Slapton Line Vulnerability Assessment

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Slapton Line Vulnerability Assessment

Executive Summary

The A379 coastal road in South Devon runs along the gravel barrier at Slapton Sands beach, Start Bay, forming the 'Slapton Line', a vital transport link for local communities and emergency services. The Slapton Line road experienced significant impact and damage following 'Storm Emma' in March 2018. Easterly waves with significant wave height of up to 5.6 m were recorded just offshore by a directional wave buoy during the peak of the storm event. Significant erosion of the gravel beach occurred, resulting in cutback of the seaward vegetation line of up to 10.6 m in places. A 1 km stretch of the road was significantly affected, with partial collapse in two places resulting in the road's closure for approximately seven months.

In this report, survey data have been analysed to assess the distance from the Slapton Line road to the vegetation line seaward of the road, and the 4 m elevation contour landward and seaward of the road, providing a high-level assessment of the natural buffer zone on either side of the Slapton Line.

Distances from the back of the road to the 4 m beach elevation contour, calculated pre- and post-Storm Emma, suggest that the beach has rotated in a counter clockwise manner – meaning the beach has narrowed at the north, and widened at the south due to southward transport of gravel, a result of the easterly wave approach during storm Emma. Where the distance from the road to the 4 m beach elevation contour (i.e. the beach width) was large prior to storm Emma, recession and damage to the vegetation line was lessened, as a result of the beach acting as a buffer to the incoming wave energy in those places. Conversely, where the beach width was narrow prior to storm Emma, the greatest recession of the vegetation line and damage to the road occurred.

Immediately following the storm and road collapse, the seaward vegetation line was very close to the road in places. Consequently, the risk of further damage to the road as a result of a similar storm event was significantly increased due to the lack of seaward buffer. In response to this threat, the damaged section of road was realigned landward by up to 20 m in places and was re-opened in October 2018. This realignment has increased the seaward buffer, mitigating some of the risk along that section of road.

By realigning the road landward, distances from the realigned road section to the landward 4 m elevation contour have been reduced, meaning the road now sits much closer (12 m in places) to the high-water levels (4 m ODN) of the inland freshwater lagoon. Future scope for moving the road inland from its

new location is therefore severely limited due to the width required for the carriageway (10m for an 8m road with 1m retaining verges either side).

Geomorphological studies of Slapton Sands have shown that the bi-modal wave climate dictates the prevailing direction of longshore transport, which varies from northward to southward, depending on whether the waves arrive from the south or east, respectively. At any moment in time, the direction of this transport controls which areas along the length of the barrier are becoming wider or narrower. This in turn provides spatially and temporally varying levels of natural defence for the Slapton Line road. As demonstrated by the impacts of Storm Emma, beach width before a storm event exerts a significant control on the amount of erosion that occurs at the vegetation line, and ultimately determined the degree and location of damage to the A379 road during Storm Emma.

The vegetation and beach widths presented in this report highlight a number of areas that are vulnerable to future storm erosion due to having a limited natural buffer. However, the beach widths are constantly changing, and only continued regular monitoring of cross-shore beach width will provide up to date estimates of the road's vulnerability before a given storm event or winter season.

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1. Introduction

1.1. Site Description

Slapton Sands is a gravel barrier beach located in the South Hams district of south Devon, and is approximately 4.5 km long, and aligned in a SSW to NNE orientation. The A379 road runs along the length of the barrier from Torcross to Strete Gate, providing access from the coastal community of Torcross to the village of Slapton and Strete, also providing a second emergency route into Dartmouth. This report is concerned with the section of the road and barrier spanning from the northern end of the Torcross Sea wall, to the access route in front of the Strete Gate Car Park.

1.2. Site Morphology

The median grain size of the gravel ranges from 2 – 10 mm. The barrier position has remained relatively stable over the last 3000 years, allowing the sediment (mainly flint) to be reworked by the sea (Hails, 1975). Behind the barrier at Slapton Sands, freshwater is held above mean sea level (Austin, 2005) in a lagoon known as Slapton Ley. The gravel barrier at Slapton Sands rises to 5 – 6 m above mean sea level with a steep reflective beach face ($\tan\beta = 0.1$), and the toe of the gravel barrier extends to an average depth of 7.5 m below ODN (Kelland, 1975), before transitioning to a shallow gradient sandy sea bed. The beach is prone to shoreline rotation, where sediment is moved from one end of the beach to the other by longshore transport, resulting in widening of the beach at one end, and narrowing of the beach at the other end. This occurs over multiple timescales, and is driven by two dominant opposing wave directions – southerly waves, which drive northward longshore transport and clockwise beach rotation, and easterly waves, which drive southward longshore transport and counter-clockwise beach rotation.

The beach and road have undergone significant changes within the last 20 years. Notable events in this period include a road collapse event caused by easterly waves in 2001 (Chadwick *et al.,* 2005), overtopping and incipient breaching of the barrier during an easterly storm in 2004 (Chadwick *et al.,* 2005), road damage and significant losses to the beach volume along Slapton Sands during the 2013/14 winter storms (Wiggins et al., 2019), and significant beach recession and road damage during Storm Emma in late February to early March of 2018. The changes to the beach and road that occurred during Storm Emma are the focus of this report.

During Storm Emma, a period of easterly waves transported sediment from the north to the south of the beach at Slapton Sands. Counter-clockwise beach rotation was observed with increased beach volumes at Torcross in the south, and decreased beach volumes in the north of the embayment (Figure 1).

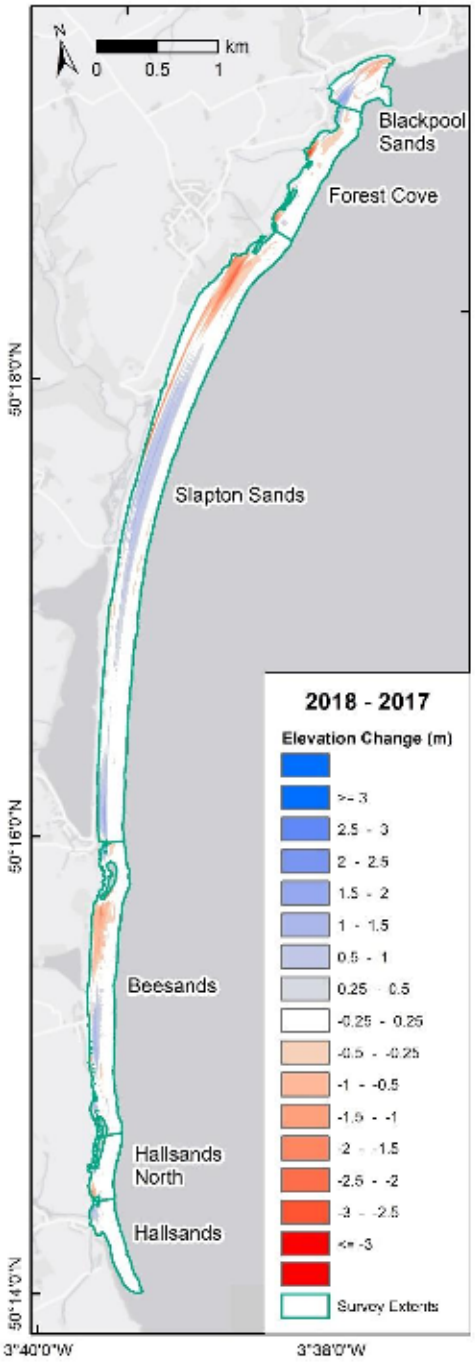

Figure 1. Full embayment difference model of Start Bay elevation changes from 2018 to 2017, highlighting the alongshore response of gravel transport under the easterly waves of Storm Emma.

On the 1st March 2018, Storm Emma reached the coast of Start Bay, with easterly wave heights exceeding 5 m. The impacts at Slapton Sands included overwashing of gravel onto the A379 road, back-beach recession and substantial erosion of the beach profile. Undermining of the northern section of the A379 resulted in its failure and collapse, leaving the road closed. Approximately 1 km of road was replaced during the summer to autumn of 2018, with the road realigned landward by up to 20 m in places.

1.3. Site Wave Climate

The wave climate is directionally bi-modal (Figure 2), receiving both short-fetch wind waves and diminished Atlantic swells from the south and wind waves from the east (Ruiz de Alegria-Arzaburu and Masselink, 2010). The embayment is macrotidal, with neap and spring tidal ranges of 1.8 m and 4.3 m, respectively.

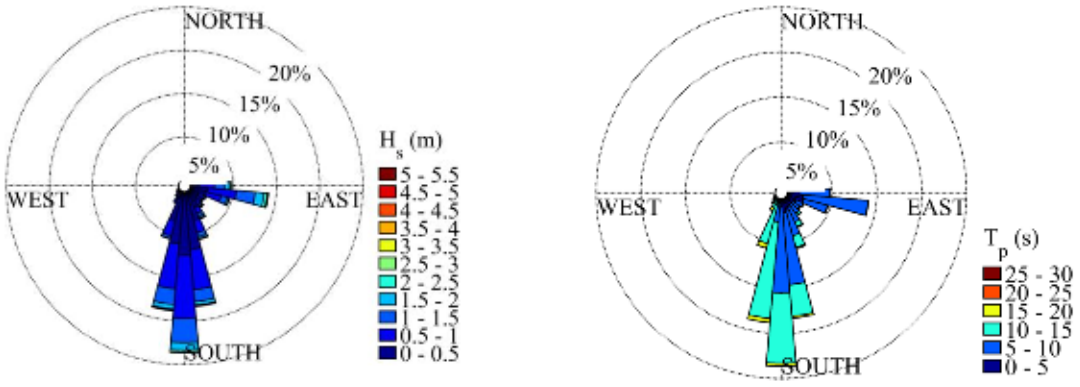

Figure 2. Directional wave roses of significant wave height (left panel) and peak wave period (right panel), measured by the Start Bay wave buoy in approximately 15 m water depth, between 01-Apr-2007 and 30-Apr-2017.

1.4. Aims and Objectives

The overall aim of this report is to determine the vulnerability of the A379 road, along Slapton Sands beach, to storm damage in the immediate future. The significant levels of damage experienced during Storm Emma will be used as the context by which this is measured. To achieve this aim, the following objectives have been set:

- Determine the distance between the landward side of the original road to the following:

  - Seaward vegetation line (i.e. the extent of the back-beach buffer), pre- and post-Storm Emma.
  - Landward 4 m elevation contour (i.e. the extents of the landward buffer), indicating the potential area for relocation of the road.
  - Seaward 4 m elevation contour (i.e. the width and volume of the beach), pre and post Storm Emma.

- Calculate the distance from the landward side of the new section of the A379 road (realigned in October 2018) to the following:
  - Seaward vegetation line, post Storm Emma.
  - Landward 4 m elevation contour.

2. Methodology

Morphological changes from Torcross to Strete Gate occurring over the time period before and after Storm Emma (01/03/2018) were calculated. DEMs (Digital Elevation Models) were utilized from a number of sources, including Environment Agency LiDAR (Light Detection and Ranging) from April 2017, and unmanned aerial vehicle surveys (UAV) from October 2017, March 2018 and May 2018 conducted by the University of Plymouth. Ortho-rectified aerial photography was also used to complement the DEMs in quantifying the changes to the beach and road.

Cross shore profiles monitored by Plymouth Coastal Observatory (PCO) were selected along the length of the Slapton line at intervals of no more than 50 m, from the end of the Torcross sea wall northward to Strete Gate car park. The use of these profiles allows for comparison with a long-term (11 year) dataset, and further monitoring data will continue to be collected yearly in future.

The back (landward side) of the road was digitized using ortho-rectified aerial photography from May 2018 for the selected section of road. Location points at the back of the road were created where this line intersects the cross-shore profiles (Figure 3 and 4). A 4 m ODN (Ordnance Datum Newlyn) elevation contour was then extracted from the April 2017 filtered LiDAR dataset to give a landward distance. The elevation of 4 m was chosen as an approximate upper water level for Slapton Ley, having reached this height only once within a single year of observations (Austin et al., 2013); however, greater levels may be possible with increased rainfall and a blocked drainage outlet. The front vegetation line was digitised from both the October 2017 and May 2018 aerial photography to give a pre- and post-Storm Emma seaward buffer line. An additional seaward buffer was calculated at 4 m ODN from both the October 2017 and May 2018 DEMs, representing the upper beach width. Once the realigned section

of the A379 road was completed, an updated set of distances were calculated from an ortho-referenced CAD drawing, using the same methodology as above.

The differences between the pre- (2017) and post- (2018) Storm Emma contours were used to identify the maximum recession observed during the storm. These maximum values were used as indicative recession distances for future extreme events, providing an estimate of the possible magnitude of recession that could occur if another event like Storm Emma were to occur. A colour coding system was developed using thresholds based on the Storm Emma maximum recession distances, and are presented in Table 1. For example, the maximum loss observed at the vegetation line during Storm Emma was 10.6m; any residual distances less than this are coloured red, indicating that another storm of a similar magnitude to Emma could potentially recede the shoreline back, and damage the road at that location. The same approach was applied to the seaward 4 m beach contour (maximum Storm Emma recession 15.2 m). For the landward 4 m elevation contour (which did not change during Storm Emma), thresholds were determined from the maximum recession of the seaward vegetation line plus one road width (10.6 m + 8 m), to identify areas with little room for future road alignment and allowing for the need for a seaward buffer in the event of realignment.

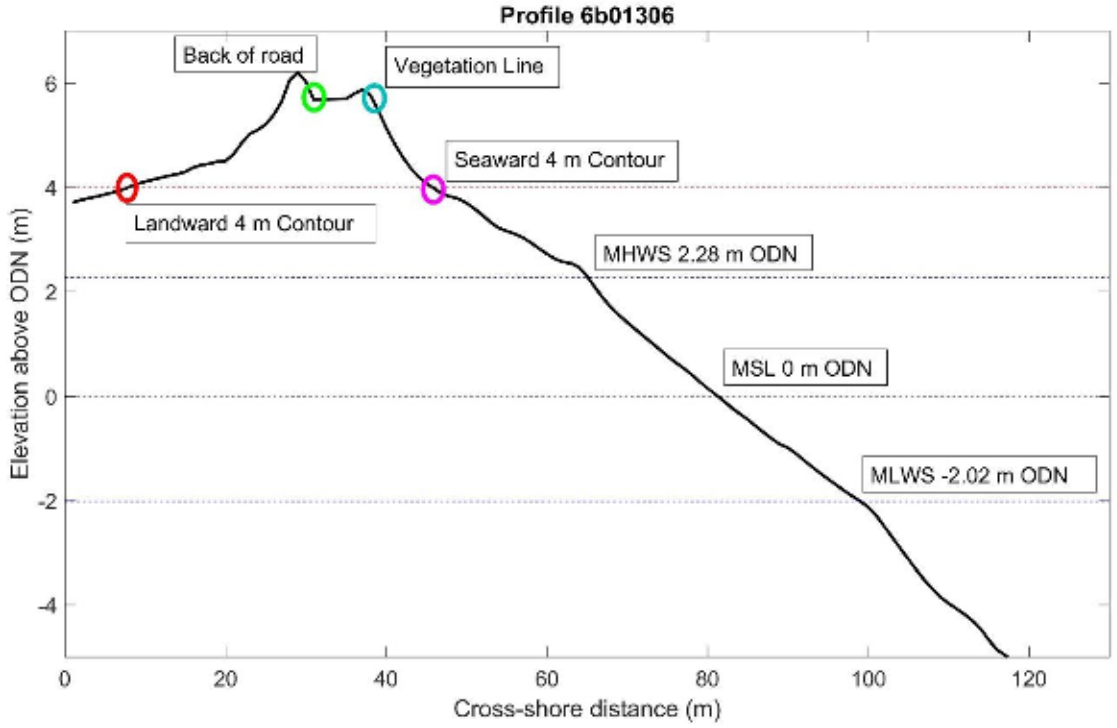

Figure 3. Example of a cross-shore profile showing the back of the road, associated contours, including the landward and seaward 4 m contour, vegetation line. Tidal elevations are displayed as mean high water springs (MHWS), mean low water springs (MLWS) and mean sea level (MSL).

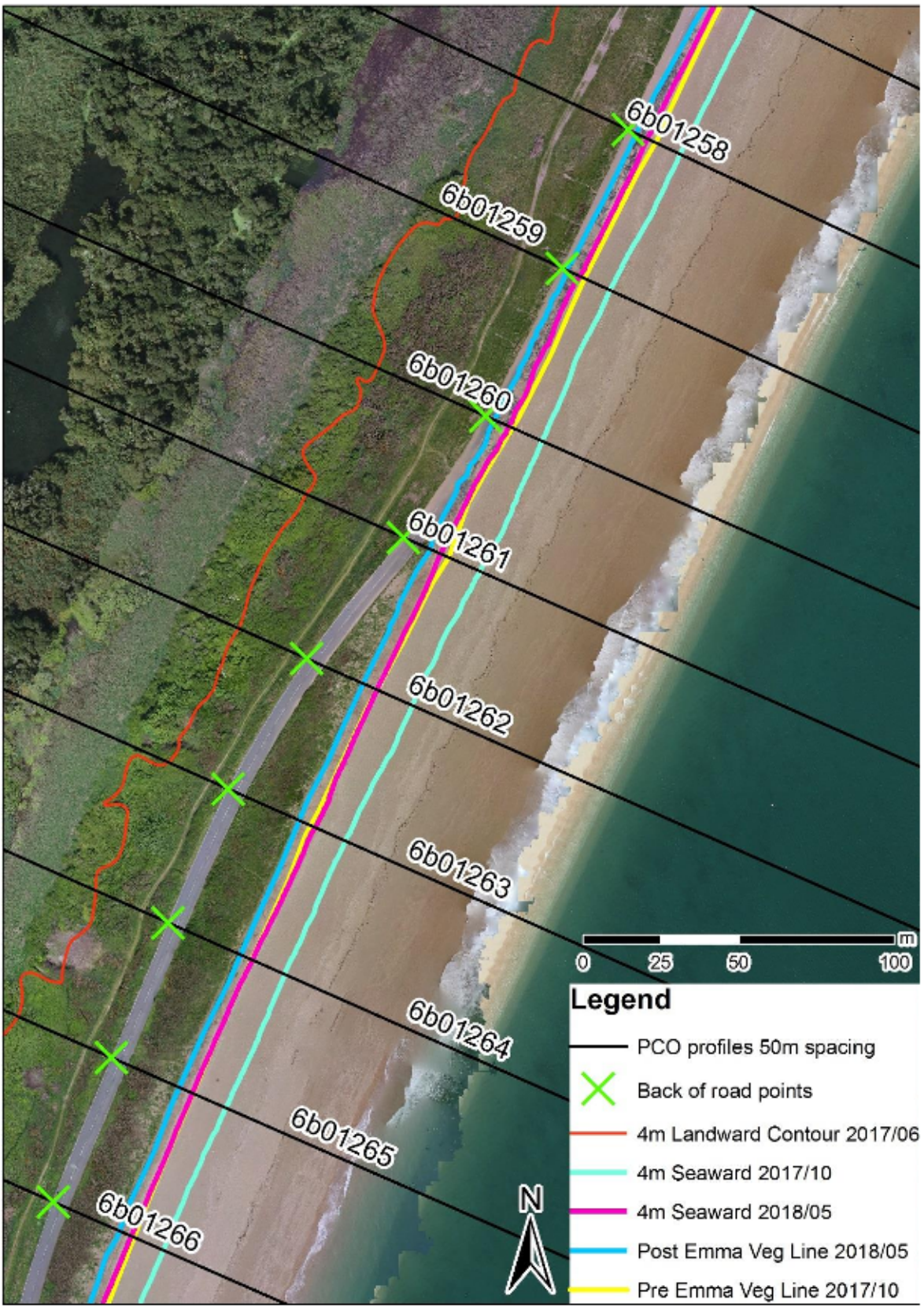

Figure 4. Example of methodological approach, calculating distances from the back of the road to various contour lines at each PCO profile location.

Table 1. Colour coding of buffer distances, based on the maximum recession that occurred during Storm Emma and the proposed new road width.

	Distances from the back of A379 road		
Vulnerability Level	4m Landward	Vegetation Line	4m Seaward
highly vulnerable	< 18.6m 8m road width plus one Storm Emma recession	< 10.6m One Storm Emma recession	< 15.2m One Storm Emma recession
vulnerable	18.6m < and < 29.2m 8m road width plus two Storm Emma recessions	10.6m < and < 21.2m Between one and two Storm Emma recessions	15.2m < and < 30.4m Between one and two Storm Emma recessions
less vulnerable	> 29.2m More than 8m road width and two Storm Emma recessions	> 21.2m More than two Storm Emma recessions	> 30.4m More than two Storm Emma recessions

3. Results

Calculated distances from the back of the original A379 road for each 50 m spaced profile are presented in Table 2. Groups of green coloured rows represent the least vulnerable stretches of the Slapton Line road, while groups of amber and red coloured rows represent vulnerable and highly vulnerable stretches of the road, respectively, as defined by the thresholds in Table 1. Each of the three contours assessed (vegetation line, seaward 4 m contour, landward 4 m contour) are discussed separately in Sections 3.1 to 3.3, and the distances calculated with the new road realignment are presented in Section 3.4.

Table 2. Distances calculated from the back of the A379 road to the extracted contours prior to road realignment. Colours correspond to the distance thresholds set out in Table 1, where red represents a highly vulnerable profile, amber a vulnerable profile, and green a less vulnerable profile.

PCO Profile	Chainage from Torcross (m)	4m Landward 2017/06 (m)	Pre-Emma Veg Line 2017/10 (m)	Post-Emma Veg Line 2018/05 (m)	Pre-Emma 4m Seaward 2017/10 (m)	Post-Emma 4m Seaward 2018/05 (m)
6b01243	3570	N/A	31.4	31.5	79.3	64.2
6b01244	3520	N/A	26.5	26.5	78.8	63.5
6b01245	3470	N/A	37.0	37.0	68.9	55.2
6b01246	3420	13.3	36.7	36.4	63.9	50.2
6b01247	3370	34.4	37.7	37.7	59.7	46.7
6b01248	3320	21.5	34.2	33.9	55.2	41.4
6b01249	3270	28.9	29.8	29.8	50.1	36.3
6b01250	3219	19.8	27.8	25.0	45.9	31.7
6b01251	3170	21.2	24.5	22.3	41.2	27.2
6b01252	3122	33.4	21.9	18.8	37.9	24.1
6b01253	3072	29.4	19.7	15.4	33.1	19.8
6b01254	3025	31.0	16.5	11.9	30.0	16.2
6b01255	2976	19.4	14.0	9.4	26.6	13.5
6b01256	2925	28.6	12.2	6.6	23.1	10.4
6b01257	2872	30.9	10.2	6.3	20.4	8.2
6b01258	2820	39.3	9.7	2.7	18.4	6.8
6b01259	2771	38.3	7.8	1.4	16.7	6.0
6b01260	2718	38.2	9.3	3.0	19.7	8.1
6b01261	2670	34.2	15.9	9.4	26.9	13.0
6b01262	2622	23.9	24.6	19.7	37.0	24.5
6b01263	2574	21.1	28.9	24.9	41.1	30.4
6b01264	2530	25.4	29.1	25.3	40.8	29.5
6b01265	2480	32.9	28.5	23.7	39.9	28.3
6b01266	2430	23.6	28.3	23.2	38.6	27.4
6b01267	2378	25.7	23.4	16.6	34.9	22.8
6b01268	2328	32.0	12.9	8.5	25.0	13.1
6b01269	2275	41.9	12.2	5.9	24.0	26.6

6b01270	2216	26.5	18.1	12.9	30.5	17.5
6b01271	2168	24.9	27.7	21.5	40.6	25.9
6b01272	2118	38.5	37.2	28.0	48.1	34.0
6b01273	2068	33.7	39.7	32.7	48.0	38.0
6b01274	2020	39.6	40.0	32.8	49.6	39.5
6b01275	1972	28.0	37.4	29.2	45.7	36.4
6b01276	1918	23.3	32.8	26.4	42.7	33.9
6b01277	1865	27.2	35.1	24.5	39.9	32.1
6b01278	1816	27.1	32.2	25.3	40.8	31.9
6b01279	1769	37.0	27.5	19.1	36.4	27.0
6b01280	1715	48.0	20.8	11.9	32.8	24.1
6b01281	1664	52.0	21.0	17.7	31.6	25.5
6b01282	1611	58.7	21.5	15.6	30.3	23.8
6b01283	1564	39.9	20.9	18.1	29.3	25.3
6b01284	1510	40.6	20.4	17.7	28.5	25.6
6b01285	1461	43.5	21.8	17.6	28.6	24.7
6b01286	1415	42.5	21.7	16.8	28.1	25.7
6b01287	1364	41.1	22.0	16.4	28.1	24.7
6b01288	1317	37.4	22.8	18.4	28.4	27.7
6b01289	1268	25.9	23.2	18.5	29.3	27.8
6b01290	1215	20.8	24.0	18.4	29.4	27.4
6b01291	1193	19.9	23.3	18.4	29.1	26.5
6b01292	1142	26.5	22.5	17.9	27.7	26.9
6b01293	1096	21.8	20.9	17.3	26.6	25.7
6b01294	1045	20.8	18.8	16.1	25.0	24.4
6b01295	995	23.3	17.1	15.4	23.1	21.8
6b01296	945	21.8	16.7	15.6	22.9	21.5
6b01297	895	21.2	16.3	16.0	22.0	21.4
6b01298	845	49.9	14.3	13.8	21.5	20.6
6b01299	795	25.5	14.4	12.3	18.1	18.7
6b01300	745	20.8	12.3	10.6	17.3	18.1
6b01301	695	22.2	11.7	10.6	14.8	16.9
6b01302	645	24.7	11.4	10.0	14.3	17.4
6b01303	595	25.7	9.4	8.7	13.7	16.4
6b01304	540	22.5	9.4	9.1	12.8	15.5
6b01305	490	26.9	9.6	9.5	12.7	15.6
6b01306	440	22.9	8.9	8.7	14.7	15.1
6b01307	390	22.7	9.8	9.6	13.5	16.1
6b01308	340	23.7	9.4	7.9	12.9	16.1
6b01309	290	23.7	8.6	8.5	12.3	16.6
6b01310	240	23.7	8.9	8.9	12.8	16.3
6b01311	200	22.6	11.1	11.1	12.3	15.9
6b01312	150	35.1	10.0	10.0	11.3	16.9
6b01313	80	37.4	10.8	10.8	11.2	17.3

6b01314	50	35.2	19.1	19.1	21.7	26.1
6b01315	0	10.6	32.3	32.3	35.0	40.5

3.1. Vegetation line

Significant cutback of the beach vegetation line occurred between 2017 and 2018, from profile 6b01294 to 6b01251 (1045 – 3170 m chainage). This resulted in undermining of the road and collapse between profile 6b01261 and 6b01257 (2670 – 2872 m chainage), where pre-storm distances were already short. In the southern section of the beach (0 – 595 m chainage), the vegetation line remained stable during Storm Emma (Figure 5), despite short pre-storm distances. This is likely due to the southward transport of gravel under the easterly waves during Storm Emma increasing the beach width in the south, thus providing a protective buffer and reducing the cutback of the vegetation line there.

Post-storm vegetation line distances are summarised in map form in Figure 6, and show the vulnerability of the remaining road (prior to road realignment) based on the colour coding system presented in Table 1. Where profile lines are red, the Slapton Line road is considered to be highly vulnerable to the impacts of another storm like Emma, whereas amber and green profiles are considered to be vulnerable and less vulnerable, respectively.

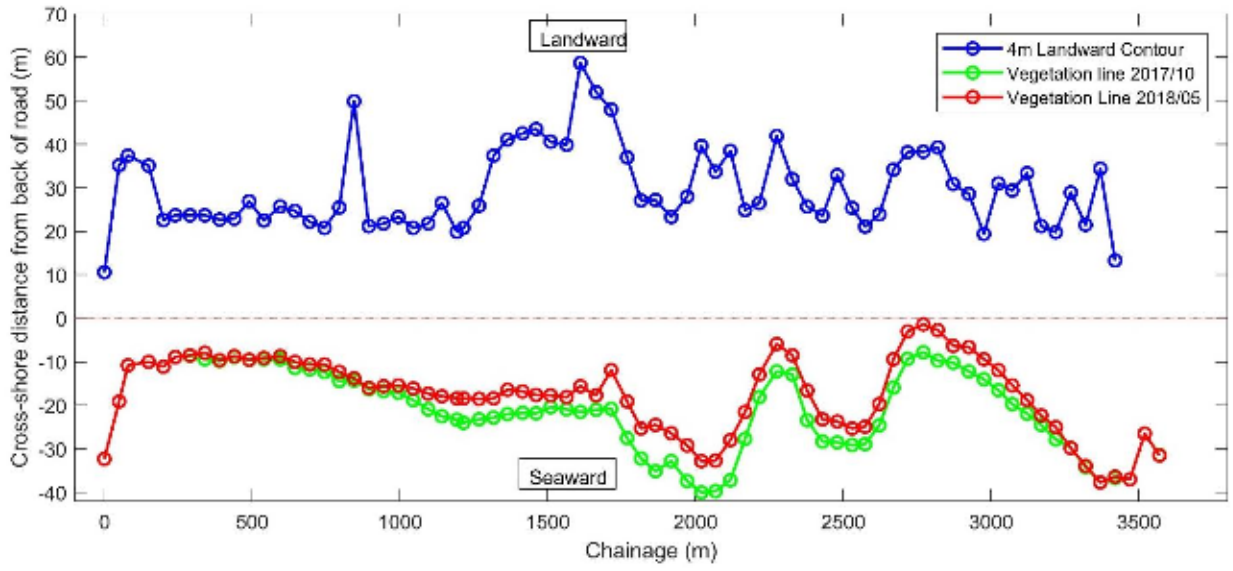

Figure 5. Graphical representation of cross-shore distance from the back of the road to the 4m landward contour, and to the pre and post Storm Emma seaward Vegetation line.

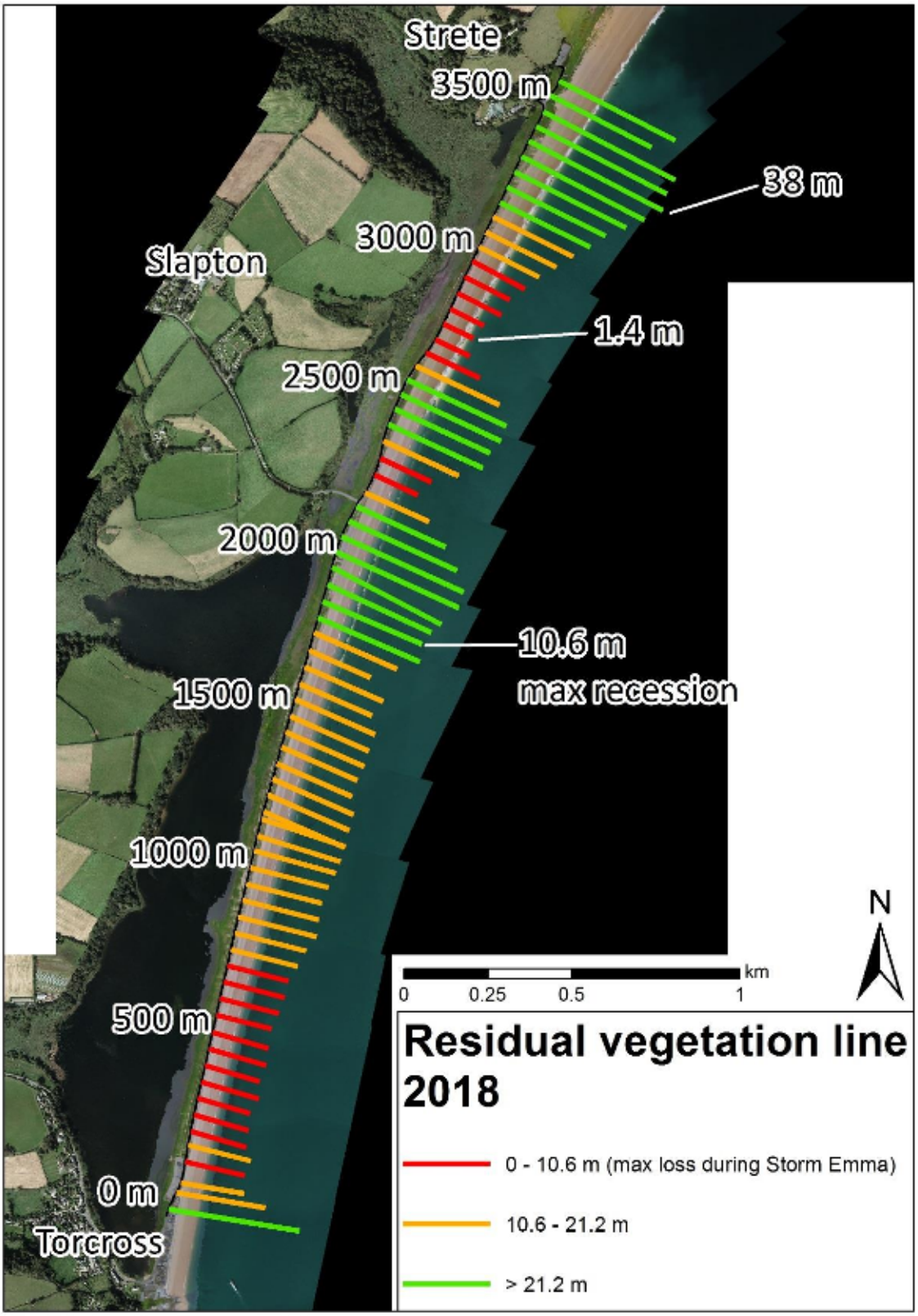

Figure 6. Distances from the back of the A379 road to the residual vegetation line, scaled and colour coded by distance (See Table 1).

3.2. Seaward 4 m contour

During Storm Emma the 4 m beach contour retreated (i.e. the beach narrowed) at the northern end of the Slapton Line, from profile 6b01298 to 6b01243 (845 – 3570 m chainage), where the distance between the back of the road and the 4 m contour decreased by up to 15.2 m (Figure 7). Transport of gravel from the north to the south during Storm Emma is apparent, with beach width increasing in the south by up to 6.1 m (Figure 7) between profile 6b01315 to 6b01299 (0 – 795 m chainage). A pivot point for the observed rotation can be seen between profile 6b01299 and 6b01298 (795 – 845 m chainage).

Post storm 4m seaward line distances are summarised in map form (Figure 8), and show the health of the beach in front of the road. Where profile lines are red ('highly vulnerable'), distances from the back of the road are less than 15.2m, which represents the maximum retreat observed at this contour as a result of Storm Emma. Where lines are amber ('vulnerable'), distances are between one and two times the maximum recession observed due to storm Emma. Green lines ('less vulnerable') have post-storm distances greater than two times the maximum loss observed during storm Emma.

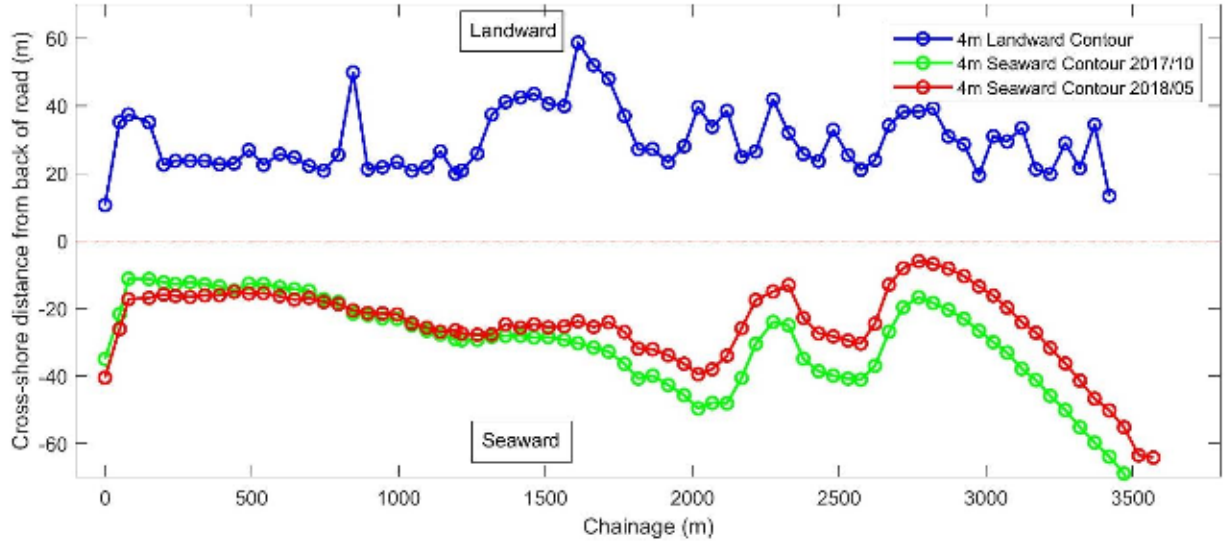

Figure 7. Graphical representation of cross-shore distances from the back of the road at 50m chainages, landward to the 4m landward contour, and seaward to the 4m contour both pre and post storm Emma.

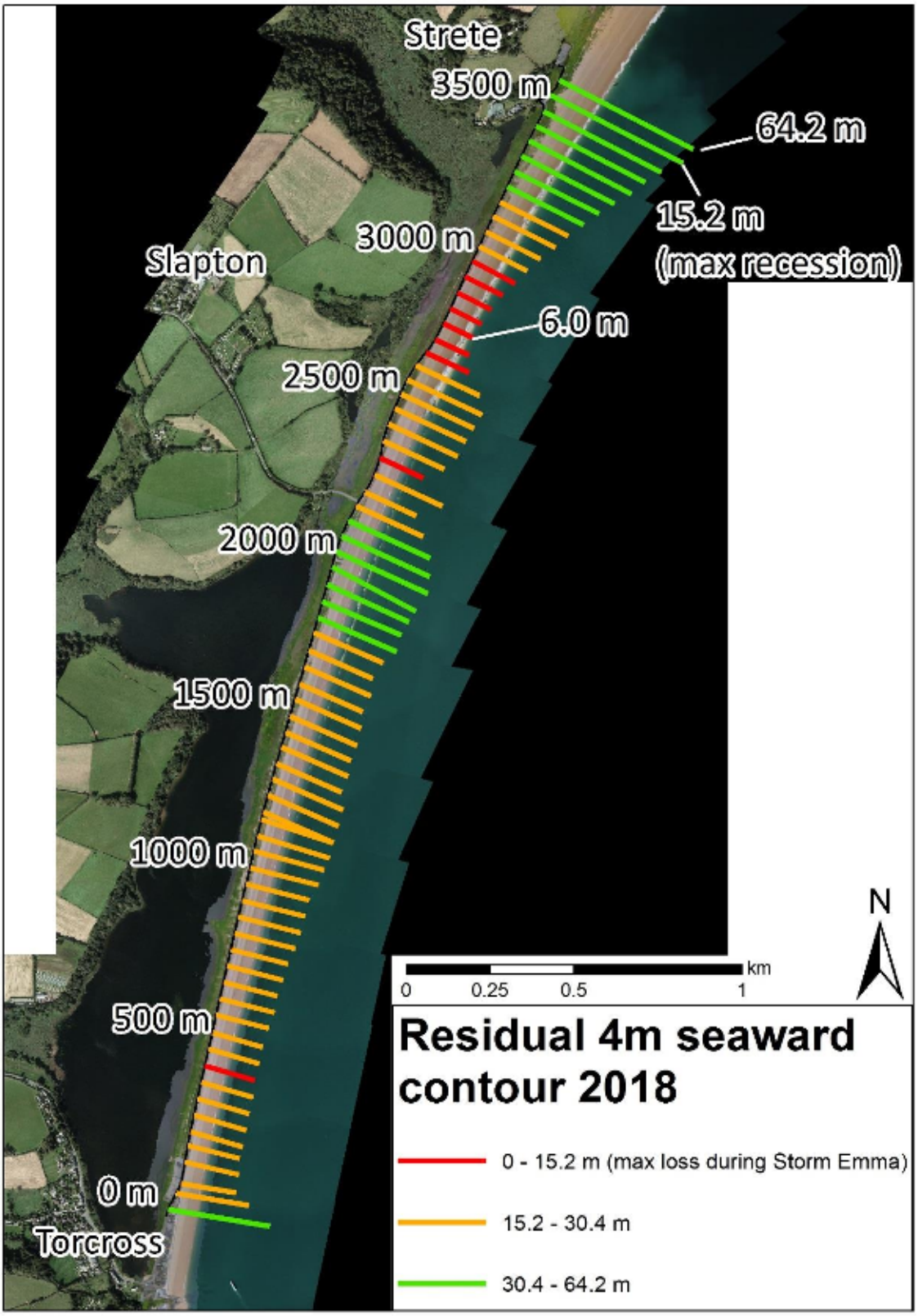

Figure 8. Distances from the back of the A379 to the residual 4m seaward contour, scaled and colour coded by length (See Table 1).

3.3. Landward 4 m contour

Distances to the 4 m landward line give an indication of the area behind the road, and scope for potential relocation (blue line, Figures 5 and 7). The distances are presented in Table 2 and are colour coded based on the thresholds from Table 1. At almost all locations along the Slapton Line, distances to the landward 4 m contour are greater than 18.6 m; at the narrowest locations this provides a potential buffer for road realignment of 8 m road width plus 10.6 m of seaward buffer for protection against future storms. The average distance is 29.6 m, with a standard deviation of 9.2 m. The stretch of road from profile 6b01289 to 6b01311 is uniformly colour coded amber (distances between 18.6 and 29.2m); these regions are classed as vulnerable, but still have space for a road width plus two Storm Emma recession distances to allow for future road realignment and seaward buffer.

The only locations classed as 'highly vulnerable' are profiles 6b01246 and 6b01315, which are at either end of the Slapton Line road (Figure 9). These 'pinch points' do not allow space to realign the road further landward including a seaward storm buffer, and are therefore highly vulnerable to the effects of a future storm of a similar magnitude to Storm Emma. At the Torcross end of the barrier, engineered sea defences protect the Torcross pinch point; similar defences may be required at the Strete Gate end of the barrier to protect the vulnerable pinch point there.

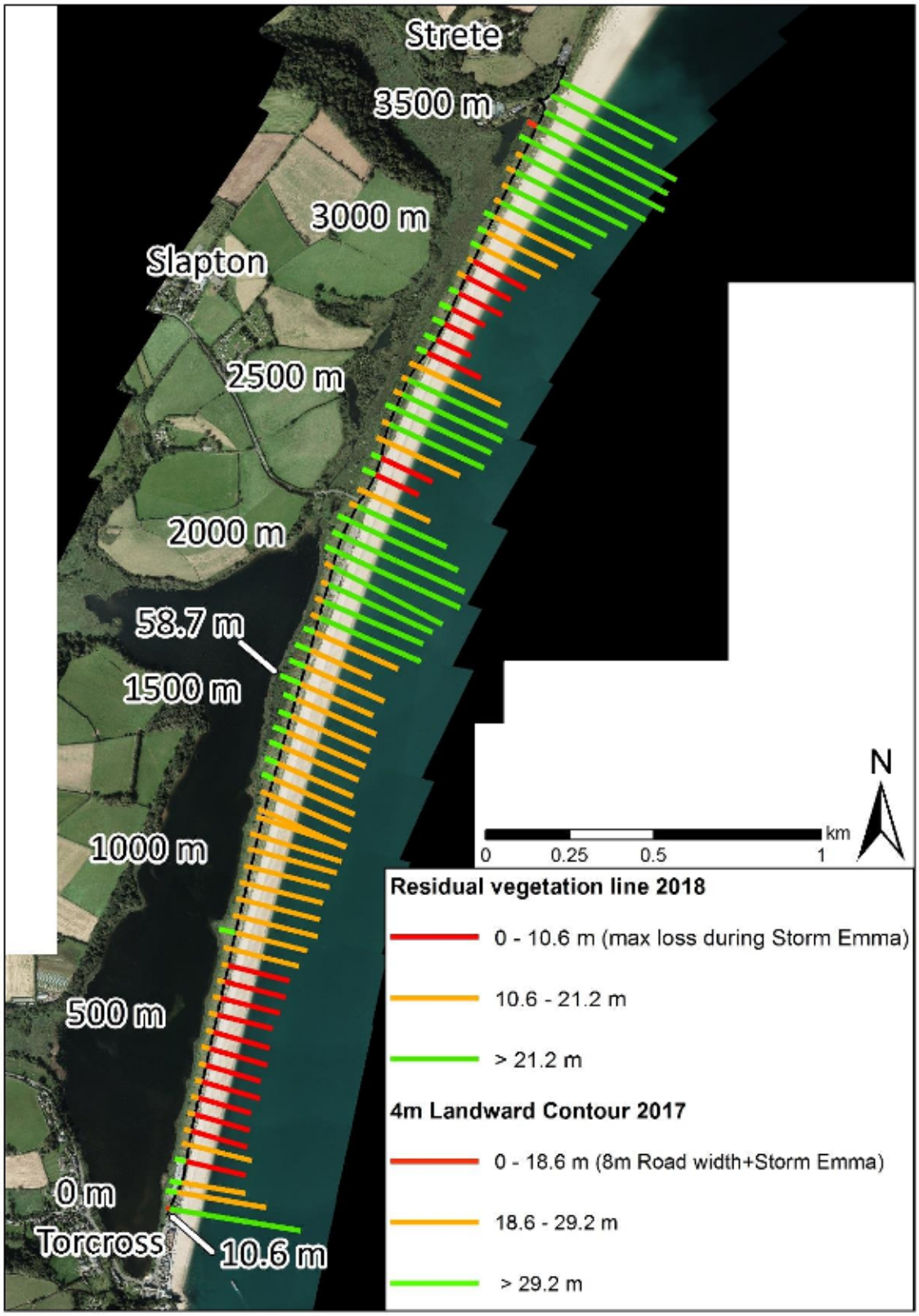

Figure 9. Distances from the back of the A379 to the residual vegetation line, and landward 4m contour, scaled and colour coded by length (See Table 1).

3.4. Road realignment

As described in Section 2, a 1 km section of road between profile 6b01254 and 6b01273 (2068 to 3025 m chainage) was realigned landward of its original position, following damage of the original road during Storm Emma. Updated buffer distances were calculated from the back of the new road to the 4m landward contour, the vegetation line, and the 4m seaward contour. Distances are presented in Table 3, and graphically in Figure 10.

The new section of road has been moved landward by up to 20 m in some places. The distances to the vegetation line for this section now lie mostly within the green category ('less vulnerable' – a seaward buffer of more than 21.2 m, representing twice the maximum recession observed during Storm Emma). This shows that the level of natural seaward defence has increased in this location.

Whilst the seaward buffers (both Vegetation line and 4 m seaward contour) have increased as a result of moving the road landward, the distance to the 4 m landward contour has decreased for this area. The road now lies closer to the freshwater Ley, limiting the future possibility of further relocation. The newly aligned road at profile 6b01270 now lies only 12.07 m from the 4 m landward contour, and it would therefore not be possible to realign the road with a seaward storm buffer at this location in future. Six of the profiles now fall within the red 'highly vulnerable' category (see Table 1), with distances less than 18.6 m to the 4m landward contour.

Table 3. Updated distances calculated from the back of the A379 road to the extracted contours, including the realigned section (profile 6b01254 to 6b01273, coloured blue on the left-hand side of the table) completed in October 2018. Colours correspond to the distance thresholds set out in Table 1.

Profile	Chainage (m)	4m Landward 2017/06 (m)	Pre-Emma Veg Line 2017/10 (m)	Post-Emma Veg Line 2018/05 (m)	Pre-Emma 4m Seaward 2017/10 (m)	Post-Emma 4m Seaward 2018/05 (m)
6b01243	3570	N/A	31.39	31.46	79.26	64.19
6b01244	3520	N/A	26.46	26.46	78.78	63.53
6b01245	3470	N/A	37.03	37.03	68.93	55.20
6b01246	3420	13.32	36.70	36.44	63.90	50.20
6b01247	3370	34.36	37.74	37.74	59.72	46.68
6b01248	3320	21.52	34.23	33.86	55.16	41.36
6b01249	3270	28.85	29.80	29.80	50.10	36.26
6b01250	3219	19.78	27.77	25.05	45.94	31.73
6b01251	3170	21.16	24.51	22.26	41.22	27.17
6b01252	3122	33.41	21.92	18.81	37.94	24.11
6b01253	3072	29.39	19.66	15.40	33.14	19.80
6b01254	3025	29.79	17.72	13.11	31.29	17.44
6b01255	2976	13.85	19.58	14.94	32.17	19.11
6b01256	2925	16.75	24.01	18.44	34.90	22.25
6b01257	2872	15.05	26.04	22.06	36.17	23.97
6b01258	2820	22.34	26.66	19.69	35.36	23.72
6b01259	2771	23.22	22.84	16.44	31.73	21.07
6b01260	2718	25.12	22.35	16.04	32.72	21.13
6b01261	2670	25.19	24.88	18.40	35.83	21.98
6b01262	2622	22.44	26.07	21.19	38.45	26.02
6b01263	2574	20.92	29.13	25.06	41.27	30.62
6b01264	2530	25.12	29.44	25.63	41.06	29.75
6b01265	2480	32.64	28.74	23.89	40.13	28.50
6b01266	2430	22.77	29.11	24.05	39.36	28.18
6b01267	2378	19.36	29.76	22.97	41.21	29.13
6b01268	2328	15.45	29.45	25.11	41.61	29.70
6b01269	2275	21.71	32.41	26.06	44.21	46.74
6b01270	2216	12.07	32.50	27.26	44.88	31.86
6b01271	2168	18.09	34.57	28.29	47.40	32.77
6b01272	2118	36.26	39.53	30.29	50.36	36.25
6b01273	2068	33.05	40.35	33.34	48.62	53.35
6b01274	2020	39.62	40.04	32.82	49.55	39.55
6b01275	1972	28.03	37.39	29.19	45.71	36.41
6b01276	1918	23.26	32.82	26.40	42.68	33.95
6b01277	1865	27.24	35.07	24.51	39.85	32.06
6b01278	1816	27.07	32.16	25.34	40.82	31.91
6b01279	1769	36.97	27.51	19.13	36.45	26.97
6b01280	1715	47.97	20.80	11.91	32.81	24.14

6b01281	1664	51.97	21.05	17.70	31.57	25.48
6b01282	1611	58.71	21.50	15.64	30.28	23.79
6b01283	1564	39.92	20.89	18.08	29.32	25.31
6b01284	1510	40.56	20.41	17.67	28.46	25.64
6b01285	1461	43.50	21.81	17.61	28.59	24.68
6b01286	1415	42.50	21.67	16.76	28.13	25.67
6b01287	1364	41.13	22.02	16.41	28.07	24.71
6b01288	1317	37.38	22.78	18.44	28.45	27.68
6b01289	1268	25.94	23.23	18.53	29.34	27.81
6b01290	1215	20.79	23.96	18.38	29.42	27.43
6b01291	1193	19.91	23.32	18.36	29.10	26.54
6b01292	1142	26.53	22.49	17.91	27.71	26.91
6b01293	1096	21.84	20.91	17.34	26.62	25.67
6b01294	1045	20.78	18.81	16.09	25.03	24.38
6b01295	995	23.33	17.09	15.37	23.08	21.75
6b01296	945	21.76	16.67	15.56	22.86	21.46
6b01297	895	21.23	16.33	16.05	22.02	21.45
6b01298	845	49.86	14.28	13.82	21.55	20.64
6b01299	795	25.48	14.44	12.29	18.06	18.68
6b01300	745	20.78	12.31	10.55	17.26	18.06
6b01301	695	22.18	11.67	10.56	14.81	16.95
6b01302	645	24.73	11.45	9.95	14.30	17.44
6b01303	595	25.73	9.45	8.66	13.68	16.38
6b01304	540	22.53	9.38	9.08	12.76	15.49
6b01305	490	26.93	9.56	9.53	12.67	15.64
6b01306	440	22.95	8.94	8.70	14.67	15.12
6b01307	390	22.75	9.84	9.64	13.51	16.10
6b01308	340	23.73	9.43	7.90	12.93	16.09
6b01309	290	23.65	8.61	8.53	12.31	16.57
6b01310	240	23.70	8.89	8.86	12.76	16.30
6b01311	200	22.59	11.10	11.10	12.34	15.90
6b01312	150	35.07	10.00	9.97	11.29	16.87
6b01313	80	37.45	10.84	10.84	11.22	17.30
6b01314	50	35.22	19.05	19.05	21.66	26.05
6b01315	0	10.57	32.25	32.25	35.03	40.51

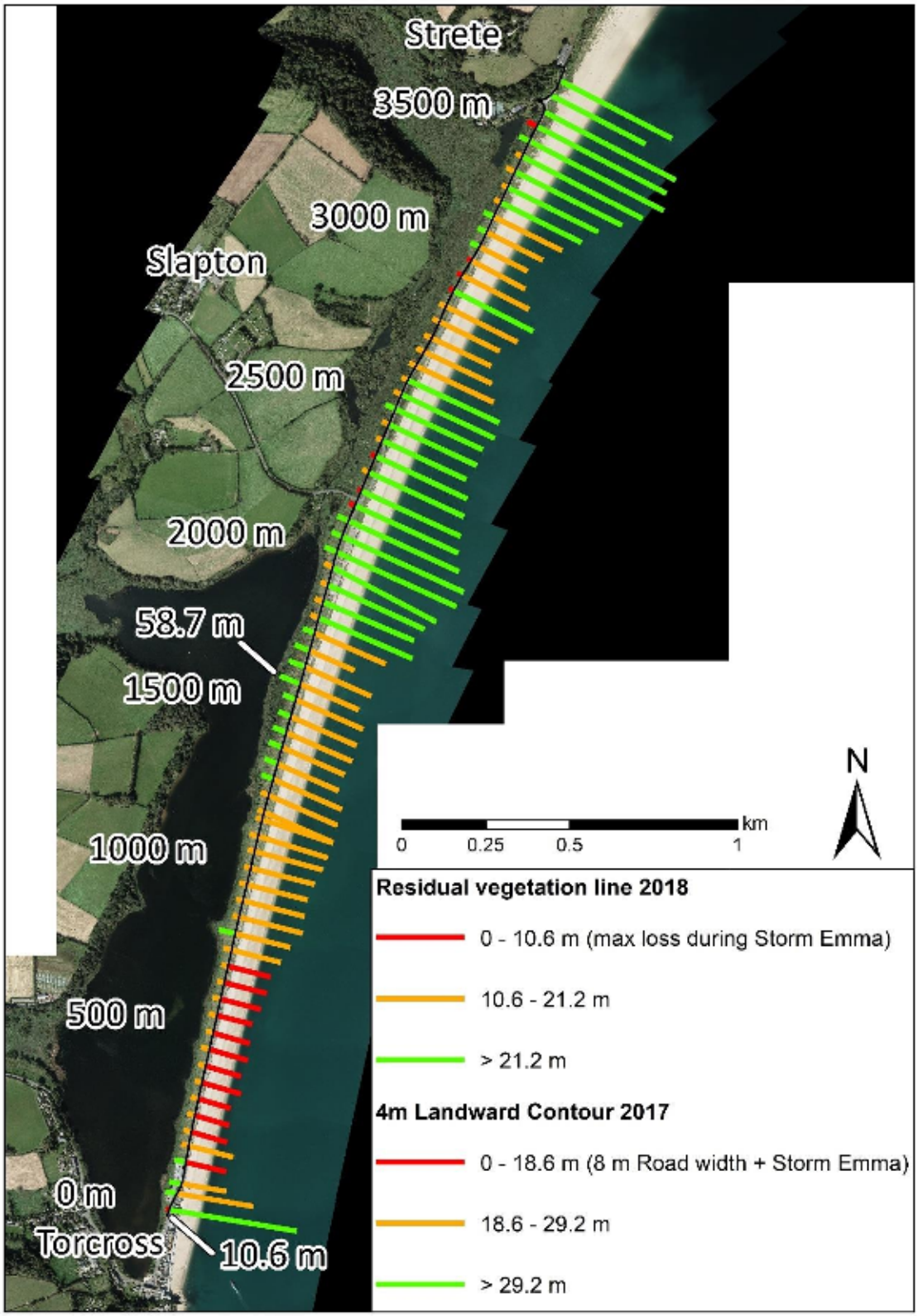

Figure 10. Updated distances from the back of the A379, including new road alignment, to the residual vegetation line, and landward 4m contour, scaled and colour coded by length (See Table 1).

4. Conclusions

Elevation datasets from April and October 2017 to May 2018 have been used to assess the impact of Storm Emma on the Slapton Line barrier, and parameterise the vulnerability of the road and its future position. Distances calculated from the back of the road to the seaward vegetation line, 4 m seaward contour, and 4 m landward contour were calculated in order to indicate the beaches response to the storm, the present seaward and landward buffer distance to the road, and the scope for realignment of the road in the future. From this data set the following conclusions can be drawn:

- Counter-clockwise rotation of the shoreline (i.e. beach narrowing in the north and widening in the south) was observed under the energetic easterly waves experienced during Storm Emma. This indicates that gravel was transported from the north end of the beach to the south end of the beach during the storm.
- Significant recession of the seaward vegetation line was recorded, and resulted in the subsequent collapse of the A379 road along a 1 km stretch of the Slapton Line.
- Landward relocation of the damaged road sections in October 2018 has increased distances to the seaward vegetation line and seaward 4 m contour. However, the new road is now less than 15 m from the 4 m landward contour in some places, meaning future realignment may not be possible if the road is damaged in these particular locations.
- The maximum beach recession during Storm Emma occurred at the northernmost extent of the road, near Strete Gate. Healthy beach levels (large distances to the 4 m beach contour) prior to Storm Emma reduced the damage experienced in that location, demonstrating the importance of beach width in controlling storm impacts along the Slapton Line.
- Beach width at a given location along the Slapton Line (in this case parameterised by the distance to the 4 m seaward contour) immediately prior to a future storm will therefore have a large influence on the amount of impact experienced at the seaward vegetation line and on the A379 road.
- Gravel moves in large quantities northward under southerly wave conditions, and southward under easterly wave conditions (Wiggins et al. 2019), and beach width along the Slapton Line can therefore change significantly over relatively short (e.g. storm) time scales.
- Present-day beach width cannot therefore be relied upon to provide protection from future storms, as beach width varies over daily to inter-annual time scales. Constant monitoring of the beach width is the only way to provide up-to-date assessment of the most vulnerable areas prior to a storm.

References

Austin, M. J., 2005. Swash, groundwater and sediment transport processes on a gravel beach. Ph.D. thesis. Department of Geography, Loughborough University, UK.

Chadwick, A., Karunarathna, H., Gehrels, R., Massey, A., O Brien, D. and Dales, D., 2005. A new analysis of the Slapton barrier beach system, UK. Proceedings-Institution of Civil Engineers Maritime Engineering. pp 147.

Hails, J.R., 1975. Submarine geology, sediment distribution and Quaternary history of Start Bay, Devon: Introduction. Journal of the Geological Society. 131, 1–5.

Kelland, N., 1975. Submarine geology of Start Bay determined by continuous seismic profiling and core sampling. J. Geol. Soc. London. 131, 7–17.

Plymouth Coastal Observatory, The South West Regional Coastal Monitoring Programme. Plymouth University. http://southwest.coastalmonitoring.org/.

Ruiz de Alegria-Arzaburu, A., Masselink, G., 2010. Storm response and beach rotation on a gravel beach, Slapton Sands, U.K. Mar. Geol. 278, 77–99. https://doi.org/10.1016/j.margeo.2010.09.004

Wiggins, M., Scott, T., Masselink, G., Russell, P., McCarroll, R.J., 2019. Coastal embayment rotation: Response to extreme events and climate control, using full embayment surveys. Geomorphology 327, 385–403. https://doi.org/https://doi.org/10.1016/j.geomorph.2018.11.014