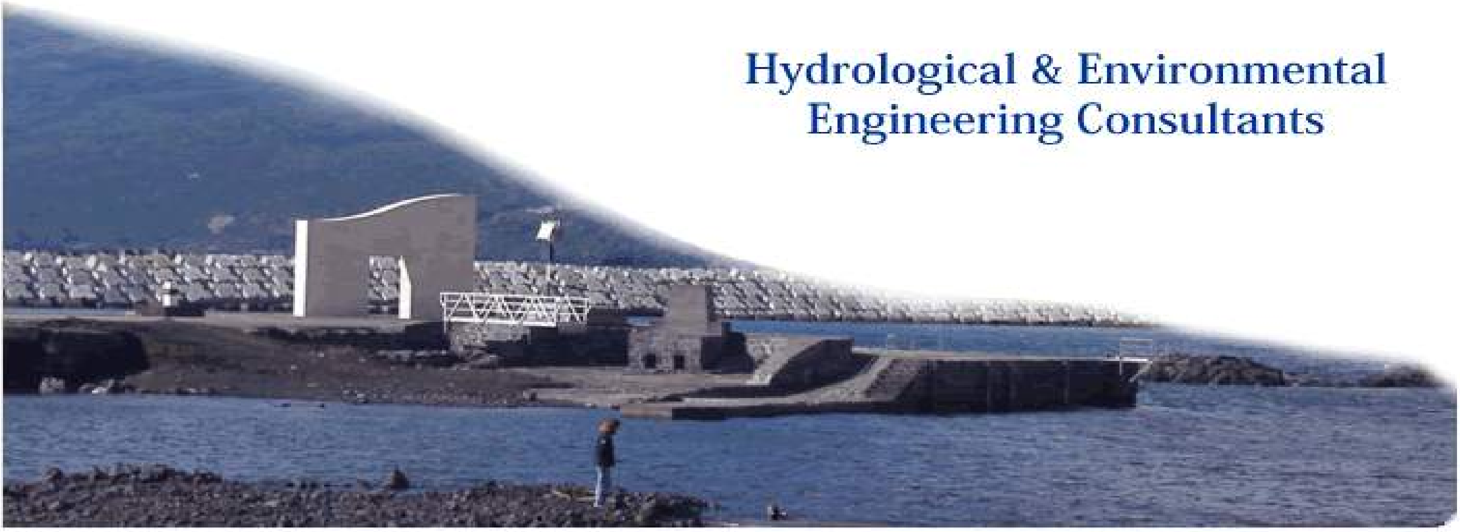
Appendix A13.3
Hydrodynamic Modelling of the Dodder Estuary

Hydrodynamic modelling of the Dodder Estuary to Assess Scour impact of the Proposed Dodder Bridge Development at Ringsend Dublin.

On behalf of

Roughan O Donovan
Consulting Engineers.

February 2021



Hydrodynamic Modelling of the Dodder Estuary to assess Scour impact of the Proposed Dodder Bridge Development at Ringsend Dublin.

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1. Introduction

1.1 Background

Hydro Environmental Ltd. was commissioned by ROD on behalf of Dublin City Council to carry out a hydrodynamic modelling study of the proposed Dodder Bridge at Ringsend for the purpose of evaluating the potential impact that the Bridge structure has on local hydrodynamics and potential scour impact.

Hydro Environmental Ltd., in association with Aquafact International Ltd., was commissioned by Roughan O'Donovan Consulting Engineers to carry out hydrodynamic modelling study of the proposed River Dodder Bridge at Ringsend Dublin in support of the preliminary design and input to the Hydrology chapter of the Environmental Impact Assessment Report (EIAR) and the Natura Impact Statement (NIS). The purpose of this study is to predict the potential change in local flow velocities within the immediate estuarine reaches of the Dodder and Liffey channel reaches and to assess the impact of the proposed development on bed scouring as a result of changes to the hydrodynamic regime by the proposed bridge structure.

This assessment involved constructing a two-dimensional hydrodynamic model using the Hydraulic Software TELEMAC2D which is industry standard for such assessments.

1.2 Proposed Bridge Development

The proposed Dodder Bridge is a bascule bridge structure with a lifting section to enable vessel navigation to and from the Dodder Estuary and specifically the adjacent Grand Canal Docks. The bridge crossing location is immediately at the confluence along the southern Liffey channel wall and upstream of the East Point Bridge.

A cross-section of the proposed bridge is presented below in Figure 2 which has a large bascule pier within the River channel which houses the lifting mechanism for the tilting bridge section and counterweight over the 19m wide, deep navigation channel section on the western Bridge opening. The total length of the lifting section is c. 30m. The bridge has three spanning sections of the Dodder estuary.

On the Eastern (right) bank of the Dodder channel at the Liffey confluence (i.e. and southern bank of the Liffey) at St. Patrick's Rowing Club, land reclamation of the shallow mud flat area is proposed for the approach road and cycle paths to the proposed Dodder bridge and to facilitate a new boat club building, hard-paved launching and set-down area, slipway and moorings. This extends the existing St. Patrick's Rowing Club site further out into the Liffey channel. The proposed reclamation boundary aligns itself with the southern Liffey Channel Wall upstream and with the Tom Clarke Bridge southern abutment downstream.

Figure 1 Proposed Bridge over Dodder at Liffey Confluence

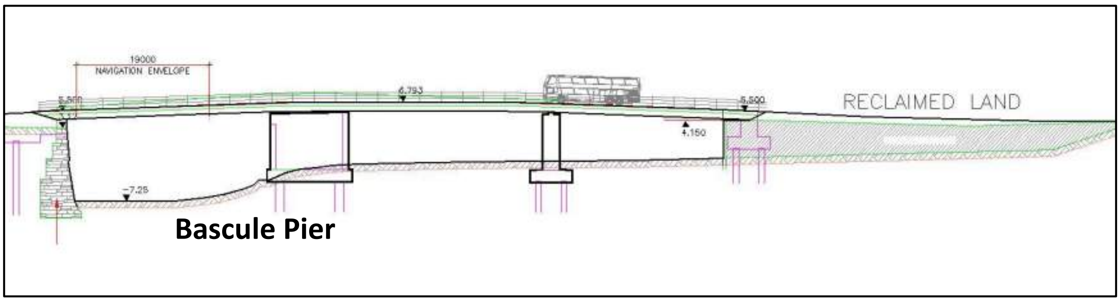

Figure 2 Cross Section of Upstream face of Bridge

This reclamation removes c. 60m of mud flat width from the Dodder / Liffey confluence on the eastern/southern channel bank, reducing the effective channel width of the Dodder to 92m that includes the Bascule pier and the eastern support pier. Based on survey information the total proposed open area of the bridge between soffit and bed is 610m^2. The bridge soffit level varies across the width from 4.15m OD at the eastern abutment to maximum height of 5.67 at 10m, east of the Bascule Pier and falling to 4.33m OD at the western abutment. The minimum deck level on the bridge is 5.5m OD. The length of the bridge from upstream face to downstream face is 20m and the width of the Bascule Pier is 15m and the eastern support pier is 2.4m wide.

2. Tidal Hydrology

2.1 Tidal Characteristics

Tide levels are recorded at Dublin Port with an almost continuous record dating back to 1924. The tidal characteristics for the Dublin Port area are presented below in Table 1. The mean spring tidal range is 3.4m and the men neap tidal range is 1.9m. The annual extreme high and low water levels are reflected by the HAT and LAT of 2.0 and -2.6m OD Malin respectively. The mean tidal period is 12.4hours.

Table 1 Tidal Characteristics of Liffey estuary at Dublin Port

Tides	Tide level m OD Malin
Highest Astronomical Tide HAT	1.99
Mean High Water Spring Tide	1.59
Mean High Water Neap Tide	0.89
Mean sea Level	-0.11
Mean Low Water Neap Tide	-1.01
Mean Low Water Spring Tide	-1.41
Lowest Astronomical Tide LAT	-2.61

The tidal period is 12.4hours. Typical lunar cycle is presented below in Figure 3 relative to chart datum which is c. 2.51m below Malin Head Datum.

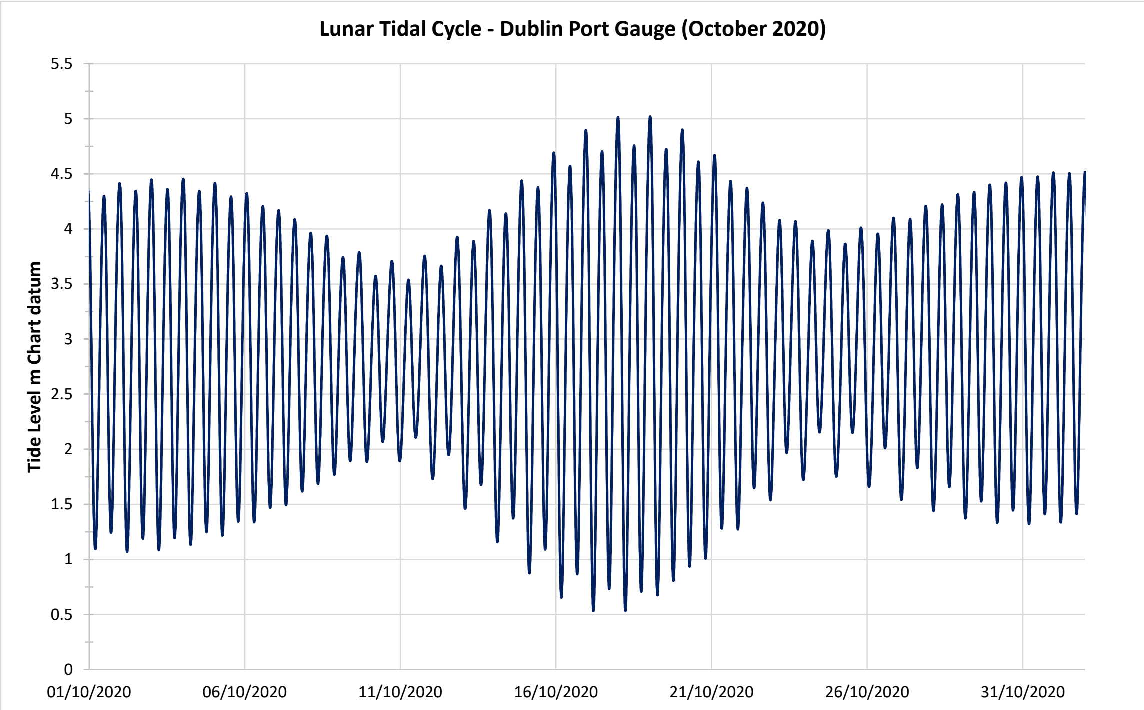

Figure 3 Lunar Tidal Cycle from Dublin Port Gauge, Alexandra Basin (October 2020)

2.2 Tidal Storm Surge Events

Tidal records are available for Dublin Port for almost 100years from 1923 onwards. The historical maximum tidal surge event occurred on the 1st February 2002and produced a highwater level of 2.95m OD Malin. This tidal flood event caused significant flooding in the Ringsend area and also flooding in Sutton, Clontarf, East Wall/North Strand, Sandymount and parts of Fingal. Prior to the 2002 surge the highest recorded tidal event of 2.59m OD occurred in 1924. A significant tidal event was more recently recorded on the 2 January 2014 producing a high tide level of 2.92m OD (second highest event and only 3cm lower than the 2002 event).

The statistical frequency analysis of the annual maximum tidal series for Dublin Port recorded from 1923 to 2020 is presented in Figure 4 fitting by l-moments the extreme value and logistic distributions. The return period high tide estimates are present in Table 2 for each of the distributions fitted.

The General Logistic distribution gives the highest estimates and graphically represents the best fit to the data. This distribution estimates a 200year return period of 2.92m OD and a 1000year of 3.21m OD. The statistical error at the 200year and 1000year return periods is estimated to be 0.16m and 0.29m respectively. Therefore at the 67% confidence interval the 200year tidal estimate falls within the range of 2.86 to 3.08mOD.

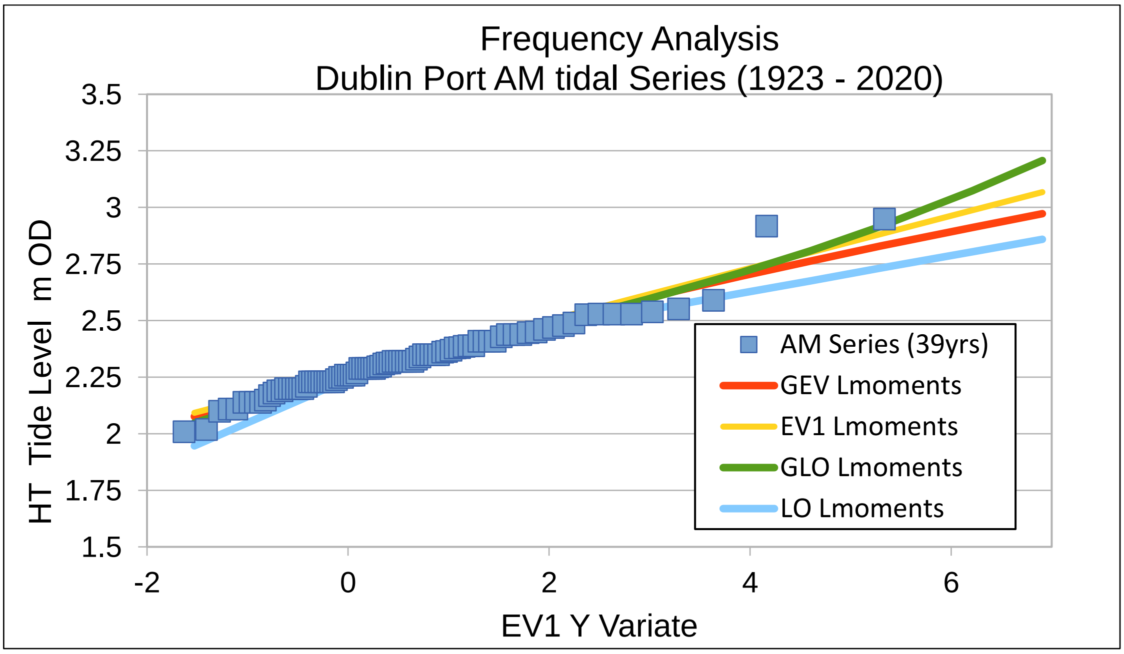

Figure 4 Statistical Frequency Analysis of the Annual Maximum Tide Level Series for Dublin Port (1923 to 2020)

Table 2 Return Period tidal flood levels for Dublin Port from at Site Frequency Analysis

Return Period T	EV1 Lmoments	GEV Lmoments	GLO Lmoments	LO Lmoments
2	2.311	2.311	2.311	2.311
5	2.443	2.442	2.430	2.421
10	2.529	2.524	2.510	2.486
20	2.612	2.601	2.593	2.545
50	2.720	2.695	2.711	2.620
100	2.801	2.763	2.809	2.676
200	2.881	2.829	2.916	2.731
500	2.987	2.912	3.074	2.804
1000	3.068	2.972	3.207	2.859

The Return period tidal estimates from the Irish Coastal Protection Strategic Study (2008) are presented below in Table 3. These estimates were used in both in the CFRAM study and the Dodder Flood Relief Scheme Study. The ICPSS (2008) study gives slightly higher estimates that the at-site statistical estimates but would be of a lower confidence than the at-site statistical method.

Table 3 ICPSS (2008) Return Period Tides for Dublin Bay defined at nearest nodes NE_22 and NE_23.

Return Period T	ICPSS Point NE_22	ICPSS Point NE_23
2	2.46	2.43
5	2.58	2.55
10	2.67	2.64
20	2.76	2.74
50	2.88	2.86
100	2.97	2.95
200	3.07	3.04
500	3.19	3.16
1000	3.28	3.25

Notwithstanding the robustness of the long duration at-site statistical analysis it is recommended that the ICPSS(2008) study estimates be used as they provide a higher and thus more conservative

3. Fluvial Hydrology

3.1 River Liffey

3.1.1 Catchment Description

The River Liffey, which rises at about 760 mOD in the Wicklow Mountains, is approximately 120km long from source to sea. The Liffey drains a total catchment area to the sea of over 1500km^2 and to Islandbridge Weir of 1150km^2. Below Islandbridge Weir the Liffey is tidally influenced. Tributaries joining the River Liffey downstream of Islandbridge are the Camac (54km2), Poddle(15km2), the Dodder (113km2) and the Tolka (151km2).

The River Liffey upstream of Leixlip is controlled by three Dams (Pollaphuca, Golden Falls and Leixlip) which were constructed between 1937 and 1949 by the ESB. The reservoir at Pollaphuca (Blessington Lake) is large at c. 19.5km^2 in area. The Golden Falls Dam is located 2km downstream of Pollaphuca and its reservoir (0.27km^2) acts a regulating reservoir for discharges from Pollaphuca allowing the generating turbines(2 No 15megawatt generators) at Pollaphuca to run for 4hours and releasing at a lower discharge (i.e. 12.5% of the Pollaphuca discharge) downstream over a 24 hour period. The catchment area contributing to the Pollaphuca and Golden Falls Dam is c. 321km^2. After passing through Golden Falls the river flows 55km through Co. Kildare to Leixlip, about 20km from Dublin. A dam impounds the water and forms a small reservoir of about 0.4km^2 with a capacity of 730,000m^3 of water and provides an 18m head to generate electricity using a 4 megawatt turbo-alternator plant similar to Golden Falls dam.

The Rye Water joins the Liffey downstream of the Leixlip dam is a natural uncontrolled river has a catchment area of 209km^2.

3.1.2 River Liffey Normal Flows

In terms of River Flows in the Liffey to Dublin the ESB hydro Operation would only attenuate the upper 321km^2 catchment area which in terms of annual runoff volume is c. 40% of the catchment runoff and 28% of the catchment area.

The estimated flow duration curve for the River Liffey was estimated by extrapolating the estimates from the EPA Hydrotool for the furthest downstream estimation node located a Leixlip and is presented in Table 4 below.

Table 4 Estimated Flow Duration Curve For Liffey using EPA Hydrotool method

Exceedance Probability (percentile)	Leixlip (1055km^2) Flow Magnitude (cumec)	Islandbridge (1150km^2) Flow Magnitude (cumec)
1	88.8	96.8
5	51.9	56.5

Exceedance Probability (percentile)	Leixlip (1055km^2) Flow Magnitude (cumec)	Islandbridge (1150km^2) Flow Magnitude (cumec)
10	36.8	40.1
25	23.3	25.4
50	13.6	14.9
75	6.5	7.0
90	3.3	3.6
95	2.6	2.8
99	1.62	1.8

Table 5 Mean Monthly and Annual Flow Estimates for the Liffey from the EPA Hydrotool Application

Calendar Month	Leixlip (1055km^2) Flow Magnitude (cumec)	Islandbridge (1150km^2) Flow Magnitude (cumec)
January	32.4	35.3
February	26.9	29.4
March	20.2	22.0
April	15.0	16.3
May	11.4	12.4
June	8.8	9.6
July	7.4	8.1
August	10.0	10.9
September	10.4	11.3
October	16.2	17.7
November	25.6	27.9
December	30.3	33.1
Annual Mean Flow	18.55	20.2

3.1.3 River Liffey Flood Flows

3.1.3.1 Gauged Annual Flood Estimate

The River Liffey has limited hydrometric flow gauging stations present to provide a statistical at-site gauged estimate of return period flood flows in the Liffey at Dublin. The nearest gauge is located on the Rye Water at Leixlip representing a catchment area of 215km^2 (19% of the total catchment area of the Liffey to Islandbridge) with a gauged record extending from 1956 to present. The median (2year) flood flow at this gauge is 35.5cumec (0.165cumec per km^2).

The ESB operated a gauge on the Liffey at Celbridge with a flow record available from (1967-1986, and 1995-1997). A review of this record as part of the Eastern CFRAM study (ref Hydrology Report RPS 2015) suggests a median flood flow of 56.5cumec for a catchment area of 821km^2 (0.069cumec per km^2 moderately low possibly reflecting the ESB Hydro power operations).

Combining these rates suggests an estimate of 102cumec for the median Flood Flow to Islandbridge Weir.

3.1.3.2 Flood Study Update Method Annual Flood Estimate

The Flood Study Update ungauged flood flow estimate to Islandbridge based on catchment descriptors gives an estimate for the median flood flow of 116.3cumec (0.101 cumec per km^2).

The FSU estimates for the Rye Water to Leixlip is 25.0 cumec and the River Liffey to Celbridge is 77.8cumec. The FSU method is 29% lower than the gauged estimate for the Rye Water and 38% higher than the ESB gauged median flood flow at Celbridge. It is considered reasonable to use the FSU ungagged median flow estimate of 116.3cumec for the River Liffey to Island Bridge.

3.1.3.3 FSU Flood Growth Curve

The FSU pooled analysis gives the following flood growth curve for the Liffey at Islandbridge based on an EV1 distribution fit.

Table 6 FSU pooled Growth Factors based on hydrological similarity

Return period	t=2	t=5	t=10	t=20	t=50	t=100	t=200	t=1000
Growth Factors	1	1.21	1.34	1.47	1.64	1.77	1.9	2.19

Based on the gauged estimate Qmed = 102cumec, the 100year flood flow Q100 = 180.5cumec for the Liffey at Islandbridge using the above FSU Growth curve. Based on the gauged estimate Qmed = 116.3cumec, the 100year flood flow Q100 = 205.8cumec for the Liffey at Islandbridge using the above FSU Growth curve.

3.1.3.4 FSR National Growth Curve

The Flood Study Report (FSR) National Flood Growth curve developed for Ireland as part of the Flood study report (NERC 1975) and used up to quite recently gives the following growth factors for a Qmed Index Flood.

Table 7 FSR National Growth Factors adjusted for a Qmed index flood

Return period	t=2	t=5	t=10	t=20	t=50	t=100	t=200	t=1000
Growth Factors	1.00	1.25	1.43	1.61	1.84	2.04	2.23	2.67

Based on the gauged estimate Qmed = 102cumec, the 100year flood flow Q100 = 208.3cumec for the Liffey at Islandbridge using the above FSR National Growth curve. Based on the FSU method Qmed = 116.3cumec, the 100year flood flow Q100 = 237.4cumec for the Liffey at Islandbridge using the above FSR National Growth curve.

3.1.3.5 The CFRAM Study Estimates

The CFRAM study based on FSU methodology estimated the Qmed flow for the Liffey at Islandbridge to be 107.45cumec and to Alexandra Basin to be 132.6cumec. The Growth factor was determined from a regional derived pooling group of gauged stations and is presented below (note this is very similar to the National Flood Study Report (NERC 1975) Growth curve presented above:

Table 8 CFRAM Growth Factors based on a regionally derived pooling group of gauged sites

Return period	t=2	t=5	t=10	t=20	t=50	t=100	t=200	t=1000
Growth Factors	1.00	1.23	1.38	1.53	1.75	1.91	2.10	2.55

3.1.3.6 Recommended Return Period Flood Flows for the River Liffey

The recommended return period design flows for the Liffey is based on the FSU Flood Flow estimate of 0.101 cumec per km2 and the CFRAM regionally pooled growth curve.

Table 9 Recommended Return Period Flows in the Liffey

Return Period	Growth Factor	Liffey to Islandbridge	Liffey to Alexandra Basin
t=2	1.00	116	137.0
t=5	1.23	143	167.9
t=10	1.38	161	188.5
t=20	1.53	178	208.9
t=50	1.75	204	238.9
t=100	1.91	222	260.2
t=200	2.10	244	286.0
t=1000	2.55	296	348.0

3.1.4 Combined tidal and fluvial flood events

The CFRAM study concluded for the Liffey Lower Reach that the combined tide and fluvial events should considered all of the return Periods of one with 2year return period of the other as follows

Table 10 Combined Return Period Liffey Fluvial Flows with 2year Tide

Combined Return Period years	Liffey Return Period flows cumec	2 year Tide Level mOD
t=2	137.0	2.46
t=5	167.9	2.46
t=10	188.5	2.46
t=20	208.9	2.46
t=50	238.9	2.46
t=100	260.2	2.46
t=200	286.0	2.46
t=1000	348.0	2.46

Table 11 Combined Return Period Tidal Flood Levels with 2year Liffey Flow

Combined Return Period years	Tidal Return Period Levels mOD	2 year Liffey Flow cumec
t=2	2.46	137
t=5	2.58	137
t=10	2.67	137
t=20	2.76	137
t=50	2.88	137
t=100	2.97	137
t=200	3.07	137
t=1000	3.28	137

3.2 River Dodder

3.2.1 Catchment Description

The Dodder River is located in Hydrometric area no 9 of the Irish River Network System. The Upper catchment with its summit at Kippure in the Dublin Mountains (c. 754m OD) is steep with the three stream tributaries draining this upland area. Two reservoirs are located in the Dublin mountains whose function are to store and supply water to the Dublin area (Bohernabreena Reservoir and the Miller's Pond Reservoir) the catchment from Kippure to the lower reservoir at Miller's Pond drops 610m in a distance of 9.65km (c. 1m in 16m). The total catchment area of the dodder is 113km^2 with 28km2 of the upland catchment serving the two reservoirs and 85k^2 draining directly to the river downstream of the reservoirs.

A number of tributaries join the river as it emerges from the reservoirs. These tributaries include the Tallaght Stream, Owendoher River, the Little Dargle and the Dundrum River. The lower section of the catchment consists of gentle undulating landscape intermingling with a considerable extent of urban development. The urban fraction for the catchment is c. 35% representing an urbanised area of 40km^2, refer to Figure 5 for Catchment Map. Such urban areas are predominantly impervious and are served by public storm sewers. The Dodder catchment has EPA hydrometric flow gauges at Waldron Bridge Gauge on the Dodder River (09010, catchment area 94.3km2), on the Owendoher tributary at Willbrook Road (09009, catchment area 20.6 km2) and on the Slang tributary at Frankfort (09011, catchment area 5.5km2).

This river is a very flashy river and has a history of flooding. Over the past century notable flooding events resulting in overtopping of river banks and inundation of the floodplain have occurred in 1905, 1912, 1915,1931, 1946 ,1958, 1965 and the historical worst event in 1986 (25th and 26th August – Hurricane Charlie),and also in November 2000. The Dodder’s downstream reach is tidal from the Liffey Estuary with the tidal flows ebbing and flooding via Dublin Port navigation channel that passes between the north and south Bull walls.

3.2.2 River Dodder Flows

The estimated flow duration curve for the Dodder River was estimated by extrapolating the estimates from the EPA Hydrotool for the furthest downstream estimation node on the Dodder located at Rathfarnan and is presented in Table 12 below.

Table 12 Estimated Flow Duration Curve For Liffey using EPA Hydrotool method

Exceedance Probability (percentile)	Rathfarham (93.3km^2) Flow Magnitude (cumec)	Irishtown (113km^2) Flow Magnitude (cumec)
1	10.44	12.65
5	6.49	7.86
10	4.81	5.83
25	2.84	3.43
50	1.47	1.78
75	0.81	0.98
90	0.50	0.61
95	0.41	0.49
99	0.29	0.35

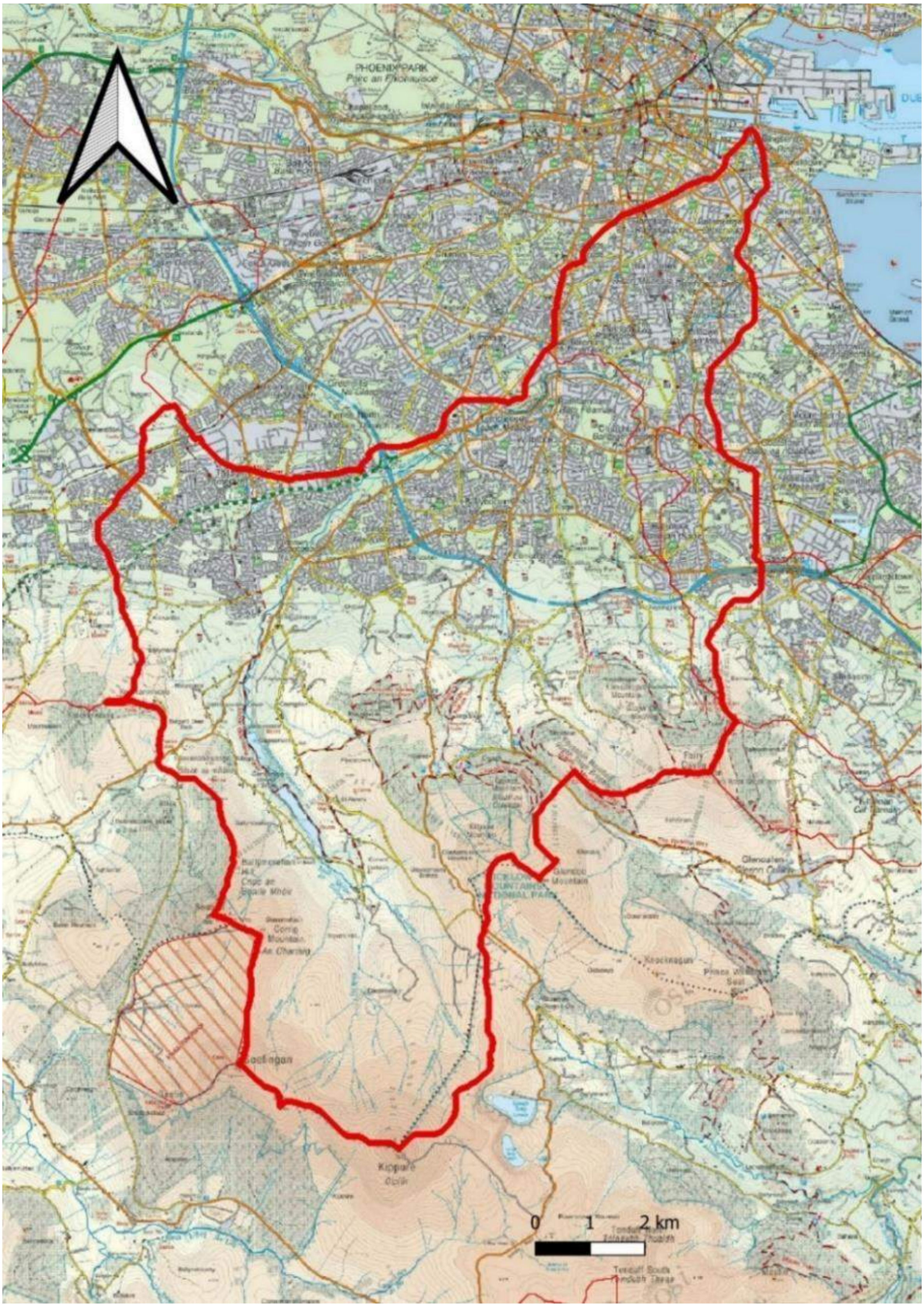

Figure 5 River Dodder Catchment Map

Table 13 Mean Monthly and Annual Flow Estimates for the Liffey from the EPA Hydrotool Application

Calendar Month	Rathfarham (93.3km^2) Flow Magnitude (cumec)	Irishtown (113km^2) Flow Magnitude (cumec)
January	3.89	4.7
February	3.22	3.9
March	2.51	3.0
April	1.86	2.2
May	1.42	1.7
June	1.13	1.4
July	0.88	1.1
August	1.14	1.4
September	1.25	1.5
October	2.07	2.5
November	3.10	3.8
December	3.58	4.3
Annual Mean Flow	2.23	2.7

3.2.3 Historical Flooding Events

A list of the reported 15 largest flood events and estimated flood flows on the Dodder, gauged at Waldron's Bridge Station (09010) over at least 120years is presented in Table 14 below. This information was derived from a combination of previous flood events on the Dodder (1880 – 1986) compiled by Jack Keyes (1987), paper by Cawley et al. 2005, and the EPA annual maximum (AM) flow series (MacCárthaigh EPA, 2005). The Hurricane Charlie Flood event in August 1986 represents the historical maximum flood in the Dodder in at least 120years if not significantly longer. This event hit the Dublin Mountains producing record rainfalls and caused extensive flooding in both the Dodder and its neighbouring catchment the Dargle that flows through Bray.

Table 14 List of highest Ranked floods on the Dodder at Orwell Weir

Date	Peak Flow (cumec)
25 August 1986	269
24 October 2011	213
25 August 1905	198
05 November 2000	156
03 September 1931	153
17 November 1965	139
19 December 1958	116
02 December 2003	112
11 June 1993	110
05 August 2008	108
05 November 1982	106

Date	Peak Flow (cumec)
14 November 2014	87
09 April 1998	87
02 November 1968	85
11 June 1993	81

The number of properties flooded by the Dodder during Hurricane Charlie was estimated to be 340. The main areas of flooding were from Lower Dodder Road, Orwell Gardens, Dartry Cottages, Clonskeagh Road, Simmonscourt Terrace, Eglinton Road, Anglesea Road, Merrion Road, Wilfield Road, Gilford Road, Shelbourne Road, Ballsbridge Avenue and Beatty's Avenue. Flooding was also observed on the Poddle (85 properties flooded), Camac (30 properties flooded) and Tolka (10 properties flooded) Rivers (Keyes, 1987).
The main hydrometric gauge for the Dodder River is at Waldron's Bridge and is operated by the EPA (09010). This gauging station provides stage and flow estimates and from a flood estimation perspective this gauge has reasonably reliable record which included the Hurricane Charlie event of August 1986. In more recent years a lot of gaps and gauge downtime have appeared.

3.2.4 Flood Flow Estimation

3.2.4.1 Flood Flow Estimation

A range of flood estimation methods are available to provide flood flow estimates in the lower reaches of the Dodder. These vary from at site statistical analysis of gauged flows to ungauged flood estimation methods and synthetic rainfall-runoff modelling.

Fortunately the Dodder catchment is gauged at Waldron's Bridge towards the downstream end of the catchment and this gauge provides a reasonable long record of flood flows which allows statistical gauged methods to be applied in the estimation of return period design flood events. A number of ungauged methods including the OPW Flood Study Update methods were found to yield poor estimates of the return period flood flows in the Dodder when compared with the gauged Annual Maximum Series.

3.2.4.2 Return Period Flood Flow Estimation – Gauged Frequency Analysis

Estimated flows using Censored EV1 distribution fitted to the estimated largest 15 floods in 120year period at Waldron Bridge (refer to Table 5 in the previous section 3.3) was performed. The results of this analysis are presented in Figure 6 and Table 15 below.

Table 15 Return Period Flood Flow estimates for the Dodder at Waldron Bridge (gauge site 09010)

Return Period (years)	Ev1 (Y-variate)	QT (cumec)
10	2.25	91.5
50	3.90	186.9
100	4.60	227.3
200	5.30	267.4
500	6.21	320.4
1000	6.91	360.5

This method is limited somewhat by uncertainty in the flow estimates for historical floods not gauged by the EPA (i.e. pre 1966).

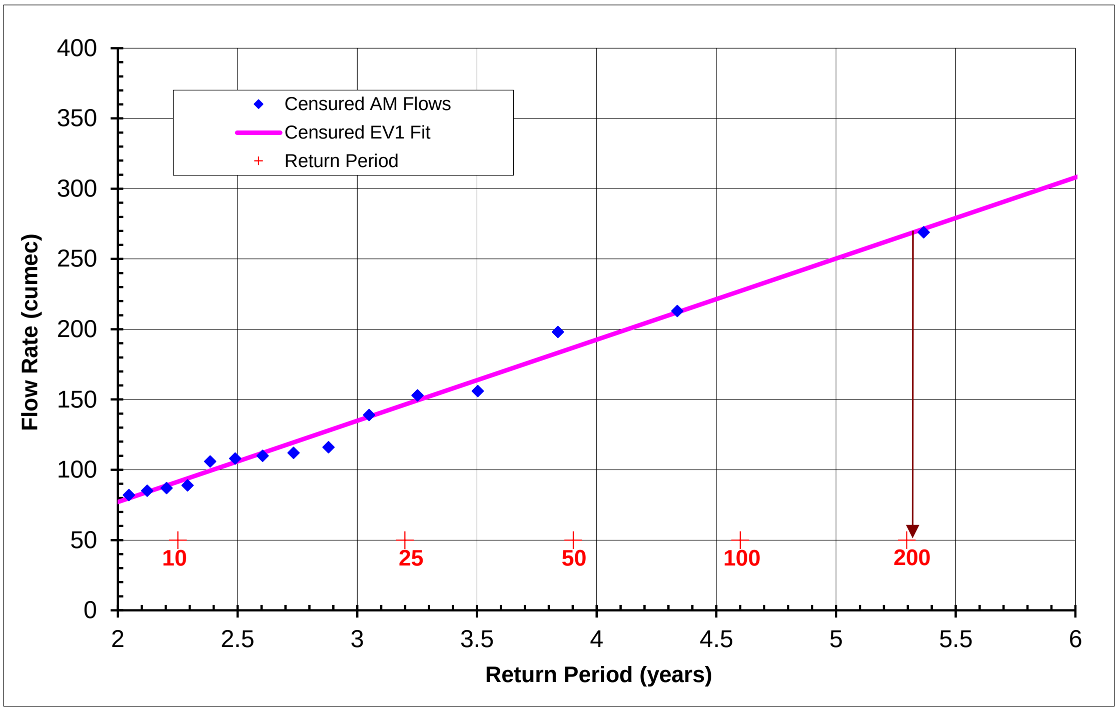

Figure 6 Censored EV1 fit to largest 14 floods in a 120year period

3.2.4.3 CFRAM Flood Flow estimates (RPS 2008 and 2010)

The RPS River Dodder Flood Relief Scheme Study hydrology Analysis report (October 2008) gives the following return period flood estimates for the Dodder at Waldron's Bridge gauge based on the fitting of an exponential distribution to Peaks over threshold series of EPA gauged flood flows from 1966 to 2006 (Threshold set at 60cumec). It should be noted that RPS used their revised rating based on modelling which generally reduced the estimate peak flows by between 5 and 7% (e.g. Hurricane Charlie EPA estimate of 269 cumec was reduced to 251 cumec (7% reduction) with the revised RPS rating equation)). Summary of the return period flood flows from the 2008 Hydrology Report are presented below in Table 16.

Table 16 RPS Dodder Flood Relief Scheme (2008/2010) return period flood flow estimates for Waldron's Bridge Gauge 09010

Return Period (years)	Flood Flow – QT (cumec)
5	108.1
10	130.6
25	159.0
50	180.1
100	201.0
200	221.8
1000	270.0

Note the Flood maps associated with the Dodder Flood Relief scheme (published 26 Nov 2010) study and presented in the Hydraulics report give the following return period flood flows under the present day scenario, refer to Table 16 below. These estimates which were used in the hydraulic modelling for the flood inundation mapping and are significantly different from the tabulated values for the gauged flows at Waldron's Bridge presented in the 2008 Hydrological Analysis and in the combined analysis in the 2010 hydraulics report.

Table 17 Published Return Period flood flow magnitudes from RPS Flood Inundation mapping for the Dodder from the CFRAM Study (refer to Dodder CFRAM Figures DR/EXT/UA/CURS/101 Nov 2010)

Return Period (years)	170m u/s of Waldron Bridge gauge 12,896	U/s of Ballsbridge Ch 17,655
	Flood Flow QT (cumec)	Flood Flow QT (cumec)
10	134.0	139.4
100	226.8	207.1
1000	486.1	529.2

Table 18 Published Return Period flood flow magnitudes from RPS Flood Hydraulics report for Joint Probability Flows used in the hydraulic flood modelling.

Return Period (years)	Waldron Bridge reach downstream of Dundrum Stream	Downstream Reach (Ringsend Reach
	Flood Flow QT (cumec)	Flood Flow QT (cumec)
5	126.5	143.8
10	151.8	173.8
50	227.6	266.0
100	270.6	319.3
200	321.9	383.7
1000	482.9	591.2

These higher return period flow estimates were generated using catchment Rainfall-Runoff modelling of the different sub-catchments and included joint probability analysis for the tributary streams and the different urban sub-catchments and their contributions. Essentially this rainfall – runoff modelling is ungauged modelling using a synthetic hydrograph and runoff coefficients and therefore not very reliable. The flow estimates are significantly higher than the gauged estimates for Waldron's Bridge at 26% and 79% for the 100 and 1000year events respectively.

In the CFRAM report there is no explanation for the large differences between the rainfall-runoff estimates used in the flood inundation modelling and the Hydrology Report gauged estimates from the frequency analysis of gauged flows, particularly the large difference in the 1000year estimates. There is also no explanation as to why the gauged estimates were ignored in favour of potentially less reliable Rainfall-Runoff model results. In any case the use of these higher estimates represent a more conservative approach.

3.2.4.4 CFRAM Combined Flood Analysis

The combined analysis between coastal and fluvial flooding for the Dodder presented in the CFRAM Hydraulic Analysis Report July 2010 give the following return period combined estimates.

Table 19 Combined Analysis Fluvial Flood Flows (gauged analysis) and Tidal Storm surge Levels

Combined Return Period (years)	Fluvial Flood Flow - Waldron's Br. (cumec)	Fluvial Return Period (years)	Tidal Flood Level in Liffey Estuary (mOD)	Tidal Return Period (years)
2	74.3	2	2.42	1.5
5	108.2	5	2.44	2
10	130.6	10	2.44	2
25	159.0	20	2.48	2.5
50	180.1	50	2.51	3
100	201.0	100	2.56	5
200	221.8	200	2.60	7
1000	270.0	1000	2.73	19
Combined Return Period (years)	**Tidal Flood Level in Liffey Estuary (mOD)**	**Tidal Return Period (years)**	**Fluvial Flood Flow - Waldron's Br. (cumec)**	**Fluvial Return Period (years)**
2	2.46	2	68.9	1.75
5	2.58	5	83.3	2.5
10	2.67	10	91.5	3.1
20	2.76	20	105.9	4.6
50	2.88	50	103.9	4.4
100	2.97	100	104.0	4.4
200	3.07	200	103.9	4.4
1000	3.28	1000	95.6	3.5

3.3 Catchment Change Allowances

The future urban development within the Dodder catchment is likely to significantly increase over the next 100year horizon given the proximity of the catchment to Dublin and the relatively small size of catchment. Therefore, the continued implementation of SUD's policy for the urbanised catchment is extremely important as is the maintenance and of existing SUD's facilities. It is not clear as to the likely footprint increase of urbanisation within the catchment as planning policy is likely to favour higher rise development to limit the urbanized spread and sprawl out into the scenic Dublin Mountains. It is assumed for the purpose of this study that future Urban development will implement SUD's in order to limit storm runoff to present day greenfield runoff rates. Therefore, no additional allowance is made for urbanisation in the future.

3.4 Climate Change Allowance

3.4.1 Introduction

According to the United Nations Intergovernmental Panel on Climate Change (2007) there is unequivocal evidence of climate change

"*most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.*" (Climate Change 2007, IPCC, Fourth Assessment Report AR4)

There is a high degree of uncertainty in relation to the potential effects of climate change, and therefore a precautionary approach is required. Examples of precautionary approach include:

- Recognising that significant changes in the flood extent may result from an increase in rainfall or tide level and accordingly adopting a cautious approach to zoning lands in these potential transitional areas.
- Ensuring that the finish levels of structures are sufficient to cope with the effects of climate change over the lifetime of the development.
- Ensuring that structures to protect against flooding (e.g. defence walls) are capable of adaptation to the effects of climate change when there is more certainty about the effects (e.g. foundations of flood defence designed to allow future raising of flood wall to combat climate change).

3.4.2 Climate Change Allowance for Fluvial Flood Flows

Climate change scenarios suggest for UK and Ireland fluvial floods in the 2080's increasing by up to 10 to 20% (low and medium low scenarios) and by up to 20 to 30% (medium high and high scenarios). Present recommendations are to include in the design flow a 20% increase in flood peaks over 50 years return period as a result of climate change. This scenario based on the Irish growth curve will result in a present day 100 year flood becoming a 25-year flood in approximately 50 year's time. The extent and expected levels of flooding are derived based on these flows.

In the UK, research is ongoing to assess regional variations in flood allowances and the rate of future change. Current research thus far does not provide any evidence for the rate of future change let alone consider regional variations in such a rate. The UK Flood and Coastal Defence Appraisal Guidance (DEFRA, 2006) gives the climate change ranges as per Table 1 below and as a pragmatic approach it is suggested that 10% should be applied up to 2025, rising to 20% beyond 2025.

In Ireland general practice is to use a medium range climate change allowance for flood flows of 20% over the next 100 years. This rate has been adopted by the OPW for all of its Catchment Flood Risk Assessment and Management Studies (Lee, Dodder, Tolka CFRAMs, Shannon, West, etc.).

Table 20 UK flood and coastal defence appraisal guidance (DEFRA, 2006)

UK Flood and coastal appraisal guidance (DEFRA, 2006)				
Parameter	**1990 – 2025**	**2025 - 2055**	**2055 - 2085**	**2085 - 2115**
Peak rainfall intensity (preferably for small catchments)	+5%	+10%	+20%	+30%
Peak river flow (preferably for larger catchments)	+10%	+20%		

3.4.3 Sea level rise

Scientists predict that global sea level rise will have two main causes. Firstly, as the oceans heat up the water expands. At present this thermal expansion accounts for about half of the observed increase in sea level. The other cause is melting land ice from glaciers and ice caps. The rate of melt and the volumes of water locked within these sources are uncertain and this is a cause for concern.

In recent years, ice shelves have broken off huge ice sheets in Antarctica and Greenland. The ways in which they are melting is only now beginning to be understood fully enough to allow estimates of how fast this melt is occurring and how much this will affect sea levels. If they melt as fast as is now thought to be possible, sea levels could rise dramatically over the next century, flooding many of the world's major cities and much of the world's most productive farmland. Consequently, guidance on sea level rise allowances for flood risk management is continually changing as more scientific research is published with allowances likely to increase as opposed to decrease in future years.

The biggest threat to coastal flood risk areas is from sea level rise. Global mean sea levels are predicted to increase from a combination of thermal expansion of the water column and melt from the glaciers and reduction of liquid water storage on land. The Intergovernmental Panel on Climate Change Third Assessment Report (*IPPC TAR)* that preceded the published *IPCC Fourth Assessment Report* (2007) has been used as the basis of future sea level projections for Ireland. A best estimate increase of 480 mm to year 2100 has been suggested by Sweeney et al (2003) and used in the *Greater Dublin Strategic Drainage Study* (GDSDS 2005). This value was not directly challenged in the 2007 *IPCC* report, with a range of 0.2 - 0.51 m given for the prudent Medium-High A2 emission scenario.

The IPCC fifth Assessment Report (2014) has investigated the current and future trends in global mean sea level rise (GMSLR) and have concluded with a high level of confidence under various emission scenarios considered (four modelled RCPS (Representative Concentration Pathways) that thermal expansion of the sea due to warming will increase Global mean sea level by between 0.15 to 0.3m by 2100. This report predicts at medium confidence the contribution of glacier mass loss to GMSLR for the four RCP scenarios. The global glacier volume is projected to decrease by 15 to 55% for RCP2.6, and by 35 to 85% for RCP8.5 and in between these rates for the other two RCP scenarios. RCP2.6 is representative for scenarios leading to very low greenhouse gas concentration level, it is a so called "peak" scenario with radiative forcing reaching a peak level of 3.1 W/m^2 mid-century and returning back to 2.6W/m^2 by 2100. RCP8.5 is characterised by increasing greenhouse gas emissions overtime leading to high greenhouse gas concentrations by 2100.

Projections of GMSLR by 2100 under the high RCP8.5 scenario are 0.53 to 0.98m with rises of 8 – 16mm/annum during 2081 to 2100 and under the low RCP2.6 scenario are a rise is 0.28 to 0.61mm.

Observations of GMSLR show that from 1901 to 1990 1.5mm per annum mean rise and from 1993 to 2010 the mean rise was 3.2mm per annum.

The IPCC concluded that it is very likely that sea level will rise in more than about 95% of the ocean area. About 70% of the coastlines worldwide are projected to experience sea level change within 20% of the global mean sea level change. GMSLR during 1901–2010 can be accounted for by ocean thermal expansion, ice loss by glaciers and ice sheets, and change in liquid water storage on land. It is very likely that the 21st-century mean rate of GMSLR under all RCPs will exceed that of 1971–2010, due to the same processes. It is virtually certain that global mean sea level rise will continue for many centuries beyond 2100, with the amount of rise dependent on future emissions.

3.4.4 Sea level rise for East Coast of Ireland

An annual rate of sea level rise for Ireland of 3.5mm per year has been observed for the period 1993 – 2003 which is higher than the longer term observed rate of 1.8mm per year for the period 1963 – 2003. This trend is likely to be more modest in the Irish Sea with a ‘net trend’ (allowing for isostatic adjustment of the earth’s crust) of 2.3 – 2.7mm per year.
Assessment of Potential Future Scenarios for Flood Risk Management’ (OPW, 2009), it is recommended that a mid-range future scenario of a 500mm rise in sea levels is considered and a 1000mm increase in sea levels is considered for the high-end future scenario. These allowances would seem appropriate and consistent with the higher end estimates from the regional climate change predictions when both sea level rise and an increase in storm surge are considered.
An allowance of 550mm mean sea level rise to the year 2120, which accounts for a 500mm increase in mean sea level and 50mm increase for isostatic land movement adjustment will be included for in this study to simulate a potential mid-range future climate change scenario for the development.

3.4.5 Recommended Climate change allowances

The recommended climate change allowance for the proposed project, summarised below in Table 21 are the Mid-Range Future Scenario representing 550mm increase in sea level and 20% increase in Flood Flow magnitudes.

Table 21 Climate Change Allowances for Future Scenarios 100 year

Criteria	Mid-Range Future Scenario MRFS	High-End Future Scenario HEFS
Mean Sea Level Rise	+500mm	+1000mm
Land Movement	-0.5mm/year	-0.5mm/year
Extreme Rainfall Depths	+20%	+30%
Flood Flows	+20%	+30%

Mid-range scenario adopted in the CFRAM studies throughout Ireland and will also be considered for this site-specific flood risk assessment and section 50 application

4. Hydraulic Model Description

4.1 General

In order to assess the potential impact of the proposed Dodder bridge crossing development with its large Bascule bridge pier and including the proposed reclamation/infill of a section of the Dodder and Liffey channel in the vicinity of St. Patrick's Boat club immediately upstream of the Tom Clarke Bridge, a high resolution 2-D hydrodynamic model of the local reaches of the Liffey and Dodder was developed. The two-dimensional hydrodynamic modelling was required to simulate the complex 2-D flow field around the supports of the proposed Dodder Bridge and the nearby existing Tom Clarke Bridge on the Liffey. In order to efficiently drive this high resolution 2-D model and accurately predict the tidal flows ebbing and flooding through these reaches a more extensive one-dimensional node-link river estuary model was employed to provide suitable upstream and downstream boundary condition hydrographs to drive the local high resolution 2-dimensional model of the Bride site.

Figure 7 ***Liffey and Dodder Reach Extents for the One-Dimensional modelling***

The 1-D model domain extended from the eastern open sea at the Bull walls upstream to the tidal extents on the Liffey at Islandbridge Weir and upstream on the Dodder to Ballsbridge, refer to Figure 7 below. This enabled the tidal flows generated within each of the tidal reaches to be computed under varying tide and fluvial inflow conditions. The tidal exchange volumes in the Liffey upstream of the Tom Clarke Bridge are far greater than the Dodder tidal volumes which as a much narrower channel and much shorter tidal reach.

4.2 HEC-RAS 1-D model

A 1D river model using HEC-RAS hydraulic software system developed by the U.S. Army Corps of Engineers was used to model the Liffey and Dodder estuarine reaches. HEC-RAS is the industry standard used internationally for hydraulic modelling of river and estuarine systems. HEC-RAS implements a 1-dimensional model of longitudinal channel flow (depth and width averaged) and solves for water elevation and average cross-sectional velocity under unsteady flows solving the full St. Venant equations that include the momentum and mass equations. HEC-RAS 1-D is ideal for modelling narrow elongated estuaries where the dominant flow is longitudinal with little variation in the energy slope in the transverse direction.

The unsteady model allows for tidal varying flow and elevation boundary conditions to be specified at the downstream Open Sea boundary and inflow hydrographs at the upstream fluvial boundaries. It also facilitates internal inflows at various nodes to allow for inclusion of lateral tributary inflows. The HEC-RAS model requires cross section survey data of bed and overbank levels versus Station distance from left overbank to right overbank and facilitates different channel roughness's and various structure types including bridges, culverts spillways and weirs.

4.3 TELEMAC Hydraulic Software System

The TELEMAC system is the software of choice for modelling the complicated two-dimensional hydrodynamics of the Liffey and Dodder Estuary in the vicinity of the bridge crossing and their confluence. TELEMAC is a software system designed to study environmental processes in free surface transient flows. It is therefore applicable to seas and coastal domains, estuaries, rivers and lakes. Its main fields of application are in hydrodynamics, water quality, sedimentology and water waves.

TELEMAC is an integrated, user friendly software system for free surface waters. TELEMAC was originally developed by Laboratoire National d'Hydraulique of the French Electricity Board (EDF-LNHE), Paris. It is now under the directorship of a consortium of organisations including EDF-LNHE, HR Wallingford, SOGREAH, BAW and CETMEF. It is regarded as one of the leading software packages for free surface water hydraulic applications and with tens of thousands of applications and installations Worldwide.

The TELEMAC system is a powerful integrated modelling tool for use in the field of free-surface flows. Having been used in the context of very many studies throughout the world (several thousand to date), it has become one of the major standards in its field. The various simulation modules use high-capacity algorithms based on the finite-element method. Space is discretised in the form of an unstructured grid of triangular elements, which means that it can be refined particularly in areas of special interest. This avoids the need for systematic use of embedded models, as is the case with the finite-difference method. Telemac-2D is a two-dimensional computational code describing the horizontal velocities, water depth and free surface over space and time. In addition it solves the transport of several tracers which can be grouped into two categories, active and passive, with salinity and temperature being the active tracers which alter density and thus the hydrodynamics.

The TELEMAC System is a set of finite element programs designed to solve free water surface problems. A series of modules are available for solution of hydrodynamics, transport and dispersion of pollutants, sediment transport and wave dynamics. These are:

- TELEMAC-2D: 2-dimensional depth averaged hydrodynamics and transport and dispersion of tracers
- TELEMAC-3D: 3-dimensional hydrodynamics, transport and dispersion and sediment movement
- TOMAWAC: A third generation spectral wave model representing the generation of waves due to winds or offshore climates and propagation into shallow waters.
- ARTEMIS: A harbor wave model that solves the mild slope equation in elliptical form and includes the processes of refraction by bed shoaling, wave breaking, diffraction and reflection of waves due to structures.
- SISYPHE: Sediment transport module solving bed and suspended load of cohesive and non-cohesive sediments and can be coupled with TELEMAC-2D, -3D and TOMAWAC for the hydrodynamic transport and bed shear stress calculations.

Each TELEMAC Module uses a completely flexible unstructured mesh of triangular elements allowing it to efficiently model complex geometry problems such as harbours and estuaries.

4.4 Data Sources

A range of Bathymetric survey data was utilised in constructing the 1D Hec Ras Model and 2D Telemac model domains and these sources are described below:

- OPW CFRAM river cross-section survey of the Dodder river channel
- OPW CFRAM river cross-section survey of the Liffey channel
- Bathymetric surveys of Liffey and Tolka Estuaries
- Lidar of part of the Tolka and particularly Bull Island (Source: OPW, 2012);
- Soundings of the Clontarf Basin/Estuary (Source: OPW, 2012)
- Soundings of the approach channel and basins (Dublin Port combined surveys 2015 to 2019)
- Infomar lidar data of Dublin Bay (2006)
- Aquafact International Local Bathymetric Survey of the Dodder and Liffey confluence area (2020).

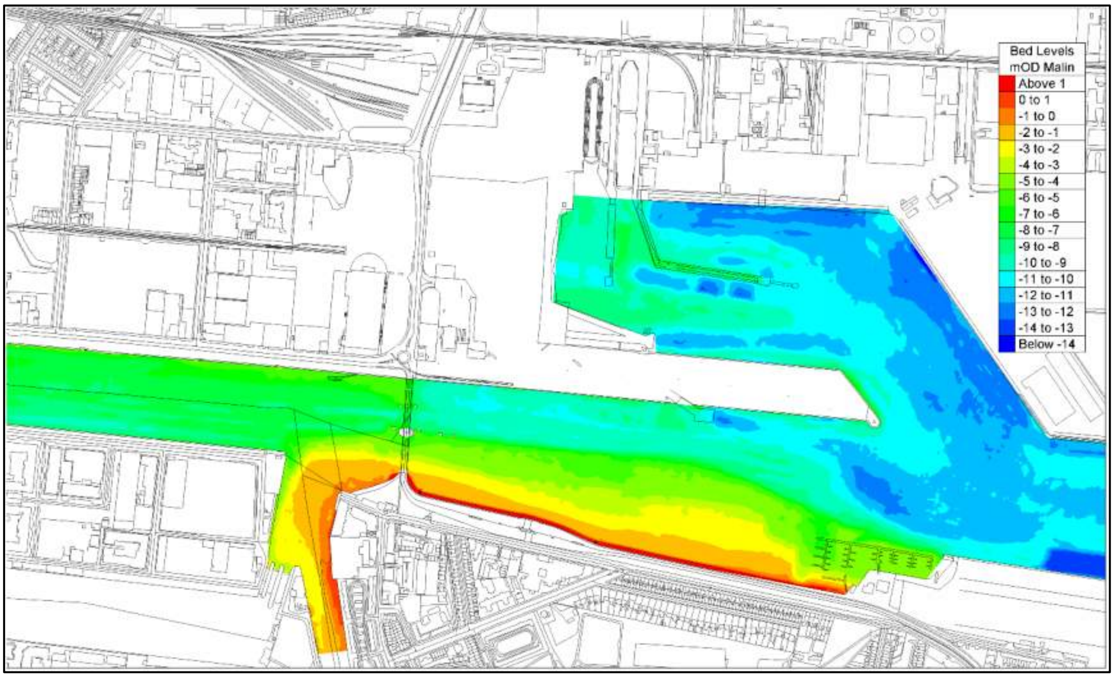

Figure 8 Contour Plot of Model Bathymetry in vicinity of Dodder/Liffey Confluence

4.4 Model Mesh Resolution

The 2-dimensional model area as presented in Figure 9 below is 52ha in area and is discretized by a variable density triangular elements with a total element number of 51,261 representing an average grid resolution of 4.5m sided triangular elements. In the area of interest surrounding the proposed bridge and existing bridge piers the grid resolution is more refined at 1.5m elements. The Model extent is presented in Figure 9 and the existing and proposed model meshes in the vicinity of the bridges are presented in Figures 10 and 11 respectively..

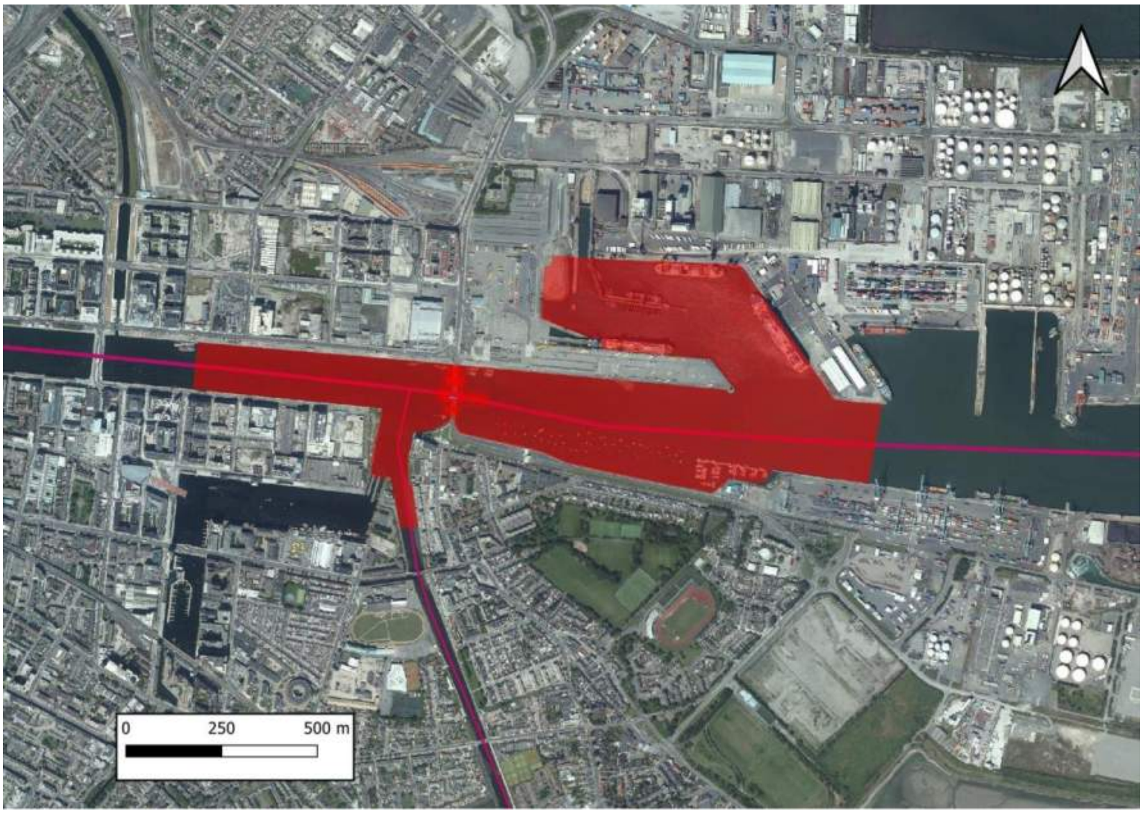

Figure 9 Local 2-D model with 1=D reaches defining flow and elevation boundary hydrographs at west (Liffey Estuary, south Dodder Estuary and east Dublin Port reach)

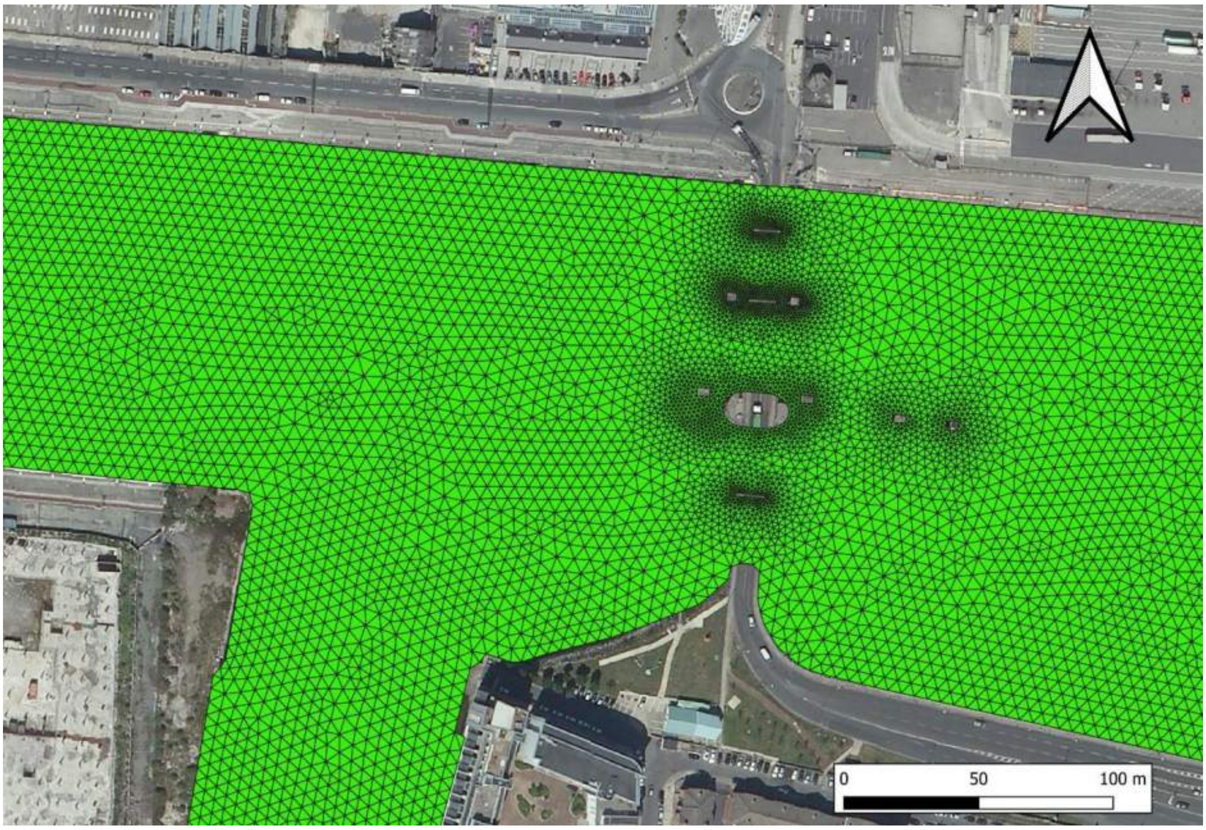

Figure 10 View of Telemac2D mesh structure – existing case.

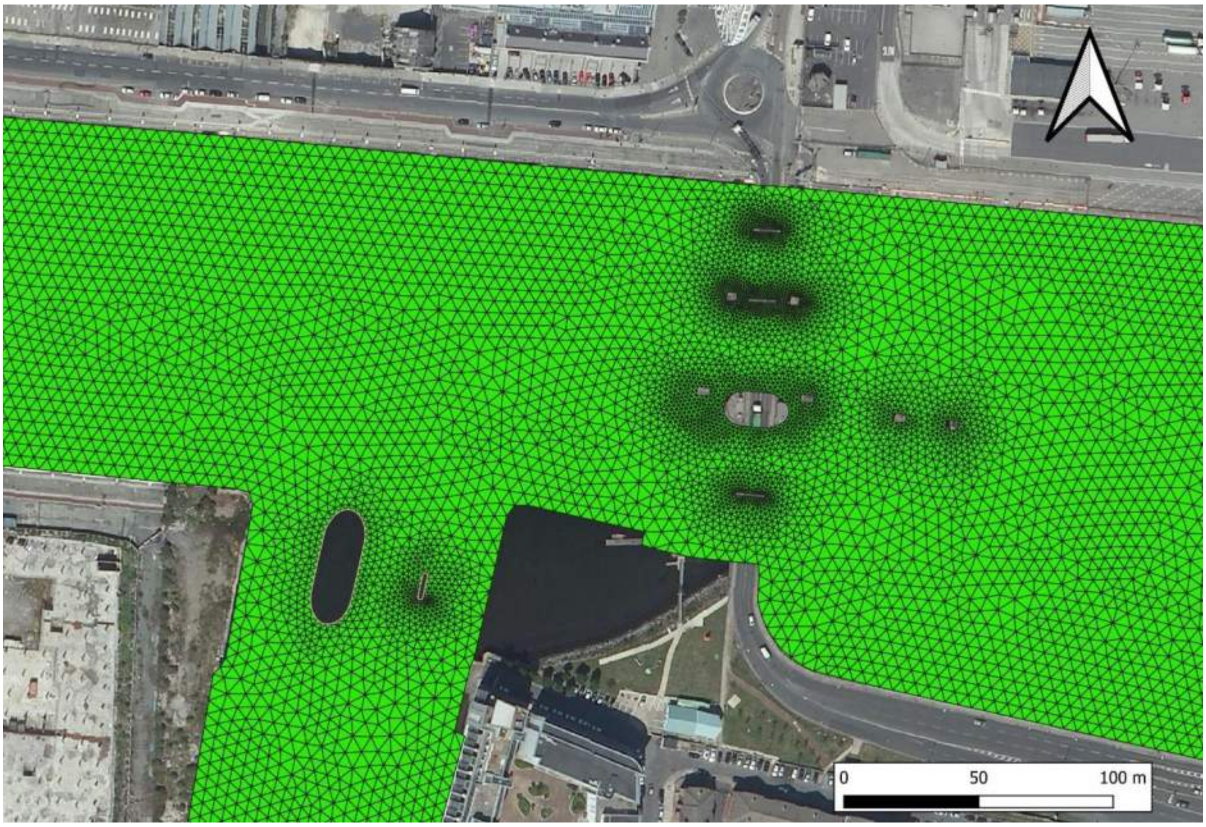

Figure 11 View of Telemac2D mesh structure – proposed case

4.5 Hydrodynamic Simulations

A number of hydrodynamic simulations were carried out to examine a range of hydrodynamic events under the existing case (i.e. No Development) and the proposed case with the proposed Dodder Bridge and infill at St. Patrick's Rowing Club. The following list a number of the simulations investigate in respect to changes in the local hydrodynamics.

Simulation	Description
1	Spring tide event (tidal range 3.3m) with median Fluvial Flow in Liffey (20cumec) and Dodder (2.7 cumec)
2	200yr tidal storm surge event (tidal range of 4.54m with mean fluvial flow in Dodder and Liffey Rivers of 2.7 and 20cumec respectively.
3	Spring Tide with large Fluvial Flood in Dodder of 110cumec (5year return period) and Median Flow in Liffey of 20 cumec.
4	Spring Tide with 100year Fluvial Flood flow in Liffey of 260cumec and mean Flow in Dodder of 2.7cumec.
5	Spring Tide with annual Fluvial Floods in Dodder and Liffey of 56cumec and 137cumec respectively.
6	Spring tide with extreme Dodder flood (311cumec CFRAM estimated 100year) and 2year flood in Liffey of 137 cumec.

These events were firstly modelled using the 1-Dim HEC-RAS model which provided the upstream flow hydrograph boundary conditions, in terms of combined fluvial and tidal fluxes, to drive the local TELEMAC2D Model. The downstream model boundary condition was a tidal elevation boundary hydrograph.

Simulation 1
This simulation was selected as it represents the typical tidal flows that ebb and flood ups and down the Liffey and Dodder estuaries with fluvial flow component in both rivers at 20 and 2.7cumec almost insignificant in magnitude. The simulation boundary conditions predicted by the HEC-RAS model are presented below in Figure 12.

Simulation 2
This simulation was selected as it represents a large tidal flood event producing ebbing and flooding flows both up the Liffey and up the Dodder. The range for this surge event increases from a typical spring tide range of 3.4m to 4.5m . Given that the more extensive estuarine reach is the Liffey extends 6km from the Dodder confluence up to Islandbridge weir the larger tidal flows occur in the Liffey channel with much smaller tidal flows in the Dodder due to its relatively short and narrow tidal reach. The computed flow conditions for this simulation computed by the one-dimensional model are presented below in Figure 13.

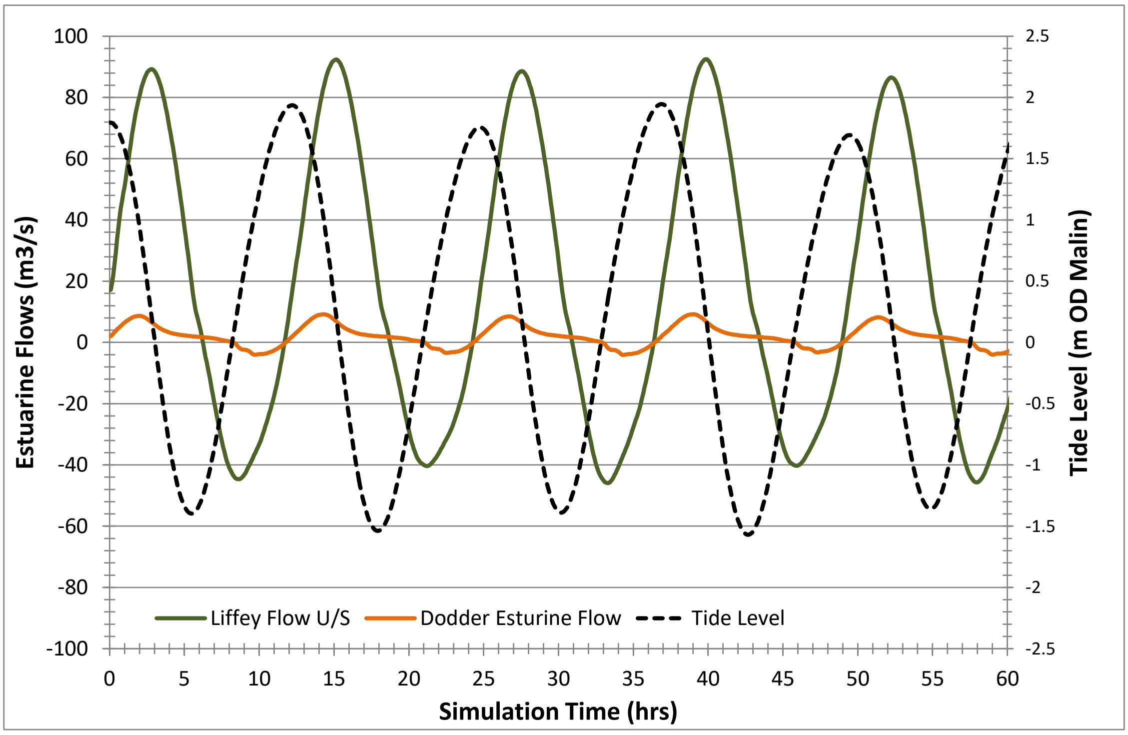

Figure 12 ***Computed Boundary conditions for Simulation 1 (Spring Tides and annual mean River Dodder and Liffey fluvial flows)***

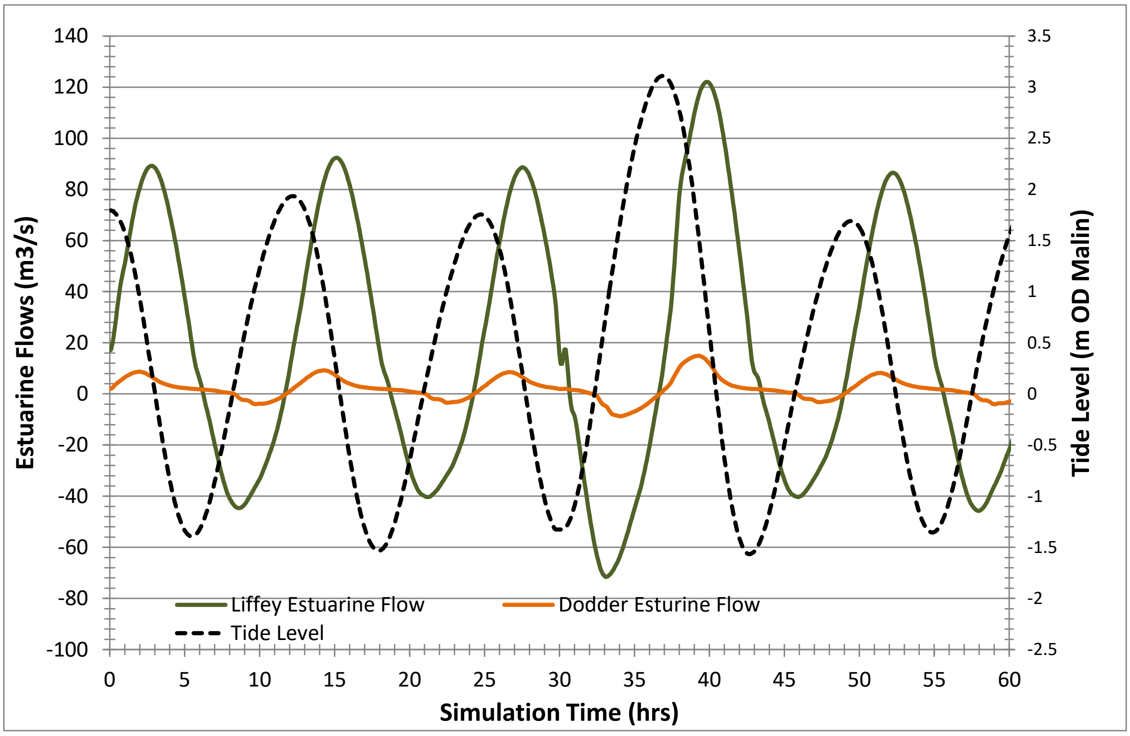

Figure 13 ***Computed Boundary conditions for Simulation 2 (Extreme Surge Tide and annual mean River Dodder and Liffey fluvial flows)***

Simulation 3
This simulation was selected as it represents a large flood flow on the Dodder (peak fluvial flow of 110cumec – estimated in CFRAM to be c 5year return period) combining with typical mean flows in the River Liffey of 20cumec and spring tide conditions of 3.3m range. The Dodder catchment is such a small flashy catchment relative to the Liffey that it is unlikely that the floods from both catchments will coincide. A modest flood flow rate of 110cumec which based on FSU predictions including the statistical analysis represents slightly less than a 20year flood which has probability of occurring 5% in any given year. Such a flow rate produces high velocities in the Dodder reach during low water periods. The CFRAM estimate the 5 year to be c. 110 cumec but this is likely to be very conservative given the focus of the study is on flooding and flood relief.

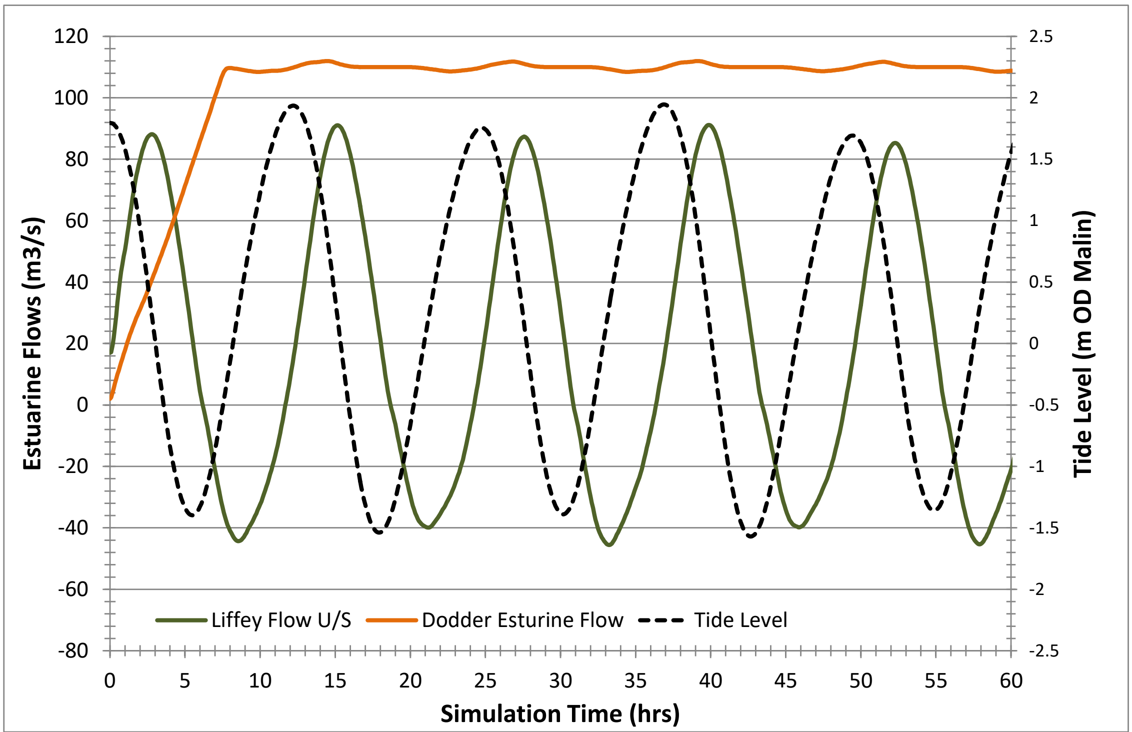

Figure 14 ***Computed Boundary conditions for Simulation 3 (Spring Tides and Large River Dodder Flood Flow (110cumec) and annual mean River Liffey Flow)***

Simulation 4
This simulation was selected as it represents a large fluvial flood event on the River Liffey of 267cumec (100year return period) combining with spring tides (3.3m tidal range) and mean flows in the Dodder of 2.7cumec. The simulation boundary conditions predicted by the one-dimensional HEC-RAS modelling are presented below in Figure 15.

Simulation 5
This simulation was selected as it represents an annual flood flow in the Dodder of 56cumec combining with annual flood in the River Liffey of 137cumec (20cumec) and spring tide conditions of 3.3m tidal range. The simulation boundary conditions predicted by the one-dimensional HEC-RAS modelling are presented below in Figure 16.

Simulation 6
This represents the conservatively estimate 100year fluvial flood on the Dodder of 311cumec and an annual flood on the River Liffey of 137cumec combining with spring tides of 3.3m tidal range. Fluvial Flooding in the Dodder and Liffey rarely coincide. The simulation boundary conditions predicted by the one-dimensional HEC-RAS modelling are presented below in Figure 17.

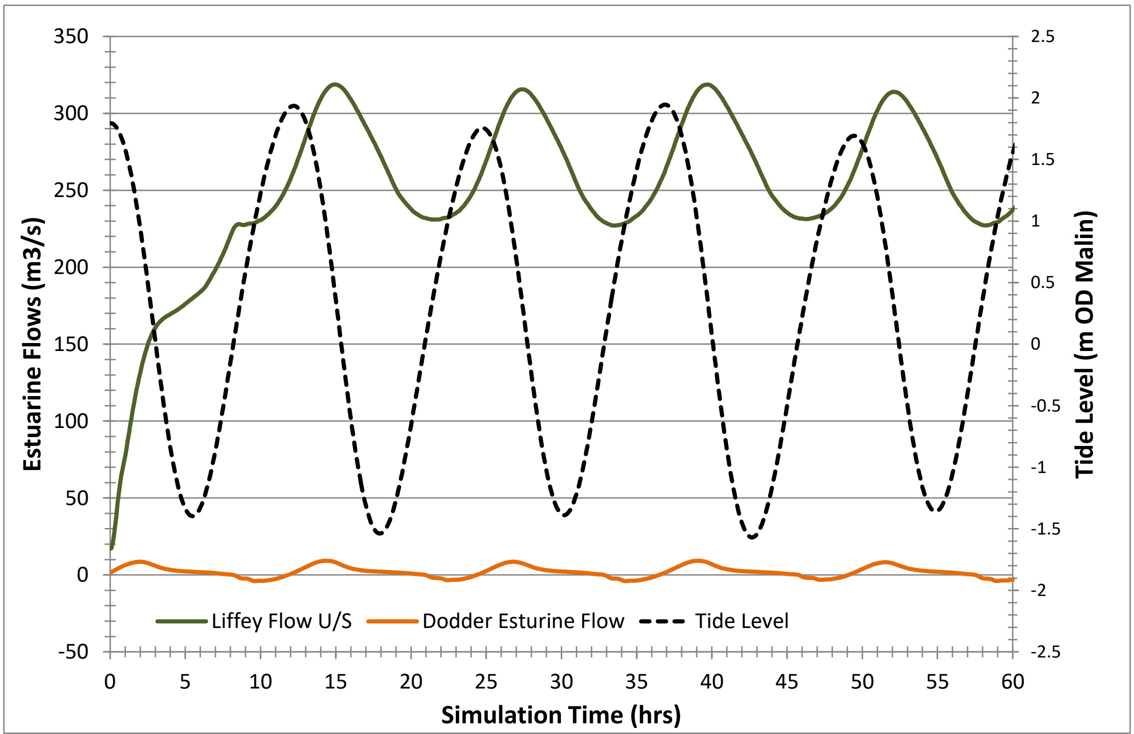

Figure 15 ***Computed Boundary conditions for Simulation 4 (Spring Tides, Mean Dodder and 100year Liffey flood flow of 267cumec)***

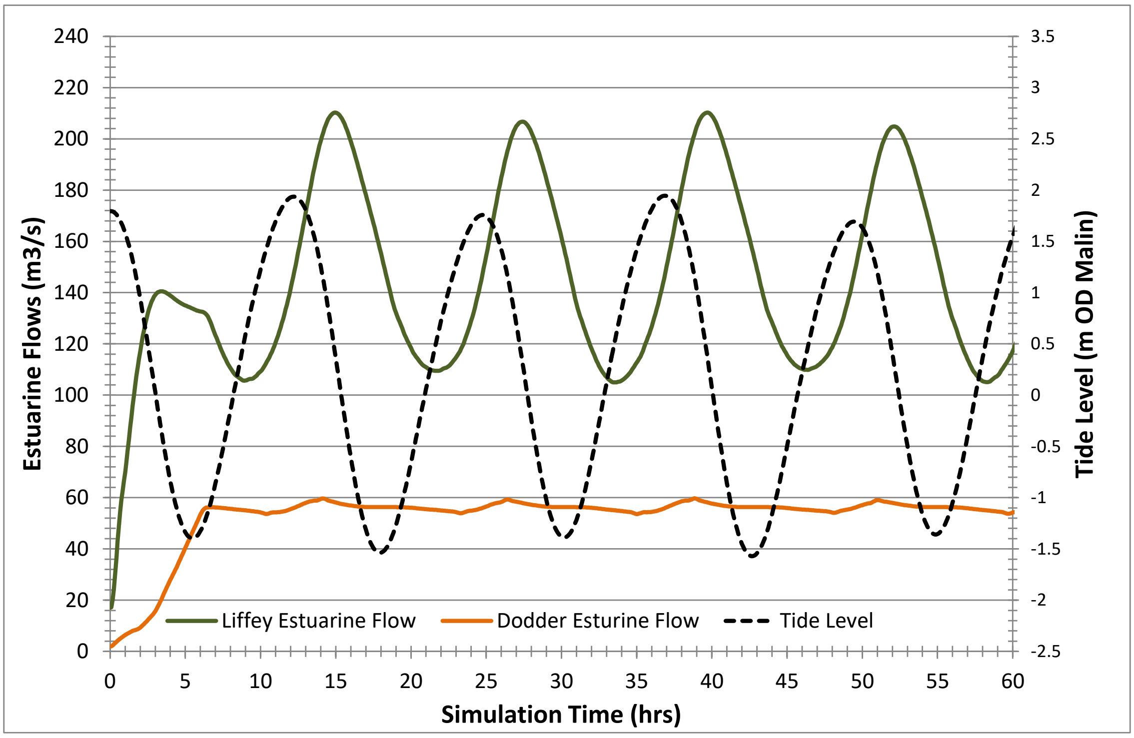

Figure 16 ***Computed Boundary conditions for Simulation 5 (Spring Tides, 2year Flood flow in Dodder and Liffey of 56 and 137cumec respectively)***

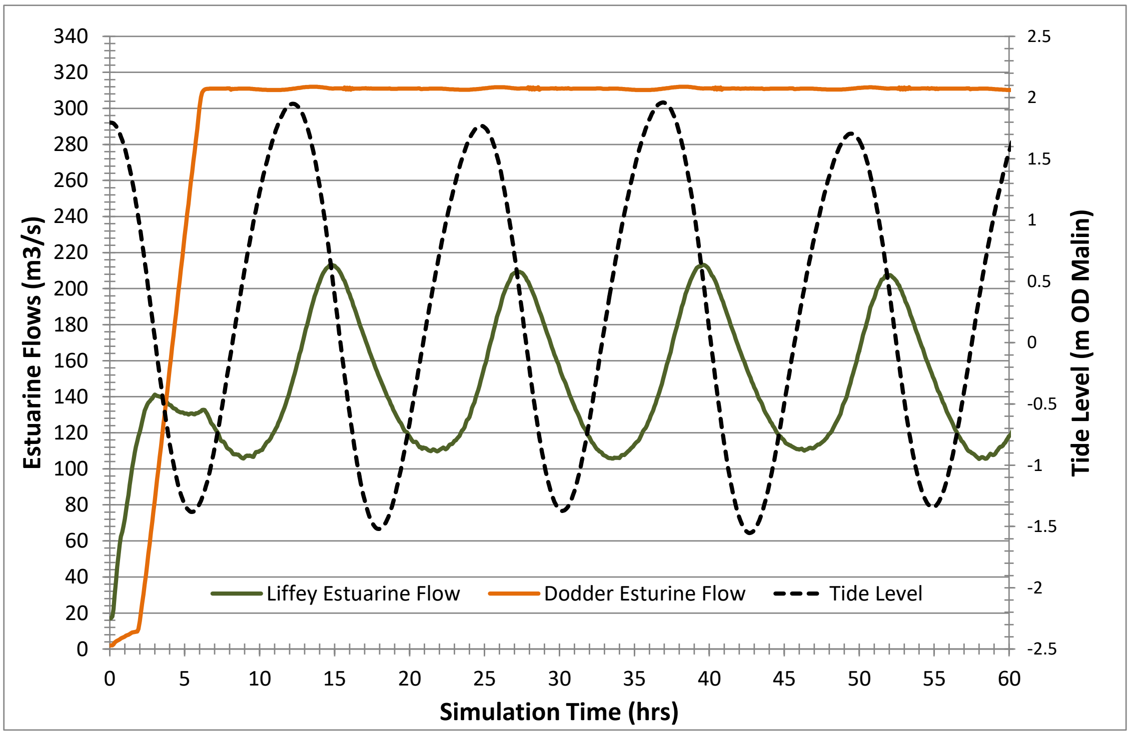

Figure 17 ***Computed Boundary conditions for Simulation 6 (Spring Tides, 100year design Flood in the Dodder of 311cumec and median flood in the Liffey of 137 cumec)***

4.6 Hydrodynamic Simulation Results

The hydrodynamic model was run for the above scenarios (Simulations 1 to 6) for repeated tides over a 41hour simulation period. The computed results in terms of flow velocities, water elevations and flow depths were output and analysed for both the existing case and the proposed case (with bridge and boat club infill). The Computed flow velocity magnitudes are presented with and without the development at the four principal stages of the tidal cycle (Low Water, Mid-Flood, Highwater and Mid-Ebb) for each of the scenarios. Refer to Figures 18-21, 26 – 29, 34 – 37, 42 – 45, 50 – 53 and 58 – 61 respectively.

In order to access the potential impact on bed sediments the bed shear stress is computed using the Chezy equation for bed shear. This is then compared to the critical bed shear of a given sediment particle size for initiation of mobilisation. In our case this is a silt which requires relatively small bed shear stresses to mobilise. The Mobility Factor M is defined as the Ratio of bed shear to critical bed shear, such that factors exceeding 1 represent mobilisation.

Where the ration of bed shear to critical bed shear (i.e. the Mobility Factor) exceeds 1, then scouring of fresh unconsolidated silt is likely.

$$\theta_{cr} = \frac{0.3}{1+1.2\mathrm{D}_{gr}} + 0.055\left[1 - e^{-0.02\mathrm{D}_{gr}}\right] \qquad (1)$$

$$D_{gr} = \mathrm{D}\sqrt[3]{\frac{g(s-1)}{\vartheta^2}} \qquad (2)$$

$$\theta_{cr} = \frac{\tau_{cr}}{\rho(s-1)gD} \qquad (3)$$

$$\tau_{cr} = \theta_{cr}\rho(s-1)gD \qquad (4)$$

Where g = 9.81m/s2, s= 2.65 (specific density), D_{gr}= dimensionless grain size, θ_{cr} Shield's parameter, ϑ viscosity = 1.2 x 10^{-6}m^2/s, ρ water density kg/m3, D is the sediment diameter and τ_{cr} is the critical shear stress.

Bed Shear Stress is calculated as follows

$$\tau = \frac{U^2\rho}{C'^2} \qquad (5)$$

Where

$$C' = \frac{H^{\frac{1}{6}}}{ng} \qquad (6)$$

U depth averaged velocity, H is water depth, n is manning roughness.

The mobility Factor is expressed as

$$\mathrm{M} = \frac{\tau}{\tau_{cr}} \qquad (7)$$

***M*=1**	At some point, the fluid shear will just be in balance with the critical shear stress for erosion (*M*=1). As flow increases past this point, the grain will start to move along the bed: at first by 'saltating' or jumping along the bed (bed load). These jumps are caused by turbulence in the flow.
1<*M*<8	In this range, the size and mass of the grain is sufficient that it falls back to the bed quite quickly after each jump. As the amount of bed load increases, bedforms such as ripples and/or dunes develop. Bedform length of ripples is mainly a function of grain-size while the height of the bedform is dependent on flow intensity. For dunes, bedform length is mainly a function of flow depth.
8<*M*<14	As flow intensity increases, the bedforms start to reduce in height, the 'hang time' of the particles increases.
14<*M*<65	Sediment is now being swept higher into the flow field. The lift forces in this increasingly turbulent flow field are sufficient to keep the grain in suspension. The onset and characterisation of suspended load is, in large part, controlled by the ratio of sediment fall velocity to the total shear velocity, (w/u_*).

The geotechnical surface and sub-surface investigation and grab samples (IGSL Geotechnical Report 2019) in the vicinity of the Dodder Bridge and Liffey Confluence confirms that the sediment deposits is a Silt. With increasing sub-surface depth the silt deposit is consolidated firm and cohesive and likely to have a much higher shield's value.

The mobility factor M (eqn 7)associated with an unconsolidated silt is mapped for each of the 6 simulation scenarios and at the four principal stages of the tidal cycle, refer to Figures 22-25, 30 – 33, 38 – 41, 46 – 49, 54 – 57 and 62 – 65 for each simulation respectively.

The first scenario, Simulation 1 represents normal conditions associated with a mean spring tide and mean river fluvial inflows. The computed velocities are relatively low with highest velocities occurring on the out-going tide at mid-ebb, refer to Figure 21. At this stage the tidal volume combined with the average river flows is discharging eastward out of the estuaries with the Liffey reach generating tidal velocities of c. 0.1m/s. Higher velocities occur through the opes of the existing Tom Clarke Bridge with maximum velocities of over 0.2m/s predicted locally at this location. At the slack tidal periods associated with low and high waters the computed flow velocities are almost negligible as the tide is turning. The mid-flood tide produces flow velocities generally of less than 0.075m/s (i.e. < 7.5cm per second). There is little or no change in velocity magnitude or circulation pattern as a result of the proposed development.

Under these conditions there is generally insufficient shear stress to mobilise the unconsolidated silty sediment, except locally at the Tom Clarke Bridge at mid-ebb tide (refer to Figure 25) and consequently limited silt mobilisation will result under both existing and proposed cases. The proposed case results in a very slight increase in potential silt mobilisation through the central opes of the Tom Clarke Bridge due to a more streamlined approach to the bridge caused by the proposed St. Patrick's Rowing Club site infill on the southern bank of the Liffey immediately upstream of the Tom Clarke Bridge. This effect on velocities and sediment scouring is considered minor and local to the bridges There are no downstream impacts identified.

The second simulation scenario includes for a large tidal surge event combining with mean fluvial flow conditions. It should be noted that the historical maximum tidal surge event observed on the 1st February 2002 combined with typically average fluvial flow conditions in the Liffey and Dodder. The simulated surge event increases the ebbing and flooding velocities in both reaches due to the larger tidal range and increased tidal volume migrating upstream and downstream through the estuaries with the tide. The maximum velocities occur on the ebbing tide achieving up to 0.3m/s through the Tom Clarke bridge in both cases. On the flooding tide maximum velocities occur through Tom Clarke bridge at c. 0.15m/s.

The modelling shows with the proposed development very localised effects on the tidal velocities immediately adjacent to the proposed Dodder Bascule Bridge and in the immediate vicinity of the Tom Clarke Bridge with slightly increased velocities through the opes of the bridges on the ebbing tide and flooding tides. These velocity increases result in local increases in potential silt mobilisation in the vicinity of the bridges but does not result in any significant change in the potential silt mobility factor downstream towards Dublin Port.

Simulation 3 represent a large flood on the Dodder and typical fluvial and spring tidal conditions on the Liffey. The upstream fluvial flow specified is 110cumec which is a significant discharge for the Dodder river channel through Dublin. The tidal curve and thus the tidal depth has a significant effect on resultant velocities in the Dodder through the proposed bridge and at the confluence. The highest velocities are predicted to occur when tidal depths are lowest, that is close to low water. At this tidal stage the Dodder flow concentrates along the western channel bank (i.e. in the existing navigation channel to the Grand canal lock gates and is to the west of the proposed Bascule Pier under both existing (without) and proposed development cases. With its momentum at low water it flows almost perpendicular across the Liffey channel towards the northern quay wall of the Liffey where it turns and flows eastward out to sea with elevated velocities along the northern side of the Liffey channel. On the southern side of the Liffey downstream of Tom Clarke Bridge a clockwise gyre is developed with velocities heading in the reverse direction westward up the Liffey. The flow patterns are similar for both existing and proposed cases with localised changes in the immediate vicinity of the proposed piers refer to figures 34 to 37. There are a no significant changes to the flow pattern or velocity magnitude downstream of Tom Clarke Bridge.

At Low Water flow velocities of up to 3 m/s is predicted in the Dodder along the western Quay wall under both cases. The proposed case at mid-flood through to mid-ebb increase the velocities over the existing case immediately to the east of the Bascule pier, but the impact is relatively localised (refer to figure 35 to 37) and does not result in any significant change downstream towards the Dublin Port area.
The Mobility Factor mapping for silt shows significant scouring potential both in the Dodder, through Tom Clarke Bridge and along the north bank of the Liffey for both existing and proposed cases. Under such a flood event the proposed Dodder Bridge development will not result in any significant impact over the existing case in respect to silt mobilisation and scouring (refer to Figures 38 to 41.

Simulation 4 examines the scenario of a large fluvial flood on the Liffey with the normal spring tidal condition in the Port and normal fluvial flows on the Dodder. It should be noted that the Dodder and Liffey have significant different fluvial flood responses and generally do not coincide with the Dodder response much quicker and produced by much shorter duration events that can occur both summer and winter whereas the Liffey is very damped slow and persistent response and generally associated with more prolonged rainfall events, typical of winter.

This simulation shows no significant impact from the proposed development on the flow velocities within the Liffey or Dodder channels. The proposed Saint Patrick's Rowing Club development streamlines better the liffey estuary flows through the Tom Clarke Bridge and maintains a good velocity along the northern boundary of the proposed rowing club site which is likely to be beneficial for the proposed slipway and boat launching, as it is likely to avoid silt deposition during such flows in the Liffey. The computed silt mobility factor at the different stages show no significant changes in the Liffey between the existing and proposed cases and particularly downstream of the Tom Clarke Bridge towards the Dublin Port area, refer to Figures 46 to 49.

Simulation 5 represents annual fluvial floods (2year return period events) in both the Dodder and Liffey Rivers coinciding. The predicted flow pattern is somewhat similar to Simulation 3 except the momentum of the Dodder for this lesser flood event combined with Liffey Flood Flow results in the Dodder deflecting eastward with the Liffey earlier and therefore towards the middle of the Liffey channel through the Tom Clarke Bridge middle opes, before eventually migrating downstream concentrated in the northern half of the Liffey Channel towards Dublin Port, refer to Figures 50 to 53. Local changes in flow patterns are predicted as a result of the proposed piers and the Rowing Club facility. Downstream there is little impact on tidal velocities or changes to potential silt mobility, refer to Figure 54 to 57.

The final Simulation 6 represents for completeness an extreme flood flow in the Dodder of 311cumec (estimated by the CFRAM study as the 100year estimate (well in excess of the infamous Hurricane Charlie flooding in August 1986) and combined with an annual flood in the Liffey and mean spring tides. This is a worst case flood for the Dodder, the scale of which has never been witnessed in the Dodder previously and many of the existing bridges upstream would offer serious restriction to such a flow magnitude reaching the Liffey within channel. The predicted hydrodynamics show the Dodder flood plume travelling across the Liffey channel at the confluence to favour the northern side of the Liffey channel and the northern opes of the Tom Clarke Bridge, refer to Figures 58 to 61 for both existing and proposed cases. The principal effect of the proposed development is to deflect more of the Dodder Flow to the east of the proposed Bascule Pier over the existing case. The silt mobility factor mapping shows potential increased local scouring during such an event on the eastern bank of the Dodder adjacent to the rowing Club at proposed bridge crossing. The simulation shows little impact on the downstream hydrodynamics of the Liffey towards the Dublin Port Area.

5. Conclusion

The conclusion from this hydrodynamic analysis is that under normal tide and fluvial flow conditions the impact of the proposed development both the bridge crossing and Rowing Club facility will not result in any significant effect either on the hydrodynamics or the morphology of the Liffey and Dodder channels. A localised effect on hydrodynamics will occur at the proposed bridge crossing site adjacent to the proposed piers during flood events. This is likely to give rise to some potential local scouring along the eastern bank of the Dodder as a result of deflection of flow by the proposed Bascule pier. The effect of this is localised to the immediate vicinity of the proposed bridge and western and northern side of the Rowing Club Site. These flood events are rare and short lived and will result in only localised changes to the potential scouring pattern with no significant morphological impacts identified downstream.

The overall conclusion reached is that the proposed Dodder Bridge development will not give rise to significant hydrodynamic or morphological changes in the Liffey reach downstream of the Tom Clarke Bridge.

Simulation 1

Spring Tide (tidal range 3.3m)

Combined with annual average flows in the Dodder and Liffey Rivers of 2.7cumec and 20 cumec respectively

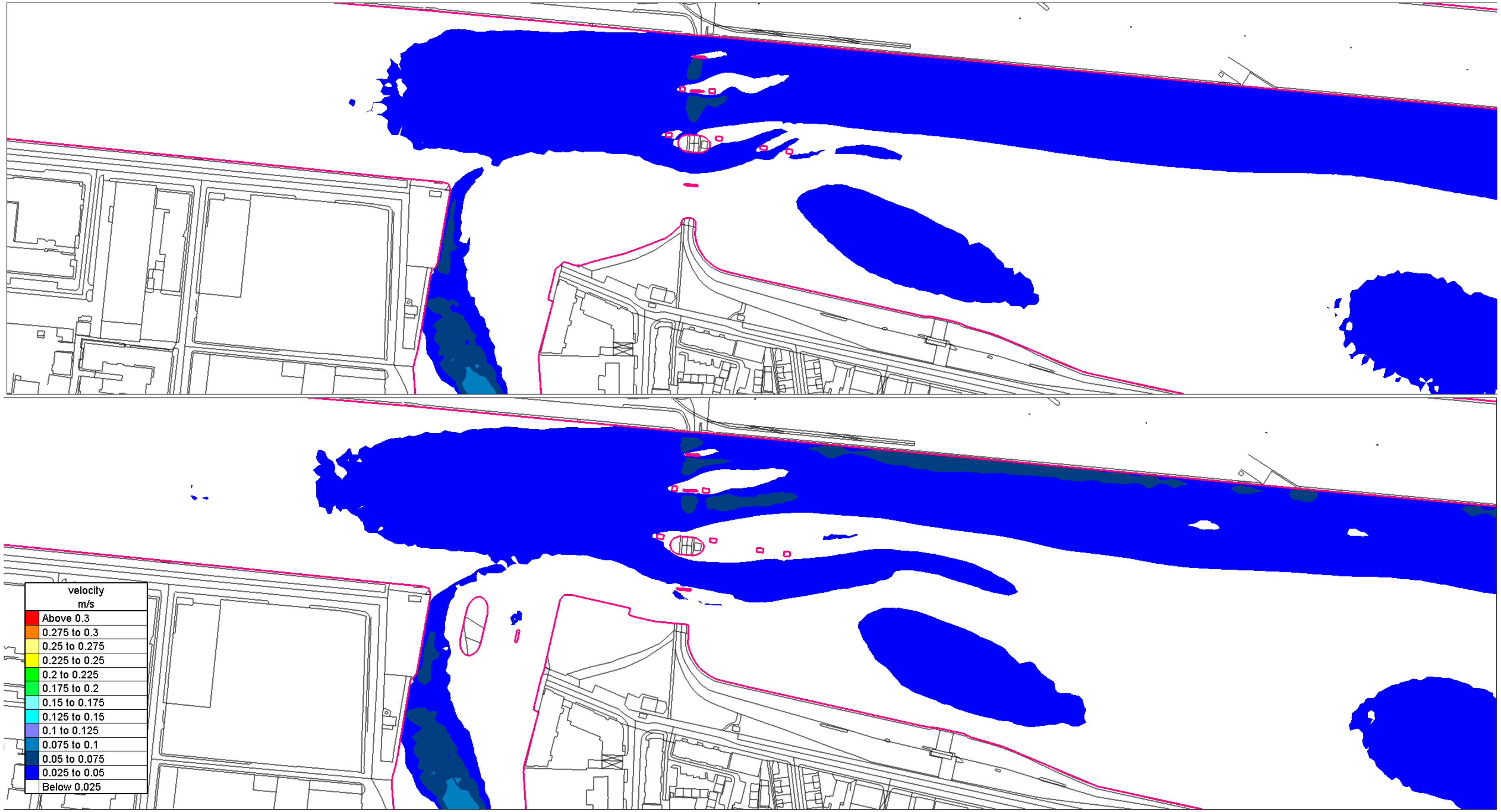

Figure 18 Computed Velocity Magnitudes at Low Water for existing and proposed cases – Simulation 1

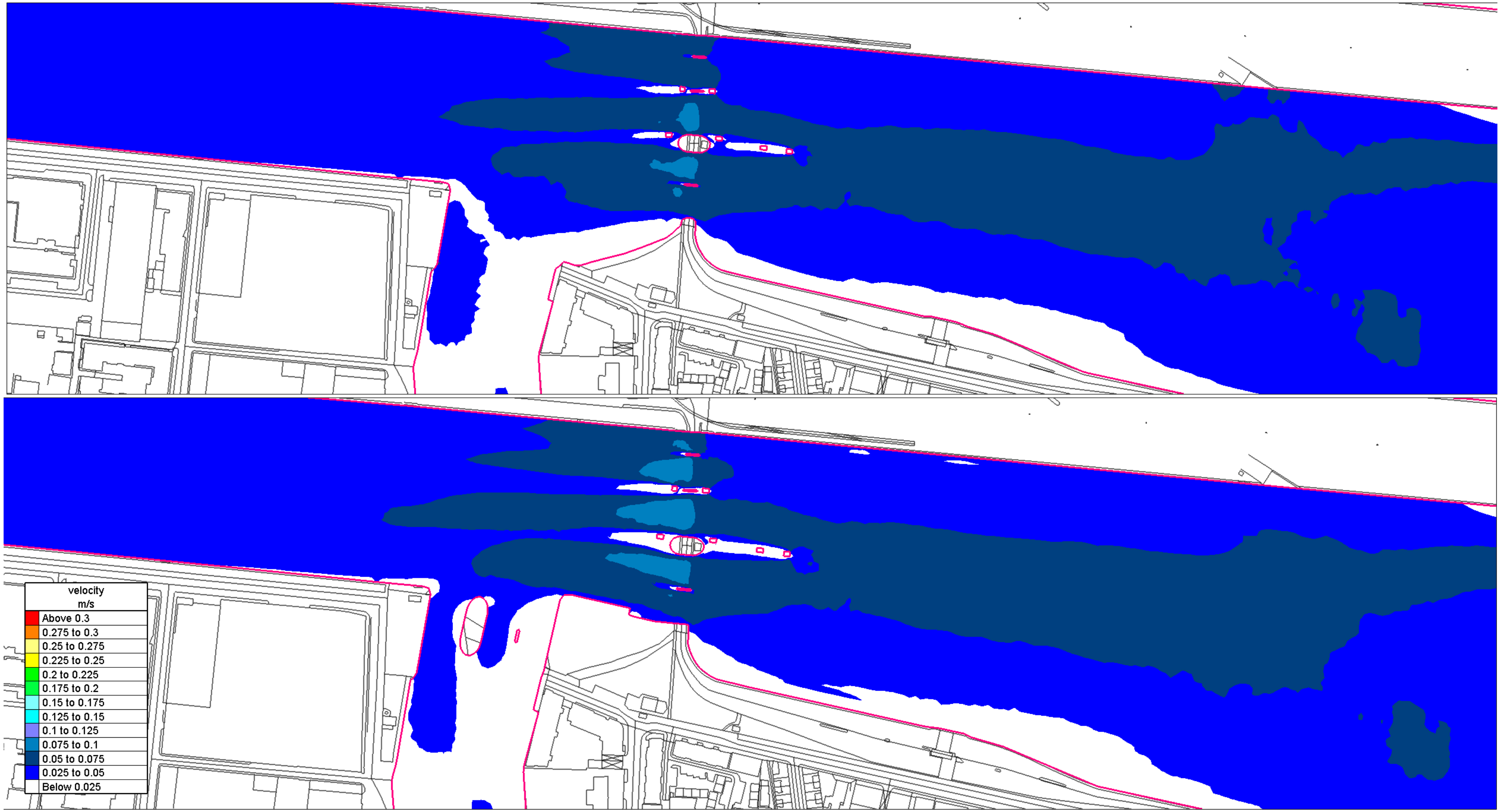

Figure 19 Computed Velocity Magnitudes at Mid-Flood for existing and proposed cases – Simulation 1

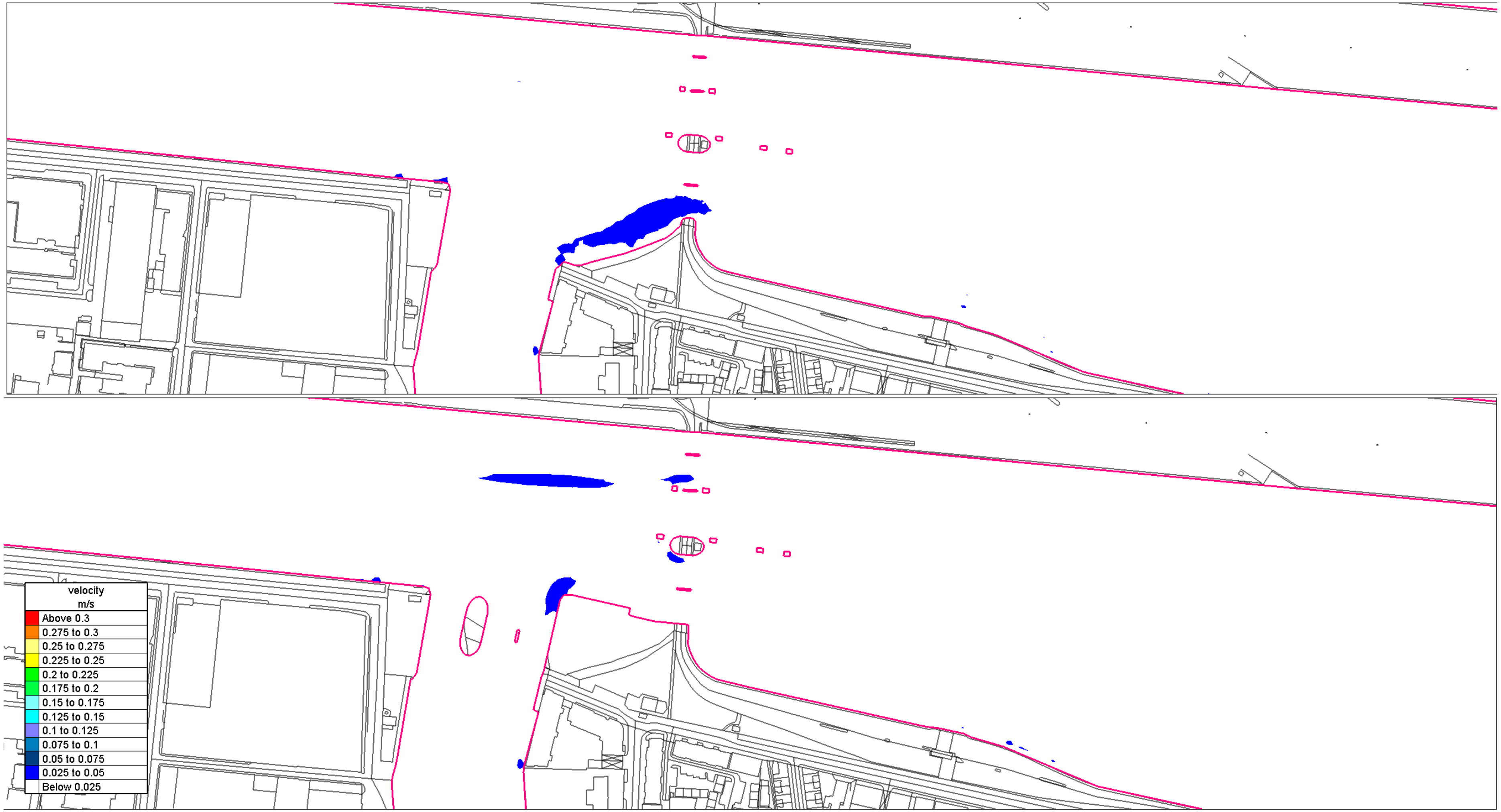

Figure 20 Computed Velocity Magnitudes at High Water for existing and proposed cases – Simulation 1

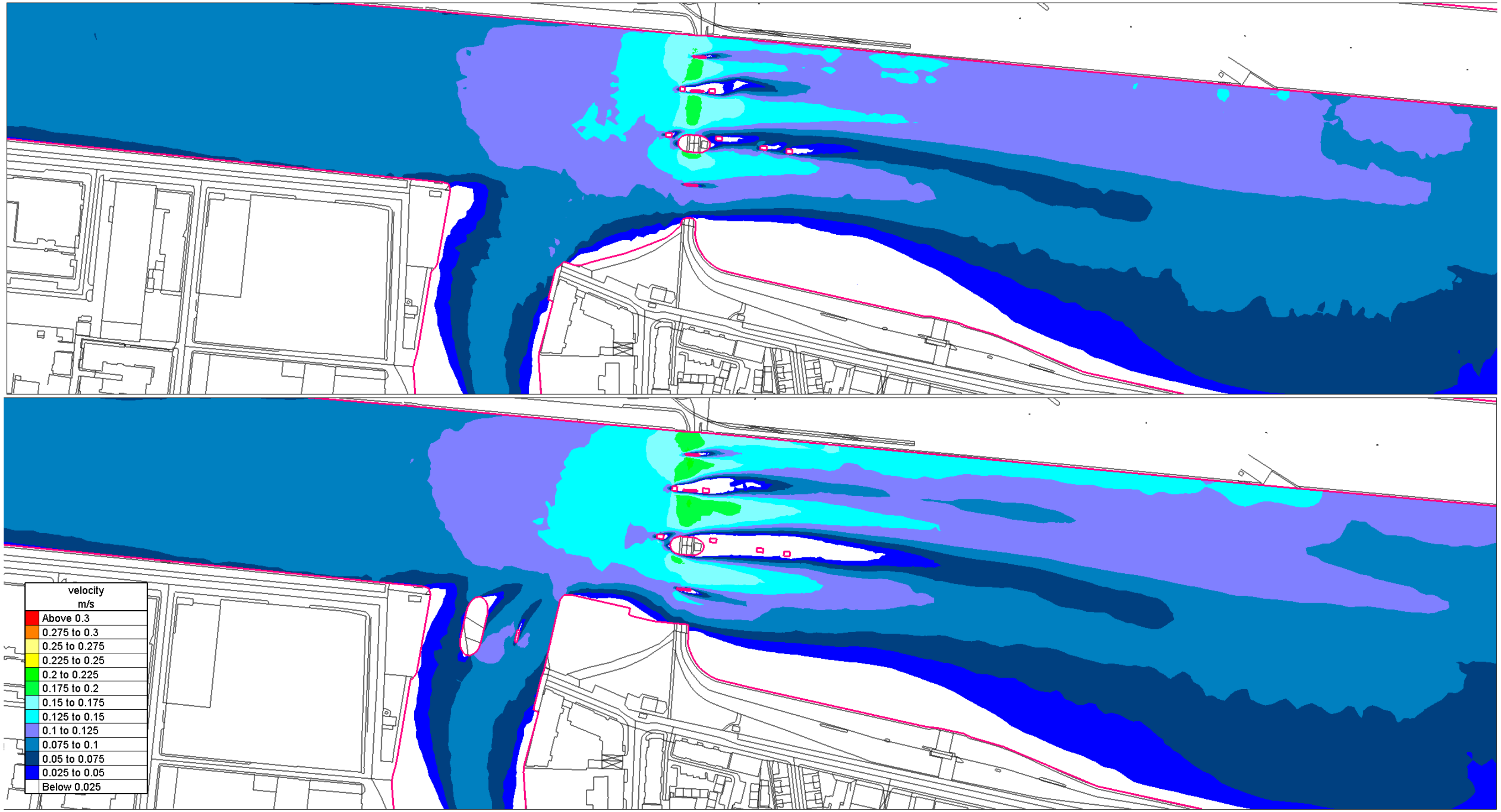

Figure 21 Computed Velocity Magnitudes at Mid-Ebb for existing and proposed cases – Simulation 1

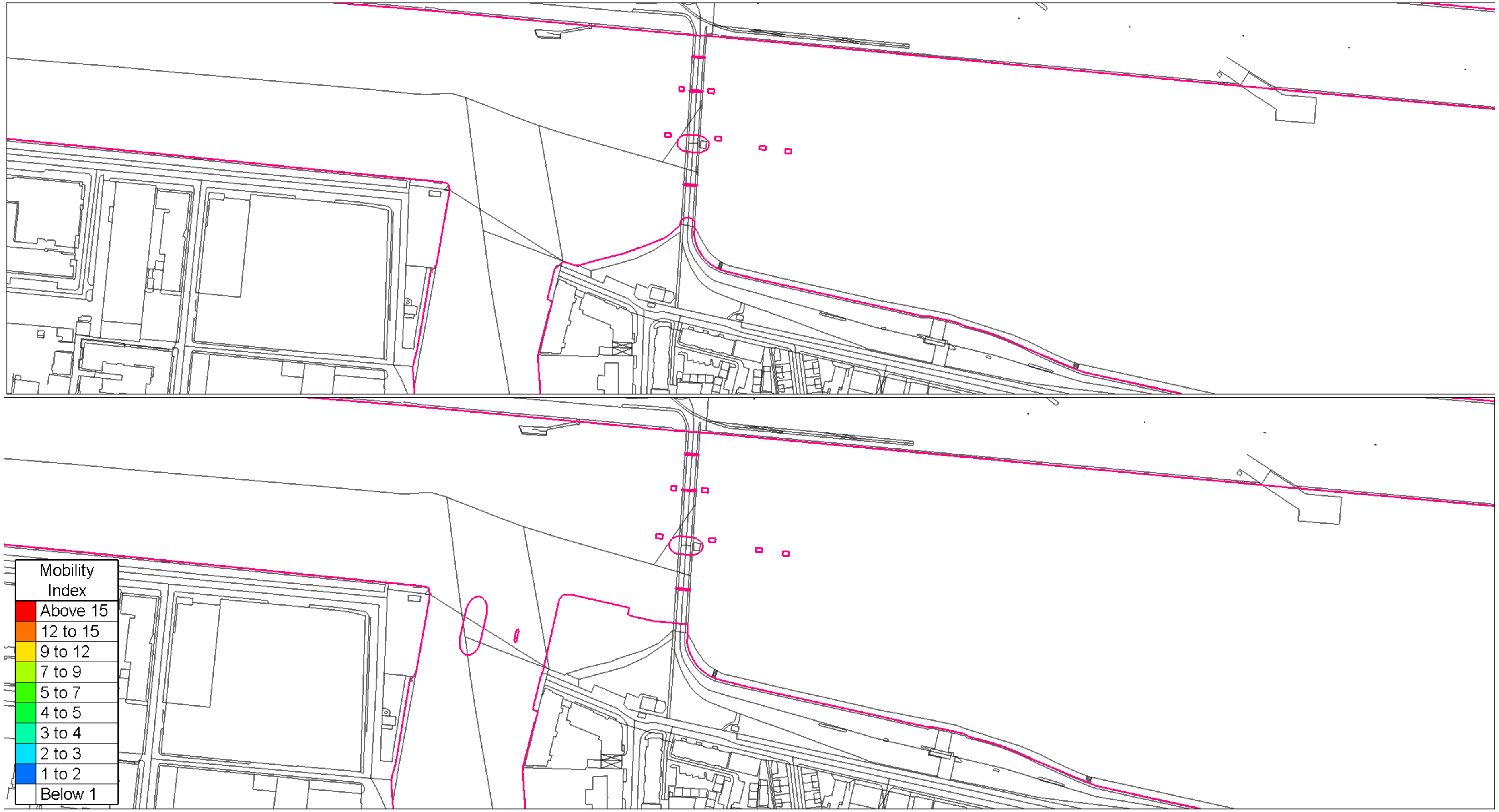

Figure 22 Silt Mobility Map at Low Water for existing and proposed cases – Simulation 1 (Mobility Index < 1 silt is not mobile)

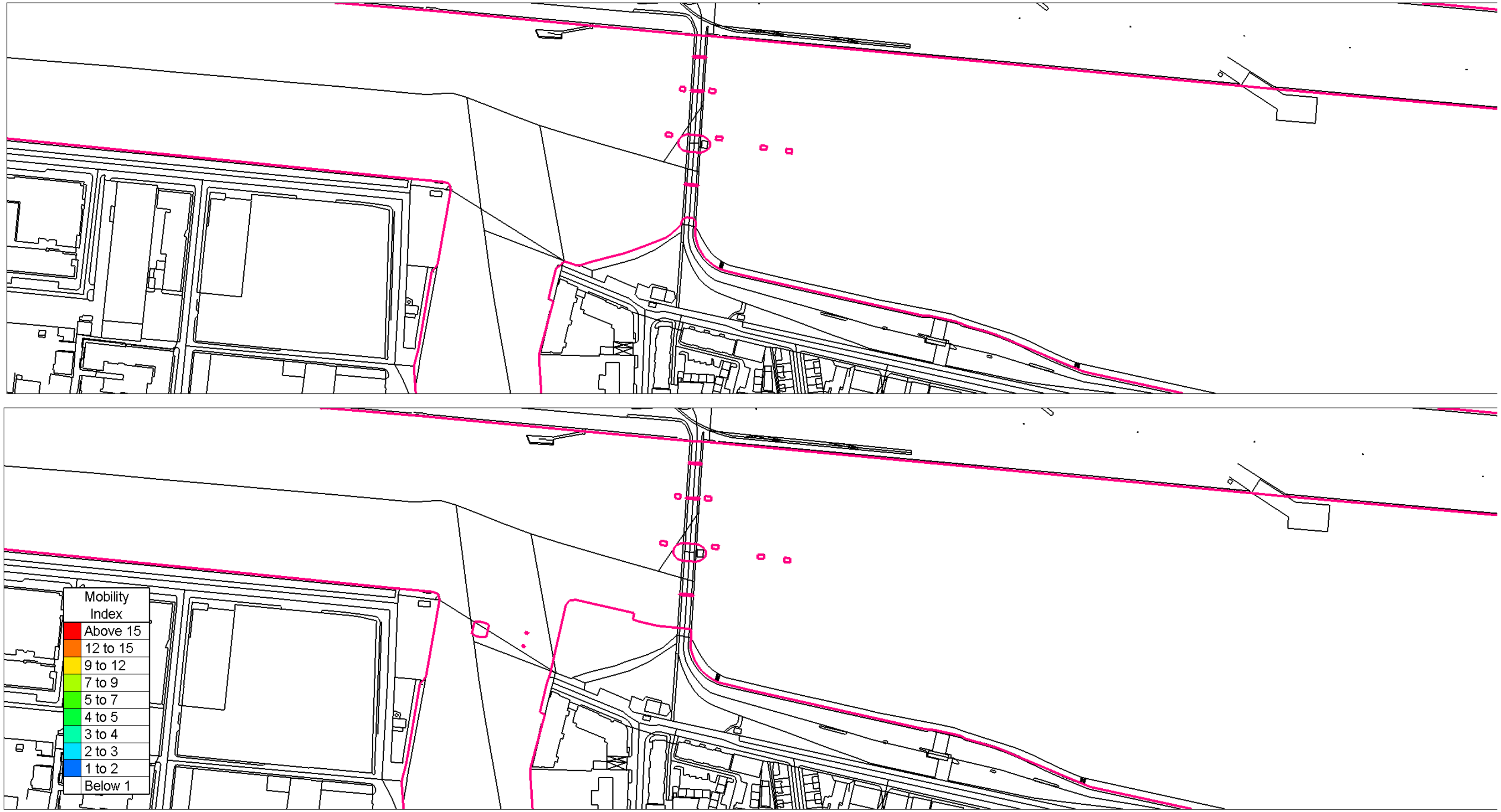

Figure 23 Silt Mobility Map at Mid-Flood for existing and proposed cases – Simulation 1 (Mobility Index < 1 silt is not mobile)

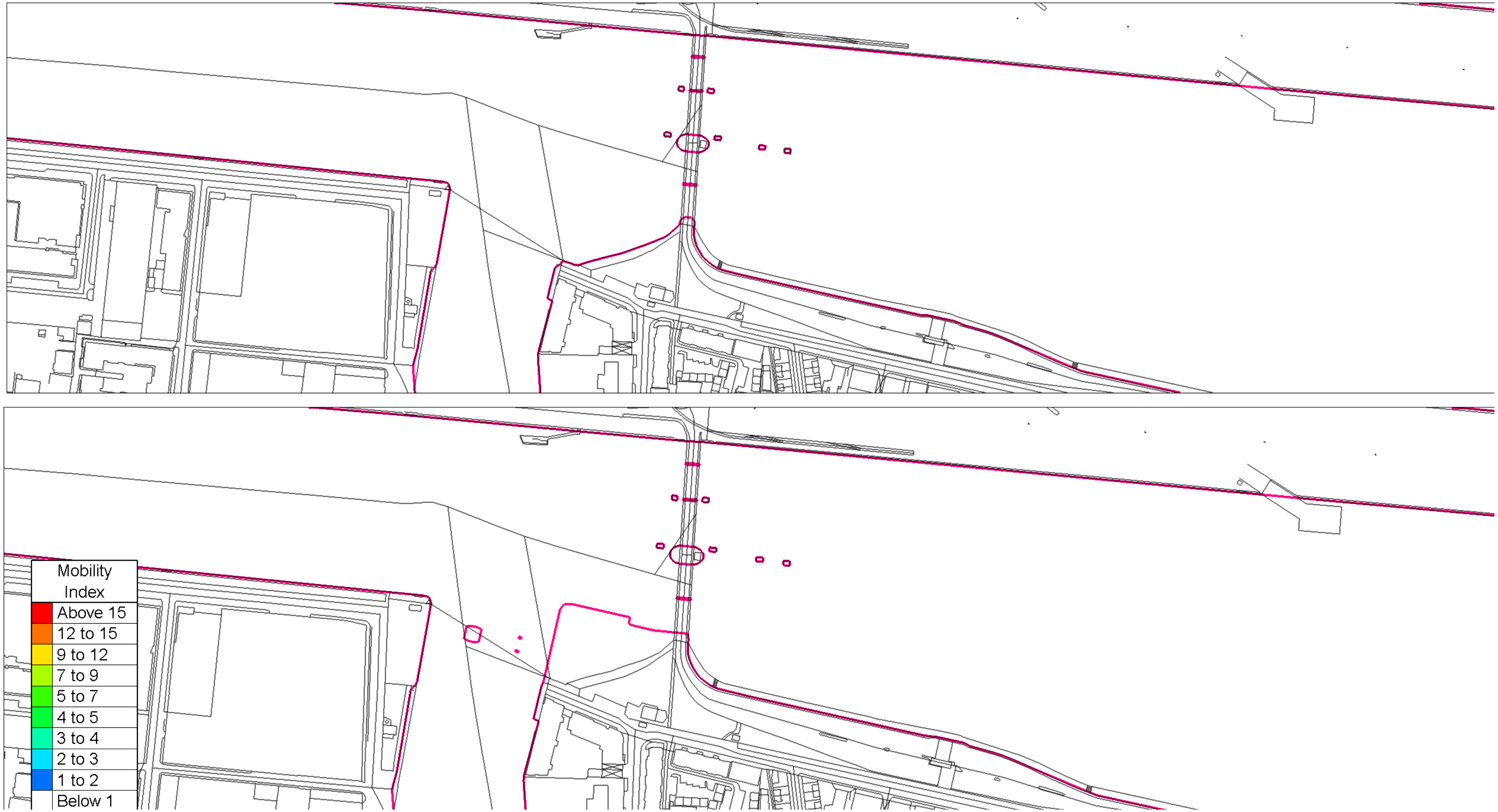

Figure 24 Silt Mobility Map at Highwater for existing and proposed cases – Simulation 1 (Mobility Index < 1 silt is not mobile)

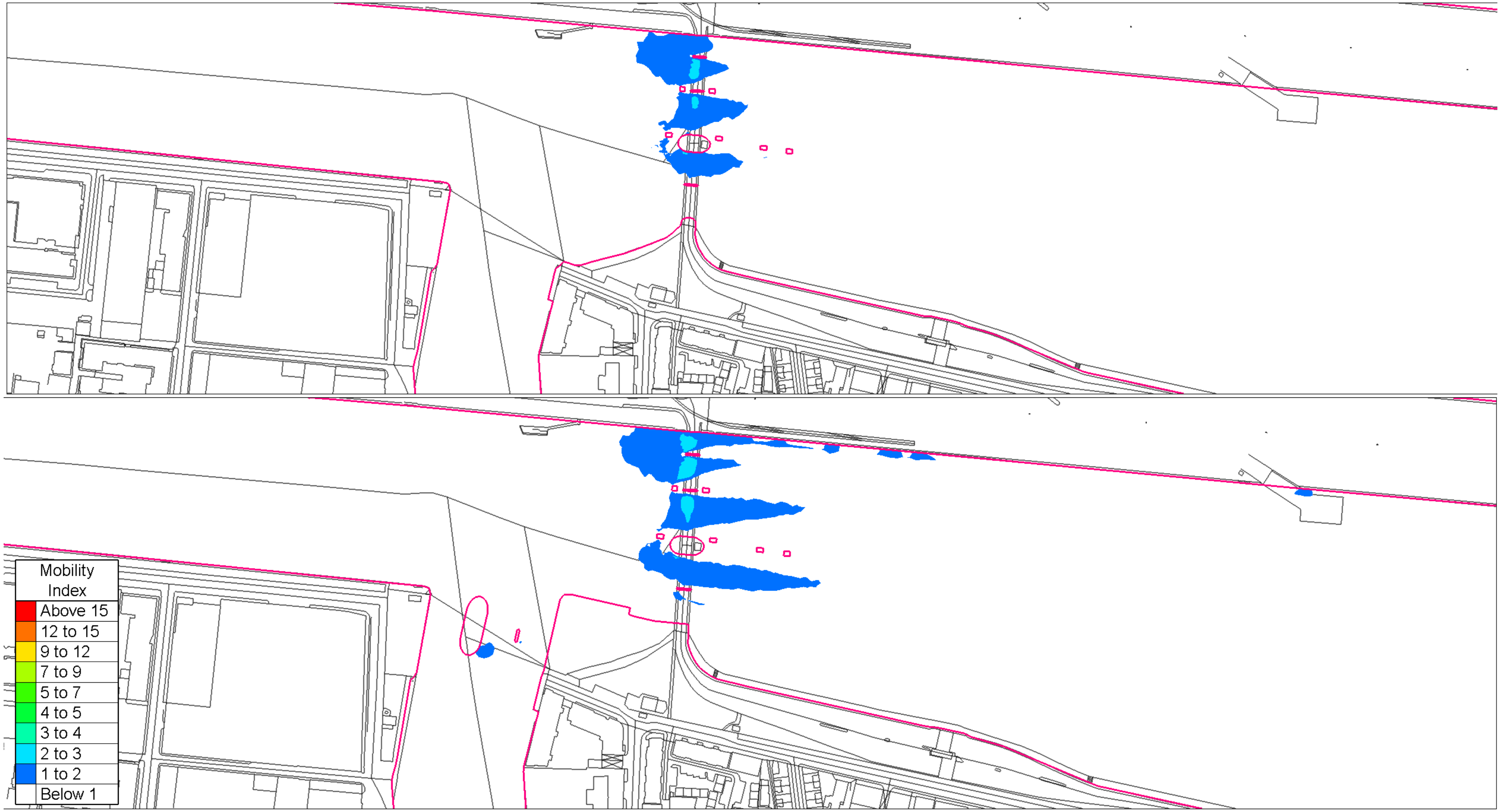

Figure 25 Silt Mobility Map at Mid-Ebb for existing and proposed cases – Simulation 1 (Mobility Index < 1 silt is not mobile)

Simulation 2

200year Tidal Surge event (HW 3.11m OD, tidal range 4.34m)

Combined with annual average flows in the Dodder and Liffey Rivers of 2.7cumec and 20 cumec respectively

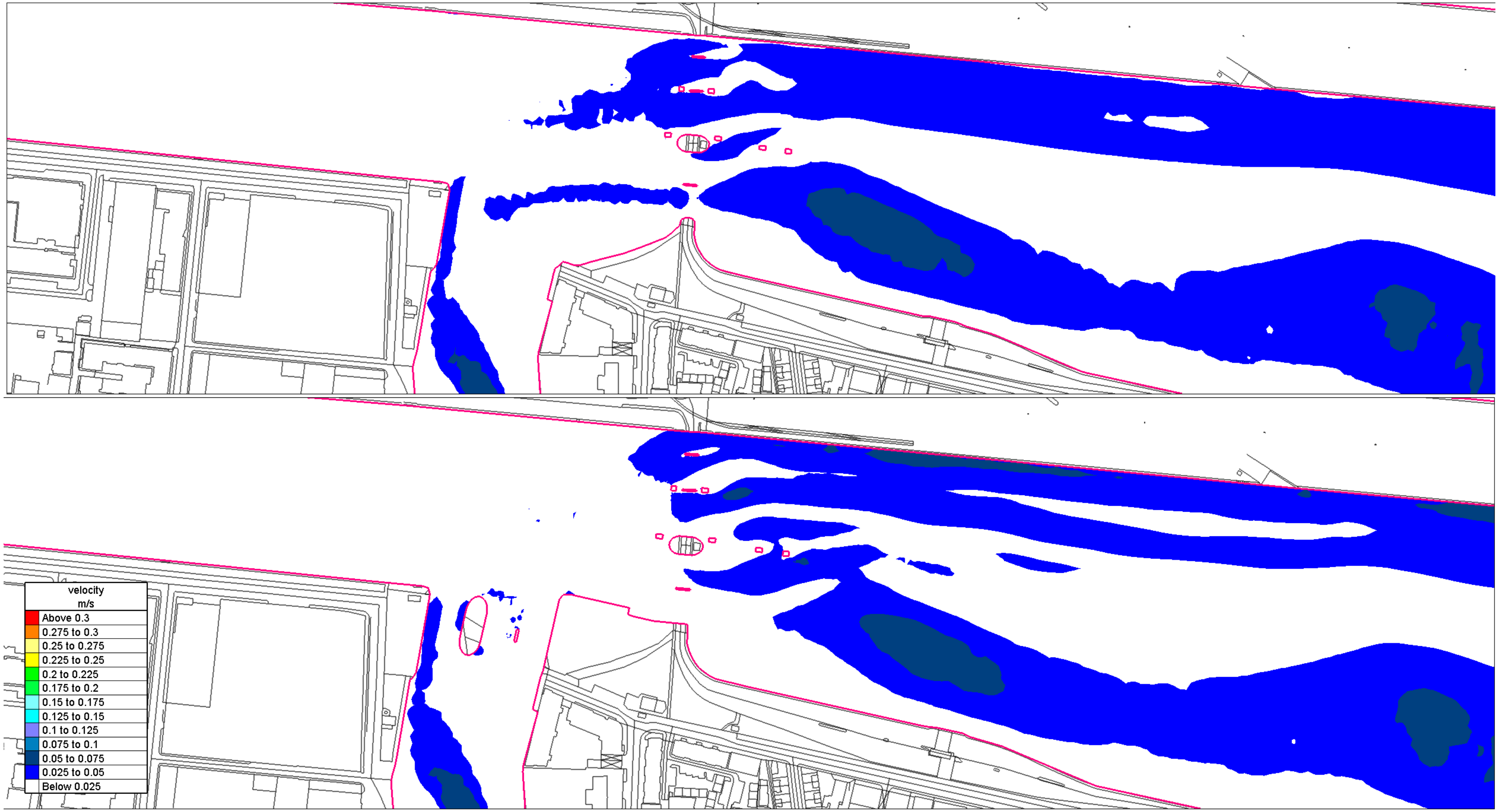

Figure 26 Computed Velocity Magnitudes at Low Water for existing and proposed cases – Simulation 2

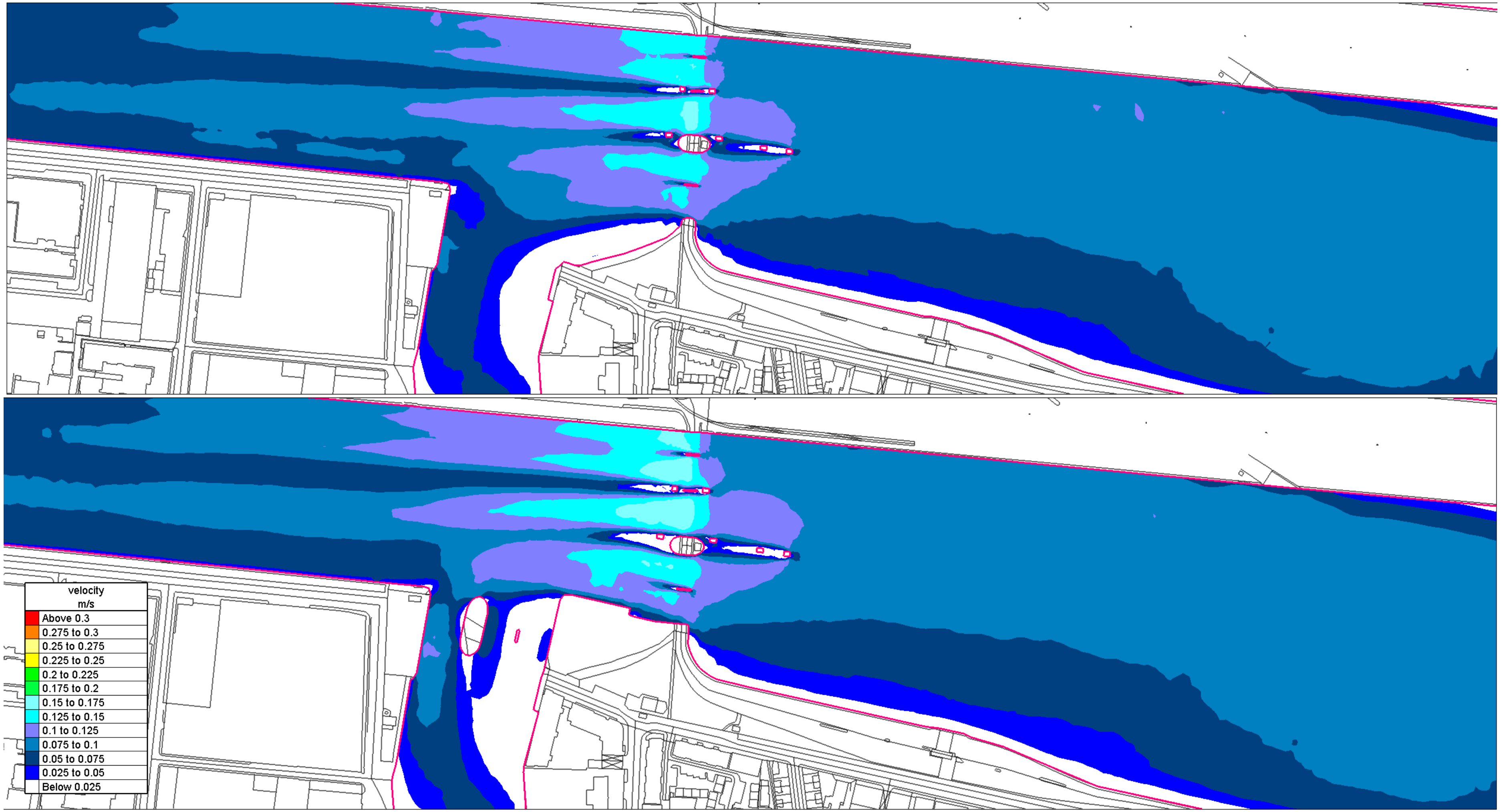

Figure 27 Computed Velocity Magnitudes at Mid-Flood for existing and proposed cases – Simulation 2

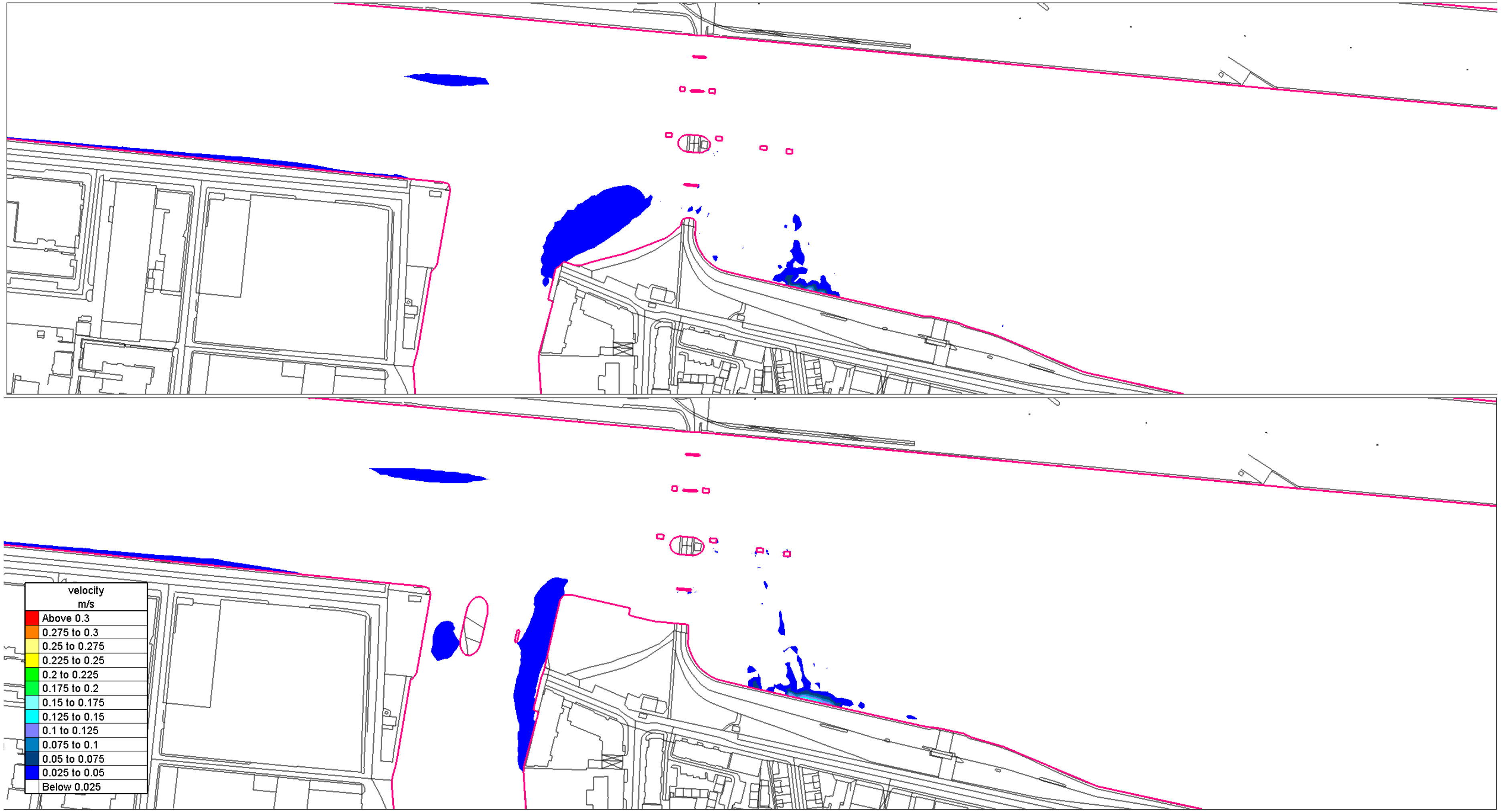

Figure 28 Computed Velocity Magnitudes at Highwater for existing and proposed cases – Simulation 2

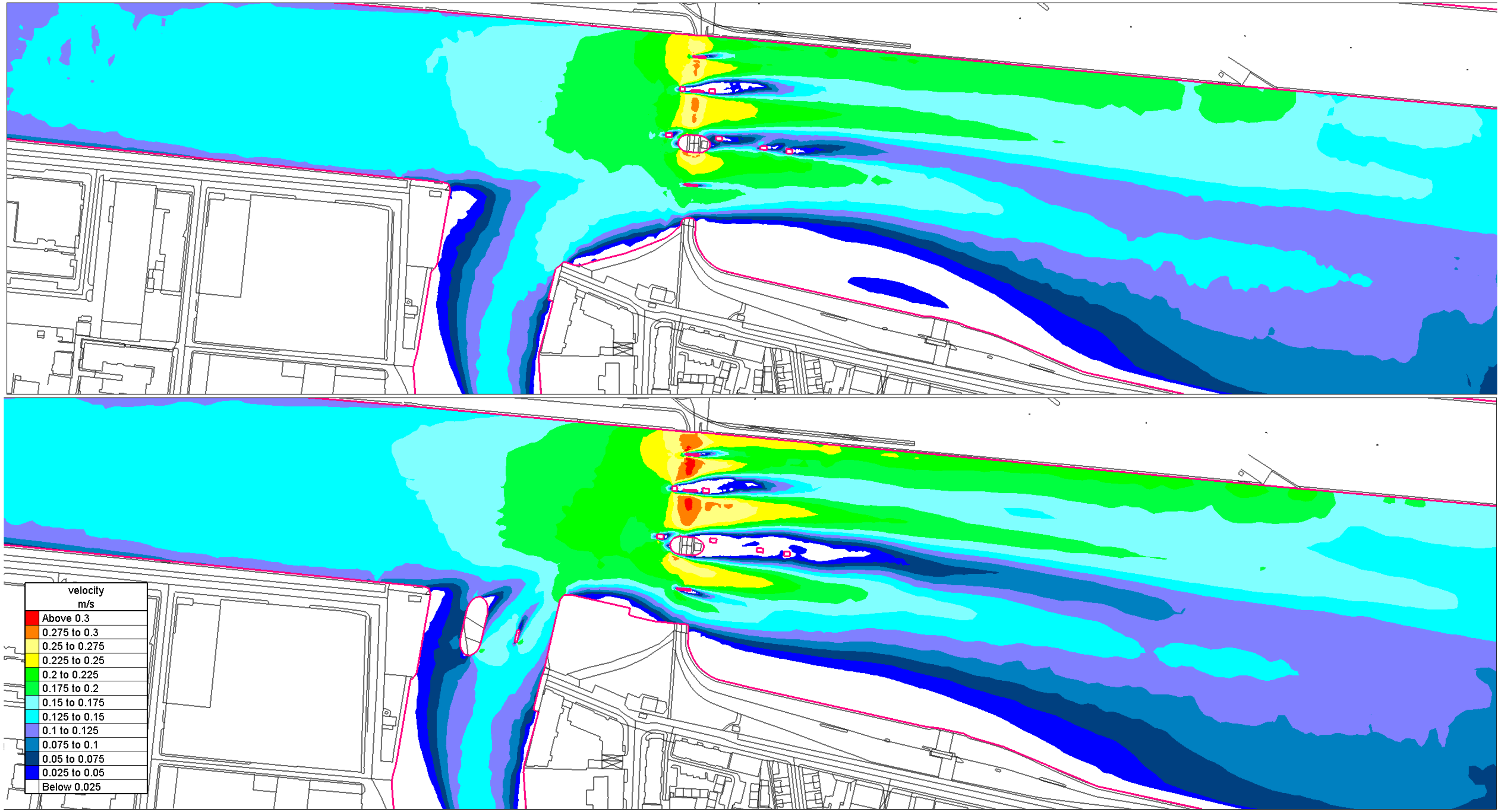

Figure 29 Computed Velocity Magnitudes at Mid-Ebb for existing and proposed cases – Simulation 2

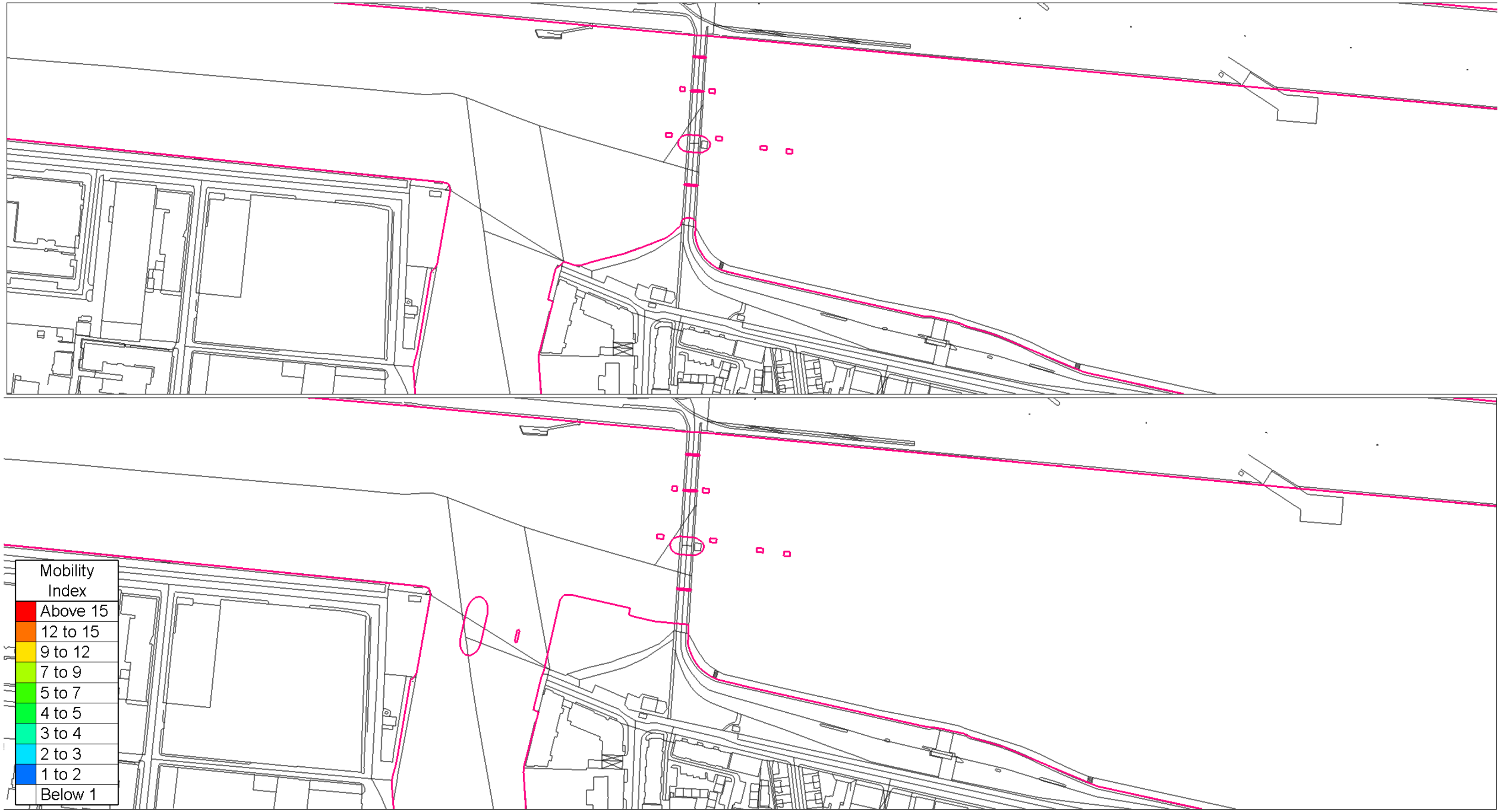

Figure 30 Silt Mobility Map at Low Water for existing and proposed cases – Simulation 2 (Mobility Index < 1 silt is not Mobile)

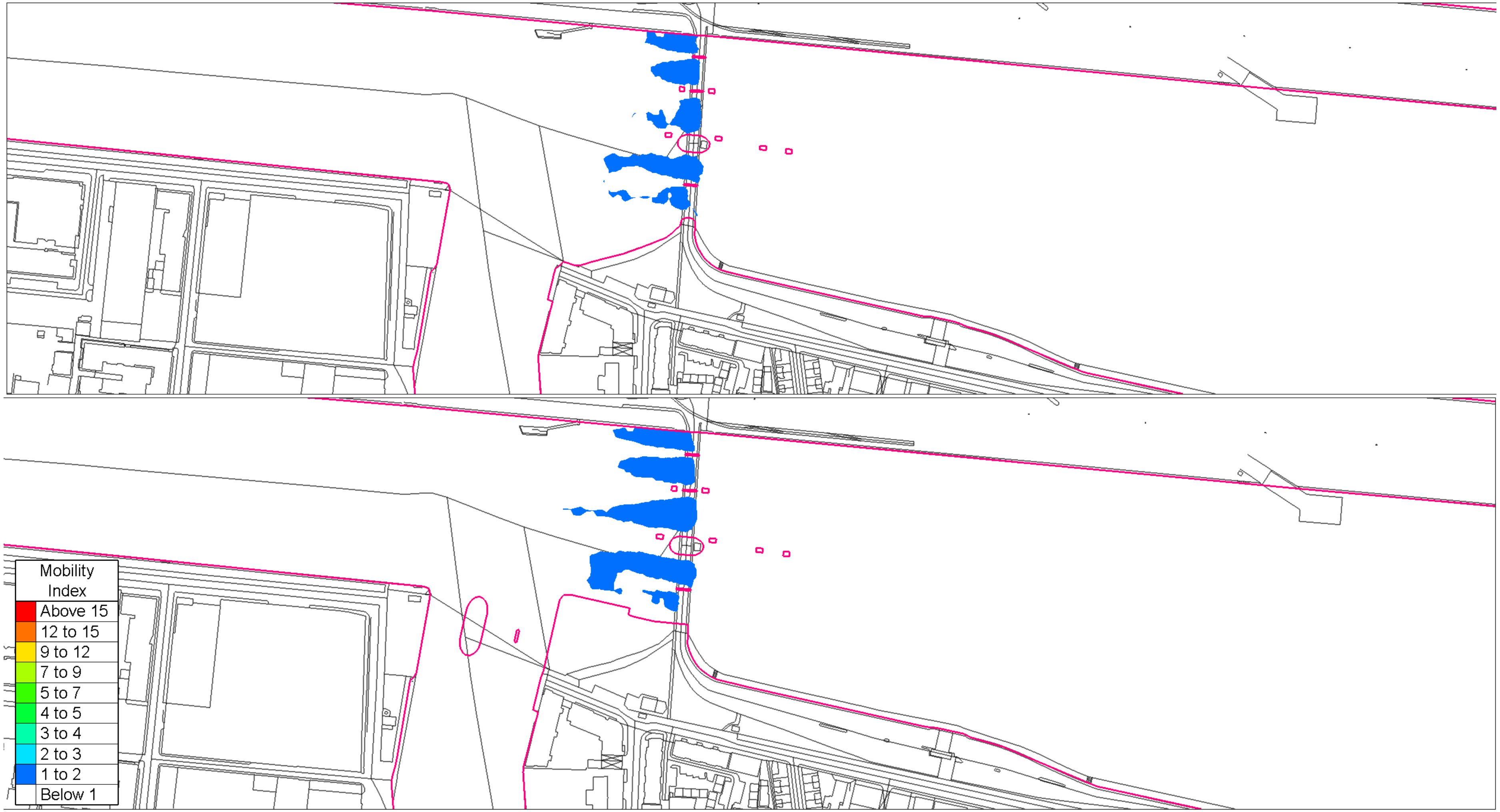

Figure 31 Silt Mobility Map at Mid-Flood for existing and proposed cases – Simulation 2 (Mobility Index < 1 silt is not Mobile)

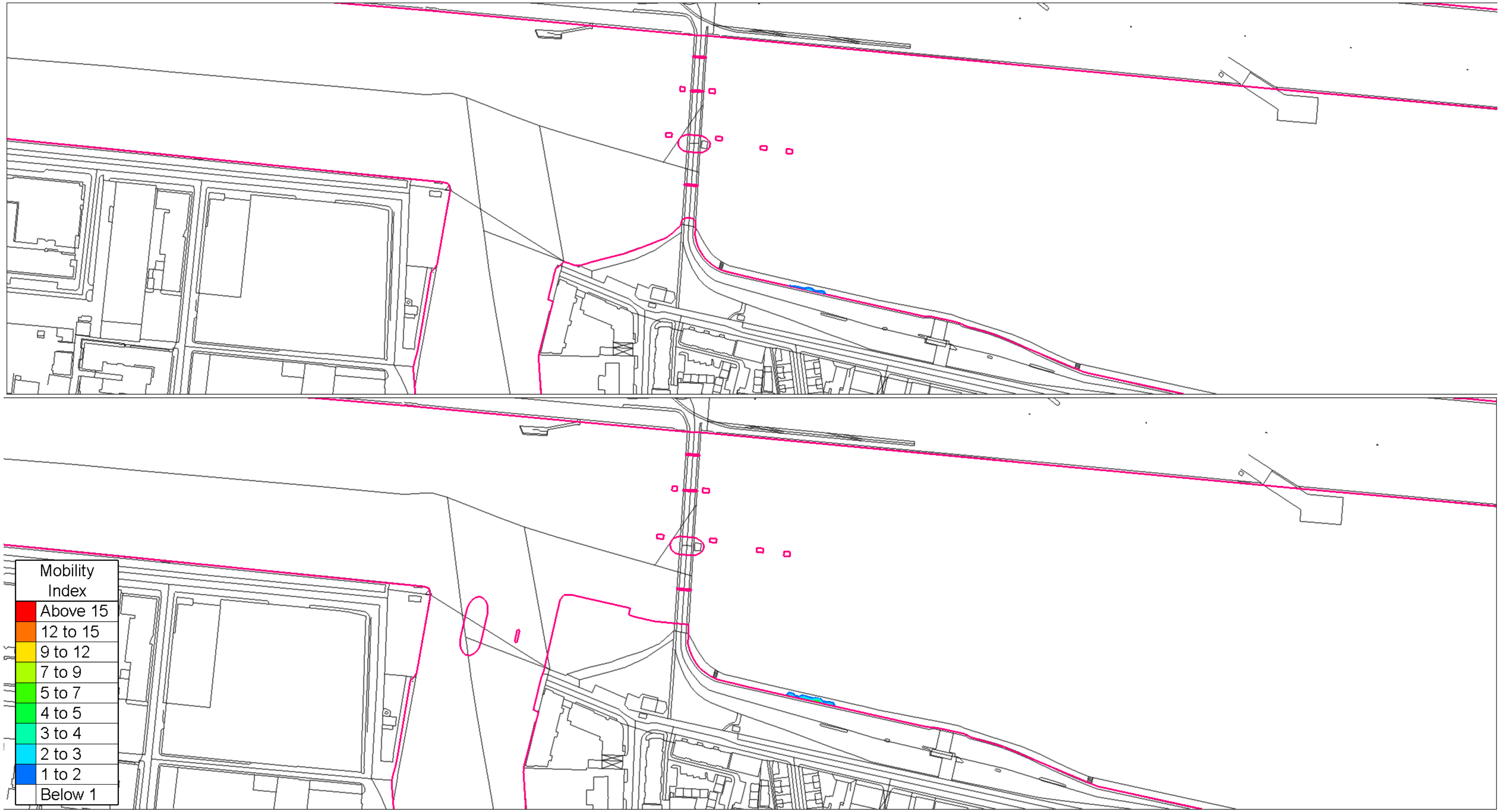

Figure 32 Silt Mobility Map at Highwater for existing and proposed cases – Simulation 2 (Mobility Index < 1 silt is not Mobile)

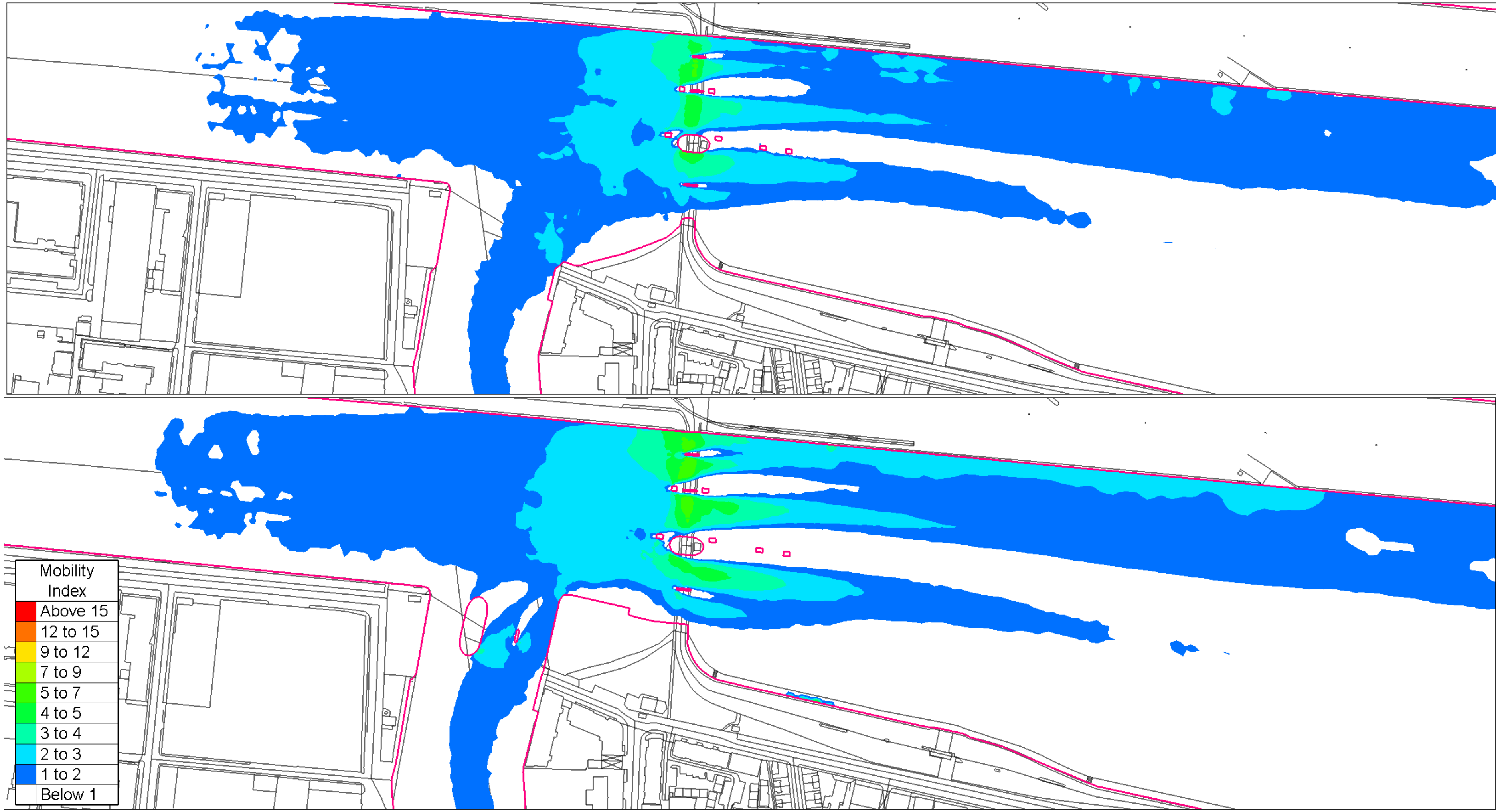

Figure 33 Silt Mobility Map at Mid-Ebb for existing and proposed cases – Simulation 2 (Mobility Index < 1 silt is not Mobile)

Simulation 3

Simulation Fluvial Flood in Dodder of 110cumec

Combined with mean Spring Tide (HW 1.75mOD, tidal range = 3.3) and mean River Liffey Inflow of 20cumec

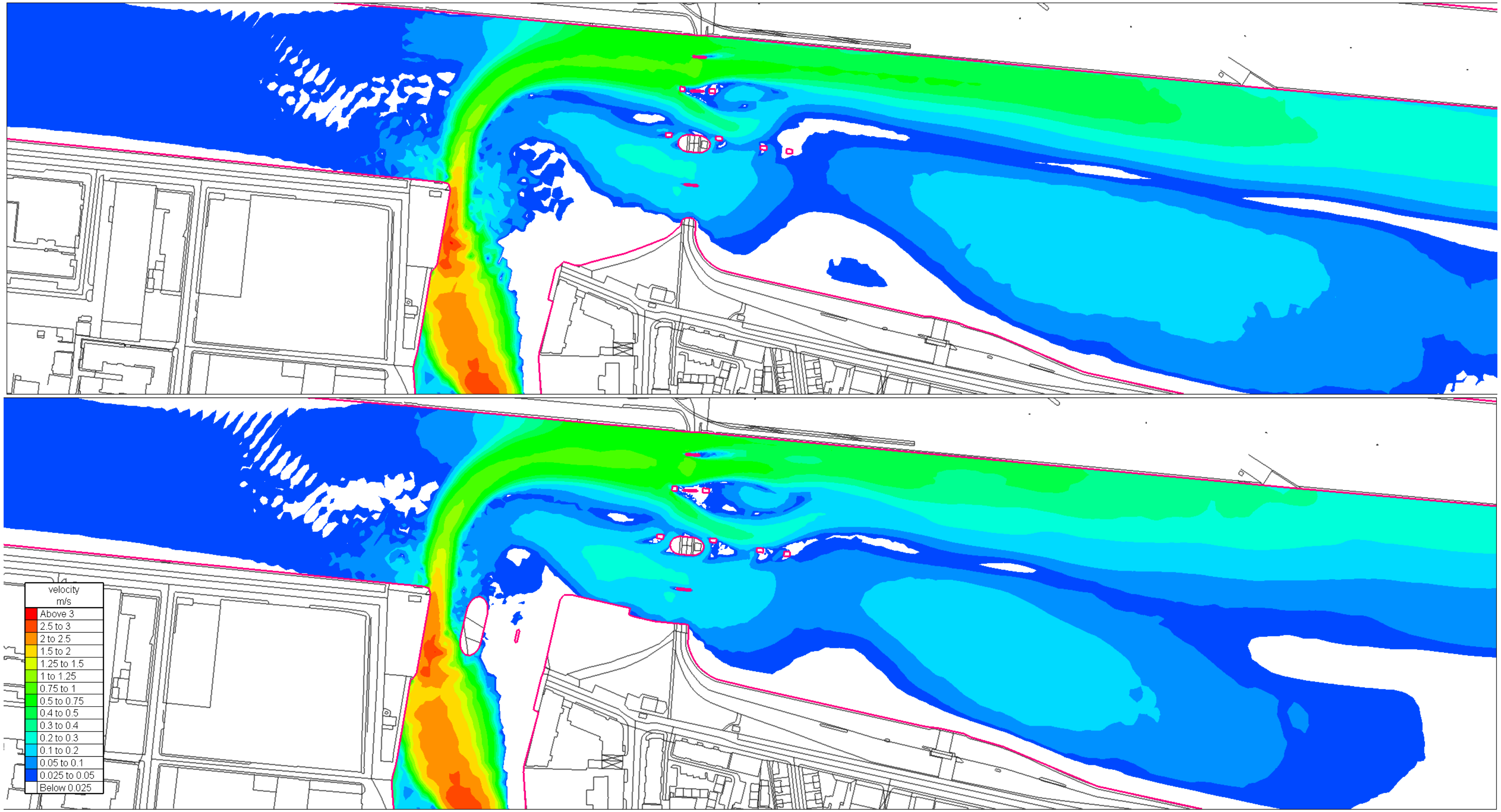

Figure 34 Computed Velocity Magnitudes at Low Water for existing and proposed cases – Simulation 3

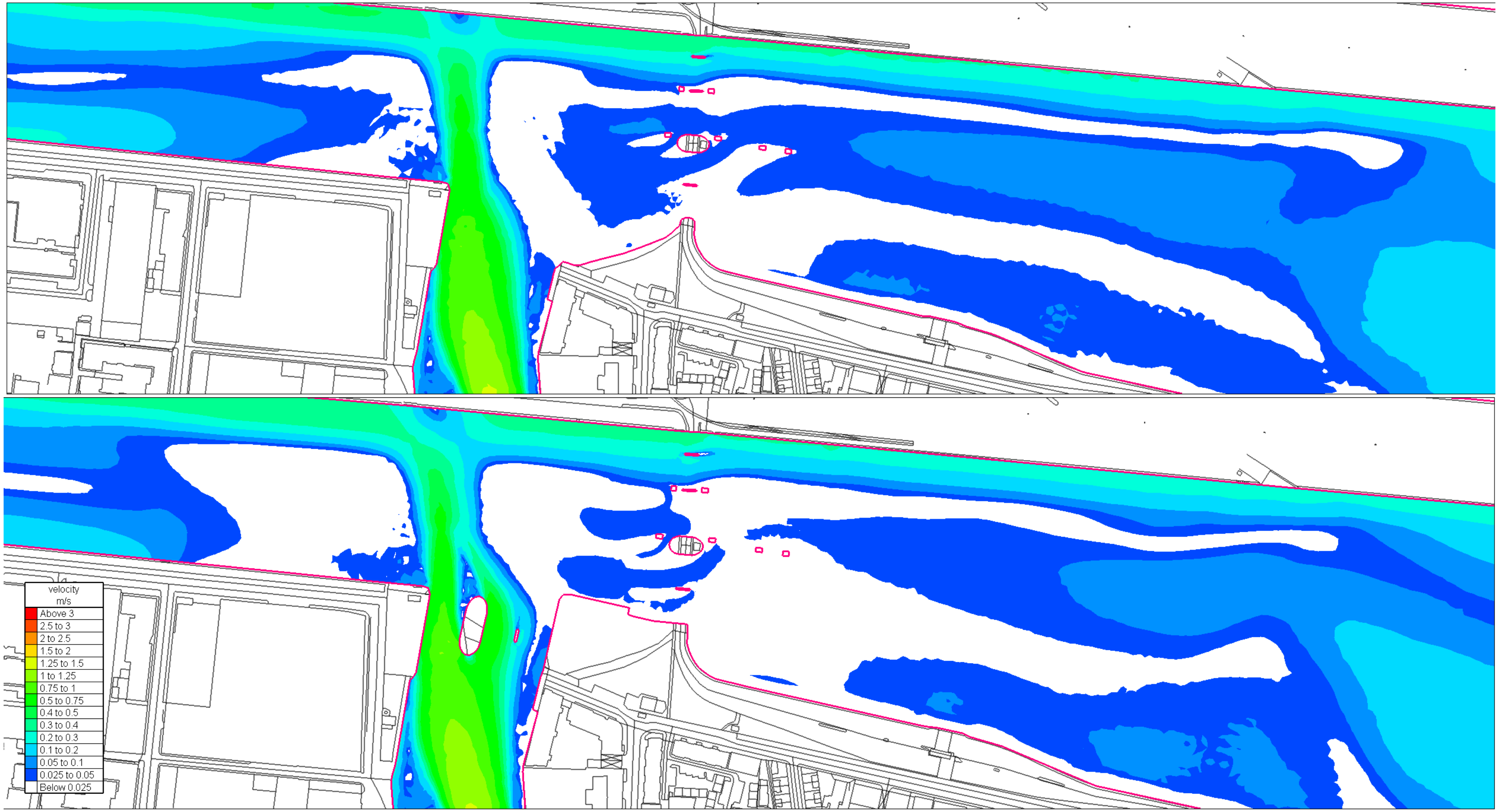

Figure 35 Computed Velocity Magnitudes at Mid-Flood for existing and proposed cases – Simulation 3

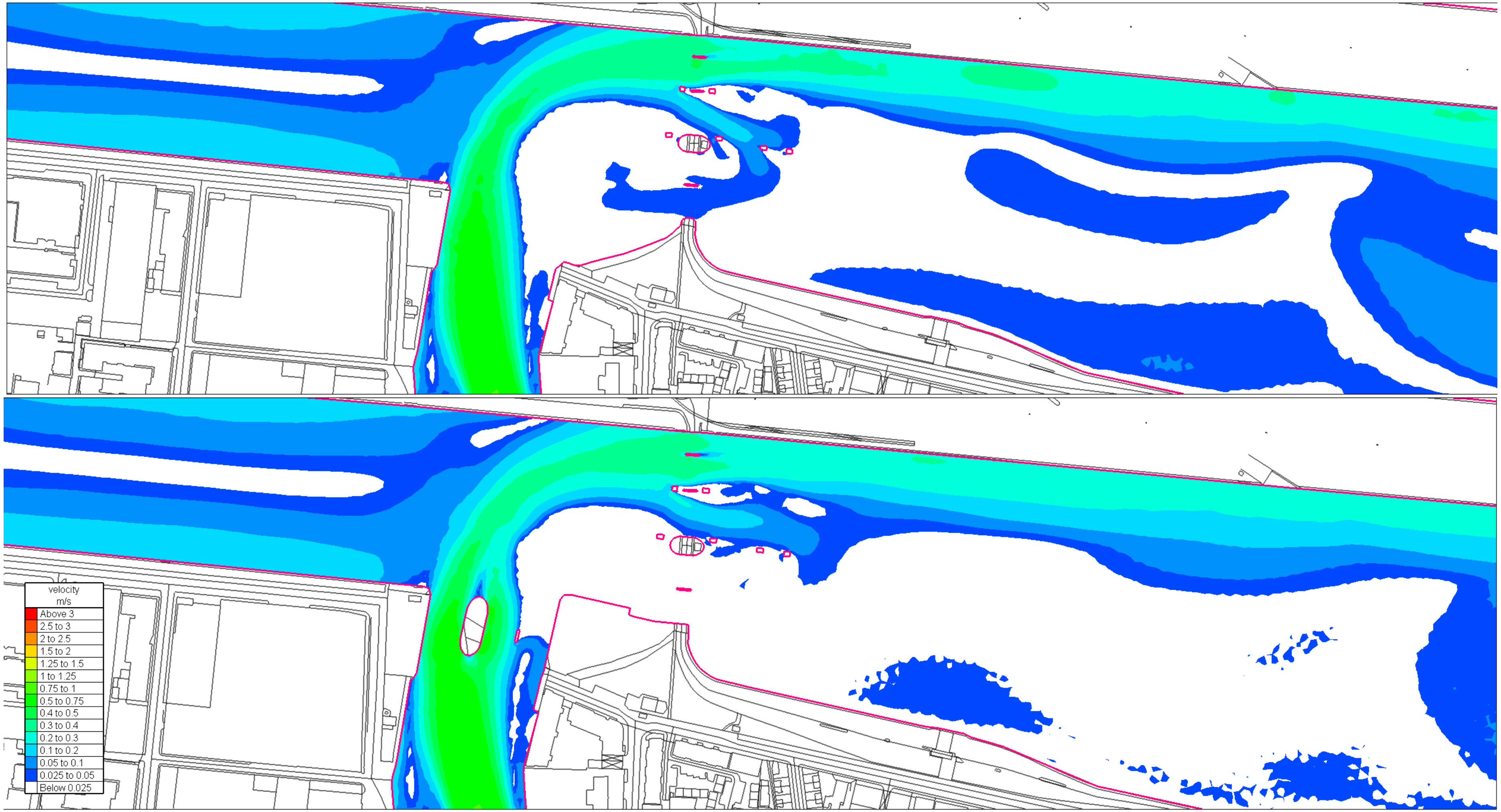

Figure 36 Computed Velocity Magnitudes at Highwater for existing and proposed cases – Simulation 3

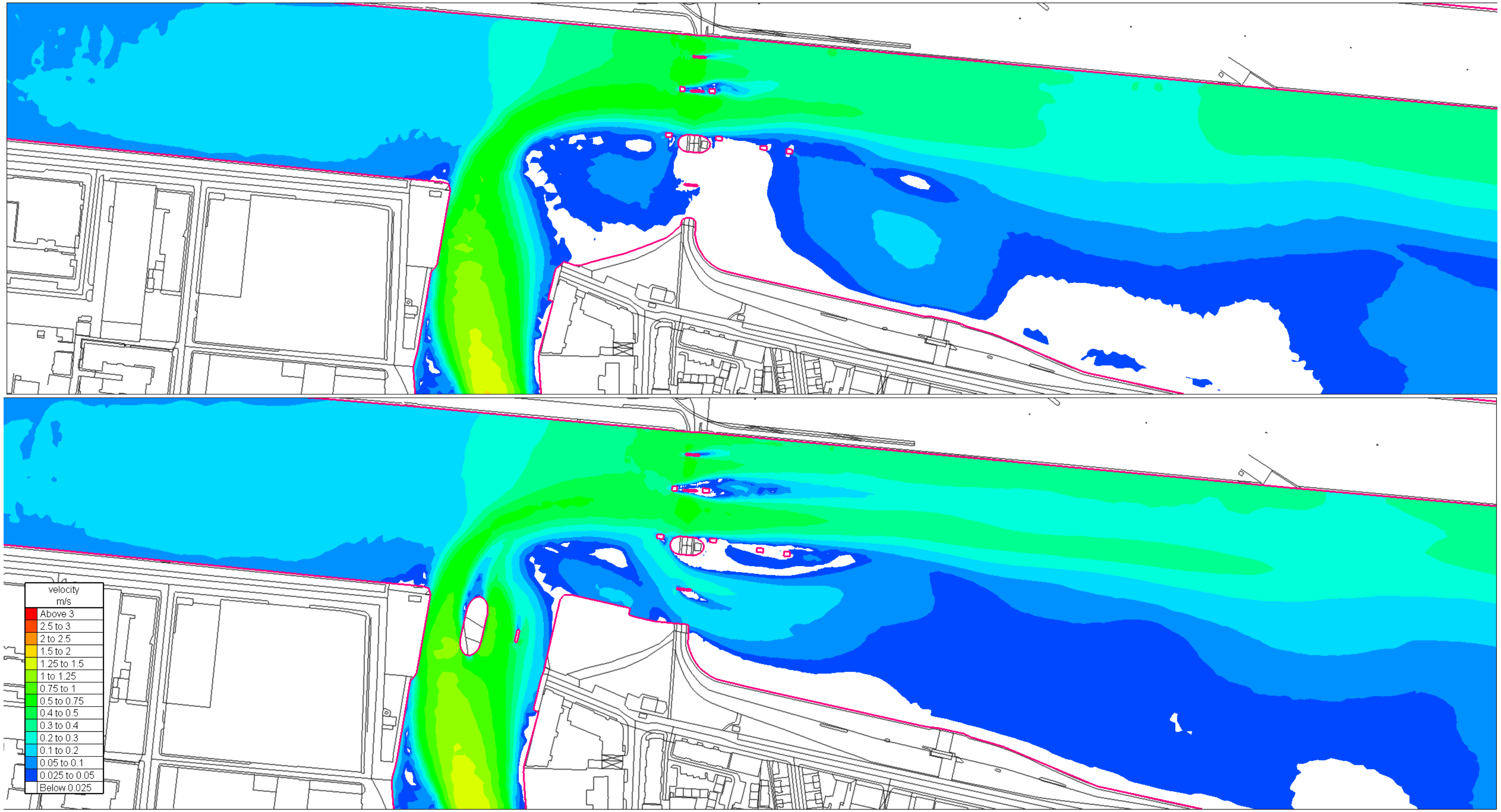

Figure 37 Computed Velocity Magnitudes at Mid-Ebb for existing and proposed cases – Simulation 3

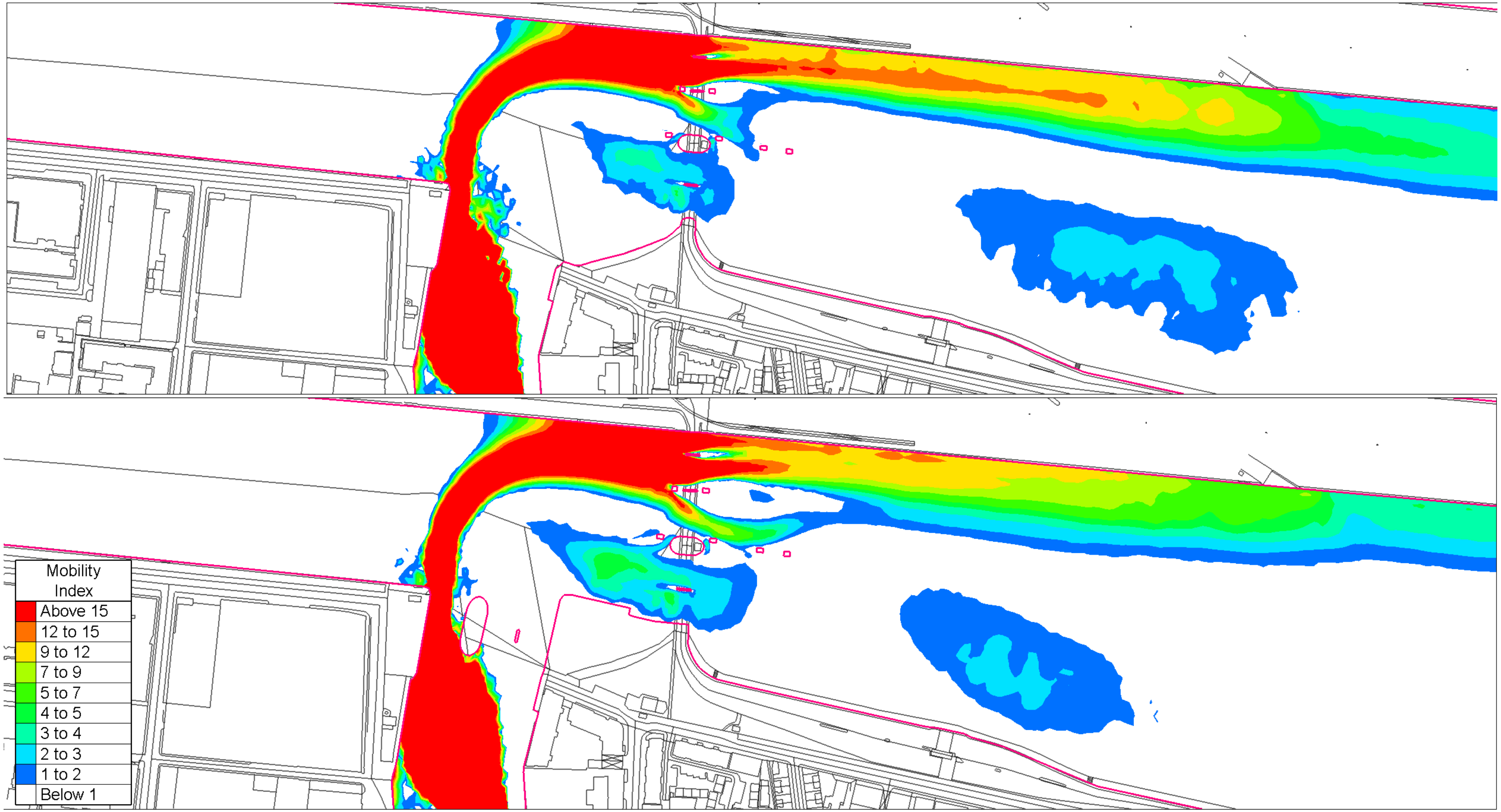

Figure 38 Computed Silt Mobility Map at Low water for existing and proposed cases – Simulation 3 (Mobility Index < 1 silt is not mobile)

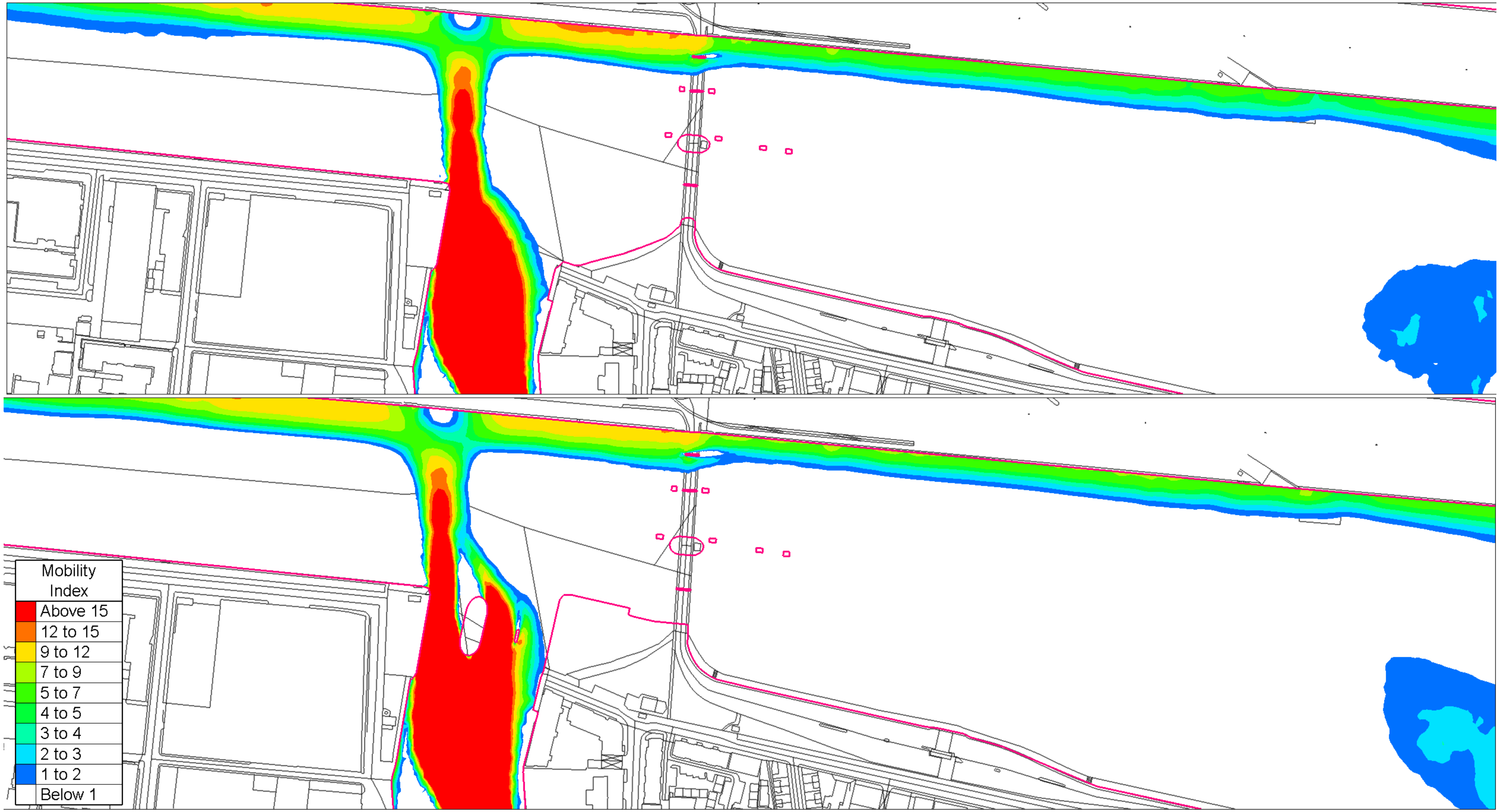

Figure 39 Computed Silt Mobility Map at Mid-Flood for existing and proposed cases – Simulation 3 (Mobility Index < 1 silt is not mobile)

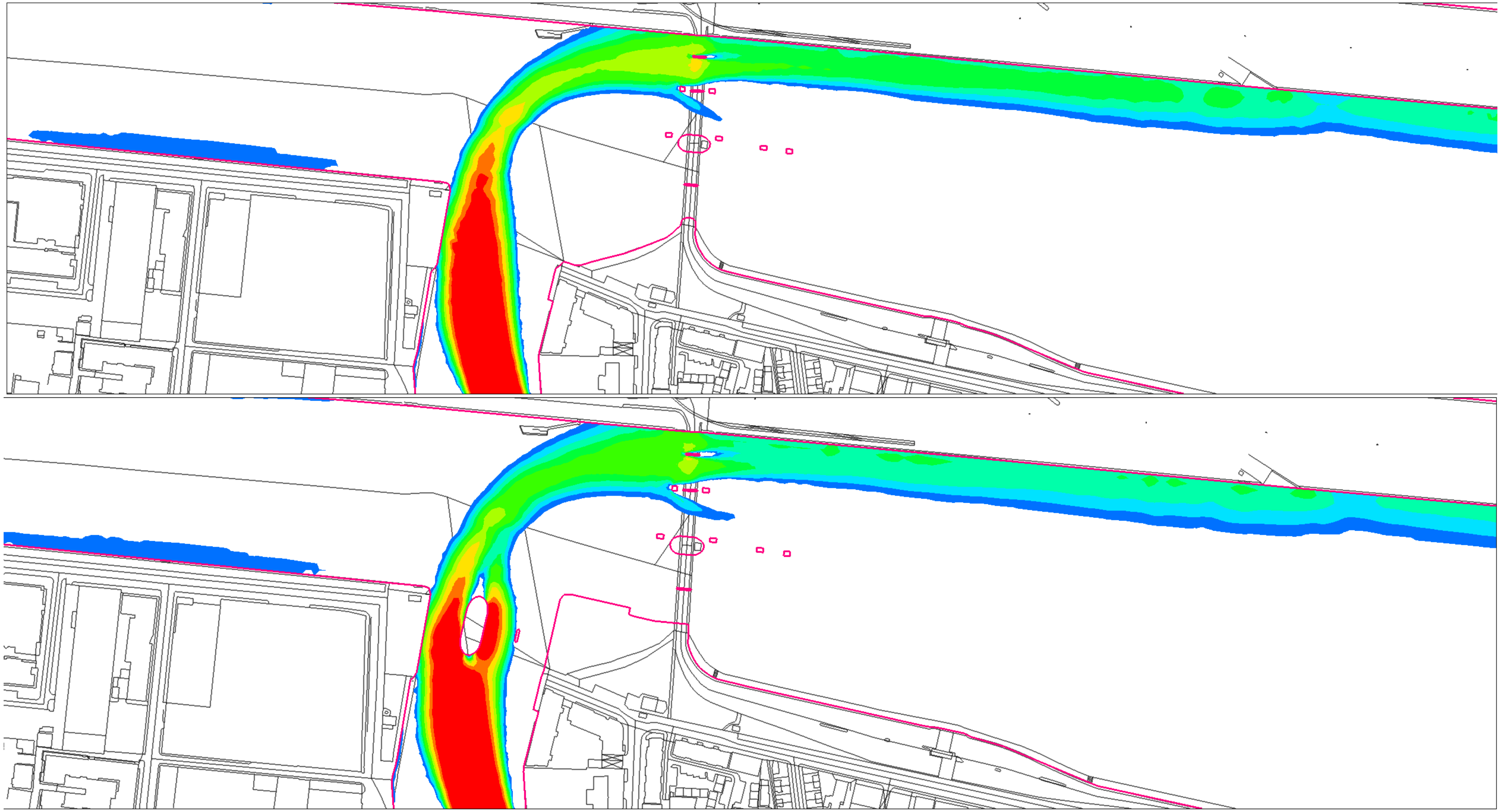

Figure 40 Computed Silt Mobility Map at Highwater for existing and proposed cases – Simulation 3 (Mobility Index < 1 silt is not mobile)

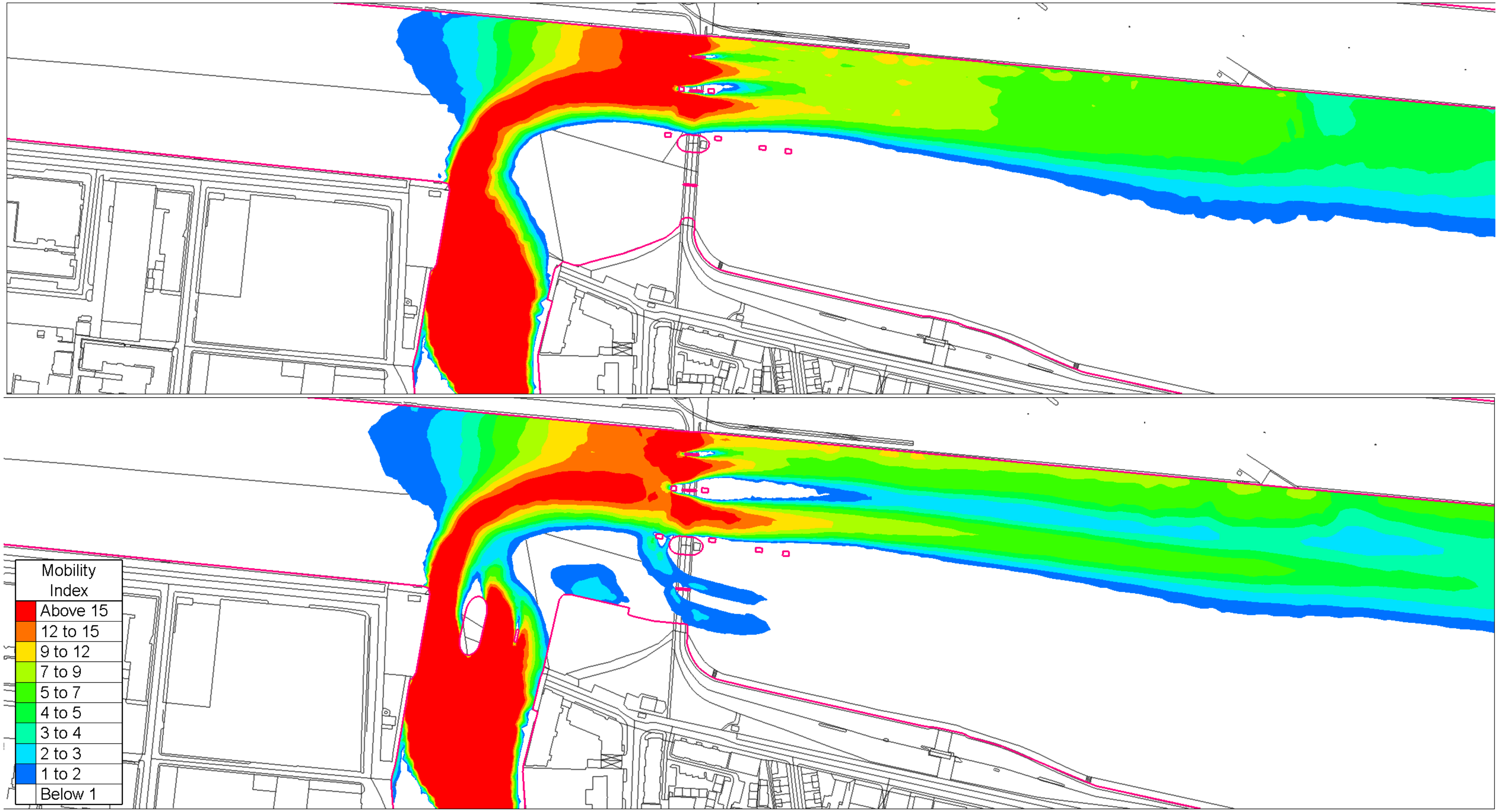

Figure 41 Computed Silt Mobility Map at Mid-Ebb for existing and proposed cases – Simulation 3 (Mobility Index < 1 silt is not mobile)

Simulation 4

Simulation 100yearFlood in River Liffey of 265cumec

Combined with mean Spring Tide (HW 1.75mOD, tidal range = 3.3) and average Dodder Flow of 2.7cumec

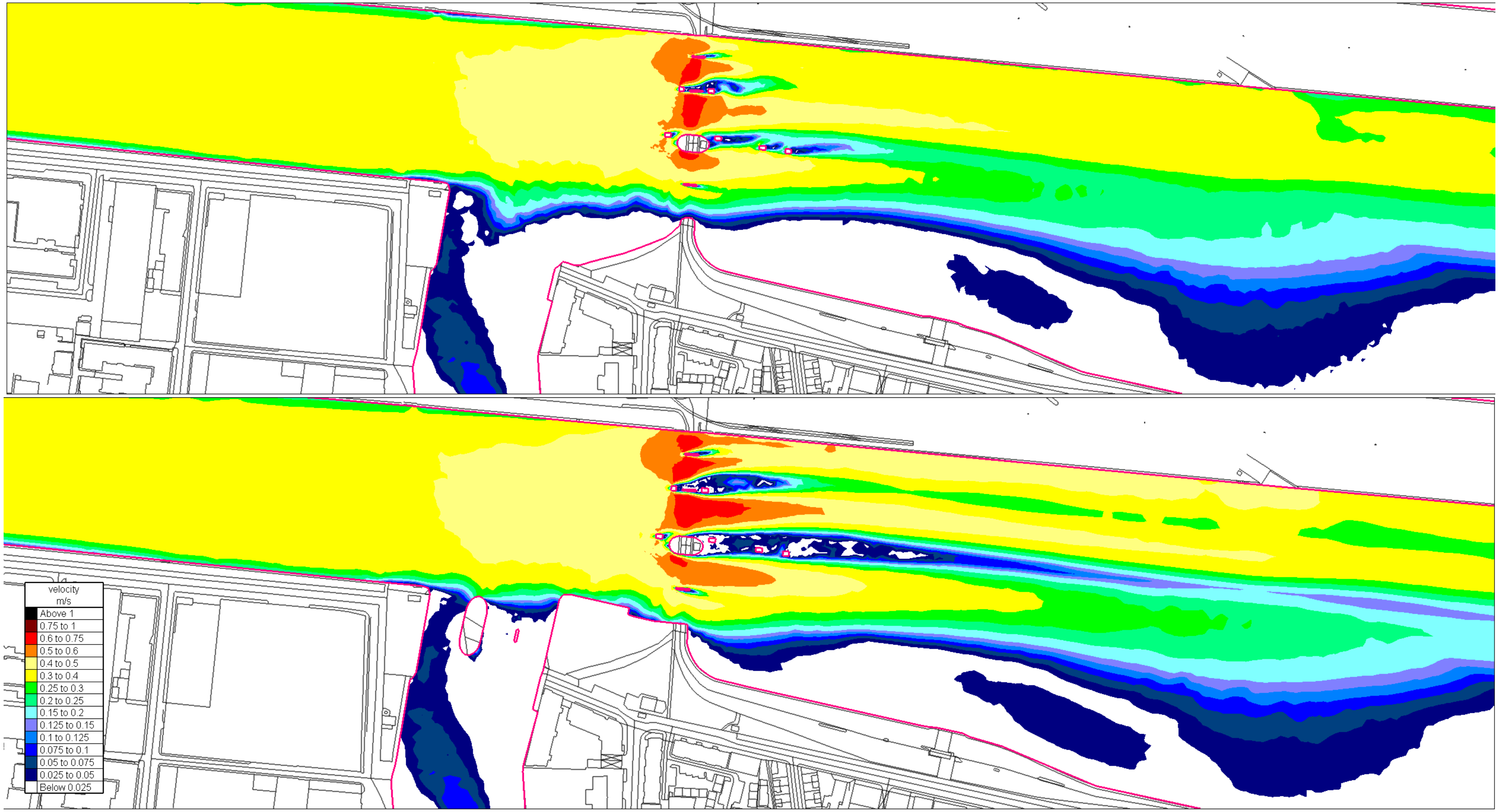

Figure 42 Computed Velocity Magnitudes at Low Water for existing and proposed cases – Simulation 4

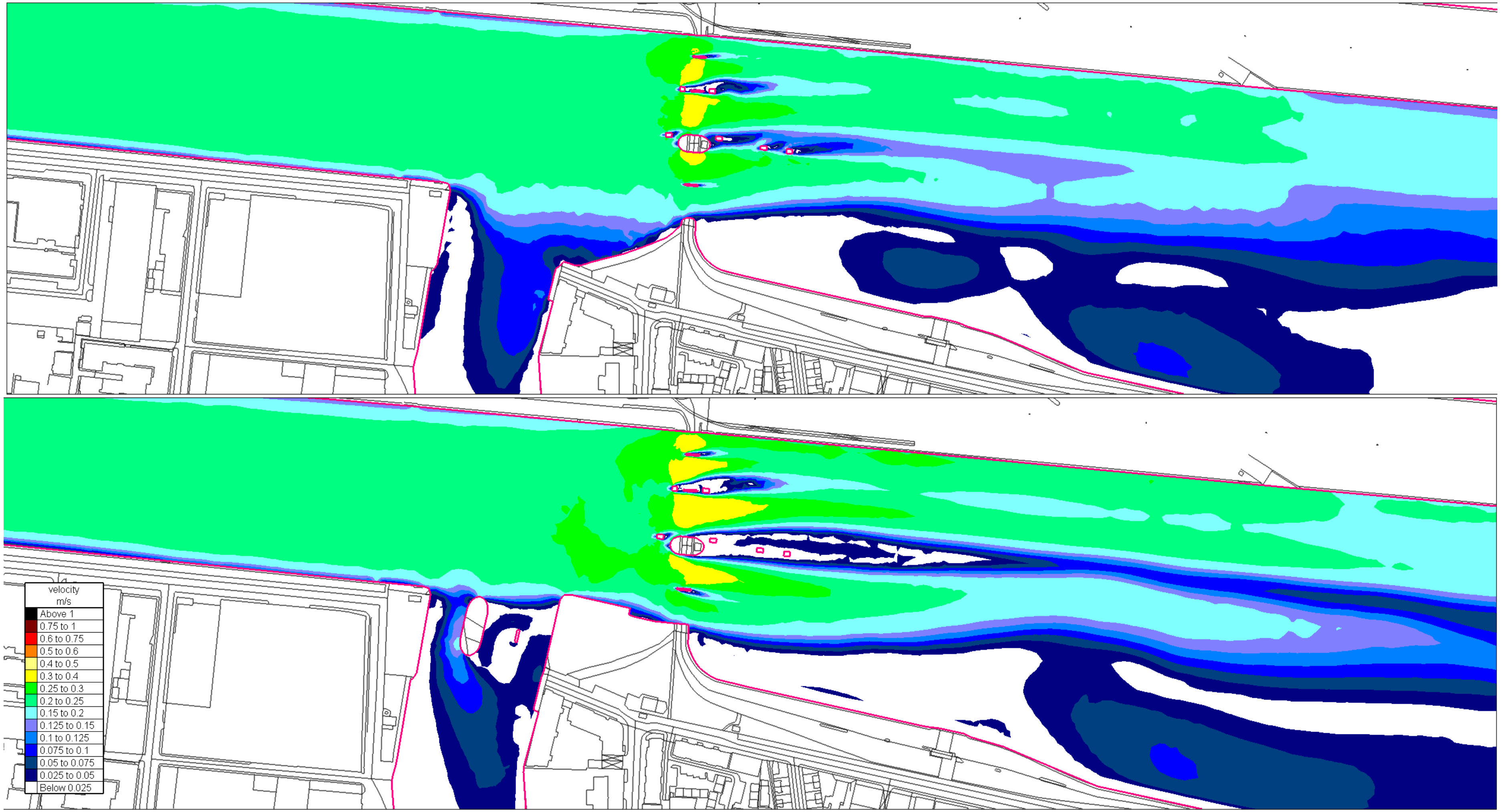

Figure 43 Computed Velocity Magnitudes at Mid-Flood for existing and proposed cases – Simulation 4

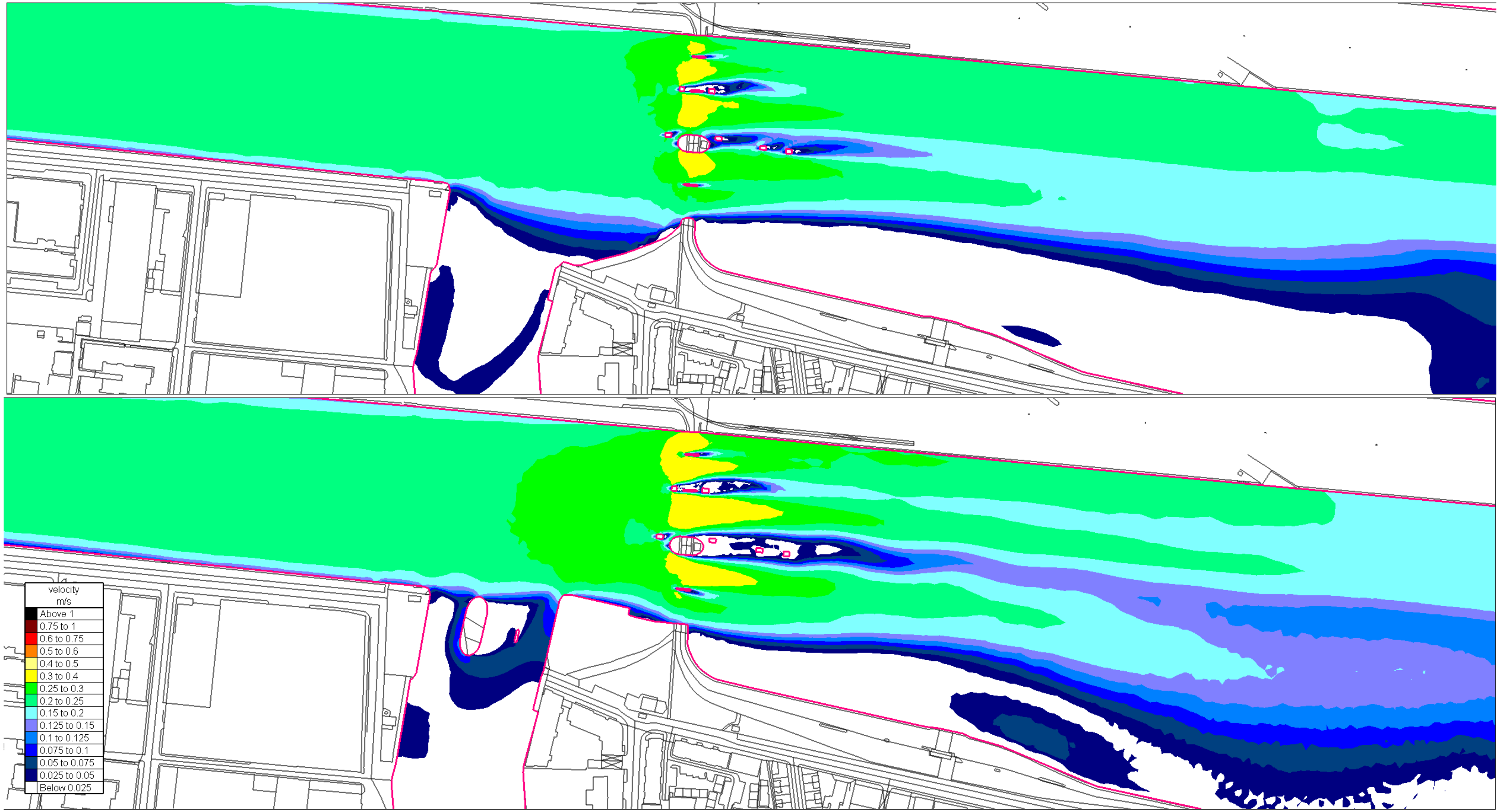

Figure 44 Computed Velocity Magnitudes at High Water for existing and proposed cases – Simulation 4

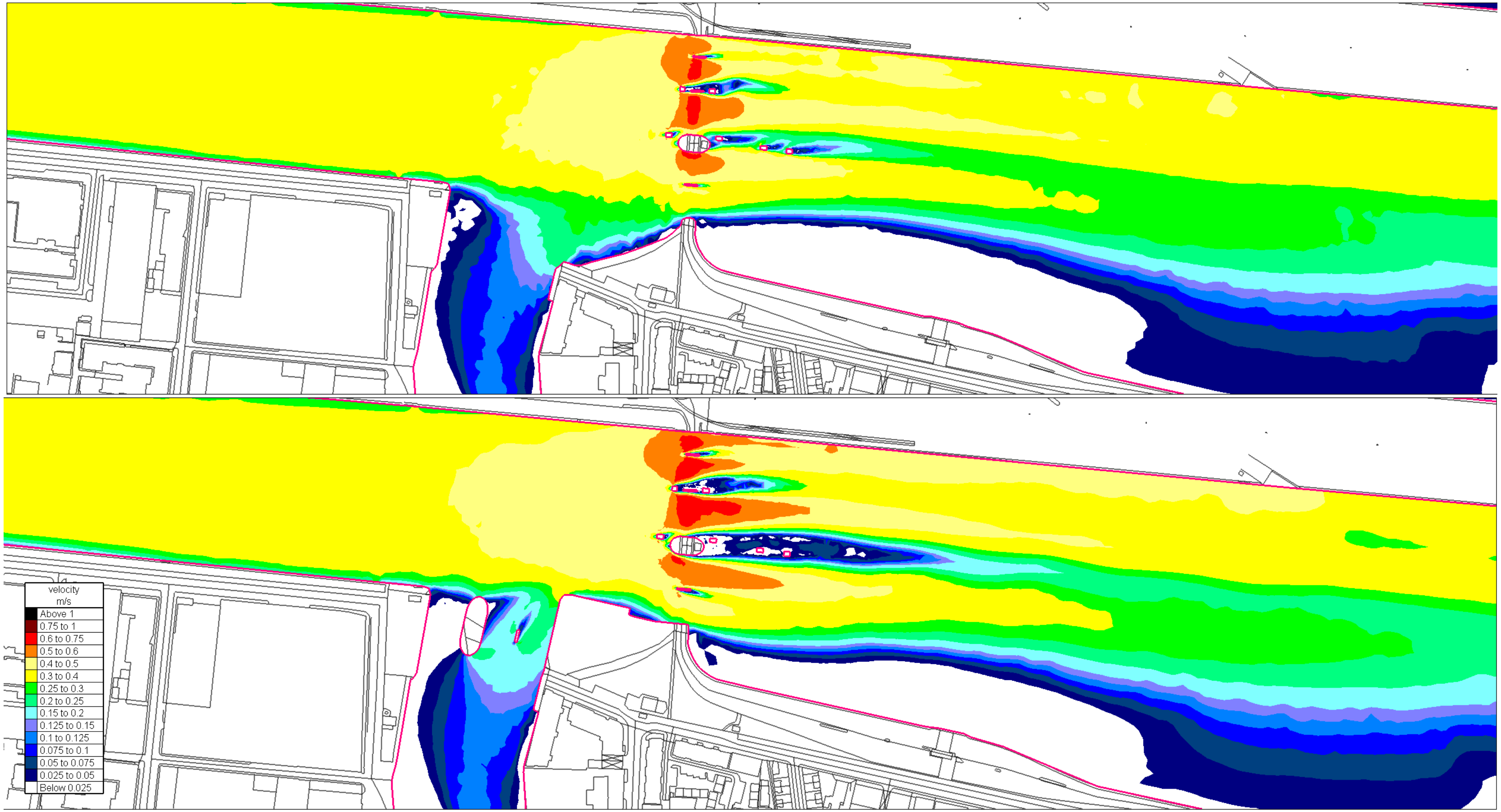

Figure 45 Computed Velocity Magnitudes at Mid-Ebb for existing and proposed cases – Simulation 4

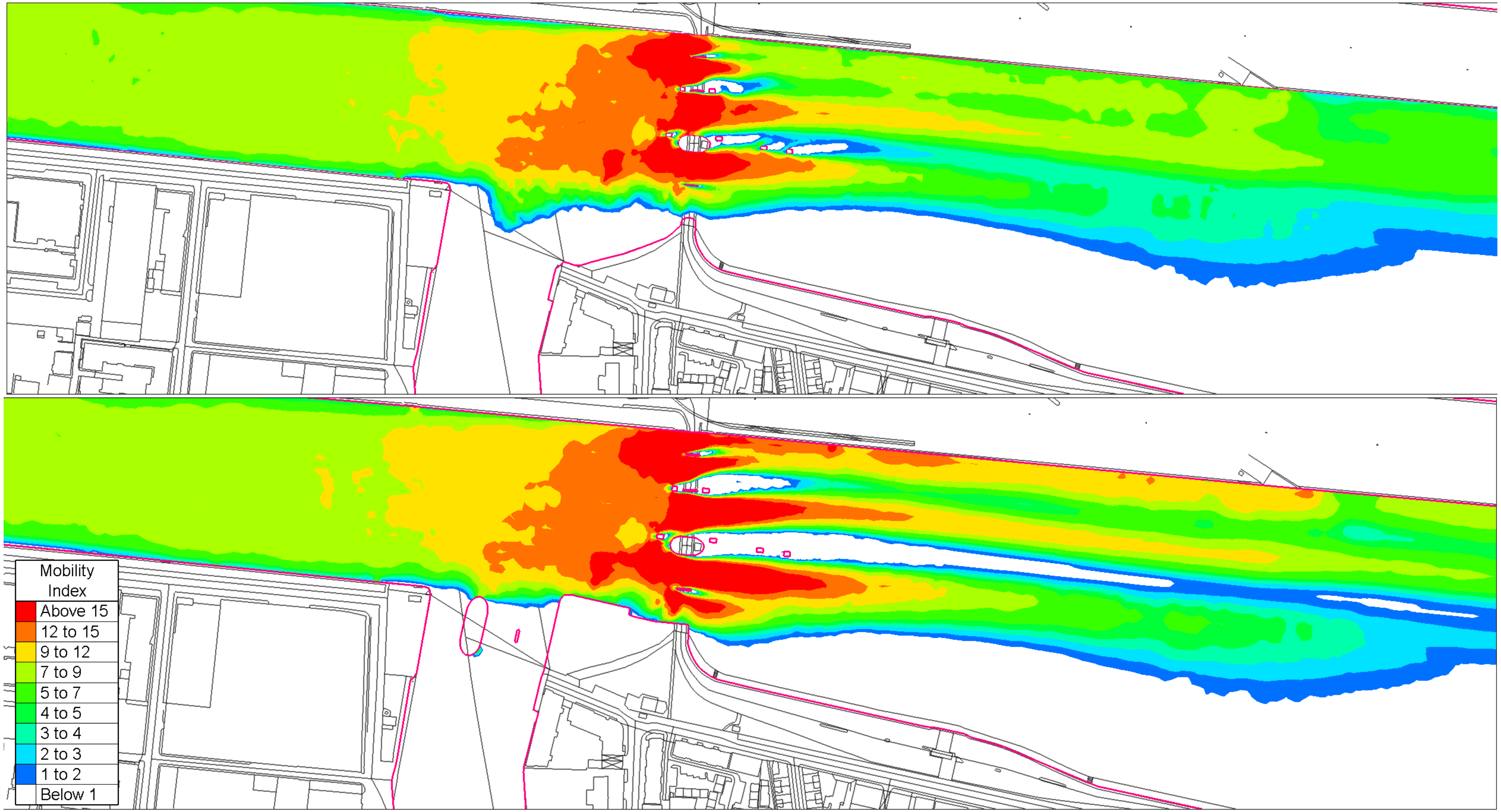

Figure 46 ***Computed Silt Mobility Map at Low Water for existing and proposed cases – Simulation 4 (Mobility Index < 1 silt is not mobile)***

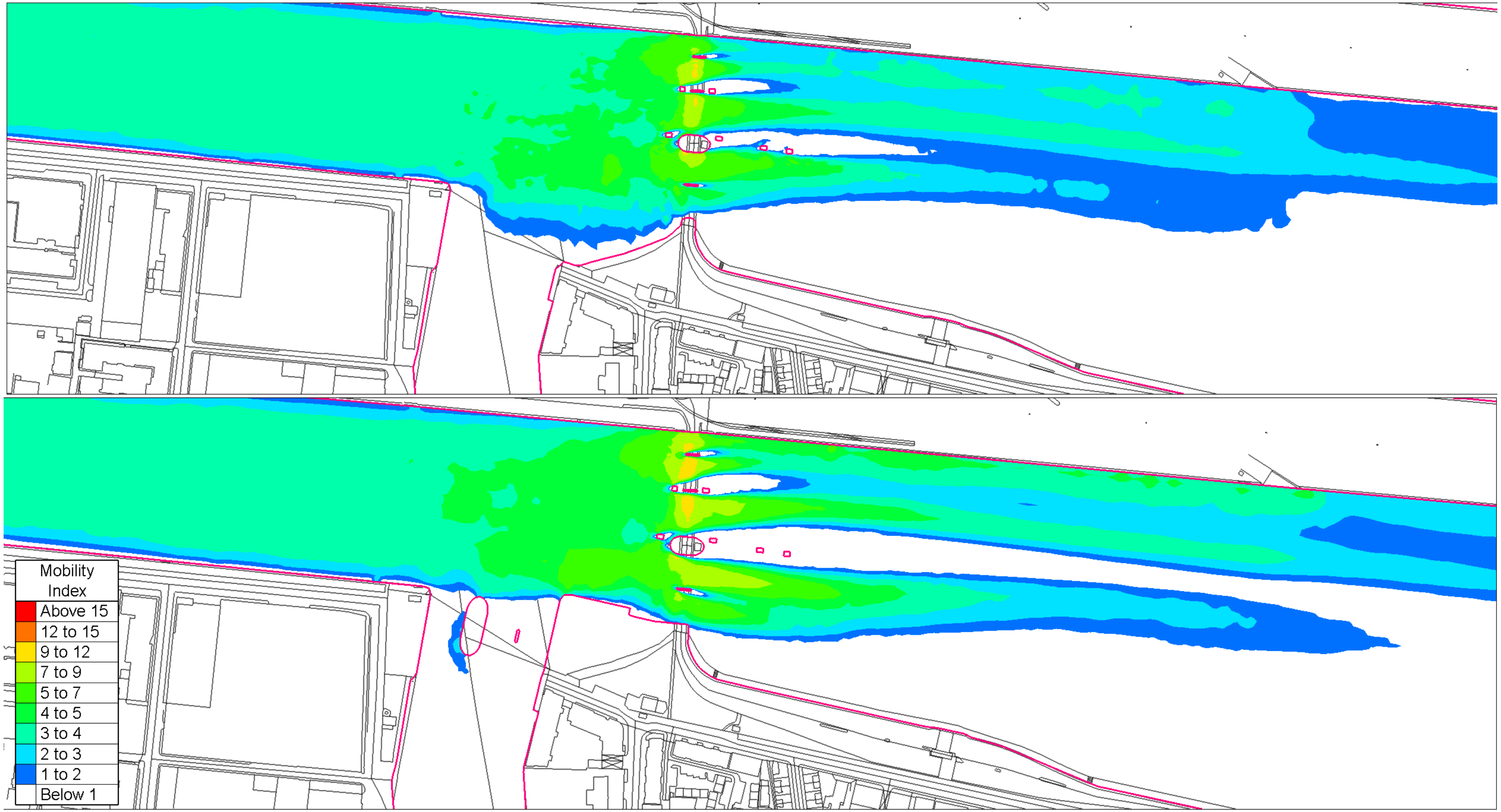

Figure 47 Computed Silt Mobility Map at Mid-Flood for existing and proposed cases – Simulation 4 (Mobility Index < 1 silt is not mobile)

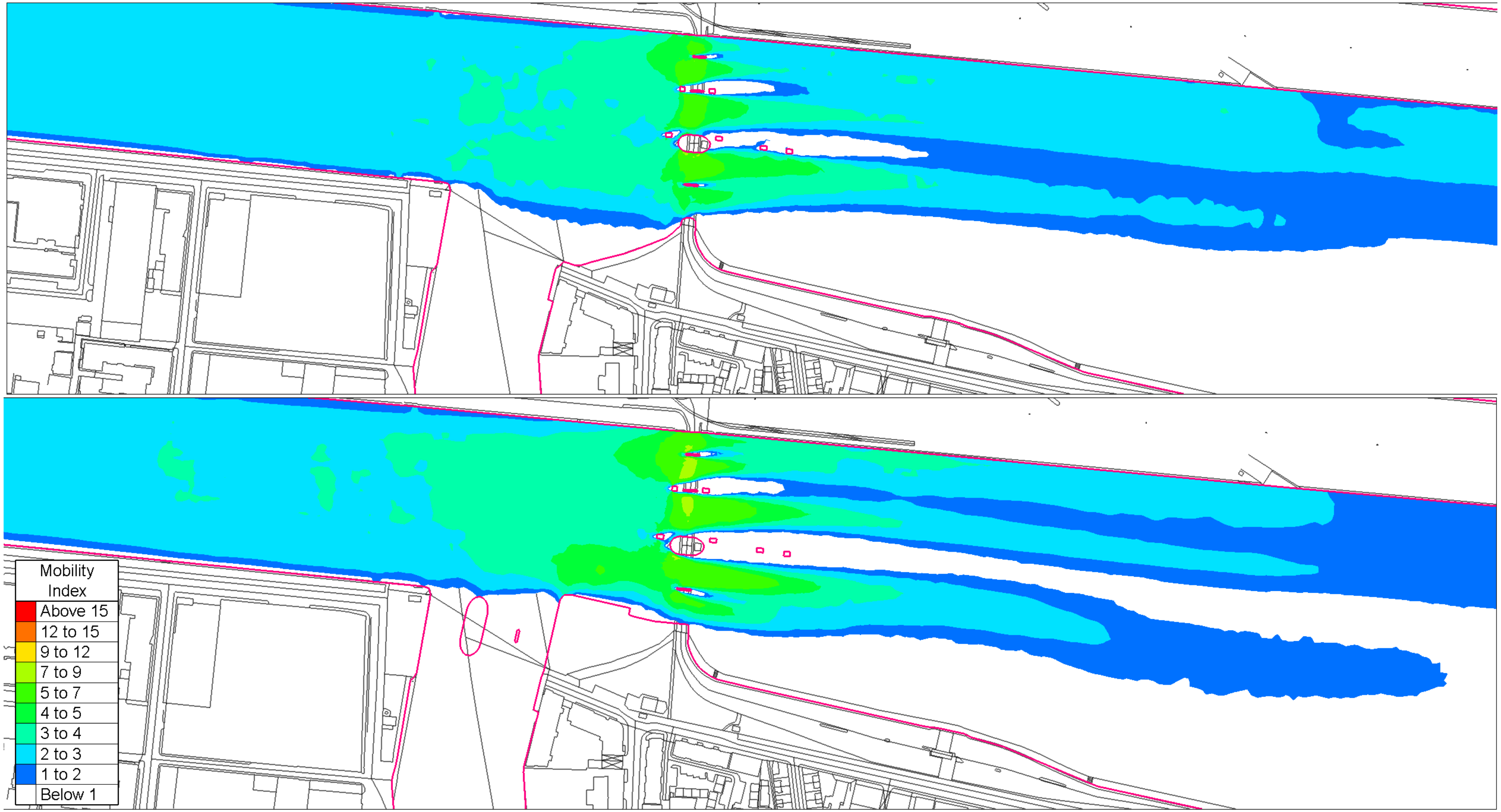

Figure 48 Computed Silt Mobility Map at High Water for existing and proposed cases – Simulation 4 (Mobility Index < 1 silt is not mobile)

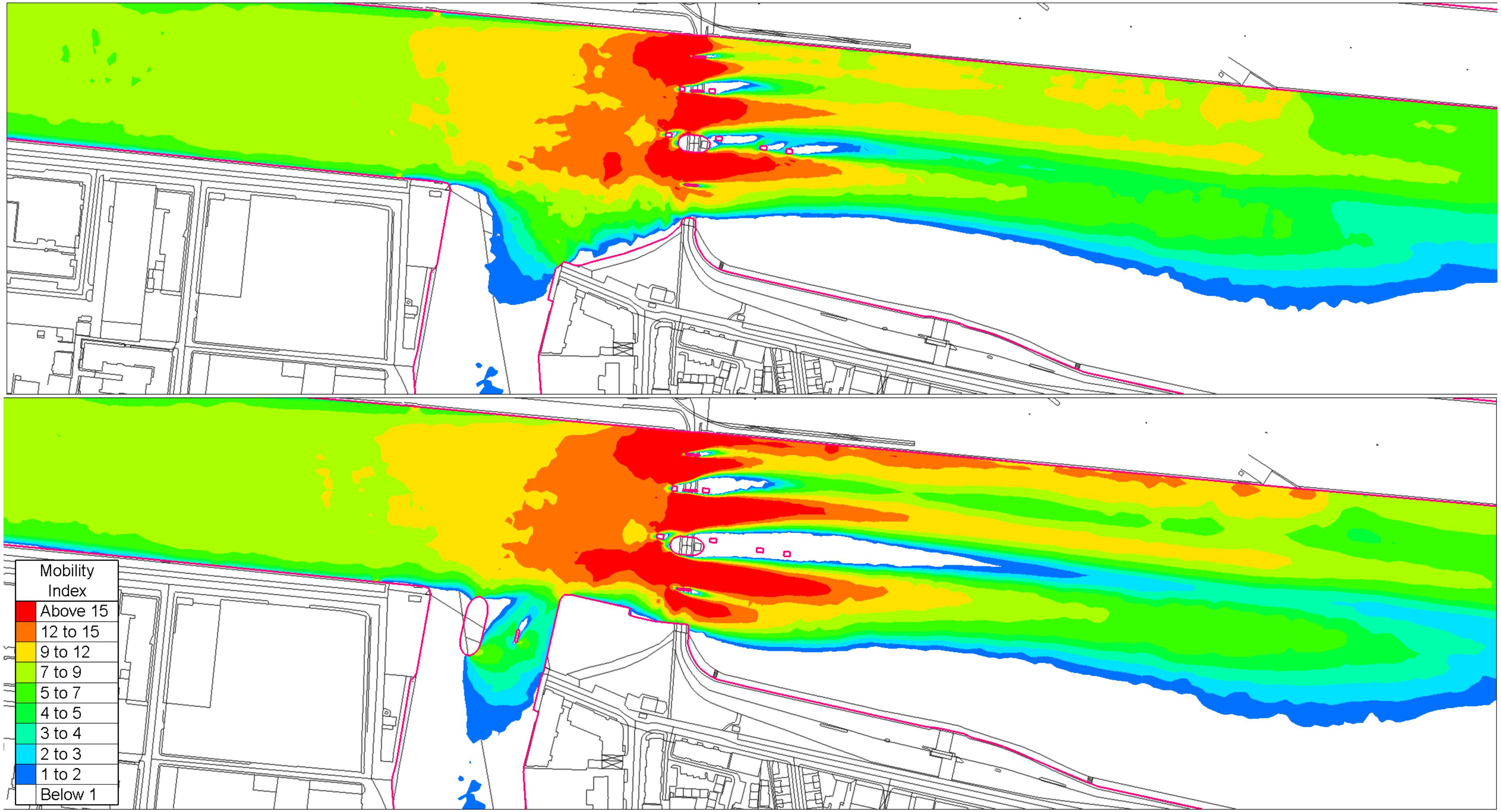

Figure 49 Computed Silt Mobility Map at Mid-Ebb for existing and proposed cases – Simulation 4 (Mobility Index < 1 silt is not mobile)

Simulation 5

Simulation of 2year fluvial flood in Dodder of 56 cumec

Combined with mean Spring Tide (HW 1.75mOD, tidal range = 3.3m) and 2year flood in River Liffey of 151cumec

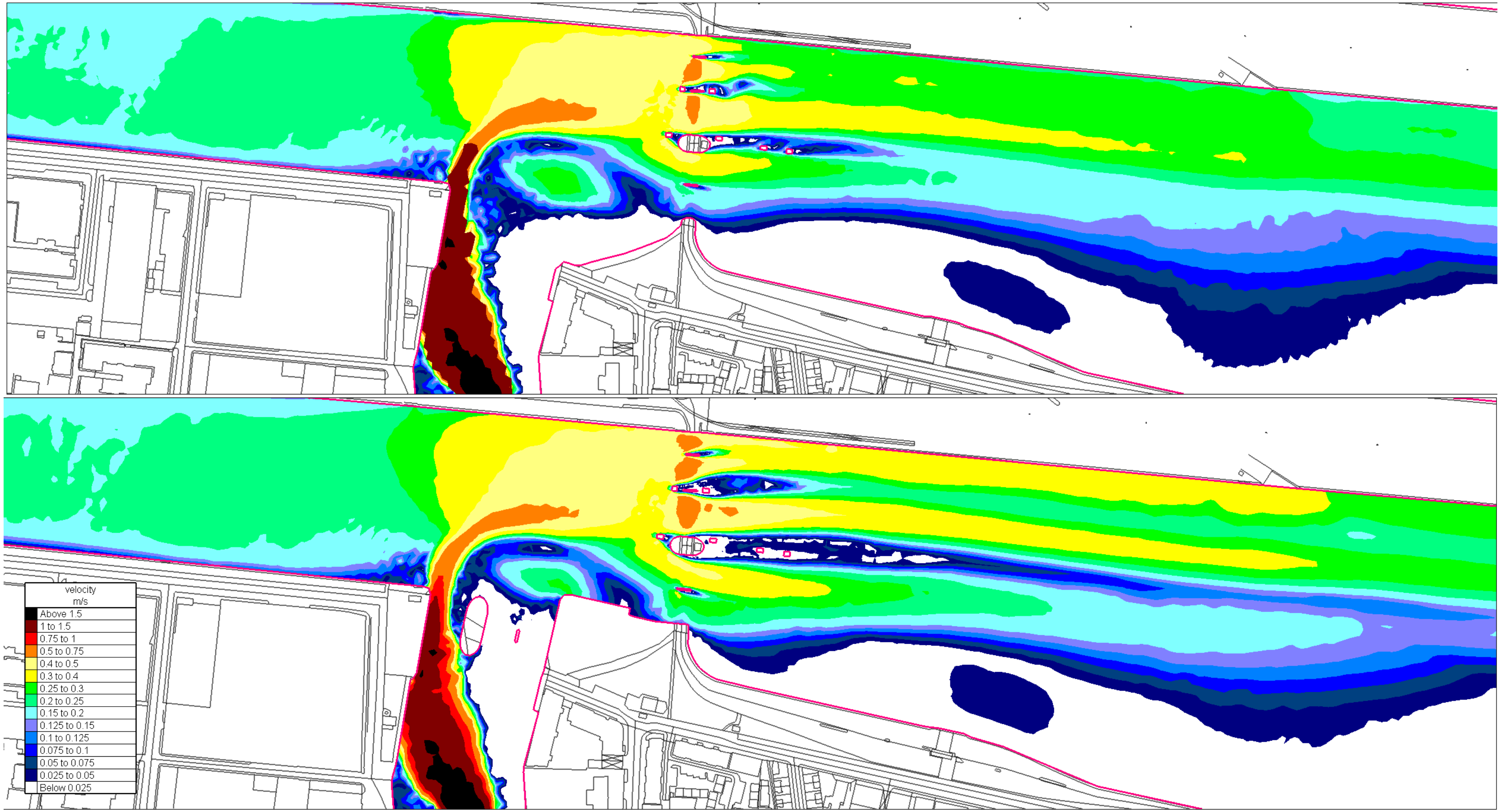

Figure 50 Computed Velocity Magnitudes at Low-Water for existing and proposed cases – Simulation 5

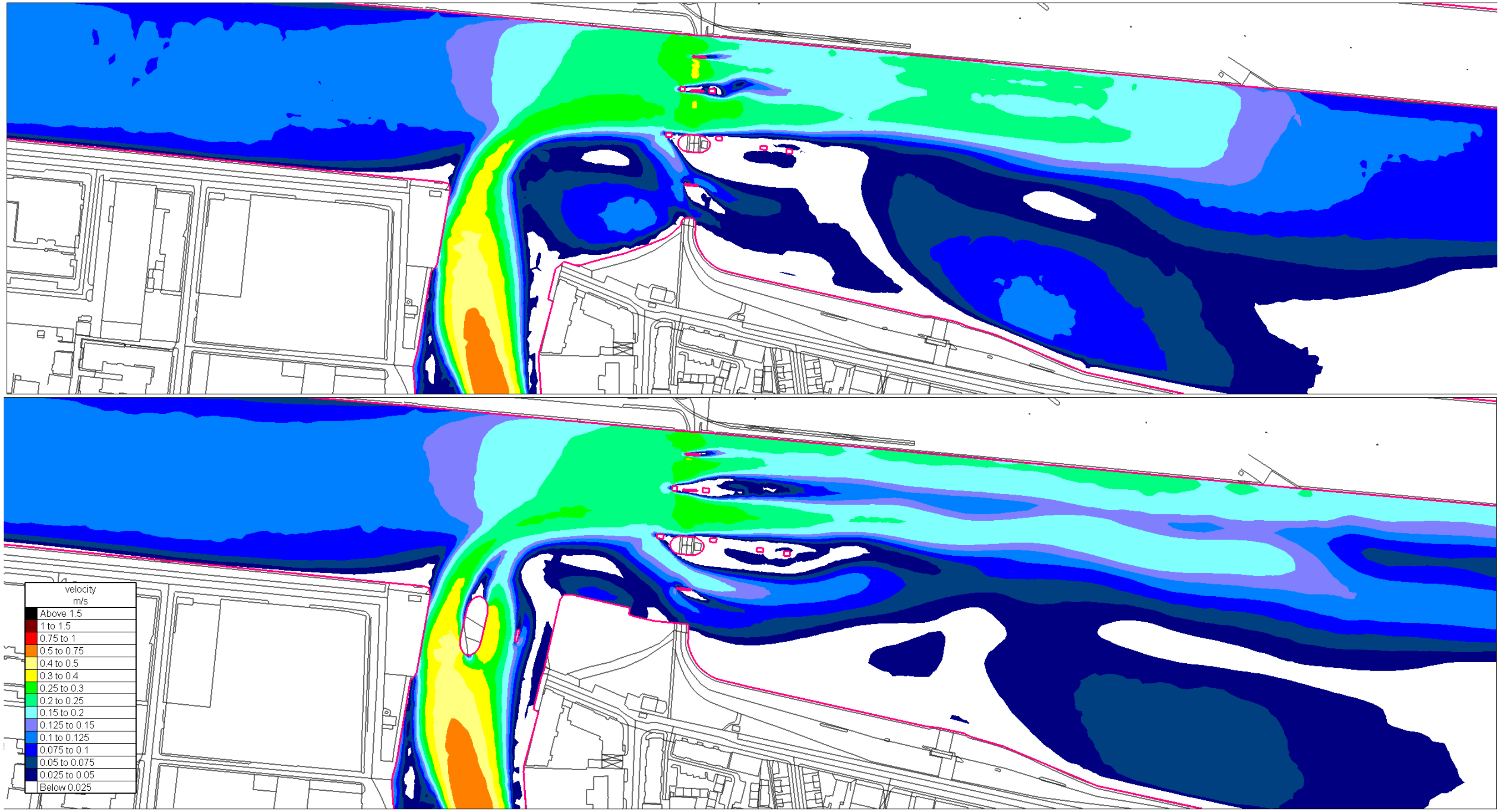

Figure 51 Computed Velocity Magnitudes at Mid-Flood for existing and proposed cases – Simulation 5

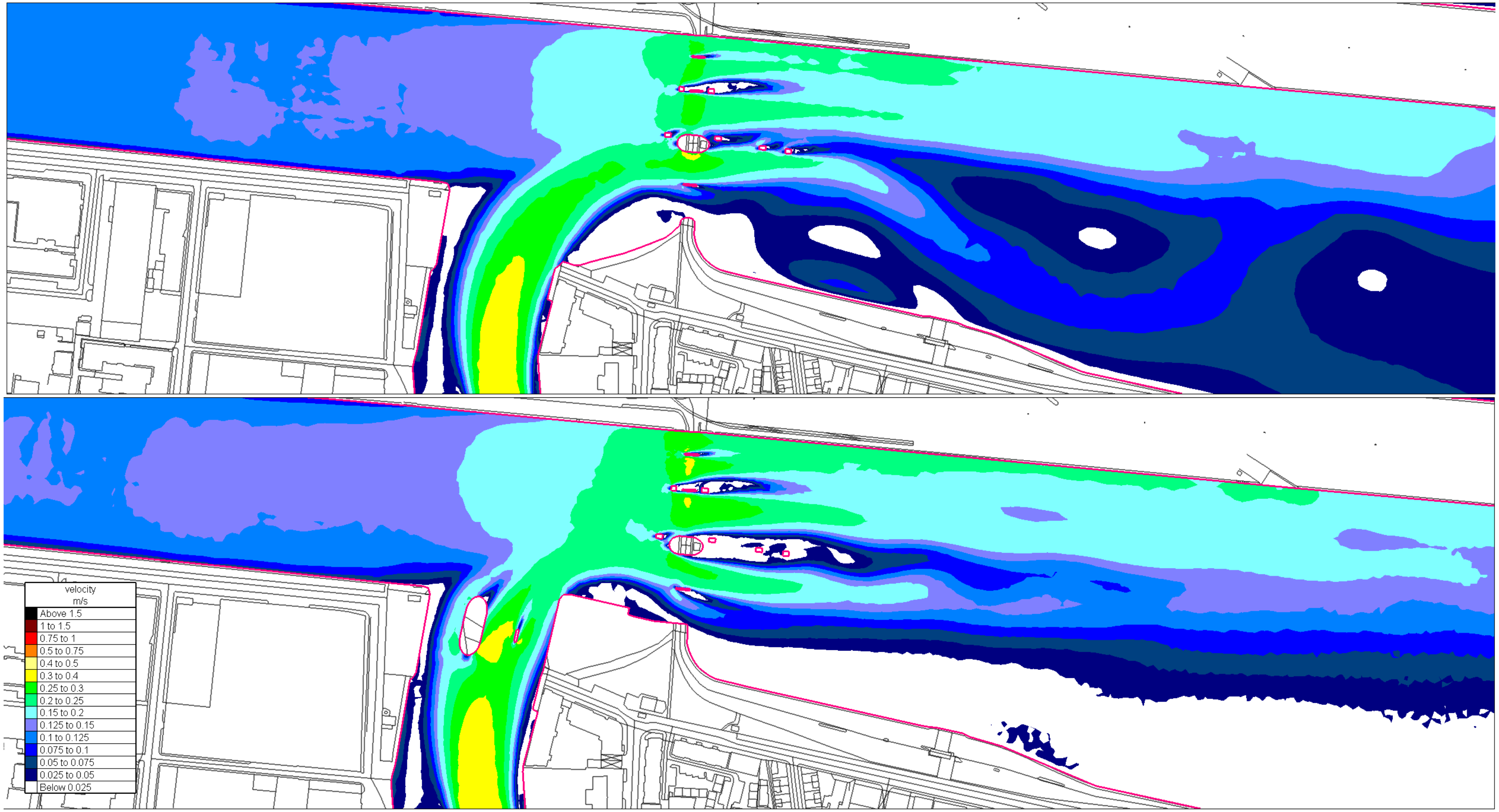

Figure 52 Computed Velocity Magnitudes at High Water for existing and proposed cases – Simulation 5

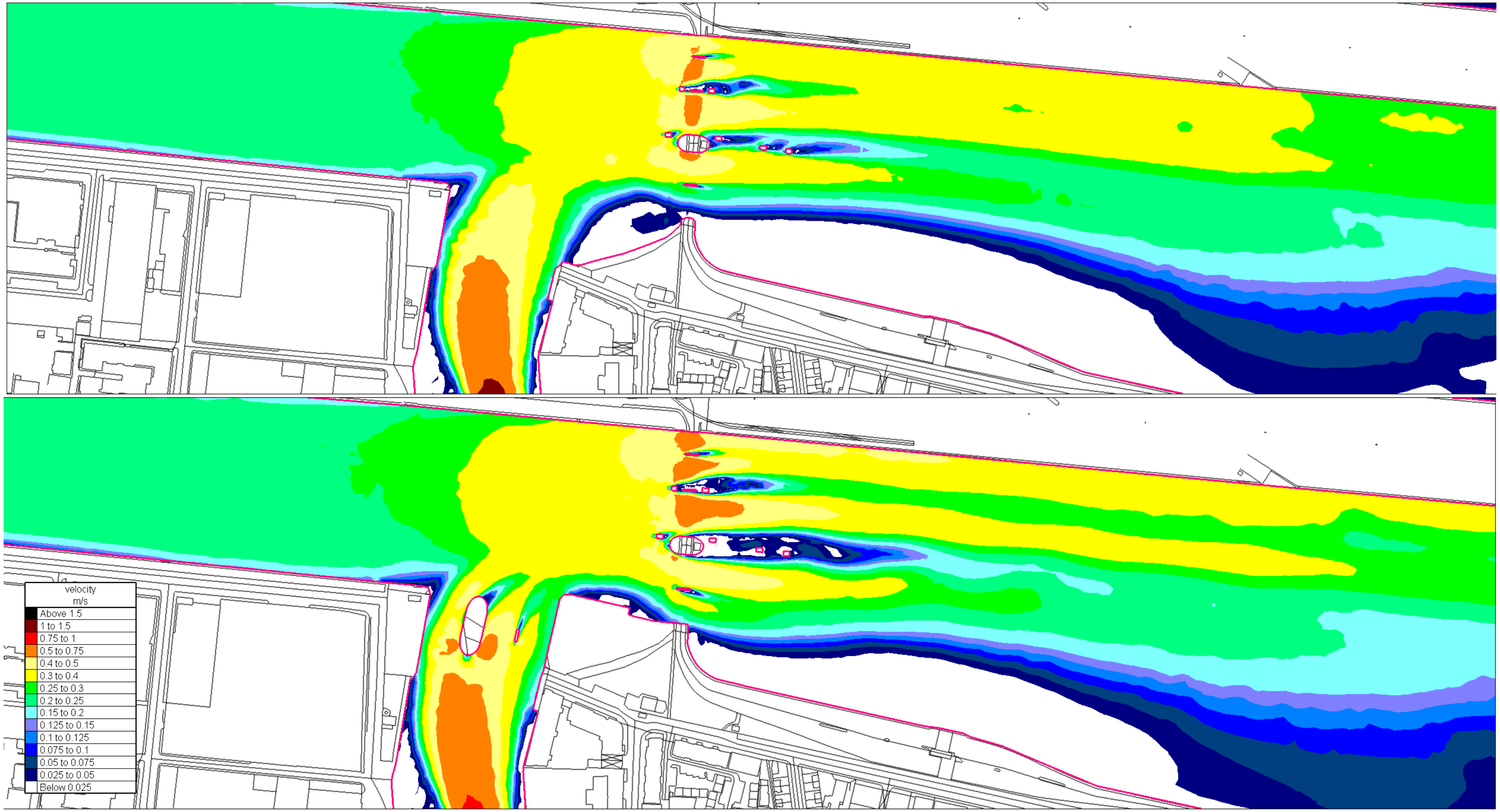

Figure 53 Computed Velocity Magnitudes at Mid-Ebb for existing and proposed cases – Simulation 5

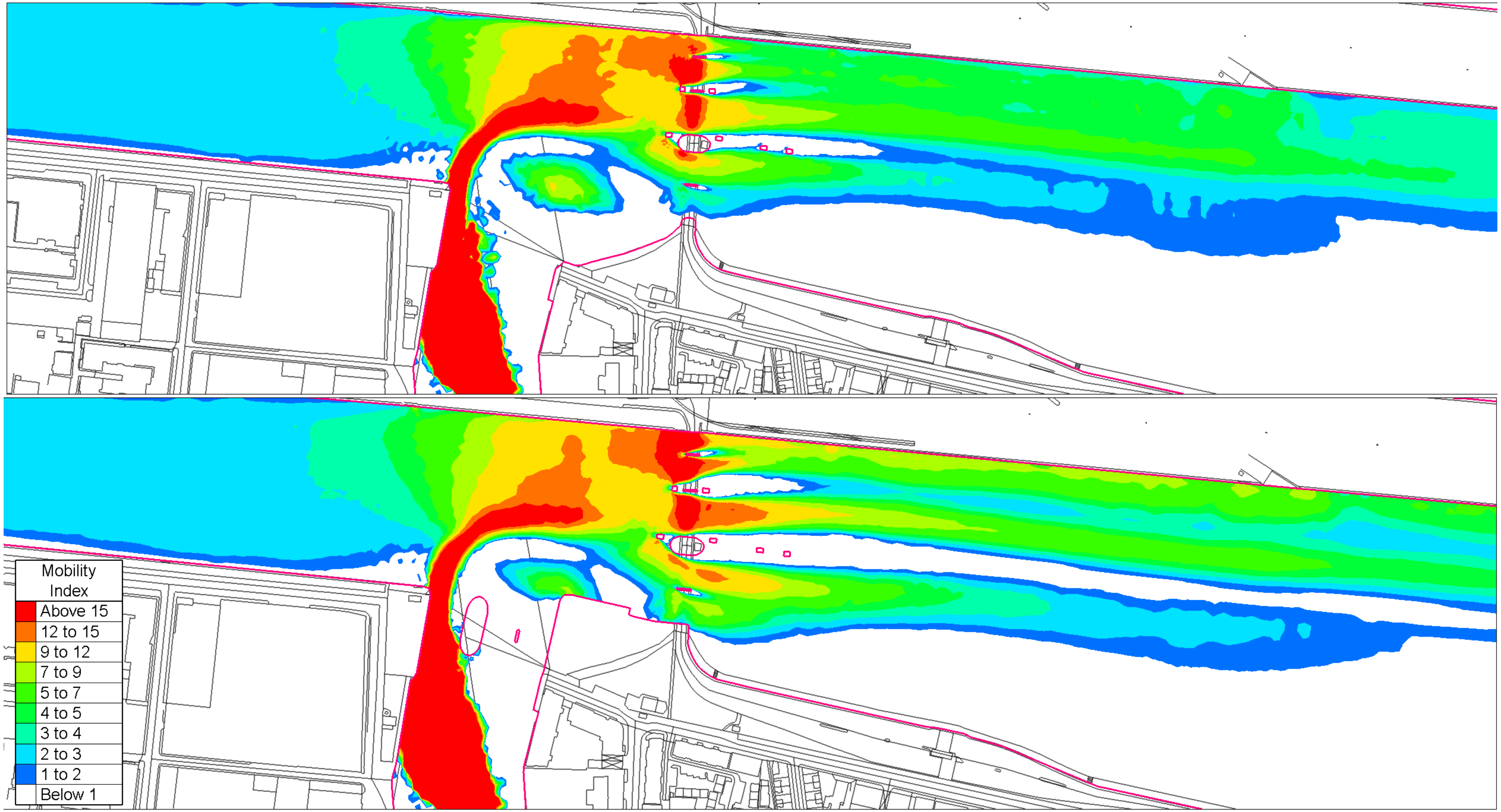

Figure 54 Computed Silt Mobility Map at Low Water for existing and proposed cases – Simulation 5 (Mobility Index < 1 silt is not mobile)

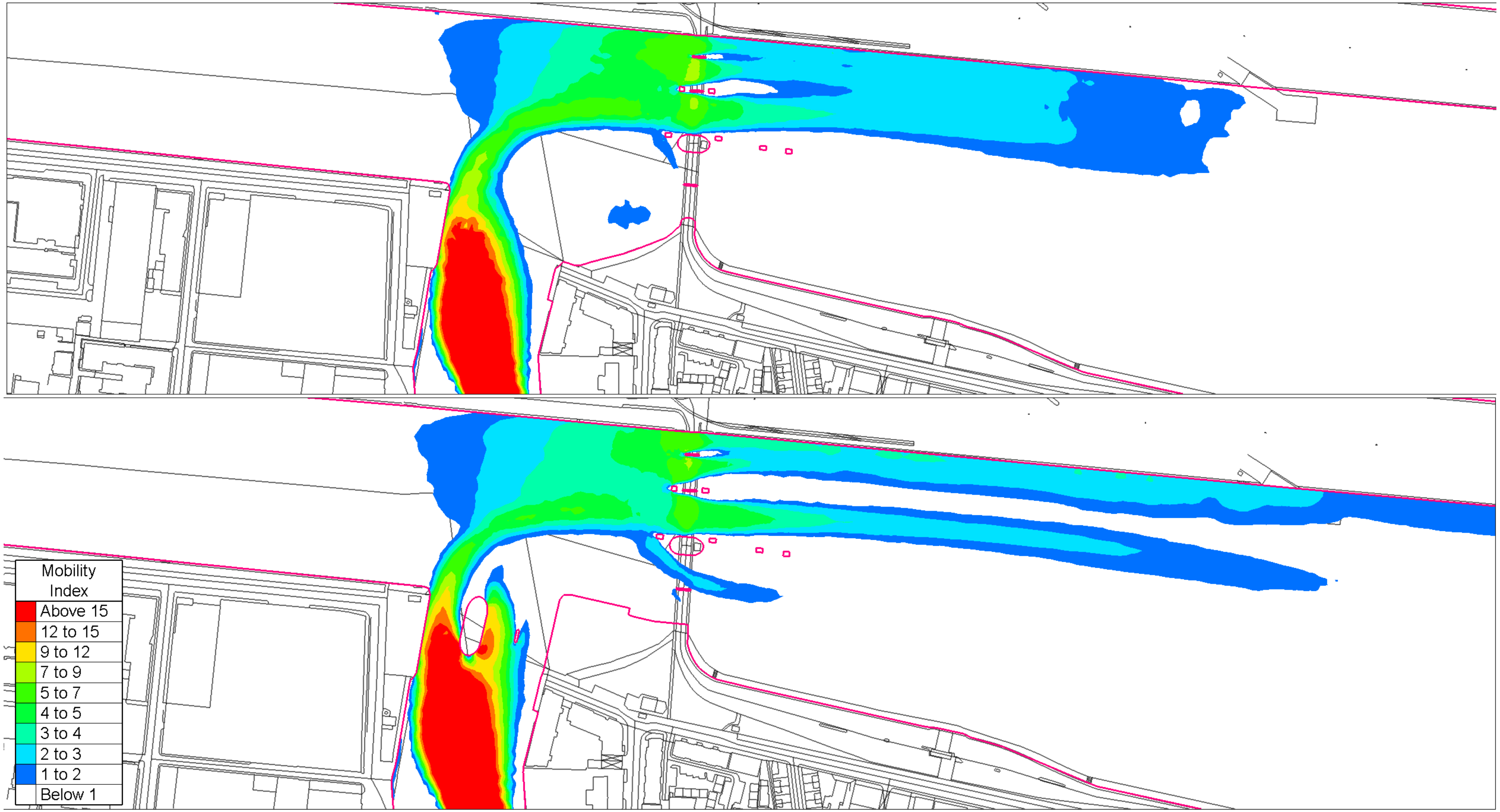

Figure 55 ***Computed Silt Mobility Map at Mid-Flood for existing and proposed cases – Simulation 5 (Mobility Index < 1 silt is not mobile)***

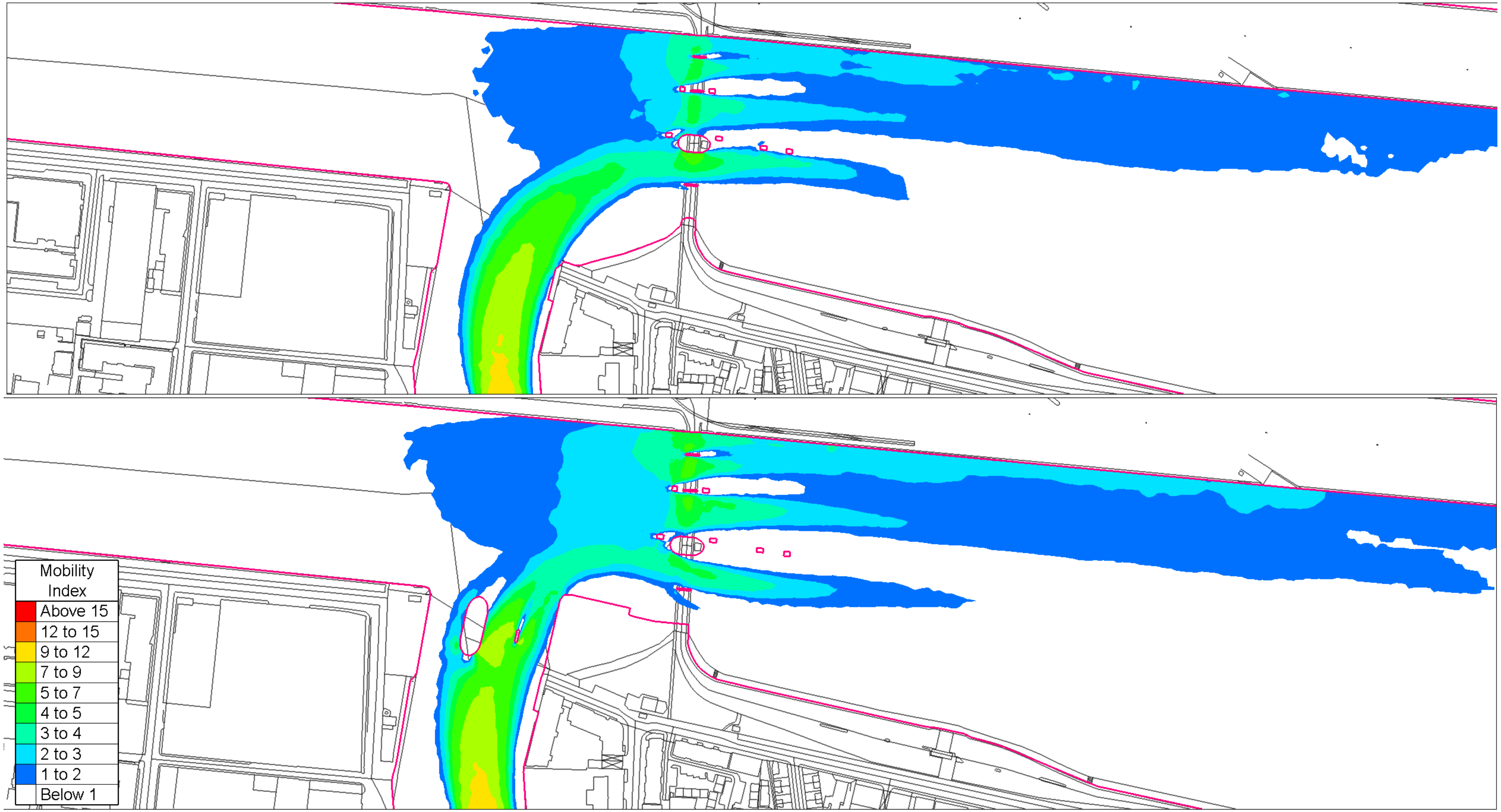

Figure 56 Computed Silt Mobility Map at Highwater for existing and proposed cases – Simulation 5 (Mobility Index < 1 silt is not mobile)

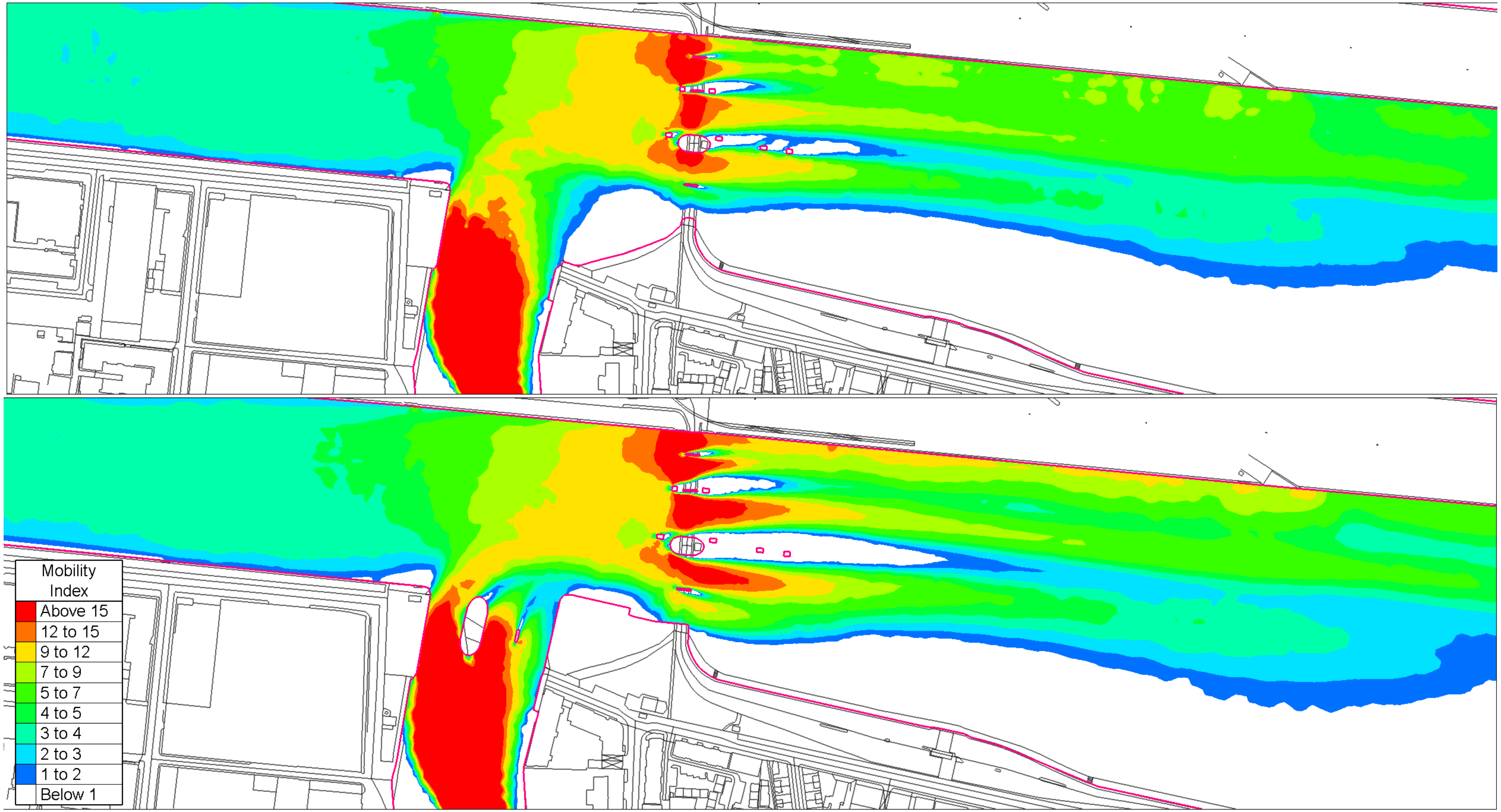

Figure 57 ***Computed Silt Mobility Map at Mid-Ebb for existing and proposed cases – Simulation 5 (Mobility Index < 1 silt is not mobile)***

Simulation 6

Simulation of Extreme Flood in Dodder of 269 cumec (hurricane Charlie EPA estimate)

Combined with mean Spring Tide (HW 1.75mOD, tidal range = 3.3) and 2year flood in River Liffey of 151cumec

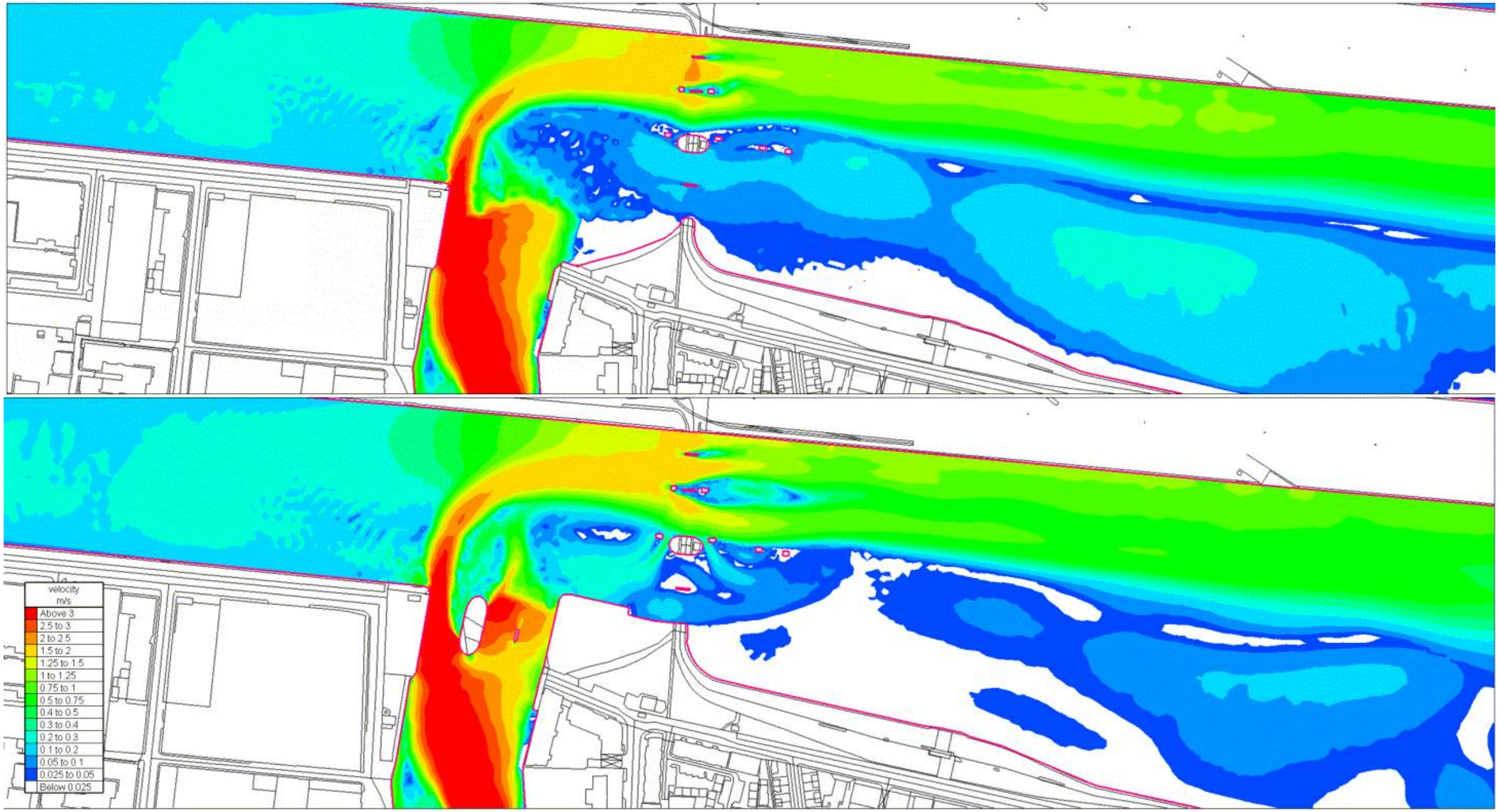

Figure 58 Computed Velocity Magnitudes at Low Water for existing and proposed cases – Simulation 6

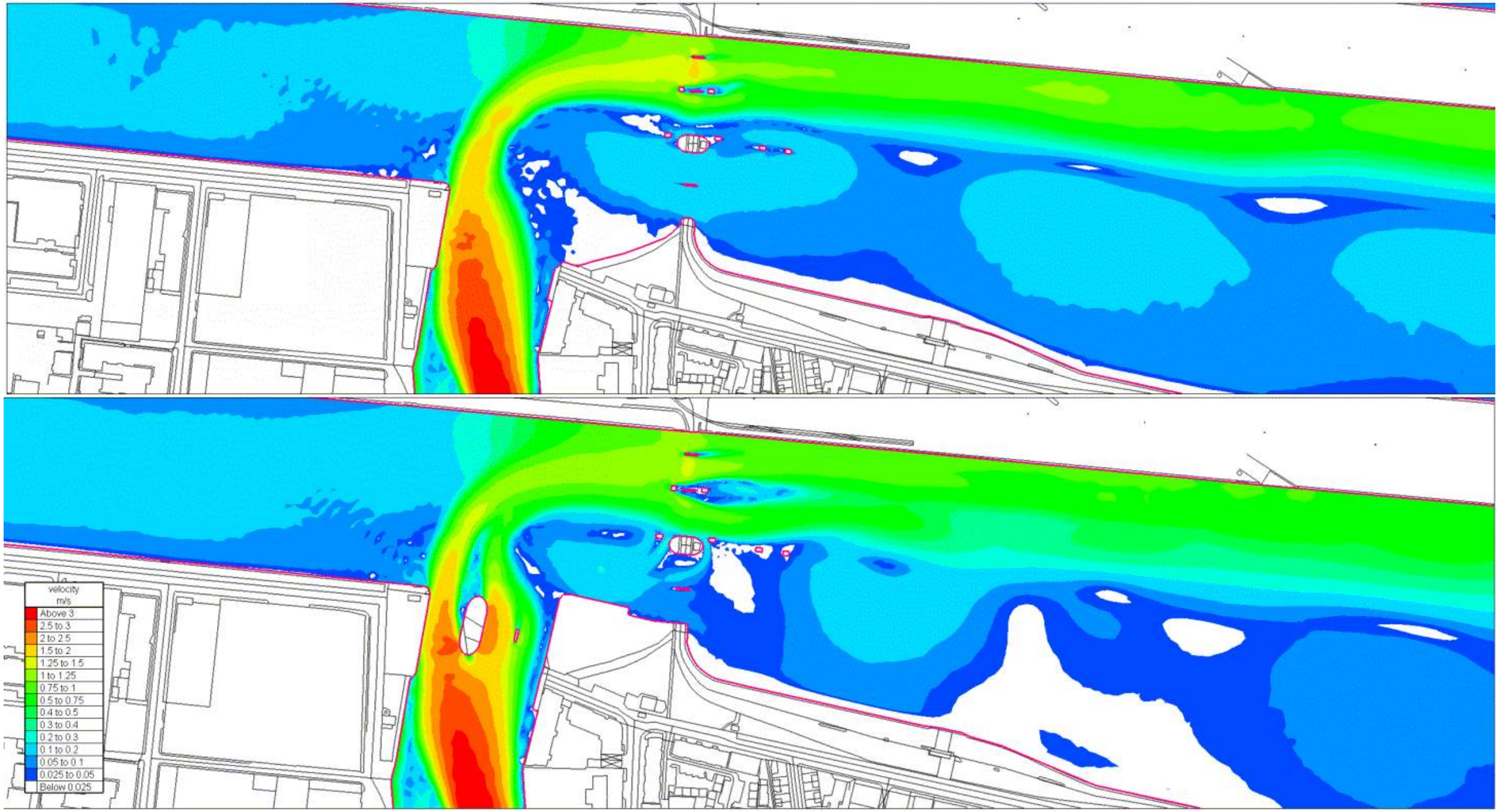

Figure 59 Computed Velocity Magnitudes at Mid-Flood for existing and proposed cases – Simulation 6

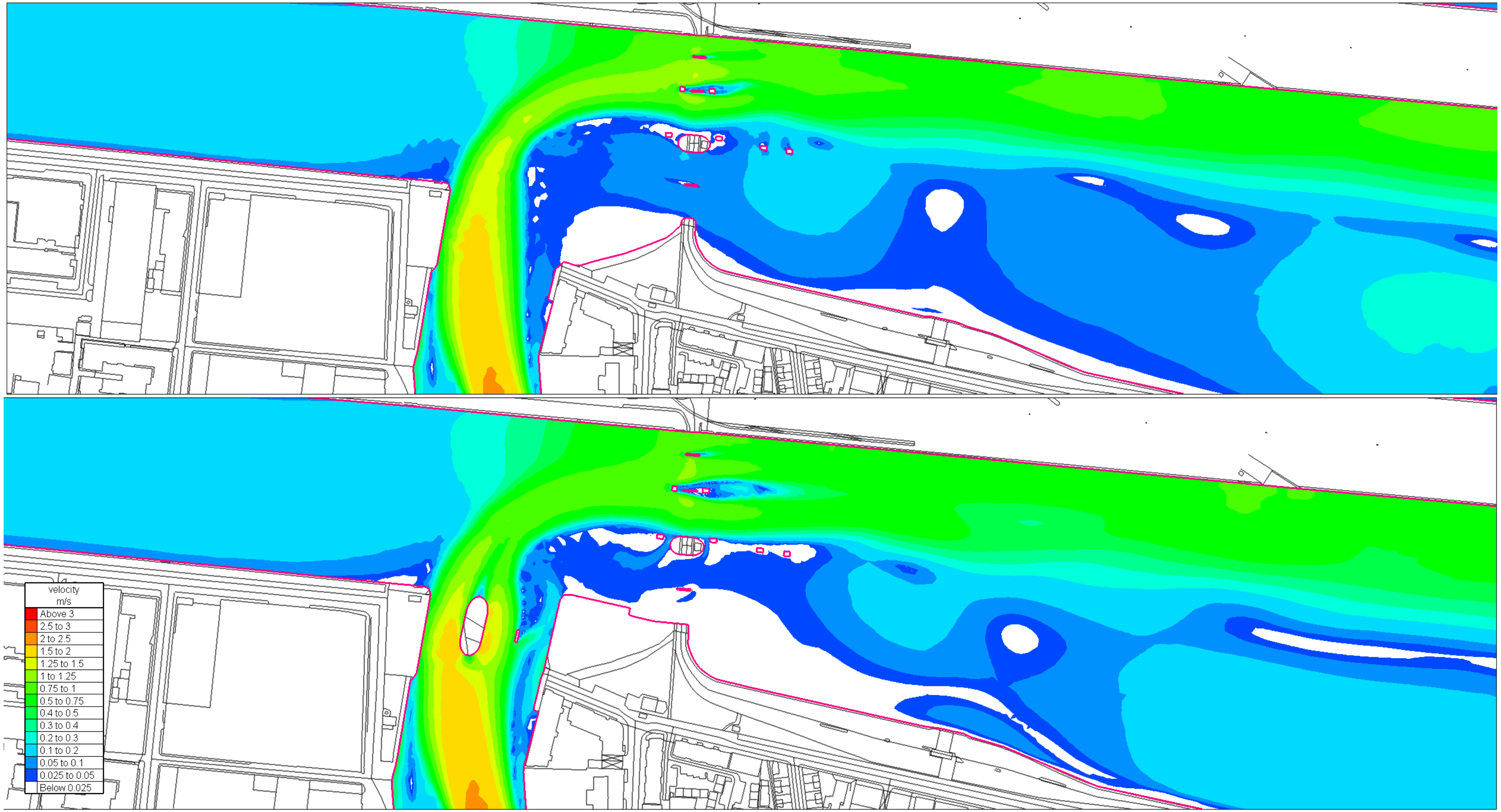

Figure 60 Computed Velocity Magnitudes at Highwater for existing and proposed cases – Simulation 6

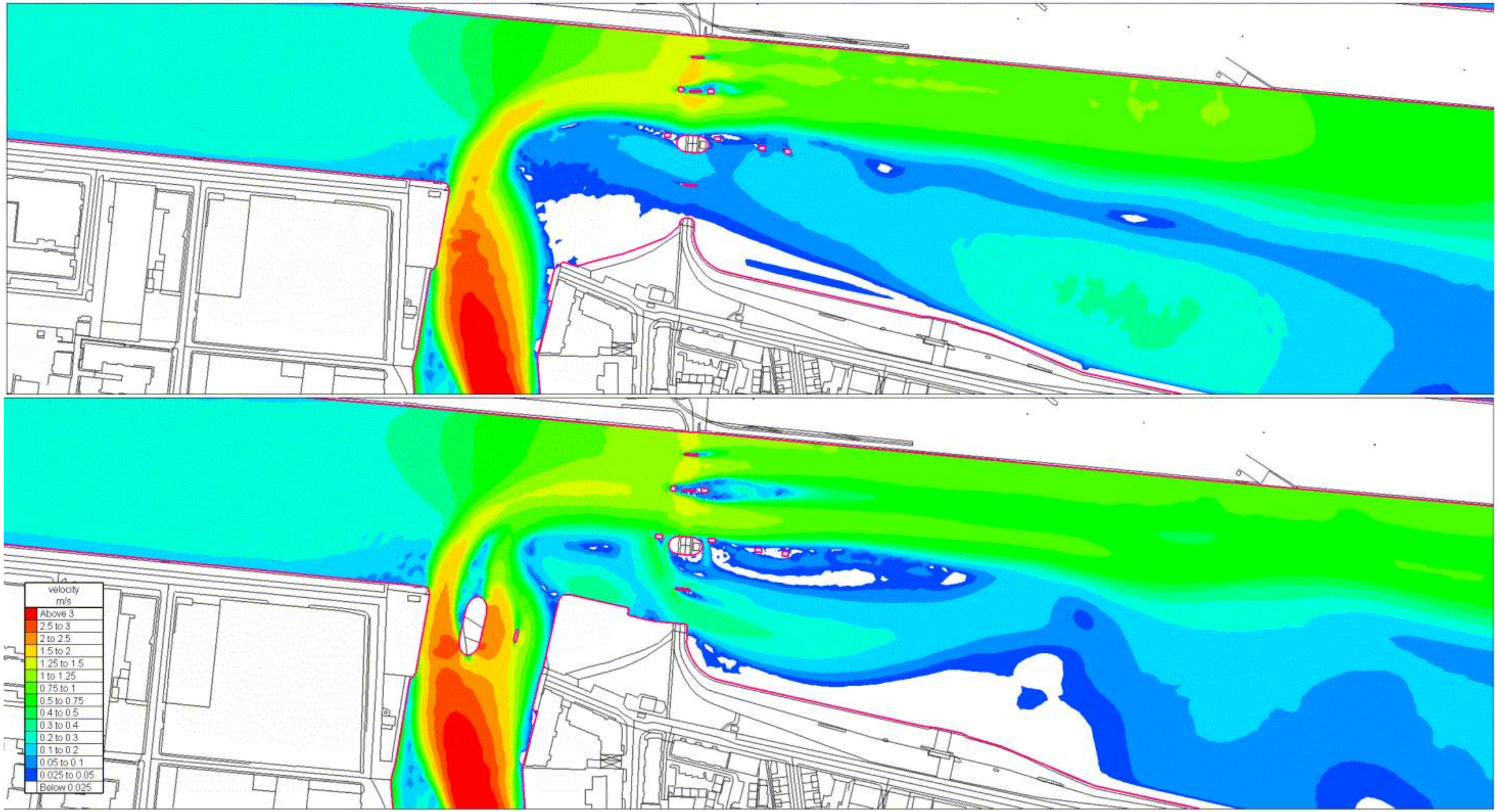

Figure 61 Computed Velocity Magnitudes at Mid-Ebb for existing and proposed cases – Simulation 6

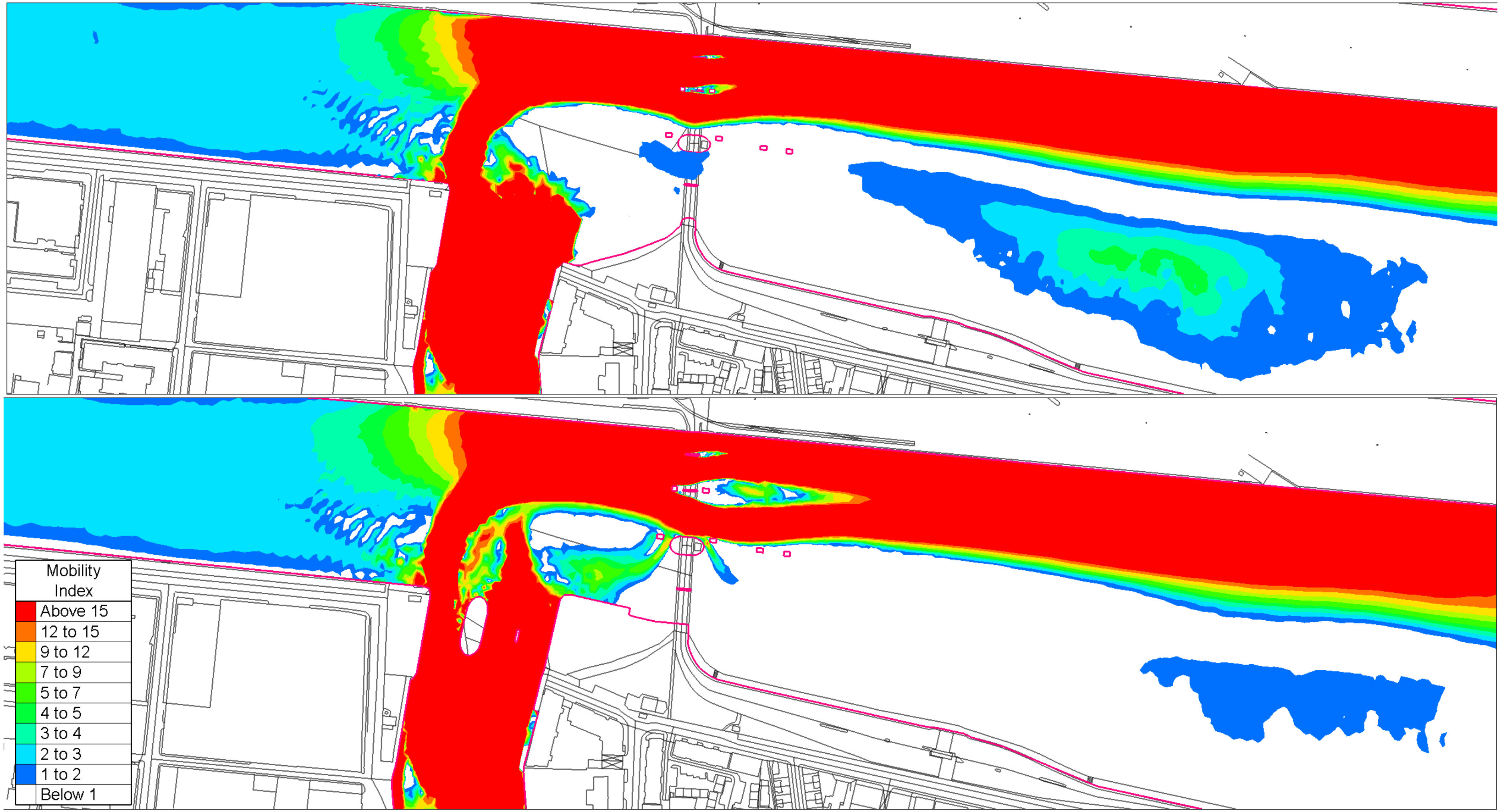

Figure 62 Computed Silt Mobility Map at Low Water for existing and proposed cases – Simulation 6 (Mobility Index < 1 silt is not mobile)

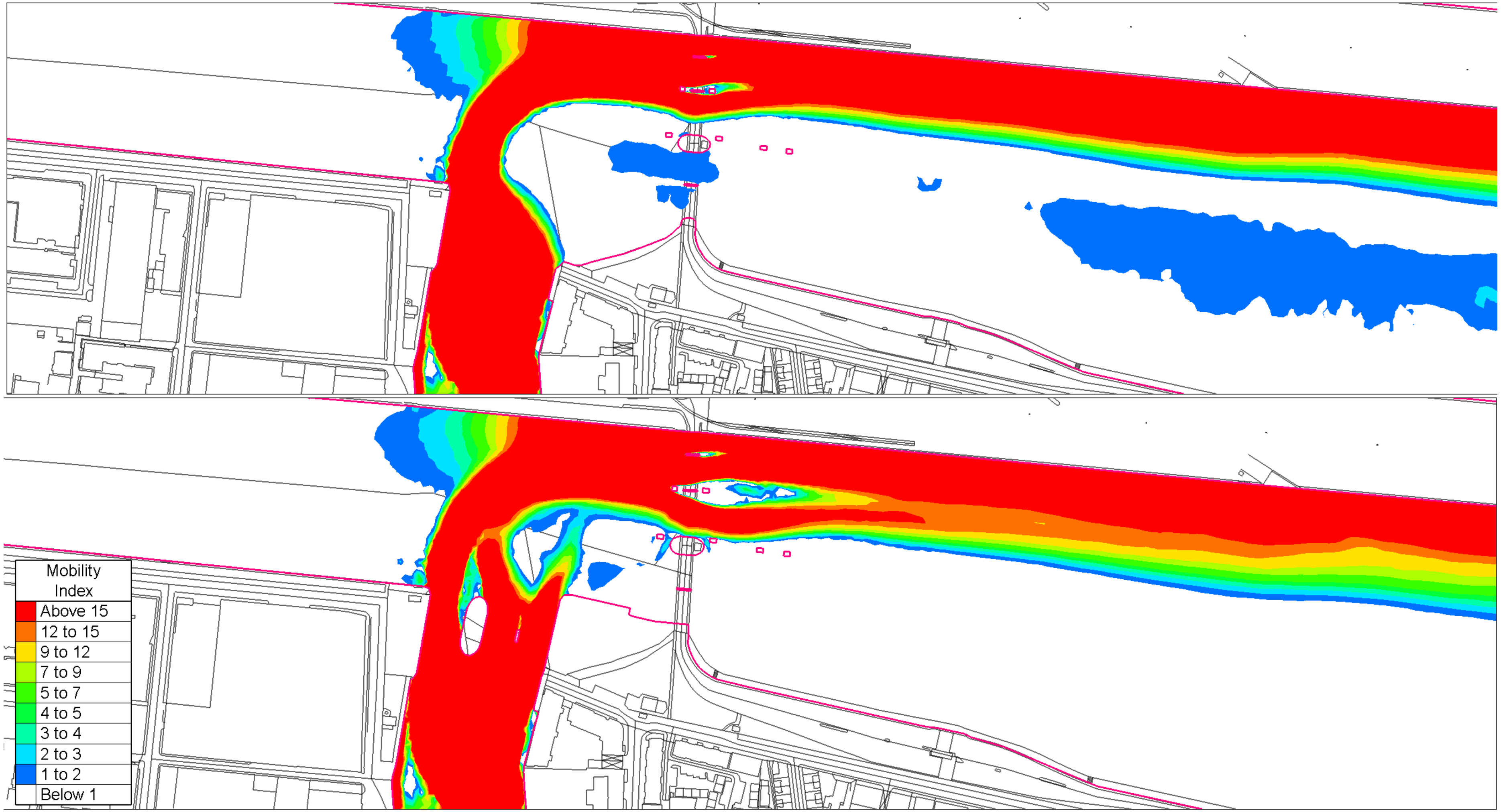

Figure 63 Computed Silt Mobility Map at Mid-Flood for existing and proposed cases – Simulation 6 (Mobility Index < 1 silt is not mobile)

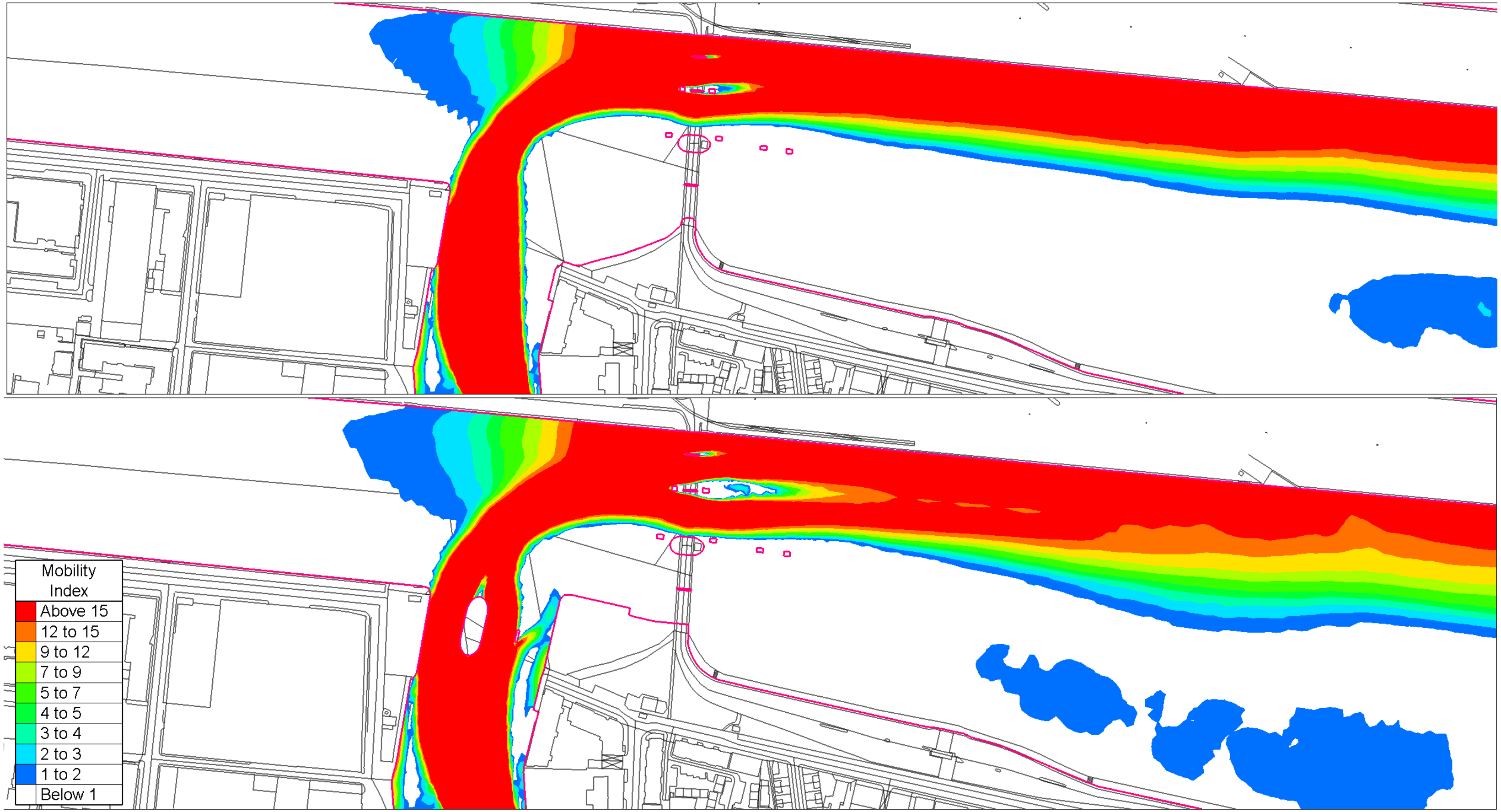

Figure 64 Computed Silt Mobility Map at Highwater for existing and proposed cases – Simulation 6 (Mobility Index < 1 silt is not mobile)

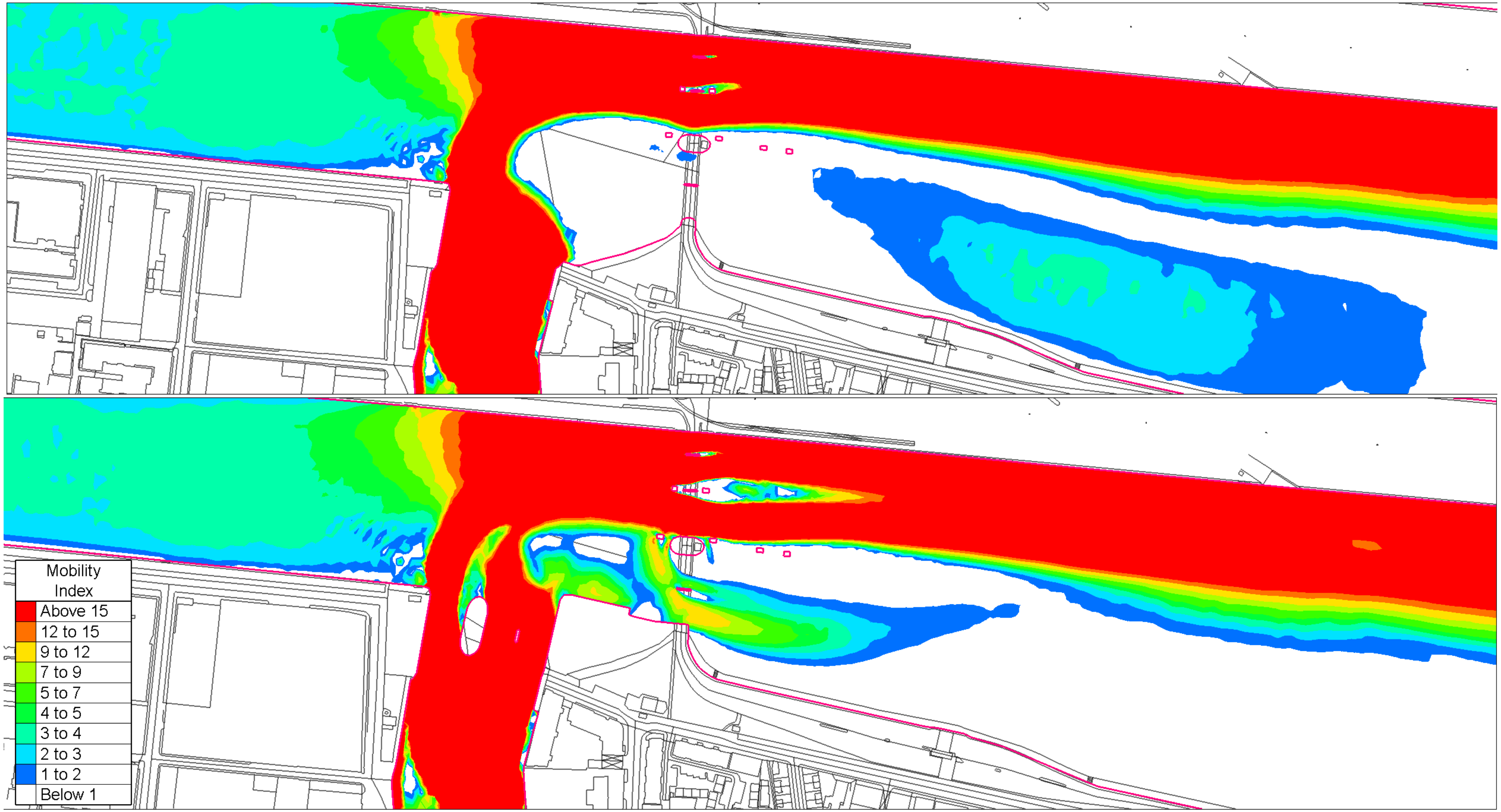

Figure 65 Computed Silt Mobility Map at Mid-Ebb for existing and proposed cases – Simulation 6 (Mobility Index < 1 silt is not mobile)