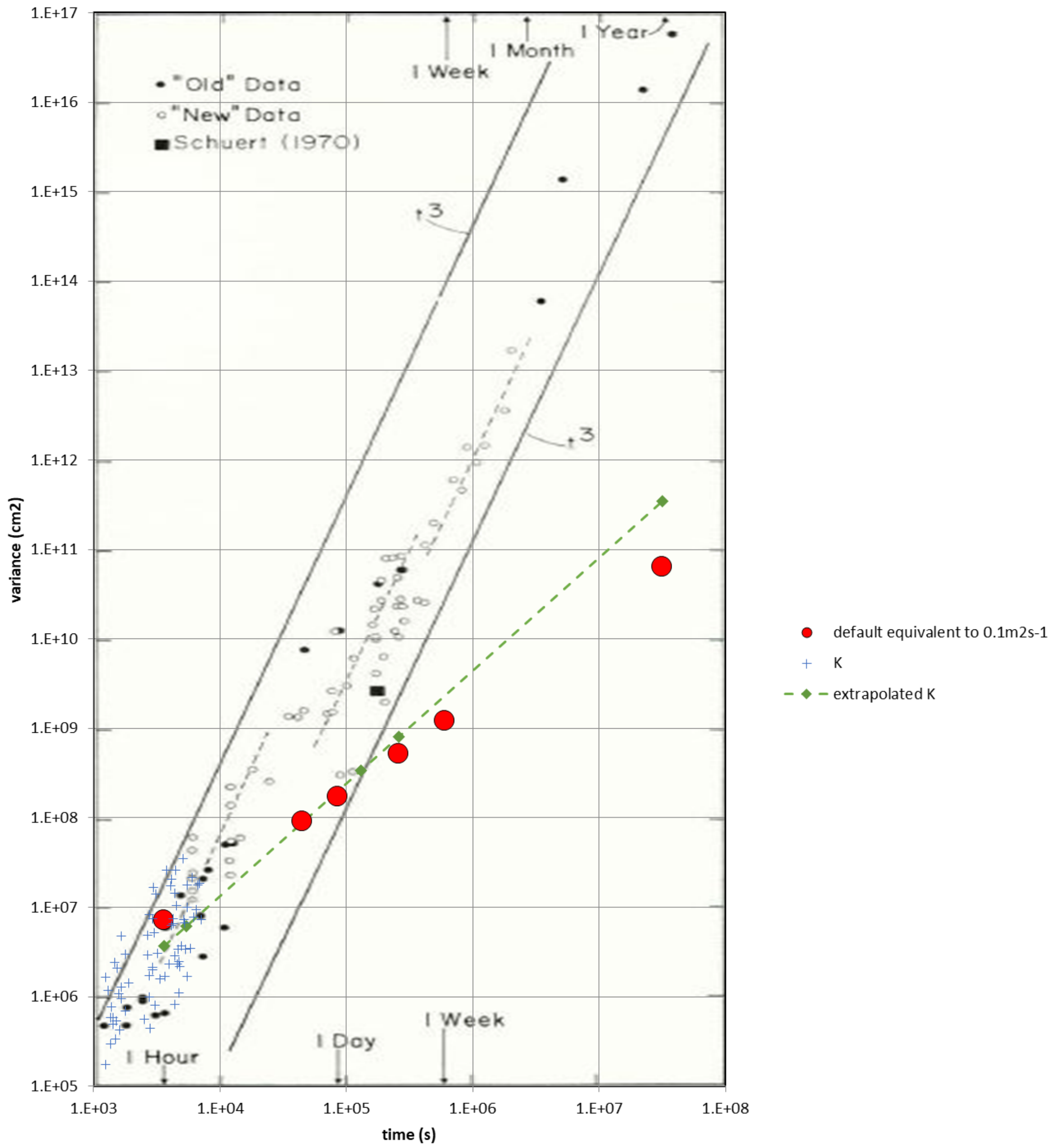

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Figure 10. Okubo plot showing data (K_x, K_y) from present study and extrapolated values of K

Recommendations

Current implementations of AutoDepomod, NewDEPOMOD and BathAuto do not allow for time-dependent values of horizontal dispersion which more accurately reflect site-specific dispersion over relevant time periods than the default 0.1 m^2/s. Although the measured diffusivity was very similar to default values, future modelling for the Shapinsay site using these models should use the relationship derived above, $K=0.006\ t^{0.2611}$ (m^2/s), to predict an appropriate value of K for an appropriate time period for the specific model. For particulate modelling using AutoDepomod and NewDEPOMOD, it is suggested that this should correspond to half the average settling period of faecal particles released at cage-bottom. For bath treatment modelling using BathAuto, this would correspond to half the relevant model period; i.e. 1.5h for cypermethrin and deltamethrin (K=0.057 m^2/s), 36h for azamethiphos (K=0.130 m^2/s).

References

Cromey C, Provost P, Mercer D & Black K (2001). Measurement of dispersion in the area surrounding the Iggesund forestry pier, near Fishnish Bay, Sound of Mull. Data report prepared for Iggesund Forestry (Ltd) June 2001. Dunstaffnage Marine Laboratory.

Elliott, AJ, Barr, AG & Kennan D (1997). Diffusion in Irish Coastal Waters. Estuarine, Coastal and Shelf Science 44, 15-23

Lewis R (1997). Dispersion in Estuaries and Coastal Waters. John Wiley & Sons ISBN 0471961620

Morales RA, Elliot AJ & Lunel T (1997). The influence of tidal currents and wind on mixing in the surface layers of the sea. Marine Pollution Bulletin 34, 15-25