Coastal Cliff Monitoring - Cowbar Nab, Staithes, N. Yorkshire

Monitoring period: September 2018 to December 2019

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Prepared for and on behalf of:

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1. Executive Summary

- This report summarizes results from monitoring coastal erosion and cliff retreat at Cowbar Nab, Staithes, over two timescales:
    - Monthly analysis over the period since our last report to Redcar and Cleveland Borough Council (RCBC) which reported data up to August 2018. This report also includes higher-frequency data collected since installation of a permanent monitoring instrument in October 2017.
    - Annual data since start of our monitoring at this site in January 2011.
- The monitoring program is being undertaken for and on behalf of Scarborough Borough Council and Redcar and Cleveland Borough Council.
- This report describes the rate of erosion and highlights features of the changes observed that are pertinent to the management of erosion risk at this site.
- Data is now collected using a permanently installed terrestrial laser scanning system, developed specifically for this project since 2017. The system scans the cliff each hour, and the data is relayed to Durham where cliff-face change (erosion / rockfalls) is calculated on a rolling basis to highlight rockfalls and cliff erosion at a high frequency without need to visit the site.
- We make recommendations based upon the changes that we have observed to date, and the outcomes from our wider program of coastal erosion monitoring along this coastline.

2. MONITORING OVERVIEW SINCE SEPTEMBER 2018

- Data is reported for the months including and between September 2018 to December 2019.
- The background to the monitoring approach using the permanent laser scanner installation is described in full in the report dated August 2018.
- The system has functioned well, with continuous monitoring during 95.2% of the period covered in this report.
- The permanent monitoring system was serviced by the manufacturer in October / November 2019, which involved shipment of the equipment to Austria. Whilst the scanner has been serviced, part of the field installation has been vandalized, but there is no damage to the core infrastructure at the site. The local landowner, Mr Colin Mann, has been supportive by keeping a watch on the system.
- We have now halted monthly surveys from the foreshore, as comparison over a period of a year has shown a good degree of comparability with the data from the permanent monitoring system.
- In this report, we continue to document the calculation of the erosion rate for the seaward facing cliff at Cowbar Nab as a whole, and also in detail for the area of the cliff face immediately before Cowbar Lane, termed the 'focus zone', as described in the previous report.

3. MONITORING RESULTS

a. Results: May 2015 – December 2019

We summarise the erosion rates between May 2015 and December 2019, presented in detail in Table 1 and 2, and Figures 1 - 5, which include higher-frequency monitoring from October 2017. We summarise this on a monthly basis for comparability:

- A total volume loss of 353.03 m^3 in 30,647 discrete rockfall events occurred during this 54-month period.
- The area-averaged rate of retreat observed in the period May 2015 to December 2019 for the whole site was 0.043 myr^{-1}.
- The modeled rate of retreat in the period May 2015 and December 2019 for the whole site was 0.053 myr^{-1}.
- The area-averaged rate of retreat observed in the period May 2015 to December 2019 for the focus zone was 0.058 myr^{-1}.

- The lowest monthly volume of rockfall was observed in April 2019 (4.65 m^3). The highest monthly volume of rockfall occurred in October 2019 (57.98 m^3) (see: Table 1). The maximum depth (relative to the cliff face) of any single rockfall observed into the cliff face during this period was 4.79 m in September 2019 (Figure 4).

- We observe several sequences of events, whereby rockfall in successive months and years appear linked. During this monitoring period, due to the relatively low levels of activity, whilst these processes continue, they are minimal in extent and impact on the overall cliff face topography. In summary, the main forms of behaviour include:

    - Upward propagation of rockfall, apparently initiated by wave quarrying of the cliff toe and subsequent failure of the overhanging cliff mass above to leave a more near-planar, near-vertical cliff face remaining.

    - Failure of small-scale convex sections of the cliff face, to leave a more near-vertical cliff face remaining.

    - Lateral across-cliff failure migration, whereby rockfall scars coalesce into cross-cliff arch structures, which are inherently more stable, and are commonly bounded above by more massive rock beds. We note this behavior within the focus zone described above, most notably immediately above the rock armour.

    - We observe that, compared to immediately preceding years, data collected with the fixed monitoring system since October 2017 has indicated that that the erosion rates and magnitude of rock failures have been low. Small failures compared to previous monitoring periods have occurred, but these have tended to be isolated, rather than contiguous upon the cliff face. Recent failures in the winter have been at the cliff toe, indicative of marine action, and subsequently in the summer months high up on the rock face. None of these failures has influenced the cliff top and within themselves indicate no pattern of wider instability.

- As observed previously, quarrying of the cliff toe immediately to the east and west of the rock armour continues (right in Figures 3 and 4), which has led to the undercutting off the cliff face above. The area to the west of the rock armour is yet to experience a larger-scale failure since the onset of monitoring. This is also captured in our analysis of Profile 3, discussed below.

- We do continue to note some additional failures from the section of cliff proximal to Profile 3, but this is largely small in scale and depth, and does not appear to reflect a wider scale instability at this stage. As observed before, this is a section of coastline where the fence line is set further back inland, so if this failure were to develop, it would be unlikely to threaten any assets on the cliff top such as the road bed.

- We note no failure of note in the glacial till during this monitoring period, beyond seasonal changes in vegetation.

- We note no significant loss of cliff top / edge material during this monitoring period.

- The spatial pattern of erosion continues to be commensurate with marine driven erosion at the toe of the cliff, in addition to the continued failure of previously active areas of the cliff expanding further, albeit at a lower rate that previously observed.

b. Results: January 2011 – December 2019

The long-term (January 2011 to December 2019) annualized erosion rates are as follows for the 108 months (3212) of monitoring at this site to date:

- 108-month area-averaged erosion rate for the whole site is 0.043 myr^{-1} (Table 2). This is based on observed rockfall alone.

- 108-month modeled erosion rate for the whole site is 0.053 myr^{-1}. This rate considers the full range of possible rockfall sizes at this site, and is observed to stabilize over time as a more complete range of event sizes is recorded. Using this measure of erosion overcomes the limitations of monitoring only a small area / non-representative sample, during a limited time period (see: Barlow *et al.*, (2012) for methodology, and Williams et al. (2019) for a wider justification).

- 108-month area averaged erosion rate for the focus zone is 0.058 myr^{-1}. This rate is based purely on the rockfalls observed at the site using the laser monitoring.

- 108-month modeled erosion rate for the focus zone is 0.051 myr^{-1}. This rate considers the full range of possible rockfall sizes at this site, and will stabilize over time as a more complete range of event sizes is recorded. This approach overcomes the limitations of monitoring only a small area / non-representative sample, during a limited time period (see: Barlow *et al.*, (2012), Williams et al (2019) and Benjamin et al., 2017).

- Since the start of monitoring in 2011 a total of 4,340.68 m^3 of rockfall has occured, sourced from 153,827 discrete rockfall events identified from monthly sequential monitoring (Tables 1 and 2). This total volume of rockfall is equivalent to a cube with dimensions of 16.3 m. Rockfalls at this site adhere to a power law volume frequency distribution. This means that the majority of rockfalls are small (ca. 2.5 x 10^{-4} m^3 or smaller) with a decreasing frequency of increasingly large failure events. As such, whilst the numbers of rockfalls observed is high, their individual volume and the erosion that the majority accrue remains small, and importantly larger events that are more likely to result in a change to the cliff line are comparatively infrequent.

- On average over 108 months 2,011 discrete rockfall events occur at this site monthly, in rockfall volumes > 2.5 x 10^{-4} m^3, up from 1,322 reported in the last report.

- Over 108 months, the average monthly volume of rockfall is 43.46 m^3, equating to 0.176 m^3 per month per metre of coastline, and equivalent to a cube of dimensions 0.561 m from each metre of coastline in each month.

- Between May 2015 and December 2019, the area-averaged erosion rates for the full site continued on average to be higher than in the years between January 2011 and May 2015 (Table 1), although more lately this pattern appears to be returning to the long-term average after a period of heightened activity. This increase is attributed to the occurrence of a small number of larger rockfall (e.g. May 2016) and no more recent recurrence of comparable events, in addition to several major winter storm periods which were observed to result in both increased rates of background rockfall activity (e.g. Storm Desmond, 3 – 8th December 2015), and substantial direct responses to these events themselves. Again, storms during the current monitoring period have not had comparable erosion / cliff collapse effects as those seen in 2015.

- The modeled erosion rate for the whole site, and for the focused site, continues to converge to a stable longer-term average (Tables 1 and 2). This reflects the tendency to capture a more complete rockfall volume-frequency distribution of all possible rockfall volumes within a longer period of monitoring. This gives more confidence in the annualized erosion rates as a function of the convergence of these two methods.

- The rates of erosion observed at this site within each month remain heavily influenced by a low number (commonly < 3 in any given month) of larger (> 1 to 10 m^3) rockfall events. This period of monitoring has witnessed a lower number of event of this size, and so rates between months remain both consistent and low throughout this period.

- As a result, the potential for retreat at any point on the coast remains best predicted with a detailed structural assessment of the rock mass and change experience at that specific location, rather than wider-area, long-term erosion rates.

- Over the 8.8 years of monitoring reported here, the development of vertically propagating rockfall scars that evolve from one year to the next is observed. In this period this process continues, albeit at a more retarded rate than in previous periods. This process is initiated by wave action at the cliff toe, which destabilises the cliff face above, tending to result in the failure of convex sections of the cliff.

- The monthly volume of rockfall for this section of cliff is slightly lower than that observed elsewhere along this coastline (see: Benjamin, 2018), most likely due to the relatively low (< 30 m) cliff height – and hence area of cliff from which rockfalls can fall - as compared to the coastline both east and west of this site. Differences in retreat rates per unit area between this site and other sites monitored elsewhere on this coastline remain comparable and broadly in proportion to the cliff height / available rockfall source area.

- Based upon this data, there is no indication that the erosion of the cliff at Cowbar is accelerating or deviating away from behavior observed at this site previously. This period of monitoring shows behavior more akin to the long-term average retreat rates observed previously at this site. The variations in rates of erosion reported here represents variability widely observed on similar cliffs, and should not be taken to infer increasing or decreasing stability. Despite the results in this monitoring period, this relative quiescence does not preclude the future possibility of a large scale rockfall that may threaten Cowbar Lane. However, the data presented here does not indicate a deterioration of the condition of the cliff that currently raises concern.

c. Analysis of profile form change

- Slope profiles have been extracted from the laser scan data through the cliff. Profile locations are provided in Figure 1, and profile change through time on an annual basis is provided in Figure 5.

- Profile 1 has experienced a degree of back-wearing in the cliff toe area that is inundated by wave action, and some alteration around small scale convexities further up the cliff face profile. This degree of back wearing (ca. 1 m max) around the bottom 10 m of the cliff face is small and reflects the coincidence of a single slab-like rockfall at this location, rather than a wider and more systematic alteration of the wider cliff form. Whilst this does contribute to undercutting at this location, the cliff toe remains seaward of the fence line, but the growth of the overhang continues (currently around 6 m at this location). As a result, whilst this profile has remained little changed in this monitoring period, it is anticipated that the rock above this section will fail in due course. The timing of this remains unknown, and our data to date shows no sign that this is imminent. Importantly, based on the style of previous failures of this type at this location, the rockfall will likely remove the overhang, rather than retreat the cliff edge back substantially, and so it is unlikely that the fence will be impacted.

- Profile 2 has remained relatively unchanged in form during this monitoring period, with only minor adjustments to small-scale convexities up profile. Some evidence of cliff toe quarrying is apparent, in line with typical changes observed on this cliff. This represents a minor additional oversteepening of the cliff, but is far from to a degree that would act to significantly destabilize the cliff mass above.

- Profile 3 shows minimal loss of material from toe to crest. Continued development of the undercut at the toe of the cliff of a degree that raises concerns of wider-scale failure and collapse is not observed. Despite this, it is still anticipated that this area of failure will develop over time, over-steepening and collapsing the cliff face above, the rate of development of this failure in this area appears to have slowed. As previously, the cliff line at this point is some 5.5 m seaward of the fence line, and so based on the style of previous failures, this would be unlikely to impact upon assets at the cliff top.

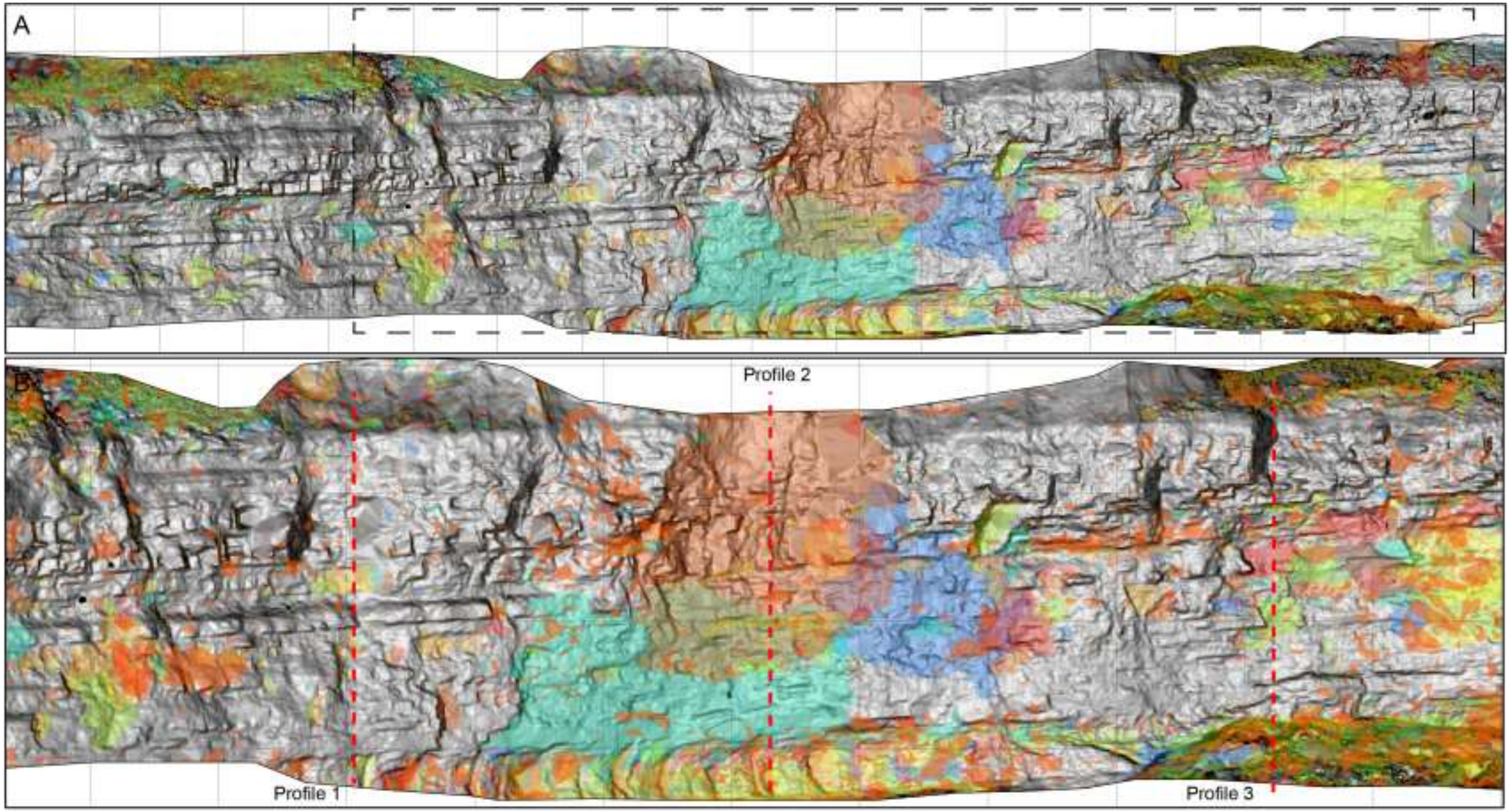


Figure 1. Monitored erosion at Cowbar Nab between January 2011 and December 2019. (A) shows an elevation view of the rock cliff at Cowbar, displayed as if viewed from a point on the foreshore at low tide. The greyscale image is the slope of the cliff face, to provide indciative topography (hillshade), and the colours show areas of rockfall since 2011 colour by year. The grid interval is 10 m in both horizontal and vertical axes. The black dashed square delimits the extents of the area shown in B. Location of profiles in Figure 4 is detailed by dashed lines. (B) shows a close up view of the cliff directly beneath Cowbar Lane and directly above the rock armour.

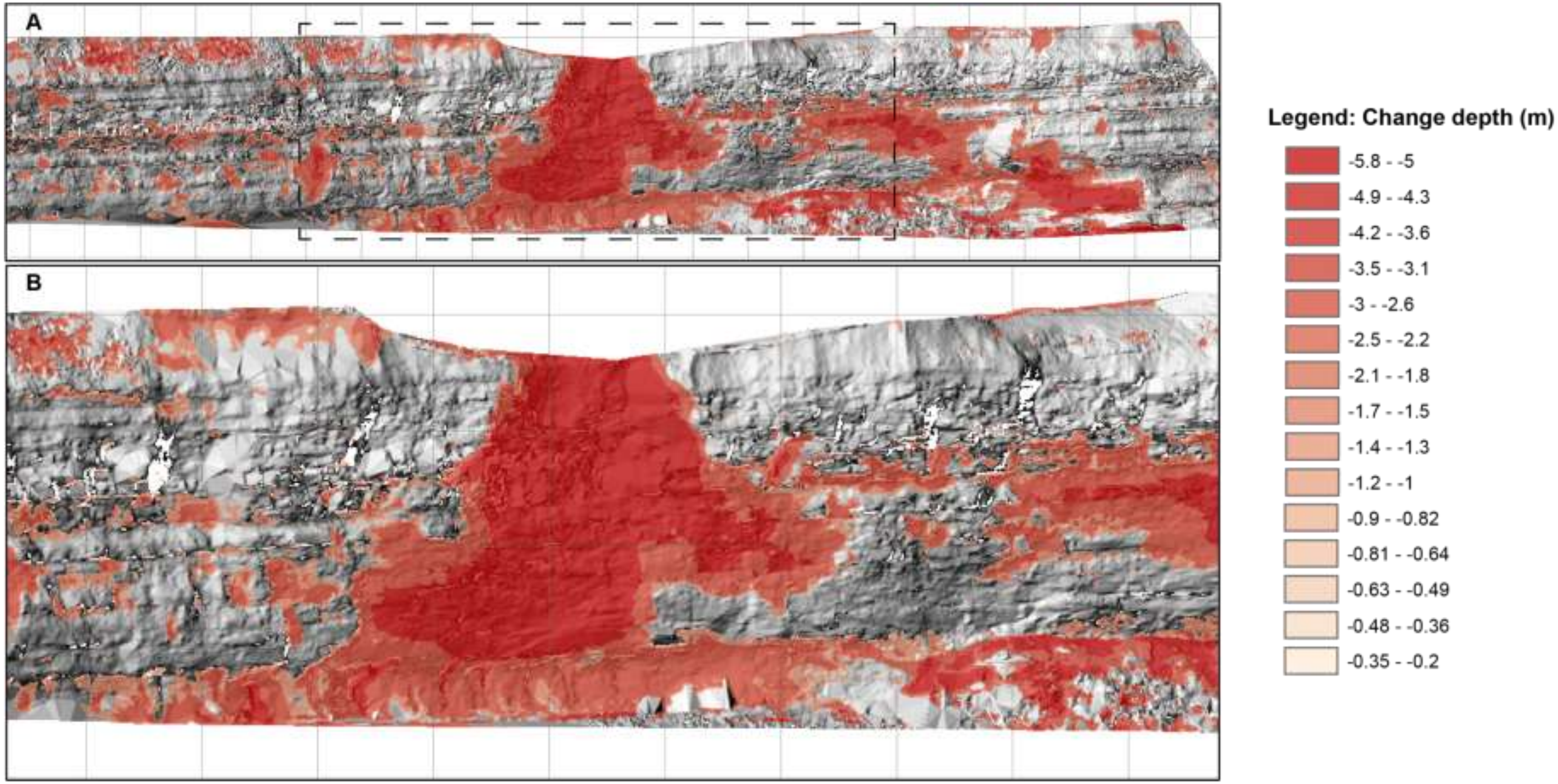


Figure 2. Monitored erosion at Cowbar Nab between January 2011 and December 2019, showing depth of erosion (increasing depths are hotter colours). (A) shows an elevation view of the rock cliff at Cowbar, displayed as if viewed from a point 100 m seaward from the cliff toe on the foreshore. The greyscale image is the slope of the cliff face, to provide indicative topography (hillshade), and the change is coloured by depth relative to the cliff, ranging from 0 to 5.8 m in inremental of geometrical interval. The grid interval is 10 m in both horizontal and vertical axes. The black square delimits the extent of the area shown in B. (B) shows a close up view of the cliff directly beneath Cowbar Lane and directly above the rock armour.

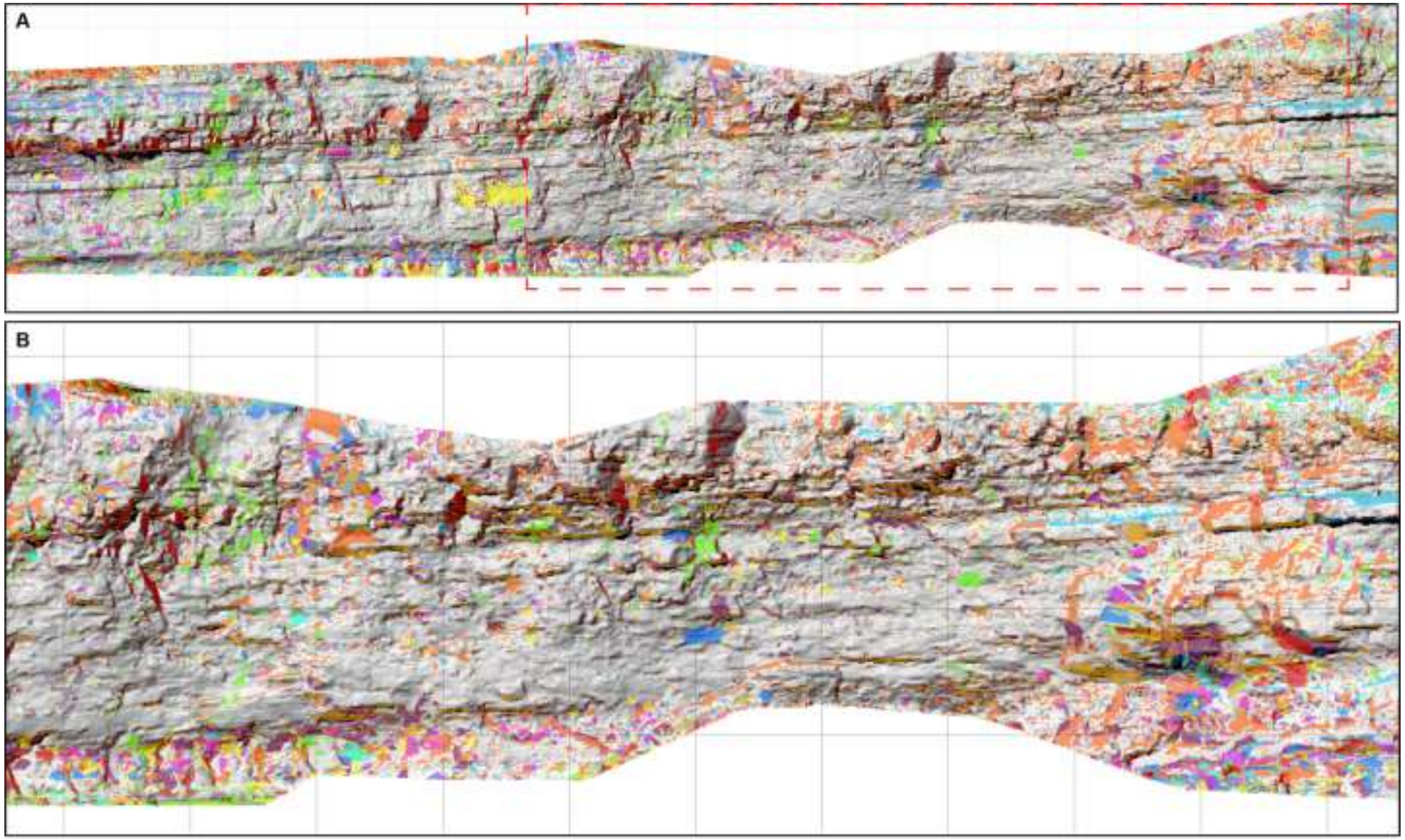
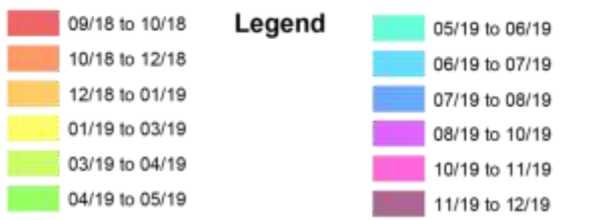


Figure 3. Monitored erosion at Cowbar Nab between September 2018 and December 2019, showing areas of failure at one month monitoring intervals. (A) shows an elevation view of the rock cliff at Cowbar, displayed as if viewed from a point 100 m seaward from the cliff toe on the foreshore. The grayscale image is a hillshade map of the cliff face to provide indicative topography, and the coloured polygons shows the location and shape of rockfalls by month. The grid interval is 10 m in both horizontal and vertical axis. The red square delimits the extent of the area shown in B. (B) shows a close-up view of the cliff directly beneath Cowbar Lane, and directly above the rock armour. Note that rockfall polygons are layered from youngest (purple) to oldest (red), so some may be obscured.



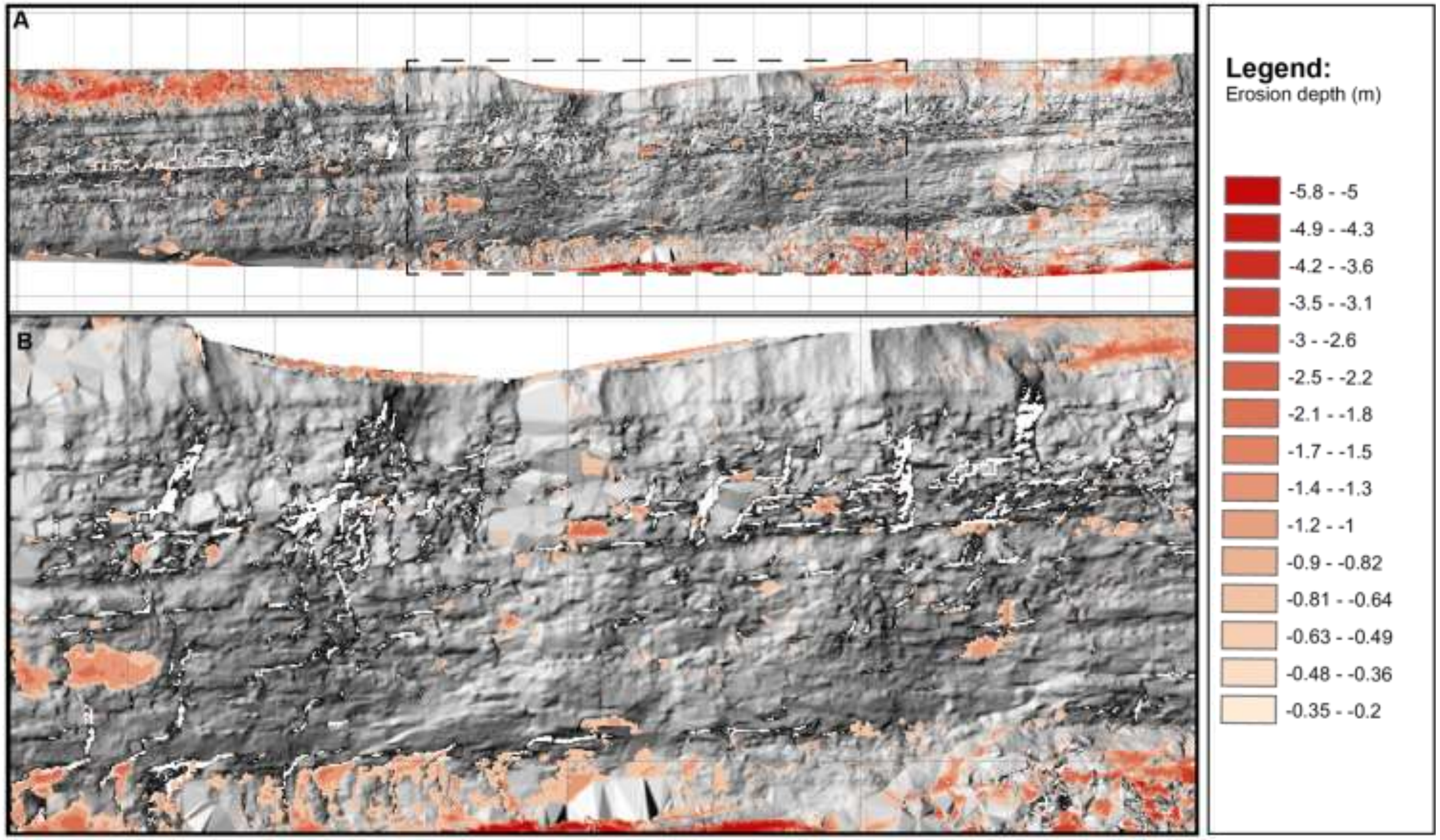


Figure 4. Total depths of monitored erosion at Cowbar Nab between September 2018 and December 2019, showing depth of erosion (increasing depths are hotter colours). (A) shows an elevation view of the rock cliff at Cowbar, displayed as if viewed from a point 100 m seaward from the cliff toe on the foreshore. The greyscale image is the slope of the cliff face, to provide indicative topography (hillshade), and the change is coloured by depth relative to the cliff, ranging from 0 to 5.8 m in inremental of geometrical interval. The grid interval is 10 m in both horizontal and vertical axes. The black square delimits the extent of the area shown in B. (B) shows a close up view of the cliff directly beneath Cowbar Lane and directly above the rock armour.

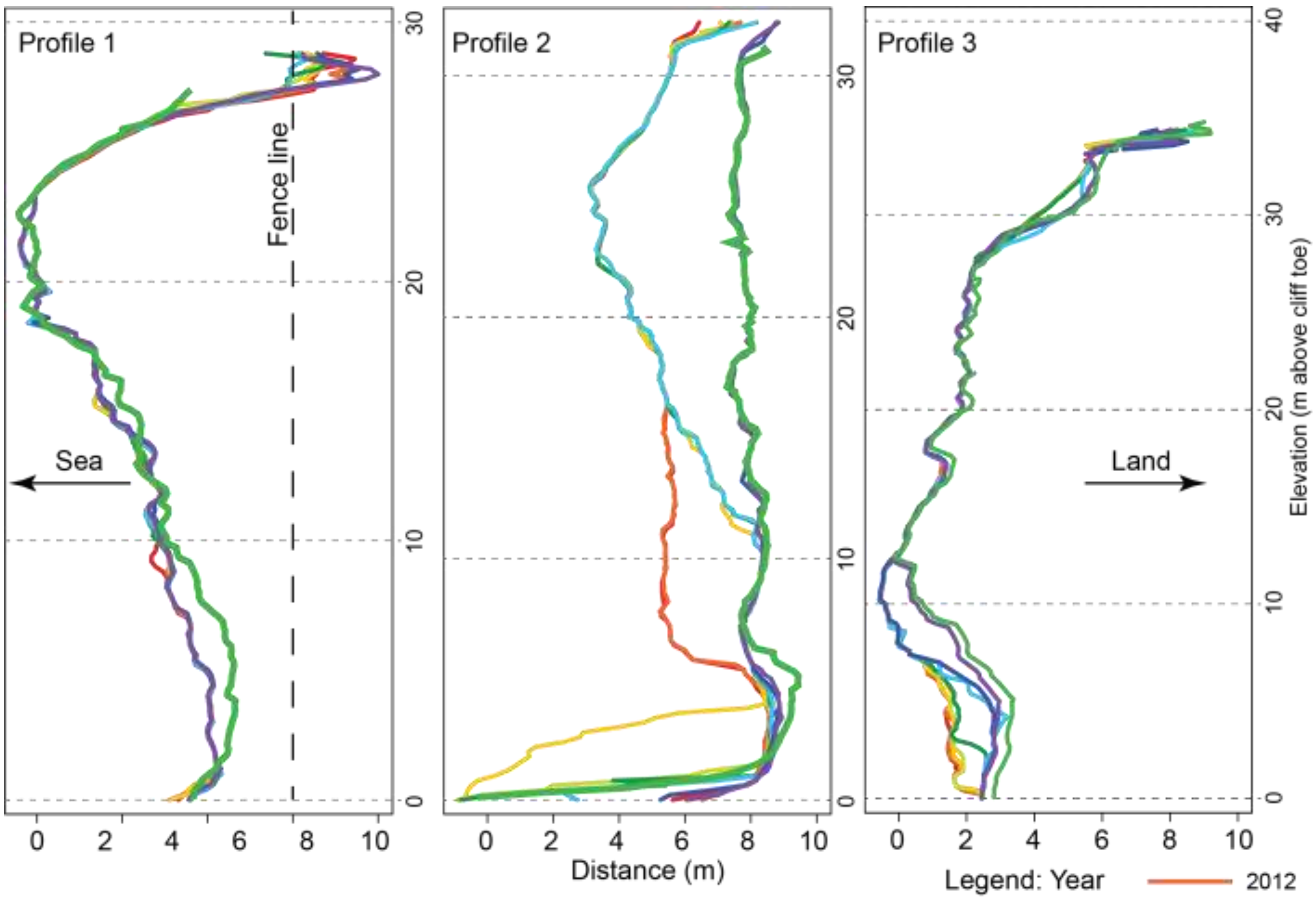


Figure 5. Cliff profiles (locations shown in Figure 1). Profile topography is taken from years 2011 through 2019. Horizontal distances are in units of m from a arbitrary datum in front of the cliff toe. Retreat of the cliff is from left to right. Note that the vertical scale is different for each profile.

4. High-frequency monitoring:

The fixed scanner at Cowbar Nab enables more information on the size, location and timing of rockfall to be derived. The praimry observations are:

- An increase in monitoring frequency to 1-hour intervals reveals a 10^3 increase in the number of rock blocks observed to fall from the cliff. This is because at 1-month intervals the rockfalls that are measured as single larger rockfall are actually a larger number of smaller neighbouring events. The absolute frequency of rockfall is therefore higher than monthly monitoring would suggest. This finding is now reported in Williams et al (2019).

- A consequence of higher-frequency monitoring is that the average size of rockfalls observed is 10^2 smaller at 1-hour intervals as compared to 1-month intervals. This is again because over 1-month intervals multiple smaller rockfalls are observed as a single larger event. Whilst the mean size observed reduces, it remains the case that a rockfall of any size can occur.

- On average, throughout the year, small rockfalls appear to occur at random, and there is importantly no period when rockfall frequency reduces to zero.

- Large rockfalls have been observed to have a higher probability of occurrence during high tides, although can feasibly occur at any time.

- The rate of rockfalls is steady through the Spring and Summer, but experiences a step-change increase at the start of Autumn, which is sustained throughout the Winter. This indicates the seasonality of cliff erosion.

- Single large storms in the winter can account for > 15% of the total rockfall volumes experienced during the year. These are times when cliff failure is most probable.

- On average, we observed a steady rise in rockfall rate (ca. 10%) through the day from dawn to dusk. A spike in rockfall frequency is also observed at sunrise, and but most notably at sunset. These findings are considered in greater detail in Williams et al., (2018) and Williams (2017).

Table 1 Combined erosion rates for January 2011 – December 2019 for the monitored cliff section.

Year of monitoring	Month	Month	Year	Survey date (Julian date)	Survey epoch length (days)	Running total of days	Number of rockfalls	Total volume of rockfalls (m^3)	Area average erosion rate (x 10^{-3} myr^{-1})	m/f modelled erosion rate (x 10-3 myr^{-1})	Monthly average erosion rates (myr^{-1})	1 year average of monthly average erosion rates (myr^{-1})	Focus area erosion rate (myr^{-1})	Focus area erosion rate (myr^{-1})
1	1	January	2011	40557	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	2	February	2011	40592	35	35	990	31.69	2.770	0.023	0.0028		0.051	
	3	March	2011	40623	31	66	969	31.00	2.710	2.816	0.0027		0.051	
	4	April	2011	40661	38	104	1036	33.15	2.900	1.716	0.0029		0.054	
	5	May	2011	40683	22	126	4	0.13	0.010	0.000	0.0000		0.000	
	6	June	2011	40711	28	154	21	0.68	0.060	0.022	0.0001		0.001	
	7	July	2011	40745	34	188	660	21.11	1.850	0.484	0.0019		0.034	
	8	August	2011	40780	35	223	560	17.93	1.570	2.684	0.0016		0.030	
	9	September	2011	40813	33	256	972	31.11	2.720	4.554	0.0027		0.053	

	10	October	2011	40837	24	280	802	25.66	2.240	4.642	0.0022		0.042	
	11	November	2011	40864	27	307	708	22.65	1.980	3.850	0.0020		0.038	
	12	December	2011	40896	32	339	207	6.62	0.580	0.176	0.0006	0.0018	0.011	0.033
2	13	January	2012	40925	29	368	609	19.48	1.700	1.760	0.0017		0.033	
	14	February	2012	40962	37	405	1323	42.33	3.700	2.816	0.0037		0.069	
	15	March	2012	40994	32	437	1108	35.45	3.100	2.860	0.0031		0.057	
	16	April	2012	41017	23	460	2074	19.39	1.620	1.480	0.0016		0.031	
	17	May	2012	41038	21	481	1346	24.51	2.950	2.370	0.0030		0.042	
	18	June	2012	41079	41	522	356	3.09	0.360	0.220	0.0004		0.005	
	19	July	2012	41104	25	547	101	2.91	0.330	0.210	0.0003		0.005	
	20	August	2012	41123	19	566	334	2.54	0.390	0.210	0.0004		0.004	
	21	September	2012	41160	37	603	598	7.79	0.880	0.170	0.0009		0.013	
	22	October	2012	41185	25	628	5312	11.15	0.570	0.350	0.0006		0.018	
	23	November	2012	41228	43	671	3231	7.32	0.630	0.360	0.0006		0.013	
	24	December	2012	41256	28	699	227	12.23	0.650	0.450	0.0007	0.0014	0.021	0.025
3	25	January	2013	41280	24	723	2891	2.85	0.510	0.140	0.0005		0.005	
	26	February	2013	41316	36	759	4379	20.24	5.290	1.090	0.0053		0.035	
	27	March	2013	41345	29	788	946	14.93	2.600	2.010	0.0026		0.025	
	28	April	2013	41389	44	832	160	366.76	4.979	1.500	0.0050		0.625	
	29	May	2013	41417	28	860	559	1.03	0.014	2.459	0.0000		0.002	
	30	June	2013	41450	33	893	251	7.23	0.098	0.234	0.0001		0.013	
	31	July	2013	41477	27	920	553	8.52	0.116	0.250	0.0001		0.014	
	32	August	2013	41506	29	949	349	6.83	0.093	0.229	0.0001		0.011	
	33	September	2013	41534	28	977	463	40.34	0.548	0.215	0.0005		0.065	
	34	October	2013	41568	34	1011	641	0.28	0.004	0.384	0.0000		0.000	
	35	November	2013	41596	28	1039	409	7.38	0.100	0.418	0.0001		0.013	

	36	December	2013	41611	15	1054	349	6.86	0.093	0.534	0.0001	0.0013	0.012	0.074
4	37	January	2014	41656	45	1099	517	7.04	0.096	0.205	0.0001		0.012	
	38	February	2014	41688	32	1131	309	1.74	0.024	1.127	0.0000		0.003	
	39	March	2014	41713	25	1156	255	4.60	0.062	2.096	0.0001		0.008	
	40	April	2014	41745	32	1188	2205	16.93	0.274	0.027	0.0003		0.028	
	41	May	2014	41773	28	1216	2245	103.93	1.683	1.265	0.0017		0.170	
	42	June	2014	41808	35	1251	1436	57.84	0.936	0.229	0.0009		0.101	
	43	July	2014	41834	26	1277	1449	10.94	0.177	0.169	0.0002		0.018	
	44	August	2014	41863	29	1306	1401	9.89	0.160	0.072	0.0002		0.017	
	45	September	2014	41892	29	1335	1470	7.65	0.124	0.074	0.0001		0.013	
	46	October	2014	41921	29	1364	3234	20.26	0.328	0.320	0.0003		0.032	
	47	November	2014	41949	28	1392	813	3.99	0.065	0.040	0.0001		0.007	
	48	December	2014	41978	29	1421	2427	14.55	0.236	0.096	0.0002	0.0004	0.024	0.038
5	49	January	2015	42025	47	1468	1944	9.65	0.156	0.103	0.0002		0.015	
	50	February	2015	42053	28	1496	983	4.88	0.079	0.067	0.0001		0.008	
	51	March	2015	42087	34	1530	727	4.24	0.069	0.031	0.0001		0.007	
	52	April	2015	42115	28	1558	3962	35.36	0.572	0.353	0.0006		0.060	
	53	May	2015	42143	28	1586	3802	19.11	0.309	0.014	0.0003		0.031	
	54	June	2015	42170	27	1613	1976	6.89	0.172	0.189	0.0002		0.012	
	55	July	2015	42195	25	1638	281	103.59	1.185	0.721	0.0012		0.170	
	56	August	2015	42227	32	1670	1411	21.97	0.363	0.004	0.0004		0.038	
	57	September	2015	42256	29	1699	758	1.91	0.017	0.068	0.0000		0.003	
	58	October	2015	42282	26	1725	522	5.65	0.097	0.008	0.0001		0.009	
	59	November	2015	42313	31	1756	228	5.31	0.066	0.010	0.0001		0.009	
	60	December	2015	42344	31	1787	2069	15.16	0.261	0.046	0.0003	0.0003	0.026	0.034
6	61	January	2016	42373	29	1816	437	0.30	0.003	0.032	0.0000		0.001	

	62	February	2016	42406	33	1849	506	0.47	0.013	0.001	0.0000		0.001	
	63	March	2016	42437	31	1880	1873	7.53	0.050	0.072	0.0000		0.013	
	64	April	2016	42471	34	1914	863	105.26	0.033	0.010	0.0000		0.168	
	65	May	2016	42501	30	1944	364	702.23	0.042	0.013	0.0000		1.191	
	66	June	2016	42533	32	1976	1747	7.18	0.481	0.076	0.0005		0.012	
	67	July	2016	42561	28	2004	1860	7.66	0.237	0.012	0.0002		0.013	
	68	August	2016	42597	36	2040	829	19.74	0.223	0.001	0.0002		0.032	
	69	September	2016	42599	2	2042	548	0.11	0.003	0.063	0.0000		0.000	
	70	October	2016	42653	54	2096	83	0.81	0.056	0.007	0.0001		0.001	
	71	November	2016	42676	23	2119	194	0.44	0.009	0.001	0.0000		0.001	
	72	December	2016	42707	31	2150	1309	4.56	0.172	0.035	0.0002	0.0001	0.007	0.130
7	73	January	2017	42740	33	2183	70	0.05	0.001	0.019	0.0000		0.000	
	74	February	2017	42773	33	2216	231	0.44	0.012	0.000	0.0000		0.001	
	75	March	2017	42802	29	2245	1190	4.83	0.048	0.071	0.0000		0.008	
	76	April	2017	42834	32	2277	500	90.33	0.006	0.007	0.0000		0.147	
	77	May	2017	42865	31	2308	175	614.22	0.300	0.007	0.0003		1.054	
	78	June	2017	42897	32	2340	358	1.15	0.356	0.035	0.0004		0.002	
	79	July	2017	42932	35	2375	1502	4.65	0.001	0.000	0.0000		0.007	
	80	August	2017	42962	30	2405	319	10.54	0.183	0.001	0.0002		0.018	
	81	September	2017	42988	26	2431	239	0.05	0.002	0.001	0.0000		0.000	
	82	October	2017	43009	21	2452	69	0.53	0.041	0.006	0.0000		0.001	
	83	November	2017	43040	31	2483	3546	89.65	0.010	0.057	0.0000		0.153	
	84	December	2017	43070	30	2513	4375	133.70	0.043	0.116	0.0000	0.0001	0.231	0.148
8	85	January	2018	43101	31	2544	3668	141.32	0.027	0.071	0.0000		0.238	
	86	February	2018	43132	31	2575	3813	107.46	0.017	0.176	0.0000		0.176	
	87	March	2018	43160	28	2603	4619	62.80	0.007	0.093	0.0000		0.108	

	88	April	2018	43191	31	2634	3649	110.92	0.006	0.027	0.0000		0.184	
	89	May	2018	43221	30	2664	2169	184.71	0.062	0.142	0.0001		0.307	
	90	June	2018	43252	31	2695	2959	37.02	0.010	0.009	0.0000		0.061	
	91	July	2018	43282	30	2725	2081	80.61	0.010	0.093	0.0000		0.128	
	92	August	2018	43313	31	2756	2252	36.99	0.004	0.057	0.0000	0.0000	0.064	0.158
	93	September	2018	43344	31	2787	2929	17.47	0.03	0.000	0.0000		0.009	
	94	October	2018	43374	30	2817	5694	49.83	0.08	0.036	0.0000		0.047	
	95	November	2018	43405	31	2848	3116	36.64	0.06	0.003	0.0000		0.024	
	96	December	2018	43435	30	2878	2052	29.07	0.05	0.002	0.0000		0.004	
9	99	March	2019	43552	117	2995	959	11.46	0.00	0.004	0.0001		0.002	
	100	April	2019	43556	4	2999	1847	4.65	0.06	0.000	0.0002		0.030	
	101	May	2019	43586	30	3029	836	7.57	0.01	0.000	0.0000		0.010	
	102	June	2019	43617	31	3060	4892	43.56	0.07	0.001	0.0000		0.049	
	103	July	2019	43647	30	3090	1391	43.74	0.07	0.002	0.0000		0.071	
	104	August	2019	43678	31	3121	1808	33.44	0.05	0.032	0.0000		0.017	
	105	September	2019	43709	31	3152	1375	17.62	0.03	0.113	0.0000		0.003	
	107	November	2019	43769	60	3212	3768	57.98	0.10	0.059	0.0000		0.077	
	108	December	2019	43799	30	3242	2840	33.14	0.04	0.036	0.0000	0.0211	0.002	0.029

Table 2 Rockfall erosion rate – average figures for entire monitoring period (2011 to 2019).

	Running total of days	Number of rockfalls	Total volume of rockfalls (m^3), total monitored area	Area average erosion rate (myr^{-1})	m/f modelled erosion rate (myr^{-1})	Monthly average erosion rates (myr^{-1})	1 year average (annualiused rate for September 2018 to December 2019) of monthly average erosion rates (myr^{-1})	Focus area erosion rate (monthly, myr^{-1})	Focus area erosion rate (annual, myr^{-1})
Total	3212	153,827	4340.68	n/a	n/a	n/a	n/a	n/a	n/a
Average	n/a	1438	40.57	0.043	0.053	0.001	0.001	0.058	0.051

5. RECOMMENDATIONS

- Monitoring since 2011 has demonstrated the continued failure of the cliff face at Cowbar Nab, Staithes. It is clear that surveys of the cliff line alone, either from visual inspection, stake measurements or from aerial imagery, would not have captured these changes, which amount to nearly 4,340 m^3 of rock in over 153,000 individual failures.

- This period of monitoring shows a period of relative quiescence in the rate, magnitude and pattern of rockfall and therefore erosion at Cowbar Nab. Where changes have been observed to occur, these have tended to be small in size and, based upon the analysis conducted, do not indicate a wider pattern of developing instability. The activity in the 'focus zone' – in which we calculate a separate set of erosion rate statistics for the section of cliff immediately underneath Cowbar Lane, that erosion rates in this period reflect longer-term rates, and show a reduction compared to the reporting period 2015 - 2018

- Some evidence of smaller rockfalls exaggerating overhanging sections of the cliff during this monitoring period, most probably driven by wave action at the cliff toe. These observations do **not** rule out the possibility of another future large rockfall that would change the position of the cliff line, and monitoring and planning for this eventuality should be continued.

- Any failure of the top of the cliff as a result of the loss of support from the erosion of the cliff face below is likely to be a rapid event. It is, however, likely that this will be preceded by either creep or rockfall from the failing cliff face area, over a period of months to days. Rockfalls from this cliff have however been shown to be rapid to evolve from a point of apparent stability, and so can occur with limited warning.

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