Kyleakin Salmon Feed Factory

Initial Dilution Assessment

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1 BACKGROUND

Marine Harvest is developing proposals for a new Salmon Feed Factory in Kyleakin, Isle of Skye, Scotland (see Figure 1.1). When operational, the proposed Salmon Feed Factory will produce a wastewater that will need to be disposed of in an environmentally acceptable manner. One option under consideration is a marine discharge that will extend from the factory to the west of the pier to between the -4m and -8m contour.

Consequently RPS was commissioned by Marine Harvest to carry out a detailed assessment of the initial dilution potential available in the vicinity the -4m and -8m contours using the CORMIX analysis package.

The results of the initial dilution assessment will be used to inform the design of the proposed wastewater treatment process and the length of the marine outfall. The combination of treatment and outfall to be provided will be based on the premise of ensuring compliance with the Environmental Quality Standards (EQS) as set out by the Scottish Environment Protection Agency (SEPA).

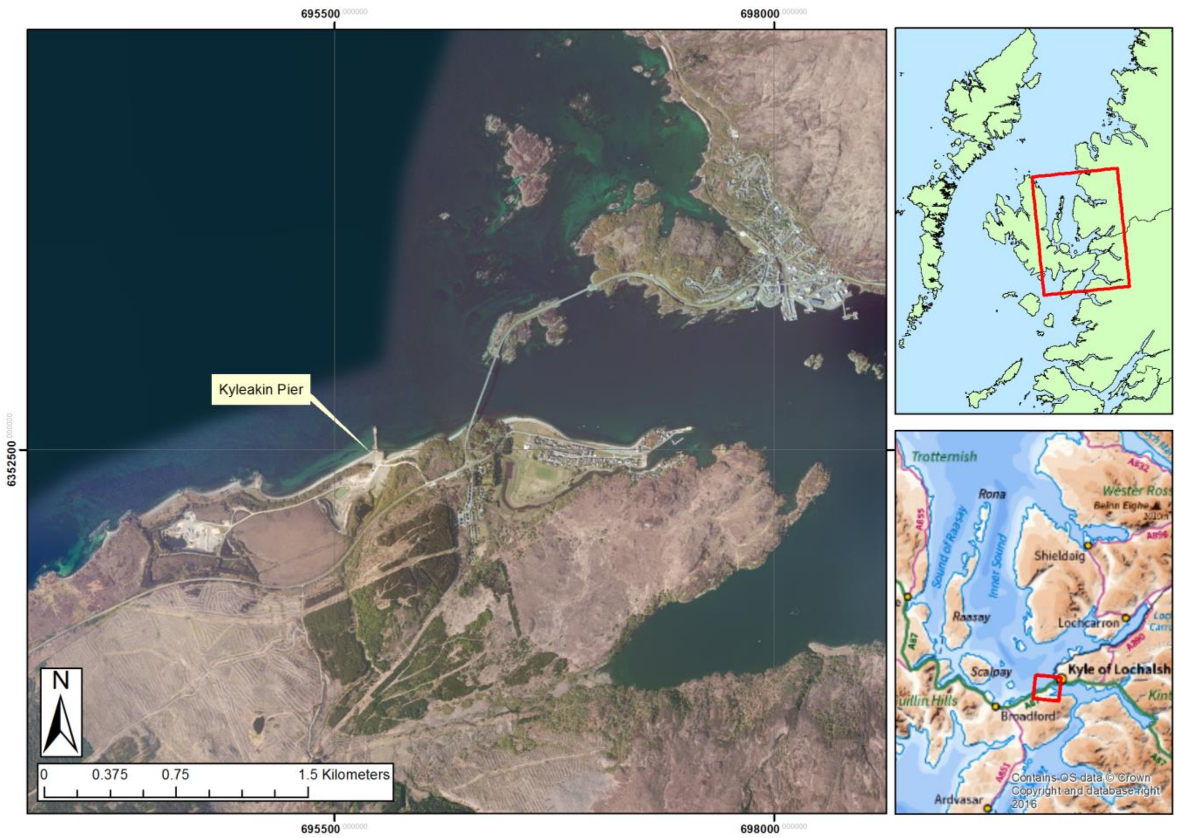

Figure 1.1: Location of Kyleakin in relation to the Isle of Skye and Outer Hebrides.

1.1 LOCATION OF THE PROPOSED MARINE DISCHARGE

One of the purposes of this study was to provide predictions of available initial dilution to inform the design of the proposed wastewater treatment process and the selection of the optimum marine outfall length. Based on RPS' previous experience of initial dilution assessment and the hydrodynamic conditions at Kyleakin, it was estimated that the marine discharge would need to extend to at least the -4m contour to achieve sufficient initial dilution.

Extending the marine outfall to the -8m contour would increase the potential initial dilution available but may not be necessary depending on the dilutions achieved at the -4m contour.

Therefore to provide a detailed assessment of the available initial dilution at the site, the initial dilution potential was assessed for two individual locations. The location of the first marine discharge point was on the -4m contour, whilst the location of the second discharge point was on the -8m contour. These locations in relation to the proposed pier and the Flameshell habitat are illustrated in Figure 1.2 below.

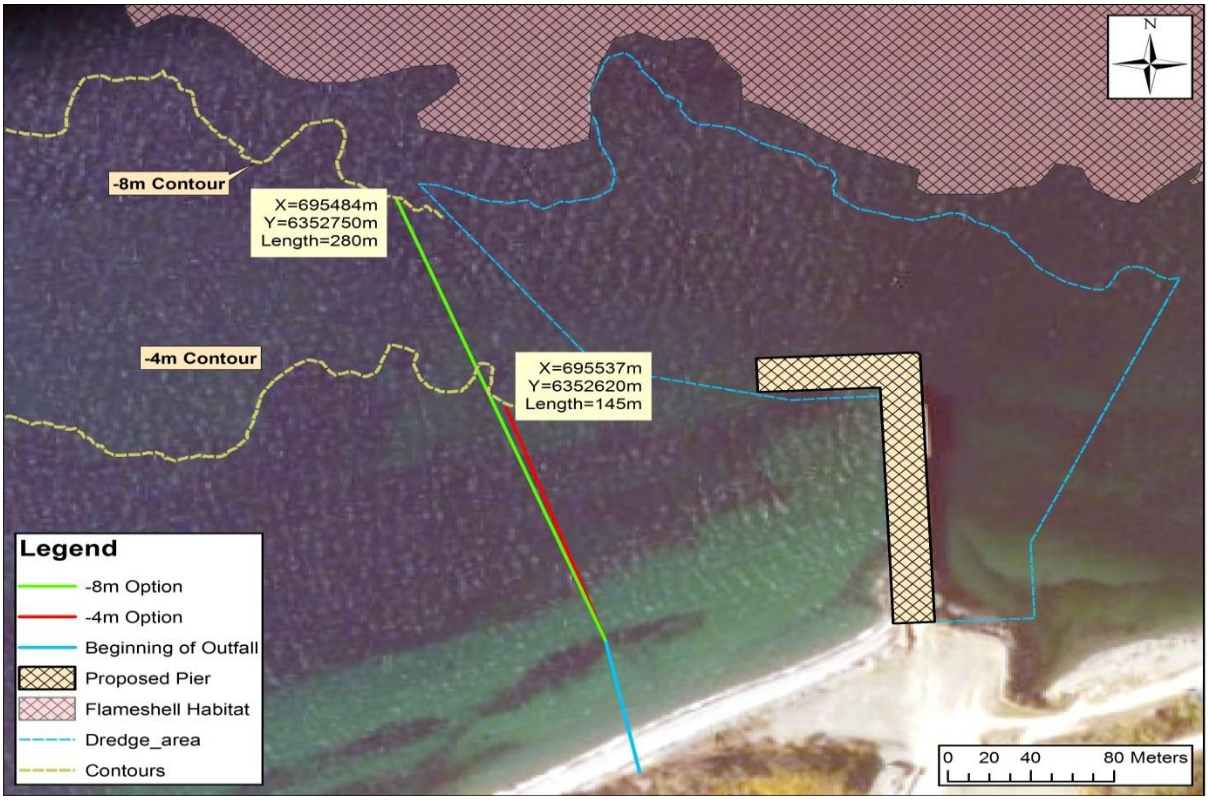

Figure 1.2: Location of the two potential marine discharge points in relation to the proposed development and the nearby Flameshell habitat.

2 DATA AND MODELS

2.1 INITIAL DILUTION MIXING PROCESS

The extent to which initial dilution takes places is a function of several physical characteristics of the effluent, including density, velocity and temperature. These together with the ambient conditions of the receiving water body, such as current speed and direction, govern the extent and rate of initial dilution.

At the discharge port, the initial plume tends to behave as a coherent jet and its behaviour and dispersion is dominated by momentum and buoyancy. As the plume interacts with the receiving water body, these forces no longer dominate and the plume becomes a diffuse mass carried by the ambient current. Mixing initially occurs by turbulent flows at the boundaries of the plume, and later primarily by pure diffusion processes.

All of these processes are numerically resolved by the CORMIX analysis packaged detailed in Section 2.2 below.

2.2 CORMIX MODELLING SYSTEM

CORMIX (Cornell Mixing Zone Expert System) is a comprehensive software system for the analysis, prediction, and design of outfall mixing zones resulting from the discharge of aqueous pollutants into diverse water bodies. The CORMIX system has been developed under several cooperative funding agreements between numerous authorities and institutions including the U.S. EPA, U.S. Bureau of Reclamation, Cornell University and MixZon Inc. amongst others.

The initial dilution and plume trajectory of an effluent is resolved by CORMIX in three different stages; submerged jet mixing, mixing at the boundary layer and surface buoyant mixing. In each stage, a solution for the steady-state simplified flow patterns characterising that stage is calculated. The solutions are then combined to provide a complete simulation from the outflow point to the distance limit set by the user.

CORMIX has been successfully used to design and monitor wastewater disposal systems in oceans, rivers, lakes, and estuaries. The CORMIX package is recognised by numerous regulatory authorities including the Scottish Environment Protection Agency (SEPA) for the assessment of initial dilution and environmental impact of marine discharges.

2.3 AMBIENT CONDITIONS

This study required that the mixing zone of the plume be established under all tidal conditions. At Kyleakin the mean spring range is *c.*4.7m whilst the neap tidal range is *c.*0.7m, this wide variation in tidal ranges results in equally varied ambient tidal current velocities as can be seen from Figure 2.1 and Figure 2.2.

Therefore to account for the full range of tidal conditions experienced at the site, initial dilution modelling using the CORMIX package was undertaken for ½ hourly intervals across typical spring and neap tidal conditions.

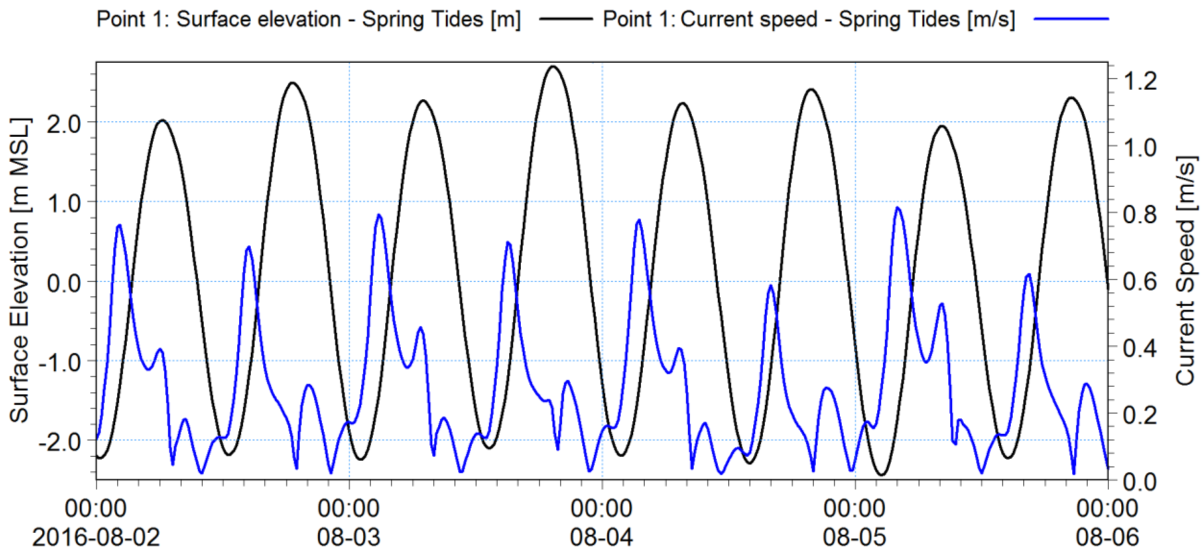

Figure 2.1: Surface elevations and current speeds at the -8m contour – Spring conditions.

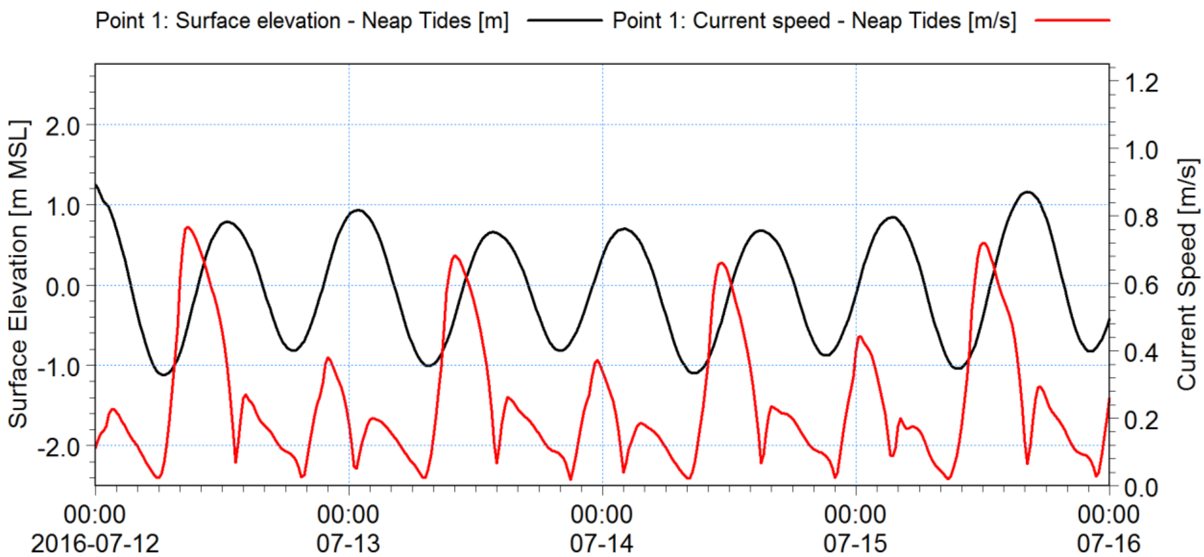

Figure 2.2: Surface elevations and current speeds at the -8m contour – Neap conditions.

The ambient current velocity data used for the CORMIX modelling was obtained from a 2D hydrodynamic model of the Kyleakin and Isle of Raasay area. This model was developed and calibrated by RPS as part of a previous study that investigated the impact of the proposed pier development at Kyleakin. The extent and mesh structure of this hydrodynamic model is illustrated in Figure 2.3. The model was developed using a range of detailed bathymetric datasets, and had a resolution varying from *c.* 200m^2 at the boundaries to *c.* 25m^2 in the area of the proposed pier at Kyleakin.

Results of the numerical simulations indicated that at Kyleakin there is a distinct phase difference between peak current velocities and surface elevation as illustrated in Figure 2.1 and Figure 2.2. As a consequence of this phase difference, peak current velocities do not coincide with the mid-ebb and mid-flood tidal regime but are instead observed *c.*1.5 hours before mid-flood and mid-ebb tides.

The current field at peak flood and ebb flows during a spring tidal cycle is illustrated in Figure 2.4 and Figure 2.5 respectively. It will be seen that at the -8m discharge point the highest current velocities approach *c.* 0.80m/s

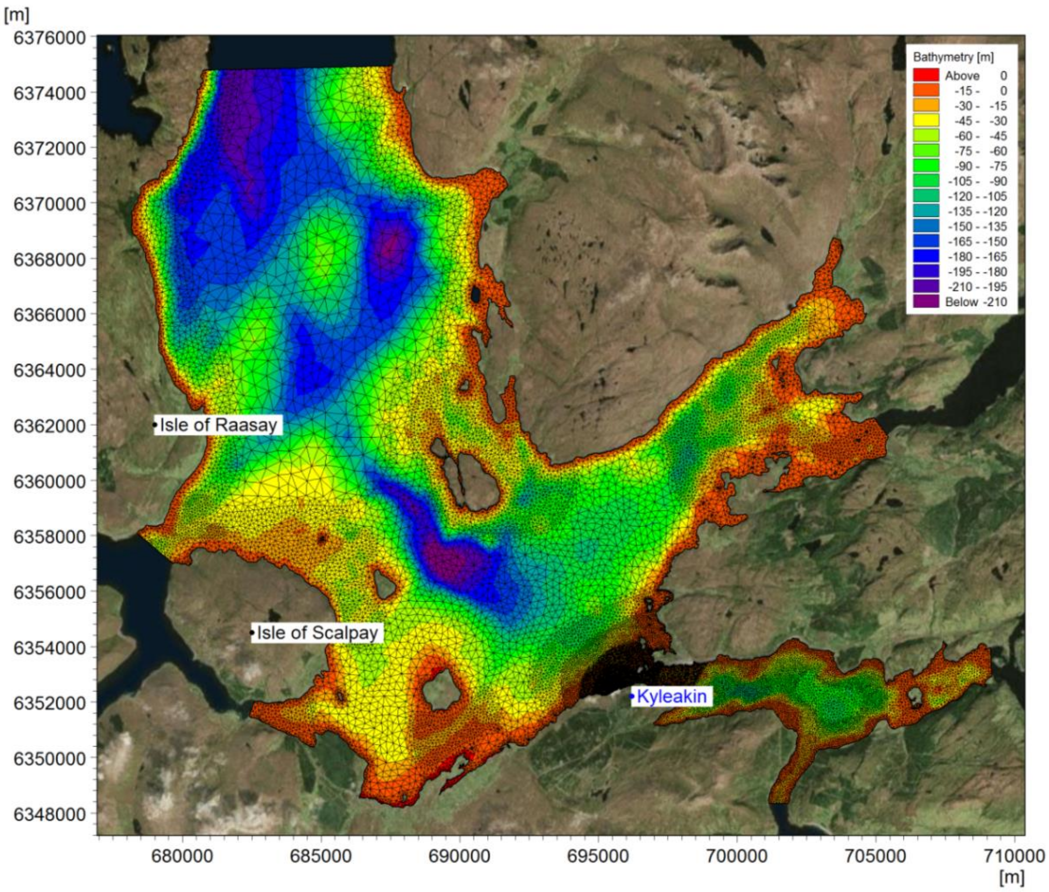

Figure 2.3: Extent and bathymetry of the Inner Isle of Raasay and Kyleakin model (to MSL).

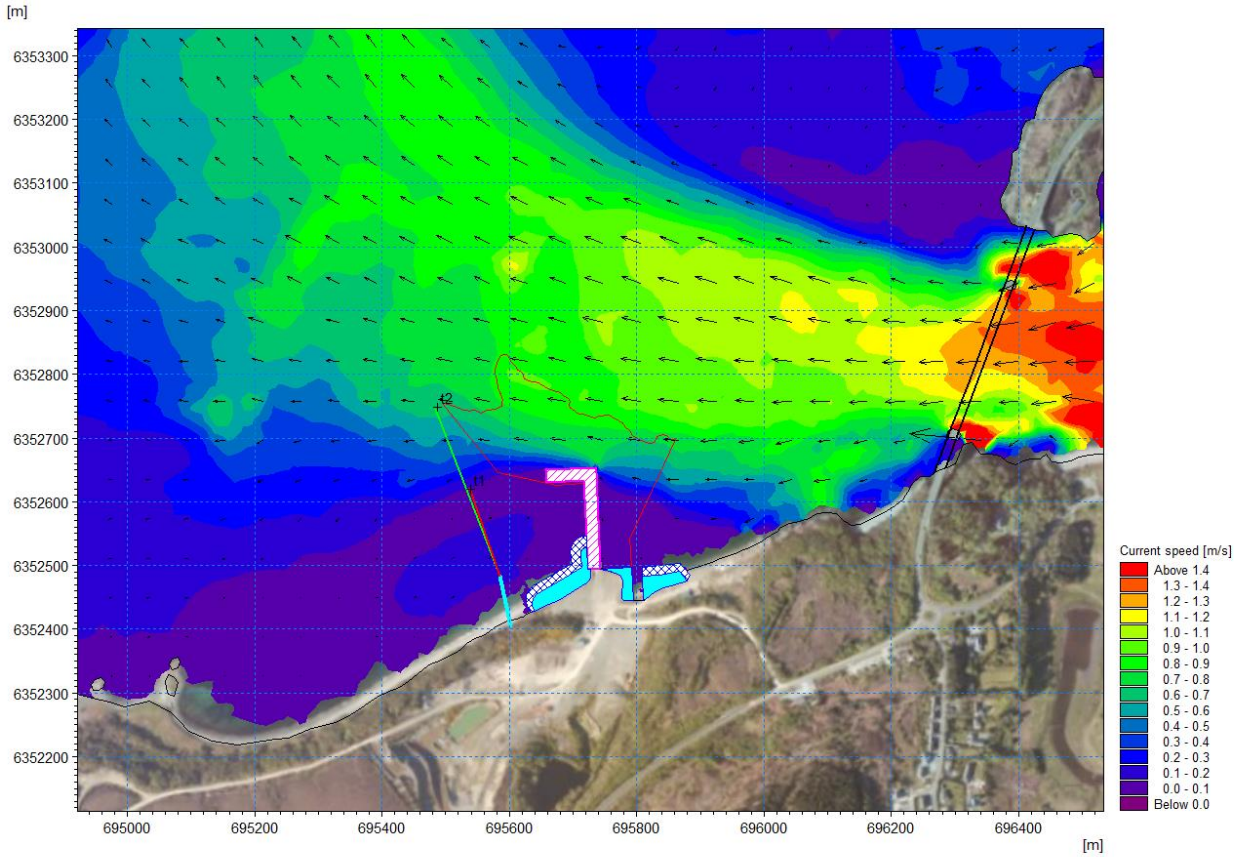

Figure 2.4: Typical current velocities observed at peak flood during spring tidal conditions.

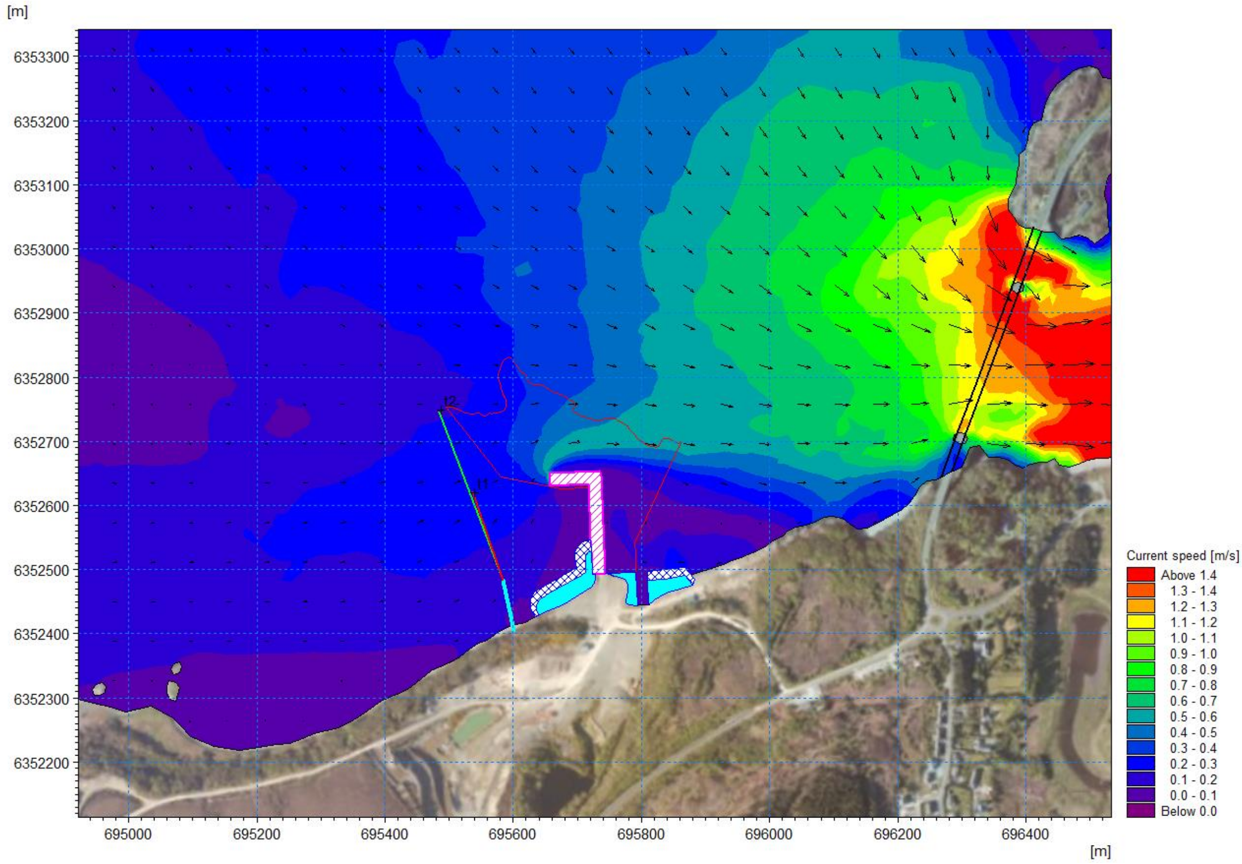

Figure 2.5: Typical current velocities observed at peak ebb during spring tidal conditions.

The ambient water depth and discharge depth are also important factors in determining the initial dilution potential. As the initial dilution modelling was undertaken for two outfall locations, the ambient water depth at ½ hour intervals at each location was also extracted from the model and applied to the corresponding initial dilution calculation.

For the purposes of this modelling exercise it was assumed that the discharge was located 0.20m above the bed. The standard salinity of seawater in the UK of 34$\%_o$ was used to obtain the typical ambient water density of 1026kg/m^3.

2.4 DISCHARGE PARAMETERS

The purpose of this assessment was to derive data relating to the initial dilution potential available at the -4m and -8m LAT over a range of tidal conditions. This data is then to be used to predict the concentration of various parameters at the boundary of the mixing zone and subsequently inform the design of the wastewater treatment process and the length of marine outfall required to ensure that the discharge is in compliance with EQS set out by SEPA.

Therefore, the effluent that was modelled using the CORMIX analyses package was assigned a uniform discharge concentration excess of 1000ppm. Other relevant physical characteristics of the marine outfall and effluent were based on information provided by the plant designers, Jacobs; this information is summarised in Table 2.1 below.

Table 2.1: Summary of marine outfall and effluent characteristics.

Parameter	Value	Unit
HPPE pipe Inside Diameter (ID)	0.16	m
HPPE pipe Outside Diameter (OD)	0.18	m
Average Flow Rate	20.00	m^3/hr
Average Flow Velocity	0.27	m/s
Salinity	0.00	%o
Density	1000.00	kg/m^3
Discharge Concentration Excess	1000.00	ppm
Port Height Above Bed	0.20	m
Vertical Angle of Discharge (THETA)	0.00	degree
Horizontal Angle of Discharge (SIGMA)	90.00*****	degree

***** 90 degrees relates to a cross current flow.

3 INITIAL DILUTION MODELLING

Details of all CORMIX simulations carried out as part of this assessment study are summarised in the following sections. Model results are presented for the submerged jet mixing and mixing at the boundary layer, i.e. the dilution achieved by the point where the effluent plume intersects the water surface or that achieved at some lesser distance from the point of discharge whichever occurs first.

3.1 OUTFALL AT THE -4M LAT CONTOUR

In order to identify the potential initial dilution available at the -4m LAT contour, the CORMIX model was run for 25 different tidal stages during both spring and neap tidal conditions; a total of 50 model simulations. The tidal stages simulated and the corresponding ambient physical characteristics of the receiving water body and the associated model inputs are listed in Table 3.2 overleaf.

Examination of the initial dilution results at the -4m contour illustrated in Figure 3.2 to Figure 3.4 show that in all instances the effluent reached the surface of the receiving water body within 40m of the point of discharge. Thus all initial dilution was shown to have occurred while the effluent plume was more than 120m away from the nearest Flameshell habitat which is located beyond the -9.0m contour. The dilution achieved within the initial jet plume and the boundary layer demonstrated a high degree of variance due to the wide range in ambient conditions of the receiving waters.

Statistical analyses of all simulation runs representing both spring and neap tidal regimes at ½ hour intervals (n=50) indicated that the maximum dilution achieved by the 40m mark did not exceed 523:1. The minimum dilution achieved before the effluent intersected with the surface was 21:1 and occurred <1m downstream of the discharge thus indicating that the initial dilution available in this instance was significantly influenced by the limited total water depth available. The mean dilution achieved across all simulations at the 40m mark was 135:1 (S.D= 137, n=50). The analyses also indicated that 95%ile of all initial dilutions was > 21:1. These results are summarised in Table 3.1 below.

Table 3.1: Summary of all dilutions (n=50) for an outfall at the -4m contour.

	Dilution			
Downstream Distance	**Min**	**Max**	**Mean**	**95th Percentile**
40m	21.66	523.45	135.38	21.66

Table 3.2: Simulated outfall characteristics and corresponding ambient tidal conditions at the -4m LAT contour.

Tide	Time relative to HW [Hr]	Simulation Number	Ambient Conditions			Effluent Charecteristics	
			Surface Elevation [m]	TWD [m]	Current Speed [m/s]	Flow Velocity [m/s]	Excess Conc. [ppm]
Spring	-6	1	-2.12	1.88	0.05	0.27	1000.00
	-5.5	2	-2.05	1.95	0.14	0.27	1000.00
	-5	3	-1.85	2.15	0.15	0.27	1000.00
	-4.5	4	-1.50	2.50	0.08	0.27	1000.00
	-4	5	-1.00	3.00	0.09	0.27	1000.00
	-3.5	6	-0.37	3.63	0.09	0.27	1000.00
	-3	7	0.31	4.31	0.06	0.27	1000.00
	-2.5	8	0.98	4.98	0.06	0.27	1000.00
	-2	9	1.57	5.57	0.08	0.27	1000.00
	-1.5	10	2.05	6.05	0.07	0.27	1000.00
	-1	11	2.41	6.41	0.03	0.27	1000.00
	-0.5	12	2.63	6.63	0.05	0.27	1000.00
	0	13	2.71	6.71	0.07	0.27	1000.00
	0.5	14	2.67	6.67	0.13	0.27	1000.00
	1	15	2.54	6.54	0.29	0.27	1000.00
	1.5	16	2.30	6.30	0.34	0.27	1000.00
	2	17	1.92	5.92	0.26	0.27	1000.00
	2.5	18	1.40	5.40	0.20	0.27	1000.00
	3	19	0.80	4.80	0.12	0.27	1000.00
	3.5	20	0.17	4.17	0.04	0.27	1000.00
	4	21	-0.45	3.55	0.04	0.27	1000.00
	4.5	22	-1.04	2.96	0.09	0.27	1000.00
	5	23	-1.54	2.46	0.10	0.27	1000.00
	5.5	24	-1.91	2.09	0.06	0.27	1000.00
	6	25	-2.13	1.87	0.03	0.27	1000.00
Neap	-6	26	-0.82	3.18	0.08	0.27	1000.00
	-5.5	27	-0.79	3.21	0.05	0.27	1000.00
	-5	28	-0.71	3.29	0.01	0.27	1000.00
	-4.5	29	-0.59	3.41	0.10	0.27	1000.00
	-4	30	-0.43	3.57	0.17	0.27	1000.00
	-3.5	31	-0.25	3.75	0.11	0.27	1000.00
	-3	32	-0.04	3.96	0.04	0.27	1000.00
	-2.5	33	0.16	4.16	0.05	0.27	1000.00
	-2	34	0.35	4.35	0.03	0.27	1000.00
	-1.5	35	0.50	4.50	0.02	0.27	1000.00
	-1	36	0.61	4.61	0.03	0.27	1000.00
	-0.5	37	0.68	4.68	0.05	0.27	1000.00
	0	38	0.70	4.70	0.11	0.27	1000.00
	0.5	39	0.68	4.68	0.20	0.27	1000.00
	1	40	0.63	4.63	0.21	0.27	1000.00
	1.5	41	0.55	4.55	0.21	0.27	1000.00
	2	42	0.42	4.42	0.20	0.27	1000.00
	2.5	43	0.26	4.26	0.17	0.27	1000.00
	3	44	0.06	4.06	0.15	0.27	1000.00
	3.5	45	-0.16	3.84	0.13	0.27	1000.00
	4	46	-0.38	3.62	0.10	0.27	1000.00
	4.5	47	-0.60	3.40	0.07	0.27	1000.00
	5	48	-0.79	3.21	0.05	0.27	1000.00
	5.5	49	-0.94	3.06	0.03	0.27	1000.00
	6	50	-1.05	2.95	0.01	0.27	1000.00

The mixing of the effluent across the plume jet and buoyant layer (i.e. the near field) during a peak flood tidal condition at the -4m contour is illustrated Figure 3.1. It will be seen from this Figure that as the discharge is positively buoyant, the effluent quickly rises to the surface of the water column. This means that virtually all of this discharged effluent is confined within the upper layer of the water column during the initial mixing process. Eventually, this plume will disperse vertically and horizontally as the density differential becomes less and the concentration of the effluent approaches uniformity. Given the direction of the current flows in this area the initial dilution and subsequent dispersion of the effluent will form an elliptical plume envelope orientated approximately in a NW to SE direction.

The dilution vs. downstream distance of the effluent at various phases of a spring tidal cycle is illustrated in Figure 3.2, whilst Figure 3.3 presents analogous data for a neap tidal cycle. Figure 3.4 shows all results combined and plotted to produce a line of best fit that most represented the average initial dilution vs. downstream distance for all simulations undertaken for the marine outfall located at the -4m contour.

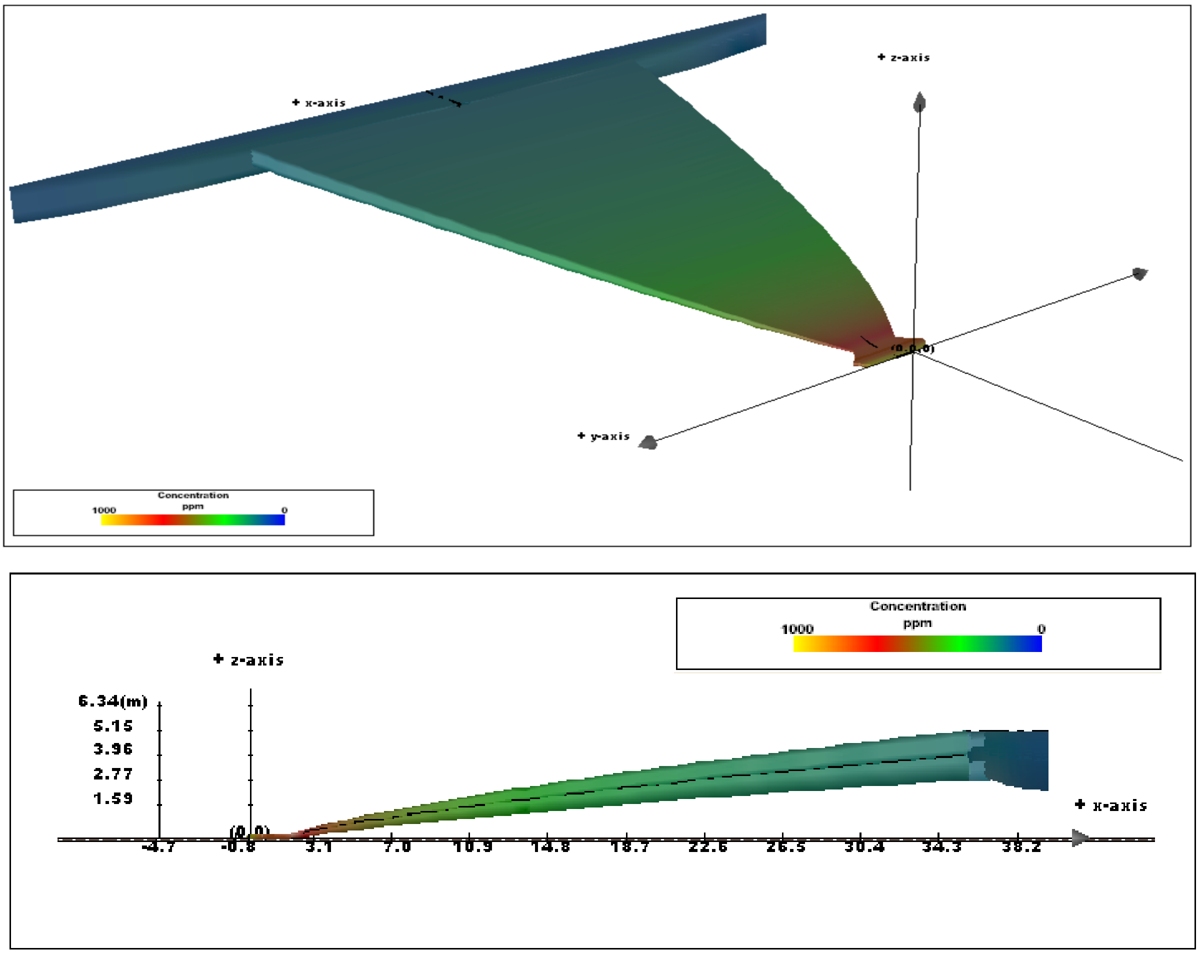

Figure 3.1: Aspect (upper) and cross-sectional (lower) representation of typical initial dilution field before surface contact at -4m contour.

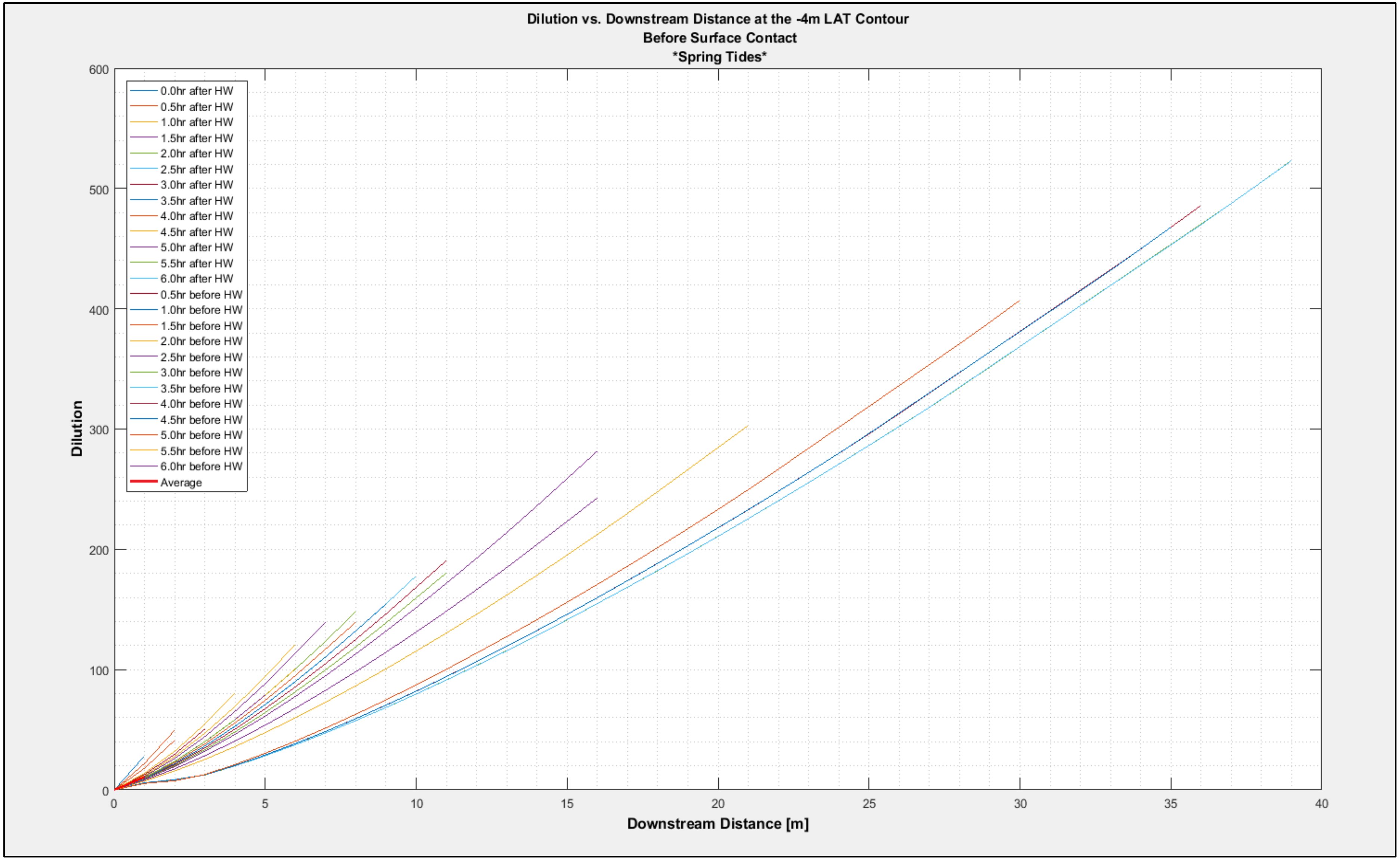

Figure 3.2: Dilution vs. Downstream distance at various phases of a spring tidal cycle (n=25) for an outfall at the -4m contour LAT

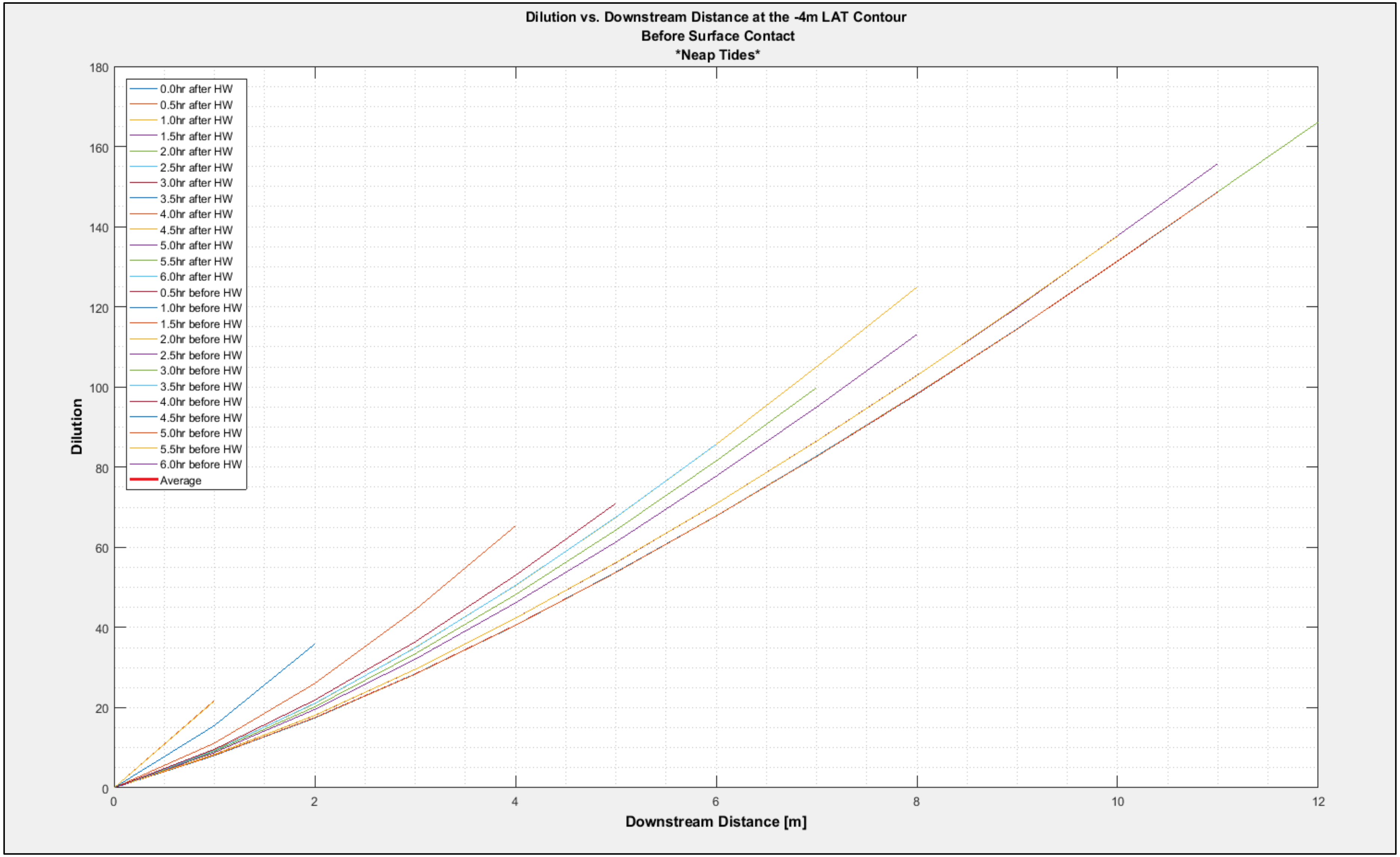

Figure 3.3: Dilution vs. Downstream distance at various phases of a neap tidal cycle (n=25) for an outfall at the -4m contour LAT

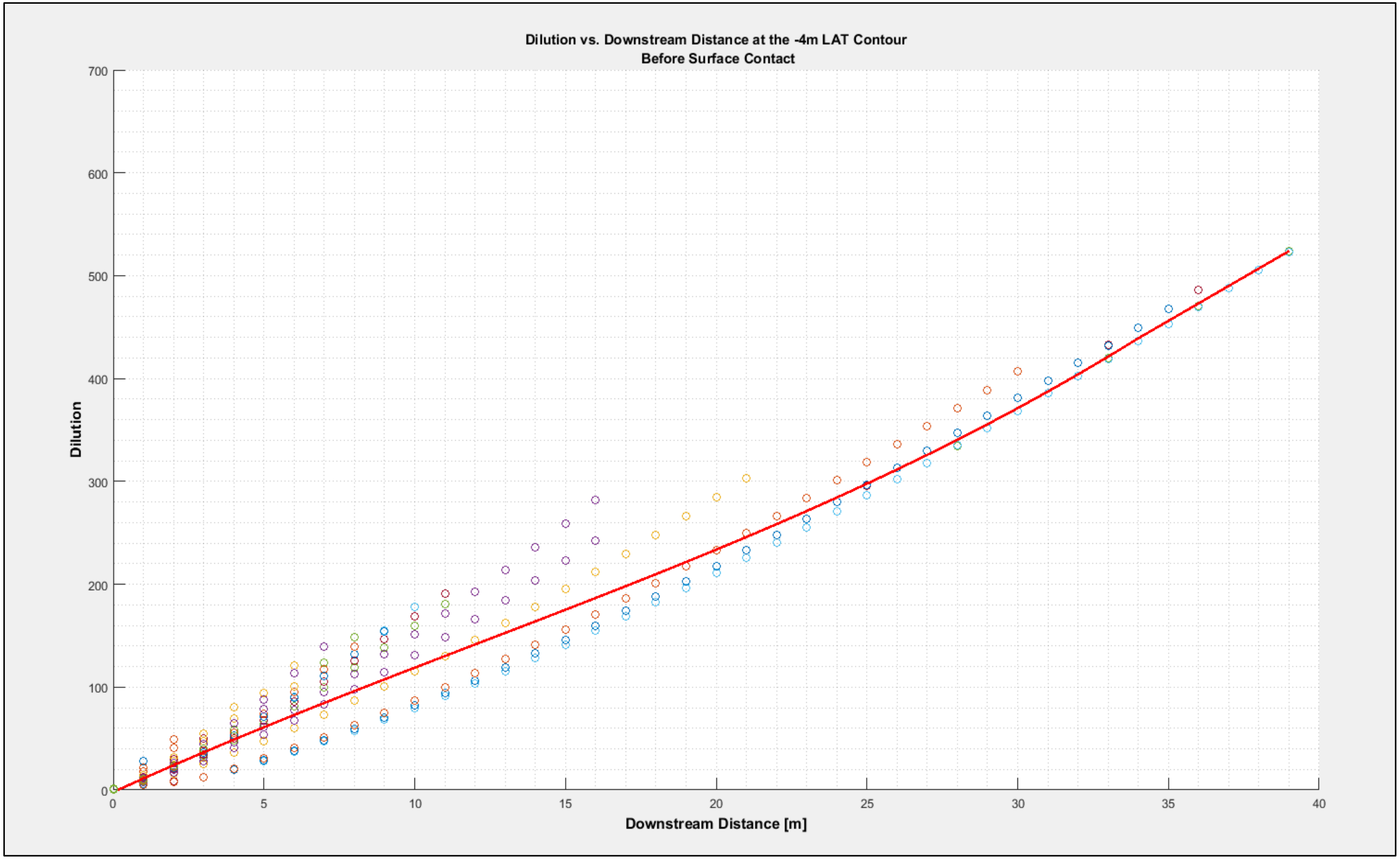

Figure 3.4: Dilution vs. Downstream line of best fit through all simulation results (n=50) for an outfall at the -4m contour LAT.

3.2 OUTFALL AT THE -8M LAT CONTOUR

For the outfall at the -8m LAT contour, a further 50 CORMIX simulations were undertaken to quantify and assess the potential initial dilution available at ½ hourly intervals across both spring and neap tidal conditions. The tidal stages simulated and the corresponding ambient characteristics of the receiving water body and the associated model inputs are listed in Table 3.4.

Examination of the initial dilution results at the -8m contour illustrated in Figure 3.6 to Figure 3.8 indicated that in all instances the effluent reached the surface of the receiving water body within 100m of the point of discharge. These results demonstrated a higher degree of variance in the initial dilutions achieved at the point of surface contact compared to the results for the discharge at the -4m contour, principally due to the wider range of ambient current velocities coupled together with the increased water depth at the -8m contour. The marine discharge at the -8m contour consistently achieved significantly higher initial dilution rates compared to the marine discharge at the -4m contour.

Statistical analyses of all simulations runs were undertaken at downstream distances of 40m and 100m. These distances correspond to the closest proximity of the nearest Flameshell habitat to the discharge point and the extent of the 100m maximum mixing zone limit normally allowed by SEPA. At both points, the minimum dilution achieved was found to be 63:1. The maximum initial dilution achieved at the 40m and 100m marks were found to be 810:1 and 1235:1 respectively. The corresponding mean dilutions for each mark were found to be 497:1 (S.D=160, n=50) and 729:1 (S.D=328, n=50) respectively. At both locations, 95%ile of all initial dilutions was found to be c. 212:1.

A summary of the statistical analyses for all initial dilution simulations at the -8m outfall is presented in Table 3.1 below.

Table 3.3: Summary of all dilutions (n=50) for an outfall at the -8m contour.

	Dilution			
Downstream distance	**Min**	**Max**	**Mean**	**95th Percentile**
40m (Flame Shell Beds)	63.76	810.51	497.88	212.16
100m (Mixing Zone Limit)	63.76	1235.76	729.71	212.16

Table 3.4: Simulated outfall characteristics and corresponding ambient tidal conditions at the -8m LAT contour.

Tide	Time relative to HW [Hr]	Simulation Number	Ambient Conditions			Effluent Charecteristics	
			Surface Elevation [m]	TWD [m]	Current Speed [m/s]	Flow Velocity [m/s]	Excess Conc. [ppm]
Spring	-6	1	-2.12	5.88	0.08	0.27	1000.00
	-5.5	2	-2.05	5.95	0.18	0.27	1000.00
	-5	3	-1.85	6.15	0.36	0.27	1000.00
	-4.5	4	-1.50	6.50	0.62	0.27	1000.00
	-4	5	-0.99	7.01	0.73	0.27	1000.00
	-3.5	6	-0.37	7.63	0.62	0.27	1000.00
	-3	7	0.32	8.32	0.48	0.27	1000.00
	-2.5	8	0.98	8.98	0.38	0.27	1000.00
	-2	9	1.57	9.57	0.33	0.27	1000.00
	-1.5	10	2.05	10.05	0.30	0.27	1000.00
	-1	11	2.42	10.42	0.30	0.27	1000.00
	-0.5	12	2.63	10.63	0.35	0.27	1000.00
	0	13	2.71	10.71	0.35	0.27	1000.00
	0.5	14	2.67	10.67	0.13	0.27	1000.00
	1	15	2.54	10.54	0.16	0.27	1000.00
	1.5	16	2.30	10.30	0.24	0.27	1000.00
	2	17	1.92	9.92	0.25	0.27	1000.00
	2.5	18	1.40	9.40	0.20	0.27	1000.00
	3	19	0.80	8.80	0.12	0.27	1000.00
	3.5	20	0.17	8.17	0.04	0.27	1000.00
	4	21	-0.45	7.55	0.04	0.27	1000.00
	4.5	22	-1.04	6.96	0.10	0.27	1000.00
	5	23	-1.54	6.46	0.12	0.27	1000.00
	5.5	24	-1.91	6.09	0.11	0.27	1000.00
	6	25	-2.13	5.87	0.09	0.27	1000.00
Neap	-6	26	-0.82	7.18	0.09	0.27	1000.00
	-5.5	27	-0.79	7.21	0.07	0.27	1000.00
	-5	28	-0.71	7.29	0.02	0.27	1000.00
	-4.5	29	-0.59	7.41	0.10	0.27	1000.00
	-4	30	-0.43	7.57	0.18	0.27	1000.00
	-3.5	31	-0.24	7.76	0.25	0.27	1000.00
	-3	32	-0.04	7.96	0.32	0.27	1000.00
	-2.5	33	0.16	8.16	0.38	0.27	1000.00
	-2	34	0.35	8.35	0.34	0.27	1000.00
	-1.5	35	0.50	8.50	0.30	0.27	1000.00
	-1	36	0.61	8.61	0.25	0.27	1000.00
	-0.5	37	0.68	8.68	0.17	0.27	1000.00
	0	38	0.70	8.70	0.04	0.27	1000.00
	0.5	39	0.68	8.68	0.10	0.27	1000.00
	1	40	0.63	8.63	0.15	0.27	1000.00
	1.5	41	0.55	8.55	0.18	0.27	1000.00
	2	42	0.42	8.42	0.18	0.27	1000.00
	2.5	43	0.26	8.26	0.17	0.27	1000.00
	3	44	0.06	8.06	0.16	0.27	1000.00
	3.5	45	-0.16	7.84	0.14	0.27	1000.00
	4	46	-0.38	7.62	0.11	0.27	1000.00
	4.5	47	-0.60	7.40	0.08	0.27	1000.00
	5	48	-0.79	7.21	0.06	0.27	1000.00
	5.5	49	-0.94	7.06	0.04	0.27	1000.00
	6	50	-1.05	6.95	0.02	0.27	1000.00

The mixing of the effluent across the plume jet and buoyant layer (i.e. the near field) during a peak flood tide at the -8m contour is illustrated in Figure 3.5. It will be seen from this Figure that as the discharge is positively buoyant, the effluent quickly rises to the surface of the water column. As virtually all of the discharged effluent is confined within the surface layer of the water column during the initial mixing process, the concentration of the effluent will be significantly lower at the seabed including at the Flameshell habitat.

The dilution vs. downstream distance of the effluent at various phases of a spring tidal cycle is illustrated in Figure 3.6, whilst Figure 3.7 presents analogous data for a neap tidal cycle. Figure 3.8 shows all results combined and plotted to produce a line of best fit that most represented the average initial dilution vs. downstream distance for all simulations undertaken for the marine outfall located at the -8m contour.

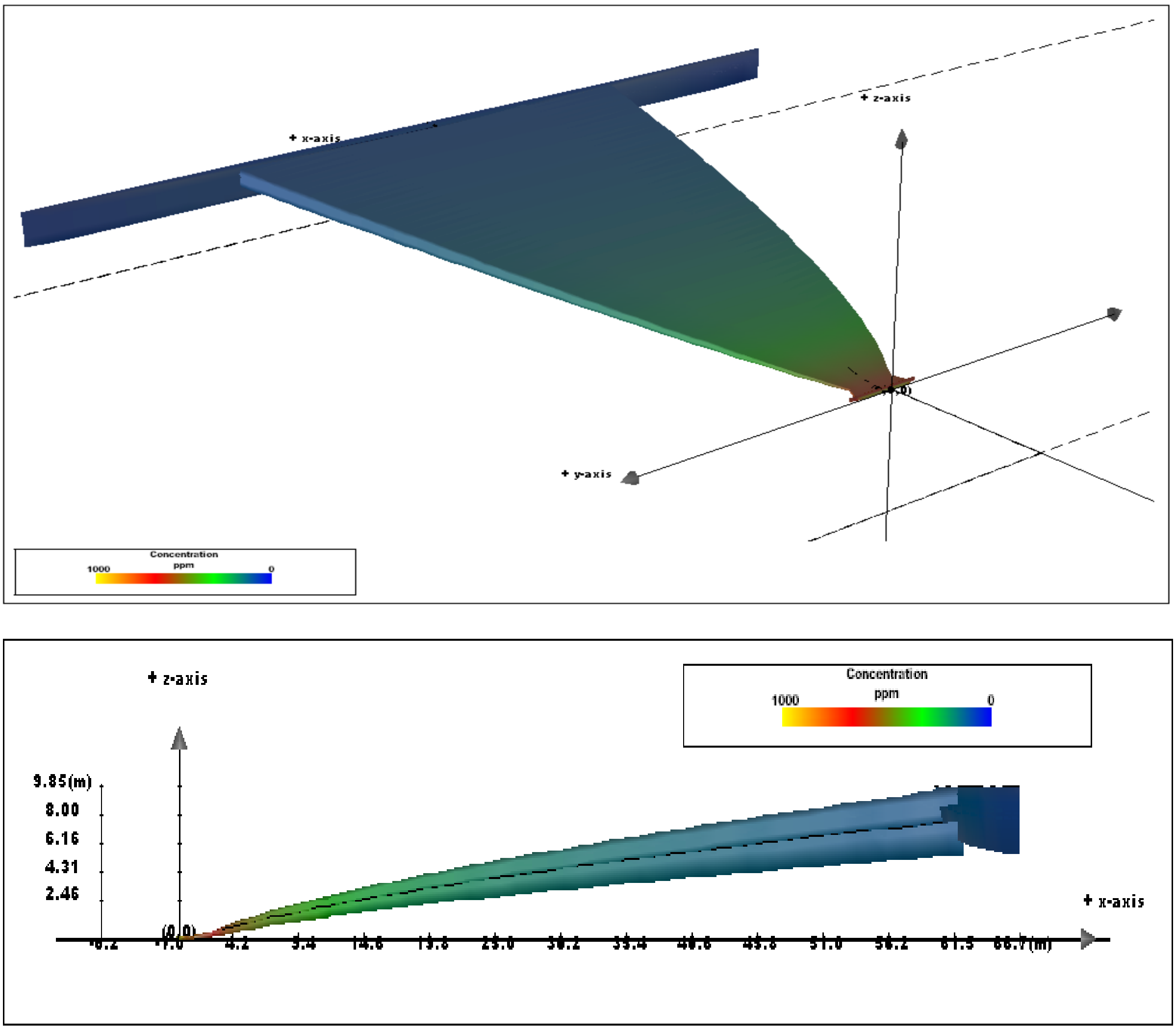

Figure 3.5: Aspect (upper) and cross-sectional (lower) representation of typical initial dilution field before surface contact at -8m contour.

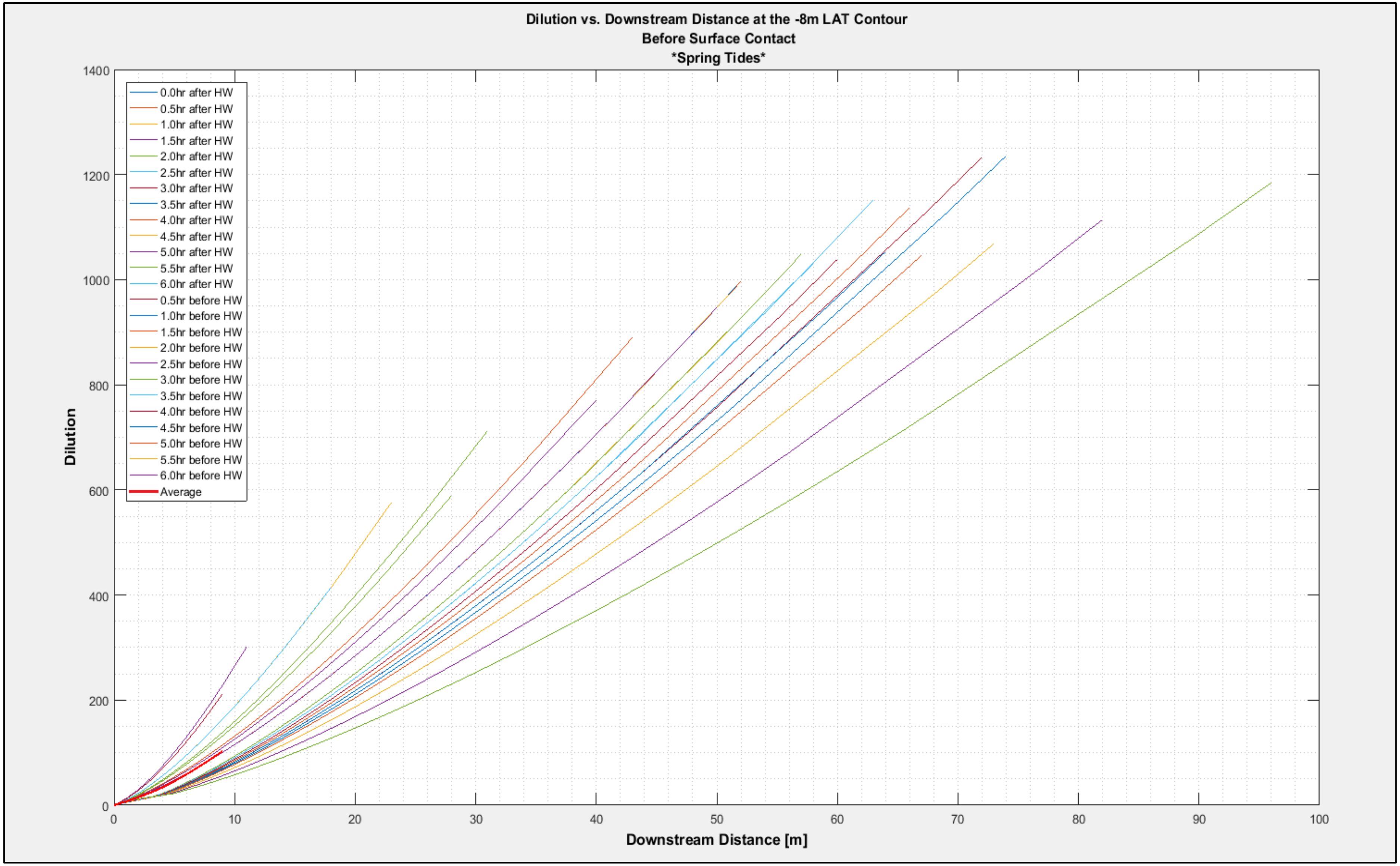

Figure 3.6: Dilution vs. Downstream distance at various phases of a spring tidal cycle (n=25) for an outfall at the -8m contour LAT

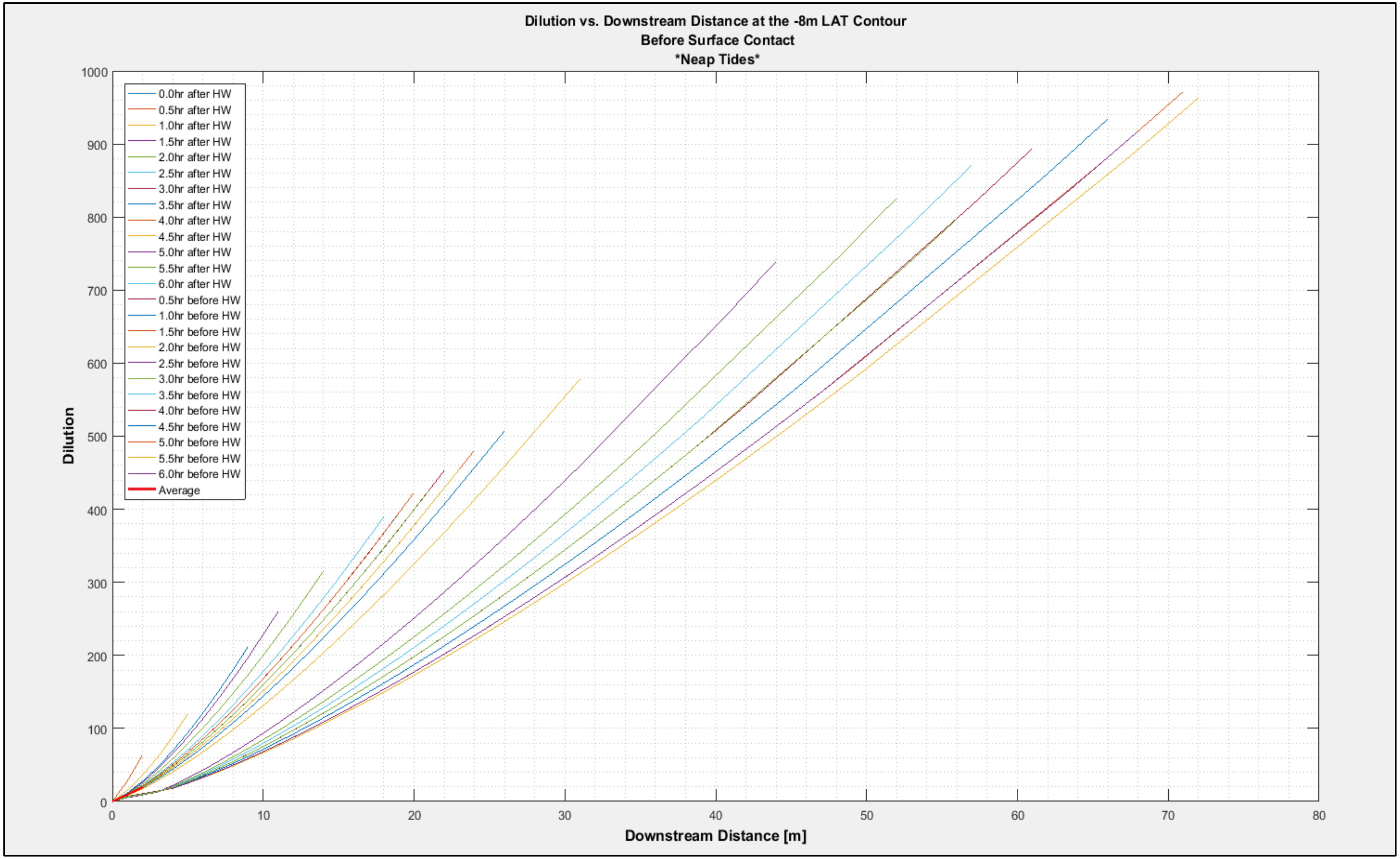

Figure 3.7: Dilution vs. Downstream distance at various phases of a neap tidal cycle (n=25) for an outfall at the -8m contour LAT

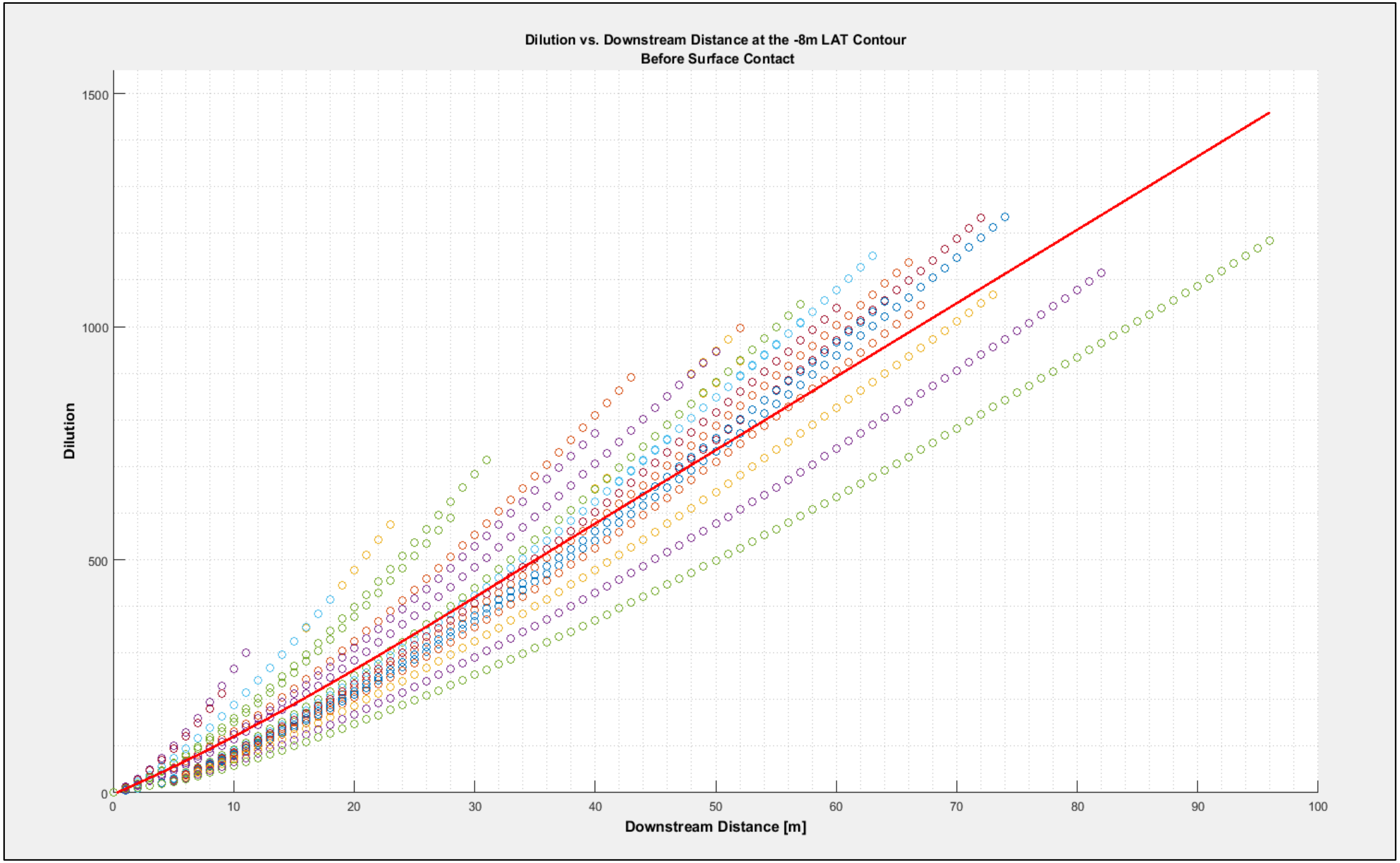

Figure 3.8: Dilution vs. Downstream line of best fit through all simulation results (n=50) for an outfall at the -4m contour LAT.

4 SUMMARY AND CONCLUSION

RPS were commissioned by Marine Harvest to undertake an initial dilution assessment for an area in close proximity to a proposed Salmon Feed Factory in Kyleakin, Isle of Skye, Scotland. Results from the assessment are to be used to inform the design of a wastewater treatment process and the selection of an optimum marine outfall length to ensure that the marine discharge is in compliance with the Environmental Quality Standards (EQS) as set out by the Scottish Environment Protection Agency (SEPA).

RPS used the CORMIX package to analyse and predict the initial dilution available at two different locations in close proximity to the proposed Kyleakin Feed Mill. The first location was located at the -4m LAT contour whilst the second was located at the -8m LAT contour. Ambient conditions representative of the tidal conditions with the proposed pier *in situ* were obtained from a calibrated hydrodynamic model of the Kyleakin area that was developed by RPS for an earlier assessment of the potential impact of the pier on local tidal conditions.

Based on 100 individual CORMIX simulations that simulated both spring and neap tidal conditions at ½ hourly intervals it was found that the marine outfall at the -8m contour consistently achieved higher initial dilution rates relative to the -4m.

The effluent from a marine discharge at the -4m contour was found to intersect with the surface within < 40m of the point of release in every simulation. The mean initial dilution rate achieved at the -4m contour was 40m mark was 135:1 (S.D= 137, n=50). The 95%ile of all initial dilutions exceeded 21:1 by a distance of 40m downstream of the discharge. .

The effluent from a marine discharge at the -8m contour was found to intersect with the surface within < 100m in every simulation. At *c.* 40m to the north the marine discharge, in an area overlapping with the assumed southern boundary of the Flameshell habitat, the mean initial dilution rate was found to be 497:1 (S.D=160, n=50). At the normal maximum 100m mixing zone limit set by SEPA, the mean initial dilution available increased to 729:1 (S.D=328, n=50). At both points, the 95%ile of all initial dilutions exceeded 212:1.

Owing to the positively buoyant nature of the discharge, the effluent will be primarily confined to the surface layer at the 40m mark in both outfall scenarios. As such, the effluent concentration will be significantly lower at seabed relative to surface layer. The effluent plume will eventually mix as it disperses across the surface layer in the far-field. Consequently, greater consideration should be given to the potential concentrations of effluent at the surface compared to the seabed.