SOUTH WEST COASTAL MONITORING

making space for sand



# Making Space for Sand – Penhale Beach Report

Topographic and LiDAR Data Analysis

SWCM TBR22 18/04/2024

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This report utilises Light Detection and Ranging (LiDAR), topography and aerial imagery data collected by the South West Coastal Monitoring (SWCM) Programme to analyse beach and dune volume at Penhale. The aim is to highlight coastal change at Penhale using SWCM data since 2007, focusing on beach and dune areas categorised into four zones: Beach, Mobile, Fixed, and Developed. Penhale is a large west facing sandy beach backed by an eroding dune system almost 5km in length and is detailed as the study site. Topographic data collected bi-annually along fixed cross-shore profile lines are presented to indicate change of the intertidal beach area over time. LiDAR data is compared from each available flight to show difference models of the intertidal area, to compare volumetric data over time and to show change in Mean Seal Level and Dune Toe contours over time.

Since 2007, 23 topographic surveys were conducted at Penhale, including 4 full coverage surveys, 17 interim surveys and 2 post-storm surveys. Analysis of topographic data suggests the survey unit remained stable between 2007 and 2014 but was heavily impacted from the 2013/2014 winter storms. Since then, the unit suggests it has remained stable at a new, much lower volume and has yet to recover to pre-2013 levels.

Beach volume was extracted from the Beach and Mobile Zones from 10 LiDAR flights between 2008 and 2023. The Mobile Zone follows a similar trend to that observed in the topographic data, whereby 25% of material was lost between the 2012 and 2014 surveys. Since 2014, the Mobile Zone remained stable, however has not returned to pre-2014 levels, indicating an overall erosive trend between 2008 and 2023. The Beach Zone also saw a considerable loss of material following the 2013/14 storms, losing 18% of volume between the 2012 and 2014 surveys, The Beach Zone recovered considerably post 2014, with the second highest volume on record observed during the 2019 survey, suggesting a relatively stable Beach Zone between 2008 and 2023. The Dune Toe contours show a retreat of ~15 m from 2008 to 2014, after the winter period, but the dune face to the north has since advanced by ~9 m between 2014 to 2023.

Overall, Penhale beach remained relatively stable between 2007 and 2014, but since the 2013/2014 storms, the beach was heavily impacted and never recovered to pre-storm levels in particular along the upper beach and within the Mobile Zone.

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# 1.0 Introduction

The aim of this report is to highlight beach and dune change at Penhale Beach using data collected as part of the South West Coastal Monitoring (SWCM) Programme since 2007. Four zones have been identified to define the beach/dune area and are defined as:

- **Beach Zone** – The wet beach area has been defined using Mean Low Water Spring (MLWS) and Mean High Water Spring (MHWS) contours extracted from all LiDAR data captured by SWCM. The Beach Zone will therefore encompass the area between the MHWS and MLWS contours, with volumes for this area extracted from each LiDAR surface.
- **Mobile Zone** – This area is defined as the active dune face and embryo dune[1] from MHWS +1 m to the back of the mobile area, often distinguished by vegetation depth or urban development. The Mobile Zone has been defined using aerial imagery from 2007 to 2021 and historic OS maps and has been verified through site visits.
- **Fixed Zone** – This area is defined by permanent dune vegetation that may also include scrub or invasive species, effectively denoting vegetation atop sandy soil.
- **Developed Zone** – This is defined as urban development areas (i.e., car parks, unnatural grassy areas, roads, houses etc.) which have been built atop previously present dune systems.

## 1.1 Study Site

Penhale is a large west facing sandy beach backed by an eroding dune system (Fig.1). It is one of the most exposed beaches on the north coast, making it an almost 5 km stretch of beach, when joined with Perranporth at low tide. It has a semi diurnal tidal type, and an average spring tide range of 6.1 m. Penhale is also part of a designated Special Area of Conservation. The beach is backed by a diverse dune system, up to 1 km wide in some areas, with a large rocky headland to the north of the unit.

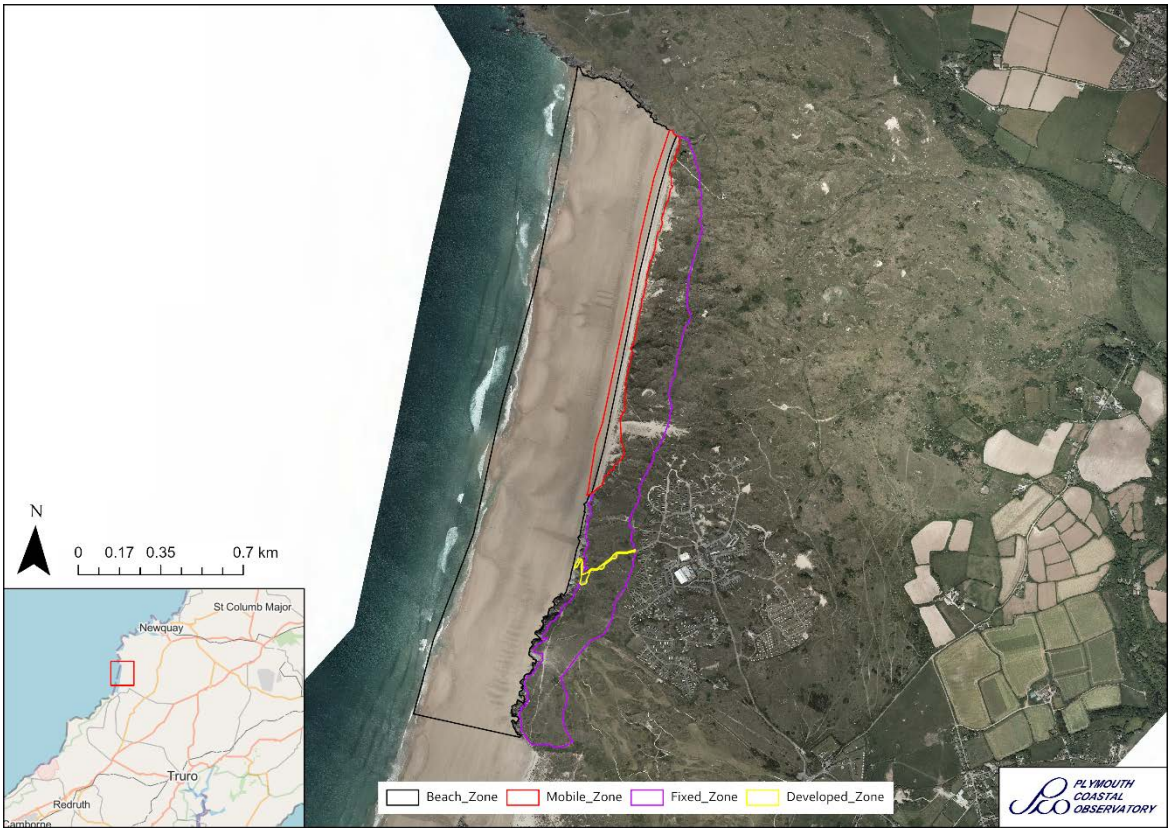



*Figure 1 - Location Map of Penhale Beach and Dune System, indicating the four defined zones outlined in section 1.0. Interim topographic profiles are also overlain to show their location, as detailed in section 2.1*

[1] An embryo dune, or yellow dune, is the earliest stage of dune growth, usually found along the seaward extent of a dune system or newly formed dune.

# 2.0 Methods

Data utilised in this report was collected by SWCM between 2007 and 2024. Information on topographic and LiDAR data collection and specifications can be found on the Website for the National Network of Coastal Monitoring Programmes.

## 2.1 Topographic Data

SWCM have undertaken routine topographic beach surveys at 34 of the 40 MS4S sites since 2006. All surveys are conducted from the MLWS contour to the backshore. On average, each surveyed beach receives two interim surveys a year and one full coverage survey every 5 years:

- Interim - Conducted twice a year in the spring (conducted between January and April), and autumn (conducted between September and December). An interim survey consists of collecting data points at 5m intervals along pre-defined profiles; these are outlined in Figure 1.
- Full coverage – Conducted once per phase (6 years), or annually at more vulnerable sites (conducted between May and September). Full coverage surveys include a full profile survey at 50 m intervals and continuous spot height data collected across a 5 m grid covering the whole beach.

Analysis of the Cross-Sectional Area (CSA) change is conducted for each individual profile between each separate survey. Changes in CSA are measured relative to the fixed master profile which is defined by a pre-determined stable landward position and the MLWS level in reference to Ordnance Datum.

### 2.1.1 Topographic Data Analysis

Topographic data is presented as the following, where applicable:

Trend Analysis Plot - The combined profile trend in CSA is presented for each survey unit (example shown in Fig.2). The sum of all interim profile CSA is combined for each survey conducted to date to provide a survey unit with a single 'beach area' value, known hence-forth as the Combined Profile Area (CPA). CPA is compared using linear trend analysis over a temporal scale (Fig.2).

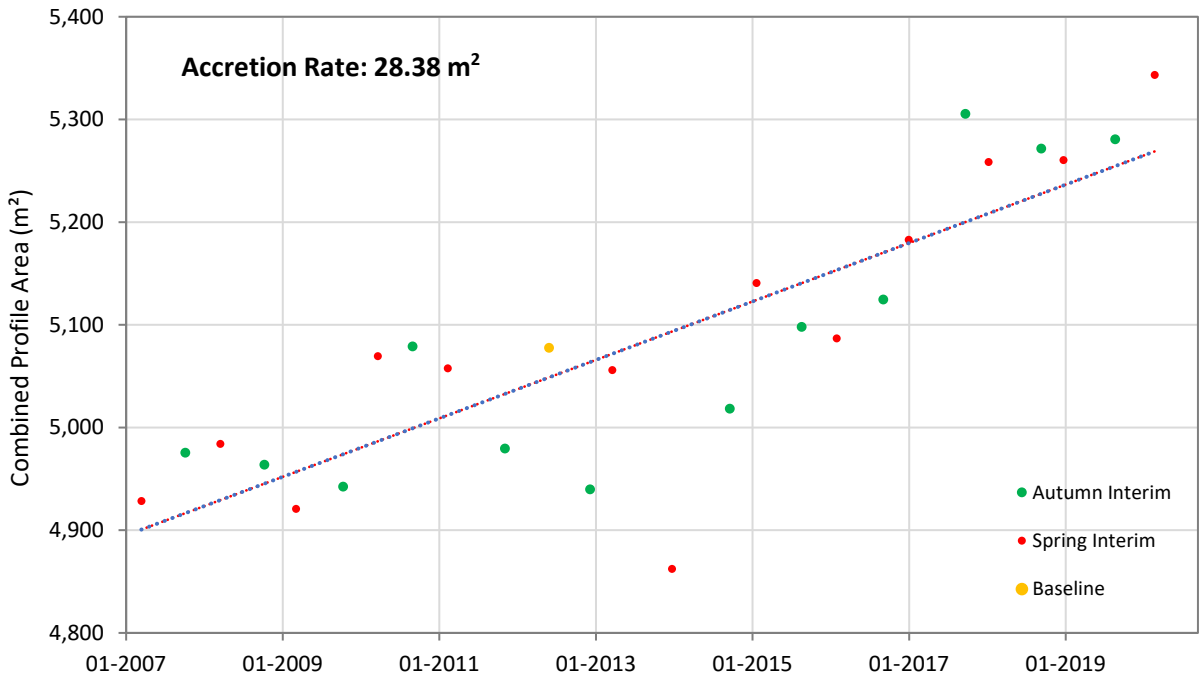



*Figure 2 - Example of trend analysis for CPA for each survey with a linear trend rate highlighted at 28.4 $m^2$ $y^{-1}$ equating to the increase of 0.56% of the average CPA per year.*

If a profile has been omitted from a particular survey, for reasons of obstruction or similar, the average CSA of that profile from all available surveys is taken to ensure a consistent 'beach area'; if fewer than 75% of surveys have been conducted for a particular profile, the profile is omitted.

Profile Extremes Analysis - This plot displays the range of CSA values recorded throughout the duration of data collection (2006-2022) for each individual interim profile; the most recent survey is represented as a green dot. An example is given in figure 3. This plot provides the reader with information on how the CSA for each interim profile from the most recent survey corresponds to the entire dataset range.

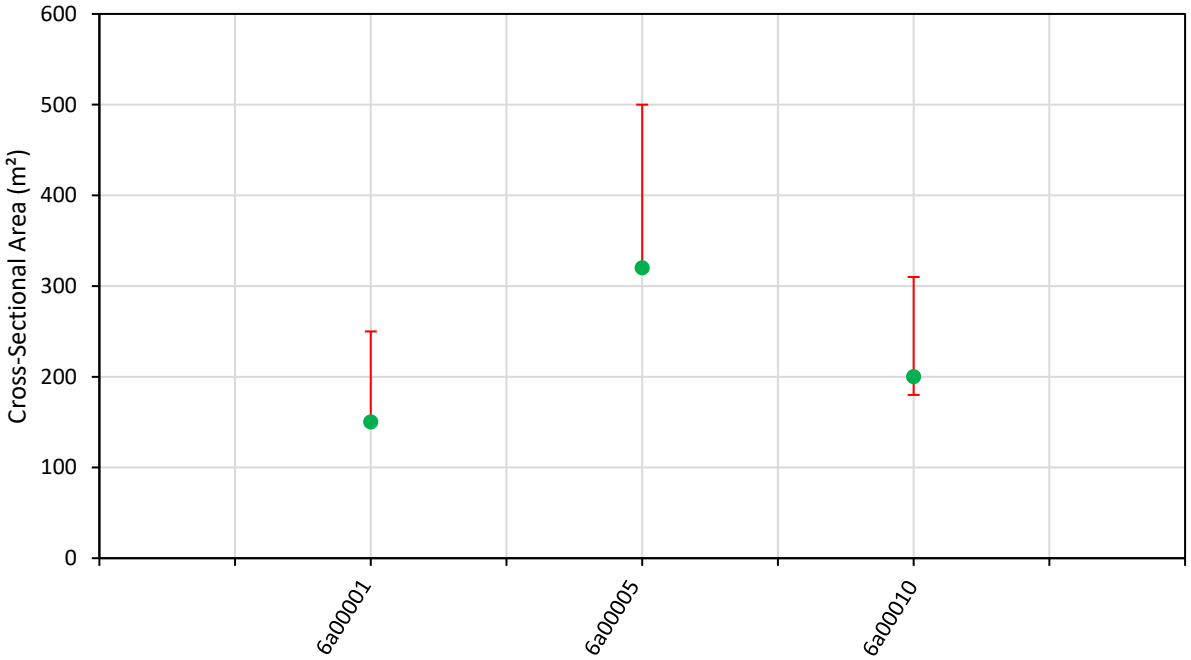



*Figure 3 - Example plot showing the most recent CSA value recorded for three separate profile lines (green dots). The error bars represent the range of CSA recorded by each profile throughout the topographic dataset.*

CSA Time Series Plot - CSA measurements for each interim profile are displayed on a separate plot representing values from each interim and full coverage survey conducted to date (example shown in Fig.4). This provides the reader with information on each interim profile's CSA evolution through time.

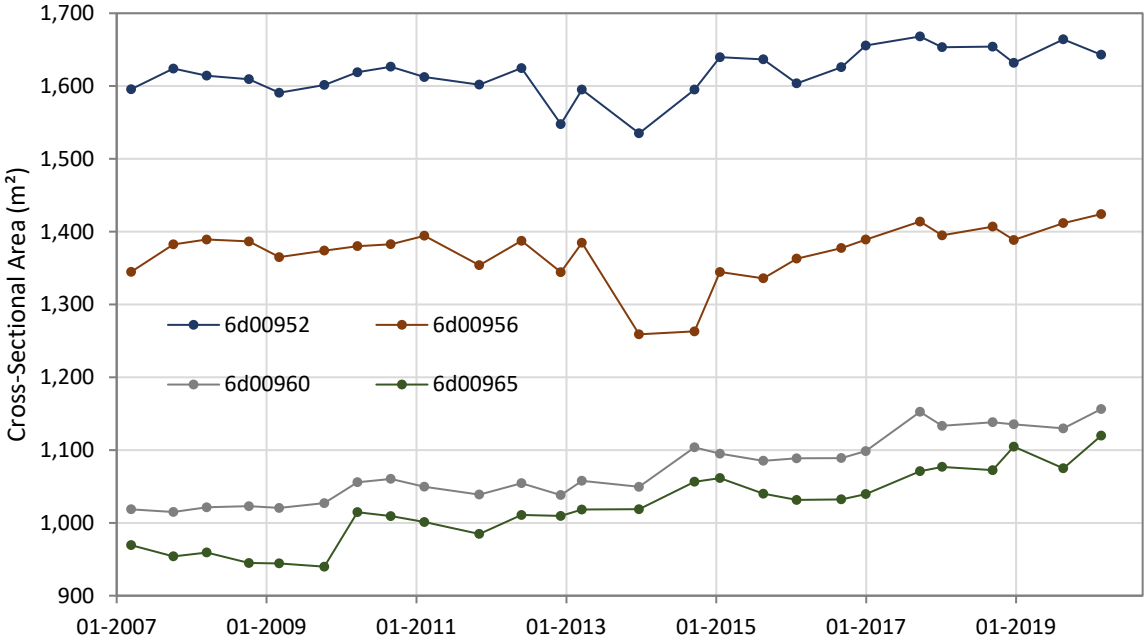



*Figure 4 - Example of a cross-sectional area plot showing each of the interim profiles recorded for every survey since the 2007 baseline.*

Individual Profile Charts - Each interim profile is portrayed as a cross-sectional profile comparing the most recent spring interim (blue), the previous spring interim (green) and the original full coverage survey (red). Profiles are displayed against the master profile (dotted red line) and are presented in the Appendices.

The 2013/2014 Storms – The winter period between September 2013 and April 2014 was, for many beaches in Cornwall, the most destructive period since SWCM records began in 2007. An abnormal number of significant storms, occurring in quick succession, heavily impacted many beaches, causing the loss of sediment from the intertidal area and dune face. This period is extensively discussed throughout this report and will hereinafter be referred to as the 2013/2014 winter period.

## 2.2 LiDAR Data

Airborne Light Detection and Ranging (LiDAR) data have been captured as part of the SWCM since 2007. Products include a point clouds, from which filtered and unfiltered 1 $m^2$ gridded surface models are derived:

- Unfiltered (Digital Elevation Model) representing the earth's surface including natural and artificial features such as trees and buildings.
- Filtered (Digital Terrain Model) representing the bare earth surface, with trees, buildings, cars etc. removed.

LiDAR is captured between September and March to minimise vegetation capture. Data is captured between MLWS and up to approximately 500 m inland. This report utilises "filtered" LiDAR data.

### 2.2.1 LiDAR Data Analysis

LiDAR data analysis is presented as the following:

Difference Modelling – Separate LiDAR surfaces are compared to produce a difference model of change based on gridded spot height elevations. The raw spot height data is processed into a gridded digital terrain model (DTM) and successive models are subtracted from one another to produce a difference model for the survey unit. Change in elevation is shown for values +/- 0.25 m and is represented by a colour scale bar.

Volume Extraction - Net sediment volume ($m^3$) is extracted for each LiDAR surface from the Beach Zone above MLWS and Mobile Zone above MHWS for trend comparison over time.

Contour Analysis – Contours are mapped from four LiDAR epochs spanning from 2007 to 2023, representing Mean Sea Level (MSL) and dune toe (calculated using the Stockdon equation by UoP, 2023[2]).

## 2.3 Accuracy Statement

Topographic Data – All survey points recorded along profiles have a measurement accuracy of +/- 0.03 m RMSE[3] in the horizontal and +/-0.03 m RMSE in the vertical.

LiDAR Data – Each LiDAR point cloud dataset has an average point density of 1.5 points per square metre. The digital terrain surfaces provide a minimum accuracy in elevation data of +/- 0.10 m RMSE with a minimum horizontal standard deviation as < 0.05 m. Please note that while every endeavour has been made to capture LiDAR as far seaward as MLWS, tidal and weather restrictions may in some instances have precluded this and coverage may be slightly reduced.

[2] Please refer to the following for Dune Toe elevation calculation: UoP, 2023. MS4S: Contemporary Dune Evolution and Future Predictions, Report, University of Plymouth, 33 pp.

[3] RMSE – Root-Mean-Square Error

# 3.0 Results

## 3.1 Topographic Data Analysis

There has been a total of 23 topographic surveys at Penhale since 2007, 4 of which are full coverage surveys, 17 are interim surveys and 2 are post-storm surveys. Exact dates of each survey for Penhale are available to view on our survey record. Analysis of the CPA indicates the survey unit has been eroding at 72.6 $m^2$ $y^{-1}$ equating to 0.54% of the average beach area per year (Fig.5). Penhale experienced the beach to be accreting up until 2013, when the beach was heavily impacted by the 2014 winter period. One of the lowest recorded combined areas was during the 2014 spring interim; the beach has not fully recovered to pre-storm beach levels since.

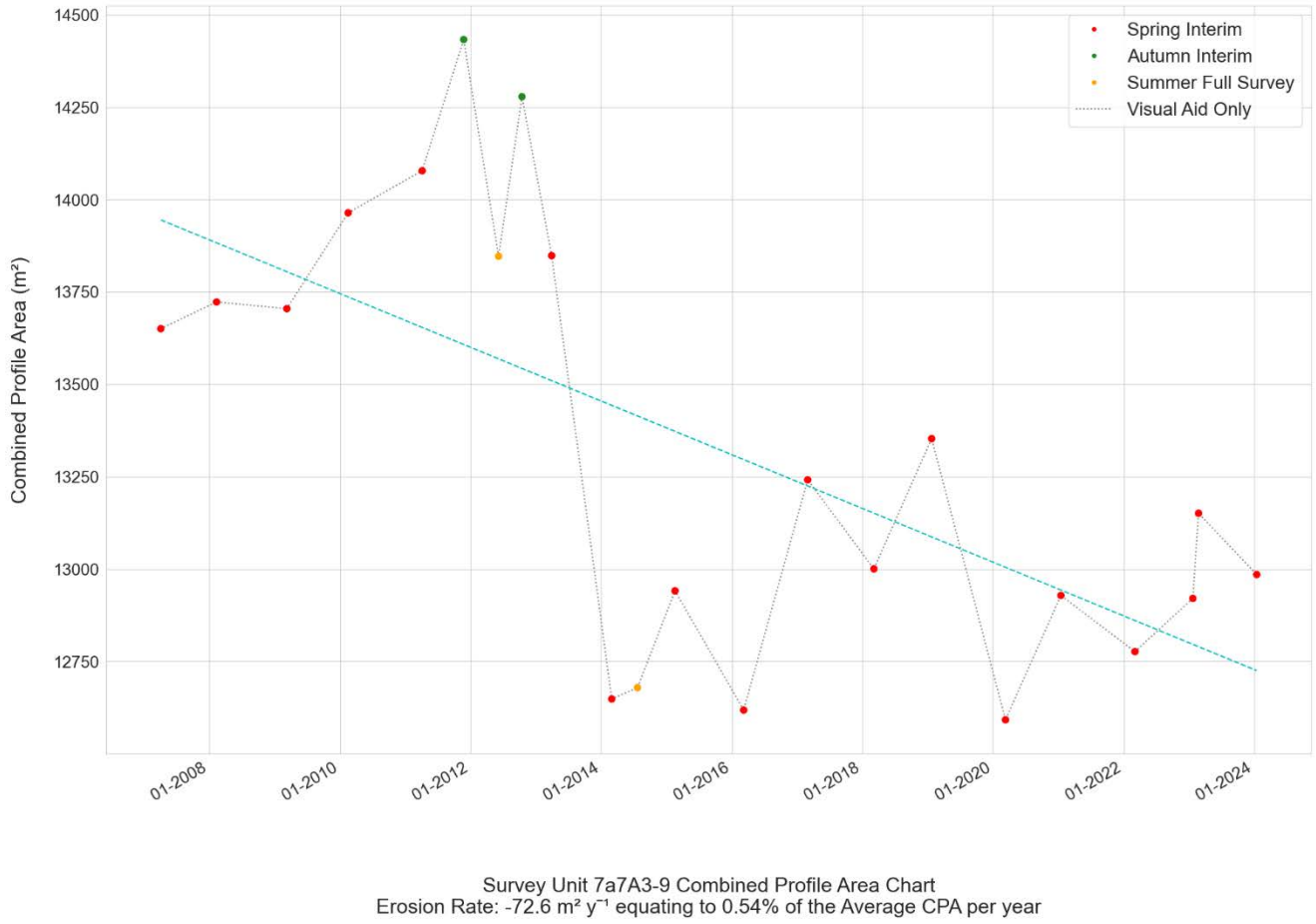



*Figure 5 - The Combined Profile Area (CPA) for Penhale, including every spring (red), summer (yellow) and autumn (green) survey completed between 2007 and 2024.*

When comparing to the entire dataset (Fig.6), during the 2024 spring interim all profiles displayed an average CSA, except for profile 7a01477 which measured a below average CSA to date.

When comparing profile cross-sectional areas to the entire time series (Fig.7), all profiles have displayed seasonal variation in all profiles, with a distinct impact after the 2014 winter period. Profile 7a01477 appears to have experienced the most impact from the 2013/14 winter season, continuing to decline to date.

Profile Charts for Penhale can be found in Appendix 1, these display the cross-sections of each profile for the initial baseline survey conducted in 2007 along with the two most recent interim surveys. The most change is experienced on profile 7a01477 seeing a retreat on the upper and lower dune system by >20 m.

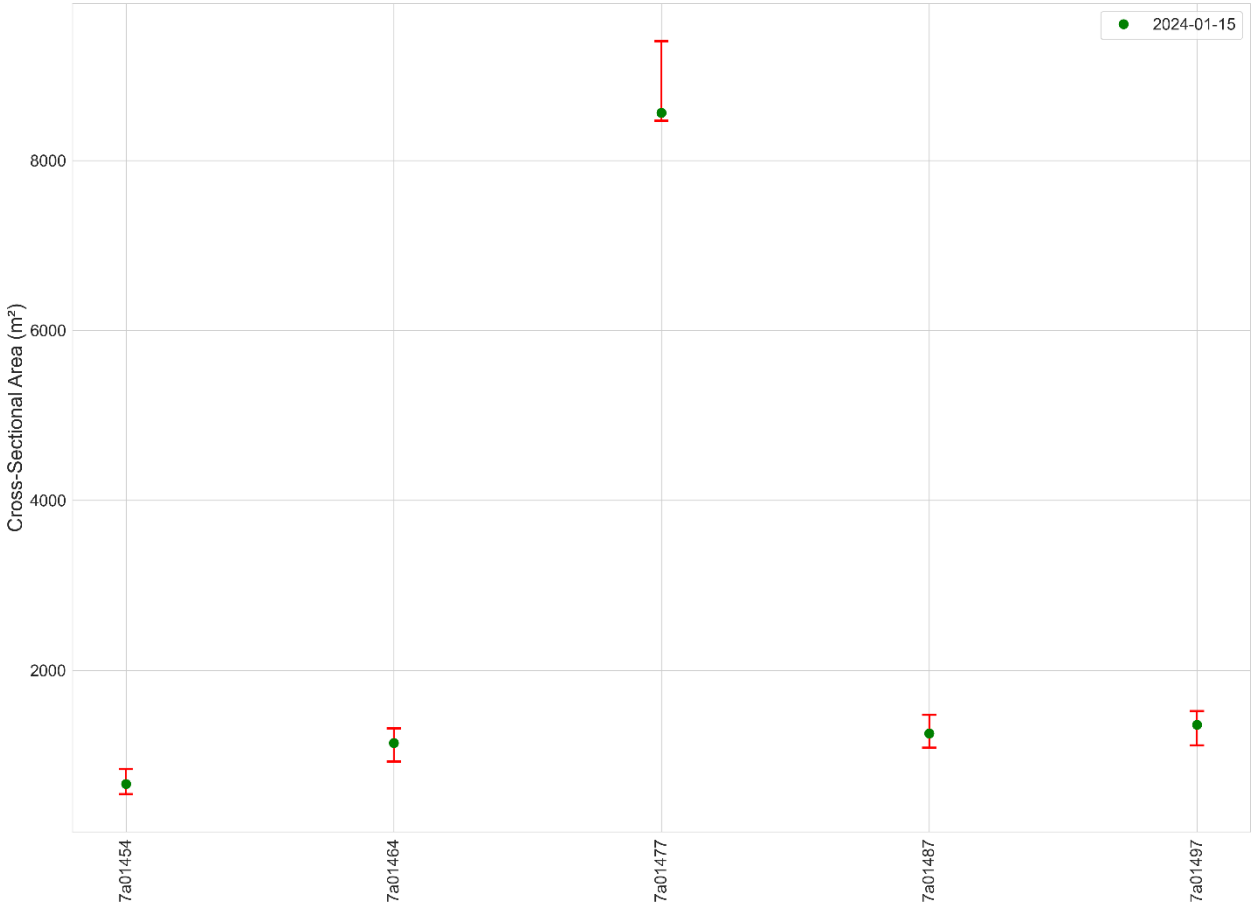



*Figure 6 - Cross-sectional area of each interim profile, comparing the current area of the profile (green dot), with the maximum and minimum values (red error bar) recorded between 2007 and 2024.*

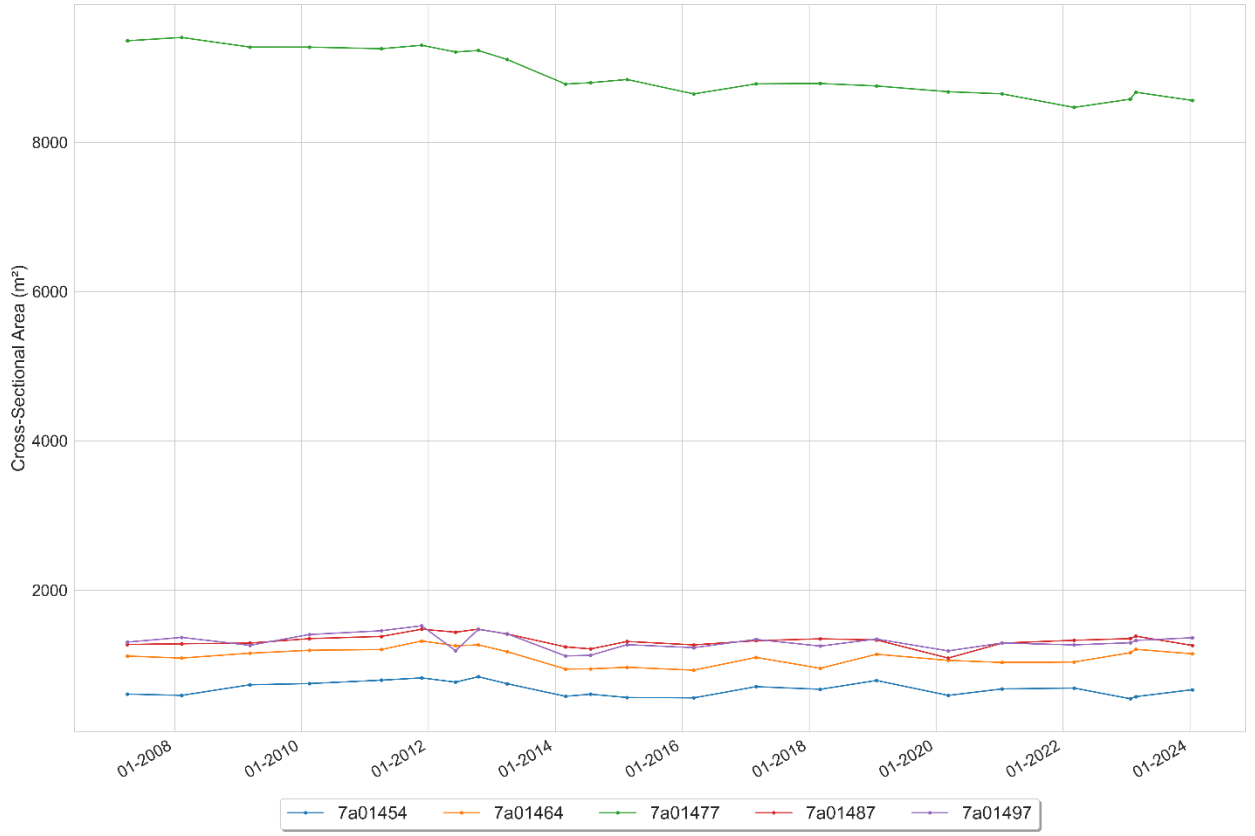



*Figure 7 - Cross-sectional area of each interim profile, comparing the values recorded during each interim and baseline survey between 2007 and 2024.*

## 3.2 LiDAR Data Analysis

There has been a total of 10 LiDAR flights captured at Penhale since 2007 through the SWCM Programme.

### 3.2.1 Difference Models

Difference models between each epoch of LiDAR data are presented here. Accretion and erosion values observed behind the dune system can be attributable to noise in the filtered LiDAR data or man-made changes in elevation and should be dismissed as such.

Please note that the difference models below (figures 8 - 17) display the analysis for the whole system, encompassing Perranporth. Analysis specific to Perranporth are available in report TBR21.

Figure 8 shows the difference in elevation between the first filtered LiDAR data from February 2008 compared to the most recent, captured in January 2023. There is considerable erosion observed along the upper beach face and mobile dune face, with the latter eroding by up to 3 m. The intertidal zone can see bar and rip features forming, where material builds-up forming a sand bar (the blue patches), followed by a depression (the red patches), then builds-up again; this is the basic process by which rip currents are formed.

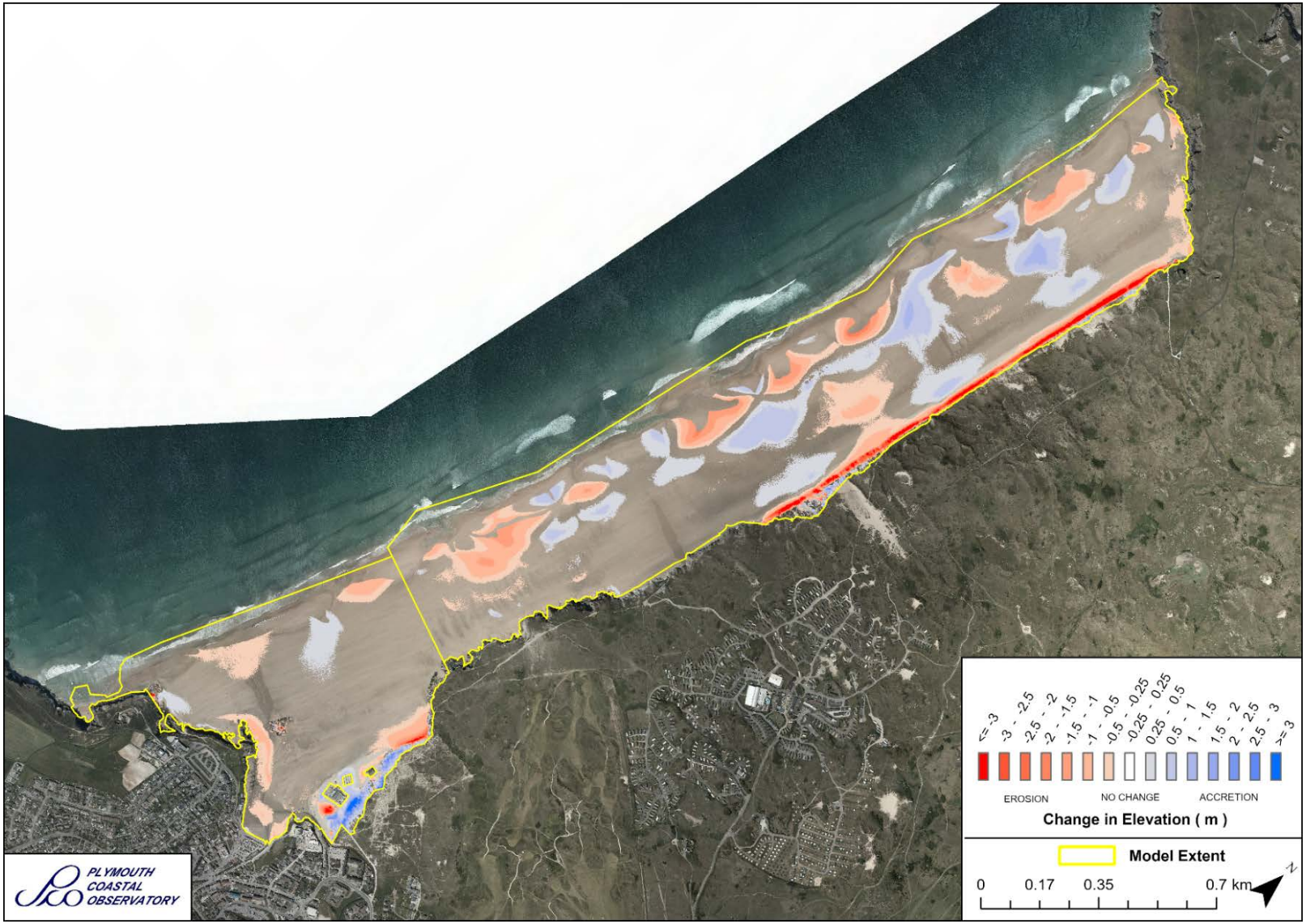



*Figure 8 – Difference model indicating the changes in elevation observed between the February 2008 and January 2023 filtered LiDAR datasets within the yellow model extent.*

Figure 9 shows differences in elevation between filtered LiDAR data from February 2008 compared to February 2009. Again, patches of erosion and accretion can be seen here, creating a bar-rip feature along the whole beach. Erosion has taken place along the beach and dune face, experiencing up to 3 m of erosion towards the north of the beach.

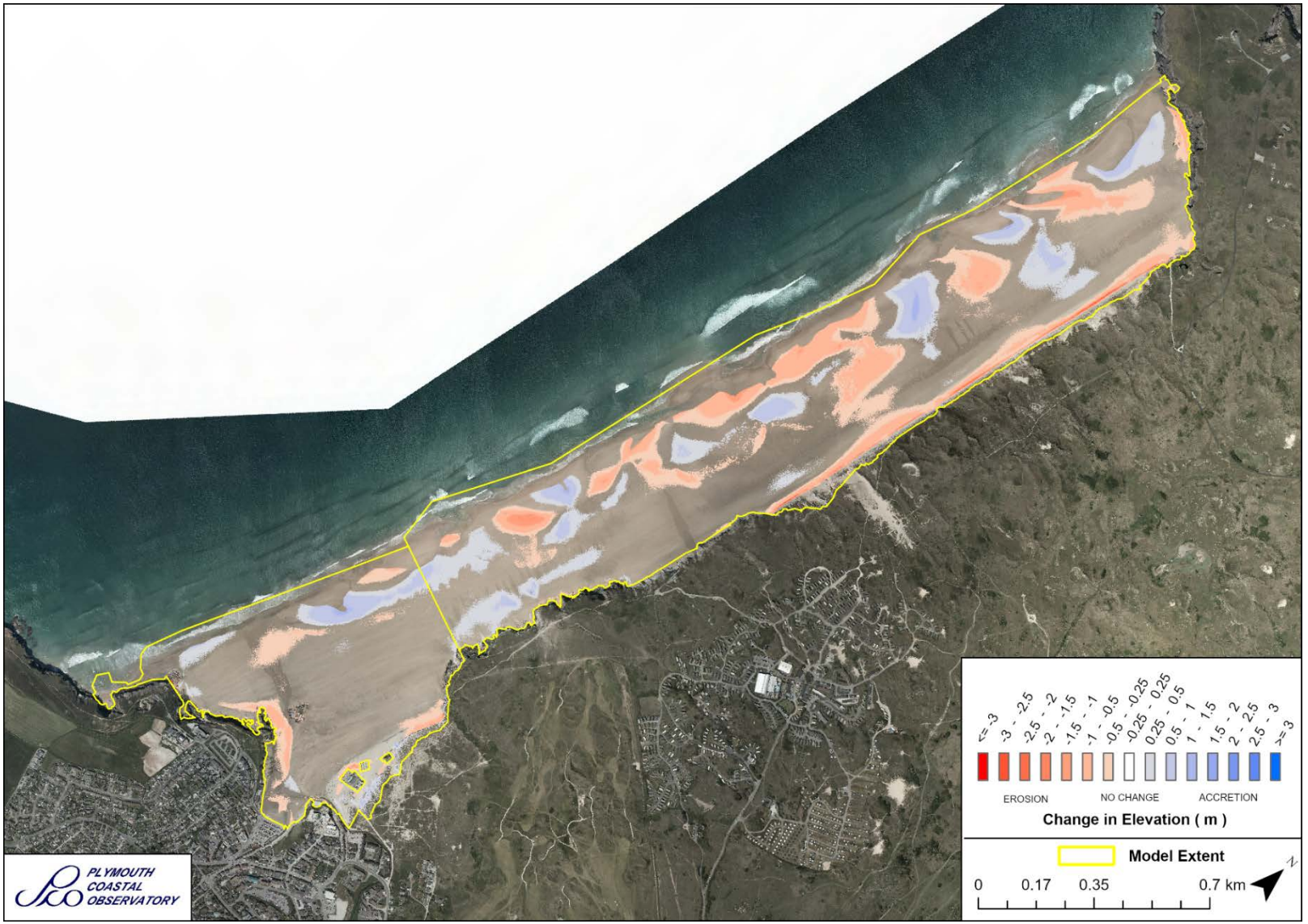



*Figure 9 - Difference model indicating the changes in elevation observed between the February 2008 and February 2009 filtered LiDAR datasets within the yellow model extent.*

Figure 10 shows differences in elevation between filtered LiDAR data from February 2009 compared to January 2011. Widespread accretion is seen across almost the entirety of the beach, up to 1.5 m, with only a couple of minor erosive patches to the seaward extent. This accretive state carries on into Perranporth, to the south.

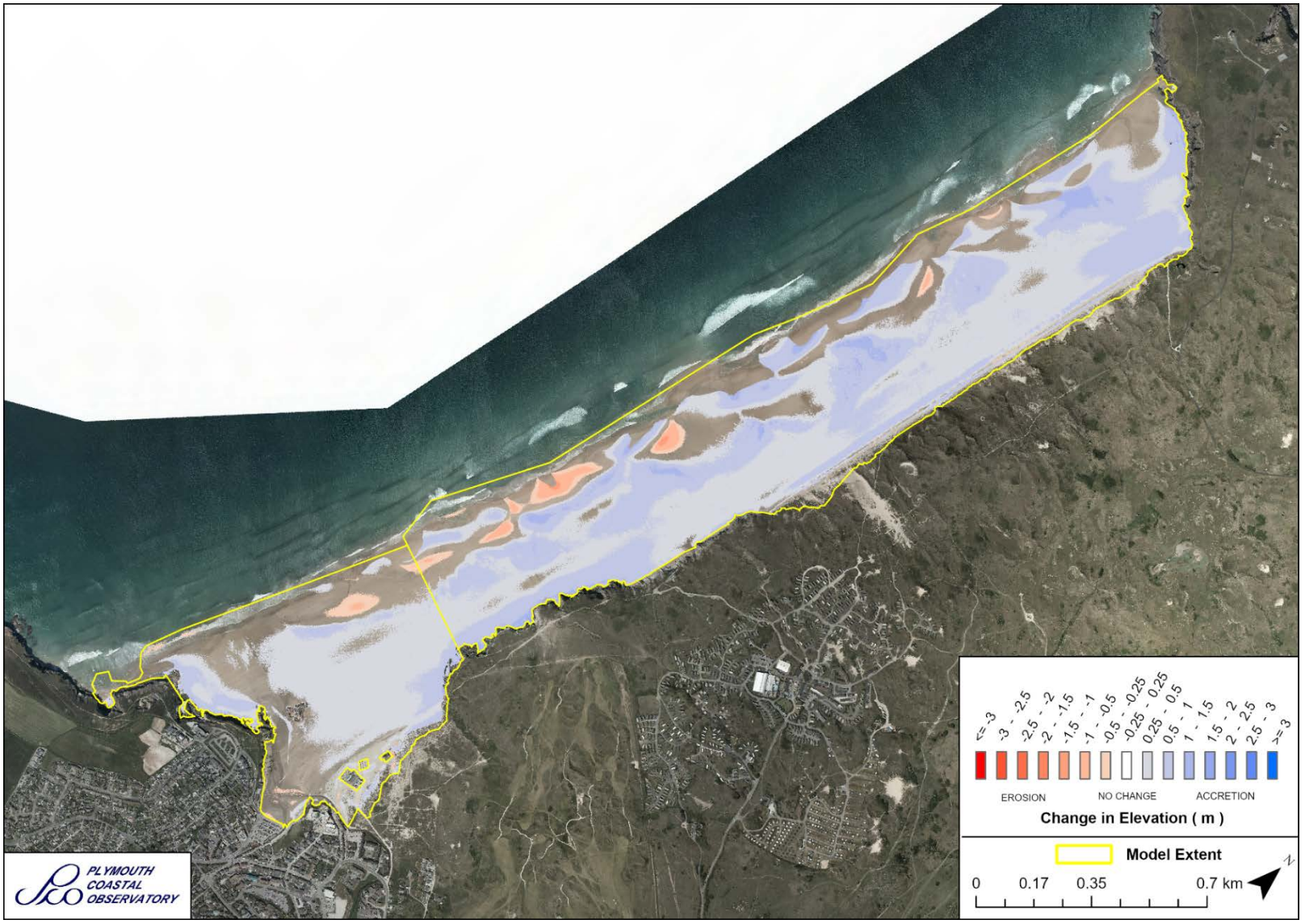



*Figure 10 – Difference model indicating the changes in elevation observed between the February 2009 and January 2011 filtered LiDAR datasets within the yellow model extent.*

Figure 11 shows differences in elevation between filtered LiDAR data from January 2011 compared to March 2012. In contrast to that observed in Figure 10, there is widespread erosion along the intertidal zone, eroding by up to 1 m in places. However, the dune and beach face has experienced a band of accretion running along the length of the beach. Small bar-like features have formed towards the seaward extent.

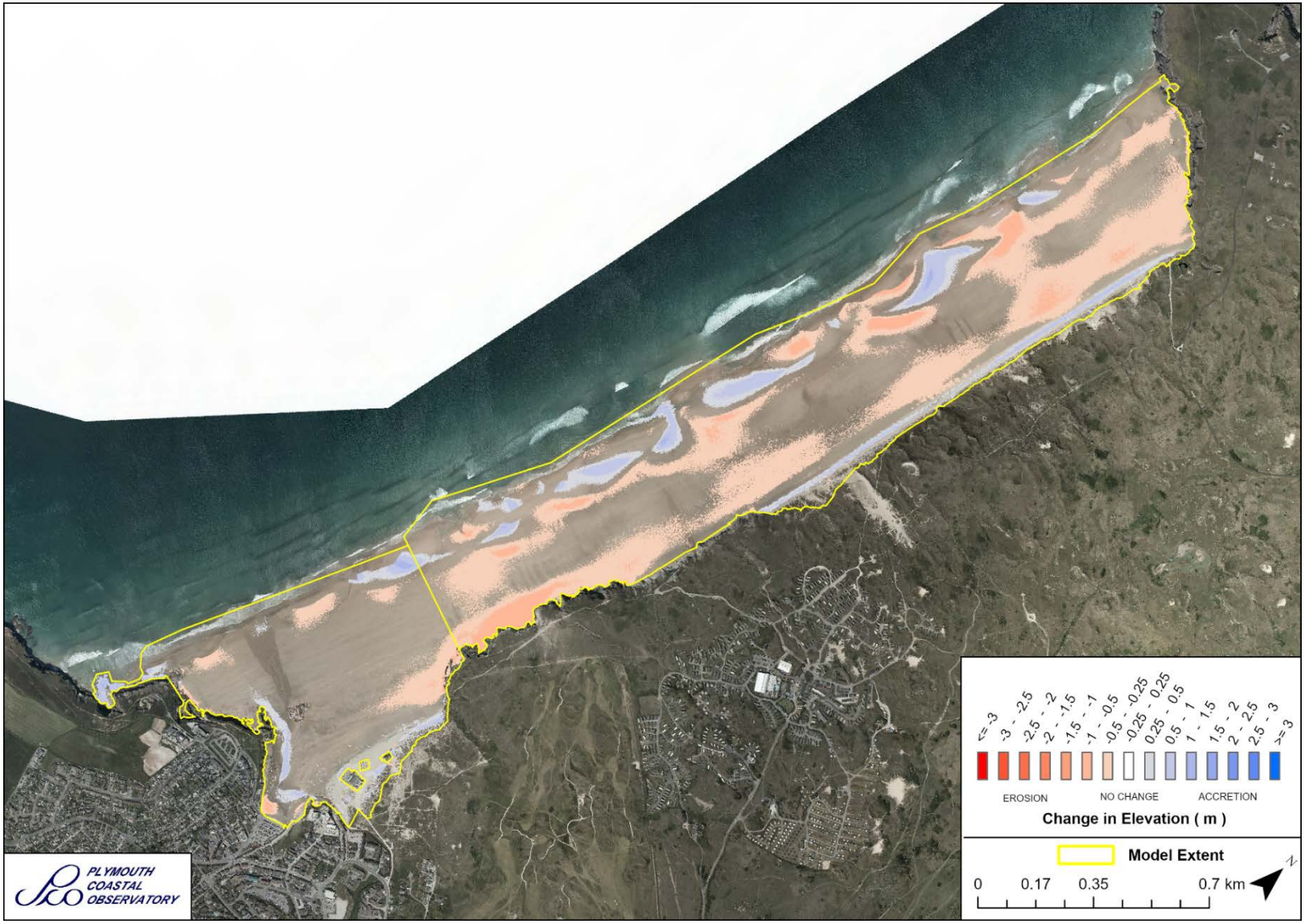



*Figure 11 - Difference model indicating the changes in elevation observed between the January 2011 and March 2012 filtered LiDAR datasets within the yellow model extent.*

Figure 12 shows differences in elevation between filtered LiDAR data from March 2012 compared to March 2014. After the 2013/2014 winter storms, large areas of change are indicated across the whole unit, experiencing a loss in elevation between 0.25 and >3 m. The entire dune face saw the most change, while the intertidal zone lost material across almost the whole beach.

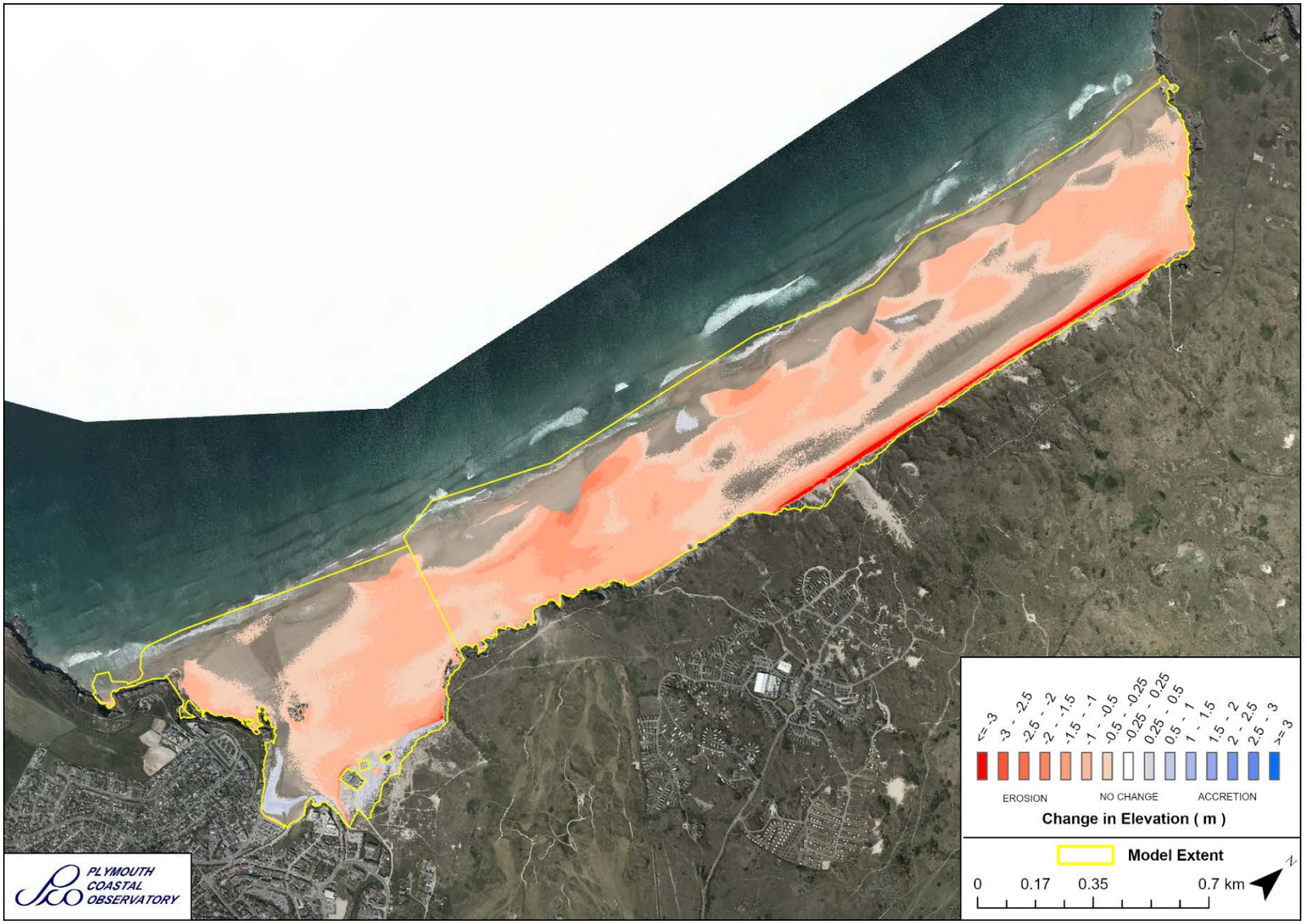



*Figure 12 - Difference model indicating the changes in elevation observed between the March 2012 and March 2014 filtered LiDAR datasets within the yellow model extent.*

Figure 13 shows differences in elevation between filtered LiDAR data from March 2014 compared to March 2016. In contrast to that of Figure 12, the dune face has observed up to 2 m in elevation gain along the entire beach. Large areas of accretion can be seen towards the north and southern extents, whilst the intertidal zone has experienced various patches of low-level erosion and accretion.

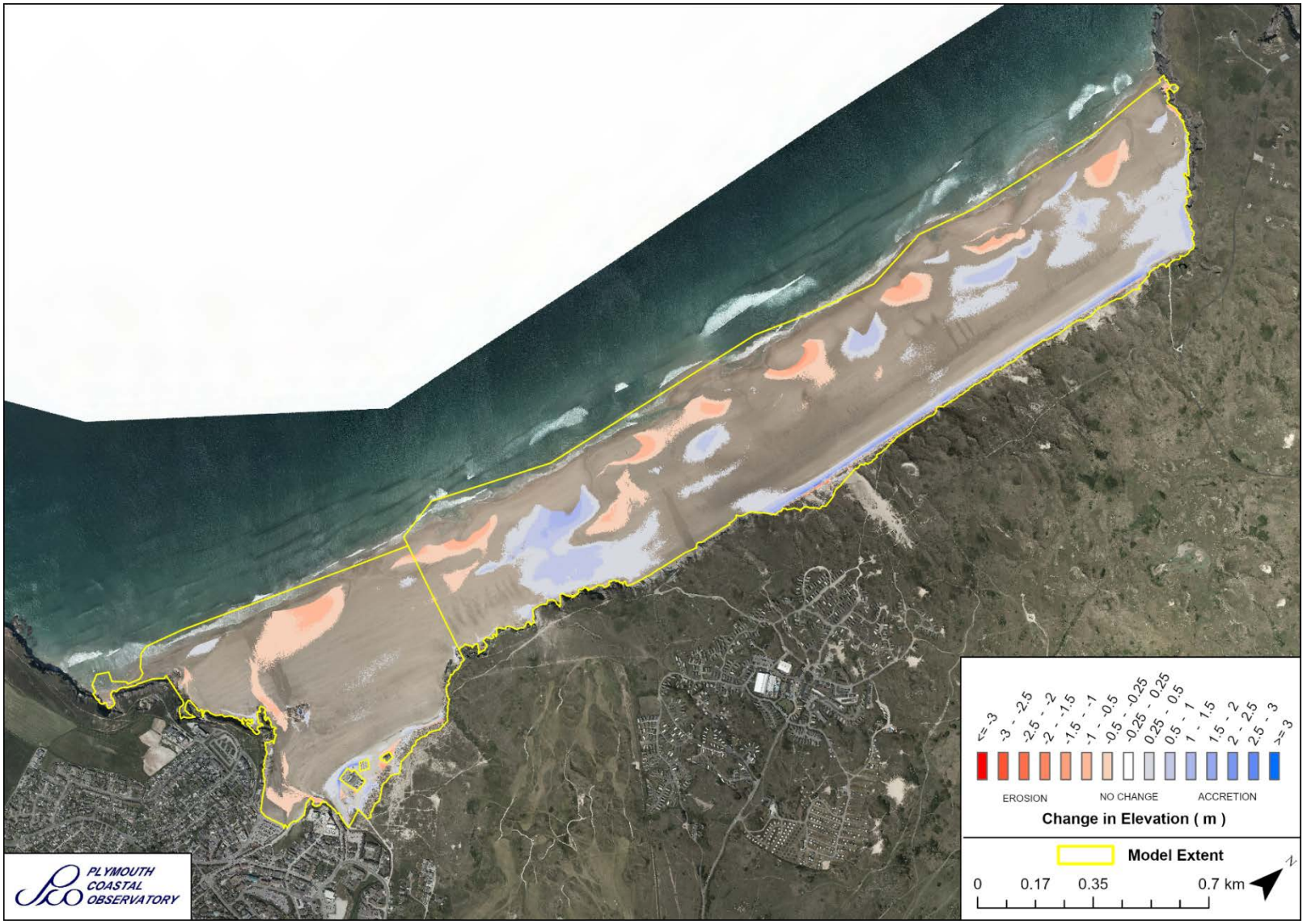



*Figure 13 - Difference model indicating the changes in elevation observed between the March 2014 and March 2016 filtered LiDAR datasets within the yellow model extent.*

Figure 14 shows differences in elevation between filtered LiDAR data from March 2016 compared to February 2017. Widespread accretion is observed across the majority of the beach, whilst the MSL mark has remained stable. Low-level erosion is indicated along the dune face, whilst the beach face has seen a band of accretion along the whole unit.

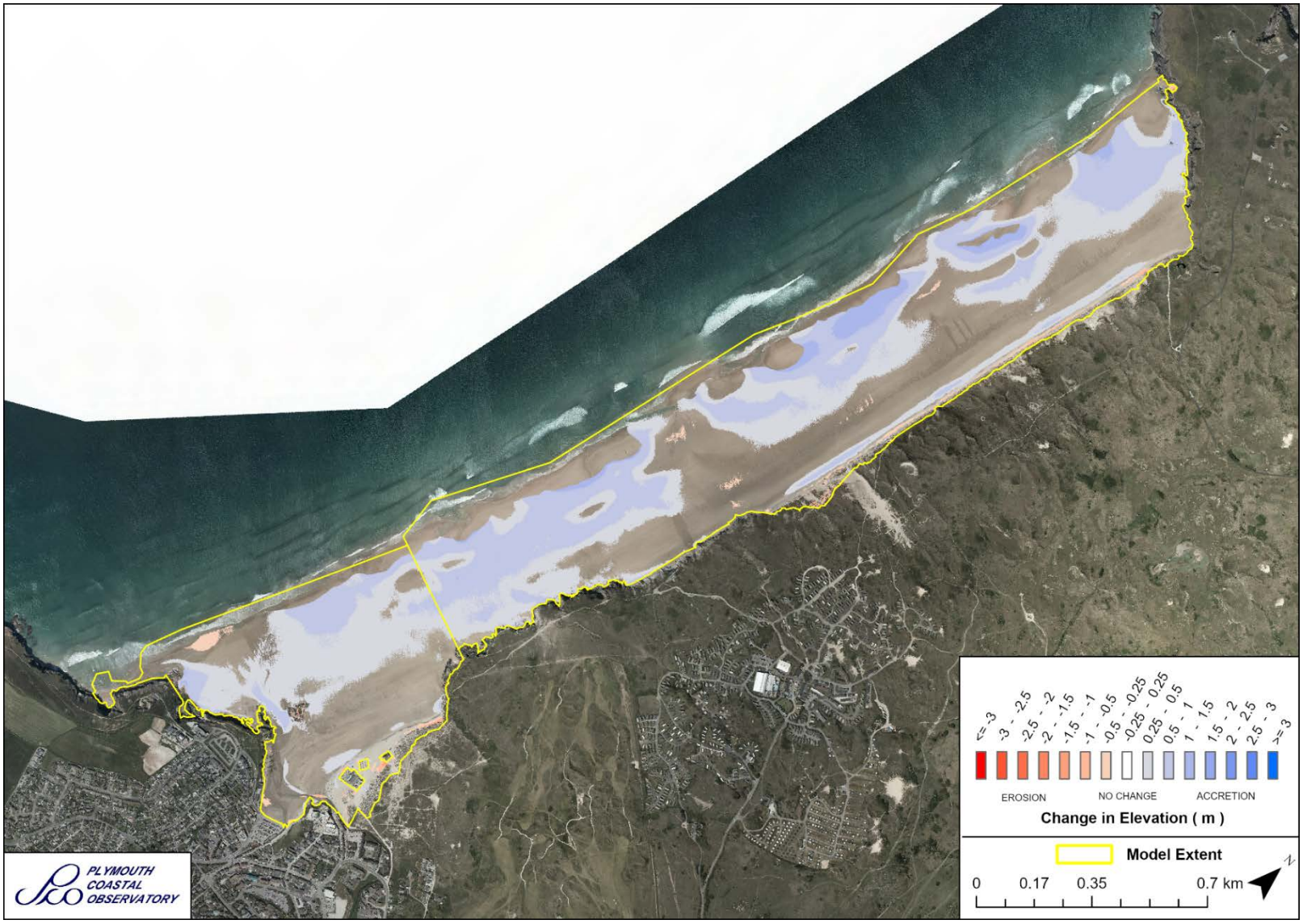



*Figure 14 - Difference model indicating the changes in elevation observed between the March 2016 and February 2017 filtered LiDAR datasets within the yellow model extent.*

Figure 15 shows differences in elevation between filtered LiDAR data from February 2017 compared to April 2019. A strip of erosion can be seen in along the dune and beach face, in the middle of the dune system, lowering by 0.25 to 1 m. The majority of the intertidal zone has seen a trend for accretion with sparse patches of erosion towards the seaward extent.

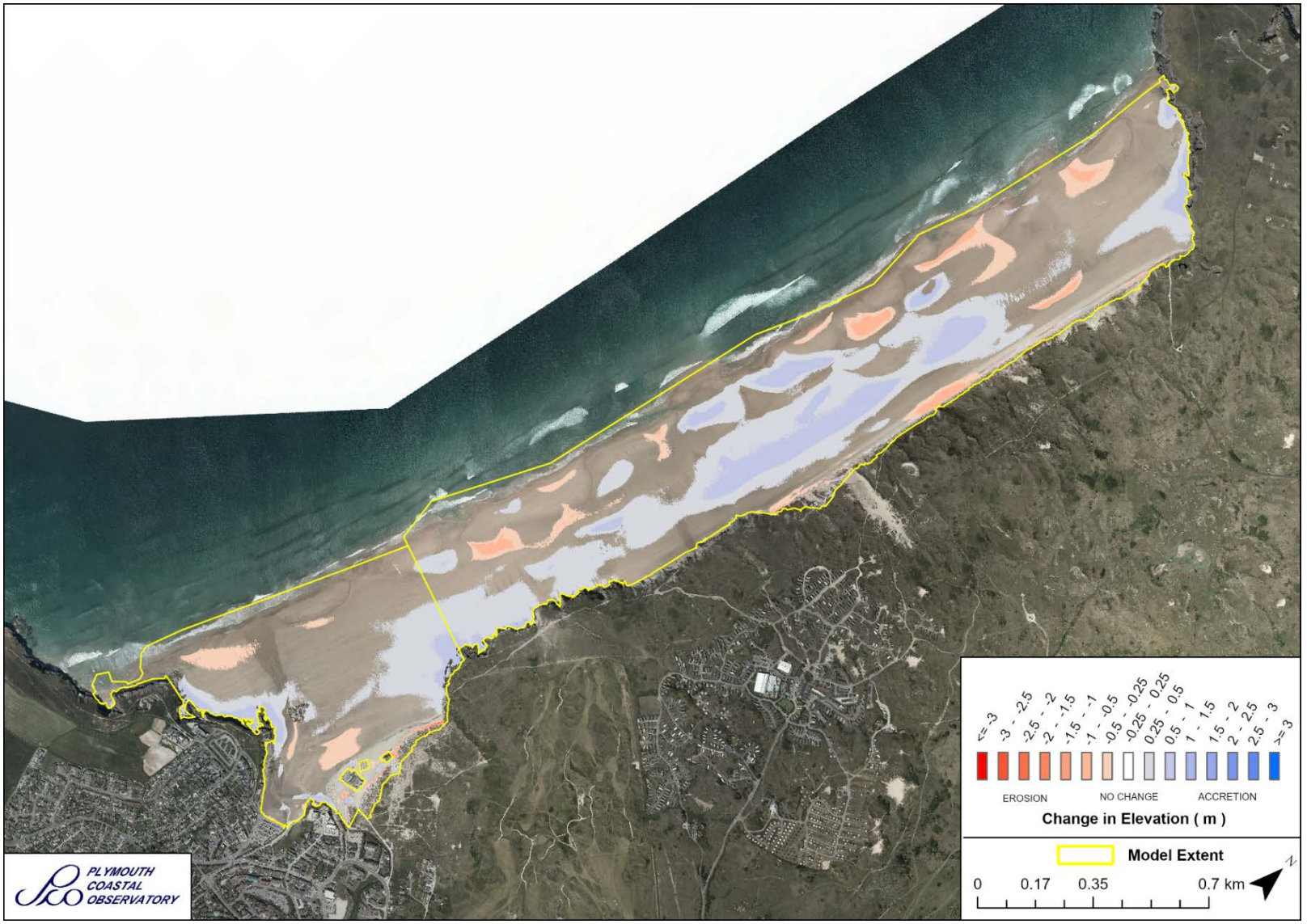



*Figure 15 - Difference model indicating the changes in elevation observed between the February 2017 and April 2019 filtered LiDAR datasets within the yellow model extent.*

Figure 16 shows differences in elevation between filtered LiDAR data from April 2019 compared to November 2020. Considerable change can be observed across the intertidal zone, observing up to 2 m of erosion along the width of the beach. The dune face has seen acute erosion, along the middle of the dune system, whilst some accretion is indicated, to the south, along the beach face.

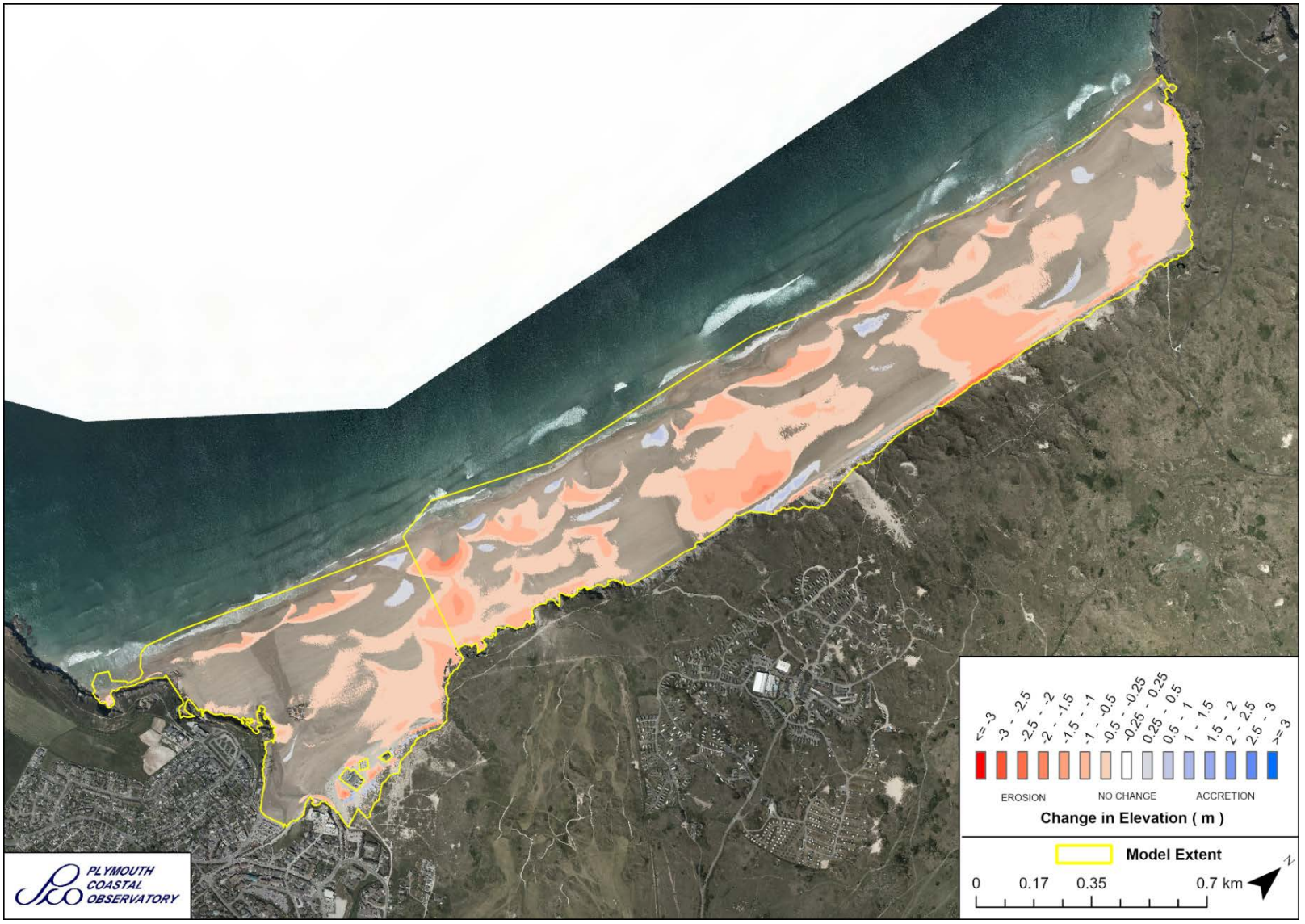



*Figure 16 - Difference model indicating the changes in elevation observed between the April 2019 and November 2020 filtered LiDAR datasets within the yellow model extent.*

Figure 17 shows differences in elevation between filtered LiDAR data from November 2020 compared to January 2023. Large areas of accretion can be observed along the beach and dune face, accreting by up to 2 m. Large areas of erosion are seen towards the south and northern ends of the beach whilst the remaining intertidal zone has experienced a patches of both erosion and accretion.

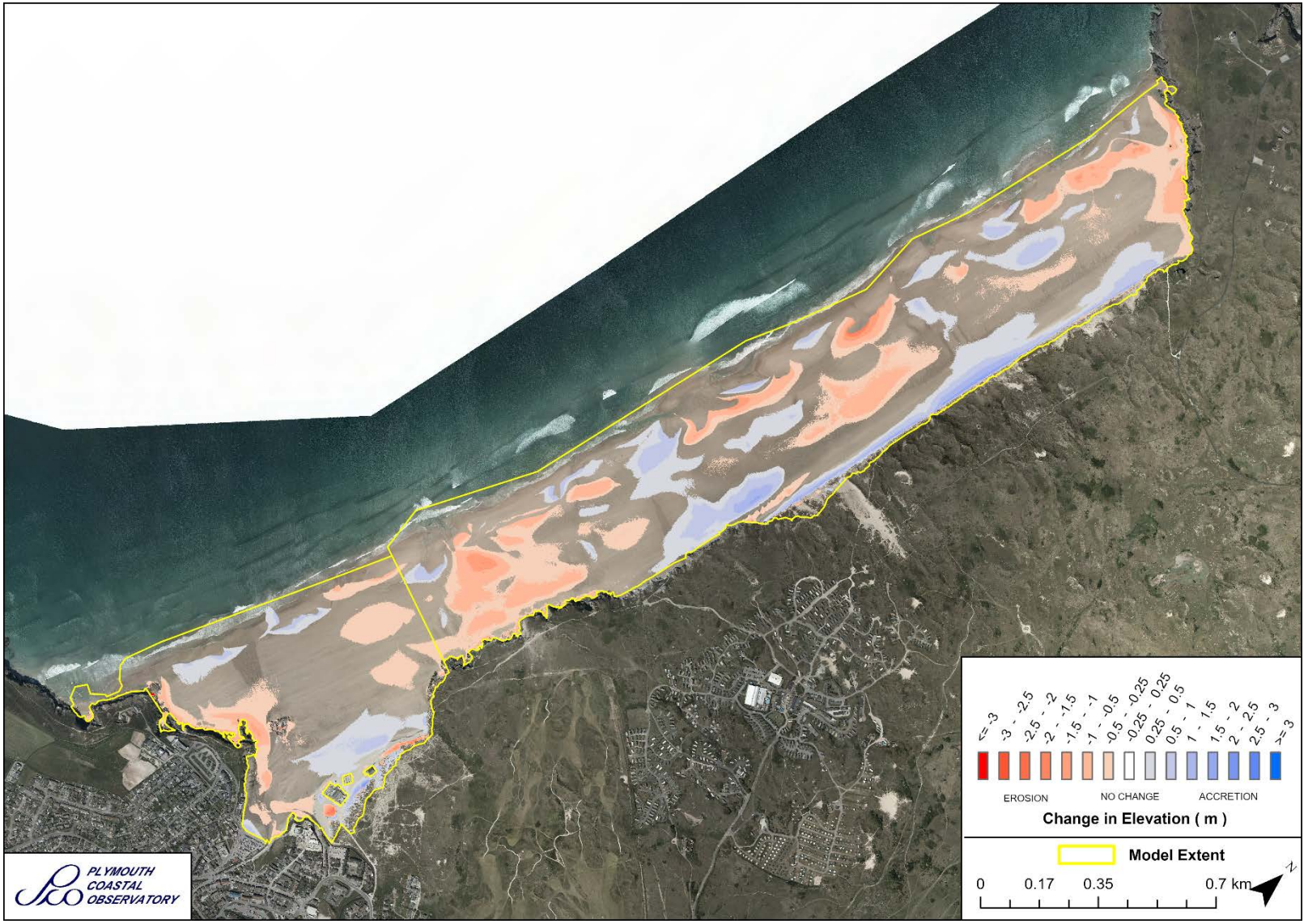



*Figure 17 - Difference model indicating the changes in elevation observed between the November 2020 and January 2023 filtered LiDAR datasets within the yellow model extent.*

### 3.2.2 Beach and Dune Volume Extraction

Surface volume extracted from each available LiDAR dataset from the Mobile Zone above the MHWS contour (3.30 m OD) are shown in Table 1 and Figure 18. The Mobile Zone suggests similar results to that seen in the topographic data: the beach was heavily impacted in 2014, losing 25% of material from the Mobile Zone (Fig.18). Since 2014, the Mobile Zone has remained relatively stable but has yet to return to pre-2014 volume levels.

Surface volume extracted from each LiDAR dataset from the Beach Zone above the MLWS contour (-2.80 m OD) are shown in Table 1 and Figure 19. The Beach Zone also saw a large loss of material following the 2013/14 winter, with a 18% loss in material between the 2012 and 2014 surveys (Fig.19). Since 2014 however, there has been considerable recovery of the Beach Zone, with the second highest volume on record observed during the 2019 survey (Table 1). Overall the Beach Zone has remained relatively stable between 2008 and 2023 despite large volume fluctuations.

*Table 1 – Surface volume values ($m^3$) extracted from all available filtered LiDAR datasets for the Mobile Zone above MHWS (3.30 m OD) and for the Beach Zone above MLWS (-2.80 m OD).*

| Date | Mobile Zone Volume ($m^3$) | Beach Zone Volume ($m^3$) |
|---|---|---|
| 02/2008 | 490,521 | 2,488,044 |
| 02/2009 | 461,533 | 2,475,545 |
| 01/2011 | 489,842 | 2,923,220 |
| 04/2012 | 499,011 | 2,740,979 |
| 04/2014 | 373,923 | 2,231,541 |
| 03/2016 | 402,580 | 2,333,063 |
| 03/2017 | 410,207 | 2,677,873 |
| 04/2019 | 406,246 | 2,852,574 |
| 11/2020 | 387,156 | 2,563,626 |
| 01/2023 | 417,649 | 2,501,157 |

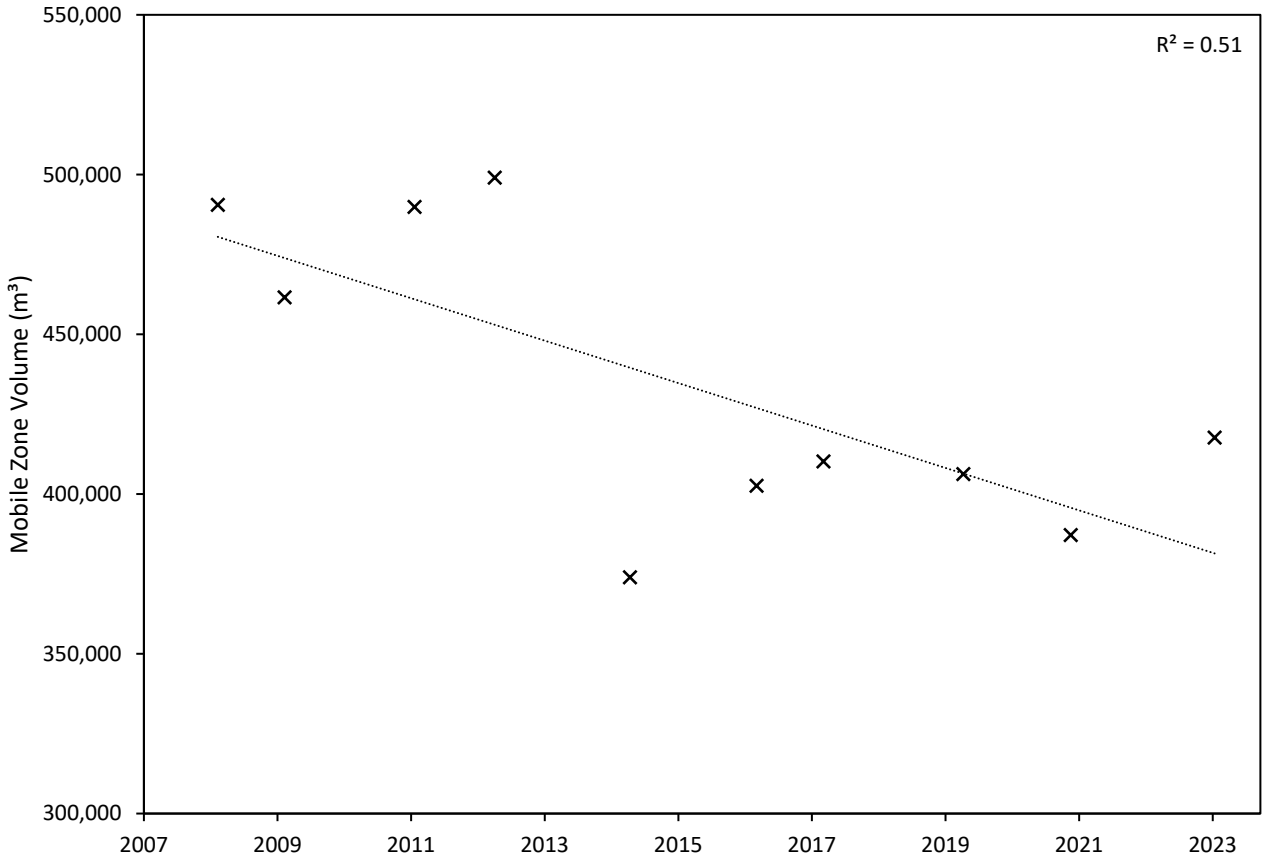



*Figure 18 – Plot indicating beach volume ($m^3$) recorded in the Mobile Zone above MHWS (3.30 m OD) for each filtered LiDAR datasets between 2008 and 2023.*

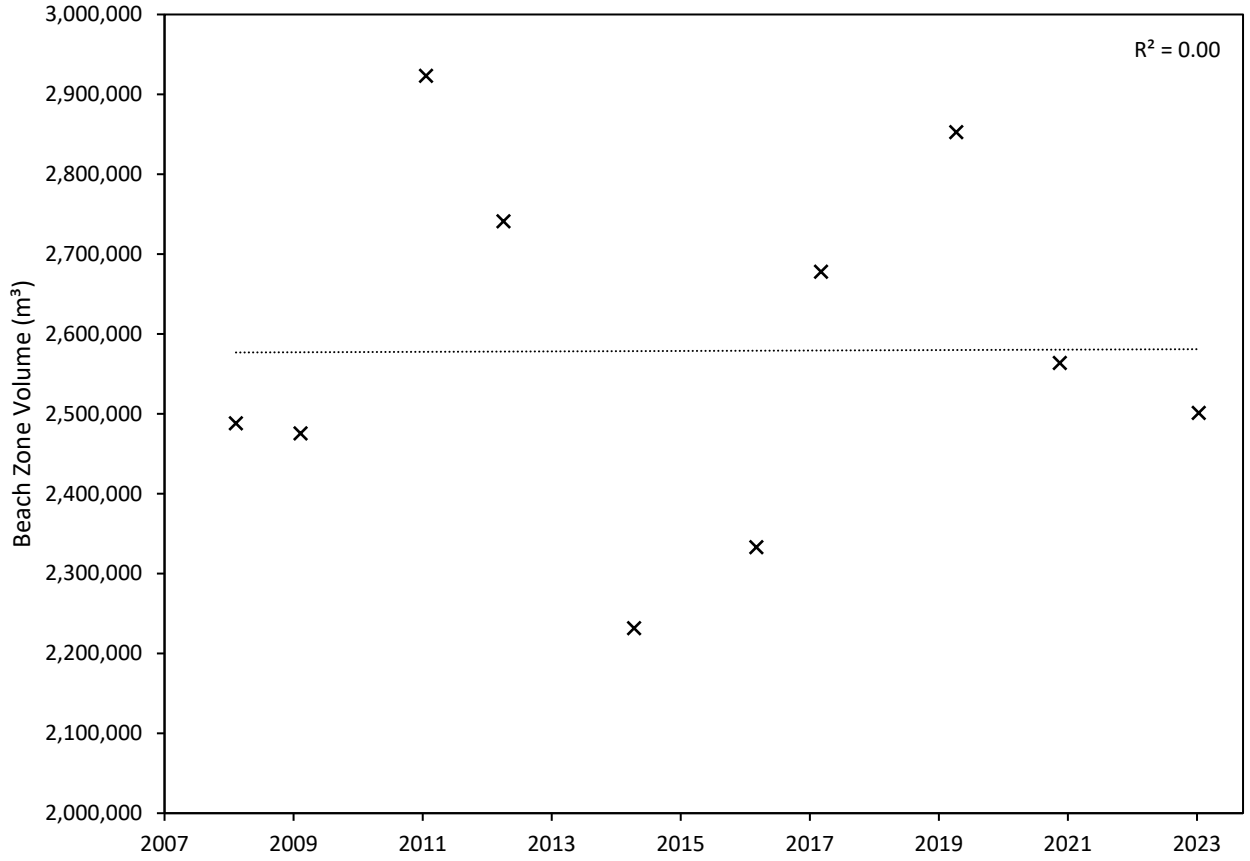



*Figure 19 - Plot indicating beach volume ($m^3$) recorded in the Beach Zone above MLWS (-2.80 m OD) for each filtered LiDAR datasets between 2008 and 2023.*

### 3.2.3 Contour Comparison

Figure 20 indicates the Mean Sea Level (MSL) and Dune Toe contours from the 2008, 2014, 2019 and 2023 LiDAR datasets. MSL contours indicate a widening of the beach in 2019 by approximately 40-50 m. The Dune Toe contours show a retreat of ~15 m from 2008 to 2014, after the winter period, but the dune face has since advanced by ~9 m between 2014 to 2023, mostly towards the northern half.

## 3.3 Historic Aerial Maps

Historic aerial photography captured in 1947 by the RAF, in 2001 by the Environment Agency and from 2007 onwards by the SWCM are presented here.




*Figure 20 – Contour map indicating Mean Sea Level (solid line) and Dune Toe (dashed line) extracted from 2008, 2014, 2019 and 2023 LiDAR datasets.*

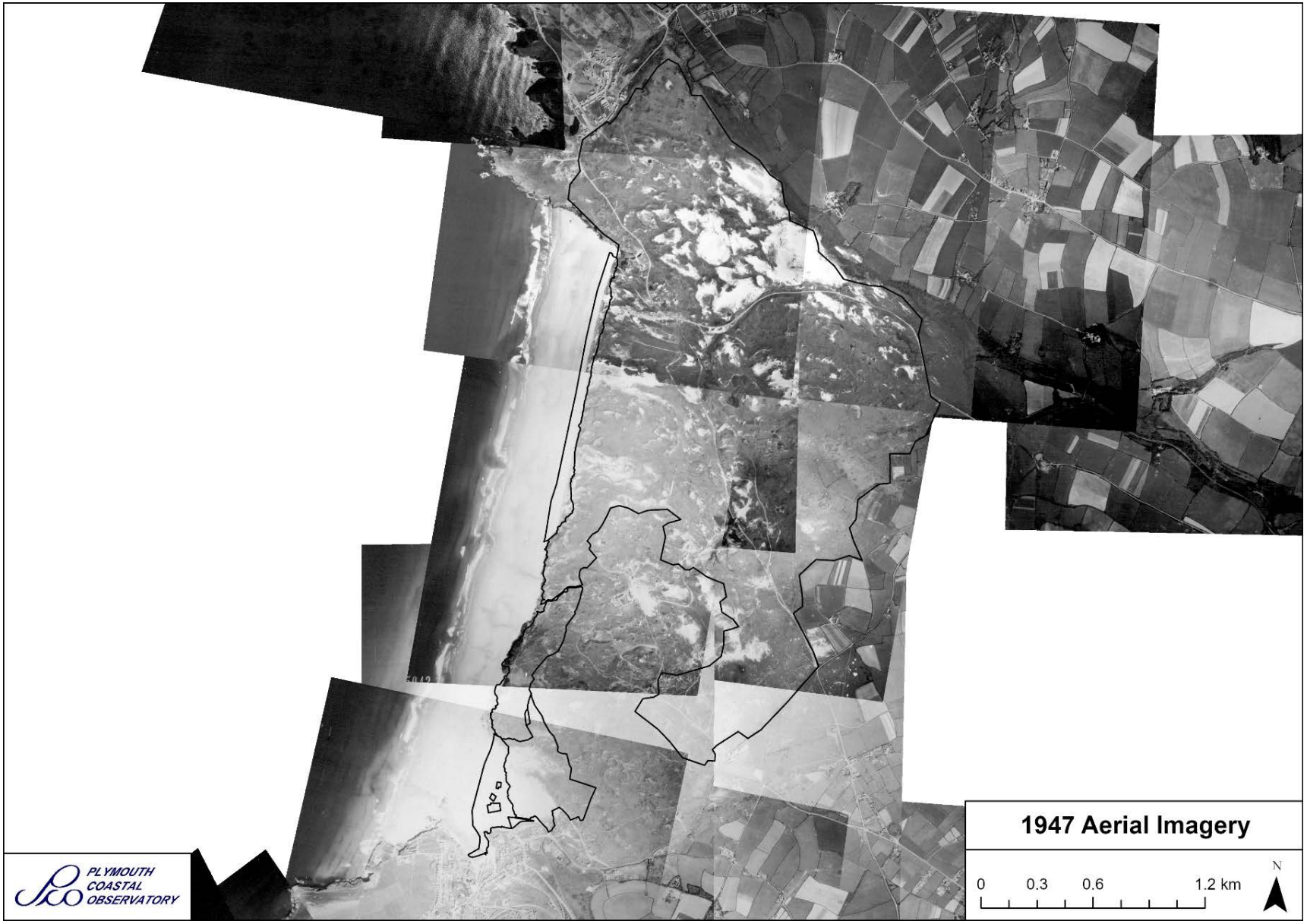



*Figure 21 – Aerial imagery from 1947.*




*Figure 22 – Aerial imagery from 2001.*




*Figure 23 – Aerial imagery from 2008.*




*Figure 24 – Aerial imagery from 2010.*

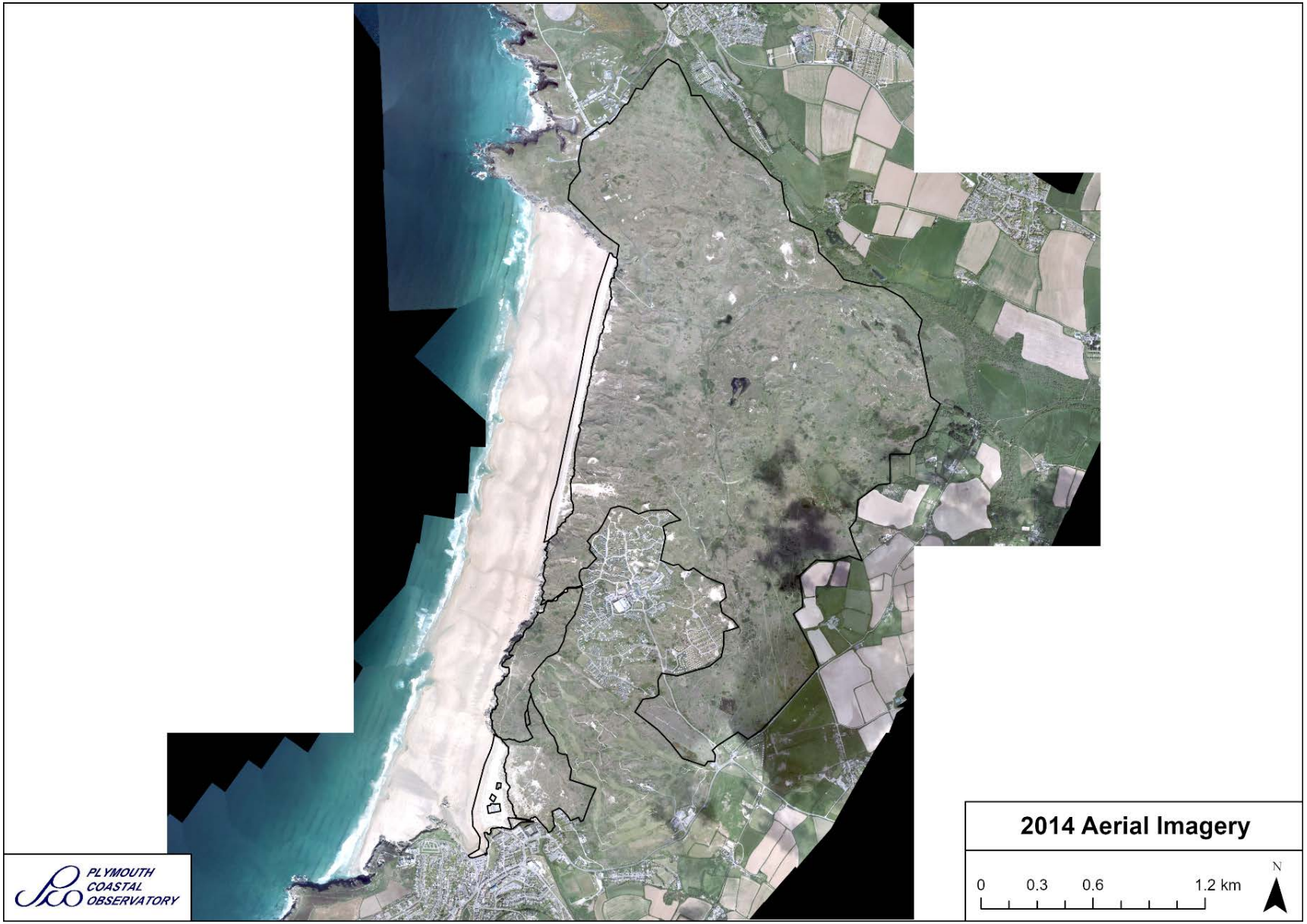



*Figure 25 – Aerial imagery from 2014.*



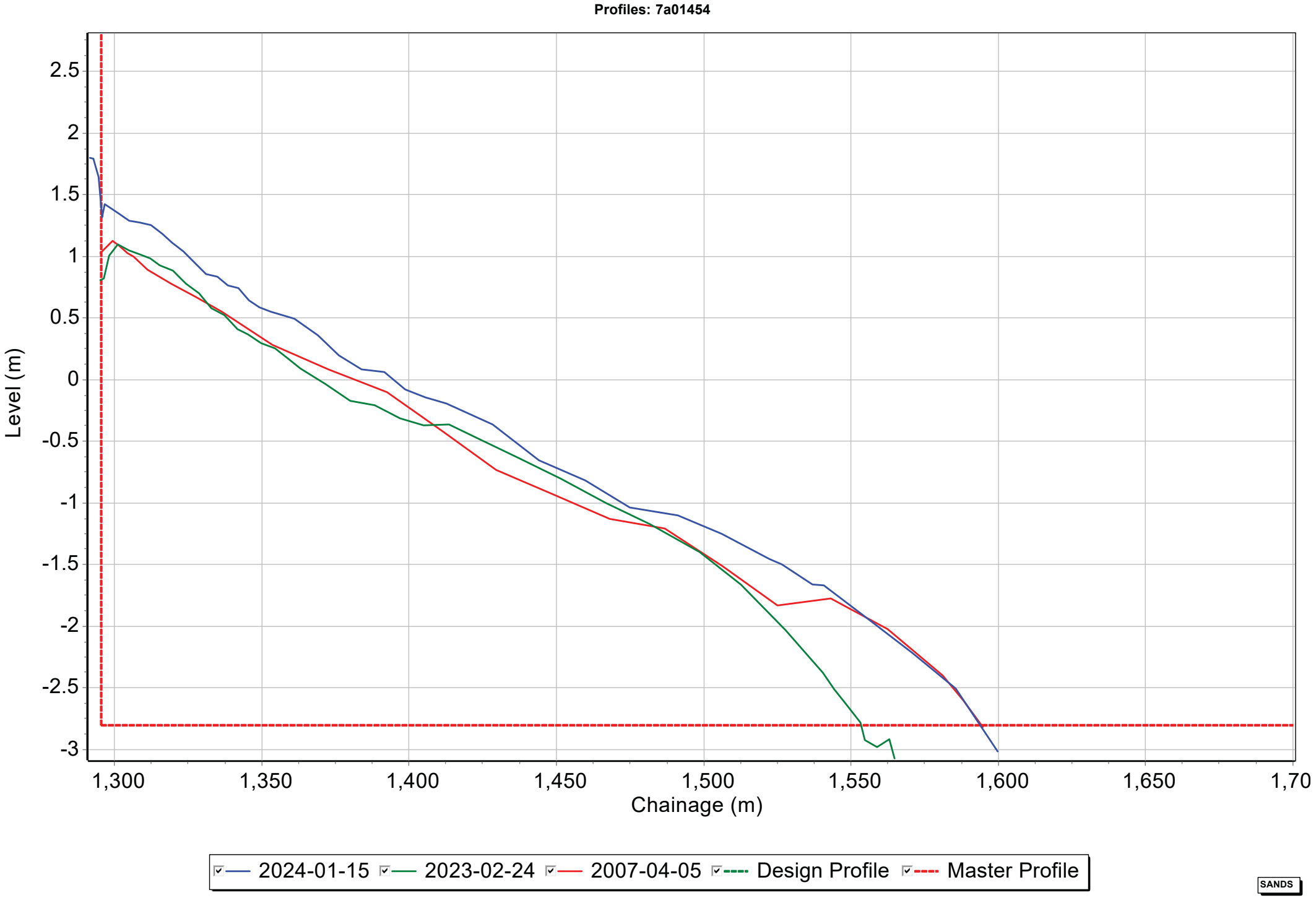

*Figure 26 – Aerial imagery from 2017.*

## Glossary

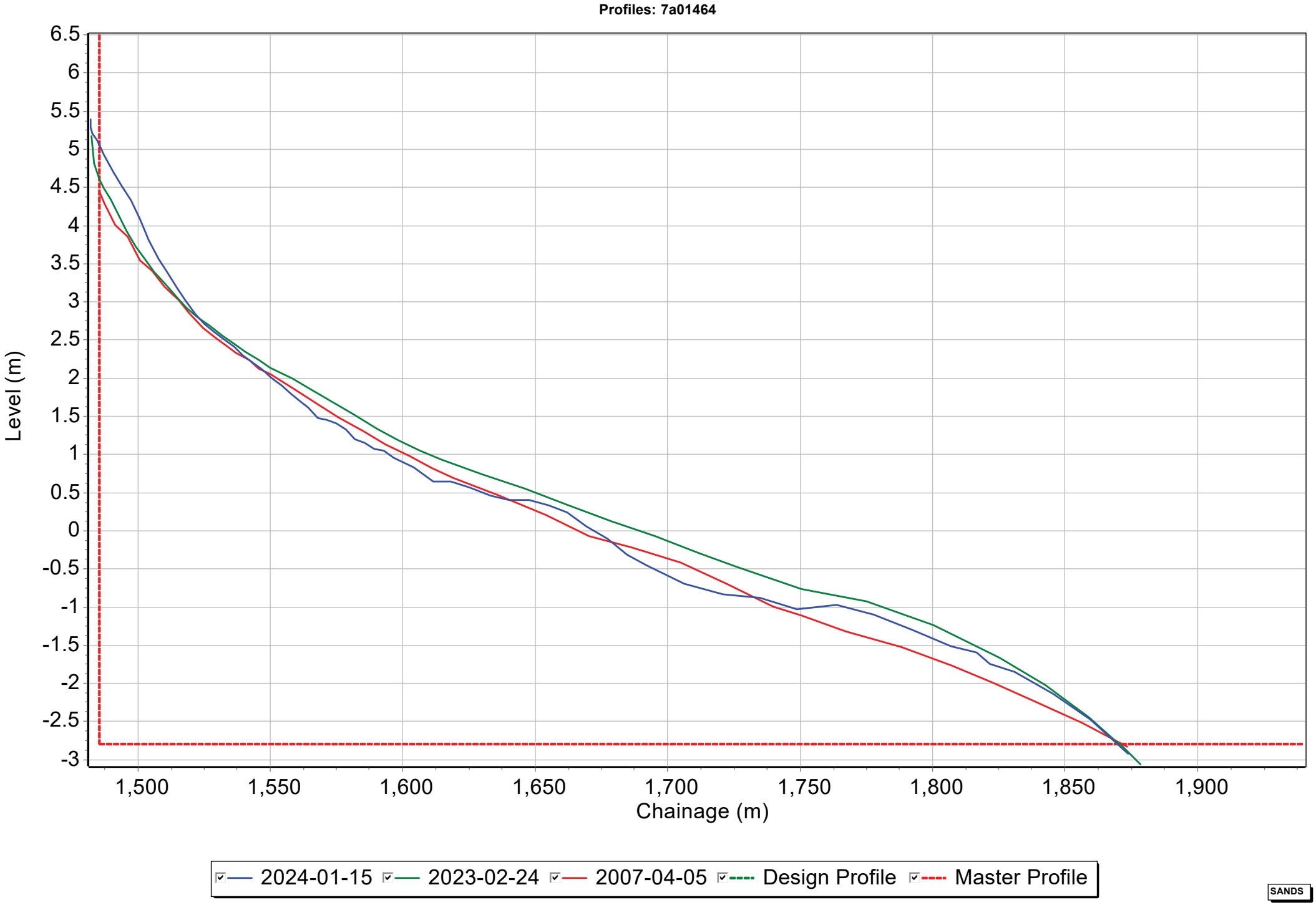
1. Accretion: The net accumulation of deposited sediment, deposited by waves, tides or current.
2. Coastal Morphodynamics: The study of changes in coastal landforms and landscapes over time.
3. Contour Analysis: Mapping of contours from LiDAR datasets to represent Mean Sea Level (MSL) and Dune Toe elevations.
4. Cross-Sectional Area (CSA): The area of a two-dimensional cross-section of a cross-shore beach profile, running between Mean Low Water Spring and the back of the beach.
5. Developed Zone: Areas of urban development built atop previously present dune systems.
6. Difference Modelling: Comparison of separate LiDAR surfaces to produce a difference model of change based on gridded spot height elevations.
7. Digital Elevation Model (DEM) and Digital Terrain Model (DTM): DEM represents the Earth's surface with all features, while DTM represents the bare earth surface, excluding vegetation and structures.
8. Embryo Dune: The earliest stage of dune growth, typically found along the seaward extent of a dune system or newly formed dune.
9. Erosion: The process by which local sea level rise, strong wave action, and coastal flooding wear down or carry away rocks, soils, and sands along the coast.
10. Fixed Zone: Area defined by permanent dune vegetation, including scrub or invasive species, denoting vegetation atop sandy soil.
11. Intertidal Bar: A ridge or mound of sand, gravel, or other sediment deposited in the intertidal zone along a shoreline.
12. LiDAR: Light Detection and Ranging, a remote sensing method that uses light in the form of a pulsed laser to measure variable distances to the Earth.
13. Mean High Water Spring (MHWS): The height of mean high-water springs is the average throughout the year of two successive high waters during those periods of 24 hours when the range of the tide is at its greatest.
14. Mean Low Water Spring (MLWS): The height of the mean low-water springs is the average height obtained by the two successive low waters during the same period.
15. Mobile Zone: The area including the active dune face and embryo dune that is in motion due to wind action or other factors.
16. Root-Mean-Square Error (RMSE): A measure of the differences between values predicted by a model and the observed values.
17. Tidal Range: The vertical difference between high tide and low tide during a tidal cycle.

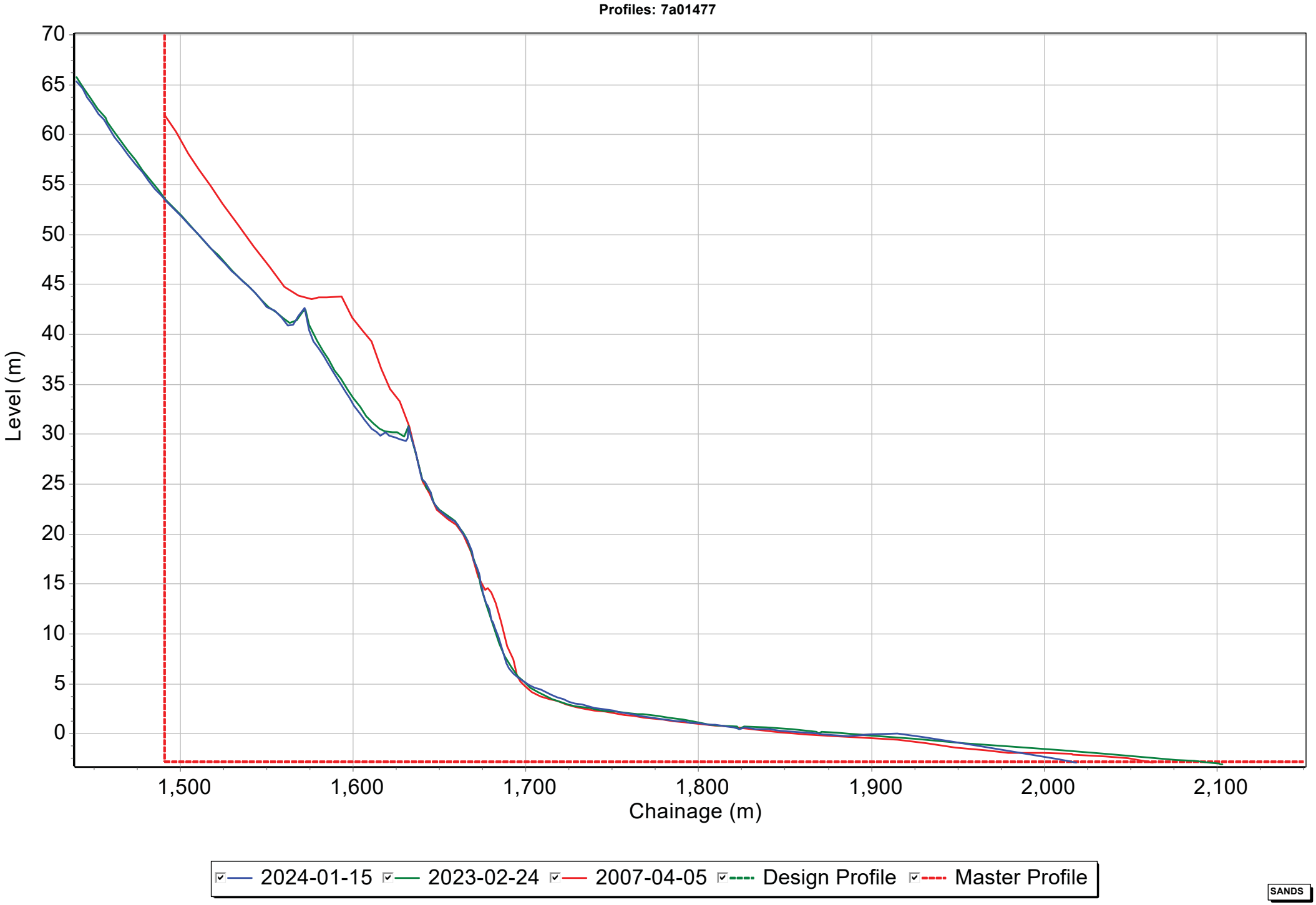
## Appendices

Appendix 1 – Profile charts showing the cross-shore area of each interim profile from the most recent survey (blue), second most recent survey (green) and first survey, also known as the baseline (red) at Penhale are presented below.

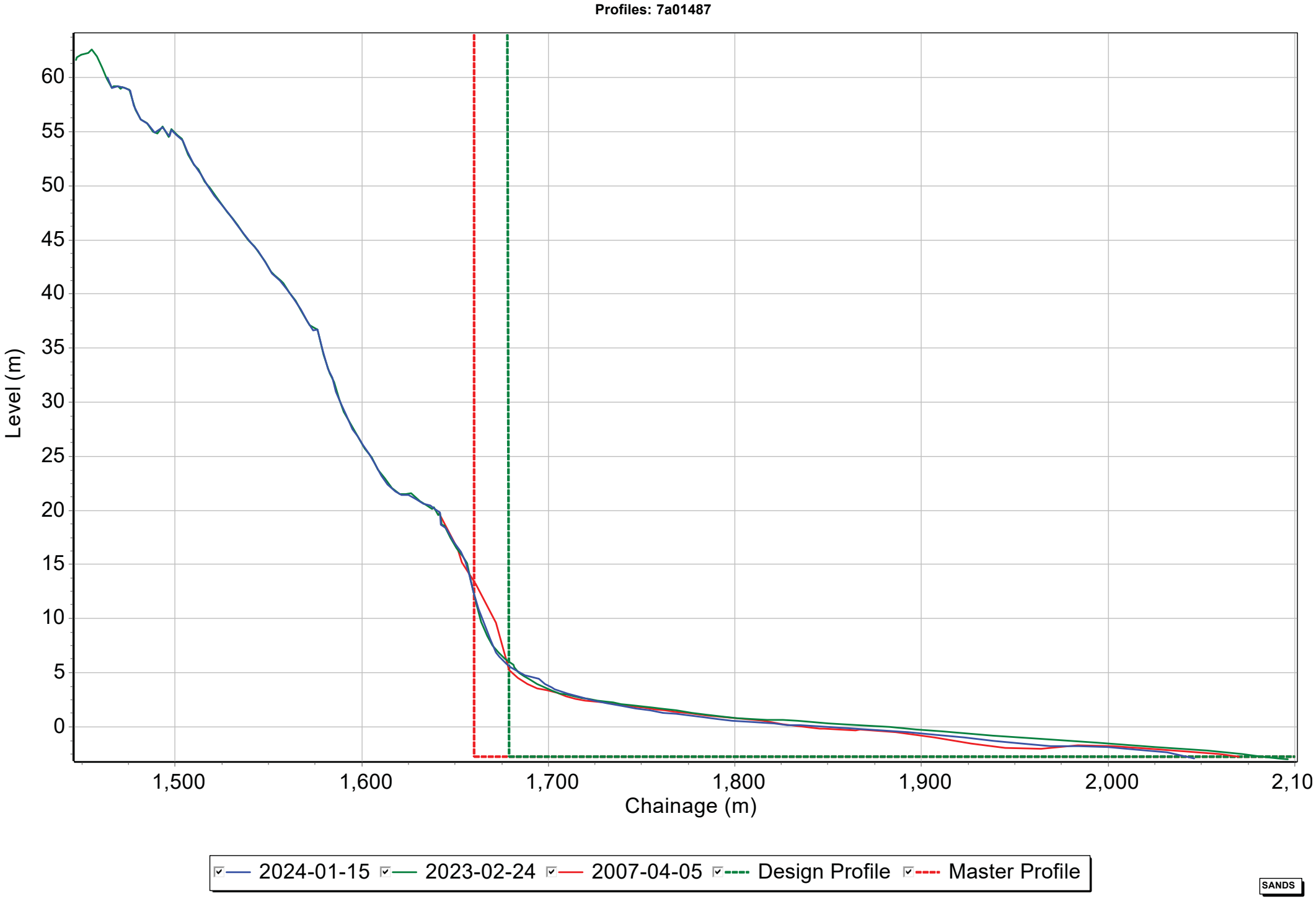

Profiles: 7a01454
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
Level (m)
1,300
1,350
1,400
1,450
1,500
1,550
1,600
1,650
1,70
Chainage (m)
2024-01-15
2023-02-24
2007-04-05
Design Profile
Master Profile

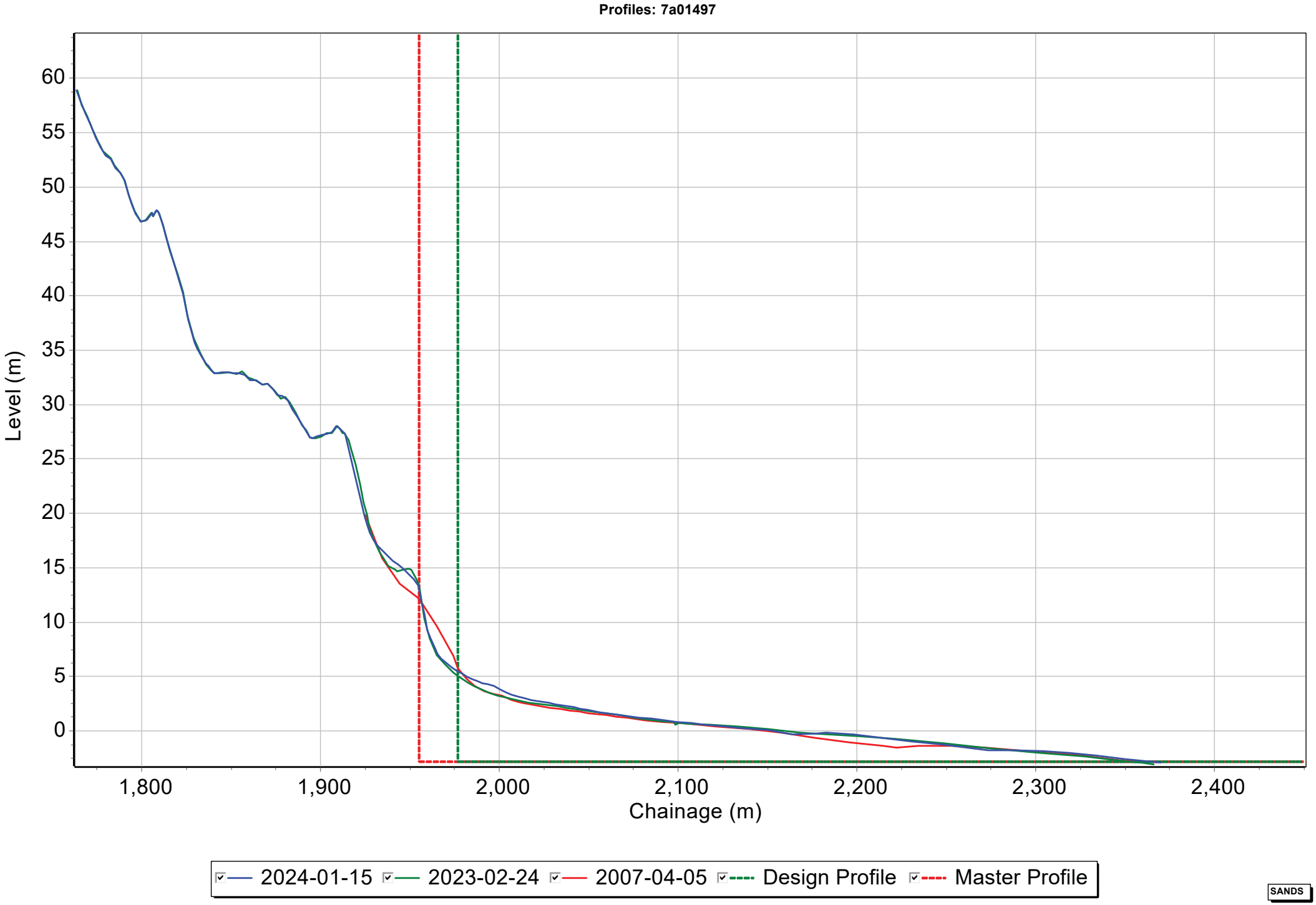
SANDS


Profiles: 7a01464
Level (m)
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
1,500
1,550
1,600
1,650
1,700
1,750
1,800
1,850
1,900
Chainage (m)
2024-01-15
2023-02-24
2007-04-05
Design Profile
Master Profile


Profiles: 7a01477
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
Level (m)
1,500
1,600
1,700
1,800
1,900
2,000
2,100
Chainage (m)
2024-01-15
2023-02-24
2007-04-05
Design Profile
Master Profile

SANDS


Profiles: 7a01487
Level (m)
60
55
50
45
40
35
30
25
20
15
10
5
0
1,500
1,600
1,700
1,800
1,900
2,000
2,10
Chainage (m)
2024-01-15
2023-02-24
2007-04-05
Design Profile
Master Profile


Profiles: 7a01497
Level (m)
60
55
50
45
40
35
30
25
20
15
10
5
0
1,800
1,900
2,000
2,100
2,200
2,300
2,400
Chainage (m)
2024-01-15
2023-02-24
2007-04-05
Design Profile
Master Profile