Local Coastal Slope Monitoring Analysis

Interpretation Report 16: December 2020 to June 2021

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Scarborough Borough Council

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P0.1		With minor client comments addressed			Paul Fish	

Contents

Disclaimer

Jacobs Engineering Group UK Ltd (previously CH2M) has prepared this report in accordance with the instructions of our client Scarborough Borough Council (SBC) for the client's sole and specific use. Any other persons who use any information contained herein do so at their own risk. This report is a review of coastal slope monitoring data collected by JBA Consulting Ltd on behalf of SBC. The objective of this report is to analyse and interpret the slope monitoring data from specific locations in order to highlight any change in cliff instability risk. Jacobs has used reasonable skill, care and diligence in the interpretation of data provided to them and accepts no responsibility for the content, quality or accuracy of the monitoring data, third party reports, or further information provided either to them by SBC or, via SBC from a third-party source, for analysis under this term contract.

The interpretation of the level of cliff instability risk presented in this document is based solely on the data provided by JBA. While every effort will be made to ensure the data are correct, Jacobs cannot be held responsible for the quality of monitoring data. This data analysis report comments on the monitoring data collected over the preceding 6-month period at specific locations. It will not make projections of future cliff instability activity or discuss cliff instability risk at areas that are not monitored. It is Scarborough Borough Council's responsibility to determine an appropriate response to the guidance on cliff instability risk provided in this report.

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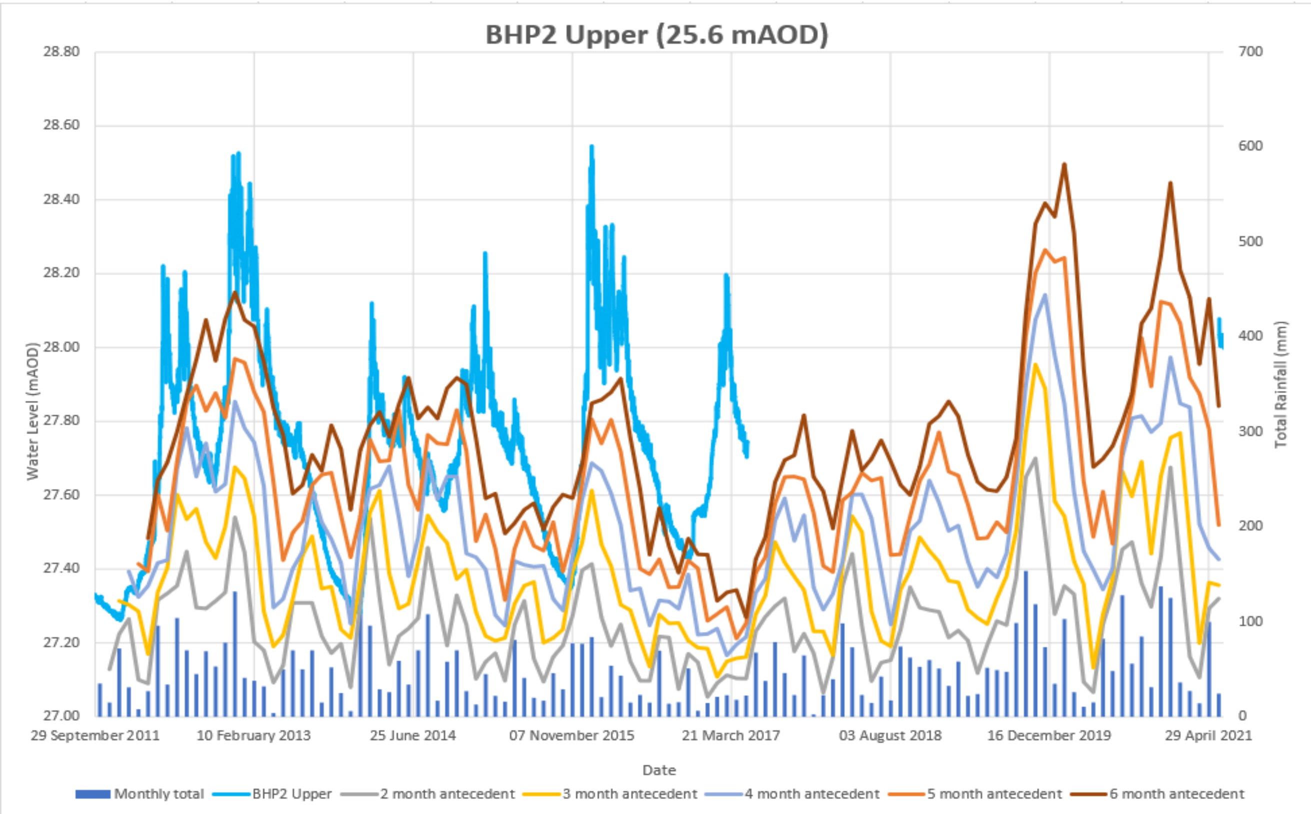
Summary of findings

This report presents an interpretation of slope monitoring data recorded between December 2020 and June 2021 along the Scarborough Borough Council coastal frontage. This report is the sixteenth in a series of six-monthly updates on the cliff instability risk of the frontage that began in 2014. It is the first report undertaken under a contract awarded to Jacobs by Scarborough Borough Council in June 2021.

Winter 2020 and spring 2021 were exceptionally wet. This pattern closely mirrors the conditions observed in the previous year. With the collection of nearly 10 years of data it is possible to establish relationships between rainfall and groundwater response. An example from Scalby Ness is presented below, which illustrates groundwater levels recorded by piezometer BHP2 Upper and antecedent rainfall. The data reveal groundwater responses to 4-5 month antecedent rainfall and intense rainstorms, both of which are known to trigger ground movement and landslides



Boreholes show that water levels have remained relatively steady around average levels or fallen during the monitoring period, except for Scalby Ness (P4b) and Scarborough South Bay Spa (H5, 1 spa, 2 spa, 4 spa, G3) that recorded atypical high levels. In situ monitoring using inclinometers does not indicate any significant slope movements.

The potential for slope instability remains elevated following the very wet winter and spring period. Monitoring data for June 2021 indicates a slightly lower average rainfall for the beginning of the summer period.

During this monitoring period, there were a substantial number of issues requiring attention. Non-functioning equipment accounts for 18% of inclinometers and over 57% of piezometers. Since the previous report, repairs have been made to the inclinometers and the majority are currently functioning. The periodic malfunction of geotechnical monitoring equipment across the Borough shows the Council should continue with their programme of repairs and upgrades to ensure that monitoring and relationships between groundwater, rainfall and ground movement are understood and slope instability risk is managed.

Specific sites of concern and issues needing attention from Scarborough Borough Council and its monitoring contractor are as follows:

- At Robin Hood's Bay, piezometer data show groundwater levels have remained relatively steady at low levels during the monitoring period. Piezometer BH3b was dry during this monitoring period and should be checked as the equipment may be damaged and require repair. This site would benefit from installation of automated piezometers to provide a continuous record of groundwater fluctuations. Inclinometer readings at BH2 were successfully taken during this monitoring period, previously this had not been possible due to parked vehicles blocking the access point. This is a regular problem in the past and the Council should consider placing a temporary warning notice and cones at the site before the monitoring contractor visits to ensure that access is possible.
- At Scalby Ness, groundwater levels have risen slightly or remained relatively steady in all boreholes, except for midslope piezometers P4b in which groundwater has risen significantly and WS6 in which groundwater levels are steady but remain at a historical high. Groundwater has risen since the last monitoring period but remains within the historical range at P1a, P2a, P4a, WS4, B9 and Sn2b. Data is only partially available for piezometers P2b and P3. Furthermore, at P2b and P3 groundwater levels fallen and risen respectively but remain high, though seem to be static since the replacement of the loggers. This appears to be a systematic error, and the piezometers should be checked to ensure calibration is correct. Inclinometer readings at BH07 show erroneous readings and this location should be checked.
- At Oasis Café, no groundwater data are available at any of the monitoring locations due to data collection errors and logger issues. The data should be downloaded and reviewed for the next monitoring period.
- At the Holms, no groundwater data was available for any of the monitoring devices, mostly resulting from communication errors or device issues. The monitoring devices should be repaired, and the data should be downloaded and reviewed for the next monitoring period. Piezometer BH9b is no longer monitored. Inclinometer readings at BH10A show erroneous readings and this location should be checked.
- At Scarborough Spa Chalet, no data has been recorded since May 2016 at piezometer BH12. This site requires attention to fix or replace the damaged cable of the piezometer.
- At Scarborough Spa, no significant ground movement was recorded over the monitoring period. Monitoring at acoustic emissions inclinometer BH105a has been discontinued.

  Groundwater levels at the Spa have remained steady or fallen slightly at most piezometers where data has been retrieved. Piezometer 1 spa shows groundwater levels have fallen slightly but remain elevated over the monitoring period; however, no ground movement was detected. The site should be inspected and monitored for evidence of ground movement, particularly following heavy rainfall events. Groundwater levels have also fallen slightly at boreholes 2 spa and G3 but also remain at an elevated position. Groundwater levels at H5 have increased significantly over this monitoring period to a historical high. The site should be inspected and monitored for evidence of ground movement, particularly following heavy rainfall events. Ground water at boreholes 4 spa and BH1 Prom have risen over this monitoring period. No data is available at boreholes BH1a spa, BH1b spa and BH104a, resulting from communication errors. Furthermore, piezometers BH108a and BH108b were damaged, and no data is available for the monitoring period. The loggers should be checked/repaired, and data collected for the next monitoring period. Access to piezometer 3 spa was not possible during this monitoring period as the borehole is buried under tarmac. The borehole should either be located and reinstated or removed from data collection. Several boreholes were dry (5 spa, G1a, BH106a). These locations require attention and should continue to be monitored.
- At the Clock Café, borehole BH15 remains dry. The integrity of the piezometer should be checked and, if possible, repairs should be made. If repairs cannot be made monitoring should be discontinued until new equipment can be installed.
- At South Cliff Gardens, no data were available for borehole piezometers BH18a or BH18b due to a cable connection problem. Additionally, data was unavailable for borehole piezometers D2a, D2b, BH3a and E2a. The issue should be investigated and remedied by the monitoring contractor. Inclinometer readings at BH17 show erroneous readings and this location should be checked.

- At Holbeck Gardens there was a problem downloading groundwater data at borehole BH4a and BH4b. The issue should be investigated and remedied ahead of the monitoring contractor.
- At Filey Town, inclinometer readings at BH6 show erroneous readings and this location should be checked. No data are available at CPBH01b, CPBH02a, CPBH02b, CPBH04b, CPBH06b, CPBH08a and CPBH08b due to issues with equipment, which should be repaired or replaced. Diver CPBH02b should be checked due to a dry reading. This equipment may be damaged and requires attention to determine whether it can be repaired. The data logger for borehole CPBH09b should be checked and recalibrated as dip meter readings and diver readings are discordant. No data was collected at borehole CPBH10a and CPBH10b as access was not possible due to dense vegetation. The vegetation should be cleared and data downloaded for the next monitoring period.
- At Filey Flat Cliffs there is a continued problem of downloading data at boreholes C4a, A3 and D1. The issue should be investigated and remedied. No data is available at inclinometer C1A, as monitoring is no longer continued at this site.

1. Introduction

1.1 Background to study

The Scarborough Borough Council coastline is affected by widespread cliff instability, largely due to its geology and climate. Since the Holbeck Hall landslide in June 1993, understanding the risk posed by landslides has been a high priority for the Council. Numerous ground investigations and associated studies at locations of concern have been undertaken in the last 20 years meaning the Council now has a widespread network of ground monitoring instrumentation installed, much of which is automated using data-loggers. The Council has also, in the past, supported the installation of experimental acoustic inclinometers by Loughborough University along its frontage. These experimental devices, which were installed adjacent to conventional inclinometers, have the potential to provide cost-effective and accurate real time information on ground movement. The dataset collected allows the Council to better understand cliff instability risk and support decisions on risk management.

A comprehensive programme of data collection and analysis was commenced by the Council in October 2008, when SBC awarded Mouchel Ltd a contract to design a monitoring strategy for the coastline. Mouchel's recommendations were adopted by the Council and a contract for regular data collection and monitoring reports was awarded that operated to spring 2012 (Mouchel 2012). SBC then commissioned Haskoning UK Ltd to undertake a review of the condition of boreholes and associated monitoring instruments (Haskoning, 2013), which highlighted locations of damaged or worn equipment that needed repair. In addition to routine repairs and maintenance of equipment the Council has upgraded piezometers with automatic dataloggers to ensure the best possible data are collected.

SBC invited tenders for a new phase of slope monitoring on 24 July 2013, with separate contracts for data collection and data analysis being let. Contracts covering an initial three-year programme were awarded on 3 September 2013 to JBA Consulting Ltd and Halcrow Group Ltd (now Jacobs), for data collection and data analysis respectively. Two project extensions were awarded to the incumbent team in March 2016 and February 2018 that permitted work to continue to the monitoring period June to November 2020.

The monitoring contracts were re-tendered in December 2020 to include 12 biannual slope monitoring reports over the period 2021 to 2027. Jacobs was awarded the contact in June 2021. JBA was also re-appointed the data collection task.

This report provides the sixteenth set of data analysis and is presented as a stand-alone document to past documents issued as part of the previous contract.

1.2 Aims and objectives of monitoring

Under the Coast Protection Act (CPA) 1949, Scarborough Borough Council, as Coastal Protection Authority, has powers to perform duties in connection with the protection of land within the borough. It is noted that the CPA is enabling legislation and does not carry with it any requirement, although a Coast Protection Authority owes a common law duty of care in performing its functions. Monitoring of coastal change and coastal slope stability conditions across the frontage are important activities informing coastal management strategy and actions. The results of the monitoring programme are available to the public and provide property and landowners with information on coastal instability hazard and risk in vulnerable areas.

The sites and monitoring devices covered by this work are summarised in Table 1-1. Some boreholes have multi-level piezometers installed to monitor water tables at variable depths; inclinometers and piezometers are never located in the same boreholes and water-levels are not recorded in boreholes instrumented with inclinometers. Some equipment has failed over the monitoring programme and been decommissioned. The number of non-functioning piezometers and inclinometers in this monitoring period are shown in brackets. The data recorded by functioning equipment is presented in the sections below.

To meet the objectives, the specific aims of the study are as follows:

- To place the preceding 6 months' monitoring data in the context of the historical record
- To highlight the implications of the data to coastal instability risk management

In addition, the ultimate aim of the study is:

- To collect sufficient monitoring data to enable site-specific relationships between rainfall, groundwater levels and ground movement to be understood. With sufficient data, threshold rainfall and groundwater levels, above which instability is likely to be triggered, can be identified. This understanding permits early warning of potential ground movement to be provided.

Table 1-1 Monitoring locations and devices.

Location	Piezometers (non-functioning)	Inclinometers (non-functioning)	Acoustic Inclinometer	Weather station
Runswick Bay		4 (2)		
Whitby West Cliff		1		
Robin Hood's Bay	4 (1)	2		
Scalby Ness	14 (4)	4 (1)		
Scarborough North Bay – Oasis Café	3 (3)	2		
Scarborough North Bay – The Holmes	5 (5)	2 (1)		
Scarborough South Bay - St Nicholas Cliff	1	1		1^
Scarborough South Bay - Spa Chalet	2 (1)	1		
Scarborough South Bay - Spa	22 (11)	9 (2)	1**	
Scarborough South Bay - Clock Cafe	1 (1)	2		
Scarborough South Bay - South Cliff Gardens	10 (7)	4 (1)		
Scarborough South Bay – Holbeck Gardens	2 (2)	1		
Filey Town	16 (10)	4 (1)		
Filey, Flat Cliffs	4 (3)	4	1**	1^^
TOTAL	84 (48)	41 (8)	2	2
TOTAL % non-functional	57%	20%	n/a	n/a

Notes:

*a single inclinometer and a diver piezometer with barometric diver were added at St Nicholas Cliff in 2014 between collection of the 1st and 2nd set of monitoring data.

**Scarborough Spa acoustic emissions inclinometer became non-functional in January 2019. Access to the site was not possible and monitoring has been discontinued. Monitoring of the equipment installed at Flat Cliffs discontinued after readings of February 2021.

^The Scarborough South Bay weather station was upgraded in July 2019 and provides monitoring data for this period. During the upgrade, a temporary rain gauge was in place to provide continuous rainfall data. Since 2020 the rain gauge has been moved to the roof of the council offices above St Nicholas Cliff.

^^the Filey, Flat Cliffs met station has not functioned reliably since 2016 and has been taken offline.

1.3 Programme of work

The planned programme of future analysis and reporting is shown in Table 1-2, which assumes the final interpretative report will be provided three months following receipt of the preceding 6 months' monitoring data.

Table 1-2 Programme of data collection and reporting.

JBA Monitoring Period	Analysis Report
Original contact	
Data set 1: June 2012 to November 2013	Report 1: March 2014 (CH2M 2014a)
Data set 2: December 2013 to May 2014	Report 2: November 2014 (CH2M 2014b)
Data set 3: June 2014 to November 2014	Report 3: March 2015 (CH2M 2015a)
Data set 4: December 2014 to May 2015	Report 4: August 2015 (CH2M 2015b)
Data set 5: June 2015 to November 2015	Report 5: February 2016 (CH2M 2016a)
Data set 6: December 2015 to May 2016	Report 6: August 2016 (CH2M 2016c)
Data set 7: June 2016 to November 2016	Report 7: January 2017 (CH2M 2017a)
Data set 8: December 2016 to May 2017	Report 8: October 2017 (CH2M 2017b)
Data set 9: June 2017 to November 2017	Report 9: February 2018 (CH2M 2018a)
Data set 10: December 2017 to May 2018	Report 10: August 2018 (CH2M 2018b)
Data set 11: June 2018 to November 2018	Report 11: February 2019 (Jacobs 2019a)
Data set 12: December 2018 to May 2019	Report 12: August 2019 (Jacobs 2019b)
Data set 13: June 2019 to November 2019 *	Report 13: February 2020 (Jacobs 2020a) *
Data set 14: December 2019 to July 2020 †	Report 14: October 2020 (Jacobs 2020b) †
Data set 15: August 2020 to December 2020 †	Report 15: February 2021 (Jacobs 2021) †
2021 to 2027 contract	
Data set 16: December 2020 to June 2021	Report 16: November 2021 (this report)
Data set 17: June 2021 to November 2021	Report 17: February 2022
Data set 18: December 2021 to May 2022	Report 18: August 2022
Data set 19: June 2022 to November 2022	Report 19: February 2023
Data set 20: December 2022 to May 2023	Report 20: August 2023
Data set 21: June 2023 to November 2023	Report 21: February 2024
Data set 22: December 2023 to May 2024	Report 22: August 2024
Data set 23: June 2024 to November 2024	Report 23: February 2025
Data set 24: December 2024 to May 2025	Report 24: August 2025
Data set 25: June 2025 to November 2025	Report 25: February 2026
Data set 26: December 2025 to May 2026	Report 26: August 2026
Data set 27: June 2026 to November 2026	Report 27: February 2027

Notes:

* report issued without acoustic inclinometer readings due to COVID-19 travel restrictions in place at the time.

† extended monitoring period due to COVID-19 travel restrictions in place at the time.

1.4 Scope of data analysis work

JBA have sole responsibility for collection and checking of all inclinometer and piezometer data at 6-month intervals. JBA provide Jacobs with the inclinometer and ground water data presented as graphs, ready for interpretation. The following graphs are provided in Appendices to this report:

- Inclinometer incremental displacement – total displacement at 0.5m intervals down the length of borehole since the baseline reading along two axes (A0 being downslope, A180 being at right angles to the slope). This plot is free from errors associated with past readings as only the most recent and original readings are compared. This plot highlights the depths where most significant movement has occurred.
- Inclinometer cumulative displacement – sum of all incremental displacements down the length of the borehole showing total deformation since the baseline reading along the two axes. If a user error has occurred, it is carried through all cumulative plots, potentially giving misleading results. Errors can usually be identified by comparison to incremental displacement plots.
- Inclinometer absolute position – this plots the absolute position of the inclinometer casing when viewed vertically. While it does not give information on the rate of movement, it highlights the direction of any deformation and can be used to assess error in the data.
- Groundwater data from piezometer divers or data loggers – these data are plotted as a continuous line showing groundwater level fluctuation relative to Ordnance Datum (OD).
- Groundwater data from monitoring wells – these data are plotted as single points, showing groundwater level relative to OD at a point in time. They provide an independent check of piezometer data or water level information from boreholes that do not have automatic data logging capability.

The scope of data analysis work involves the following tasks:

- Checks of inclinometer and piezometer monitoring data provided by JBA to ensure the correct information is provided, and identification of any obvious errors in the data.
- Downloading and analysis of meteorological data from the weather station installed at Filey Flat Cliffs and Scarborough Spa. The weather station at Filey Flat Cliffs was non-functional from 2016, and it has since been replaced with a permanent rain gauge collecting data since October 2018. Meteorological data from Scarborough Spa has been used from 2016 and has been upgraded. A temporary rain gauge was in put in place from January 2018 after the weather station malfunctioned. Meteorological data are now obtained from a replacement weather station located on the roof of the council offices above St Nicholas Cliff.
- Acquisition of experimental acoustic inclinometer data from Loughborough University. Data reported herein provide a trial period of this successful research and development exercise.
- Analysis and interpretation of the data, including commentary on short and long-term patterns of change and observed relationships between rainfall, groundwater levels and ground movement.
- Comment on the implications of the observed data regarding cliff instability hazard and risk management, allowing SBC to take any appropriate action.

The following sections provide a site-by-site discussion of the history of cliff instability and the monitoring regime, and interpretation of the new monitoring data. Comment is made on the relationships between rainfall, groundwater and ground movement, and the implications of the new data regarding cliff instability hazard and risk management.

1.5 Cliff instability hazard assessment

Cliff instability hazard at each monitoring location is presented using a simple colour-coding system that summarises the significance of the result (Table 1-3). The assessment provides a simple record of activity that will be developed in subsequent reports to indicate changing levels of hazard.

Table 1-3 Cliff instability hazard assessment guidance level.

Hazard (low to high)	Definition
Green	Situation normal. No change in groundwater level from previous records, which are low or falling. Movement in inclinometers within margin of error (<5mm).
Orange	Site requires attention. Moderate or large increase in groundwater level from previous records or moderate movement in inclinometers. Failure of equipment, unreliable or no data requires attention.
Red	Immediate action required. Significant movement of inclinometer indicating high cliff instability hazard potential. Carry out site inspection, consider increasing the frequency of monitoring and managing public access to the area.

1.6 Checks of monitoring equipment integrity

Following completion of checking and interpretation of the first round of monitoring in early 2014, several inclinometer readings appeared to be erroneous, with some locations showing potential ground movement. A series of checks were undertaken during 2014 to determine whether the data were accurate, the source of any errors, and the implications to cliff instability risk management. In most cases, the errors were systematic and represent minor settlement of the borehole casing that gives rise to a sinuous pattern of deformation. However, where random errors were reported, it is likely that the borehole is partially blocked, leading to the probe coming away from the key-ways. The 17 potentially blocked boreholes were therefore repaired by means of high-pressure water jetting in early 2015.

In all cases where systematic or random errors have been identified, it has been recommended that the current reading is taken as a new baseline against which future recordings are made. In this way, potentially misleading historical results leading to cumulative errors will be removed. However, to determine whether change has occurred in the preceding 6-month period, data are also compared to the original baseline.

2. Weather Summary

2.1 Introduction

The project has a near-complete record of meteorological data from 2011 to the present day, allowing the response of groundwater to rainfall to be examined. Equipment upgrades and periodic outages mean that the sources of data have varied over this time.

A meteorological station that records wind speed and direction, air temperature, humidity, air pressure, rainfall and rainfall intensity every 15 minutes was present at Flat Cliffs, central Filey Bay, between 29 September 2011 and March 2016. The device was inoperative from September 2014 to July 2015 and therefore supplemental MetOffice rainfall data were acquired from recording station Filey No 2 (54.20395, -0.30127), c. 3km north-northwest of Flat Cliffs. The Flat Cliffs weather station again failed in the period March to May 2016, however at this time a new weather station at Scarborough Spa had become operational and data from that site have been used from 11 January 2016 to until early 2018. The Scarborough Spa weather station became non-functional during January 2018, and rainfall data were acquired by the Met Office weather station at Scarborough to fill the gap. The weather station at Scarborough Spa was upgraded and a temporary rain gauge was in put in place from January 2018, collecting data until November 2018. A permanent rain gauge was installed at Filey Flat Cliffs and has been collecting data since October 2018. Filey Flat Cliffs rain gauge temporarily ceased recording data in early May 2019. Data from the Eastfield rain gauge, inland of Filey, was used to complete the record for May 2019. Data from the Filey Flat Cliffs rain gauge was used for the period June to early July 2019, until Scarborough Spa weather station (since moved onto the roof of the council offices above St Nicholas Cliff) came online on 9 July 2019, providing rainfall, temperature and windspeed data from July 2019 onwards.

2.2 New data

Data from all sources are summarised in Table 2-1 and Figure 2.1. Weather data for this monitoring period includes January to June 2021 (mid-winter to early summer).

The records for the last six months highlight that both winter and spring 2021 were exceptionally wet when compared to past records. The winter 2021 rainfall totalling of 298.8 mm is the greatest for this season since 2011. Rainfall totals for January equalled 125.2 mm, which is the highest for this month since 2011 and represents 41.9% of total winter rainfall. Spring 2021 was the third wettest since 2011, with May accounting for a considerable part of Spring 2021 rainfall. Data for the additional month assessed indicates that June was relatively dry, with 24.4 mm rain.

Daily rainfall totals recorded by the Scarborough South Bay weather station are presented in Figure 2.2, which highlights peaks in daily rainfall over 10 mm occurring in December 2020 to February 2021 and May 2021. During the winter, rainfall peaked between 18 to 20 mm on 5th December and 18th December. The highest daily rainfall total over this monitoring period equalled 20.4 mm on 3rd May.

The combined dataset has been used for comparison with all coastal slope monitoring data to identify relationships. The data are taken to be representative of the whole Scarborough Borough Council frontage, but it is accepted that micro-climate effects may lead to local variations.

Seasonal totals are shown in Figure 2.3, which shows that the wettest season tends to be winter, and that the summer is the driest, though data from this season is partially missing. The wettest season on record was autumn of 2019 (i.e. September, October and November) that received a total of 371mm rainfall, which is exceptional when compared to previous years. The next wettest season is the winter of 2020/2021 (i.e. December, January and February), totalling 298.8 mm of rainfall. When overlooking the part season of summer 2021, the winter of 2016/17 and summer 2013 were the driest on record.

Wind speed and air temperature records are presented in Figure 2.4 and Figure 2.5. Occasional failure of the Scarborough South Bay met station means there are no data for some of the previous monitoring periods.

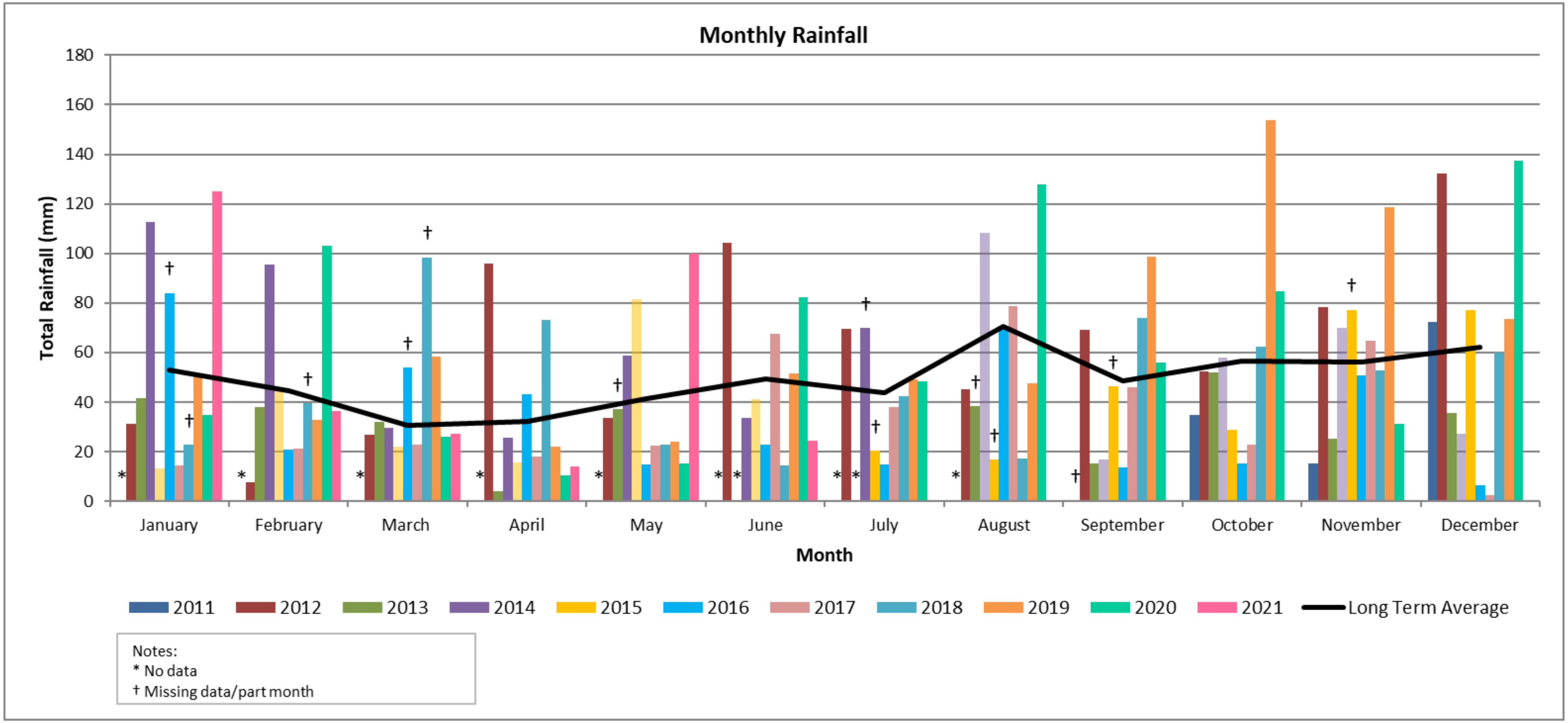


Figure 2.1 Comparison of monthly rainfall records (2011 to 2021).

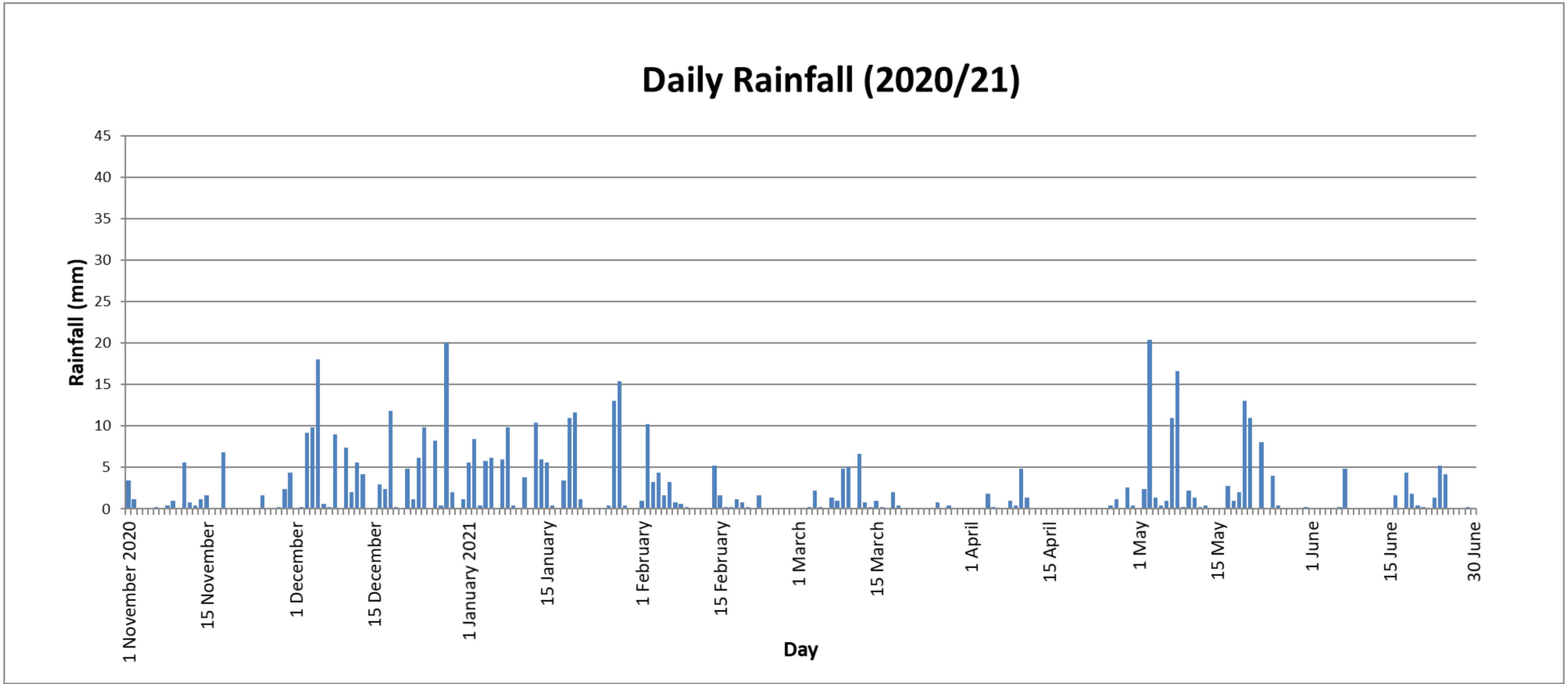


Figure 2.2 Daily rainfall recorded at Scarborough Spa from November 2020 to June 2021.

Table 2-1 Monthly rainfall (mm) recorded at Flat Cliffs or Scarborough Spa met station.

Month	Met Office long-term mean	Monitoring data long-term mean	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
January	80	53	No Data	31	41	113 (84.2)	No Data (13.4)	84 [part month]	14.5	22.8	50.8	34.8	125.2
February	60	44	No Data	8	38	96 (71.2)	No Data (44.8)	20.7	21.1	39.6	32.6	103	36.2
March	60	31	No Data	27	32	29 (40.4)	No Data (22.2)	53.9 [part month]	22.7	98.4	59.2	26	27.2
April	60	32	No Data	96	4	26 (33)	No Data (15.8)	43.4	17.8	73.2	22	10.6	14.2
May	60	42	No Data	34	37 [part month]	59 (50.8)	No Data (81.4)	15	22.4	23.6	24	15.2	100
June	80	49	No Data	104	No Data	34 (61)	No Data (41.2)	23	67.5	14.6	51.6	82.2	24.4
July	60	44	No Data	70	No Data	70 (93.2)	20	14.9	37.9	42.4	49.2	48.2	
August	80	71	No Data	45	38 [part month]	No data (108.2)	17	69.7	78.7	17.2	47.4	128	
September	80	49	0.14 (part month)	69	15	No data (17)	46	13.8	46.1	74	98.8	56	
October	80	57	35	53	52	No Data (58)	29	15.4	22.9	62.4	153.6	84.6	
November	80	56	15	78	25	No Data (70)	77.3	50.9	64.6	52.6	118.6	31.2	
December	80	62	72	132	6	No Data (27.2)	76.9	6.4	2.5	59.8	73.4	137.4	

Note: Data in brackets are from Filey No 2 station. Data from January 2016 to January 2018 are from Scarborough South Bay. Data between January 2018 to May 2018 were provided by the Met Office Scarborough rainfall gauge. Data from June 2018 to November 2018 are from the temporary rain gauge at Scarborough South Bay. Data from November 2018 to 10 May 2019 are from Filey Rain Gauge. Data from Eastfield rain gauge have been used to complete the rainfall record for May 2019. Data from Filey Flat Cliffs rain gauge was used for the period June to early July 2019, until Scarborough South Bay weather station came online on 9 July 2019.

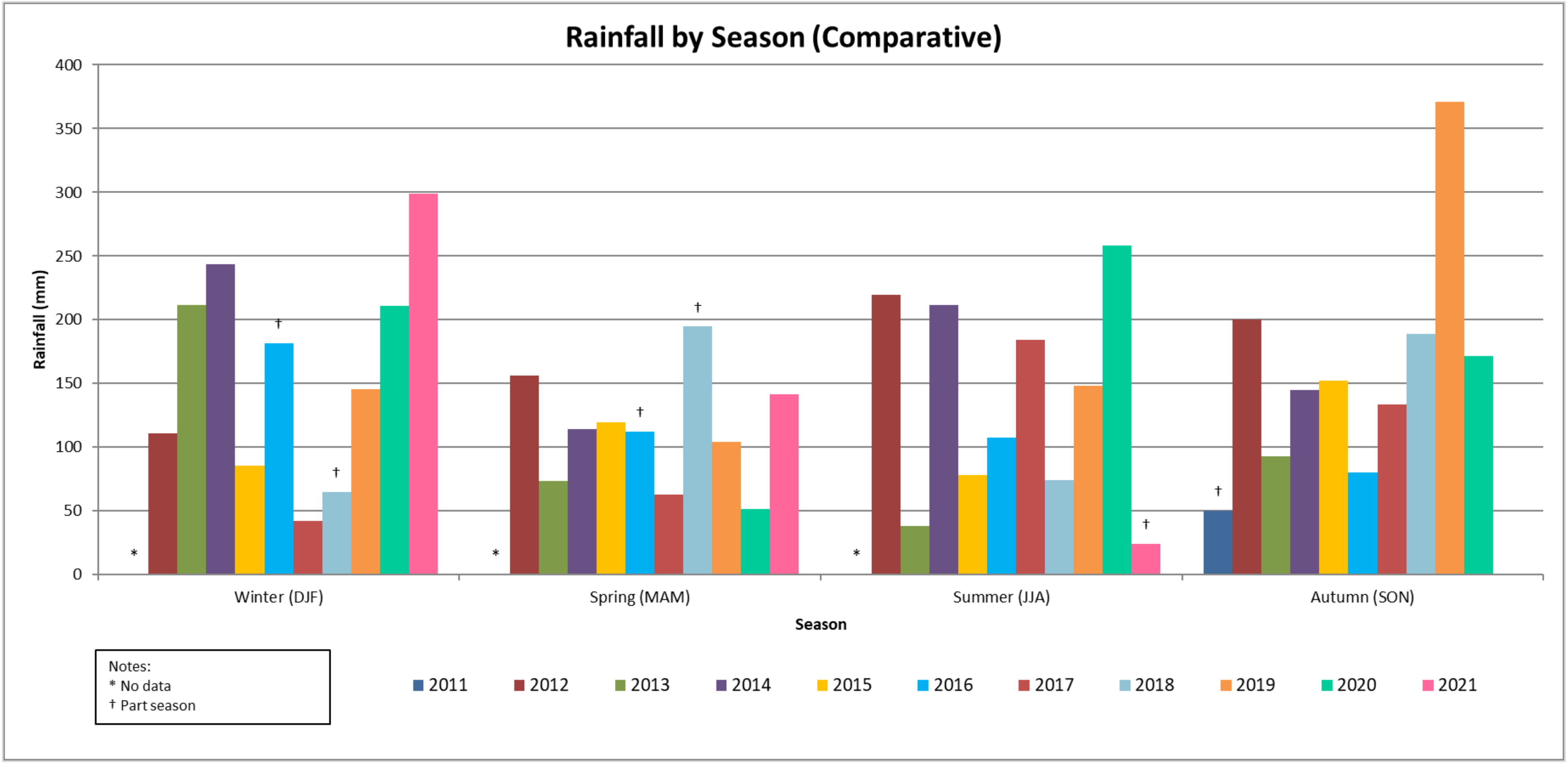


Figure 2.3 Seasonal rainfall comparison (2011 to 2021).

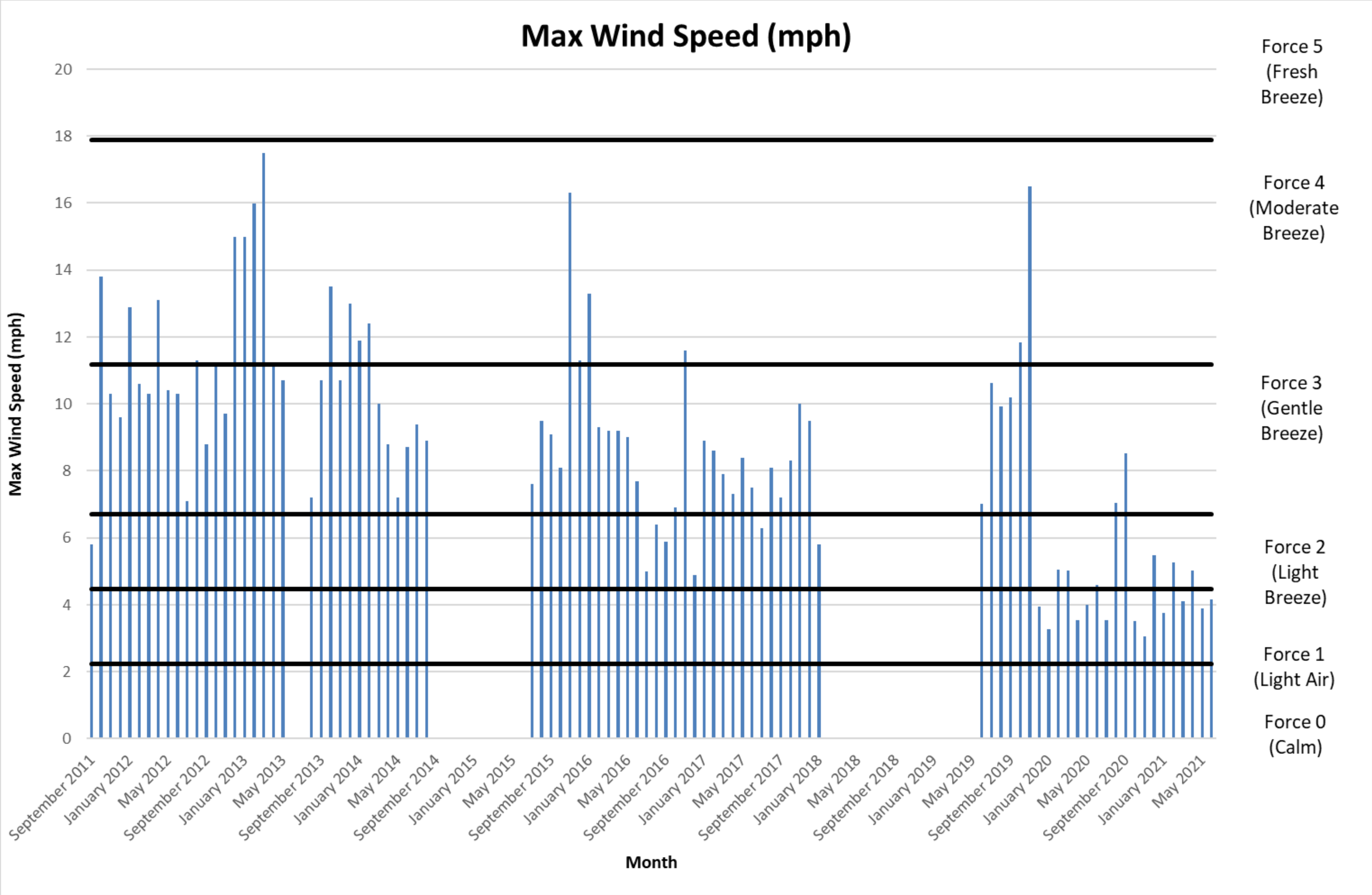


Figure 2.4 Maximum daily wind speed (2011 to 2021).

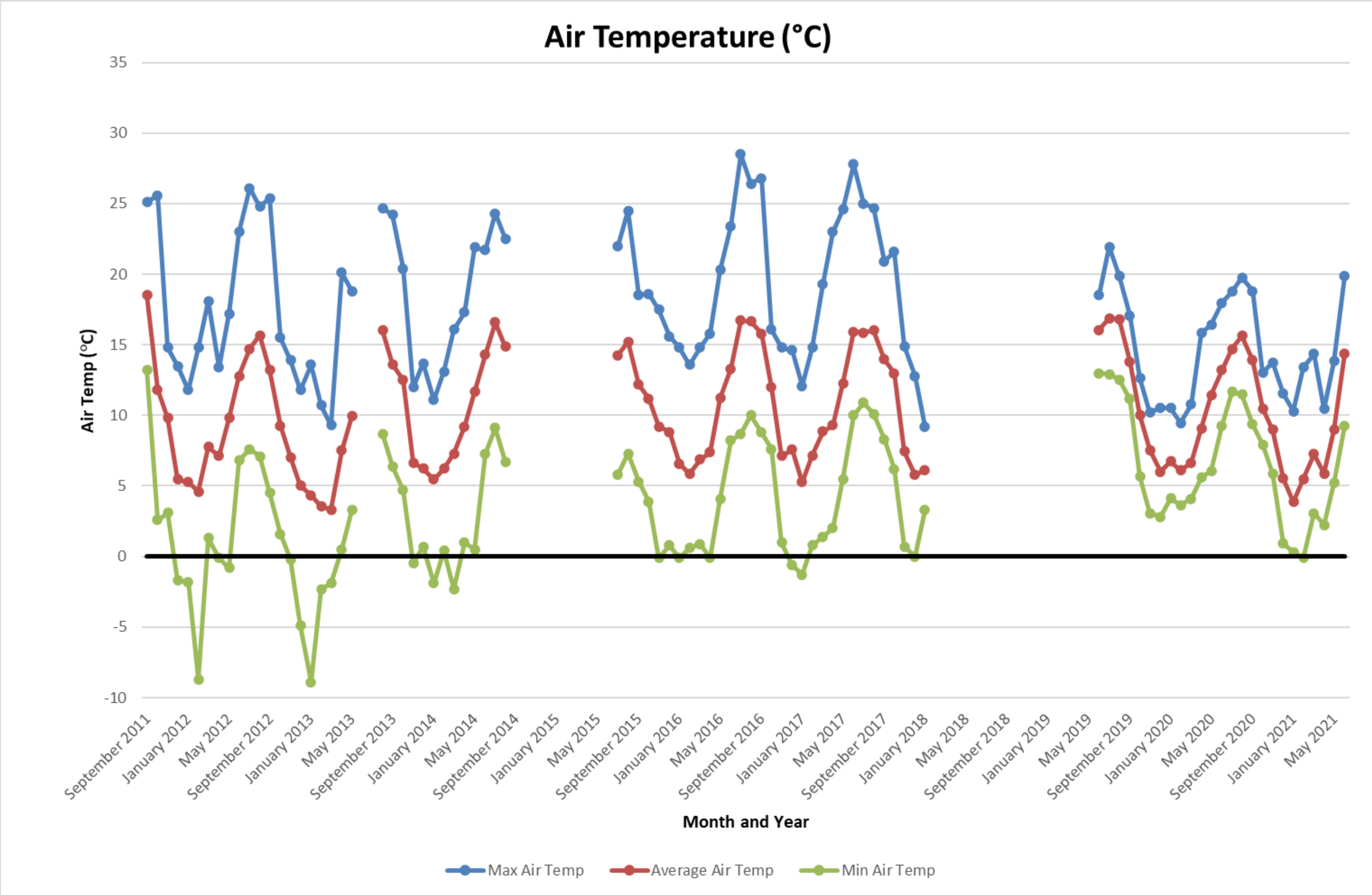


Figure 2.5 Air temperature variation (2011 to 2021).

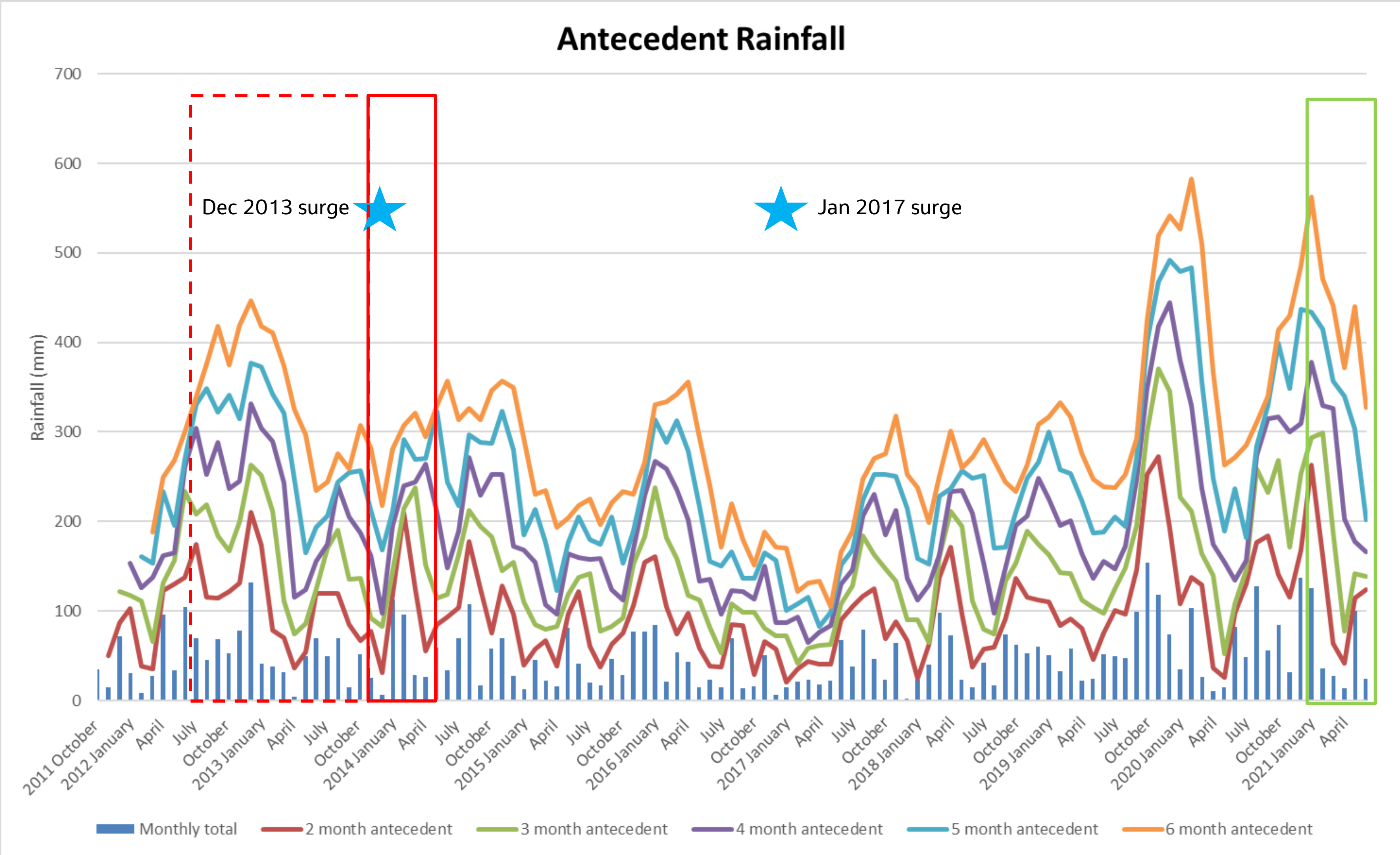


Figure 2.6 Monthly rainfall, two to six-month antecedent totals (2011 to 2021) and notable storm surges. Ground movements were recorded at Scalby Mills during June-Dec 2010 and Feb-June 2011 at times of high groundwater levels. Slight movement was recorded during June 2012-Nov 2013 (red dashed box) with significant movements between November 2013 and May 2014 (solid red box). Current monitoring period shown by green box.

2.2.1 Rainfall and landslides

The relationship between rainfall and the occurrence of landslides is complex and site-specific. It is often the case that a single intense rainfall event has little effect on a slope formed of relatively impermeable clay strata, and instead cliff instability is only triggered after a period of sustained rainfall that allows groundwater levels to rise above a threshold level. This cumulative effect of sustained wet weather is known as antecedent rainfall. The time period over which antecedent rainfall exceeds a threshold for instability will vary from site to site, based principally on the local hydrogeology. It may vary from a period of days or weeks for sites formed of relatively higher permeability strata where groundwater responds rapidly to rainfall, to a period of several months at locations with lower permeability.

The weather records for the SBC frontage span about 10 years and includes the particularly wet winters of 2011/12, 2019/20 and 2020/21. The monitoring period also includes the two notable storm surge events of December 2013 and January 2017, which affected the Scarborough borough frontage. Monthly rainfall totals are provided in Table 2-1 and antecedent totals are presented in Figure 2.6.

Significant ground movements have been recorded in BH7 at Scalby Ness. During the previous monitoring regime, movement was first detected during June to December 2010 with a reactivation between February and June 2011. Antecedent rainfall records are not available, but piezometers recorded elevated groundwater levels, which indicates a relationship with rainfall. Under the current monitoring programme, a small reactivation was detected during the period June 2012 to November 2013 which was associated with high antecedent rainfall. However a more significant reactivation occurred during the period November 2013 to May 2014 when antecedent rainfall levels were lower than the previous winter. It is noted that this significant reactivation occurred at the time of a storm surge, which is known to have raised water levels in Scalby Beck. It is therefore likely that the marginally stable slope was reactivated by toe erosion caused by the combined effects of high rainfall and tidal surge during December 2013.

At Filey Flat Cliffs accelerated slope movement occurred following high antecedent rainfall levels in winter 2012/13. The inclinometer monitoring interval 17 January 2013 to 22 March 2013 showed c. 13 mm of resultant incremental shear surface deformation. Acoustic emission monitoring collected since 2011 was used to increase the temporal resolution of the inclinometer deformation information through conversion of measured acoustic emission rates to cumulative displacement (Smith et al., 2017). It showed a period of increased AE rates at the end of January 2013 which was interpreted as the initiation of landslide movement. Periodic accelerated slope movement was identified at the end of February and middle of March 2013. Antecedent rainfall over the weeks and months prior are considered to have caused the build-up of porewater pressures, which triggered the movement. The absence of movements elsewhere on the coast at that time suggests that the antecedent rainfall threshold levels are above this at other locations.

Antecedent conditions prior to the current monitoring over the winter of 2020/21 show peaks higher than those seen in 2012, meaning ground movements could be expected. However, no ground movements were recorded by in situ monitoring. After a fall in rainfall over the summer of 2020, levels began to rise in the autumn and exceeded the peak recorded in 2012. The winter of 2020/21 almost reached the peak of 2019/20, and the likelihood of ground movement was therefore high.

To further investigate rainfall relationships, groundwater data for each monitoring location are plotted with rainfall data to allow antecedent relationships to be determined. These graphs are presented for each monitoring location and are supported by the available monitoring record that begins in September 2011.

2.3 Summary

Both winter and spring 2021 were exceptionally wet, with both seasons exceeding the previous year’s sum of rainfall for the season. Antecedent rainfall conditions have increased in response to heavy rainfall events in summer 2020, having exceeded conditions recorded in December 2012 when ground movement occurred at Scalby Ness. Similarly to 2019/2020, there remains an elevated risk of ground movement. This risk will increase if the summer and winter 2021/2022 follow the previous year’s total rainfall.

The weather data collected to date highlights the following:

- Winter and spring 2021 were exceptionally wet, though spring was slightly drier than average. The resulting antecedent rainfall conditions fell but remained close to conditions recorded in December 2012 when ground movement occurred at Scalby Ness.
- Winter 2019/2020 was exceptionally wet; however, spring was comparatively dry. As a result, antecedent rainfall conditions fell during the monitoring period, but remained close to conditions recorded in December 2012 when ground movement occurred at Scalby Ness.
- Summer and autumn 2019 was exceptionally wet. Rainfall totals for the months September to November all exceeds records since 2011, with October rainfall totals reaching 154 mm, which is double the long-term average. Antecedent rainfall rapidly increased over the autumn, well above conditions in December 2012 when ground movement occurred at Scalby Ness, but no ground movement was recorded.
- Winter 2018/19 has been slightly wetter than the previous two winters, and antecedent rainfall increased in response to several heavy rainfall events in December and January. Spring 2019 has been drier on average, except for March which had above average rainfall. Antecedent rainfall was elevated in response to these conditions.
- Summer 2018 has been drier than average, and antecedent rainfall declined rapidly in response. However, Autumn has been wetter than average, particularly during September. Exceptionally high daily rainfall totals were experience on 20 September when Storm Bronagh passed over the region. Antecedent rainfall increased to typical levels in Autumn.
- Winter 2017/18 has been drier than average, however spring experienced above average rainfall particularly during March and April where several heavy rainfall events occurred. Antecedent rainfall has risen early in spring compared to previous years.
- Summer 2017 has been wetter than the previous two summers, with rainfall above average during June. High daily rainfall totals were experienced 23 August, when an exceptional storm occurred. Overall, autumn 2017 experienced average conditions, whereby in November antecedent rainfall peaked.
- Between June and November 2016, rainfall has been lower than average apart from August where significant rainfall occurred on 4 and 25 August. Conditions over the 6-month period have been relatively dry and mild. Overall, data shows the 6-month period to have been relatively dry, with mild weather conditions suggesting a low likelihood of rainfall-induced landslides occurring.
- Scarborough Spa weather station data collected over 2016 has shown that January, March and April have been slightly wetter than average. Rainfall peaked on 3 January and 28 March. Overall, data has shown Dec 2015 to May 2016 to have been typically wet, with mild weather conditions.
- Data from Flat Cliffs collected in late 2015 shows September was wetter than average, and December was wet, although not exceptionally so. Rainfall peaks occurred on 14 September and 21 November and a sustained period of wet weather occurred from 25 to 30 December.
- MetOffice data purchased from Filey shows that the period Dec 2014 to April 2015 was generally much drier than average. Only May 2015 shows wetter than average conditions
- While no data were recorded from early September 2014 to February 2015, a review of Met Office records shows the Autumn 2014 period was characterised by dryer than average conditions.
- January and February 2014 were much wetter than average, and the period March to July 2014 was comparatively dry.
- 2013 was dry. After an unusually stormy spring period the temperatures remained high throughout the summer and rainfall in all months was below average.
- 2012 was exceptionally wet, particularly in the months of April, June, July, November and December. This resulted in ground movement at Scalby Mills.

3. Runswick Bay

3.1 Site description

Runswick Bay is the northern-most instrumented site on the Scarborough Borough Council coastline and is located 16 km north west of Whitby. The bay is formed in weak glacial sediments between the more resistant Jurassic-age bedrock headlands of Caldron Cliff to the north and Kettleness to the south. The village of Runswick Bay is developed on a coastal slope formed in glacial sediments and weathered shale bedrock and is bordered by incised valleys of the Runswick Beck and Nettledale Beck. The village and all existing monitoring devices are located in cliff behaviour unit MU7/1 (Figure 3.1).

The village has a long history of coastal instability, with records dating back to 1682 when the whole village was destroyed by landslides. It benefits from a coast protection and slope stabilisation scheme that was constructed in 2001-02 that comprises sections of seawall and rock armour together with drainage, piling and earthworks. The village has been subject to a strategy study review to improve the standard of protection of the coast protection measures and remedy minor issues with the 2001-02 scheme (Halcrow, 2016b). A scheme to implement the recommendations of the strategy study was completed in summer 2018.

3.2 Ground model and monitoring regime

The ground model for Runswick Bay was developed by High Point Rendel in the 1990s as part of the original strategy study for the area (High Point Rendel 1998). Their work included drilling a series of instrumented boreholes, geomorphological mapping and stability analysis. This work highlighted three landslide complexes that threaten properties and infrastructure:

- Topman End (MU7/1) steep till slopes (30° to 40°) between Nettledale Beck and continuing north to Runswick Beck. The village is sited on this landslide complex. The slopes are characterised by an extensive pattern of small scarps and tension cracks behind small shallow failures. Mid-way down the slope the profile shallows to between 5°and 10° over a distance of 10-15m. Where the slope angle exceeds 35° there are numerous shallow failures that tend to be caused by excessive water entrainment and generally leave behind triangular scars bounded by steep sides and disrupted vegetation. The mechanism is uncertain, but High Point Rendel (1998) suggests a model of superimposed mudslide lobes.
- Upgarth Hill (MU 7/1) is the area north of Runswick Beck, beyond the village. The cliffs are formed in weathered Upper Lias shales capped by sandstone beds of the Saltwick Formation and thin veneer of till. Cliffs are fronted by steep talus slopes (20 to 30°) that are protected by a reinforced concrete sea wall. The toe of the southern facing slopes is continually undercut by stream flow in Runswick Beck. Over the years Runswick Beck has cut down through the weathered shale forming an incised valley with sides that are characteristically over-steep. The failure mechanism is believed to be rockfalls with shallow mudslides developed in the talus slope.
- Ings End (MU 7/2 and 7/3) comprises a series of sub-vertical head scarps, up to 2.5m in height, below the cliff top between incised valleys of Nettledale Beck and Limekiln Beck, south of the village. Movement here would adversely impact the village car parks and could trigger movement in Topman End. The headscarps front undulating, low angle slopes formed in till, characterised by springs, streams and water ponding. Shear surfaces are believed to be curved, suggesting the landslide is an ancient degraded multiple-rotational complex with superimposed shallow mudslides that are active during periods of prolonged heavy rainfall.

The monitoring regime at Runswick Bay comprises four inclinometers that are installed within piles of a portal frame shear-key system designed to stabilise the slope within the Topman End landslide (Figure 3.1). The inclinometers were originally intended to monitor the response of the piles to loading, but due to uncertainty over methods to achieve this, the data has been used to simply monitor ground movement and performance of the piles.

3.3 Historical ground behaviour (2009 to 2012)

A summary of historical data adapted from Mouchel (2012) is summarised in Table 3-1. Overall, the data show no ground movement since 2009 and only subtle variation in groundwater levels, and therefore no relationship between groundwater level and ground movement has been identified.

Table 3-1 Summary of historical ground behaviour at Runswick Bay.

Observations in Mouchel 2012 (covering 6-month period between Dec 2011 and June 2012)	Total change observed between July 2009 and June 2012
Slopes indicated as stable. Groundwater levels variable across site in inclinometers, with no change since previous reading, except for A002 that showed a marked drop in water level since Dec 2011.	5mm movement indicated in A001 between 22.0 and 20.0 metres depth and in A004 from 10.0m depth increasing to 15mm at 2.0m depth. Groundwater is relatively static in each borehole, although A002, A003 and A004 experienced lowering of levels in summer 2011, with recovery to previous levels by Dec 2011.

3.4 Review of data collected under this programme (2012 to 2021)

A review of the data collected under this programme from 2012 to 2021 is summarised in Table 3-2. Inclinometers A002 and A003 highlight displacement that is likely result of erroneous readings, therefore, inclinometers A001 and A004 show no significant ground movement.

All monitoring data at Runswick Bay is at the Topman End landslide and is solely intended to monitor the effectiveness of the piles installed in the late 1990s to stabilise the slope. Water-levels within inclinometer tubes installed in the piles were recorded under the previous Mouchel contract. This was not continued in the current phase of work as it was recognised that the data were of limited value to slope stability assessments and could be misleading.

Table 3-2 Summary of data collected at Runswick Bay under this programme (2012 to 2021)

		Report status															
Borehole	Details	06/12 to 11/13	12/13 to 05/14	06/14 to 11/14	12/14 to 05/15	06/15 to 11/15	12/15 to 05/15	06/16 to 11/16	12/16 to 05/17	06/17 to 11/17	12/17 to 05/18	06/18 to 11/18	12/18 to 05/19	06/19 to 11/19	12/19 to 07/20	08/20 to 12/20	01/21 to 06/21
Inclinometer	Borehole depth (base)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A001	22 m BGL													2			
A002	17 m BGL				2												2
A003	10.5 m BGL																2
A004	10.5 m BGL	2															

Note: cells with '1' indicate boreholes where ground movement or elevated groundwater was observed during the given monitoring period of the report; cells with '2' indicate boreholes where there were equipment errors, or where the data was unable to be collected.

3.5 New data

Inclinometer data are summarised in Table 3-3. Data from the inclinometers was collected in June 2021. These data indicate no movement in the piles.

Table 3-3 Summary of inclinometer data at Runswick Bay.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
A001	22 m BGL Upper slope, within concrete pile	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
A002	17 m BGL Upper slope, within concrete pile	Readings are less than 1mm and therefore not significant.	Erroneous readings. The borehole should be cleaned and inclinometer readings taken more carefully
A003	10.5 m BGL Lower slope, within concrete pile	Readings are less than 1mm and therefore not significant.	Erroneous readings. The borehole should be cleaned and inclinometer readings taken more carefully
A004	10.5 m BGL Lower slope, within concrete pile	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant

3.6 Causal-response relationships

No unequivocal ground movements have been recorded at Runswick Bay over the monitoring period. Inclinometer readings are taken to monitor performance of concrete slope stabilisation piles and no groundwater levels are monitored. It is therefore not possible to determine a relationship between rainfall, groundwater response and ground movement.

3.7 Implications and recommendations

Monitoring of the inclinometers should be continued to check the integrity and stability of the piles. In early 2019, residents reported to the local authority apparent movement at the sailing club below borehole A001, where the ground has recently been resurfaced and levelled due to deformation of the old surface. The cause of this apparent movement is uncertain, but probably relates to shallow creep processes. Inclinometers A002 and A003 highlight displacement that is likely result of erroneous readings, therefore, its recommended that the borehole is cleaned, and inclinometers checked.

4. Whitby West Cliff

4.1 Site description

Whitby West Cliff extends from the West Pier of Whitby harbour to Upgang Beach and Sandsend (Figure 4.1). A short (c. 500m long) section at the eastern-most extent fronting the Whitby Spa Complex comprises Jurassic-age limestone, sandstone and mudstone of the Scalby Group overlain by glacial sediments (CBUs 11/3 and 11/4), but the greater part of the cliff line is cut entirely in glacial sediments (CBUs 11/1 and 11/2). The cliffs cut in glacial sediments have a long history of instability and numerous relict landslide scars associated with shallow failures and seepage lines are visible. West Cliff benefits from coastal defences and slope stabilisation measures comprising a seawall, slope drainage and slope re-profiling that were installed in phases between the 1930s and 1970s. These measures have significantly reduced the risk of cliff instability, but they are near the end of their design life and distress in the slope has been observed.

4.2 Ground model and monitoring regime

The cliff instability features of West Cliff comprise shallow mudslides that are periodically active, but there is a concern that deep-seated failures may develop. The defended stretches show evidence of historical failures and despite toe protection the slopes are susceptible to periodic phases of movement associated with sustained rainfall. The unprotected cliff sections at Upgang beach has active mudslides. Historically, the monitoring regime at Whitby West Cliffs has comprised a series of survey pins that follow the line of the slope, which were intended to record deformation associated with cliff instability, and a single inclinometer (BH2) located near the base of the slope to the west of the Whitby Spa complex within CBU 11/2 (Figure 4.1). The inclinometer was read at 6 monthly intervals and dipped to record water level. Survey pin data revealed no significant change during the period of monitoring by Mouchel. As water-level data derived from inclinometers is not recommended and liable to error, these readings are no longer taken, and the current monitoring regime comprises six-monthly inclinometer readings only.

4.3 Historical ground behaviour (2009 to 2012)

A summary of historical data adapted from Mouchel (2012) is summarised in Table 4-1. Overall, the data show no deep ground movement since 2009 and only subtle creep of the upper metre of the slope, which is typical of glacial sediments. Groundwater data collected by dipping the inclinometer tube appeared to show a relationship with tide level and not groundwater. Groundwater data collected in this way are known to be very unreliable and therefore no relationship between groundwater level and ground movement can been identified.

The single monitoring location means the data from BH2 may not be representative of all West Cliff. Caution should therefore be taken before extrapolating results across the site and monitoring should be supplemented with regular site inspection.

Table 4-1 Summary of historical ground behaviour at Whitby West Cliff.

Observations in Mouchel 2012 (covering 6-month period between Dec 2011 and June 2012)	Total change observed between July 2009 and June 2012
Survey pins show a total of 3mm movement at ground surface. Inclinometer indicates local slopes are stable, with surface creep in the top metre of ground.	Survey pins show -7mm movement in the top metre of ground. Inclinometer indicates local slopes are stable.

4.4 Review of data collected under this programme (2012 to 2021)

A review of the data collected under this programme from 2012 to 2021 is summarised in Table 4-2. Overall, the data show no significant ground movement at the inclinometer.

Table 4-2 Summary of data collected at Whitby West Cliff under this programme (2012 to 2021).

		Report status															
Borehole	Details	06/12 to 11/13	12/13 to 05/14	06/14 to 11/14	12/14 to 05/15	06/15 to 11/15	12/15 to 05/15	06/16 to 11/16	12/16 to 05/17	06/17 to 11/17	12/17 to 05/18	06/18 to 11/18	12/18 to 05/19	06/19 to 11/19	12/19 to 07/20	08/20 to 12/20	01/21 to 06/21
Inclinometer	Borehole depth (base)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
BH2	20 m BGL (-6.22 m OD)															2	

Note: cells with '1' indicate boreholes where ground movement or elevated groundwater was observed during the given monitoring period of the report; cells with '2' indicate boreholes where there were equipment errors, or where the data was unable to be collected.

4.5 New data

Current data from the single inclinometer installed at Whitby West cliff is documented in Table 4.2 below. Data for this monitoring period was collected in June 2021. Data from this monitoring period highlights no significant ground movement.

Table 4-3 Summary of inclinometer data at Whitby West Cliff.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
BH2	20 m BGL (-6.22 m OD) Lower slope, within glacial sediment	No data. Inclinometer needs repairing.	Readings are less than 1mm and therefore not significant

4.6 Causal-response relationships

No relationships have been detected at this location.

4.7 Implications and recommendations

Monitoring at Whitby West Cliff is limited to a single inclinometer located near the base of the cliff to the west of the Whitby Spa complex. The device has not highlighted any cliff instability within the glacial sediments, although shallow failures have been observed on the cliff face during past walk-over inspections by SBC. No further evidence of cliff instability has been reported since 2014. The absence of any water level data at Whitby means it is not possible to determine the relationship between rainfall and ground movement, therefore, opportunities for installation of automated piezometer(s) should be considered.

5. Robin Hood's Bay

5.1 Site description

Robin Hood's Bay village is located on the coastal slopes and cliff top area of the northern-most part of Robin Hood's Bay. The cliff top part of the village is known as Mount Pleasant. The old village, situated on the coastal slope, has a long history of landsliding and currently benefits from a coast protection and slope stabilisation scheme that was installed in 2001.

The area being monitored in this study is the Mount Pleasant area, between Victoria Hotel and the cliffs to the north, where cliff instability is a concern. Cliff behaviour units in this area are composite cliffs formed of near-vertical sea-cliffs cut in Lower Jurassic clays overlain by glacial sediments. CBU 16/1 fronts Mount Pleasant and CBU 16/2 fronts the Victoria Hotel and the slope down to the old village (Figure 5.1). This section of coastline is not defended and has no slope stabilisation measures. Despite the bedrock cliff eroding at a slow rate, the overlying glacial sediments are prone to instability, and landslides occur episodically in response to sea cliff erosion and/or prolonged wet weather.

5.2 Ground model and monitoring regime

In response to the risk from landslides affecting the village, four instrumented boreholes have been installed in CBUs 16/1 and 16/2. These comprise two inclinometers and two double piezometers installed in bedrock and overlying glacial sediments (Figure 5.1).

5.3 Historical ground behaviour (2009 to 2012)

Robin Hood's Bay was not included in the original programme of monitoring and the first readings were taken in March 2010. The readings documented by Mouchel (2012) are summarised in Table 5-1.

Table 5-1 Summary of historical ground behaviour at Robin Hood's Bay.

Observations in Mouchel 2012 (covering 6-month period between Dec 2011 and June 2012)	Total change observed between July 2009 and June 2012
Inclinometer BH2 shows movement at 22m depth. BH4 shows movement at 25m depth. Groundwater levels reduced.	n/a. First investigated in Dec 2011. Total change is as recorded between Dec 2011 and June 2012.

5.4 Review of data collected under this programme (2012 to 2021)

A review of the data collected under this programme from 2012 to 2021 is summarised in Table 5-2. Overall, the data show that elevated groundwater levels have occurred in the past, however, there has been no significant ground movement at any of the inclinometers.

Table 5-2 Summary of data collected at Robin Hood's Bay under this programme (2012 to 2021).

Borehole	Details	Report status															
		06/12 to 11/13	12/13 to 05/14	06/14 to 11/14	12/14 to 05/15	06/15 to 11/15	12/15 to 05/15	06/16 to 11/16	12/16 to 05/17	06/17 to 11/17	12/17 to 05/18	06/18 to 11/18	12/18 to 05/19	06/19 to 11/19	12/19 to 07/20	08/20 to 12/20	01/21 to 06/21
Inclinometer	**Borehole depth (base)**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
BH2	22 m BGL (33.1 m OD)	2	2	2					2						2	2	
BH4	20 m BGL (34.2 m OD)	2	2	2													
Piezometer	**Tip depth**																
BH1a	51.6 m OD				2	2	1				2						
BH1b	51.6 m OD				2	2			2	2				2	2		
BH3a	60.4 m OD	1	2	1	1	1	2	2							2		
BH3b	60.4 m OD						2	2	2				2	1	2	2	2

Note: cells with '1' indicate boreholes where ground movement or elevated groundwater was observed during the given monitoring period of the report; cells with '2' indicate boreholes where there were equipment errors, or where the data was unable to be collected.

5.5 New data

The inclinometer and piezometer data recorded up to June 2021 is summarised in Table 5-3 and Table 5-4. Inclinometer data shows no significant movements recorded at borehole at BH2 or BH4

The piezometer data show groundwater levels have remained relatively steady over the monitoring period, only rising slightly in shallow piezometers BH3a. BH1a remains near the historical low after mistakenly being covered with tarmac during an earlier monitoring period (CH2M, 2016c). Meanwhile, deeper piezometer BH3b was dry during this monitoring period and should be checked as equipment may be damaged and requires attention to determine whether it can be repaired.

Table 5-3 Summary of inclinometer data at Robin Hood's Bay.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
BH2	22 m BGL (33.1 m OD) Cliff top	No access to site. Readings to be taken on next site visit.	Readings are less than 1mm and therefore not significant.
BH4	20 m BGL (34.2 m OD) Cliff top, within glacial sediment and siltstone bedrock	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.

Table 5-4 Summary of groundwater data at Robin Hood's Bay.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
BH1a	Shallow horizon Cliff top	Groundwater levels have risen slightly to 29.5 m OD.	Groundwater levels are steady at 29.5 m OD
BH1b	Deep horizon Cliff top	Groundwater levels are steady at 38.8 m OD.	Groundwater levels are steady at 38.8 m OD.
BH3a	Shallow horizon Cliff top	Groundwater levels have risen slightly to 47.8 m OD.	Groundwater levels have risen slightly to 48.6 m OD.
BH3b	Deep horizon Cliff top	Borehole dry. Check piezometer integrity.	Borehole dry. Check piezometer integrity.

5.6 Causal-response relationships

A subtle relationship between rainfall and groundwater levels, particularly in the shallower piezometer BH1a, was observed for the wet December of 2011 and the wet summer of 2012, and wet winter of 2015/2016. However, the dry conditions of 2013 were not reflected in the groundwater data, suggesting surcharge of groundwater from local sources may be occurring. Water levels in BH3a had fallen significantly in 2017 to their lowest since 2012, which may reflect the exceptionally dry conditions during winter 2016/17 and spring. There is also the possibility that the low resolution of monitoring at this location, particularly in shallow piezometers, may simply be picking-up short duration responses to brief but intense rainfall events. There is no clear response in the groundwater levels to wetter than average conditions between spring and winter 2018, autumn and winter 2019/2020, summer 2020 and winter 2021.

5.7 Implications and recommendations

The groundwater data indicates a continuation of past patterns at Robin Hood's Bay. BH1a shows groundwater level has remained relatively steady at the level observed before the borehole was mistakenly covered with tarmac in 2016. However, deeper piezometer BH3b was dry and its integrity should be checked, and the next monitoring data reviewed.

Results from inclinometers are hard to interpret, meaning there is uncertainty over the nature of any recent ground movement. These data should be carefully reviewed in future monitoring reports and erroneous data removed from record. To improve understanding of the relationship between groundwater and rainfall, this site would benefit from installation of automated piezometers to provide a continuous record of groundwater fluctuations.

6. Scalby Ness

6.1 Site description

Scalby Ness is the promontory that forms the northern boundary of Scarborough's North Bay. The headland is incised by Scalby Beck which flows through a steep-sided valley cut in glacial sediments and the underlying Jurassic sandstone/siltstone bedrock. Scalby Beck acts as a flood relief channel for the River Derwent via the 'Sea Cut', a man-made channel connecting the Derwent with the headwaters of Scalby Beck. The south side of the beck has housing that is threatened by ground instability in the over-steepened slopes cut in glacial sediments.

6.2 Ground model and monitoring regime

This site includes the cliff behaviour units MU19/11 and MU20/1 (Figure 6.1). The strategy study into the instability problems (Halcrow, 2005) characterised the area into three distinct landslide systems:

- CBU1 (northwest slopes) – periodically active translational landslides in glacial sediment that lead to gradual headscarp recession. Instability is partly caused by toe erosion by Scalby Beck, but rising ground water levels following prolonged or intense rainfall are the principal trigger.
- CBU2 (northern part of the northeast slopes) – large, ancient, deep-seated, periodically active landslide. Back-tilted blocks indicate a rotational failure, but translational mechanisms are also possible. Instability is partly caused by toe erosion by Scalby Beck but rising ground water levels following prolonged or intense rainfall are the principal trigger.
- CBU3 (southern part of the northeast slopes) – stable slopes that have been reprofiled when the Sealife Centre access road was constructed.

Both CBUs 1 and 2 are at risk of failure, particularly if groundwater levels rise significantly. CBU3 is not considered to be at risk.

The monitoring regime at Scalby Ness is summarised in Figure 6.1. The slope is instrumented with three inclinometers and fourteen piezometers, seven of which are automated. Two inclinometers and nine piezometers are on the slope itself and the remaining installations are positioned on the cliff top.

6.3 Historical ground behaviour (2009 to 2012)

Ground movement and groundwater levels were monitored by Mouchel from July 2009 to June 2012 and limited additional records of groundwater data back to June 2004. Mouchel's observations showed significant movement in BH7 between June and December 2010, at time of high antecedent rainfall and several periods of high-water level. No relationship between groundwater level and ground movement was reported by Mouchel, although relationships between rainfall and ground water levels in piezometers with shallow tips are identified. The readings documented by Mouchel (2012) are summarised in Table 6-1.

Table 6-1 Summary of historical ground behaviour at Scalby Ness.

Observations in Mouchel 2012 (covering 6-month period between Dec 2011 and June 2012)	Total change observed between July 2009 and June 2012
Mouchel's piezometer graphs show notable increases in groundwater level in some piezometers (WS4 and WS6) to May 2012.	Ground movement reported at 12.0m BGL in BH7 at contact between gravelly sand and sandstone between June and December 2010, indicative of a developing shear plane although this movement has not yet manifested itself as recession of the headscarp. A failure was observed near the base of CBU1 between March and April 2010. They report decreasing groundwater levels in CBU1, and peaks in groundwater levels in the shallower piezometers linked to intense rainfall events. Deeper piezometers remained at approximately the same level and were therefore less susceptible to variations in rainfall.

6.4 Review of data collected under this programme (2012 to 2021)

A review of the data collected under this programme from 2012 to 2021 is summarised in Table 6-2. Between winter 2013/14 and spring 2014 there was significant displacement along the shear surface in BH07, which is situated mid-slope in CBU2 (Figure 6.1). The shear surface lies c. 1m above the contact between the sandstone bedrock and gravelly sand at ca. 4.7m OD (12m BGL). The cumulative displacement was c. 25mm. This movement occurred between November 2013 and March 2014 and is likely to be associated with the period of high groundwater levels (nearby piezometers P4a and P4b show elevated groundwater peaking in mid-February 2014). This suggests a threshold groundwater level for movement occurred. Surface creep was also evident in borehole L3 during the same time period. Since 2014, the data show that elevated groundwater levels have occurred, however, there has been no further significant ground movement at any of the inclinometers.

Table 6-2 Summary of data collected at Scalby Ness under this programme (2012 to 2021).

		Report status															
Borehole	Details	06/12 to 11/13	12/13 to 05/14	06/14 to 11/14	12/14 to 05/15	06/15 to 11/15	12/15 to 05/15	06/16 to 11/16	12/16 to 05/17	06/17 to 11/17	12/17 to 05/18	06/18 to 11/18	12/18 to 05/19	06/19 to 11/19	12/19 to 07/20	08/20 to 12/20	01/21 to 06/21
Inclinometer	**Borehole depth (base)**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
L1 (C003)	32 m BGL (2.5 m OD)																
L2 (C002)	35 m BGL (1.0 m OD)		2														
L3 (C004)	17 m BGL (3.6 m OD)		1														
BH07	20.5 m BGL (3.8 m OD)	1	1												2	2	2
Piezometer	**Tip depth**																
P1a	25.65 m OD		2	2	2		2	2	2	2	2	2				2	
P1b	18.1 m OD						2	2	2	2	2	2	2	2	2	2	
P2a	25.6 m OD				2		1			2	2	2	2	2	2	2	
P2b	0.6 m OD									2	2	2	2	2	2	2	2
P3	10.5 m OD							2	2	2	2	2	2	2	2	2	2

Borehole	Details	Report status															
		06/12 to 11/13	12/13 to 05/14	06/14 to 11/14	12/14 to 05/15	06/15 to 11/15	12/15 to 05/15	06/16 to 11/16	12/16 to 05/17	06/17 to 11/17	12/17 to 05/18	06/18 to 11/18	12/18 to 05/19	06/19 to 11/19	12/19 to 07/20	08/20 to 12/20	01/21 to 06/21
Inclinometer	**Borehole depth (base)**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
P4a	8.3 m OD	1	1				1			2	1	2			2	2	
P4b	6.35 m OD	1	1	2	2	2	2	2	2	2	1	2		2	2	2	1
WS4	9.9 m OD						1				1						
WS5	6.5 m OD	1	2	2	2	2											
WS6	9.72 m OD										1	1	1	1	1	1	
B6	10.0 m OD				2				2		2	2	2	2	2	2	2
B9	9.25 m OD				1		1		1	2		1					
Sn2a	13.9 m OD	2					1		2	2	1			2			
Sn2b	8.35 m OD	2			1		1	1			1						

Note: cells with '1' indicate boreholes where ground movement or elevated groundwater was observed during the given monitoring period of the report; cells with '2' indicate boreholes where there were equipment errors, or where the data was unable to be collected.

New data

Table 6-3 and Table 6-4 summarise the monitoring data from the inclinometers and piezometers at Scalby Ness. Data for this monitoring period was collected in June 2021.

The new data indicate:

- No significant ground movements recorded by inclinometers L1, L2 and L3. BHO7 highlighted displacement, though this is Likely result of erroneous reading, therefore, this inclinometer should be checked.
- Groundwater has risen since the last monitoring period but remains within the historical range at P1a, P2a, P4a, WS4, B9 and Sn2b.
- Data is only partially available for piezometers P2b and P3. Furthermore, at P2b and P3 groundwater levels have fallen and risen respectively but remain high, though seem to be static since the replacement of the loggers. Additionally, some data in this monitoring period at P3 is extreme appears to be systematic error. The integrity of the piezometers should be checked on the next site visit. The data should be downloaded and reviewed for the next monitoring period.
- Groundwater levels have risen slightly or remained relatively steady in all other boreholes, except for midslope piezometers P4b in which groundwater has risen significantly and WS6 in which groundwater levels are steady but remain at a historical high.
- Piezometer in boreholes B6 was dry and its integrity requires checking on next site visit.

Table 6-3 Summary of inclinometer data at Scalby Ness.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
L1 (C003)	32 m BGL (2.5 m OD) Cliff top, within glacial sediment and sandstone/ mudstone bedrock	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
L2 (C002)	35 m BGL (1.0 m OD) Cliff top, within glacial sediment and mudstone bedrock	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
L3 (C004)	17 m BGL (3.6 m OD) Upper slope, within glacial sediment and mudstone/ sandstone bedrock partly weathered	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
BH07	20.5 m BGL (3.8 m OD) Mid slope, within glacial sediment and sandstone/ mudstone bedrock	No data. Inclinometer needs repairing.	Displacement of up to 10mm from 11 to 21m OD in sandstone bedrock. Likely result of erroneous reading. The inclinometer should be checked.

Table 6-4 Summary of groundwater data at Scalby Ness.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
P1a	25.65 m OD Cliff top co-located P1b	No data available. Data logger communication error. SBC to arrange for repair of equipment.	Groundwater has risen since 06/07/2020 reading to 27.8m OD, though current reading is well within historical range.
P1b	18.1 m OD Cliff top co-located P1a	Groundwater levels remained static at 19.2m OD, which appears to be systematic error. Data is available only up to 31 August 2020. Logger should be checked to ensure that readings are correct. Data to be collected during next site visit.	Groundwater has fallen to 18.3 m OD.
P2a	25.6 m OD Cliff top co-located P2b	No data available. Data logger communication error. SBC to arrange for repair of equipment.	Groundwater has risen since last reading 25/04/17 to 28 m OD but remains in the historical range.
P2b	0.6 m OD Cliff top co-located P2a	Groundwater levels remained at 1.2m OD and remain almost static, which appears to be systematic error. Data is available only up to 21 August 2020.	Groundwater levels have fallen to 0.8 m OD and remain almost static, which appears to be systematic error. Data are only available to 23/06/2021

Borehole	Details	Report status	
		Change 08/20 to 12/20 15	Change 01/21 to 06/21 16
		Logger should be checked to ensure that readings are being recorded. Data to be collected during next site visit; logger to be replaced if faulty	Logger should be checked to ensure that readings are being recorded. Data to be collected during next site visit, logger to be replaced if faulty.
P3	10.5 m OD Cliff top	Groundwater levels remained at 14.1m OD and remain almost static, which appears to be systematic error. Data is available only up to 21 August 2020. Logger should be checked to ensure that readings are correct. Data to be collected during next site visit.	Groundwater level has risen slightly to 14.4 m OD. Though some readings in 2021 are extreme and appears to be systematic error. Logger should be checked to ensure that readings are correct. Data to be collected during next site visit.
P4a	8.3 m OD Mid slope co-located P4b	No data available. Data logger communication error. SBC to arrange for repair of equipment.	Groundwater has risen since last recording to 14 m OD. Though appear to be falling over recent months and is within the historical range.
P4b	6.35 m OD Mid slope co-located P4a	Groundwater levels fell to 12.9m OD. Data is available only up to 21 August 2020. Data to be collected during next site visit.	Groundwater levels have risen to 13.4 m OD
WS4	9.9 m OD Mid slope	Groundwater levels are steady around 11.6m OD.	Groundwater levels have risen to 12.2 m OD.
WS5	6.5 m OD Lower slope	Borehole no longer functioning.	Borehole no longer functioning.
WS6	9.72 m OD Mid slope	Groundwater levels have risen to new historical high of 14.5 m OD.	Groundwater levels are steady around 14.5 m OD but remain at a historical high.
B6	10.0 m OD Mid slope	Borehole dry. Check piezometer integrity.	Borehole dry. Check piezometer integrity.
B9	9.25 m OD Upper slope	Groundwater levels have risen slightly to 15.2m OD.	Groundwater levels have risen slightly to 15.4 m OD.
Sn2a	13.9 m OD Mid slope co-located Sn2b	Groundwater levels are steady around 12.6m OD.	Groundwater levels are steady around 12.6m OD.
Sn2b	8.35 m OD Mid slope co-located Sn2a	Groundwater levels have fallen to 10.8m OD.	Groundwater levels have risen to 11.4 m OD.

6.5 Causal-response relationships

Most shallow piezometers at Scalby Ness closely reflect the pattern of rainfall. During this monitoring period, groundwater levels have remained steady or increased slightly across most functioning boreholes following an exceptionally wet winter and spring.

Deeper piezometers have a longer lag between rainfall and groundwater response. Those with data loggers show a much more muted response.

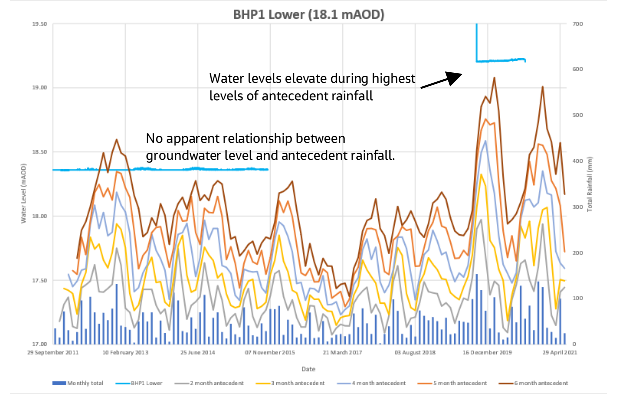
The inclinometers in BH7 and L2 show significant periodic sub-surface movement. BH7 is the most pronounced and indicates movement on an existing shear surface in glacial sediments above sandstone bedrock. Movement occurred between November 2013 and March 2014, associated with a period of high groundwater levels. Rainfall over the monitoring period was exceptionally high and ground water levels are very high at some locations and most ground water readings had risen from the last monitoring period. No ground movement has been recorded. This area is at high risk of ground movement, particularly as 2020/2021 was wet, and antecedent conditions remain elevated.

Figure 6.2 presents the groundwater levels at Scalby Ness recorded by each piezometer (with a data logger) and antecedent rainfall. The relationship to different antecedent rainfall periods have been assessed visually.

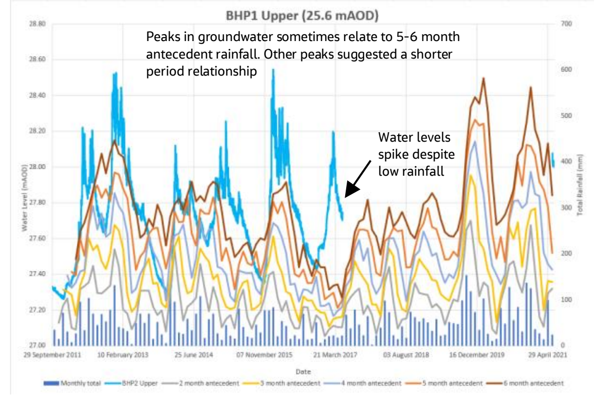
BHP1 Upper (a) has a 6-month antecedent rainfall relationship, but the data from the deep piezometer at this location, BHP1 Lower (b), does not have any apparent antecedent rainfall relationship. BHP2 Lower (b), BHP2 Upper (a) and BH3 have 4–5-month antecedent rainfall relationships. The deeper piezometer at BHP4 Lower (b) has a 4-5 month relationship, while the shallower tip at this location, BHP4 Upper (a), has a 2-3 month relationship.

These data confirm that deeper piezometers take longer to respond to rainfall than shallower piezometers and suggests a 4 to 5 month antecedent rainfall relationship at depth, and a 2-3 month relationship for shallower piezometers. These long response times reflect the impermeable nature of the glacial sediments.

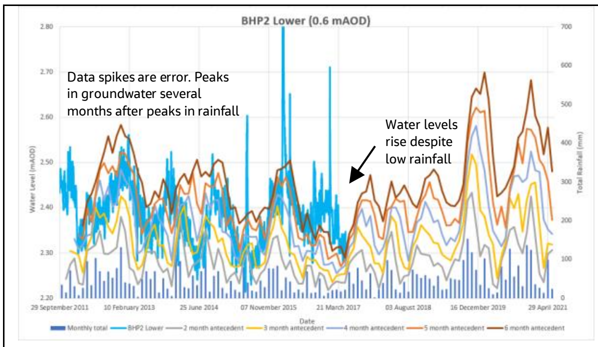
Multiple piezometers record a spike in groundwater levels in March 2017, during a period of low antecedent rainfall. This is likely due to a very intense local rainfall event at Scalby Ness that was not recorded at the meteorological station at Scarborough Spa.



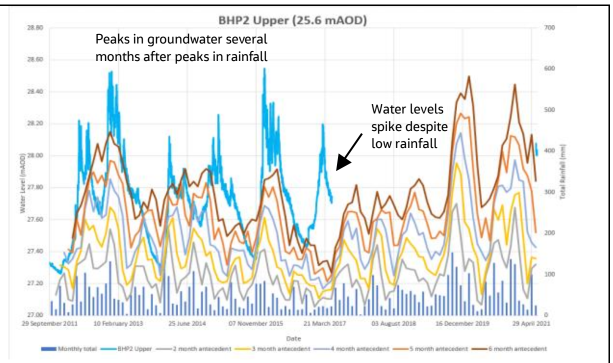
A – BHP1 Lower (tip at 18.1m OD at base on cliff top). No apparent antecedent rainfall relationship.



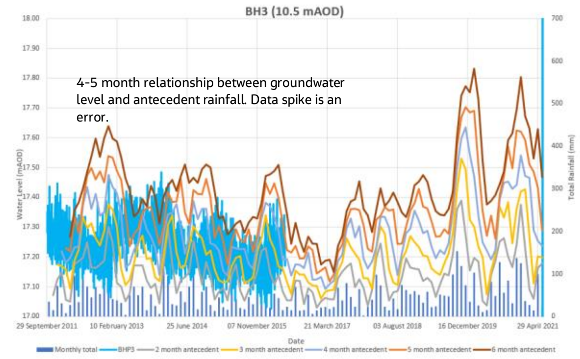
B – BHP1 Upper (tip at 25.6m OD at base on cliff top). The data show a complex 5 to 6 month antecedent relationship.



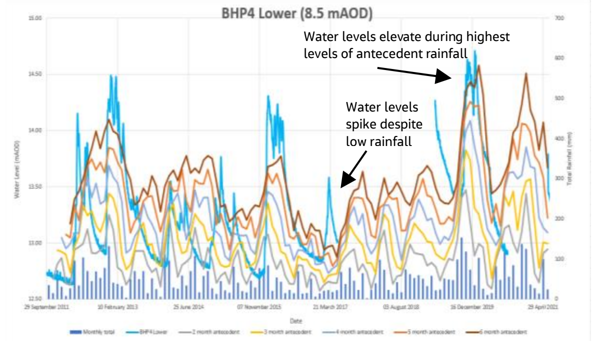
C – BHP2 Lower (tip at 0.6 m OD at base on cliff top) 4-5 month antecedent rainfall relationship



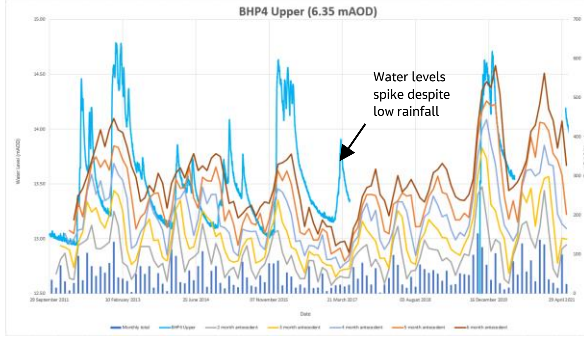
D – BHP2 Upper (tip at 25.6 m OD at base on cliff top) 4-5 month antecedent rainfall relationship



E – BHP3 Upper (tip at 10.5 m OD at base on cliff top) 4-5 month antecedent rainfall relationship



D – BHP4 Lower (tip at 8.5 m at base on cliff top) 4-5 month antecedent rainfall relationship



D – BHP4 Upper (tip at 6.35 m at base on cliff top) 2-3 month antecedent rainfall relationship.

Figure 6.2: Relationship between groundwater levels and antecedent rainfall.

6.6 Implications and recommendations

The groundwater data indicates levels have increased slightly or remained steady in the area. The piezometer located mid-slope at WS6 show groundwater levels had become increasingly elevated. It is recommended this trend in groundwater levels is monitored and reviewed in the next monitoring report, together with inclinometer readings. Piezometers P1a, P2a and P4a had data logger communication errors and should be repaired. Piezometer in borehole B6 was dry. These locations should continue to be monitored. In addition, auto-piezometers on the cliff top in boreholes P1b, P2b and P3, show groundwater levels are static since replacement of the data loggers, which appears to be erroneous. These piezometers should be checked to ensure calibration is correct. Data was not available beyond August 2020 for piezometers P1b, P2b, P3 and P4b. The data should be downloaded and reviewed for the next monitoring period.

Inclinometer readings at BH7 could not be taken due to logger issues, and the equipment should be repaired for the next monitoring period.

Observations during the winter/spring of 2019 suggested ground movement had occurred at the cliff toe at the lower end of the valley. An eye-witness account reported to JBA indicated that during high rainfall events the discharge of the stream increases and causes bank erosion at the end of the valley. It is suggested this site is visually inspected following high rainfall events for evidence of continued bank erosion and instability on the slope.

7. Scarborough North Bay – Oasis Café

7.1 Site description

Oasis Café cliffs are situated in the southern part of Scarborough's North Bay and occupy part of Clarence Gardens, which are landscaped coastal slopes open to the public (Figure 7.1). The cliffs rise to c. 30m OD and have a typical angle of 25-30°, although the main headscarp reaches 50°. The upper c. 15m of cliff is cut in glacial sediments and Jurassic sandstones and mudstones form the basal part of the cliff. The Holbeck to Scalby Mills strategy study (High-Point Rendel, 1999) classified the cliffs as multiple rotational landslides formed predominantly in the Jurassic bedrock. The landslides are fronted by the Marine Parade road and coast protection scheme and have not experienced toe erosion for over 100 years. Despite the toe protection, cliff instability risk in response to extreme rainfall remains a concern.

7.2 Ground model and monitoring regime

This frontage is covered by a single cliff behaviour unit, MU20/4a. Geomorphological mapping undertaken as part of the strategy study recognises a series of discrete landslides within this CBU, but all are classified as multiple rotational landslides formed predominantly in bedrock. It is assumed the basal shear surface is near Ordnance Datum and has formed in weak layers within the interbedded sandstones and mudstones. The monitoring regime comprises inclinometers and co-located automated piezometers at the cliff top, mid-slope and cliff toe positions aligned along a southwest to northeast bearing (Figure 7.1).

7.3 Historical ground behaviour (2009 to 2012)

Table 7-1 summarises the observations in Mouchel (2012) from the monitoring undertaken at the Oasis Café.

Table 7-1 Summary of historical ground behaviour at Oasis Café.

Observations in Mouchel 2012 (covering 6-month period between Dec 2011 and June 2012)	Total change observed between July 2009 and June 2012
Static groundwater at around 8.05m at BH2p and increase in water levels at BH3p and a decrease at BH4p. Slopes here appear to be stable from inclinometer readings although shallow ground movements were observed.	Apparent movements reported but these are attributed to operator error or temperature fluctuation rather than actual ground movements.

7.4 Review of data collected under this programme (2012 to 2021)

A review of the data collected under this programme from 2012 to 2020 is summarised in Table 7-2. Overall, the data show that elevated groundwater levels have occurred in the past (specifically at BH4p), however, there has been no significant ground movement at any of the inclinometers.

Table 7-2 Summary of data collected at Oasis Café under this programme (2012 to 2021).

Borehole	Details	Report status															
		06/12 to 11/13	12/13 to 05/14	06/14 to 11/14	12/14 to 05/15	06/15 to 11/15	12/15 to 05/15	06/16 to 11/16	12/16 to 05/17	06/17 to 11/17	12/17 to 05/18	06/18 to 11/18	12/18 to 05/19	06/19 to 11/19	12/19 to 07/20	08/20 to 12/20	01/21 to 06/21
Inclinometer	**Borehole depth (base)**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
BH3	5.5 m BGL (12.3 m OD)																
BH4	13.5 m BGL (17.6 m OD)																
Piezometer	**Tip depth**																
BH2p	8.05 m OD																2
BH3p	12.4 m OD													2	2	2	2
BH4p	17.0 m OD					1	1	1	1	1	1		1			2	2

Note: cells with '1' indicate boreholes where ground movement or elevated groundwater was observed during the given monitoring period of the report; cells with '2' indicate boreholes where there were equipment errors, or where the data was unable to be collected.

7.5 New data

Table 7-3 and Table 7-4 summarise the monitoring data from inclinometer and piezometer installations at the Oasis Café. Data for this monitoring period was collected in June 2021.

The new data indicate:

- No significant ground movements recorded in any of the inclinometers.
- No groundwater data is available at any of the monitoring locations due to data collection errors and logger issues. The data should be downloaded and reviewed for the next monitoring period.

Table 7-3 Summary of inclinometer data at Oasis Café.

Borehole	Details	Report status	
		Change 08/20 to 12/20	**Change 01/21 to 06/21**
		15	**16**
BH3	5.5 m BGL (12.3 m OD) Mid slope, within glacial sediment and weathered mudstone	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
BH4	13.5 m BGL (17.6 m OD) Cliff top, within glacial sediment and sandstone bedrock	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.

Table 7-4 Summary of groundwater data at Oasis Café.

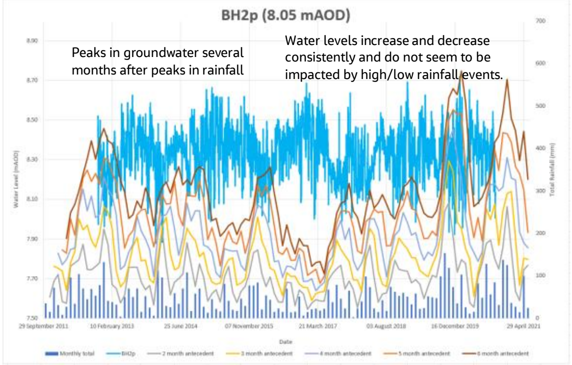
Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
BH2p	8.05 m OD Lower cliff	Continuation of past pattern fluctuating weekly around an average of 8.3m OD, decreasing to 8.0m OD in September. Groundwater levels averaged 8.1m OD at the end of the monitoring period.	No data available, data collection binary error. Equipment to be repaired or replaced.
BH3p	12.4 m OD Mid slope	No data available. Data logger communication error. Equipment to be repaired or replaced.	No data available, communication or battery error. Equipment to be repaired or replaced.
BH4p	17.0 m OD Cliff top	No data available. Data logger communication error. Equipment to be repaired or replaced.	No data available, communication or battery error. Equipment to be repaired or replaced.

7.6 Causal-response relationships

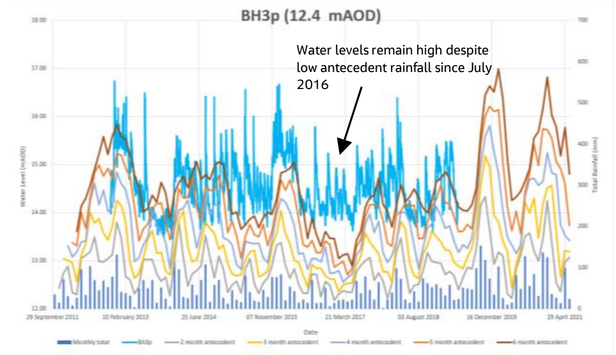
The higher than average rainfall in early winter 2015/2016 is reflected by elevated groundwater levels which fall in response to drier than average conditions which follow into 2017. On 23 August 2017 extremely heavy rainfall occurred, coinciding with a spike in groundwater levels at borehole BH2p, however this occurs only once in the record during high rainfall events. For example, the response of groundwater level in this borehole to the extreme rainfall on 20 September 2018 was indistinguishable. Borehole BH2p has an unclear response to rainfall and/or tides. Shallow piezometer BH3p shows a very rapid response to rainfall events (which probably explains the spikes on 10 Aug and 8 Oct 2014, and 9 May and 12 Dec 2015, 3 Jan and 27 August 2016, 12 March, 2 April, 27 July and 20 September 2018). Although a peak in groundwater in response to the 23 August 2017 rainfall event is evident, it is muted when compared to other high rainfall events. This piezometer showed a very clear response to the rainfall on 15 December, 27 January, and 5 to 6 March 2019. Only marginally deeper piezometer BH4p shows a lag response to prolonged periods of high rainfall, of up to 4 months antecedent rainfall. Groundwater levels in all boreholes remain below their peaks of winter 2012/13 and the inclinometers do not indicate movement. The heavy rainfall events during autumn and winter 2019/20 is not clearly reflected by the changes in groundwater levels.

Figure 7.2 presents the groundwater levels at Oasis Café recorded by each piezometer (with data logger) and antecedent rainfall. The relationships to different antecedent rainfall periods have been assessed visually.

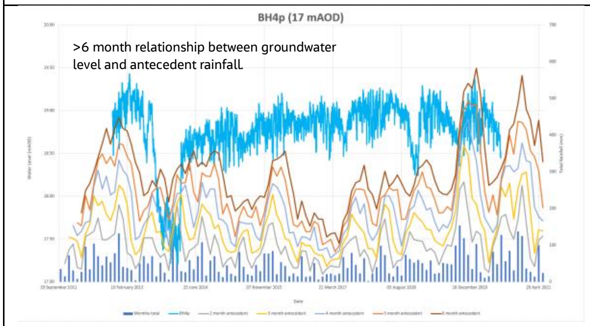
BH3p, located mid-way down the cliff, has a 4-5 month antecedent rainfall relationships. In contrast BH2p and BH4p , at the base and top of the cliff respectively, appear to have antecedent rainfall relationship greater than 6 months. These complex spatial relationships probably reflect variation in the glacial sediments that are typically low permeability clays, but locally high permeability sands.



A – BH2p (tip at 8.05 m OD at base on lower cliff). >6 month antecedent rainfall relationship.



B – BH3p (tip at 12.4 m OD at base on midslope). 4-5 month antecedent rainfall relationship.



C – BH4p (tip at 17 m OD on cliff top). >6 month antecedent rainfall relationship.

Figure 7.2: Relationship between groundwater levels and antecedent rainfall at Oasis Café.

7.7 Implications and recommendations

No data are available for BH2p, BH3p and BH4p resulting from data collection errors and logger issues. SBC should arrange for issues with the data loggers to be repaired and the data should be downloaded and reviewed for the next monitoring period. Future reports should pay attention to the midslope piezometer (BH3p) which has shown rapid response to rainfall conditions, but no associated ground movements to date. No significant ground movements have been recorded at Oasis Café, and there are no other specific recommendations at this location beyond on-going collection and analysis of data.

8. Scarborough North Bay – The Holms

8.1 Site description

The Holms is situated towards the southern end of North Bay, adjacent to Castle Headland. It is an area of sloping, hummocky, open parkland with a deeply indented, arcuate headscarp between the castle at the cliff top and Marine Drive along the coast.

The slopes rise from Marine Drive at angles of c. 25-30° to a midslope bench at 35m OD and upper cliff at c. 55m OD, where a near-vertical cliff face rises to the cliff top at c 85m OD. A variable thickness of glacial sediments overlies interbedded sandstones and mudstones of Jurassic age. Two faults cross the site, one of which delineates the boundary of younger more resistant geological strata that form Castle Headland from the succession underlying much of the rest of North Bay.

The Holbeck to Scalby Mills strategy study (High-Point Rendel, 1999) classified the cliffs as multiple rotational landslides formed predominantly in the Jurassic bedrock. The landslides are fronted by the Marine Parade road and coast protection scheme and have not experienced toe erosion for over 100 years. Previous instability problems include a 200mm displacement of the sea wall, likely a result of reactivation of the pre-existing landslides. Movements of the main landslide body are estimated to be in the order of 10s of centimetres. Therefore, despite the toe protection, cliff instability risk in response to extreme rainfall remains a concern.

8.2 Ground model and monitoring regime

This site includes the Cell 1 cliff units MU21/1, which is the main landslide embayment, and MU20/4b which covers the cliffs to the west towards Oasis Café.

Mouchel (2012) state 'The Holms landslide system comprises 10 to 17m of landslide debris which overlies the intact Scalby Formation'. Two units within the landslide have been identified from ground investigations undertaken in 2000:

- An eastern unit, comprising a deep-seated landside which daylights close to the foreshore
- A western unit, composed of a shallower landslide which daylights approximately 1.5m above Marine Drive (c. 8.5m OD)

The monitoring regime at The Holms comprises:

- Lower slope – two co-located piezometers. Each piezometer measures groundwater level at a different depth.
- Midslope – two sets of two co-located piezometers, one set on the more north-easterly midslope bench and one set on the more westerly slopes. Each multiple piezometer location measures groundwater levels at different depths.
- Upper slope – inclinometer in the central part, c. 50m NE and downslope of the bridge on the entrance road to the castle.
- Cliff top – one inclinometer on the cliff top at the northern end of Mulgrave Place c. 50m to the west of the western end of the arcuate headscarp of The Holms.

8.3 Historical ground behaviour (2009 to 2012)

The Holms was monitored by Mouchel between summer 2009 and summer 2012. A summary of their results is provided at Table 8-1. The pattern of groundwater variation at L1 appears to be affected by tidal influences and all other piezometers are affected by accuracy issues which prevent meaningful conclusions being reached about the groundwater regime at The Holms.

Table 8-1 Summary of historical ground behaviour at The Holms.

Observations in Mouchel 2012 (covering 6-month period between Dec 2011 and June 2012)	Total change observed between July 2009 and June 2012
Mouchel (2012) comments that no ground movement has been indicated at BH10A. They mention continued ground movements of around 14mm between 13 and 10m depth (ca. 46-43m OD) in BH11. They report erratic groundwater readings from BH8 and BH9 a & b, and recommended flushing them as they believed they were blocked. As such, they report it was not possible to provide definitive information about the groundwater regime at The Holms.	Displacements of around 18mm at 10-13m depth (46-43m OD in BH11, 4mm of which occurred between December 2010 and June 2011 and a further 14mm between June 2011 and June 2012. Groundwater at L1 shows fluctuations of between 40mm and 120mm which is attributed by Mouchel (2012) to tidal level fluctuations.

8.4 Review of data collected under this programme (2012 to 2021)

A review of the data collected under this programme from 2012 to 2020 is summarised in Table 8-2. Overall, the data show that elevated groundwater levels have occurred in the past (specifically at BH9b), however, there has been no significant ground movement at any of the inclinometers.

Table 8-2 Summary of data collected at The Holms under this programme (2012 to 2021).

		Report status															
Borehole	Details	06/12 to 11/13	12/13 to 05 14	06/14 to 11/14	12/14 to 05/15	06/15 to 11/15	12/15 to 05/15	06/16 to 11/16	12/16 to 05/17	06/17 to 11/17	12/17 to 05/18	06/18 to 11/18	12/18 to 05/19	06/19 to 11/19	12/19 to 07/20	08/20 to 12/20	01/21 to 06/21
Inclinometer	**Borehole depth (base)**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
BH10A	42 m BGL (4.75 m OD)	2	2	2	2									2			2
BH11	22 m BGL (34 m OD)																
Piezometer	**Tip depth**																
L1a	-8.03 m OD														2	2	2
L1b	-2.96 m OD																2
BH8a	10.16 m OD																2
BH8b	3.16 m OD														2		2
BH9a	9.49 m OD					2	2	2		2		2	2	2	2	2	2
BH9b	0.49 m OD		1			1	2		2								

Note: cells with '1' indicate boreholes where ground movement or elevated groundwater was observed during the given monitoring period of the report; cells with '2' indicate boreholes where there were equipment errors, or where the data was unable to be collected.

8.5 New data

Tables 8.2 and 8.3 summarise the readings from the inclinometers and piezometers at The Holms up to June 2021. The new data indicate:

- No groundwater data was available for any of the monitoring devices, mostly resulting from communication errors or device issues. The data should be downloaded and reviewed for the next monitoring period.

- Piezometer BH9b is no longer monitored.

Table 8-3 Summary of inclinometer data at The Holms.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
BH10A	42 m BGL (4.75 m OD) Upper slope, within made ground, clay/sand, and sandstone bedrock	Readings are less than 1mm and therefore not significant.	No movement detected
BH11	22 m BGL (34 m OD) Cliff top, within glacial sediment and weathered sandstone	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.

Table 8-4 Summary of groundwater data at The Holms.

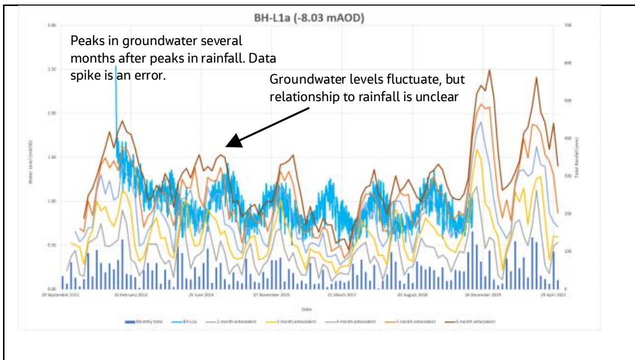
Borehole	Details	Report status	
		Change 08/20 to 12/20 15	Change 01/21 to 06/21 16
L1a	-8.03 m OD Lower slope co-located with L1b	No data available. Data logger communication error. Equipment to be repaired or replaced.	No data available, communication or battery error. Equipment to be repaired or replaced.
L1b	-2.96 m OD Lower slope co-located with L1a	Continuation of 2 to 3-week cyclical pattern, with variations up to 0.5 m over the monitoring period. Groundwater levels peaked on 17 September at 3.8m OD and falls to an average of 3.5m OD by the end of the monitoring period.	No data available, download issue. Equipment to be repaired or replaced.
BH8a	10.16 m OD Mid slope co-located with BH8b	Groundwater levels have remained steady at an average of 10.3 m OD. Groundwater levels peaked at 10.5 m OD on 16 September. Variations of up to 0.5 m occurred during September.	No data available, download error. Equipment to be repaired or replaced.
BH8b	3.16 m OD Mid slope co-located with BH8a	Groundwater levels continue a saw-tooth pattern, rising during the monitoring period gradually to peak on 17 September at 9.5m OD. Groundwater levels fall rapidly to 8.9m OD by October.	No data available, device appeared to have good connection but received a download error. Equipment to be repaired or replaced.
BH9a	9.49 m OD Mid slope co-located with BH9b	Logger removed. Equipment to be replaced.	Logger removed. Equipment to be replaced.
BH9b	0.49 m OD	Logger removed as piezometer no longer functioning.	Logger removed as piezometer no longer functioning.

Borehole	Details	Report status Change 08/20 to 12/20 15	Change 01/21 to 06/21 16
	Mid slope co-located with BH9a		

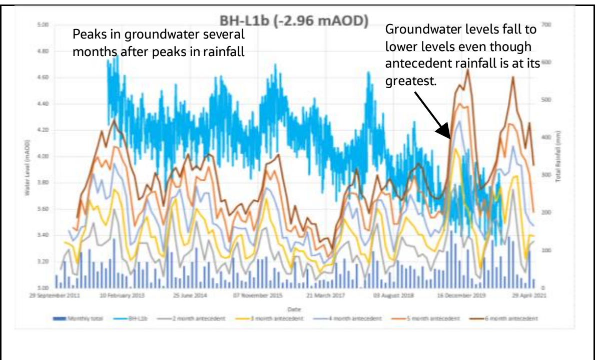
8.6 Causal-response relationships

The piezometers at The Holms show a lagged response to above average rainfall conditions, with only BH8a showing a rapid response. Groundwater levels in BH8a responded rapidly to higher than average rainfall in May 2015, March and November 2016. Levels fell during winter 2016/2017 following months of dry conditions then stabilised following a wet summer in 2017. Levels increased again over the drier than average winter 2017/18 and have stabilised at average levels following this. Other boreholes show a continuation of past fluctuating or steady levels of groundwater, suggesting they respond to several months' antecedent rainfall. Over the whole record, BH8b shows a different pattern of gradual highs followed by sharp falls, however movements are not shown in the inclinometer upslope at BH10A. There is no clear response in any of the boreholes to the extreme rainfall events experienced on 23 August 2017, 20 September 2018 or during autumn. During this monitoring period, the response to the wetter than average conditions in summer are not clear at the functioning piezometers. The steady and falling groundwater levels recorded may be representative of 3-month antecedent rainfall conditions.

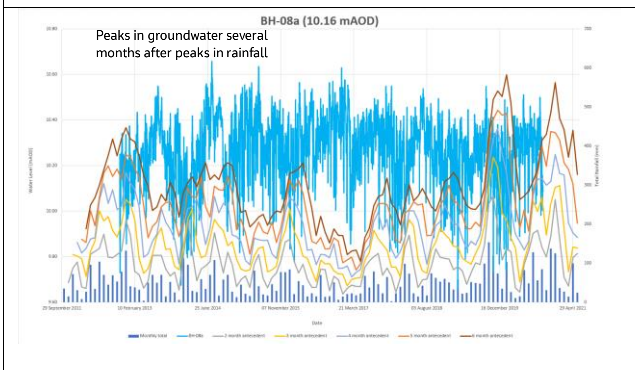
Figure 8.2 presents the groundwater levels at the Holmes recorded by each piezometer (with a data logger) with enough continuous data and highlights the best relationship to antecedent rainfall, which has been assessed visually by plotting various antecedent rainfall totals against the piezometer records. BH-L1a, BH-L1b and BH-08a all have an observed antecedent rainfall relationship of greater than 6-months, whereas BH-08b and BH-09a have 5-6 month and 4-5 month antecedent rainfall relationships respectively. A groundwater level spike at BH-08b in late 2016 does not coincide with antecedent rainfall levels, which probably reflects a very localised rainfall event at The Holmes.

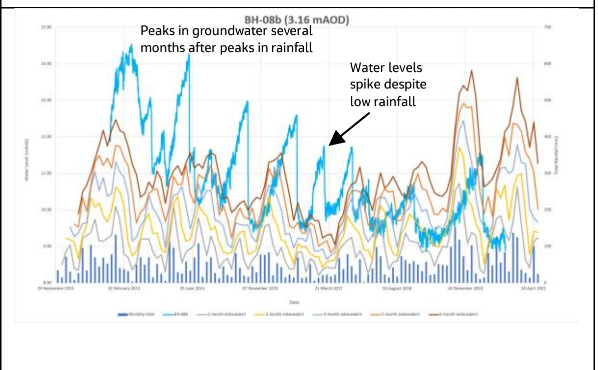


A – BH-L1a (tip at -8.03 m OD at base on lower slope). >6 month antecedent rainfall relationship



B – BH-L1b (tip at -2.96 m at base on lower slope). 6 month antecedent rainfall relationship or greater.





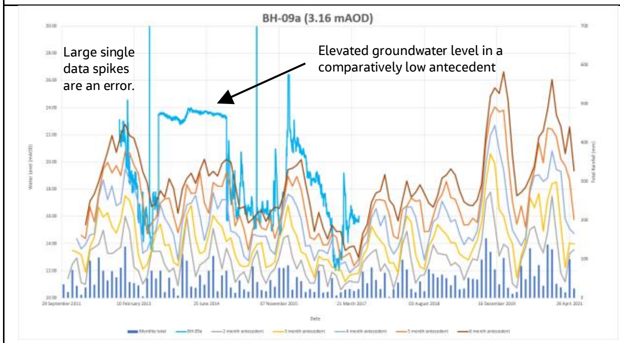
C – BH-08a (tip at 10.16 m OD at base on mid slope). 6 month antecedent rainfall relationship or greater.	D – BH-08b (tip at 3.16 m OD at bas on mid slope). 5-6 month antecedent rainfall relationship
	
D – BH-09a (tip at 3.16 m OD at base on mid slope). 4-5 month antecedent rainfall relationship.	

Figure 8.2: Relationship between groundwater levels and antecedent rainfall at the Holmes

8.7 Implications and recommendations

No groundwater data was available for any of the monitoring devices, mostly resulting from communication errors or device issues. The devices should be checked/repaired where required. The data should be downloaded and reviewed for the next monitoring period.

9. Scarborough South Bay

9.1 Site description

South Bay is formed from cliffs cut in Jurassic sandstones and siltstones that are overlain by a thick sequence of glacial sediments. A series of deep-seated landslides have developed in the glacial sediments and underlying weathered bedrock in post-glacial times. Since Victorian times, the cliffs have been extensively landscaped into public areas that include the Spa conference centre complex. The coastline has marginal stability, but first-time failures do occur: the Holbeck Hall Hotel landslide occurred in June 1993 and there are records of similar cliff failures occurring elsewhere along the frontage over the last several hundred years. The whole frontage benefits from coastal defences, but ground movements in pre-existing landslides and over-steep cliff sections continue to occur, particularly in response to periods of elevated ground water levels, and there remains concern of first-time failures and reactivation failures in the cliffs. Instability risk is therefore a concern along the whole of South Bay.

The majority of South Cliff (from St Nicholas Cliff to Holbeck Gardens) was mapped in 2011 as part of the Scarborough Spa Coast Protection scheme. This mapping underpins the ground model for this site. Cliff behaviour units (CBUs) have been defined and their activity status classified under the Cell 1 Regional Monitoring Programme.

9.2 Ground model and monitoring regime

Pre-existing landslides have developed in the thick sequence of glacial sediments that form the upper coastal slope. Their geomorphology generally comprises arcuate landslide embayments with mid-slope benches that are fronted by elongate mudslide tracks and vertical *in situ* bedrock cliffs. The basal shear surface typically appears at the contact between the glacial sediment and underlying Jurassic bedrock, but it is likely that the significant local variation in the glacial sediments allows secondary shear surfaces to form along clay layers.

The monitoring regime at South Bay is summarised in Appendix A and Figure 9.1. It comprises an extensive suite of inclinometers and piezometers, most of which are automated, and an experimental acoustic inclinometer installed near the Spa Centre.

The areas being monitored comprise, from north to south:

- St Nicholas Cliff – till cliff fronting the Grand Hotel and cliff lift with a co-located single inclinometer and diver piezometer with barometric diver that were installed in 2014 (MU22/0)
- Spa Chalet Gardens – till cliff with groundwater monitoring at its toe and an inclinometer inland of the cliff top (MU22/1).
- Spa Centre and gardens – rotational landslide (MU 22/2) and very steep till cliff (MU22/3) in the vicinity of the Spa buildings. Extensive monitoring of groundwater levels and ground movements at locations inland of the cliff top, on the slope and at the cliff toe.
- Clock Café – rotational landslide (MU 22/3) that is monitored with transect of devices comprising two inclinometers on the slope and a piezometer inland of the headscarp.
- South Cliff Gardens – till cliff with a mudslide embayment north of the Rose Garden (CBU 22/5), a small rotational landslide at the Rose Garden and a much larger rotational landslide at the Italian Garden, known at the South Bay Pool landslide (CBU 22/6). The area is monitored by three transects of devices that cover each of the landslides.
- Holbeck Gardens (CBU 22/7) – till cliff monitored at three locations.

These areas include both pre-existing landslides and intact cliffs and headscarps where instability is a risk. The Spa Centre is the focus of monitoring and is also the subject of an on-going coast defence scheme to improve the seawall and stabilise the slope.

At each location, a suite of instruments are installed on the promenade, on the coastal slope and at the cliff toe allowing ground models to be developed and stability modelling to be undertaken.

9.3 Historical ground behaviour (2009 to 2012)

South Bay was monitored by Mouchel Ltd for the period between summer 2009 and summer 2012. A summary of their results is provided in Table 9-1, which shows slight movement in a number of inclinometers and variable groundwater levels. No relationship between groundwater level and ground movement was reported by Mouchel.

Table 9-1 Summary of historical ground behaviour at Scarborough South Bay.

Observations in Mouchel 2012 (covering 6-month period between Dec 2011 and June 2012)	Total change observed between July 2009 and June 2012
AA10 (Clock Cafe) and AA08 (south Cliff Gardens) showed slight movement at shallow depths. Movement at greater depth was indicated in BHs 12, 13, 14 (at the Spa) and 16A (South Cliff Gardens). No movements indicated by other inclinometers. Groundwater levels are generally variable across the sites, except in the south of the Spa, where levels were reduced.	In addition to observations between Dec 2011 and June 2012, slight movement was recorded at AA04 in the upper 7m of ground, at AA10 in the upper 3.5m and at AA11 in the upper 3m. All net movements have been less than 10mm.

9.4 Review of data collected under this programme (2012 to 2021)

A review of the inclinometer data collected under this programme from 2012 to 2021 is summarised in Table 9-2. Piezometer data are summarised in Table 9-3. Overall, the data show:

- Shallow surface creep at Scarborough Spa (BH14 and BH105) between December 2018 and May 2019. Nearby piezometers indicated groundwater levels remained steady, with the exception of piezometer in BH104b which showed levels had risen.
- Possible movement along a shear surface within the sandstone/siltstone bedrock at an elevation of 29 m OD in BH20 at South Cliff Gardens between June 2012 and November 2013. Nearby piezometers indicated groundwater levels remained steady. No ground movements were reported on site, although evidence of failures in the lower cliff and water seepage were mapped at this location in 2011.
- Minor displacement (4 mm) in siltstone at 55m depth in AA07 at Holbeck Gardens between December 2013 and May 2014. This would be anticipated from experience at Holbeck Hall Hotel and other pre-existing landslides in South Bay. No ground movements were reported on site during the August 2014 coastal inspection.

Table 9-2 Summary of inclinometer data collected at South Bay under this programme (2012 to 2021).

Location	ID	Details	06/12 to 11/13	12/13 to 05 14	06/14 to 11/14	12/14 to 05/15	06/15 to 11/15	12/15 to 05/15	06/16 to 11/16	12/16 to 05/17	06/17 to 11/17	12/17 to 05/18	06/18 to 11/18	12/18 to 05/19	06/19 to 11/19	12/19 to 07/20	08/20 to 12/20	01/21 to 06/21
	Inclino-meter	Borehole depth (base)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
St Nich Cff	FR01	20 m BGL (-8.5 m OD)															2	
Chalet	BH12	65 m BGL (-16.95 m OD)		2														
Spa	AA04 (G2)	40.5 m BGL (7.1 m OD)	2										2	2		2		
	BH13	61 m BGL (-7.07 m OD)	2								2				2	2	2	2
	BH14	55 m BGL (0.73 m OD)											2	1	1	2		
	BH101	26.5 m BGL (-19.7 m OD)	2												1	1		
	BH103	10 m BGL (3.35 m OD)	2	2														
	BH107	18 m BGL (2.4 m OD)	2										2			2		
	BH109	15 m BGL (16.6 m OD)	2													2		
	BH105	45 m BGL (3.25 m OD)	2	2										1	2	2		
	BH105a	40 m BGL (2 m OD)												2	2			

Location	ID	Details	06/12 to 11/13	12/13 to 05 14	06/14 to 11/14	12/14 to 05/15	06/15 to 11/15	12/15 to 05/15	06/16 to 11/16	12/16 to 05/17	06/17 to 11/17	12/17 to 05/18	06/18 to 11/18	12/18 to 05/19	06/19 to 11/19	12/19 to 07/20	08/20 to 12/20	01/21 to 06/21
	Inclino-meter	Borehole depth (base)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Clock Café	AA10 (F2)	30 m BGL (5 m OD)								2					2	2		
	AA11 (F4)	20 m BGL (Unconfirmed)													2	2		
South Cliff Gardens	AA08 (D3)	24 m BGL (14.4 m OD)														2		
	BH17	50 m BGL (7.5 m OD)	2													2		2
	BH16A	54 m BGL (8.9 m OD)														2		
	BH20	41 m BGL (18 m OD)	1													2		
Hbk Gardens	AA07 (BH2)	60 m BGL (-3.7 m OD)		1											2			

Note: cells with '1' indicate boreholes where ground movement or elevated groundwater was observed during the given monitoring period of the report; cells with '2' indicate boreholes where there were equipment errors, or where the data was unable to be collected.

Table 9-3 Summary of piezometer data collected at South Bay under this programme (2012 to 2021).

Location	ID	Detail	06/12 to 11/13	12/13 to 05 14	06/14 to 11/14	12/14 to 05/15	06/15 to 11/15	12/15 to 05/15	06/16 to 11/16	12/16 to 05/17	06/17 to 11/17	12/17 to 05/18	06/18 to 11/18	12/18 to 05/19	06/19 to 11/19	12/19 to 07/20	08/20 to 12/20	01/21 to 06/21
		Tip depth	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
S Nich Cff	FR02	-6.5 m OD														2	2	
Spa Chalet	BH12	-8.4 m OD							2	2	2	2	2	2	2	2	2	2
Spa Chalet	BH12 a	3.6 m OD													2	2		
Spa	H2a	17.3 m OD																
Spa	H2b	11.1 m OD									2							
Spa	H5	15.5 m OD		2		1	1	1	1	1						2	2	1
Spa	1 spa	6.3 m OD		1		2					2	2	2		1	1	1	1
Spa	2 spa	6.4 m OD											2		2		1	1
Spa	3 spa	7.2 m OD				2						1		1	2	2	2	2
Spa	4 spa	10.9 m OD										1		1				1
Spa	G3	13.6 m OD				1						1	2	2	2	2	2	1
Spa	5 spa	9.4 m OD	2	2	2	2	2	2	2	2	2	2	2	1	2	2	2	2
Spa	BH1a spa	2.0 m OD										1				2	2	2
Spa	BH1b spa	10.1 m OD														2		2
Spa	BH1 Prom	41.4 m OD						1	1	2		2	2	2	2	2	2	1
Spa	G1a	55.48 m OD			2	2	2	2		2	2			1		2	2	2

Location	ID	Detail	06/12 to 11/13	12/13 to 05 14	06/14 to 11/14	12/14 to 05/15	06/15 to 11/15	12/15 to 05/15	06/16 to 11/16	12/16 to 05/17	06/17 to 11/17	12/17 to 05/18	06/18 to 11/18	12/18 to 05/19	06/19 to 11/19	12/19 to 07/20	08/20 to 12/20	01/21 to 06/21
		Tip depth	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	G1b	55.48 m OD				2				2		2	2	2				2
	BH108a	Deep tip	2		1		1								2	2	2	
	BH108b	Shallow tip	2		1	1	1	1	1	2	2	2	2	2	2	2	2	2
	BH106a	32.13 m OD	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	BH106b	40.79 m OD	2	2	2	2	2	2	2	2	2	2	2		2		1	
	BH104a		2	1												2	2	2
	BH104b	5.89 m OD	2			1	1	1	1	1	1	1		1	2	1	1	
	BH102a	2.89 m OD	2								2	2	2			2	2	2
	BH102b	15.27 m OD	2								2	2						2
Café	BH15	53.14 m OD	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
South Cliff Gardens	BH18a	26.8 m OD		2	2	2		1		1	1	1		2	2	2	2	2
	BH18b	23.8 m OD		2	2	2	2	2	2									2
	BH19a	53.8 m OD	2	2	2	2					1							
	BH19b	47.3 m OD	1	1							1					2	2	
	D2a	27.5 m OD	2						2								2	2
	D2b	41.5 m OD		2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

Location	ID	Detail	06/12 to 11/13	12/13 to 05 14	06/14 to 11/14	12/14 to 05/15	06/15 to 11/15	12/15 to 05/15	06/16 to 11/16	12/16 to 05/17	06/17 to 11/17	12/17 to 05/18	06/18 to 11/18	12/18 to 05/19	06/19 to 11/19	12/19 to 07/20	08/20 to 12/20	01/21 to 06/21
		Tip depth	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	Bh3a	41.5 m OD		2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Bh3b	10.5 m OD		2	2	2			2	2								2
	E2a	31.4 m OD						1				1			2	2	2	2
	E2b	43.6 m OD				2												
Hbk Gardens	BH4a	31.5 m OD					2	2	2	2	2	2	2	2	2	2	2	2
	BH4b	35 m OD		2	2	2	2	1	1	2	2	2	2	2	2	2	2	2

Note: cells with '1' indicate boreholes where ground movement or elevated groundwater was observed during the given monitoring period of the report; cells with '2' indicate boreholes where there were equipment errors, or where the data was unable to be collected.

9.5 New data

For clarity, new data for South Bay are presented for each of the monitoring areas separately.

9.5.1 St Nicholas Cliff (MU 22A)

The cliff here is around 30m high and heavily landscaped with terraces and footpaths and formed in fine-grained glacial sediments (Figure 9.1A). Average slope angle is 20 to 30° but is locally steeper with sections supported by retaining walls. The cliff is crossed by a cliff lift and the cliff top is occupied by the Grand Hotel. There is no history of instability in recent years and this CBU was not reported on by Mouchel.

Inclinometer data for this monitoring period show no significant readings. Piezometer FR02 fell since the last monitoring period to 7m OD. Dip meter readings at this site indicate water levels remain near the historical low.

Table 9-4 Summary of inclinometer data at St Nicholas Cliff.

		Report status	
Borehole	Details	Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
FR01	20 m BGL (-8.5 m OD) Mid slope above Foreshore Road in front of the Grand Hotel, within glacial sediment	No data available. Inclinometer needs repairing.	Readings are less than 1mm and therefore not significant.

Table 9-5 Summary of groundwater data at St Nicholas Cliff.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
FR02	-6.5 m OD Mid slope, influenced by tidal cycles	Groundwater levels began recording in July, showing a step change from 7m OD to 17.2m OD. Dip meter readings indicate groundwater level is steady at 6.4m OD, suggesting a systematic error in the piezometer. The monitoring shows a continuation of past cyclical patterns. SBC to arrange for logger repair.	Groundwater level fell to 7 m OD. Dip meter reading equals 6.4 m

9.5.2 Spa Chalet (MU 22/1)

This cliff is very steep and formed in glacial sediment that does not appear to have been affected by landsliding. The cliff has been previously stabilised with soil nails and netting. Monitoring comprises a single inclinometer on the promenade and a pair of closely located piezometers at the cliff toe. Inclinometer data are summarised in Table 9-6 and piezometer data in Table 9-7. The inclinometer indicated no significant ground movement. Piezometer BH12a highlights that groundwater has remained steady. The piezometer in borehole BH12 requires attention to fix or replace faulty equipment

Table 9-6 Summary of inclinometer data at Spa Chalet.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
BH12	65 m BGL (-16.95 m OD) Cliff top, within glacial sediment and sandstone/ mudstone bedrock	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.

The inclinometer indicated no significant ground movement. Piezometer BH12a highlights that groundwater has remained steady. The piezometer in borehole BH12 requires attention to fix or replace faulty equipment.

Table 9-7 Summary of groundwater data at Spa Chalet.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
BH12	-8.4 m OD Lower slope, influenced by tidal cycles	No data. Data logger communication error. SBC to arrange for repair of equipment.	No data. Data logger communication error. SBC to arrange for repair of equipment.
BH12a	3.6 m OD Lower slope	Groundwater levels increase slightly between mid-Aug and Sept, peaking on 17 Sept at 3.8m OD. Levels fell in Oct to a low of 3.3m OD, averaging around 3.5m OD.	Groundwater levels increase slightly between Jan and Feb, peaking on 27th Feb at 3.9 m OD. Levels fell in May to a low of 3.3 m OD, averaging around 3.6 m OD over the monitoring period.

9.5.3 Spa (MU 22/2 and 22/3)

The Spa is the focus of monitoring in South Bay, with eight inclinometers and 21 piezometers installed in the area (Figure 9.1B). The cliffs are generally steep and formed in glacial sediment. Shallower cliff sections are associated with a deep-seated landslide seen immediately north of the Spa Centre and localised shallow landslides. The monitoring results are described in Table 9-8 and Table 9-9. Several of the inclinometer readings were collected in December 2020 and are indicated in the table.

These data indicate:

- No significant ground movement was recorded over the monitoring period.
- Most locations show continuation of past patterns, and groundwater remaining steady or falling slightly over the monitoring period.
- Piezometer 1 spa shows groundwater levels have fallen slightly but remain elevated over the monitoring period; however, no ground movement was detected. The site should be inspected and monitored for evidence of ground movement, particularly following heavy rainfall events. The ground movement and groundwater trends will be reviewed in the next monitoring report. Groundwater levels have also fallen slightly at boreholes 2 spa and G3 but also remain at an elevated position.
- Groundwater levels at H5 have increased significantly over this monitoring period to a historical high. The site should be inspected and monitored for evidence of ground movement, particularly following heavy rainfall events
- Ground water at boreholes 4 spa and BH1 Prom have risen over this monitoring period.
- No data is available at boreholes BH1a spa, BH1b spa and BH104a, resulting from communication errors. Devices should be checked and repaired
- Piezometers 5 spa, G1a and G1b should be checked because they were dry. This equipment may be damaged and required attention to determine whether they can be repaired.
- No data available at piezometers BH106a and BH108b. The equipment should be repaired, and data collected on the next site visit.
- Access to piezometer 3 spa was not possible during this monitoring period as the borehole is buried under tarmac. The borehole should either be located and reinstated or removed from data collection.

Table 9-8 Summary of inclinometer data at the Spa.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
AA04 (G2)	40.5 m BGL (7.1 m OD) Upper slope, within glacial sediment and sandstone/ siltstone bedrock	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
BH13	61 m BGL (-7.07 m OD) Cliff top inland of headscarp, within glacial sediment and sandstone bedrock	Displacement of 30mm recorded at 57m depth in sandstone. Likely a result of erroneous readings or the inclinometer becoming loose in keying. Inclinometer should be checked.	Readings in bedrock are error. The inclinometer should be checked and re-monitored carefully.
BH14	55 m BGL (0.73 m OD) Cliff top, within glacial sediment and sandstone bedrock	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
BH101	26.5 m BGL (-19.7 m OD) In the seawall beyond toe of Spa landslide, within glacial sediment, sandstone/ mudstone bedrock	Readings are less than 1mm and therefore not significant. No further significant shearing in the clay at 13m BGL, that may relate to disturbance of the slope.	Readings are less than 1mm and therefore not significant.
BH103	10 m BGL (3.35 m OD) In the seawall beyond toe of Spa landslide, within glacial sediment	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
BH107	18 m BGL (2.4 m OD) Lower slope, within glacial sediment and sandstone/ mudstone bedrock	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
BH109	15 m BGL (16.6 m OD) Lower slope, within glacial sediment and sandstone/ mudstone bedrock	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
BH105	45 m BGL (3.25 m OD) Mid slope, within glacial sediment and sandstone bedrock	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
BH105a	40 m BGL (2 m OD) Mid slope, within glacial sediment	No data available. Monitoring discontinued at site.	No data available. Monitoring discontinued at site.

Table 9-9 Summary of groundwater data at the Spa.

Borehole	Details	Report status	
		Change 08/20 to 12/20 15	Change 01/21 to 06/21 16
H2a	17.3 m OD Upper slope near the headscarp of the Spa landslide	Groundwater levels have risen slightly between mid-August and September, peaking on 20 September at 17.3m OD. Groundwater levels fall in October to a low of 16.6m OD.	Groundwater levels follow a falling tend over the monitoring period, peaking on 28th Feb at 17.2 m OD and fall to a low on 13th March at 16.6 m OD.
H2b	11.1 m OD Upper slope near the headscarp of the Spa landslide	Groundwater levels have fallen slightly during the monitoring period to an average of 11.8m OD. Groundwater peaked on 16 September to 11.9m OD. Variation around the average is 0.4m over the monitoring period.	Groundwater levels remain generally steady at around 11.7 m OD. Groundwater peaked on 28th Feb at 12 m OD and a low on 11th March at 11.4 m OD.
H5	15.5 m OD Lower slope near the base of the cliff behind the Spa building	No data available. Data should be collected on next site visit.	Ground water has increased to its highest since 2012 at 25.3 m OD on 10 April after a period of sustained increase in groundwater. Groundwater has fallen since April but remains significantly higher than the historical record at 24.4 m OD on 30th June.
1 spa	6.3 m OD Lower slope near the base of the cliff	Groundwater levels have risen slightly to 10.7m OD and remain at an elevated position.	Groundwater levels fallen slightly to 10.6 m OD, but remain elevated.
2 spa	6.4 m OD Lower slope near the base of the cliff	Groundwater levels have risen to 10.4m OD.	Groundwater levels have fallen to 10.2 m OD.
3 spa	7.2 m OD Lower slope near the base of the cliff	Borehole buried under tarmac. Locate and reinstate borehole or remove from data collection.	Borehole buried under tarmac. Locate and reinstate borehole or remove from data collection.
4 spa	10.9 m OD Lower slope near the base of the cliff	Groundwater levels have fallen slightly to 11.6m OD.	Groundwater levels have risen to 12.2 m OD.
G3	13.6 m OD Lower slope near the base of the cliff	No data available for monitoring period. The integrity of the piezometer should be checked.	Groundwater has fallen from a historical high level, however, remains high compared to past levels at 16.2 m OD on 30th June.
5 spa	9.4 m OD Lower slope near the base of the cliff	Borehole dry. Check piezometer integrity.	Borehole dry. Check piezometer integrity.
BH1a spa	2.0 m OD Lower slope at the toe of the Spa landslide	No data available. Data logger communication error. Equipment repair or replace.	No data available. Data logger communication error. Equipment repair or replace

Borehole	Details	Report status	
		Change 08/20 to 12/20 15	Change 01/21 to 06/21 16
BH1b spa	10.1 m OD Lower slope at the toe of the Spa landslide	Groundwater levels have fallen slightly to an average of 11.9m OD. Groundwater levels peaked on 17 September at 12.2m OD.	No data available. Data logger communication error. Equipment repair or replace
BH1 Prom	41.4 m OD Cliff top inland	No telemetry data available at present. Equipment repair or replace, or remove from data collection.	Groundwater has increased over this monitoring period to a peak on 30 June at 43.5 m OD.
G1a	55.48 m OD Cliff top inland	Borehole dry. Check piezometer integrity.	Borehole dry. Check piezometer integrity.
G1b	55.48 m OD Cliff top inland	Groundwater levels have fallen to 20.0m OD.	Borehole dry. Check piezometer integrity.
BH108a	31.6 Deep Mid slope co-located with BH108b (telemetry)	Piezometer damaged. No dip readings available. Equipment to be repaired and data collected on next site visit.	Groundwater level is low at 4.8 m OD on 23 June. No dip meter readings available.
BH108b	Shallow Mid slope co-located with BH108a	Piezometer damaged, no access. Equipment to be repaired and data collected on next site visit.	No data available. No access. Data should be collected on next site visit.
BH106a	32.13 m OD Deep. Cliff top co-located with BH106b	Borehole dry. Check piezometer integrity.	No data available. Data should be collected on next site visit.
BH106b	40.79 m OD Cliff top co-located with BH106a	Groundwater levels have risen to 13.3m OD.	Groundwater levels have remained steady at 13.3 m OD. Hitting a lot of mud from around 34m.
BH104a	Lower slope co-located with BH104b	No data available. Data logger communication error. Repair equipment.	No data available. Data should be collected on next site visit.
BH104b	5.89 m OD Lower slope co-located with BH104a	Groundwater levels had risen at the end of Aug, peaking at 13.0m OD. Levels then fell to 8.2m OD in Oct. Levels remain elevated compared to the historical range.	Groundwater levels have fallen continuously since the previous monitoring period to the lowest level at 7.4 m OD.
BH102a	2.89 m OD Lower slope behind seawall co-located with BH102b	No data available. Data logger communication error. Repair equipment.	No data available. New lid with Allen key bolt, no access bolt is seized. Repair or replace lid
BH102b	15.27 m OD Lower slope behind seawall co-located with BH102a	Groundwater levels have fallen to 1.0m OD.	New lid with Allen key bolt, No access bolt is seized. Repair or replace lid

9.5.4 Clock Café (MU 22/4)

Monitoring at the Clock Café comprises a line of three boreholes from the promenade (BH15) to the midslope (AA10 F2) and lower slope (AA11 F4) (Table 9-10, Figure 9.1B).

No significant ground movement was detected at the Clock Café. The one piezometer at this location continues to be dry. This equipment may be damaged and required attention to determine whether it can be repaired and/or should continue to be read.

In mid-March 2018, a retaining wall behind chalets south of the Clock Café failed, resulting in significant cracks forming on the footpath behind the chalets. There are no inclinometers or piezometers in the vicinity of the wall failure, however adjacent data do not indicate any movement nearby. A ground investigation concluded that bedrock was at shallow depth and the failure was the result of collapse of the retaining wall structure rather than ground movement. High antecedent groundwater levels due to heavy rainfall in early spring 2018 were probably a trigger of the failure

Table 9-10 Summary of inclinometer data at the Clock Café.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
AA10 (F2)	30 m BGL (5 m OD) Upper slope at the headscarp of the Clock Café landslide, within glacial sediment and siltstone/ sandstone bedrock	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
AA11 (F4)	20 m BGL / Unconfirmed Lower slope near the toe of the Clock Café landslide, within glacial sediment and siltstone/ sandstone bedrock	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.

Table 9-11 Summary of groundwater data at the Clock Café.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
BH15	53.14 m OD Cliff top inland of the landslide headscarp	Borehole dry. Check piezometer integrity	No data available. Borehole dry. Check piezometer integrity

9.5.5 South Cliff Gardens (MU 22/5 and 22/6)

The South Cliff Gardens area comprises landscaped public areas and the former South Bay Pool, which lies at the foot of a relict landslide complex (the South Bay Pool landslide). There are three transects of monitoring locations (Table 9-12 and Table 9-13; Figure 9.1C).

These data indicate:

- No significant ground movement was recorded over the monitoring period at of the other inclinometers.
- Groundwater has slightly increased, remained steady or fallen at boreholes E2b, BH19a and BH19b respectively.
- No groundwater data was available at BH18a or BH18b due to a cable connection problem. These piezometers should be checked and repaired.
- No data were available for borehole piezometers D2a, D2b, BH3a, Bh3b and E2a. These piezometers should be checked and repaired.

Table 9-12 Summary of inclinometer data at South Cliff Gardens.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
AA08 (D3)	24 m BGL (14.4 m OD) Mid slope, within glacial sediment and interbedded bedrock	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
BH17	50 m BGL (7.5 m OD) Upper slope at the top of a mudslide embayment, within glacial sediment and siltstone bedrock	Readings are less than 1mm and therefore not significant.	Erroneous readings in bedrock. The borehole tubing should be cleaned and carefully re-monitored.
BH16A	54 m BGL (8.9 m OD) Upper slope inland of the Rose Garden rotational landslide, within glacial sediment and siltstone/ sandstone bedrock	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
BH20	41 m BGL (18 m OD) Mid slope in the body of a small landslide, within glacial sediment and sandstone bedrock	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.

Table 9-13 Summary of groundwater data at South Cliff Gardens.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
BH18a	26.8 m OD Lower slope near the base of the cliff and Rose Garden landslide co-located with BH18b	No data available. Data logger and cable connection problem. Repair equipment.	No data available. Data logger and cable connection problem. Repair equipment.
BH18b	23.8 m OD Lower slope near the base of the cliff and Rose	Groundwater levels fell to 34.1m OD during the period. Levels peaked at the end of Aug at 34.6m OD, which	No data available. Data logger and cable connection problem. Repair equipment.

Borehole	Details	Report status Change 08/20 to 12/20 15	Change 01/21 to 06/21 16
	Garden landslide co-located with BH18	corresponds with a period of heavy rainfall.	
BH19a	53.8 m OD Cliff top inland of the headscarp of the South Bay Pool landslide co-located with BH19b	Cyclical pattern with variation of 0.6 m. Levels have fallen during the monitoring period to an average of 52.0m OD, peaking on 17 Sept at 52.3. Levels fell to 51.7m OD by the end of the monitoring period.	Cyclical pattern with variation of 0.6 m. Groundwater levels have remained steady at 52 m OD.
BH19b	47.3 m OD Cliff top inland of the headscarp of the South Bay Pool landslide co-located with BH19a	Continuation of past patterns through most of the monitoring period. Groundwater levels increased during the period to 47.6m OD. Levels spike on 28 Aug, suggesting ingress of water during heavy rainfall. Equipment to be repaired and data collected on next site visit.	Groundwater levels fell to 47.3 m OD. All groundwater readings in the current monitoring period appear to be within the historical range.
D2a	27.5 m OD Upper slope at the headscarp of the South Bay Pool landslide co-located with D2b	No data available. Data logger communication error. Repair equipment.	No data available. Data logger communication error. Repair equipment.
D2b	41.5 m OD Upper slope at the headscarp of the South Bay Pool landslide co-located with D2a	No data available. Data logger communication error. Repair equipment.	No data available. Data logger communication error. Repair equipment.
Bh3a	41.5 m OD Mid slope adjacent to the South Bay Pool landslide co-located with Bh3b	No data available. Data logger communication error. Repair equipment.	No data available. Data logger communication error. Repair equipment.
Bh3b	10.5 m OD Mid slope adjacent to the South Bay Pool landslide co-located with Bh3a	Levels steady around 10.6m OD with sub-weekly fluctuations of up to 0.5 m. Peak on 16 Sept does not coincide with high daily rainfall totals and may suggest another influence.	No data available. Data logger communication error. Repair equipment.
E2a	31.4 m OD Upper slope below the headscarp of the mudslide embayment co-located with E2b	No data available. Data logger communication error. Repair equipment.	No data available. Data logger communication error. Repair equipment.
E2b	43.6 m OD Upper slope below the headscarp of the	Groundwater levels have fallen slightly to an average of 50.5m OD, varying up to 0.5m in Sept.	Groundwater levels have risen slightly to 50.6 m OD. With minor variations over this monitoring period.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
	mudslide embayment co-located with E2a	Peak on 17 Sept at 50.7m OD does not coincide with high daily rainfall totals and may suggest another influence.	Peak on 28 Feb at 50.8 m OD does not coincide with high daily rainfall and may suggest another influence

9.5.6 Holbeck Gardens (MU 22/7)

This area comprises two monitoring locations (Figure 9.1C); water levels are monitored at two depths along the promenade and ground movements are recorded by an inclinometer on the upper slope (Table 9-14 and Table 9-15).

The data logger was at fault for Bh4a and Bh4b and data were not downloaded. The integrity of the piezometers should be checked. No evidence of movement is shown in the current inclinometer data.

Table 9-14 Summary of inclinometer data at Holbeck Gardens.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
AA07 (BH2)	60 m BGL (-3.7 m OD) Cliff top, within glacial sediment and siltstone/ sandstone bedrock	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.

Table 9-15 Summary of groundwater data at Holbeck Gardens.

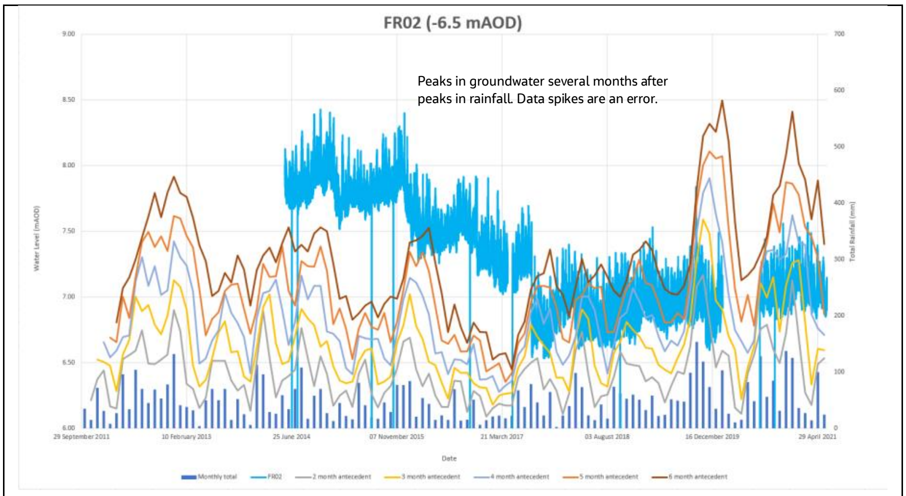
Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
BH4a	31.5 m OD Cliff top co-located with BH4b	No data available. Data logger communication error. Repair equipment.	No data available. Data logger communication error. Repair equipment.
BH4b	35 m OD Cliff top co-located with BH4a	No data available. Data logger communication error. Repair equipment.	No data available. Data logger communication error. Repair equipment.

9.6 Causal-response relationships

Groundwater levels in South Cliff tend to show stable or gradual decrease in groundwater levels following historical high levels, which suggests a very lagged response to rainfall (Figure 2.6).

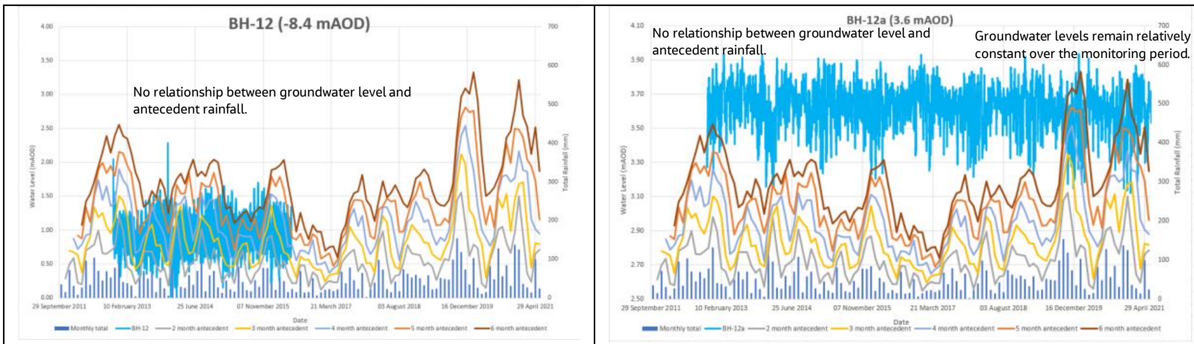
Figures 9.2, 9.3, 9.4 and 9.5 present the groundwater levels recorded by each piezometer (with a data logger) together with different antecedent rainfall periods to highlight relationships.

At St Nicholas cliff (Figure 9.2) BH-FR02 shows an antecedent rainfall relationship that appears greater than 6 months. At Spa Chalet (Figure 9.3), antecedent rainfall relationships are unclear, with responses often appearing significantly greater than 6 months. The picture is similar at The Spa (Figure 9.4), where BH-01a Spa and BH-01 Prom also show responses of greater than 6 months. In contrast BH-H5, which is at the base of the slope behind the Spa building, suggests an antecedent rainfall relationship of 4 months. All other automated piezometers at the Spa do not have an apparent antecedent rainfall relationship. At South Cliff Gardens (Figure 9.5), the antecedent rainfall relationship is greater than 6 months at BH-D2a, BH-E2a and BH-E2b. Relationships at other automated piezometers at the South Cliff Gardens remain complex.



A – BH-FR02 (tip at -6.5 m OD at base on mid-slope, influenced by tidal cycles) >6 month antecedent rainfall relationship.

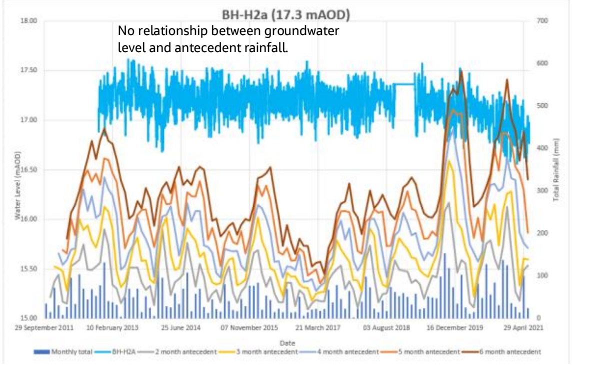
Figure 9.2: Relationship between groundwater levels and antecedent rainfall at St Nicholas Cliff.



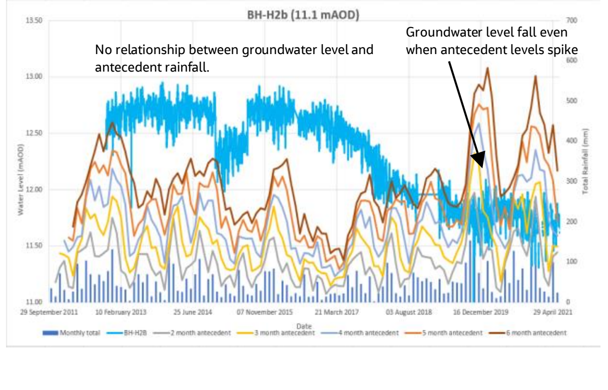
A – BH-12 (tip at -8.4 m OD at base on lower slope, influenced by tidal cycles). No apparent antecedent rainfall relationship.

B – BH-12a (tip at 3.6 m OD at base on lower slope). No apparent antecedent rainfall relationship.

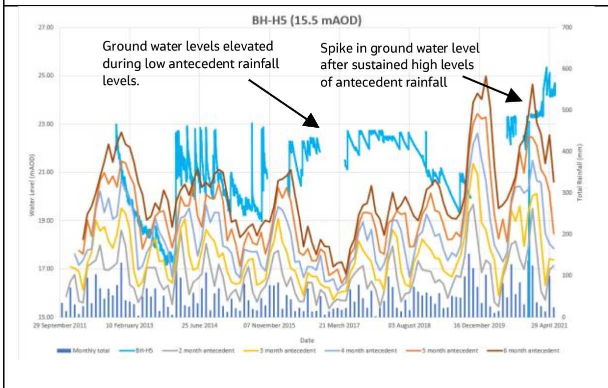
Figure 9.3: Relationship between groundwater levels and antecedent rainfall at Spa Chalet.



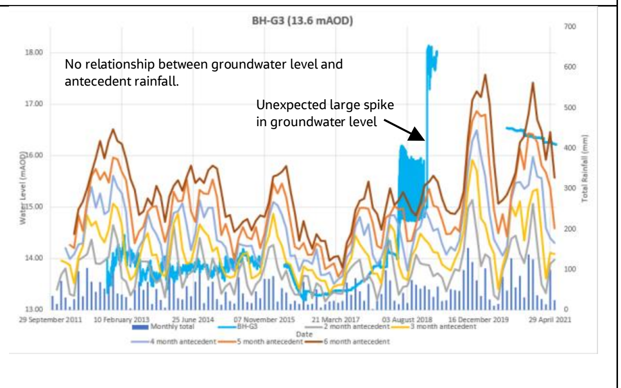
A – BH-H2a (tip at 17.3 m OD at base on upper slope near the headscarp of the Spa landslide). No apparent antecedent rainfall relationship.



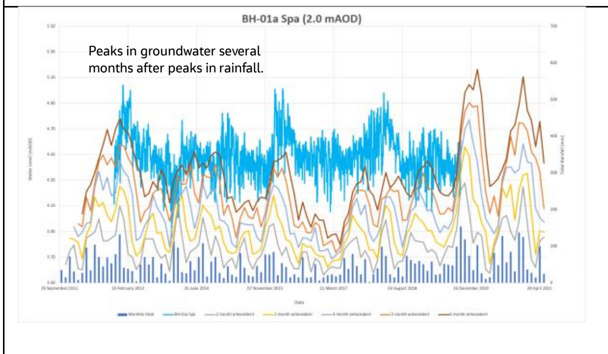
B – BH-H2b (tip at 11.1 m OD at base on upper slope near the headscarp of the Spa landslide). No apparent antecedent rainfall relationship.



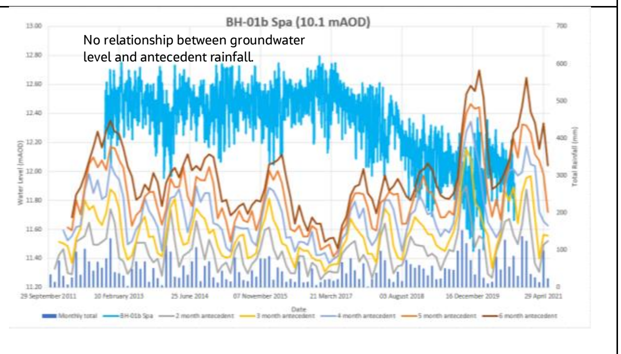
C – BH-H5 (tip at 15.5 m OD at base on lower slope near the base of the cliff behind the Spa building). Antecdent rainfall relationship is unclear dur to spikes in day, but could be 4 months



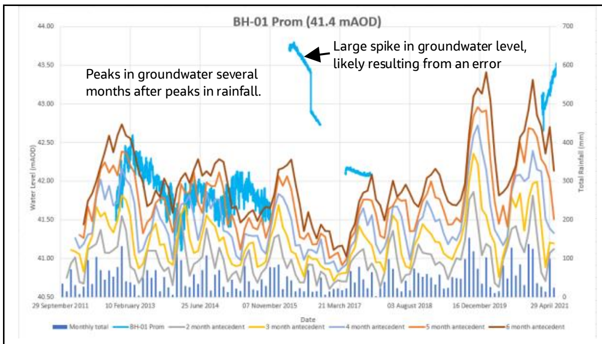
D – BH-G3 (tip at 13.6 m OD at base on lower slope near the base of the cliff). No apparent antecedent rainfall relationship.



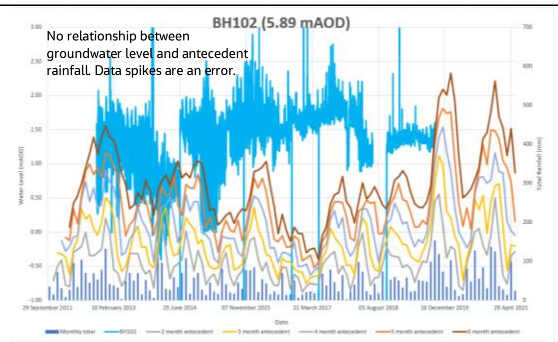
E – BH-01a Spa (tip at 2 m OD at base on lower slope at the toe of the Spa landslide). >6 month antecedent rainfall relationship.



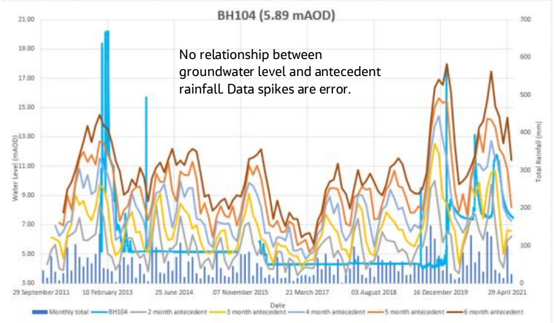
F – BH-01b Spa (tip at 10.1 m OD at base on lower slope at the toe of the Spa landslide) >6 month antecedent rainfall relationship.



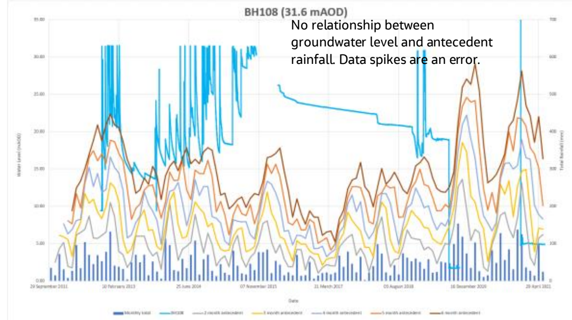
G – BH-01 Prom (tip at 41.4 m OD at base on cliff top inland) >6 month antecedent rainfall relationship.



H – BH102 (tip at 5.89 m OD at base on lower slope behind sea wall). No apparent antecedent rainfall relationship.

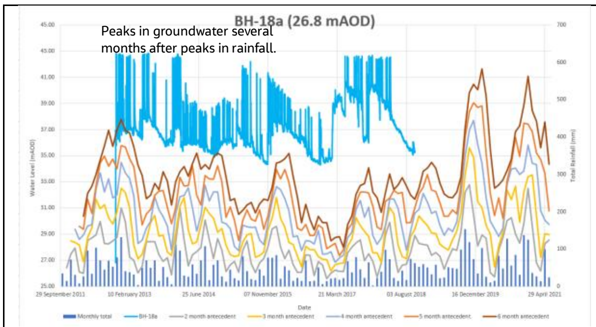


I – BH104 (tip at 5.89 m OD at base on lower slope) No apparent antecedent rainfall relationship.

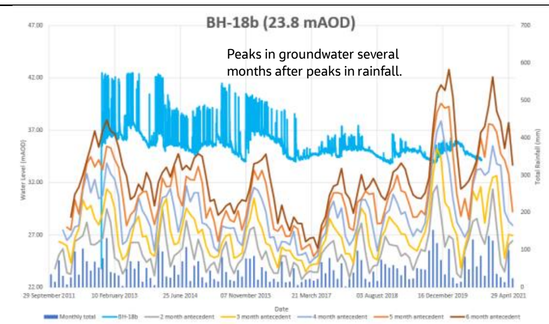


J – BH108 (tip at 31.6 m OD at base on mid slope) No apparent antecedent rainfall relationship.

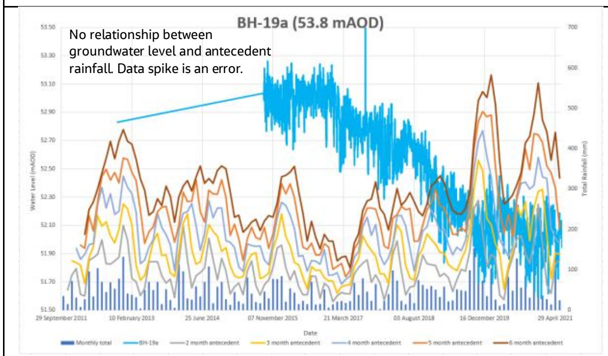
Figure 9.4: Relationship between groundwater levels and antecedent rainfall at Spa.

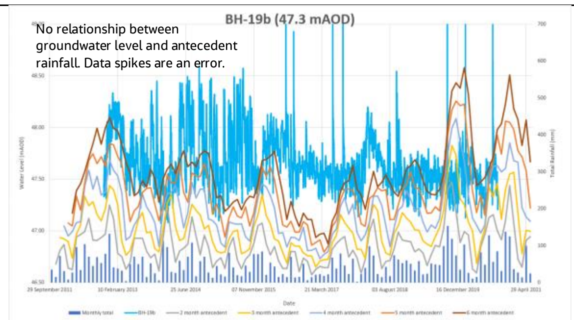


A – BH-18a (tip at 26.8 m OD at base on Lower slope near the base of the cliff and Rose Garden landslide). 6 month or greater antecedent rainfall relationship.



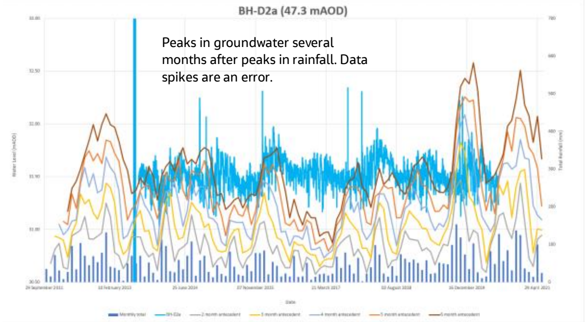
B – BH-18b (tip at 23.8 m OD at base on Lower slope near the base of the cliff and Rose Garden landslide). >6 month antecedent rainfall relationship.

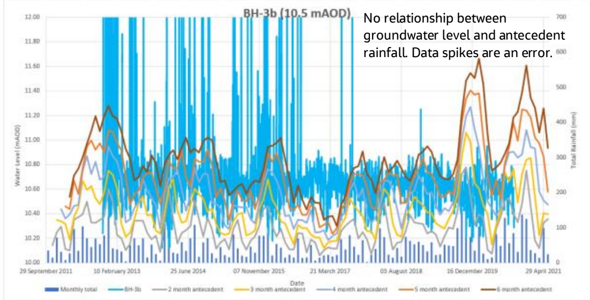




C – BH-19a (tip at 53.8 m OD at base on cliff top inland of the headscarp of the South Bay Pool landslide). No apparent antecedent rainfall relationship.

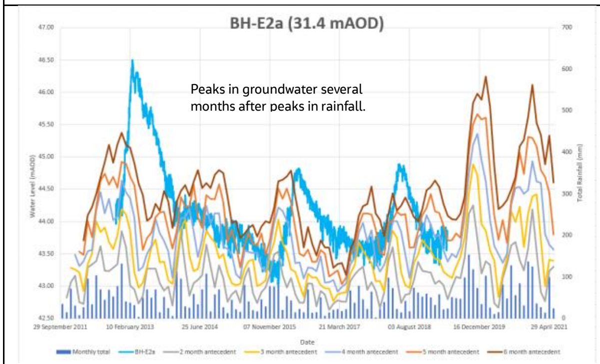
D – BH-19b (tip at 47.3 m OD at base on cliff top inland of the headscarp of the South Bay Pool landslide). No apparent antecedent rainfall relationship.

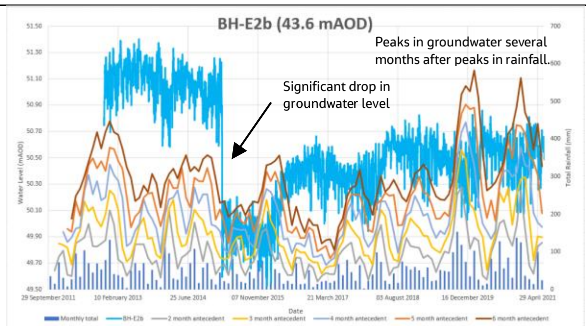




E – BH-D2a (tip at 47.3 m OD at base on upper slope at the headscarp of the South Bay Pool lansdlide). 6 month or greater antecedent rainfall relationship.

F – BH-3b (tip at 10.5 m OD at base on upper slope at the headscarp of the South Bay Pool lansdlide). No apparent antecedent rainfall relationship.





G – BH-E2a (tip at 31.4 m OD at base on upper slope below the headscarp of the mudslide embayement). >6 month antecedent rainfall relationship.

G – BH-E2b (tip at 43.6 m OD at base on upper slope below the headscarp of the mudslide embayement). >6 month antecedent rainfall relationship.

Figure 9.5: Relationship between groundwater levels and antecedent rainfall at South Cliff Gardens.

9.7 Implications and recommendations

Inclinometers BH13 (Spa) and BH17 (South Cliff Gardens) both gave erroneous readings that suggest blockage of the keyways. These locations should be cleaned.

Most functioning piezometers show that groundwater levels have either remained steady or slightly decreased. Piezometer 1 spa shows groundwater levels have fallen slightly but remain elevated over the monitoring period; however, no ground movement was detected. The site should be inspected and monitored for evidence of ground movement, particularly following heavy rainfall events. Groundwater levels at H5 have increased significantly over this monitoring period to a historical high. The site should be inspected and monitored for evidence of ground movement, particularly following heavy rainfall events

No data were collected at several piezometers (BH12 (Spa Chalet), 5 spa, BH1a spa, BH1b spa, G1a, BH108b, BH106a, BH104a, BH102a and BH102b (Spa), BH18a, BH18b, D2a, D2b, Bh3a, Bh3b and E2a (South Cliff Gardens), and BH4a and BH4b (Holbeck Gardens) due to data logger communication errors or damage to the equipment and consequently there are significant gaps in knowledge at this location over the monitoring period. Access to piezometer 3 spa (Spa) was not possible during this monitoring period as the borehole is buried under tarmac. Piezometers G1a, G1b, 5 spa (Spa) and BH15 (Clock Café) are recorded as dry. The integrity of piezometer tips should be checked, and the next monitoring data reviewed, whether these trends continue.

10. Filey Town

10.1 Site description

The cliffs at Filey are formed in thick (c. 50m) glacial sediments that overlie the Upper Jurassic Kimmeridge Clay Formation across the town frontage and Upper Calcareous Grit north of the town towards Filey Brigg. The cliffs are protected by a sea wall at Filey and unprotected to the north and south of the town. Outflanking of the seawall and cliff instability of both the protected and unprotected cliffs at Filey is a concern. The cliffs across the town frontage have been landscaped and are criss-crossed with public footpaths. The glacial sediments have been deeply incised to form Church Ravine to the north of the town and Martin's Ravine to the south.

In July 2007, an intense rainstorm resulted in severe and widespread flooding throughout Filey; the storm water run-off caused many slope failures and extensive scour damage to paths and bridge abutments within Martin's Ravine. Existing drainage was overwhelmed and extensively damaged due to the excessive storm water run-off around Glen Gardens and this also caused drainage to collapse leading to slope instability behind Royal Parade chalets and Crescent Hill (Mouchel, 2012). The unprotected cliffs to the north and the south of the town are susceptible to toe erosion by the sea and are actively retreating. Cliff behaviour units (CBUs) have been defined and their activity status classified under the Cell 1 Regional Monitoring Programme.

10.2 Ground model and monitoring regime

Cliff behaviour units, reflecting individual mudslides and areas of relict cliff protected by the seawall, have been mapped for the frontage (Figure 10.1):

- MU29/AA and /AB are cliffs and mudslides south of the town
- MU 28/Z is a till cliff protected by rock armour immediately south of the sea wall
- MU27/X and MU28/Y are dormant cliffs protected by the seawall
- MU27/T /U, /V and /W are cliffs and mudslides north of the town

Halcrow (2012a) provides an overview of the ground models throughout the Filey Town frontage. The whole cliff line is comprised of weak glacial sediments that tend to fail through simple landslides triggered by both toe erosion and elevated groundwater levels.

The cliffs at Filey town, which are protected by a seawall, display evidence of historical instability. Shallow failures last occurred in this area in response to the intense storm event of July 2007.

Within the ravines, the steep till slopes are susceptible to shallow failure resulting from toe undercutting and excess groundwater levels due to intense and prolonged rainfall events.

The monitoring regime at Filey Town comprises the following:

- Filey Country Park – Till cliff with ground water monitoring at the cliff top.
- Golf Course – Ground water monitoring at the cliff top.
- Church Ravine/Coble Landing – Ground water monitoring at the cliff top and an inclinometer at the cliff toe.
- The Crescent/Rutland St – Groundwater monitoring at the cliff top and an inclinometer at the cliff toe.
- Glen Gardens/Martin's Ravine – Ground water monitoring on the cliff top and toe. Inclinometers at the cliff top and toe.
- Muston Sands – Ground water monitoring at the cliff top.
- Inland North – Groundwater monitoring near Church Cliff Farm, Pinewood Avenue and Parish Wood.
- Inland South – Groundwater monitoring near Filey Fields Farm, Long Plantation (west of Rivelin Way and Fewston Close) and Filey School.

10.3 Historical ground behaviour (2009 to 2012)

Filey town was monitored by Mouchel Ltd for the period between summer 2009 and summer 2012. A summary of their results is provided in Table 10-1, which shows minor movement in one borehole during the autumn of 2009 but without subsequent movement and limited fluctuation in ground water level which Mouchel attribute to tidal variation in some boreholes and variations in stream flow in others. No relationship between groundwater level and ground movement was reported by Mouchel. Additional monitoring covering the period April 2011 to Dec 2012, associated with the recent seawall outflanking study, are provided in Halcrow (2013a).

Table 10-1 Summary of historical ground behaviour at Filey Town.

Observations in Mouchel 2012 (covering 6-month period between Dec 2011 and June 2012	Total Change observed between July 2009 and June 2012
Groundwater levels in BH5B (toe of Glen Gardens/Martin's Ravine) and BH6 (midslope Glen Gardens/Martin's Ravine) rose by 49mm and 560mm respectively. BH1 (cliff top Glen Gardens/Martin's Ravine, now inactive) rose 152mm which appeared to reflect prevailing water level in Martin's Ravine. BH04 (midslope Glen Gardens) was noted to be recording erratically. The inclinometer in BH3 was not readable during this time and no new movement was reported at BH6.	Mouchel report that ground water levels have increased since December 2011, the maximum rise having been identified as 560mm at BH4, Mouchel also describe erratic readings from this borehole. Mouchel describe an increase of 49mm at BH5b and attribute this to tidal fluctuations. Ground water readings from BH1 and BH2 appear to have remained relatively constant at about 15m OD. Only 'baseline' inclinometer readings have been determinable from BH3. Mouchel observe that ground water readings from BH1 seem to reflect water levels within the stream flowing in Martin's Ravine. Initially (between September and December 2009), displacements of <5mm were noted in BH6 but no further movements have been identified.

10.4 Review of data collected under this programme (2012 to 2021)

A review of the data collected under this programme from 2012 to 2021 is summarised in Table 10-2 and Table 10-3. Overall, the data show that elevated groundwater levels have occurred in the past, however, there has been no significant ground movement at any of the inclinometers.

Table 10-2 Summary of inclinometer data collected at Filey Town under this programme (2012 to 2021).

		Report status															
Borehole	Details	06/12 to 11/13	12/13 to 05 14	06/14 to 11/14	12/14 to 05/15	06/15 to 11/15	12/15 to 05/15	06/16 to 11/16	12/16 to 05/17	06/17 to 11/17	12/17 to 05/18	06/18 to 11/18	12/18 to 05/19	06/19 to 11/19	12/19 to 07/20	08/20 to 12/20	01/21 to 06/21
Inclinometer	Borehole depth (base)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
CPBH03	10 m BGL (-4.0 m OD)								2	2		2	2	2	2		
CPBH05	10 m BGL (-3.5 m OD)														2	2	
CPBH07	20 m BGL (-15 m OD)																
BH6	30 m BGL (-2.6 m OD)		2														1

Note: cells with '1' indicate boreholes where ground movement or elevated groundwater was observed during the given monitoring period of the report; cells with '2' indicate boreholes where there were equipment errors, or where the data was unable to be collected.

Table 10-3 Summary of piezometer data collected at Filey Town under this programme (2012 to 2021).

Borehole	Details	06/12 to 11/13	12/13 to 05 14	06/14 to 11/14	12/14 to 05/15	06/15 to 11/15	12/15 to 05/15	06/16 to 11/16	12/16 to 05/17	06/17 to 11/17	12/17 to 05/18	06/18 to 11/18	12/18 to 05/19	06/19 to 11/19	12/19 to 07/20	08/20 to 12/20	01/21 to 06/21
Piezometer	**Tip depth**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
BH5b	1.09 m OD																
BH4	18.1 m OD		1	1						2							
CPBH01a	16.93 m OD			1	1		1		1	1	1	1		1		1	1
CPBH01b	32.6 m OD						2	2	2	2	2	2	2	2	2	2	2
CPBH02a	1.6 m OD			2	2			1	1	1	1	1	1	1	1	1	2
CPBH02b	8.2 m OD								2	2	2	2		2	2	2	2
CPBH04a	2.9 m OD		2														
CPBH04b	9.9 m OD							2	2	2	2	2	2	2	2	2	2
CPBH06a	0.13 m OD					2			2	1			1		2	2	
CPBH06b	8.63 m OD	1	2		2	2	2	2	2	2	2	2	2	2	1	1	2
CPBH08a	8.7 m OD		1	1												1	2
CPBH08b	27.4 m OD		2		2	2	2		2	2	2	2	2	2	2	2	2
CPBH09a	0.6 m OD										1	1			1		
CPBH09b	17.7 m OD		2	2	2	2	2	2		2	2	2	2	2	2	2	2
CPBH10a	23.8 m OD								1	1	1	1	1	2	2	2	2
CPBH10b	11.9 m OD			2	2	2	2	2	2	2	2	2	2	2	2	2	2

Note: cells with '1' indicate boreholes where ground movement or elevated groundwater was observed during the given monitoring period of the report; cells with '2' indicate boreholes where there were equipment errors, or where the data was unable to be collected.

10.5 New data

Table 10-4 and Table 10-5 summarise the inclinometer and piezometer data from Filey Town to June 2021.

These data indicate:

- Inclinometer BH6 highlights displacements at 30 m depth in glacial clay. The pattern of deformation suggests error that is likely a result of the inclinometer becoming loose in the keyways. The inclinometer should be checked, and the data reviewed in the next monitoring period. No significant movement has been recorded in any of the other boreholes at Filey Town.
- Groundwater levels have fallen at boreholes BH5b
- Groundwater levels have risen at BH4, CPBH01b, CPBH04b and CPBH09a but remain within historical range.
- No data is available at CPBH01b, CPBH02a, CPBH02b, CPBH04b, CPBH06b, CPBH08a and CPBH08b due to issues with device or communication errors. SBC to repair or replace.

- Diver CPBH02b should be checked due to a dry reading. This equipment may be damaged and required attention to determine whether it can be repaired.
- The data logger for borehole CPBH09b should be checked and recalibrated as dip meter readings and diver readings are discordant.
- No data was collected at borehole CPBH10a and CPBH10b. Access was not possible due to dense vegetation. The vegetations should be cleared and data downloaded for the next monitoring period.

Boreholes BHA, BHB, BHC, BHD, TP3, TP6, TP8 and TP9 are no longer included in this monitoring programme.

Table 10-4 Summary of inclinometer data from Filey Town.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
CPBH03	10 m BGL (-4.0 m OD) Lower slope, within made ground and glacial sediment	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
CPBH05	10 m BGL (-3.5 m OD) Lower slope, within glacial sediment	Displacement of 4mm recorded at 9.4m depth. Likely a result of erroneous readings or the inclinometer becoming loose in keying. The inclinometer should be checked.	Readings are less than 1mm and therefore not significant.
CPBH07	20 m BGL (-15 m OD) Lower slope, within glacial sediment	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
BH6	30 m BGL (-2.6 m OD) Cliff top, within glacial sediment	Readings are less than 1mm and therefore not significant.	Erroneous readings. The borehole should be cleaned and future readings taken carefully.

Table 10-5 Summary of groundwater data from Filey Town.

Borehole	Details	Report status	
		Change 08/20 to 12/20 15	Change 01/21 to 06/21 16
BH5b	1.09 m OD Mid slope	Groundwater levels have risen slightly to 1.8m OD.	Groundwater levels have fallen to 1.5 m OD.
BH4	18.1 m OD Cliff top	Groundwater levels have fallen slightly to 20.6m OD.	Groundwater levels have risen slightly to 20.8 m OD.
CPBH01a	37.43 m OD Cliff top co- located with CPBH01b	Groundwater levels have risen to 26.0m OD.	Groundwater levels have risen to 34.32 OD.
CPBH01b (Diver)	32.6 m OD Cliff top co- located with CPBH01a	No data available. Piezometer damaged. Repair equipment.	No data available. SBC to repair or replace diver.

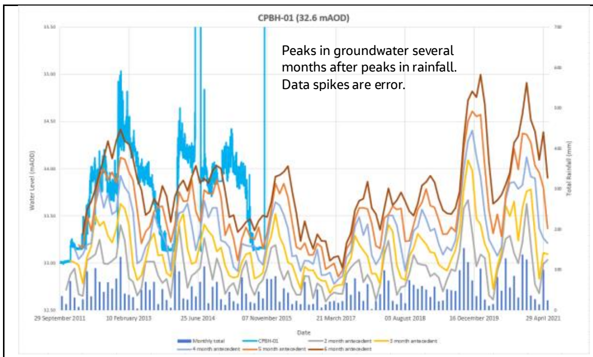
Borehole	Details	Report status	
		Change 08/20 to 12/20 15	Change 01/21 to 06/21 16
CPBH02a	1.6 m OD Cliff top co- located with CPBH02b	Groundwater levels have risen to elevated level of 5.1m OD.	No data available. Borehole is dry.
CPBH02b (Diver)	8.2 m OD Cliff top co-located with CPBH02a	No data available. Piezometer damaged. Repair equipment.	No data available. Piezometer damaged. Repair/replace lid.
CPBH04a	2.9 m OD Cliff top co-located with CPBH04b	Groundwater levels have risen slightly to 7.4m OD.	Groundwater level equals 13.2 m OD, which is within the historical range.
CPBH04b (Diver)	9.9 m OD Cliff top co-located with CPBH04a	No data available. Data logger communication error. Repair equipment. Manual dip readings at 13.2 m OD suggest levels have fallen very slightly.	No data available. Repair or replace.
CPBH06a	0.13 m OD Cliff top co-located with CPBH06b	No data available. Data logger communication error. Repair equipment. Manual dip readings at 19.0 m OD suggests levels are steady.	Groundwater levels have remained steady at 19 m OD.
CPBH06b (Diver)	8.63 m OD Cliff top co-located with CPBH06a	Groundwater levels have fallen to 19.8m OD, but remain at an elevated position close to the historical high.	No data available. Repair or replace
CPBH08a	8.7 m OD Cliff top co-located with CPBH08b	Groundwater levels are at 13.3m OD, which is a new historical high.	No data available. Borehole is dry.
CPBH08b (Diver)	27.4 m OD Cliff top co-located with CPBH08a	No data available. Data logger communication error. Repair equipment.	No data available. Repair or replace.
CPBH09a	0.6 m OD Cliff top co-located with CPBH09b	Groundwater levels have fallen to 20.1m OD.	Groundwater levels have risen slightly to 20.5 m OD.
CPBH09b (Diver)	17.7 m OD Cliff top co-located with CPBH09a	Data logger indicates water level is at 2.8 m OD, however manual dip readings are at 20.5 m OD, suggesting an error with the logged data. Repair/collect on next site visit.	Data logger indicates water level is at 2.8 m OD, however manual dip readings are at 20.5 m OD, suggesting an error with the logged data. Repair/collect on next site visit.
CPBH10a (Diver)	23.8 m OD Upper slope co-located with CPBH10b	No data available. Piezometer could not be located.	No data available. Piezometer could not be located.

Borehole	Details	Report status: Change 08/20 to 12/20 15	Report status: Change 01/21 to 06/21 16
		Clear vegetation to enable access to borehole.	Clear vegetation to enable access to borehole or use a metal marker post.
CPBH10b	11.9 m OD Upper slope co-located with CPBH10a	No data available. Piezometer could not be located. Clear vegetation to enable access to borehole.	No data available. Piezometer could not be located. Clear vegetation to enable access to borehole or use a metal marker post

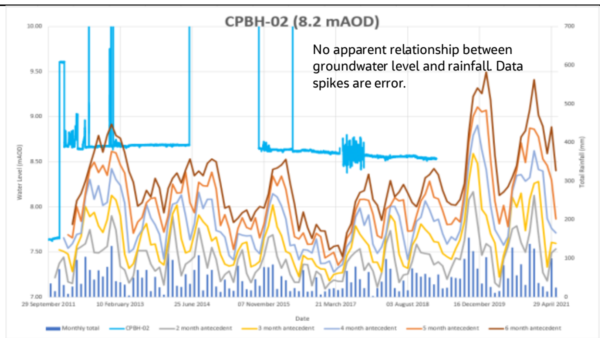
10.6 Causal-response relationships

There has been no movement in inclinometers and therefore no relationships between groundwater and ground movement have been identified.

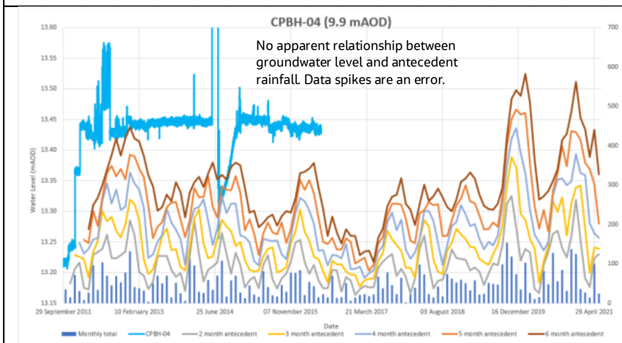
Figure 10.2 presents the groundwater levels at Filey town recorded by each piezometer (with a data logger) to highlight the relationships to antecedent rainfall. CPBH-01 and CPBH-10 have antecedent rainfall relationships of 4-5 months and 5-6 months respectively. Other automated piezometers at Filey Town have an unclear antecedent rainfall relationship.



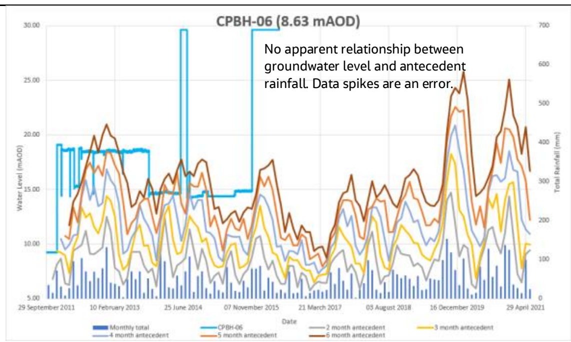
A – CPBH-01 (tip at 32.6 m OD at base on cliff top). 4-5 month antecedent rainfall relationship.



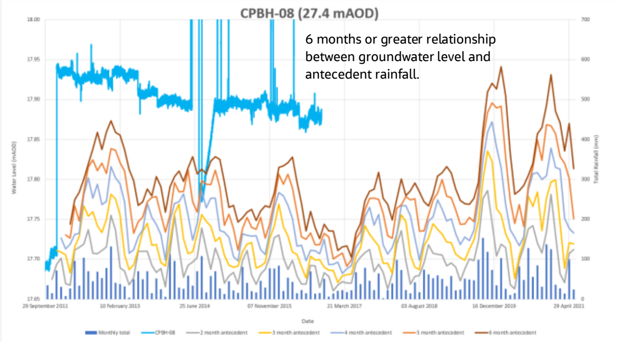
B – CPBH-02 (tip at 8.2 m OD at base on cliff top). No apparent antecedent rainfall relationship.



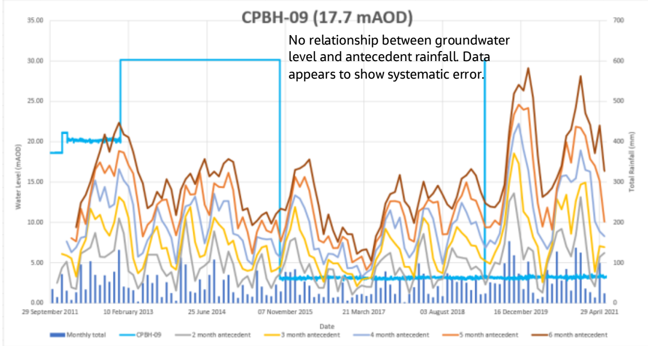
C – CPBH-04 (tip at 9.9 m OD at base on cliff top). No apparent antecedent rainfall relationship.



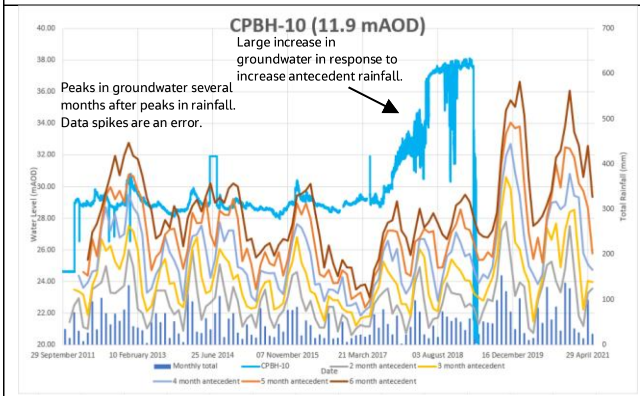
D – CPBH-06 (tip at 8.63 m OD at base on cliff top). No apparent antecedent rainfall relationship.



E – CPBH-08 (tip at 27.4 m OD at base on cliff top). 6 month or greater antecedent rainfall relationship.



F – CPBH-09 (tip at 17.7 m OD at base on cliff top). No apparent antecedent rainfall relationship.



G – CPBH-10 (tip at 11.9 m OD at base on upper slope). 5-6 month antecedent rainfall relationship.

Figure 10.2: Relationship between groundwater levels and antecedent rainfall at Filey Town.

10.7 Implications and recommendations

No data are available for piezometers CPBH01b, CPBH02a, CPBH04a, CPBH06a, CPBH08a and CPBH08b and require readings to be re-taken on the next site visit. Data from manual readings in CPBH9b show different results to the diver data and it is recommended the diver calibration is checked to ensure accuracy. No access was possible to boreholes CPBH10a and CPBH10b, and vegetation should be cleared to enable data collection for the next monitoring period.

11. Filey Flat Cliffs

11.1 Site description

Flat Cliffs is a private residential settlement located on coastal slopes in central Filey Bay. The settlement includes private homes and a Yorkshire Water pumping station accessed via a private road down the cliffs that is particularly steep near the top of the cliffs (Halcrow, 2012b). The cliffs are formed in thick and variable glacial sediments that continue to at least 12.4m below OD and which are prone to cliff instability. There is concern that ongoing cliff instability threatens properties and the only access road to about 40 homes at Flat Cliffs (Halcrow, 2012b).

11.2 Ground model and monitoring regime

This site comprises three cliff behaviour units: MU29/AQ, which is an active mudslide complex north of the main settlement and MU29/AR and MU29/AS that form the main landslide undercliff upon which the settlement has been developed.

The undercliff ground model can be described as a complex landslide system that is backed by a steep headscarp and fronted by a sea-cliff (Halcrow, 2012b). The undercliff morphology comprises landslide scarps and benches, some of which are back-tilted although interpreted as failing on translational shear surfaces rather than rotational failure. A large mudslide complex in the north of the site is periodically active and threatens the access road and properties. Activity is generally associated with accelerated toe erosion and elevated groundwater levels.

The monitoring regime at Flat Cliffs includes the following (Figure 11.1):

- North of site – automated piezometer on the cliff top and inclinometer on the access road.
- Central site – Piezometers with data loggers on the cliff top and next to the access road in the lower slope. Two inclinometers either side of the main access road (Flat Cliffs Road and Lower Flat Cliffs) on the coastal slope (one of which is an experimental acoustic inclinometer installed by Loughborough University).
- South of site – Co-located automated piezometer and inclinometer on the Lower Flat Cliffs part of the coastal slope.

11.3 Historical ground behaviour (2009 to 2012)

Filey Flat Cliffs was monitored by Mouchel Ltd for the period between summer 2009 and summer 2012. A summary of their results is provided in Table 11-1, which shows some movement in Borehole A2. No relationship between groundwater level and ground movement was reported by Mouchel. Additional monitoring covering the period April 2011 to Dec 2012, associated with a landslide investigation, are provided in Halcrow (2013b).

Table 11-1 Summary of historical ground behaviour at Filey Flat Cliffs.

Observations in Mouchel 2012 (covering 6-month period between Dec 2011 and June 2012)	Total Change observed between July 2009 and June 2012
Mouchel monitored inclinometer A2 during this period and reported no movement. Mouchel report a groundwater level reading from B1 in June 2012 as revealing a reduction of 520mm relative to December 2011. The report mentions that groundwater readings up to May 2012 are reported in Appendix E to that report, but no readings after June 2010 are identifiable from the graph.	Deviation of 15mm near the surface indicated in A2 between December 2010 and June 2011. This had increased by a further 5mm to 20mm by December 2011. No specific comment is made on ground water levels, but it appears from the chart in the appendix that ground water levels remain relatively constant at piezometers A2, A3 and D2, with minor fluctuations in B1 and major fluctuations in D1.

11.4 Review of data collected under this programme (2012 to 2021)

A review of the data collected under this programme from 2012 to 2021 is summarised in Table 11-2. Overall, the data show that elevated groundwater levels have occurred in the past, however, there has been no significant ground movement at any of the inclinometers. Only minor movement was detected by the acoustic emissions inclinometer which showed small magnitude deformations within the active waveguide column due to straining internally within the slide mass (i.e. not shear surface deformation).

Table 11-2 Summary of data collected at Filey Flat Cliffs under this programme (2012 to 2021).

		Report status															
Borehole	**Details**	**06/12 to 11/13**	**12/13 to 05 14**	**06/14 to 11/14**	**12/14 to 05/15**	**06/15 to 11/15**	**12/15 to 05/15**	**06/16 to 11/16**	**12/16 to 05/17**	**06/17 to 11/17**	**12/17 to 05/18**	**06/18 to 11/18**	**12/18 to 05/19**	**06/19 to 11/19**	**12/19 to 07/20**	**08/20 to 12/20**	**01/21 to 06/21**
Inclinometer	**Borehole depth (base)**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
A2	27.5 m BGL (-9.6 m OD)																
C1	25 m BGL (0.7 m OD)	2	2														
C2	21 m BGL (-4.5 m OD)																
C5	16 m BGL (-4.0 m OD)	2															
C1A	No longer monitored	2	1											2			
Piezometer	**Tip depth**																
B1	-7.6 m OD	1	1			1					1	1		1			
D1	15.62 m OD						1				2	2	2	2	2	2	2
A3	6.4 m OD										2	2	2	2	2	2	2
C4a	-3.7 m OD							2	2	2	2	2	2	2	2	2	2

Note: cells with ‘1’ indicate boreholes where ground movement or elevated groundwater was observed during the given monitoring period of the report; cells with ‘2’ indicate boreholes where there were equipment errors, or where the data was unable to be collected.

11.5 New data

Table 11-3 and Table 11-4 summarise the monitoring results from inclinometers and piezometers at Flat Cliffs up to June 2021.

The new data indicate:

- No evidence for ground movements is shown by inclinometers.
- No data is available at inclinometer C1A, as monitoring is no longer continued at this site.
- Groundwater data show levels have fallen at borehole B1.
- No data collected at boreholes A3 and D1, due to data logger communication error. SBC to arrange for repair of equipment. Requires readings to be retaken.

- No data collected at boreholes C4a, due to no access resulting from overgrown vegetation. SBC to arrange for clearing of vegetation and to be located in next monitoring period.

Table 11-3 Summary of inclinometer data from Filey Flat Cliffs.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
A2	27.5 m BGL (-9.6 m OD) Mid slope, within glacial sediment	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
C1	25 m BGL (0.7 m OD) Mid slope co-located with C1a, within glacial sediment	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
C2	21 m BGL (-4.5 m OD) Lower slope, within glacial sediment	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
C5	16 m BGL (-4.0 m OD) Lower slope, within glacial sediment	Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
C1A	Mid slope co-located with C1, within glacial sediment	AE measurements to December 2020 do not show significant slope movements.	Monitoring discontinued at site.

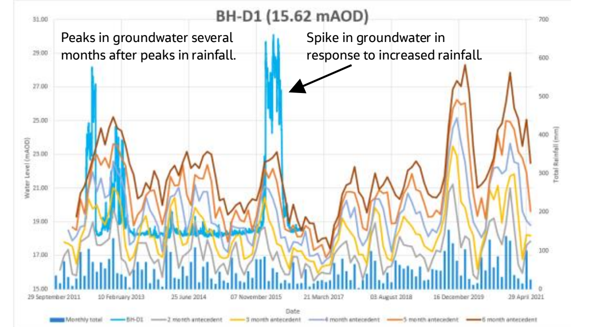
Table 11-4 Summary of groundwater data from Filey Flat Cliffs.

Borehole	Details	Report status	
		Change 08/20 to 12/20	Change 01/21 to 06/21
		15	16
B1	-7.6 m OD Lower slope	Groundwater levels have risen to 13.5m OD, which is well within historical range.	Groundwater levels have fallen to 11.9 m OD
D1	15.62 m OD Cliff top	No data available. Data logger communication error. Repair equipment.	No data available. Data logger communication error. Repair equipment.
A3	6.4 m OD Cliff top	No data available. Data logger communication error. Repair o equipment.	No data available. Data logger communication error. Repair equipment.
C4a	-3.7 m OD Lower slope	No data available. Data logger communication error. Repair equipment.	No data available. No access buried and overgrown. To be located in next monitoring period.

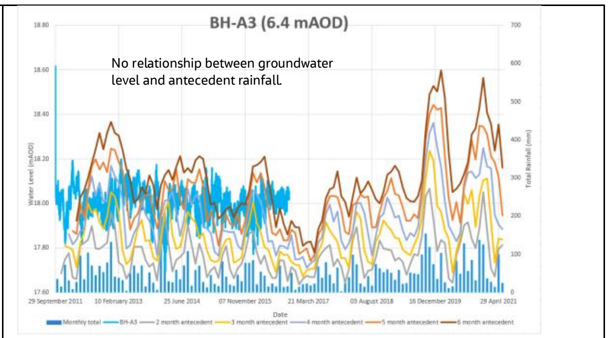
11.6 Causal-response relationships

No relationship is identifiable between ground movements and rainfall as no substantial ground movements have occurred. Acoustic emissions data indicates low rate and slow magnitude movement in borehole C1a at the end of November 2017 lasting for 5 days coincident with a period of high rainfall. However, there was no significant movement recorded during the extreme rainfall event on 23 August 2017. Borehole D1 appears to show a response to above average rainfall in January and February 2014 and borehole C4a clearly shows the effect of the 5 December 2013 storm surge on groundwater levels as the highest peak in the record. B1 gradual decrease in groundwater level follows a month antecedent rainfall. There is no clear response in groundwater levels to the extreme rainfall event on 23 August 2017, or heavy rainfall event on 12 March 2018. Following a sustained period of heavy rainfall in autumn 2019 groundwater levels had significantly increased again in B1, however levels have fallen again, possibly in response to drier conditions in spring 2020. During Autumn and winter 2020, groundwater levels increased, likely in response to wet conditions in summer 2020. During this monitoring period, groundwater levels fell, likely in response to the slightly drier conditions in spring 2021.

Figure 11.2 presents the groundwater levels at Filey Flat Cliffs recorded by each piezometer (with a data logger) to highlight the relationships to antecedent rainfall. BH-D1 has an antecedent rainfall relationship of 3-4 months. BH-A3 has an unclear antecedent rainfall relationship.



A – BH-D1 (tip at 15.62 m OD at base on cliff top) 3-4 month antecedent rainfall relationship.



B – BH-A3 (tip at 6.4 m OD at base on cliff top) No apparent antecedent rainfall relationship.

Figure 11.2: Relationship between groundwater levels and antecedent rainfall at Filey Flat Cliffs.

11.7 Implications and recommendations

Previous reports have highlighted a possible relationship between groundwater levels in piezometer D1 and movements in inclinometer C1. Groundwater levels in piezometer D1 have previously shown a strong relationship with rainfall and this relationship should be specifically reviewed in future reports when data is available to refine understanding of that relationship. Piezometers in borehole A3, C1a and D1 require attention and should be repaired or cleared for access.

12. References

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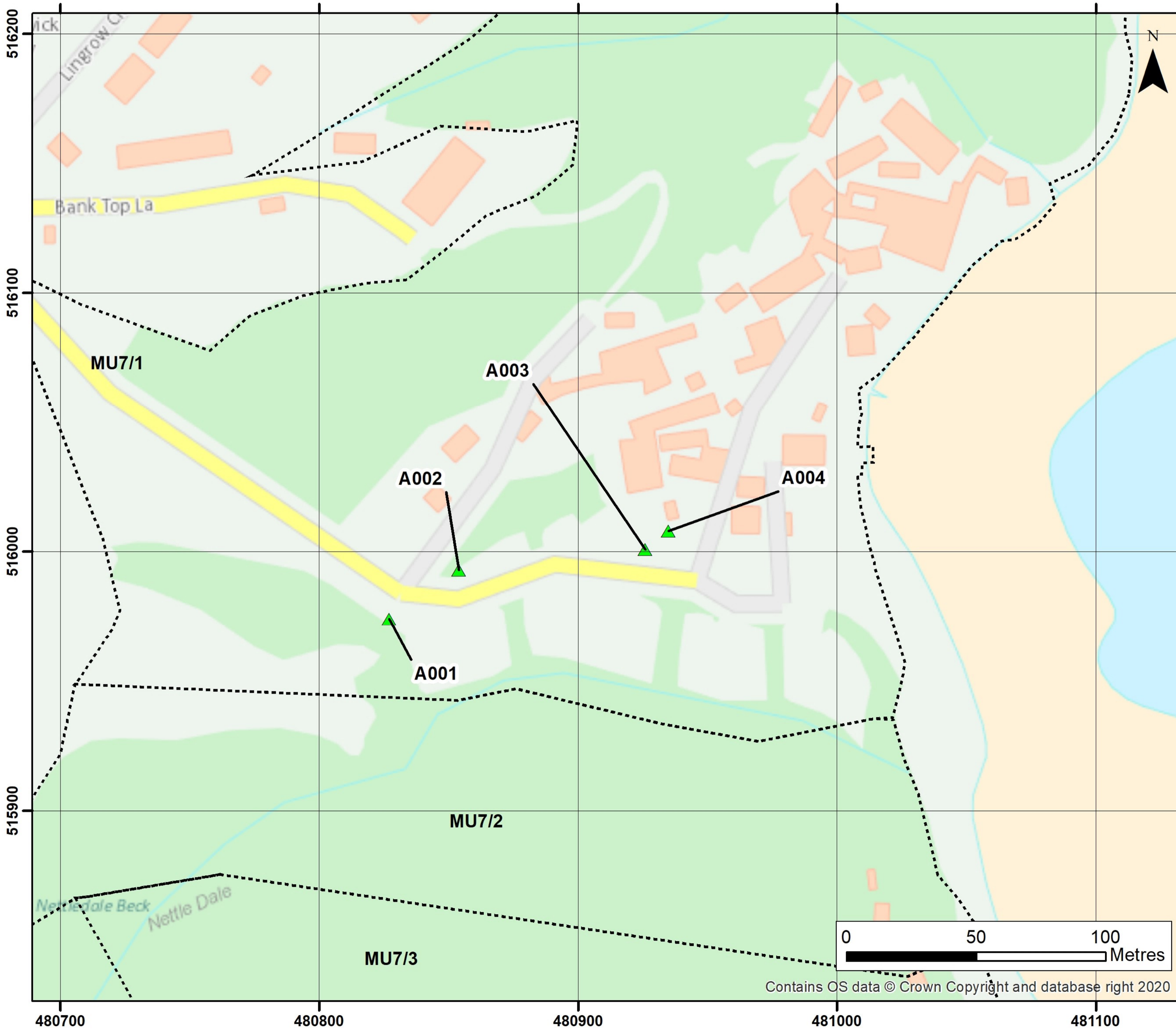
Appendix A. Digital data



Legend

Active

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)
- Cliff behaviour unit

Client: Scarborough Borough Council

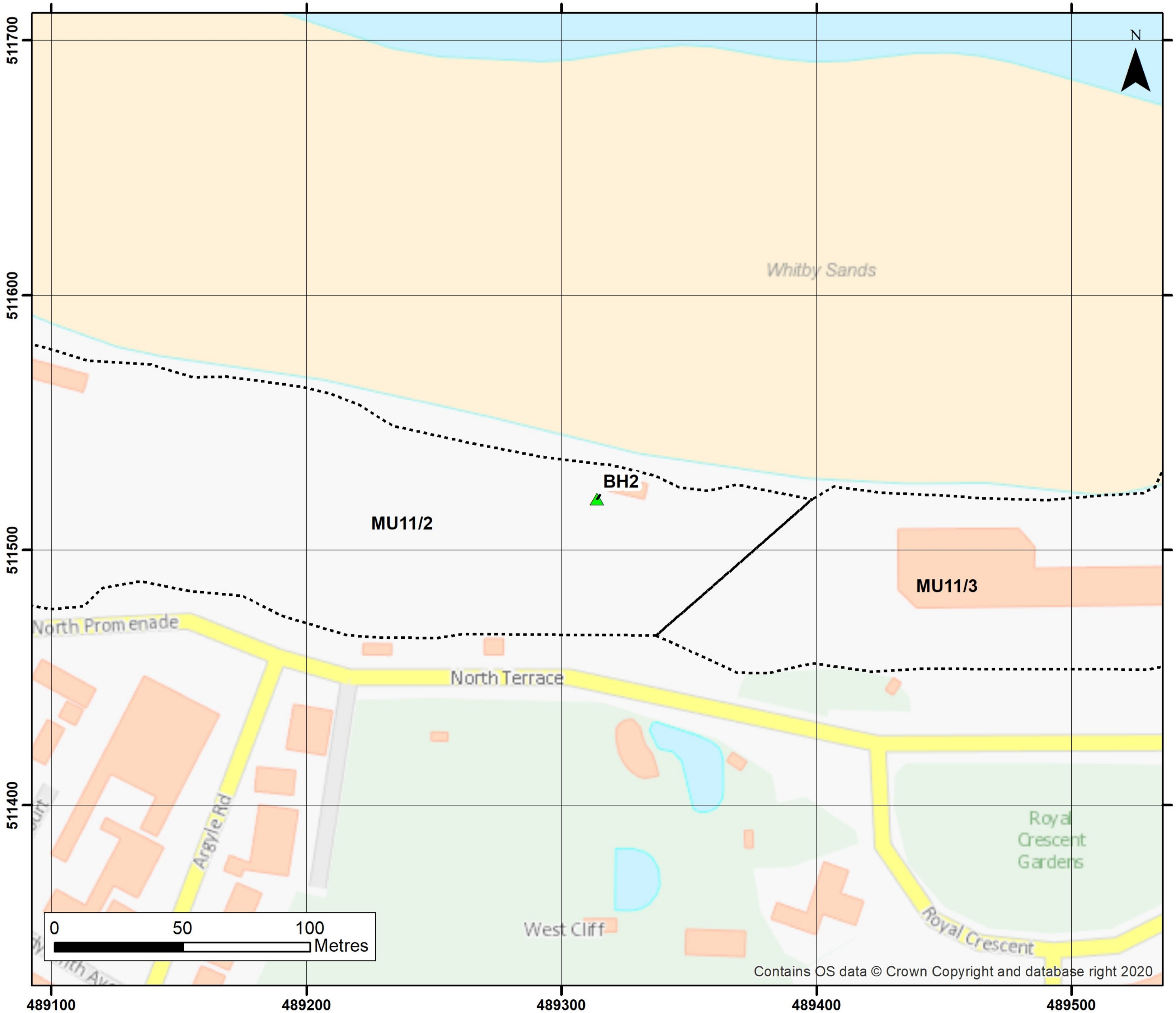
Project: Scarborough Borough Council Geotechnical Monitoring

Figure 3.1 Location of slope monitoring at Runswick Bay

Jacobs

Jacobs, 7th Floor, 2 Colmore Square, 38 Colmore Circus, Queensway, Birmingham, B4 6BN.

Tel: +44 (0)121 237 4000
www.jacobs.com



Legend

Active

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)
- Cliff behaviour unit

Client: Scarborough Borough Council

Project: Scarborough Borough Council Geotechnical Monitoring

Figure 4.1 Location of slope monitoring at Whitby West Cliff

Jacobs

Jacobs, 7th Floor, 2 Colmore Square, 38 Colmore Circus, Queensway, Birmingham, B4 6BN.

Tel: +44 (0)121 237 4000
www.jacobs.com

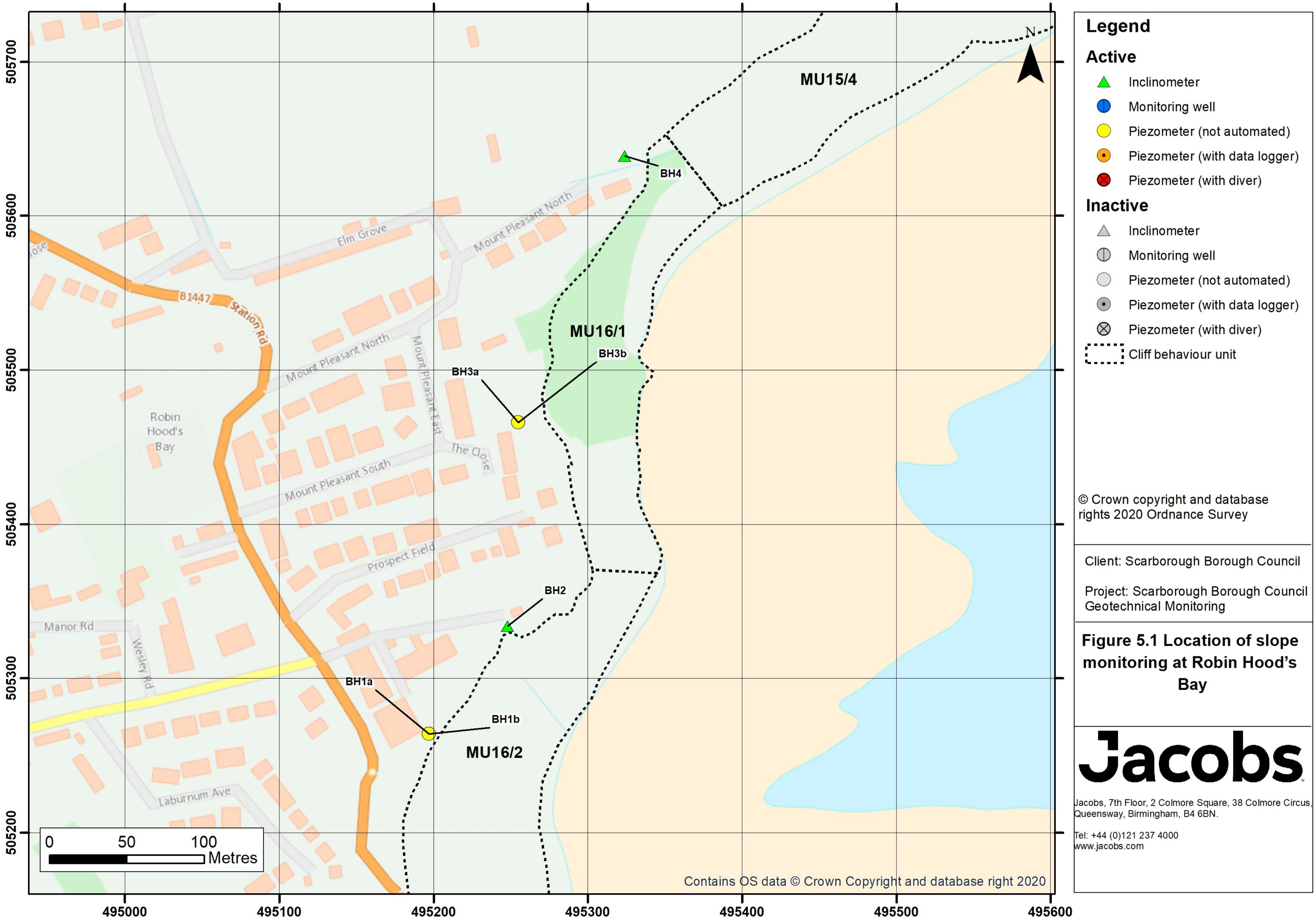
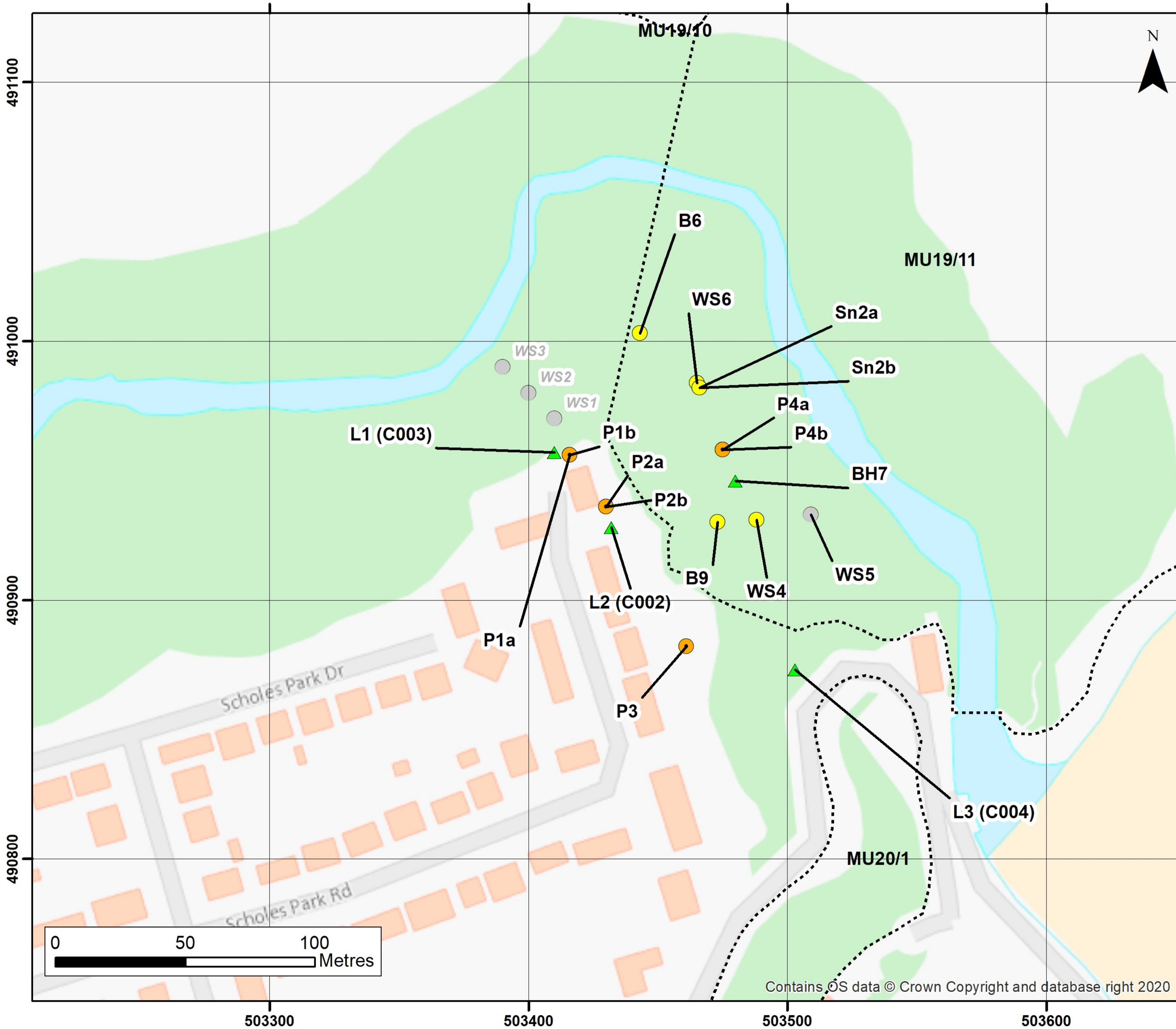


Figure 5.1 Location of slope monitoring at Robin Hood's Bay



Legend

Active

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)
- Cliff behaviour unit

Client: Scarborough Borough Council

Project: Scarborough Borough Council Geotechnical Monitoring

Figure 6.1 Location of slope monitoring at Scalby Ness

Jacobs

Jacobs, 7th Floor, 2 Colmore Square, 38 Colmore Circus, Queensway, Birmingham, B4 6BN.

Tel: +44 (0)121 237 4000
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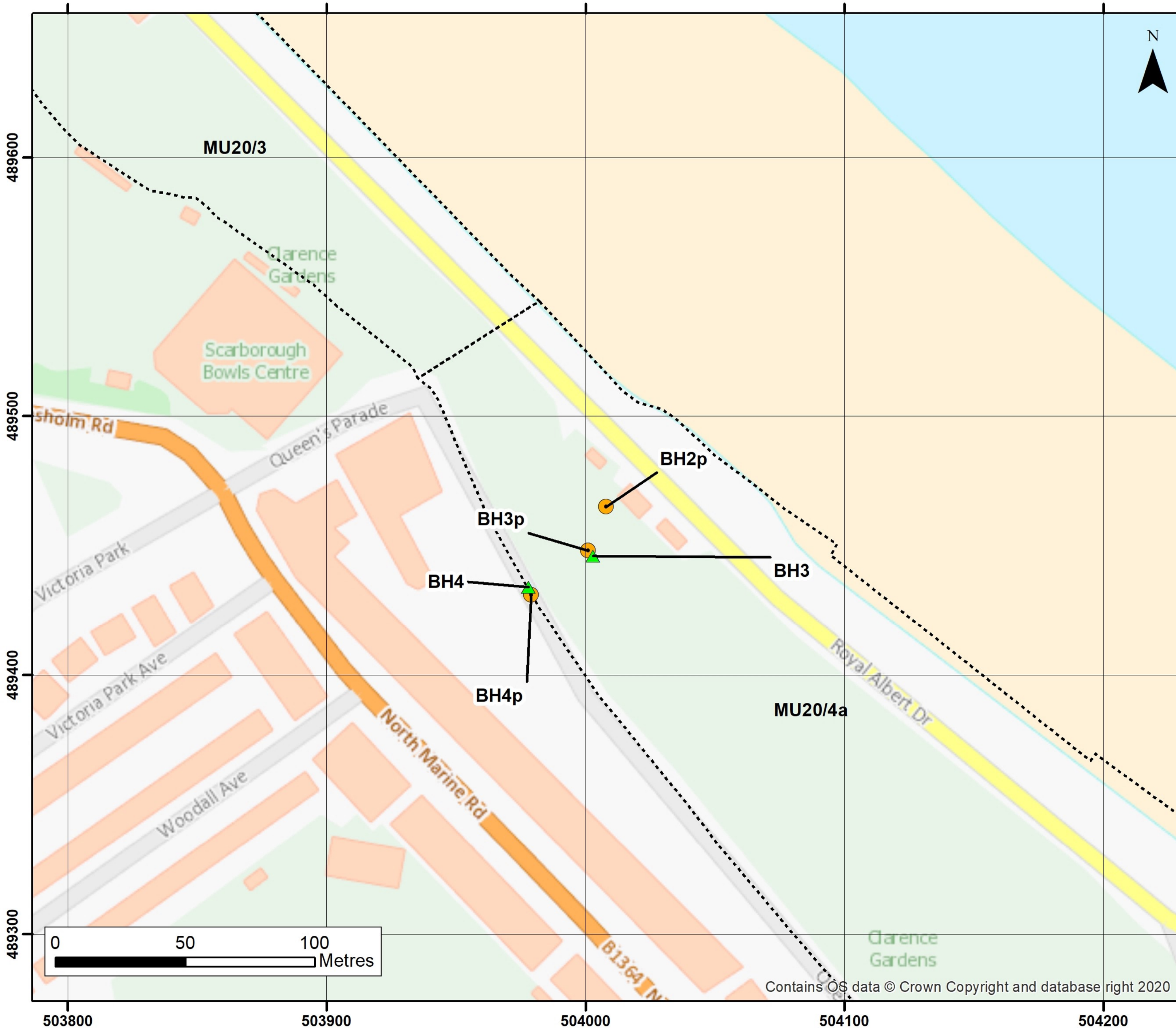


Legend

Active

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)
- Cliff behaviour unit

Client: Scarborough Borough Council

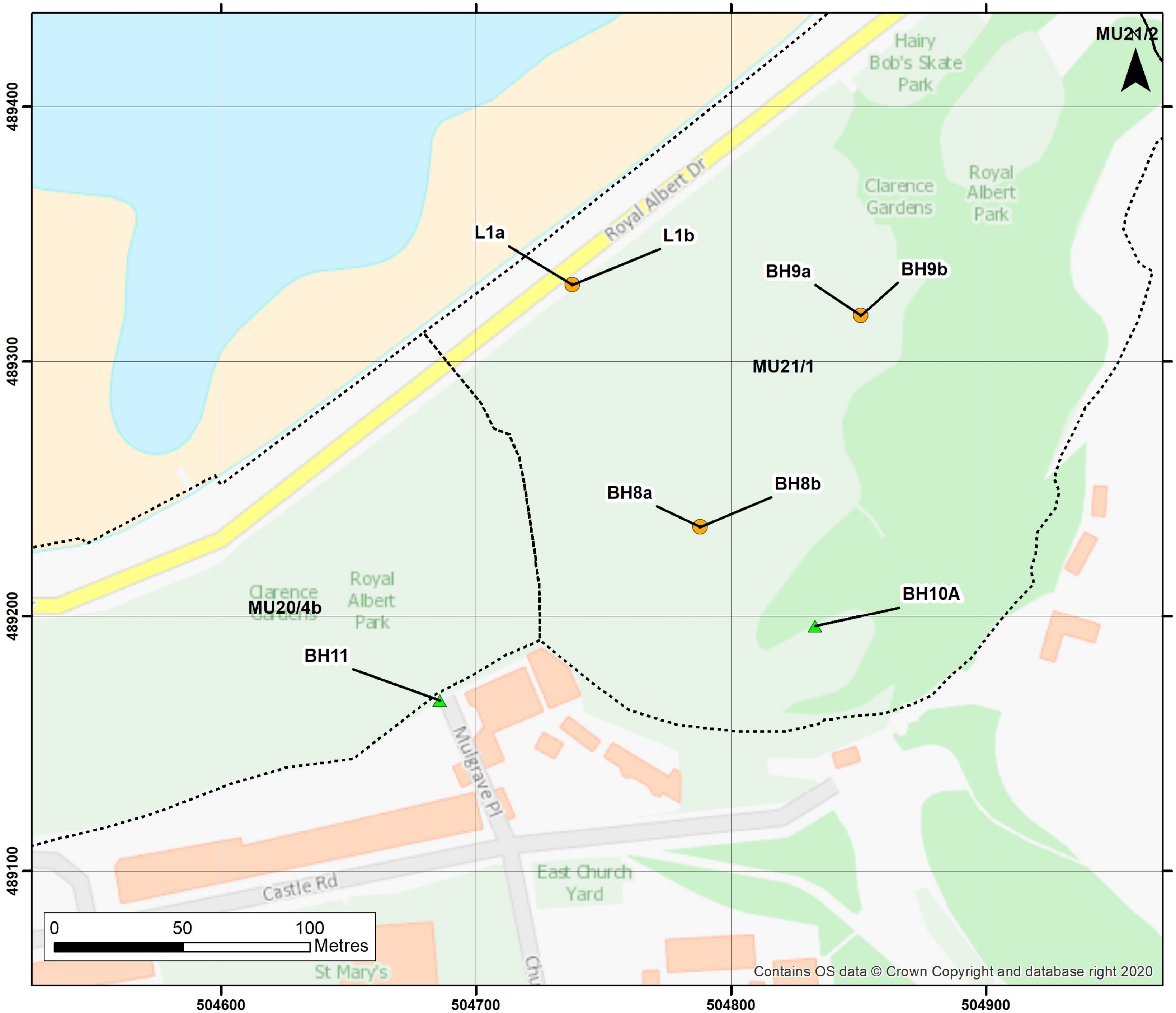
Project: Scarborough Borough Council Geotechnical Monitoring

Figure 7.1 Location of slope monitoring at Scarborough North Bay –Oasis Cafe

Jacobs

Jacobs, 7th Floor, 2 Colmore Square, 38 Colmore Circus, Queensway, Birmingham, B4 6BN.

Tel: +44 (0)121 237 4000
www.jacobs.com



Client: Scarborough Borough Council

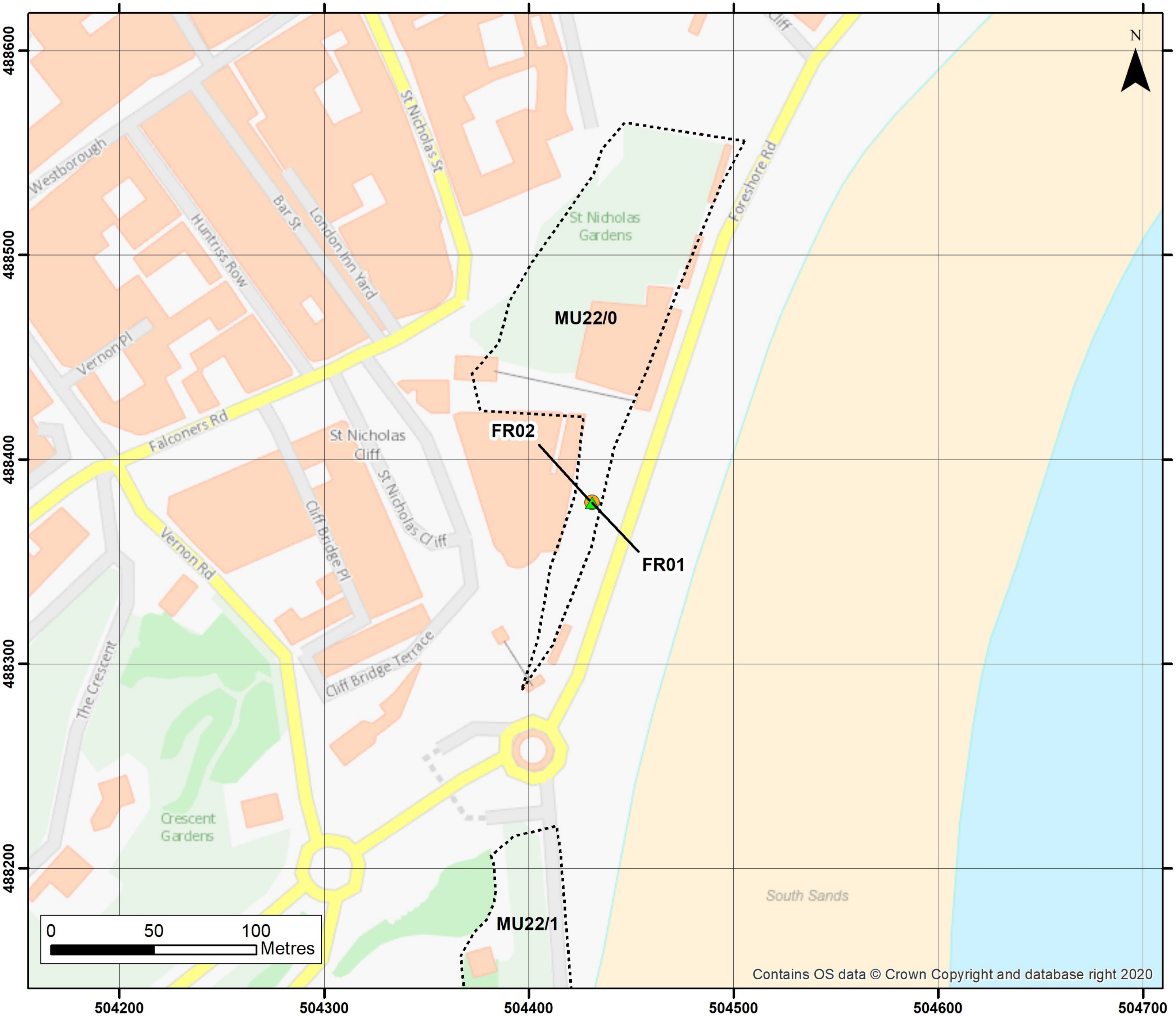
Project: Scarborough Borough Council Geotechnical Monitoring

Figure 8.1 Location of slope monitoring at Scarborough North Bay (The Holms)

Jacobs

Jacobs, 7th Floor, 2 Colmore Square, 38 Colmore Circus, Queensway, Birmingham, B4 6BN.

Tel: +44 (0)121 237 4000
www.jacobs.com



Legend

Active

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)
- Cliff behaviour unit

Client: Scarborough Borough Council

Project: Scarborough Borough Council Geotechnical Monitoring

Figure 9.1A Location of monitoring at Scarborough South Bay

Jacobs

Jacobs, 7th Floor, 2 Colmore Square, 38 Colmore Circus, Queensway, Birmingham, B4 6BN.

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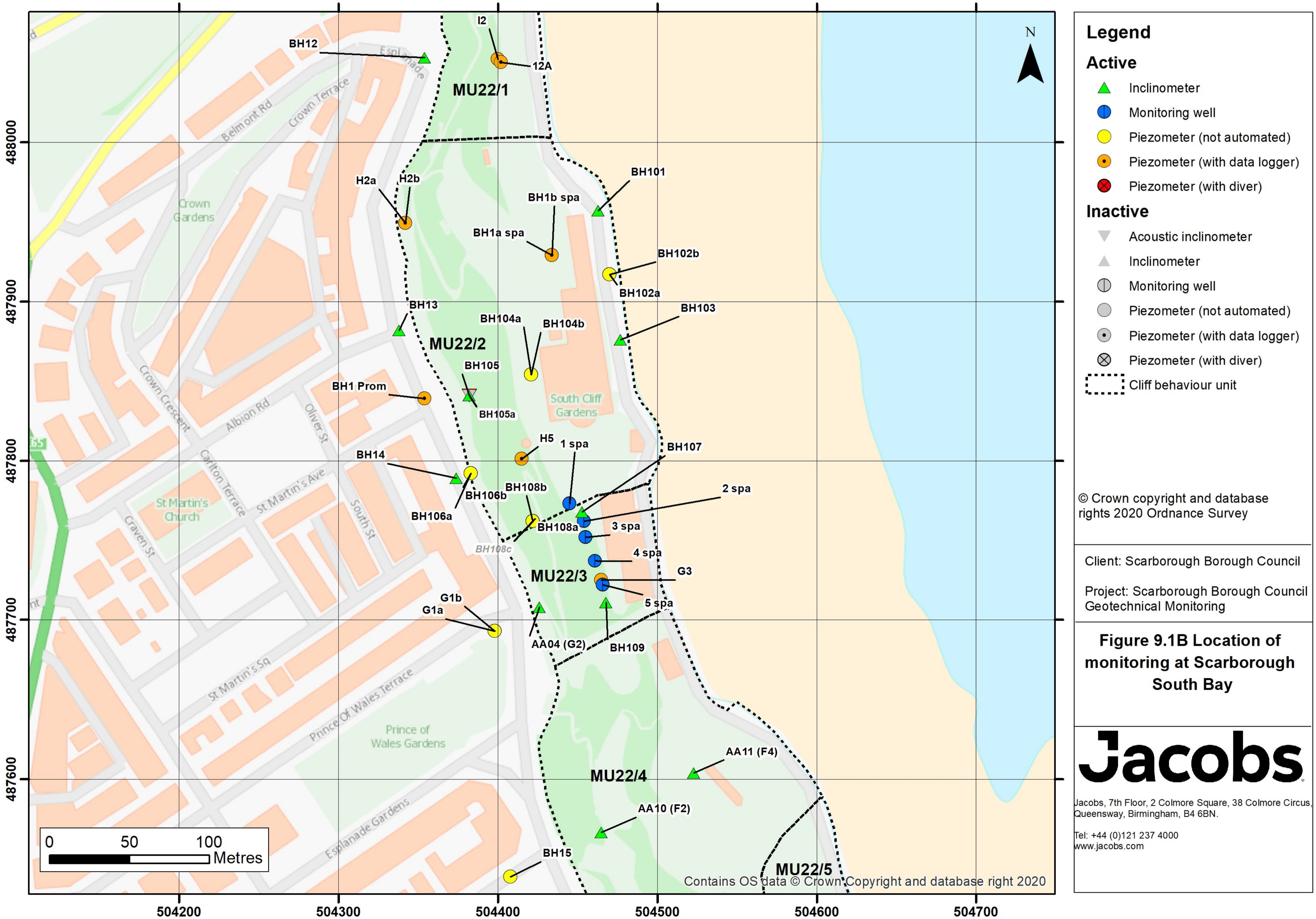


Client: Scarborough Borough Council

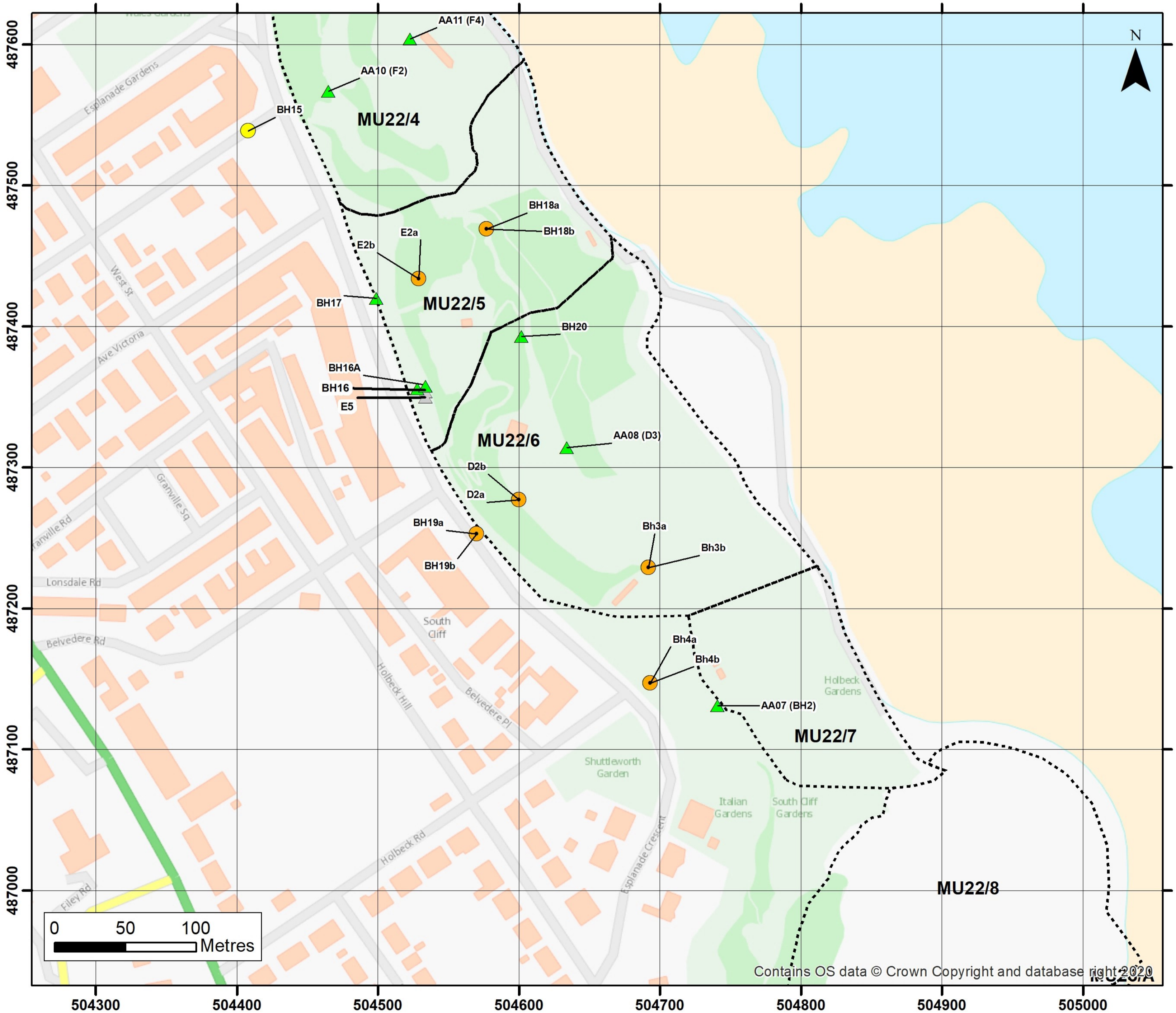
Project: Scarborough Borough Council Geotechnical Monitoring

Figure 9.1B Location of monitoring at Scarborough South Bay

Jacobs

Jacobs, 7th Floor, 2 Colmore Square, 38 Colmore Circus, Queensway, Birmingham, B4 6BN.

Tel: +44 (0)121 237 4000
www.jacobs.com



Legend

Active

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)
- Cliff behaviour unit

Client: Scarborough Borough Council

Project: Scarborough Borough Council Geotechnical Monitoring

Figure 9.1C Location of monitoring at Scarborough South Bay

Jacobs

Jacobs, 7th Floor, 2 Colmore Square, 38 Colmore Circus, Queensway, Birmingham, B4 6BN.

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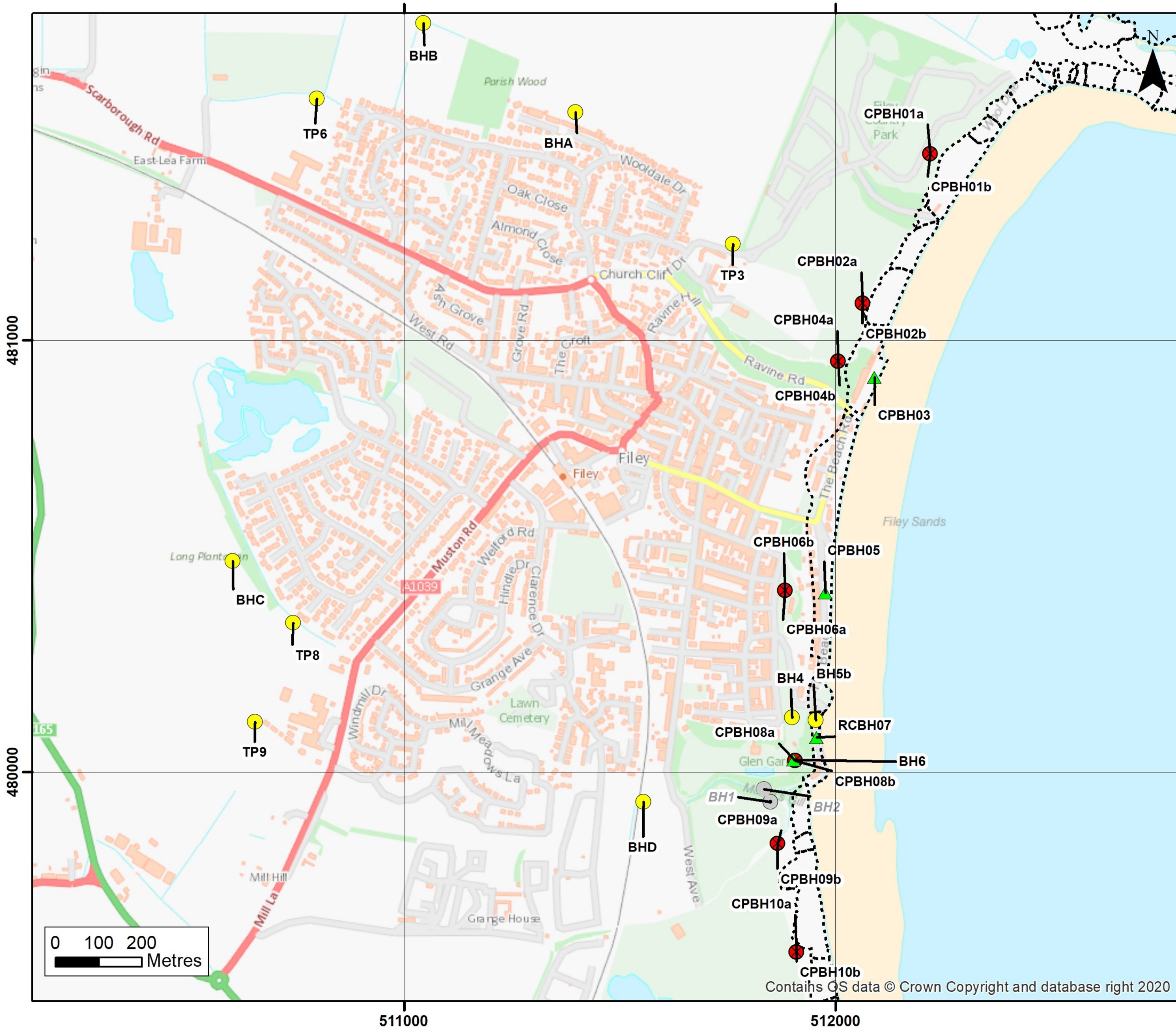


Legend

Active

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)
- Cliff behaviour unit

Client: Scarborough Borough Council

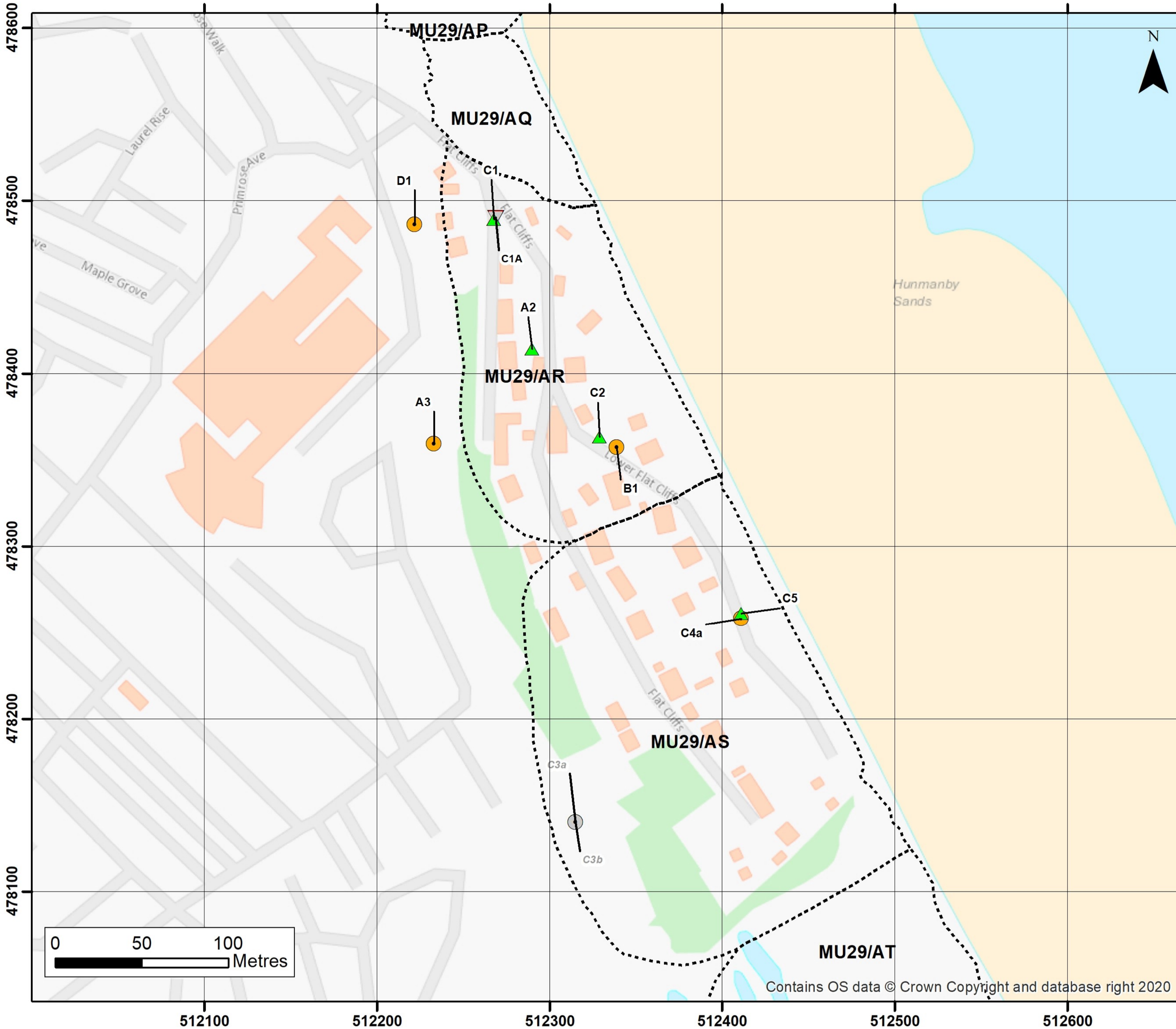
Project: Scarborough Borough Council Geotechnical Monitoring

Figure 10.1. Location of slope monitoring at Filey

Jacobs

Jacobs, 7th Floor, 2 Colmore Square, 38 Colmore Circus, Queensway, Birmingham, B4 6BN.

Tel: +44 (0)121 237 4000
www.jacobs.com



Legend

Active

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

- Acoustic inclinometer
- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)
- Cliff behaviour unit

Client: Scarborough Borough Council

Project: Scarborough Borough Council Geotechnical Monitoring

Figure 11.1 Location of slope monitoring at Filey Flat Cliffs

Jacobs

Jacobs, 7th Floor, 2 Colmore Square, 38 Colmore Circus, Queensway, Birmingham, B4 6BN.

Tel: +44 (0)121 237 4000
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