Roinn Cumarsáide, Gníomhaithe ar son na hAeráide & Comhshaoil
Department of Communications, Climate Action & Environment

Geological Survey
Suirbhéireacht Gheolaíochta
Ireland | Éireann

Research Programme
- Short Calls, Final Report -

Date: Nov 8th 2018

This report covers the period November 1st 2017 to October 31st 2018

2. (a) Project information:

Final project report (*max **2500**words, excluding figures and headings*):

(i) *Progress* of objectives and scientific/engineering targets beyond the state of the art & *methods* used

Objective in section one: Using Sentinel-2 satellite imagery to conduct intertidal zone feature recognition and classification using contemporary image classification algorithms applied within state of the art (GSI licenced) image processing software.

Delivery of objective in section one: This involved an assessment of the potential for Sentinel-2 satellite imagery to be used to conduct intertidal zone feature recognition. Outcomes in section one included, the successful extraction of intertidal feature classes, bathymetric depth-classes and onshore land cover classes; using a GIS-based methodology that runs as a Toolbox in ArcGIS. This Toolbox was developed by Envo-Geo as a re-useable product for GSI to use in any future work that requires it.

Methods used to deliver objective in section one:

- Development of a prototype 'Intertidal Feature Extraction' Toolbox for ArcGIS using ArcGIS Model Builder and Python
- Application of the toolbox, to attempt intertidal feature extraction in two sub-sites within Dublin Bay, namely Bull island and Sandymount beach
- Generation of polygonal features for the intertidal zone later encoded with feature attributes to demonstrate the potential of the approach to generate GIS features, to which a wide range of standard GIS analyses could be potentially applied
- Examination of the potential for the approach to be applied to assess feature stability over short time scales or feature change over longer time scales.

Objective in section two: Conducting shoreline extraction modelling from Sentinel-2 satellite intertidal imagery using SHOREX (both as a standalone research question and complementing the work in task 1).

Delivery of objective in section two: This involved an evaluation of the prospects for conducting accurate shoreline extraction from Sentinel-2 satellite imagery. Outcomes in section two included the accurate extraction of 20 shorelines (representing a range of tidal conditions) from Sentinel-2 images of Dublin bay. Shoreline extraction was carried out using the SHOREX Python toolbox (provided to the INTREPID project by Universidad Polytecnica Valencia). Elevation values were applied to these shorelines using contemporaneous (5-minute resolution) tide heights from the Dublin Port tide gauge (Marine Institute, 2018). The accuracies of these shoreline elevations were validated by GNSS survey, confirming that tide-derived elevation accuracies for the extracted shorelines at 0.3m RMSE. These elevation-encoded shorelines were subsequently used to generate an intertidal DTM product for Bull Island, demonstrating the potential to generate Sentinel-2 derived DTMs elsewhere around the Irish coast.

Methods used to deliver objective in section two:

- Shoreline extraction for the 20 best Sentinel images using SHOREX
- Shorelines extracted from time-stamped Sentinel-2 images were encoded with tide heights from 5-minute tide levels (Malin OD) recorded at the Dublin Port tide gauge
- Shoreline tide-heights were validated relative to GNSS elevation, expressed relative to Malin OD by walking sample sections of each SHOREX-extracted shoreline, using a Trimble R8 Rover, acquiring points in Realtime Kinematic (RTK) mode at an RMSE elevation positioning uncertainty of (RMSE <0.015m & a max elevation error of 0.031m)
- An intertidal Digital Terrain Model was generated from the tide-encoded shorelines, demonstrating the potential to link high temporal-resolution tide height data with shoreline extraction. The approach might be usefully applied for the generation of intertidal DEM products in further Priority bays.

Objective in section three: Assessing the potential for intertidal feature recognition and classification from existing GSI UAS imagery and 3D DSM data, using new approaches developed by Envo-Geo.

Delivery of objective in section three: This involved examining the possibility to undertake intertidal feature recognition and extraction from GSI UAS imagery and its derived DSM and DTM data products. Outcomes in section three included the generation of a re-useable model for the extraction of feature polygons from intertidal, nearshore and terrestrial features from GSI drone survey data. The results demonstrated that this feature extraction approach can derive useful added-value from existing and future GSI drone survey data sets. Potential practical applications for the approach might include coastal erosion quantification, condition monitoring of flood defences, assessment of risk to infrastructure and vulnerabilities of archaeological heritage.

Methods used to deliver objective in section three:

- The UAV survey and data processing was undertaken by GSI staff and was provided (courtesy of Ronan O'Toole, GSI) as DSM, DTM and Normalised Difference Vegetation Index (NDVI) data
- A DSM-DTM difference model was generated, which was used to segregate above-ground from ground-based features
- The NDVI data was used to segregate vegetated from non-vegetated, above-ground and ground-based features
- The vegetated, non-vegetated, above-ground and ground-based classes were then segregated based upon feature height and vegetation / non-vegetation status into seven Meta classes
- These were segmented by elevation of NDVI values to define 24 distinct feature classes which included: 5 tall vegetation classes, 4 built-structures classes, 4 coastal rock-outcrop classes, 2 non-vegetated open-area classes, 4 ground vegetation classes, 4 intertidal vegetation classes, and a single nearshore water feature class.

Objective in section four: Undertaking high-resolution shoreline modelling from GSI UAS DSM data using licenced GIS toolsets.

Delivery of objective in section four: This involved an assessment of the potential to use GSI drone DTM data to validate shorelines derived from Sentinel-2 imagery. Outcomes in section four included the development and initial evaluation of a repeatable methodology that might contribute usefully to any future research on the topic of shoreline extraction for intertidal DTM generation from Sentinel-2 imagery.

Methods used to deliver objective in section four

- Eight cloud-free Sentinel-2 images were identified and downloaded for the drone survey site from within the entire Sentinel-2 image archive
- Manual digitisation of apparent shorelines was carried out for all 8 satellite images to determine the potential to extract shorelines without using SHOREX or Water Indices
- Shoreline vectors were linked to 5-minute tide levels (Malin OD) recorded at the Dunmore East tide gauge
- Shoreline tide-heights were evaluated relative to GSI drone DTM elevation (Malin OD) values.

(ii) Implementation (please include any issues with timelines, milestones, management etc. or deviations from the original implementation plan)

Implementation in section one involved the development of a prototype 'Intertidal Feature Extraction' Toolbox for ArcGIS, implemented as follows:

- The individual 10-metre Sentinel-2 band images are clipped to the spatial extent of the study are
- The Red, Green, Blue and near infrared bands are stacked into a four-band 10-m resolution image
- Iterative Self Organising Data Analysis (ISODATA) clustering is applied, to segment the image
- A majority filter is applied to the clustered image
- Cluster classes are converted to polygon feature objects, to which feature attributes can be attached and to which GIS analyses may be applied
- Generation of feature rasters and polygon feature object shapefiles for the Bull Island and Sandymount test sites.

Implementation in section two involved the application of a newly developed Toolset (developed at, and made available for the INTREDID project by Universidad Polytecnica Valencia) to a macrotidal environment for the first time. Implementation involved the following:

- Shoreline extraction for the 20 best Sentinel images using SHOREX
- Encoding extracted shorelines with 5-minute resolution tide levels (Malin OD) from the Dublin Port tide gauge
- Validation of tide encoded shoreline elevations with GNSS elevation, using long residence time Realtime Kinematic (RTK) survey
- Generation of a prototype intertidal Digital Terrain Model for Bull Island.

Implementation in section three involved the development of a repeatable prototype model for the extraction of intertidal, onshore and nearshore features from GSI (or similar very high-resolution photogrammetric drone data). Implementation involved the following:

- Generation of a height-difference difference model to facilitate segregating above-ground from ground-based features using the GSI drone DSM and DTM data
- Segmentation of vegetated above-ground features, non-vegetated above-ground features, vegetated ground-based features and non-vegetated ground-based features using the GSI drone NDVI data
- Sub-segmentation of these meta-classes by elevation and NDVI values to define 24 distinct feature classes encompassing: 4 coastal rock-outcrop classes, 2 non-vegetated mineral (open-areas) classes, 4 intertidal vegetation classes, 4 terrestrial ground vegetation classes, 5 tall vegetation classes, 4 built-structures classes and a single nearshore water feature class
- Generation of feature raster layers and a 24-feature polygon object shapefile for the Bunmahon drone data survey area.

Implementation in section four involved the following:

- Identification and download of all extant cloud-free Sentinel-2 images for the drone survey site
- Manual digitisation of apparent shorelines from cloud-free Sentinel-2 images to assess the potential of a rapid shoreline extraction approach
- Encoding shoreline vectors with 5-minute resolution tide levels (Malin OD) from the Dunmore East tide gauge
- Comparison of shoreline tide-heights relative to GSI drone DTM elevation (Malin OD) values.

(iii) Outputs (please provide a short description *and* complete the table below)

Outputs in section one

- A prototype 'Intertidal Feature Extraction' Toolbox for ArcGIS
- A repeatable methodology for Intertidal Feature Extraction from Sentinel-2 satellite imagery
- A demonstration of Intertidal feature extraction mapping from Sentinel-2 imagery, producing re-suable intertidal, nearshore and onshore feature mapping for Bull Island and Sandymount.

Outputs in section two

- A proven methodology that can be implemented for shoreline extraction from Sentinel-2 satellite imagery in macrotidal locations
- A prototype intertidal Digital Terrain Model (DTM) product for Bull island, constructed from the tide-level encoded (and GNSS validated) Sentinel-2 shorelines.

Outputs in section three

- A repeatable desktop-GIS based methodology for feature extraction from GSI drone data, utilising drone imagery and drone DTM data inputs
- An onshore, intertidal and nearshore feature extraction (shapefile) data set for Bunmahon, county Waterford.

Outputs in section four

- An initial evaluation of the potential to use drone DEM data to evaluate the accuracy of Sentinel-2 shoreline extraction.

Task No.	Deliverable description	Planned delivery (as per proposal)	Date of delivery
1	S-2 intertidal feature classification	Start of April 2018	As scheduled
2	S-2 shoreline extraction	Start of June 2018	As scheduled
3	Drone shoreline extraction	Start of July 2018	As scheduled
4	Drone intertidal feature classification	Middle of August 2018	October 2018

Publications to date: *(digital copies of these are included in the data disk submitted with the technical report)*

Coveney, S. Butler, D., Monteys, X., O'Toole, R., Pardo-Pascual, J. and Almonacid-Caballer, J. (2018) Intertidal Feature Mapping from Sentinel and Drone (INTREPID), *Geoscience 2018*, Dublin Castle, Ireland, 06-NOV-18

Coveney, S. Butler, D., Monteys, X., O'Toole, R. (2018), Intertidal Feature Mapping from Sentinel and Drone (INTREPID), *Geological Survey Ireland Short Call project no. 2017-sc-031,* Geological Survey of Ireland. Unpublished Report

Coveney, S. (2018), Intertidal Feature Mapping from Sentinel-2 satellite imagery and GSI Drone imagery and 3D data, INFOMAR 2018, Trident Hotel, Kinsale Ireland, 09-NOV-18.

4. Data/outputs submitted with final report *(please list the documents, presentations, datasets etc. submitted with this report)*

Documents

a. Technical report
b. Final financial and activity report

Presentations

a. INFOMAR presentation
b. Geoscience Poster

Data

a. Section 1 data
b. Section 2 data
c. Section 3 data
d. Section 4 data

Toolsets and Model Diagrams

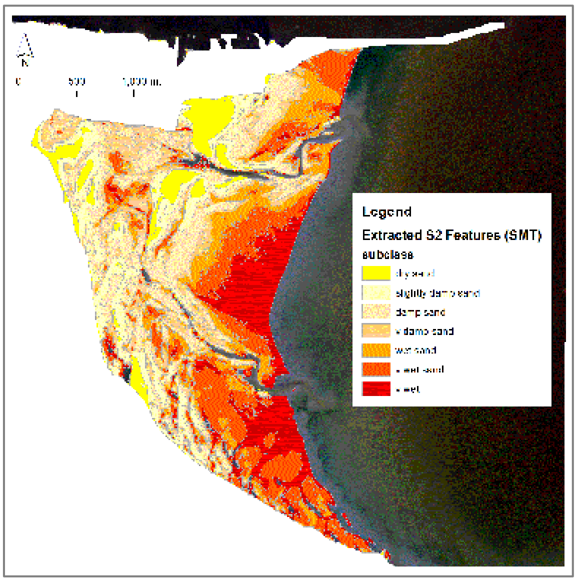
a. Intertidal satellite Toolbox
b. Intertidal and coastal drone feature extraction Data Flow Diagram
c. Intertidal (satellite image) feature extraction Data Flow Diagram.

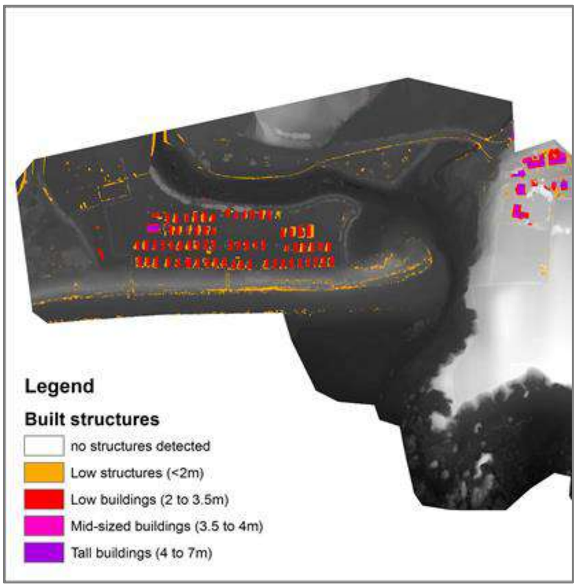
SUPPLEMENTARY MATERIAL

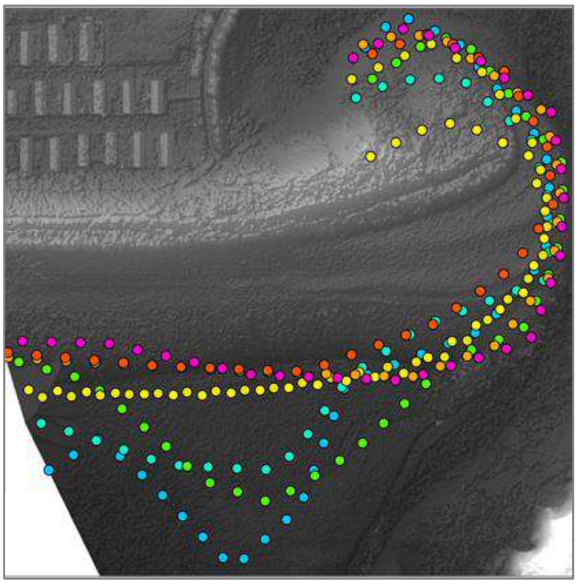
(This section will be included in your published report unless otherwise instructed. If you have a published report, publication, etc. you may include it here).

Intertidal Feature Mapping from Sentinel and Drone (INTREPID)

2017-SC-031







Acknowledgement: This project was funded by GSI within the 2017 Short Call funding scheme.

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Intertidal Feature Mapping from Sentinel and Drone (INTREPID)

2017-SC-031

Project participants:

Dr Seamus Coveney & Damien Butler (Envo-Geo Environmental Geoinformatics)

Xavier Monteys & Ronan O'Toole (GSI INFOMAR)

Josep Pardo-Pascual & Jaime Almonacid-Caballer, Universidad Polytecnica Valencia.

Project lead: Dr Seamus Coveney (Envo-Geo Environmental Geoinformatics)

Acknowledgement: This project was funded by GSI within the 2017 Short Call funding scheme.

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Executive Summary

The study was undertaken in, and is reported here in four sections. These address the four strategic aims established at the outset of the INTREPID project.

Section one assessed the potential for Sentinel-2 satellite imagery to be used to conduct intertidal zone feature recognition. Outcomes in section one included, the successful extraction of intertidal feature classes, bathymetric depth-classes and onshore land cover classes; using a GIS-based methodology that runs as a Toolbox in ArcGIS. This Toolbox was developed by Envo-Geo as a re-useable product for GSI to use in any future work that requires it.

Section two evaluated the prospects for conducting accurate shoreline extraction from Sentinel-2 satellite imagery. Outcomes in section two included the accurate extraction of 20 shorelines (*representing a range of tidal conditions*) from Sentinel-2 images of Dublin bay. Shoreline extraction was carried out using the SHOREX Python toolbox (*provided to the INTREPID project by Universidad Polytecnica Valencia*). Elevation values were applied to these shorelines using contemporaneous (5-minute resolution) tide heights from the Dublin Port tide gauge (Marine Institute, 2018). The accuracies of these shoreline elevations were validated by GNSS survey, confirming that tide-derived elevation accuracies for the extracted shorelines at 0.3m RMSE. These elevation-encoded shorelines were subsequently used to generate an intertidal DTM product for Bull Island, demonstrating the potential to generate Sentinel-2 derived DTMs elsewhere around the Irish coast.

Section three examined the possibility to undertake intertidal feature recognition and extraction from GSI UAS imagery and its derived DSM and DTM data products. Outcomes in section three included the generation of a re-useable model schema for the extraction of feature polygons from intertidal, nearshore and terrestrial features from GSI drone survey data. The results demonstrated that this feature extraction approach can derive useful added-value from existing and future GSI drone survey data sets. Potential practical applications for the approach might include coastal erosion quantification, condition monitoring of flood defences, assessment of risk to infrastructure and vulnerabilities of archaeological heritage.

Section four assessed the potential to use GSI drone DTM data to validate shorelines derived from Sentinel-2 imagery. Outcomes in section four included the development and initial evaluation of a repeatable methodology that might contribute usefully to any future research on the topic of shoreline extraction for intertidal DTM generation from Sentinel-2 imagery.

The four strategic aims of the INTREPID project inform the four sections of this report, listed below as was outlined in the INTREPID proposal.

1. Using Sentinel-2 satellite imagery to conduct intertidal zone feature recognition and classification using contemporary image classification algorithms applied within state of the art (GSI licenced) image processing software
2. Conducting shoreline extraction modelling from Sentinel-2 satellite intertidal imagery using SHOREX (both as a standalone research question and complementing the work in task 1)
3. Assessing the potential for intertidal feature recognition and classification from existing GSI UAS imagery and 3D DSM data, using new approaches developed by Envo-Geo
4. Undertaking high-resolution shoreline modelling from GSI UAS DSM data using licenced GIS toolsets.

SECTION 1 - Intertidal zone feature recognition and classification from Sentinel-2 imagery

We have developed a new 'Intertidal Feature Extraction' Toolbox for ArcGIS, which generates GIS-format polygonal intertidal features from Sentinel-2 satellite imagery. The modelling tools that the Toolbox implements can also be run as a step-wise process using existing ArcGIS Geoprocessing tools (*schematised in Figure 1.2*). We applied the 'Intertidal Feature Extraction' toolset to generate Sentinel-2 intertidal feature extraction mapping for Dublin Bay, subsequently assessing the potential for the intertidal feature extraction approach to be repeated reliably over short time scales; and to assess intertidal feature change over longer time-scales.

1.1 Methodological approach

- Development of a new 'Intertidal Feature Extraction' Toolbox for ArcGIS using ArcGIS Model Builder and Python (Figure 1.1). The geoprocessing workflow is itemised in schematic form in (Figure 1.2)
- Application of the toolbox, to attempt intertidal feature extraction in two sub-sites within Dublin Bay, namely Bull island and Sandymount beach (Figure 1.3)
- Generation of polygonal features for the intertidal zone (Figures 1.4 & 1.5) later encoded with feature attributes (Table 1.1) to demonstrate the potential of the approach to generate GIS features, to which a wide range of standard GIS analyses could be potentially applied.
- Examination of the potential for the approach to be applied to assess feature stability over short time scales (Figure 1.5) or feature change over longer time scales (Figure 1.6).

1.2 Summary of the algorithm operation *(schematised in figure 1.2)*

- The individual 10-metre Sentinel-2 band images are clipped to the spatial extent of the study are
- The Red, Green, Blue and near infrared bands are stacked into a four-band 10-m resolution image
- ISODATA (iterative Self Organising Data Analysis) clustering is applied, to segment the image
- A majority filter is applied to the clustered image
- Cluster classes are converted to polygon feature objects, to which feature attributes can be attached and to which GIS analyses may be applied.

1.3 Deliverable products

- A new 'Intertidal Feature Extraction' Toolbox for ArcGIS
- A repeatable methodology (Figure 1.2) for Intertidal Feature Extraction from Sentinel-2 satellite imagery
- A demonstration of Intertidal feature extraction mapping from Sentinel-2 imagery, producing re-suable intertidal, nearshore and onshore feature mapping for Bull island and Sandymount (Figures 1.4, 1.5 & 1.6)

1.4 Summary conclusions

Feature extraction from Sentinel -2 imagery offers potential for application to further INFOMAR Priority bays. The 'Intertidal Feature Extraction' Toolbox developed for ArcGIS is re-usable, and could potentially form a basis for subsequent application within future GSI projects.

Figure 1.1: Implementation of the model as a new Intertidal Classification Toolbox in ArcGIS.

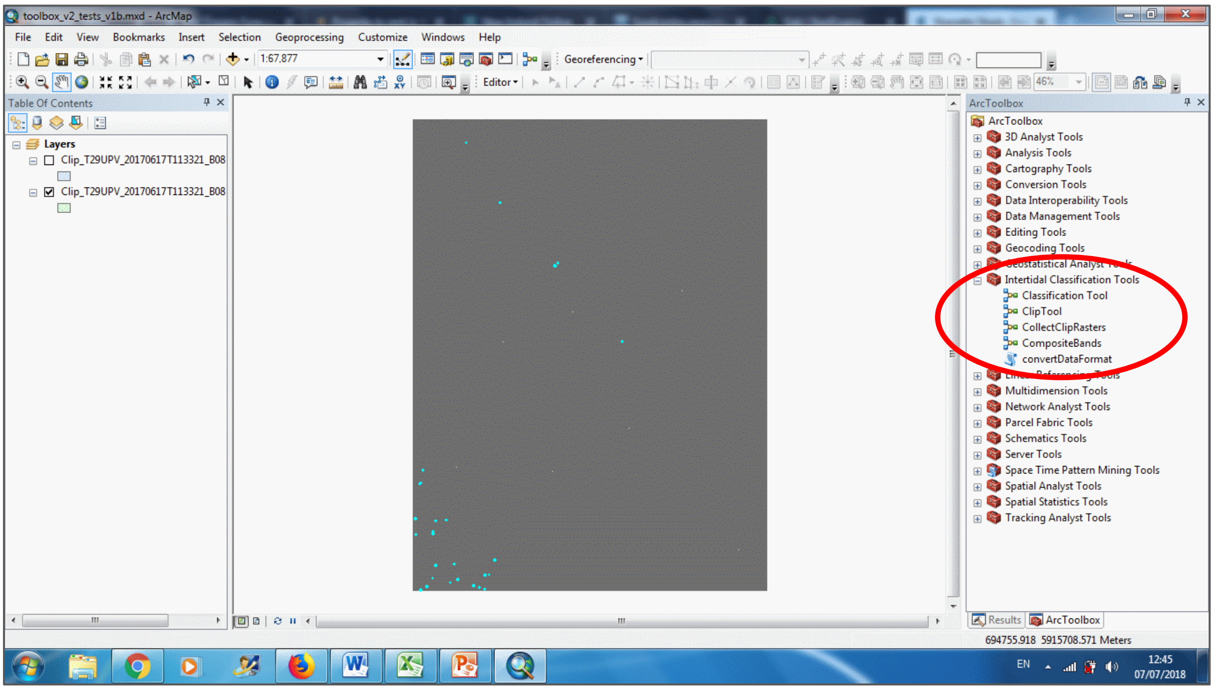


Figure 1.2: Sentinel-2 satellite image feature extraction model

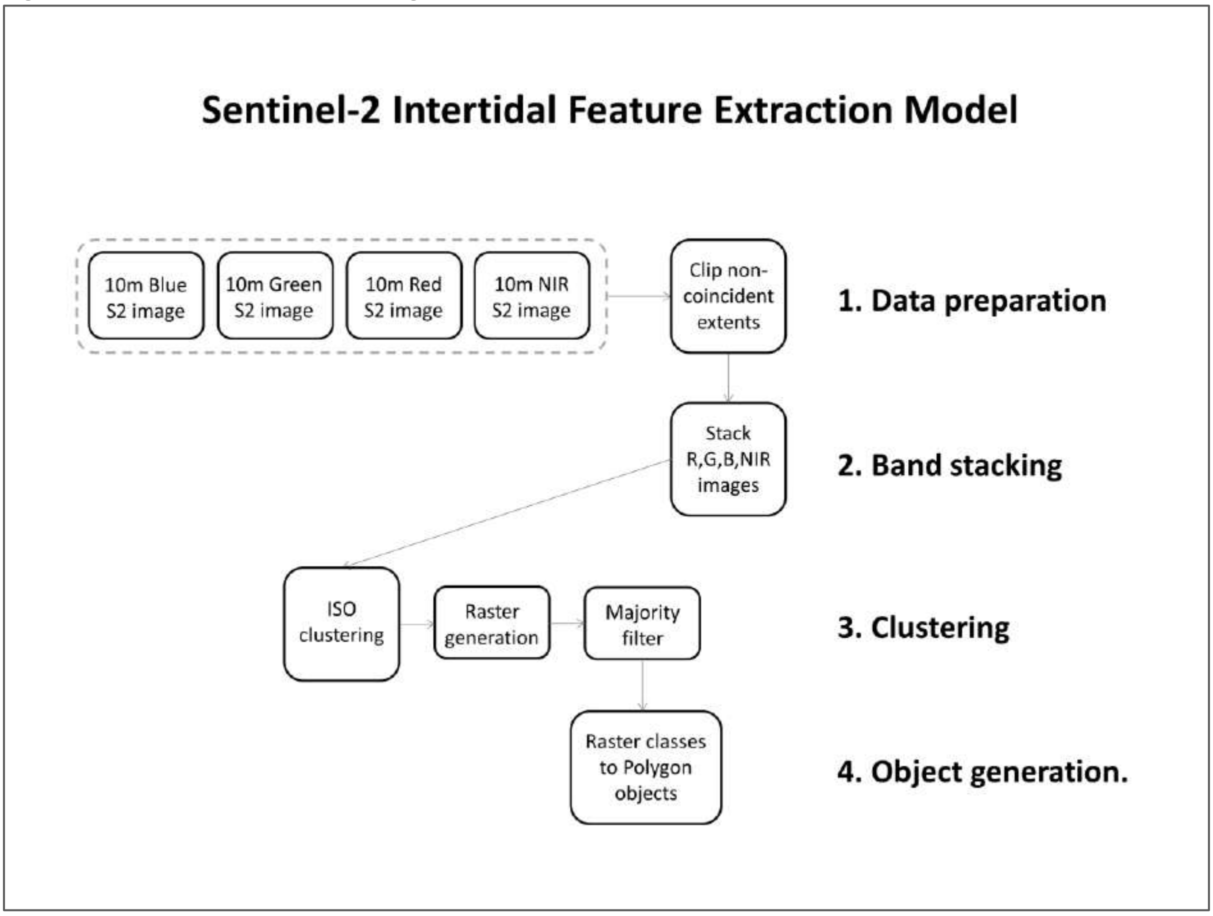


Figure 1.3: Location of study areas within Dublin Bay

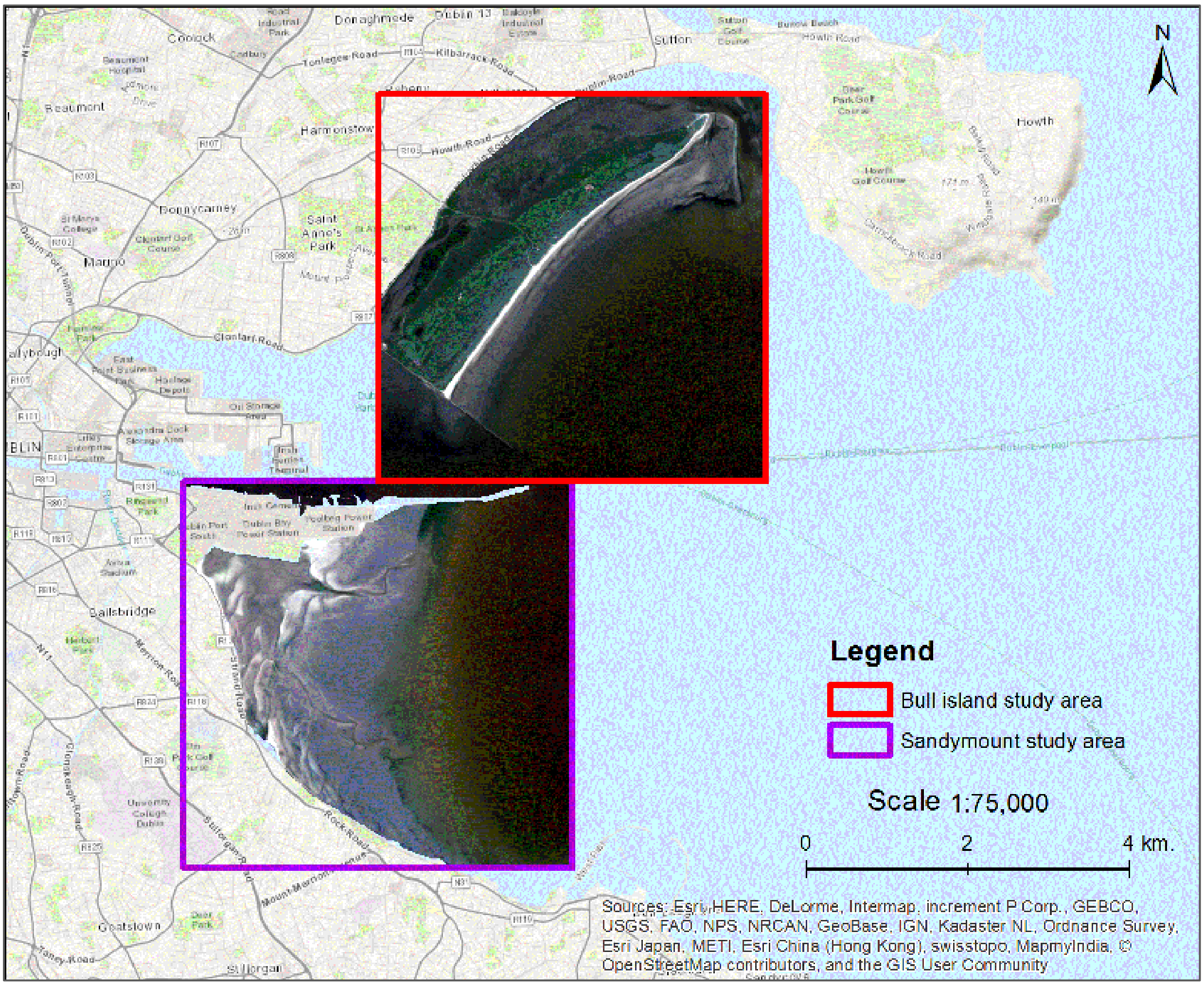


Table 1.1: Sentinel-2 images used for feature extraction

Date	Time	Filename	Sat	Dublin Port Malin (m)	Dublin Port LAT (m)
17/07/17	11:33:21	S2A_MSIL2A_20170717T113321_N0205_R080_T29UPV_20170717T113326	S2A	-1.334	1.48
25/02/18	11:43:51	S2A_MSIL2A_20180225T114351_N0206_R123_T29UPV_20180225T170025	S2A	-1.111	1.70
17/06/17	11:33:21	S2A_MSIL2A_20170617T113321_N0205_R080_T29UPV_20170617T113319	S2A	-1.071	1.81
27/12/17	11:45:01	S2A_MSIL2A_20171227T114501_N0206_R123_T29UPV_20171227T135533	S2A	-1.014	1.81
12/11/17	11:43:39	S2B_MSIL1C_20171112T114339_N0206_R123_T29UPV_20171112T133854	S2B	-0.856	1.96
24/03/18	11:33:21	S2A_MSIL2A_20180324T113321_N0206_R080_T29UPV_20180324T115416	S2A	-0.816	1.99

1.5 Assessment of Feature Extraction outputs

Analysis of model outputs involved three components:

1. A general assessment of model outputs to determine if coherent intertidal features could be extracted from Sentinel-2 images using the Intertidal Feature extraction toolbox
2. An initial determination of the potential for intertidal feature extraction results to be repeated over short time-scales, by comparing feature extraction outputs derived from Sentinel-2 images that were acquired within approximately one month of one another
3. To make a preliminary evaluation of the extent to which intertidal feature extraction might be used to highlight quantifiable changes of intertidal features that have been extracted from Sentinel-2 images acquired across longer time periods.

1.5.1 Examination of model performance

The best quality cloud-free image (*acquired on 17/06/2017*) was used to make an initial examination of model performance for Bull Island (Figure 1.4) and Sandymount (Figure 1.5). Twenty-five feature classes were extracted from the Bull island image (Table 1.2), which included four onshore classes, six intertidal (beach) feature classes, 11 nearshore (water-depth inference) classes and four offshore depth-inference classes. Nineteen feature classes were extracted from the Sandymount image (Table 1.3), which included seven intertidal (beach) feature classes, seven nearshore (water-depth inference) classes and five offshore depth-inference classes. The outcomes suggest from Bull Island and Sandymount suggested that Sentinel-2 imagery offers definite potential for the automated feature extraction within the intertidal, nearshore and onshore coastal domains.

The Feature extraction model was applied to a further Sentinel-2 image (*acquired on 17/07/2017*) to determine if the same features were detectable on images acquired of the Bull island test site on nearby dates (Figure 1.6). This later application of the feature extraction model for Bull island highlighted very similar features (Figure 1.6), suggesting the approach is repeatable, and may be used to track feature changes, over short-term time scales. The model is available as an ArcGIS Toolbox, so it will be possible to further evaluate this in any future GSI work that may require it.

The model was then run on a Sentinel-2 image acquired 8 months later (*image acquired on 25/02/2018*) focusing this time at the Sandymount site (Figure 1.7). This late-winter image provided an opportunity to assess the potential for the model to highlight intertidal feature changes either end of a winter season. The same major intertidal drainage and sandbar features were evident in the feature extraction output for June 2017 (Figure 1.7b) and February 2018 (Figure 1.7b and 1.7d) providing further evidence of model repeatability. However, additional subtle, but definite changes were evident at the exit points of each of the two major drainage channels in the Sandymount images, indicating that the feature extraction model might be usefully applied to assess intertidal feature changes over inter-seasonal timescales.

Figure 1.4: Initial analysis of the Feature Extraction algorithm at the Bull island test site (Sentinel-2 image date 17/06/2017, coincident with a tide level of -1.071 Malin OD at Dublin Port tide gauge.

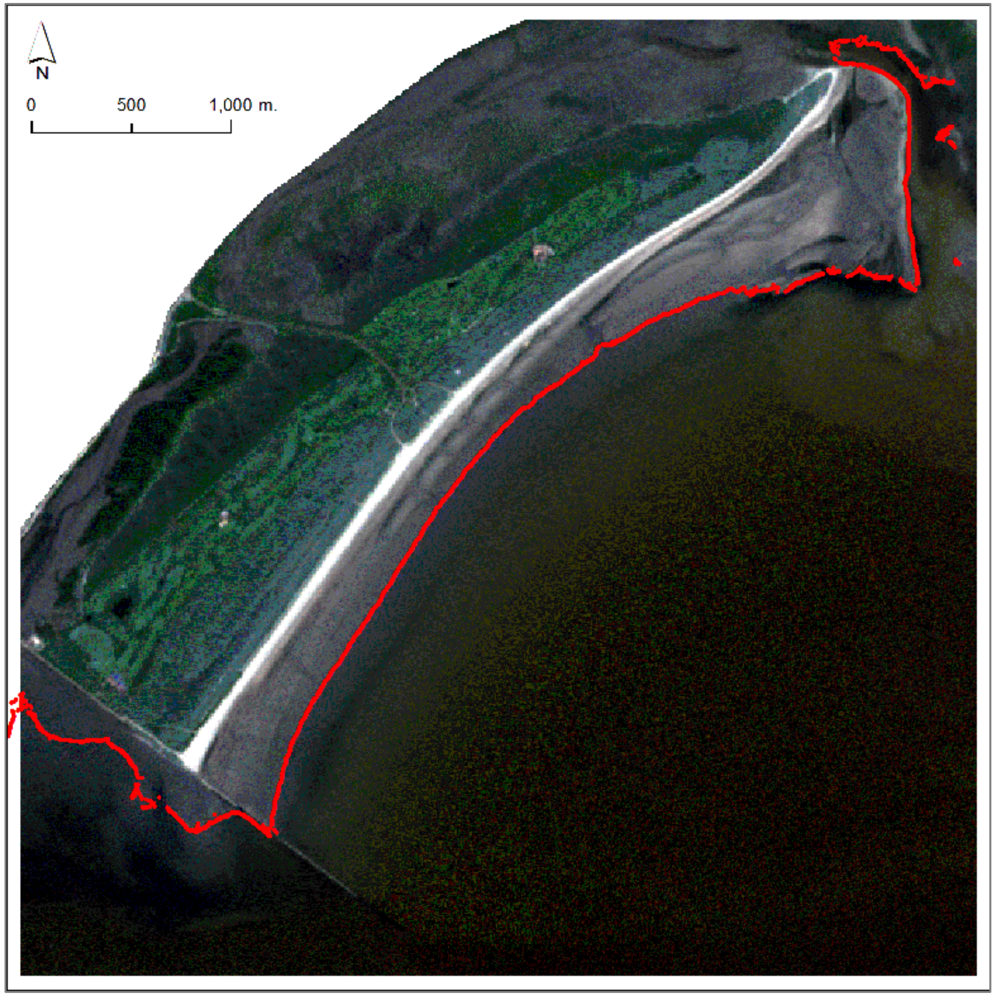


Fig 1.4 (a): Bull island S2 image composite (R,G,B,NIR) 17/06/2017

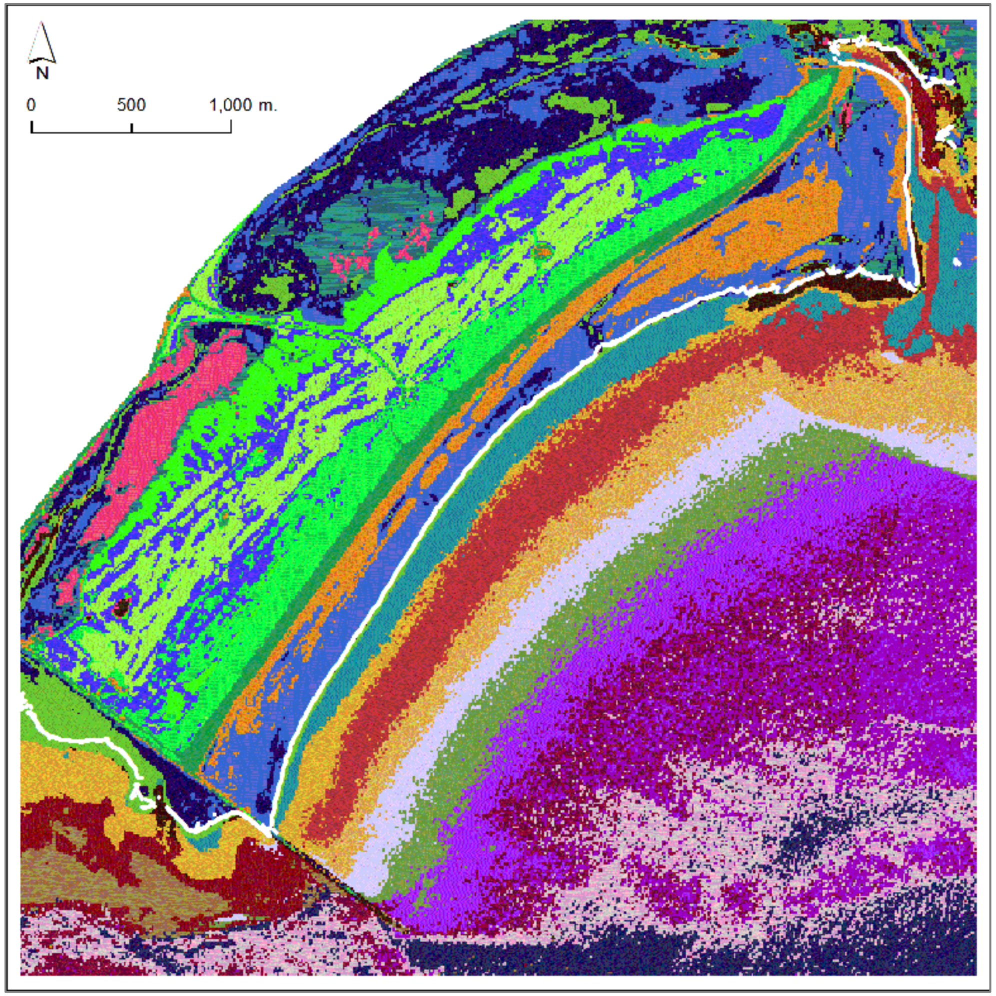


Fig 1.4(b): Bull island ISO Cluster classes (25) of S2 image composite (R,G,B,NIR) 17/06/2017

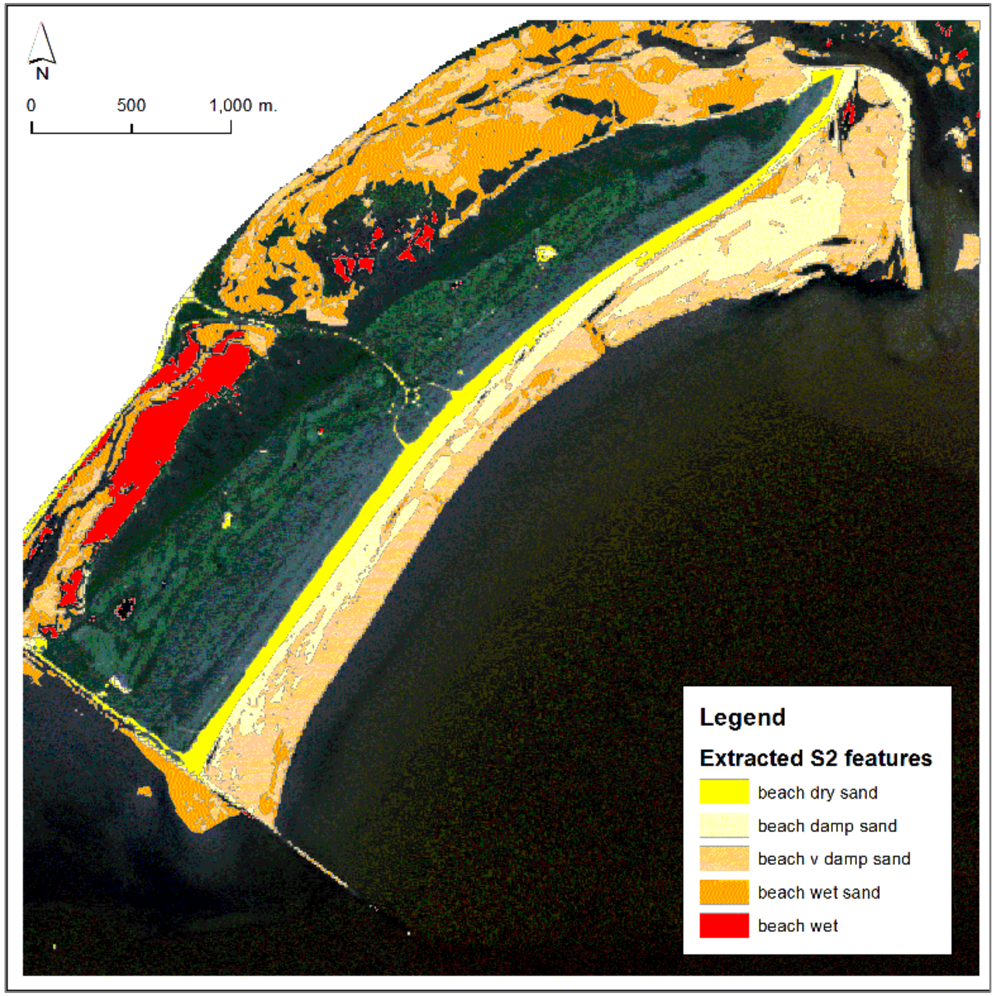


Fig 1.4(c): Bull island S2 image ISO Cluster Dry Intertidal Polygon Features 17/06/2017

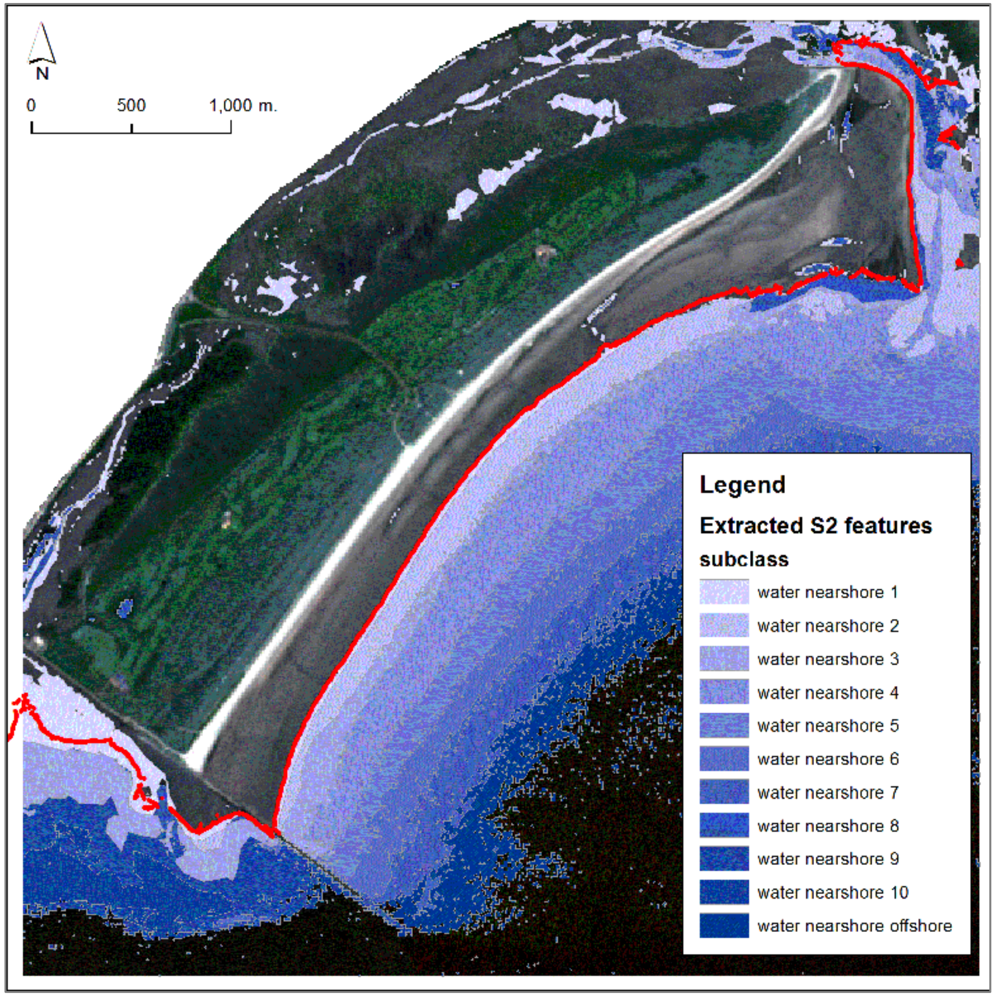


Fig 1.4(d): Bull island S2 image ISO Cluster Nearshore depth-apparent Polygon Features 17/06/2017

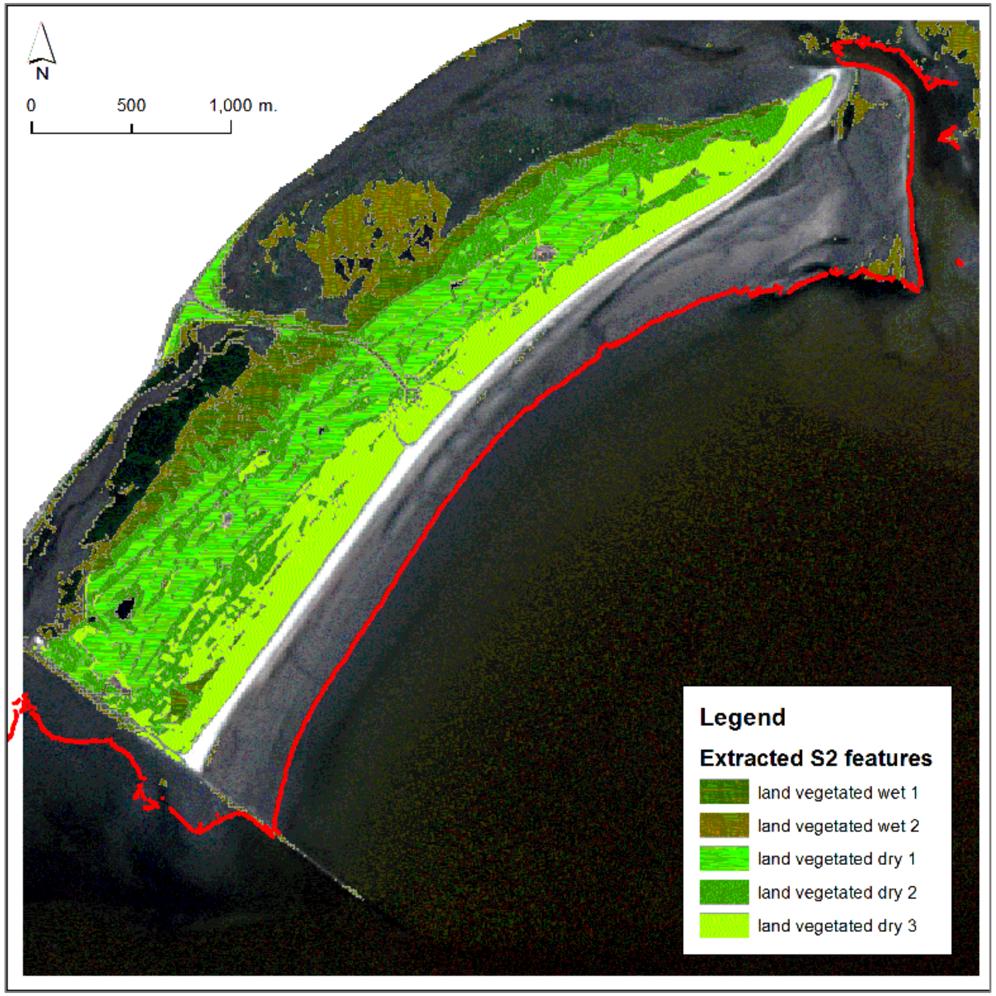


Fig 1.4(e): Bull island S2 image ISO Cluster Dry Onshore Polygon Features 17/06/2017

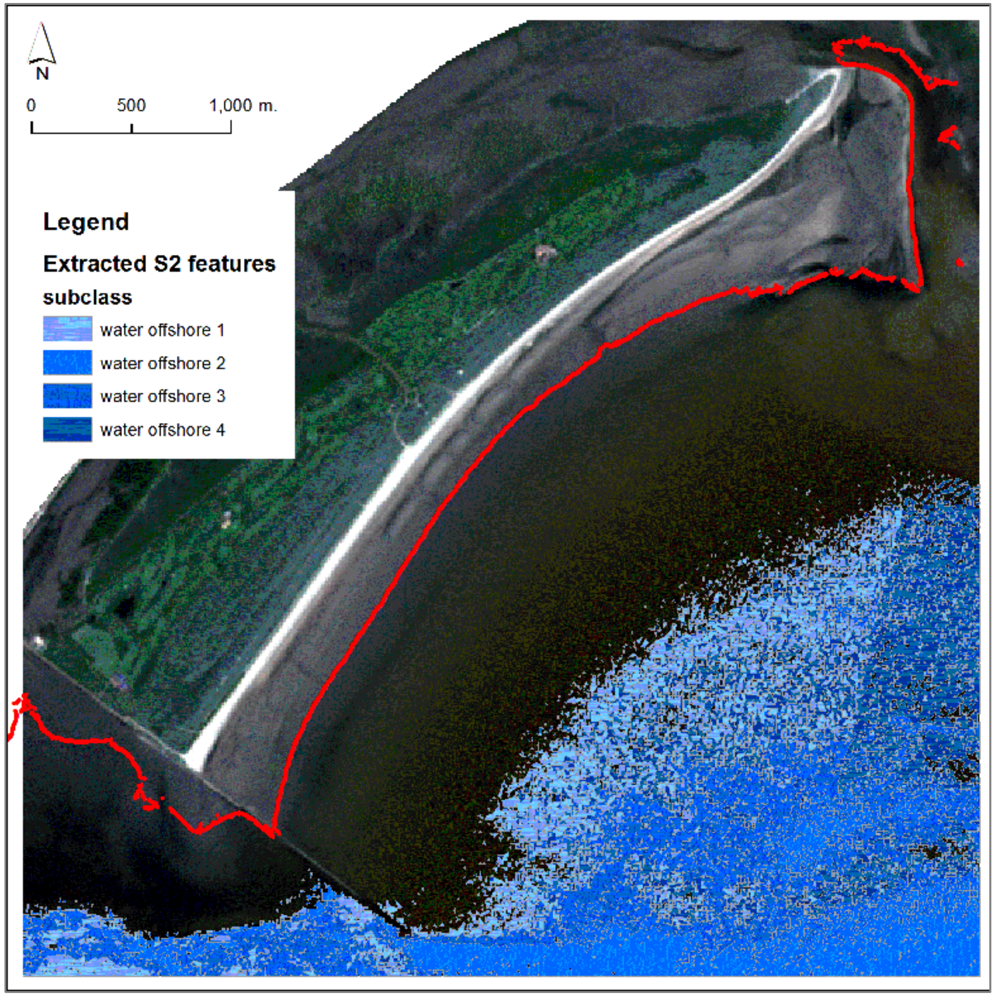


Fig 1.4(f): Bull island S2 image ISO Cluster Offshore possible depth-related Polygon Features 17/06/2017

Table 1.2: Polygon Feature attributes for **Bull island** study sub-area 17/06/2017

Id	Gridcode	Class	subclass	Area_Ha
1	0	Beach	beach wet sand	125.64
2	1	Water	water offshore 1	113.61
3	2	Water	water offshore 2	87.74
4	3	Water	water nearshore 6	65.95
5	4	Land	land vegetated dry 1	91.26
6	5	Water	water nearshore 8	22.40
7	6	Water	water nearshore 9	40.46
8	7	Water	water nearshore 3	62.05
9	8	Beach	beach dry sand	39.30
10	9	Beach	beach wet	29.88
11	10	Land	land vegetated wet 1	52.62
12	11	Land	land vegetated dry 2	90.52
13	12	Water	water nearshore 10	26.62
14	13	Water	water nearshore 5	87.68
15	14	Land	land vegetated dry 3	98.14
16	15	Beach	beach v damp sand	149.85
17	16	Water	water nearshore 1	62.71
18	17	Water	water nearshore 4	105.71
19	18	Water	water nearshore offshore	110.71
20	19	Water	water nearshore 2	73.52
21	20	Beach	beach damp sand	78.71
22	21	Water	water offshore 3	156.51
23	22	Water	water offshore 4	138.76
24	23	Water	water nearshore 7	73.93
25	24	Beach	land vegetated wet 2	54.69

Figure 1.5 (overleaf) assesses model performance at the Sandymount test site. Please refer to discussion in section 1.5.1 when viewing Figure 1.5.

Figure 1.5: Initial analysis of the Feature Extraction algorithm at the Sandymount test site (Sentinel-2 image date 17/06/2017, coincident with a tide level of -1.071 Malin OD at the Dublin Port tide gauge.

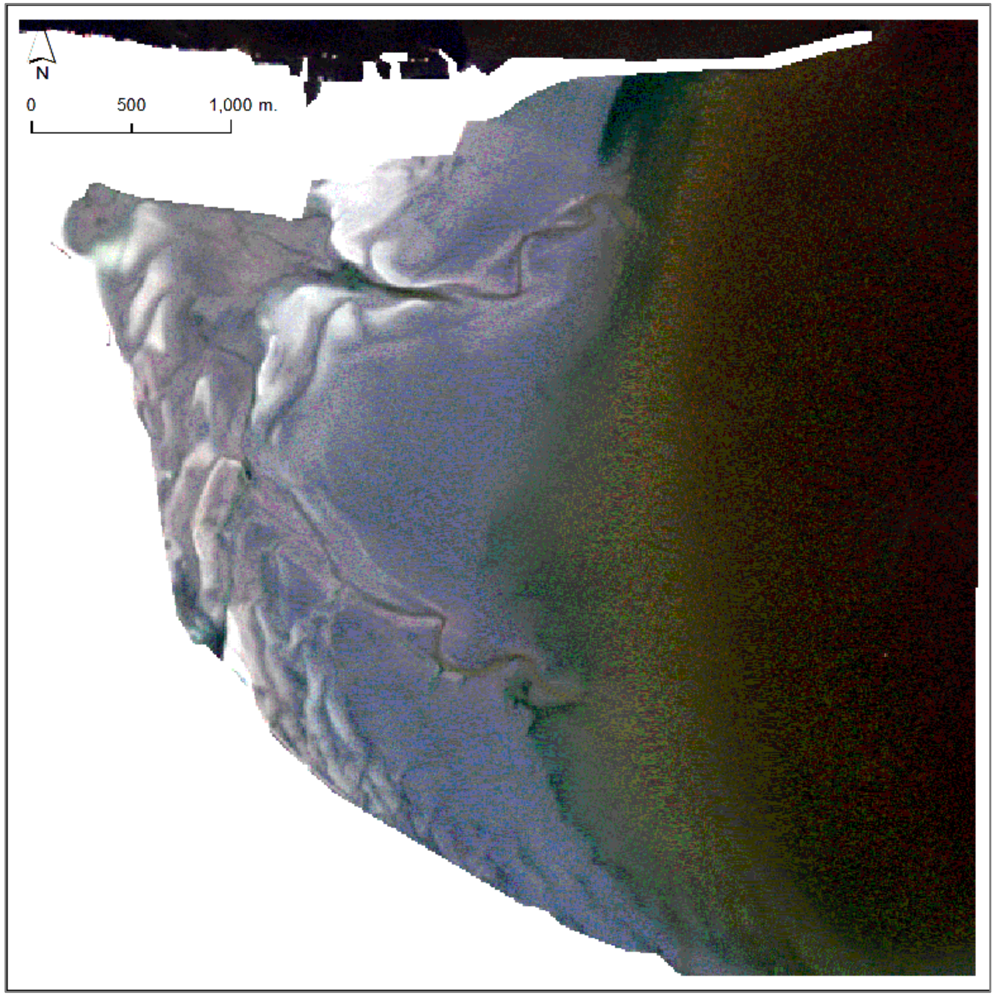


Fig 1.5(a): Sandymount S2 image composite (R,G,B,NIR) 17/06/2017

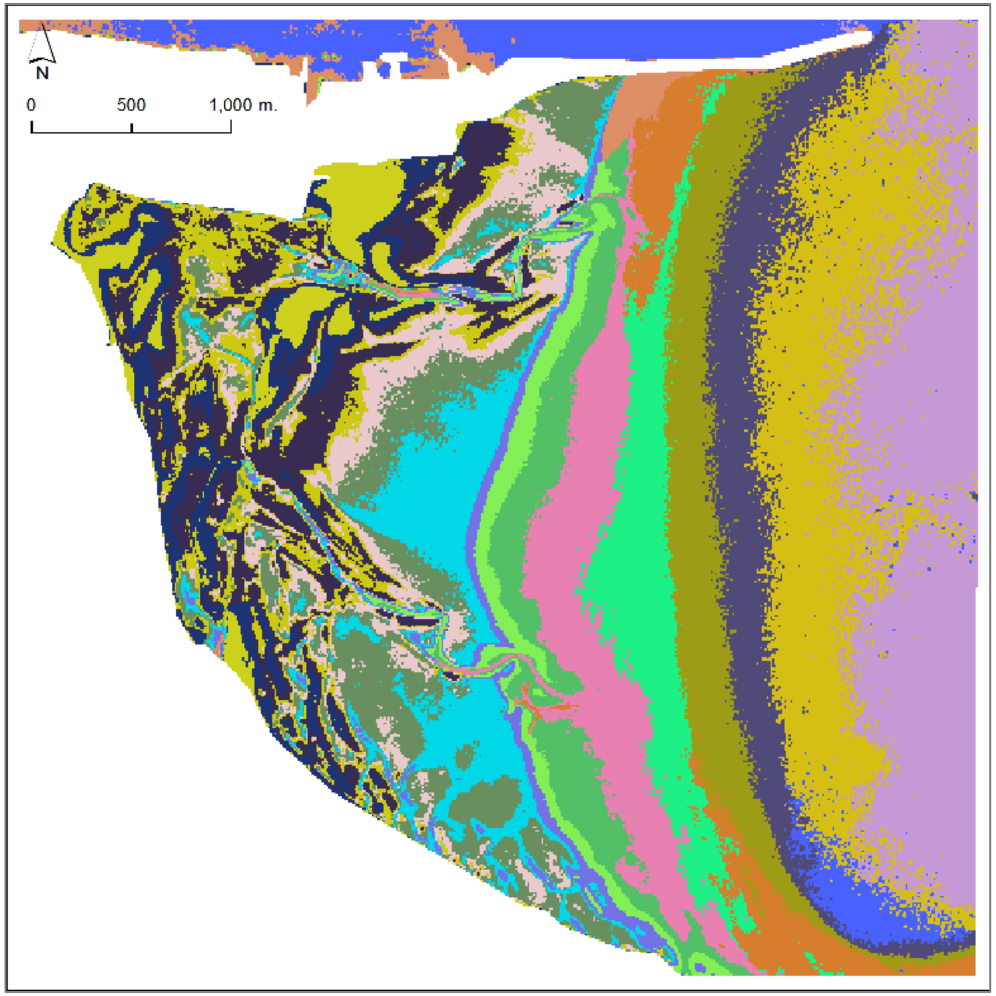


Fig 1.5(b): Sandymount ISO Cluster classes (25) of S2 image composite (R,G,B,NIR) 17/06/2017

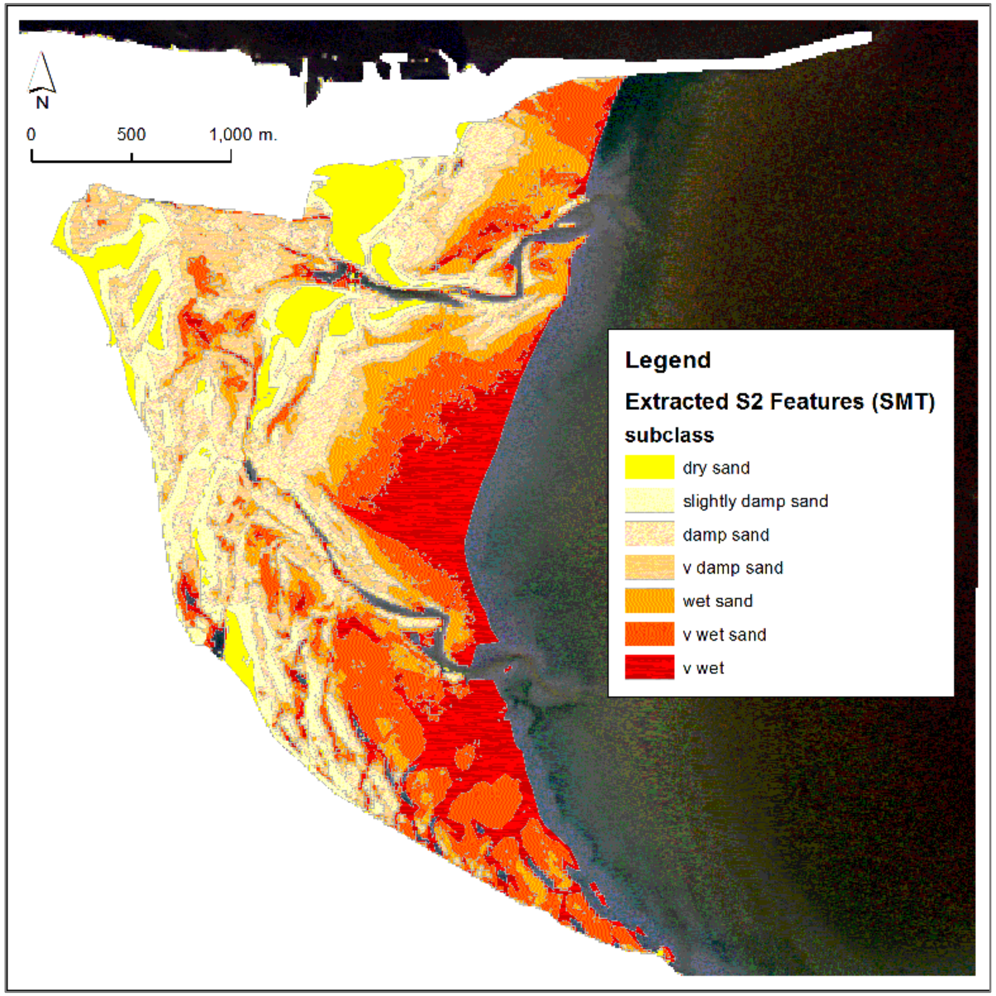


Fig 1.5(c): Bull island S2 image ISO Cluster Dry Intertidal Polygon Features 17/06/2017

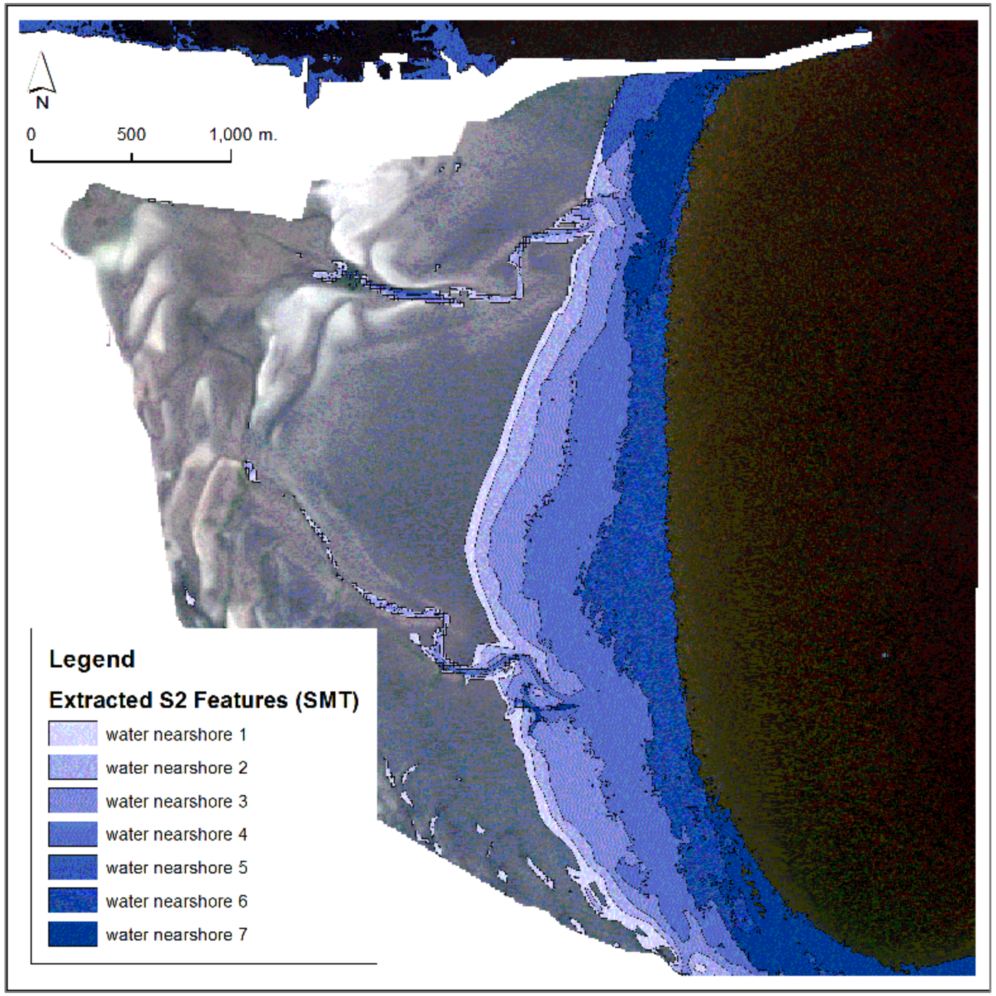


Fig 1.5(d): Sandymount S2 image ISO Cluster Nearshore depth-apparent Polygon Features 17/06/2017

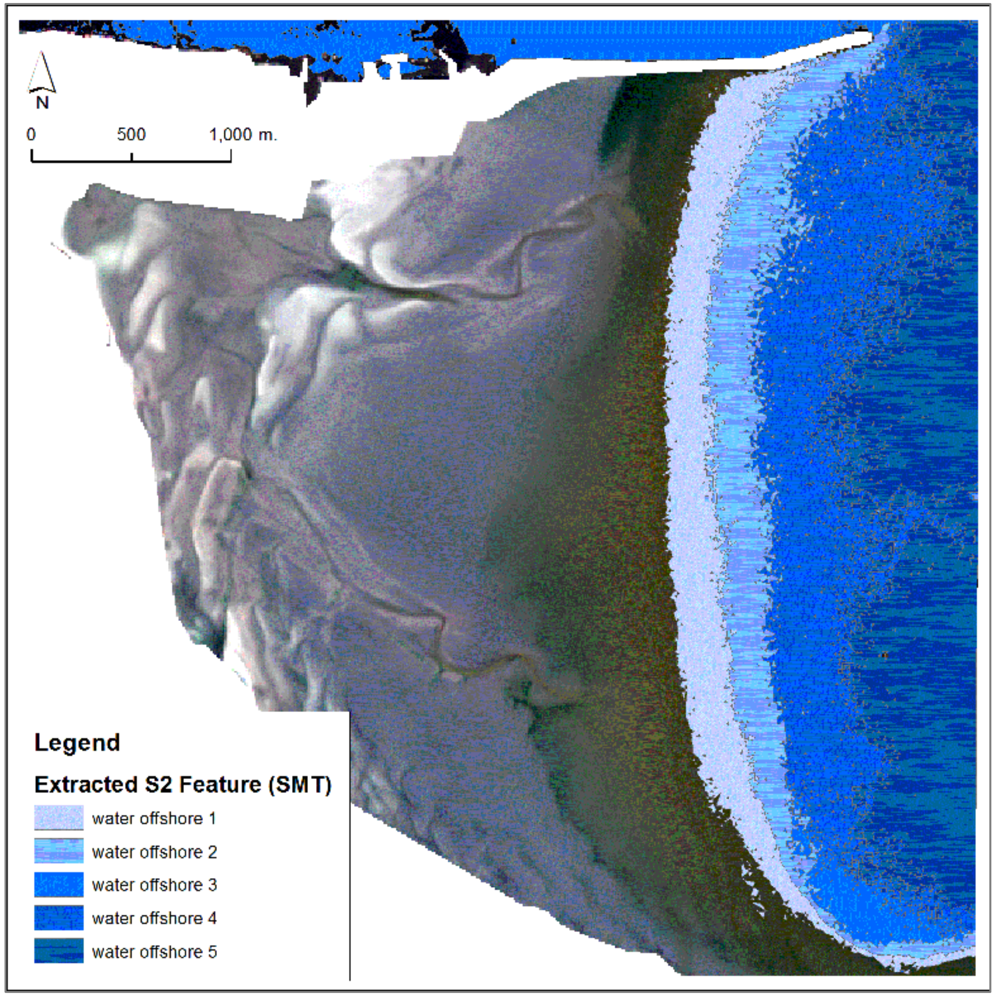


Fig 1.5(e): Sandymount S2 image ISO Cluster Offshore possible depth-related Polygon Features 17/06/2017

Table 1.3: Polygon Feature attributes for **Sandymount** study sub-area 17/06/2017

Id	Gridcode	Class	subclass	Area_Ha
1	0	Offshore	water offshore 5	214.40
2	1	nearshore	water nearshore 4	100.03
3	2	Beach	wet sand	78.60
4	3	nearshore	water nearshore 3	67.65
5	4	Offshore	water offshore 4	198.13
6	5	nearshore	water nearshore 7	52.53
7	6	nearshore	water nearshore 5	25.50
8	7	nearshore	water nearshore 2	39.49
9	8	Offshore	water offshore 3	83.68
10	9	Beach	v wet sand	121.95
11	10	Beach	dry sand	43.43
12	11	Offshore	water offshore 1	102.05
13	12	nearshore	water nearshore 1	29.68
14	13	nearshore	water nearshore 6	84.31
15	14	Offshore	water offshore 2	107.65
16	15	Beach	v wet	92.26
17	16	Beach	damp sand	117.15
18	17	Beach	v damp sand	80.71
19	18	Beach	slightly damp sand	62.14

1.5.2 Assessment of potential for model repeatability

Figure 1.6 (overleaf) assesses model repeatability when applied to Sentinel-2 images acquired one month apart. Please refer back to section 1.5.1 for discussion of the outcomes of this assessment when viewing Figure 1.6.

Figure 1.6: Examination of potential for repeatability of the Feature Extraction algorithm over a short time-scale at the Bull island test site (Sentinel-2 image date 17/07/2017, coincident with a tide level of -1.334 Malin OD at Dublin Port tide gauge.

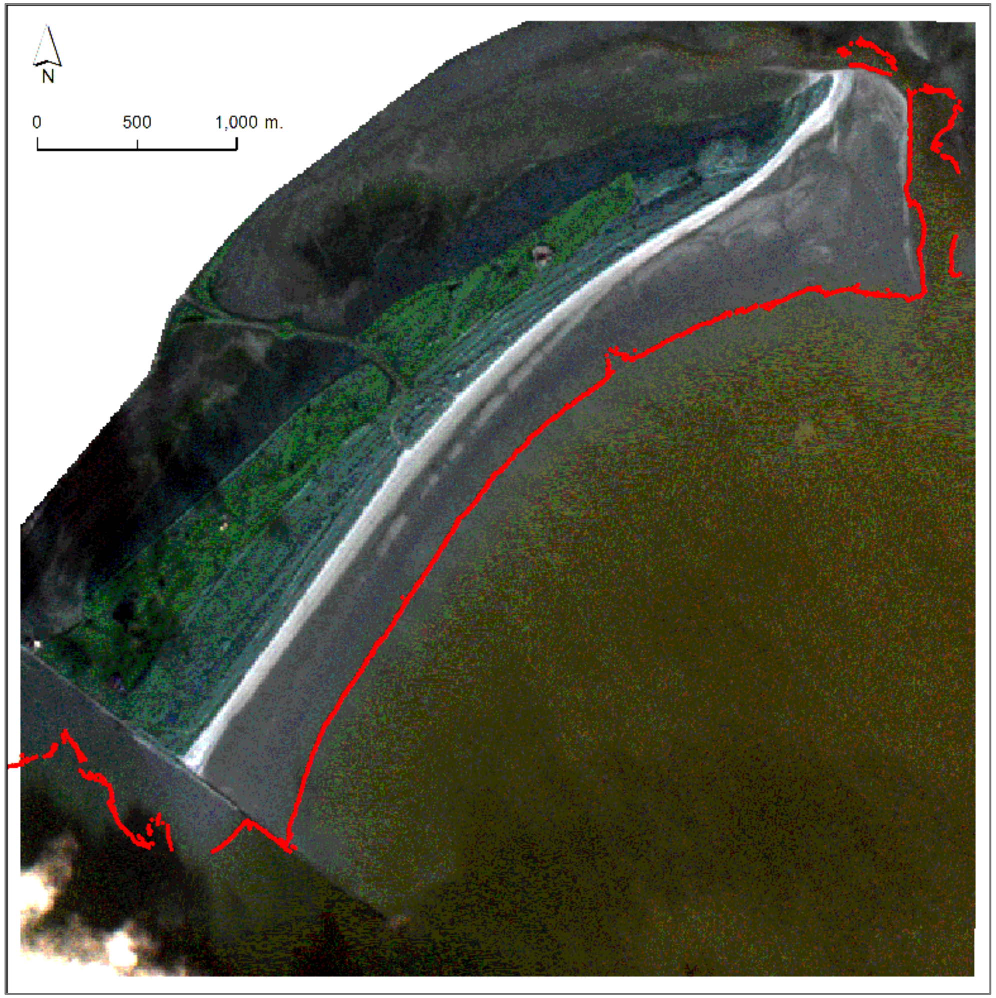


Fig 1.6(a): Bull island S2 image composite (R,G,B,NIR) **17/07/2017**

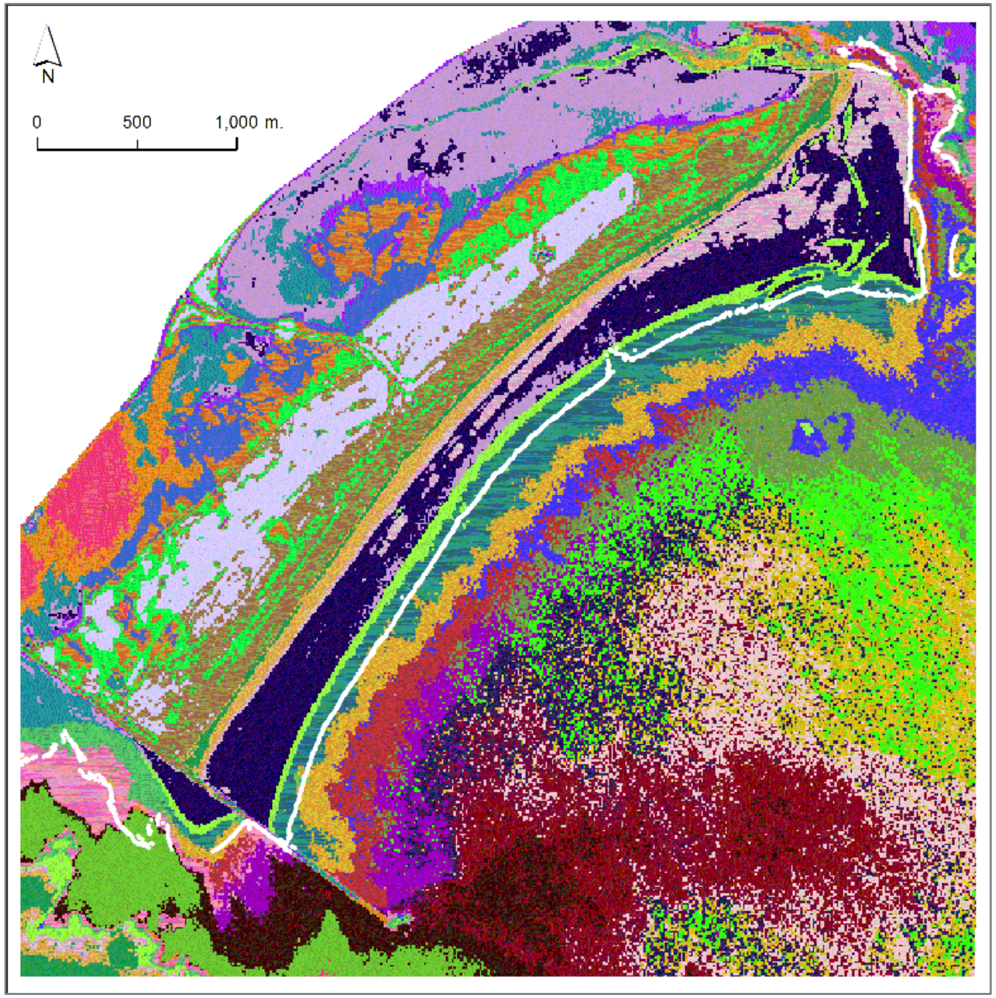


Fig 1.6(b): Bull island ISO Cluster classes (25) of S2 image composite (R,G,B,NIR) **17/07/2017**

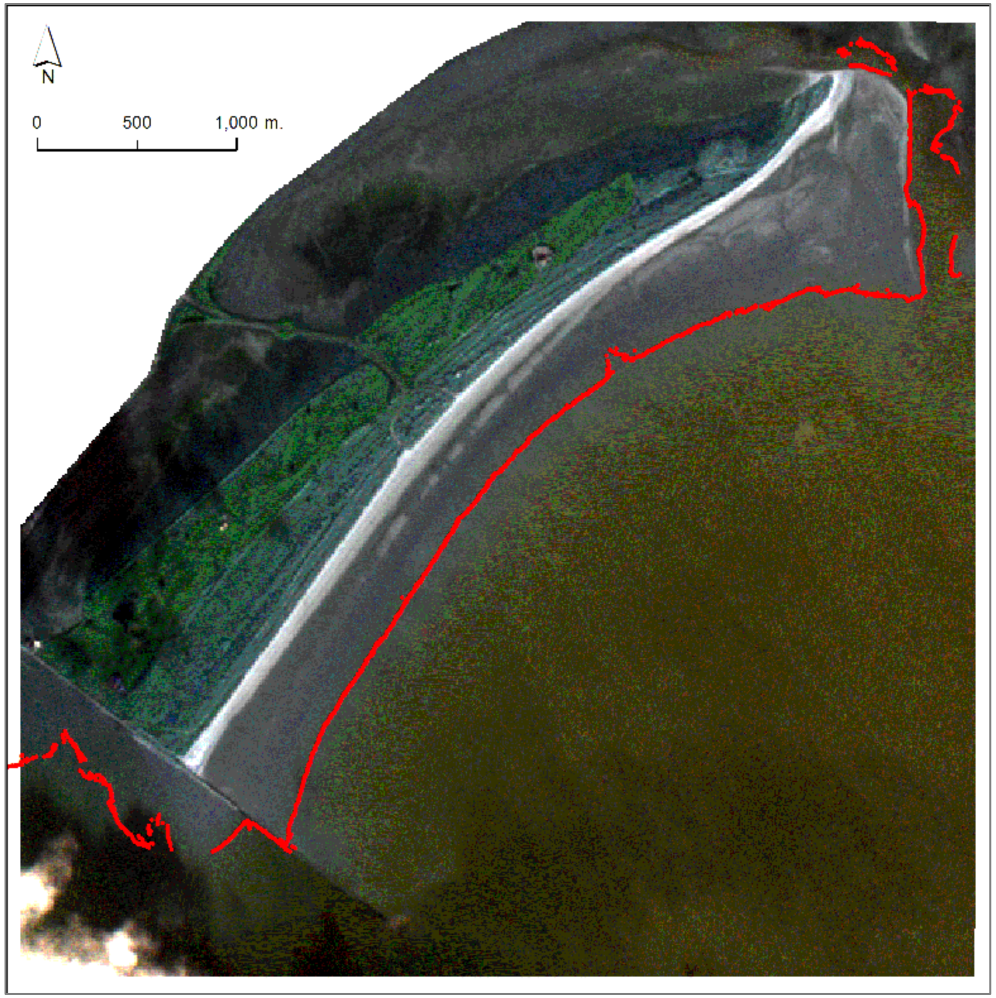


Fig 1.6(c): Bull island S2 image composite (R,G,B,NIR) **17/07/2017**

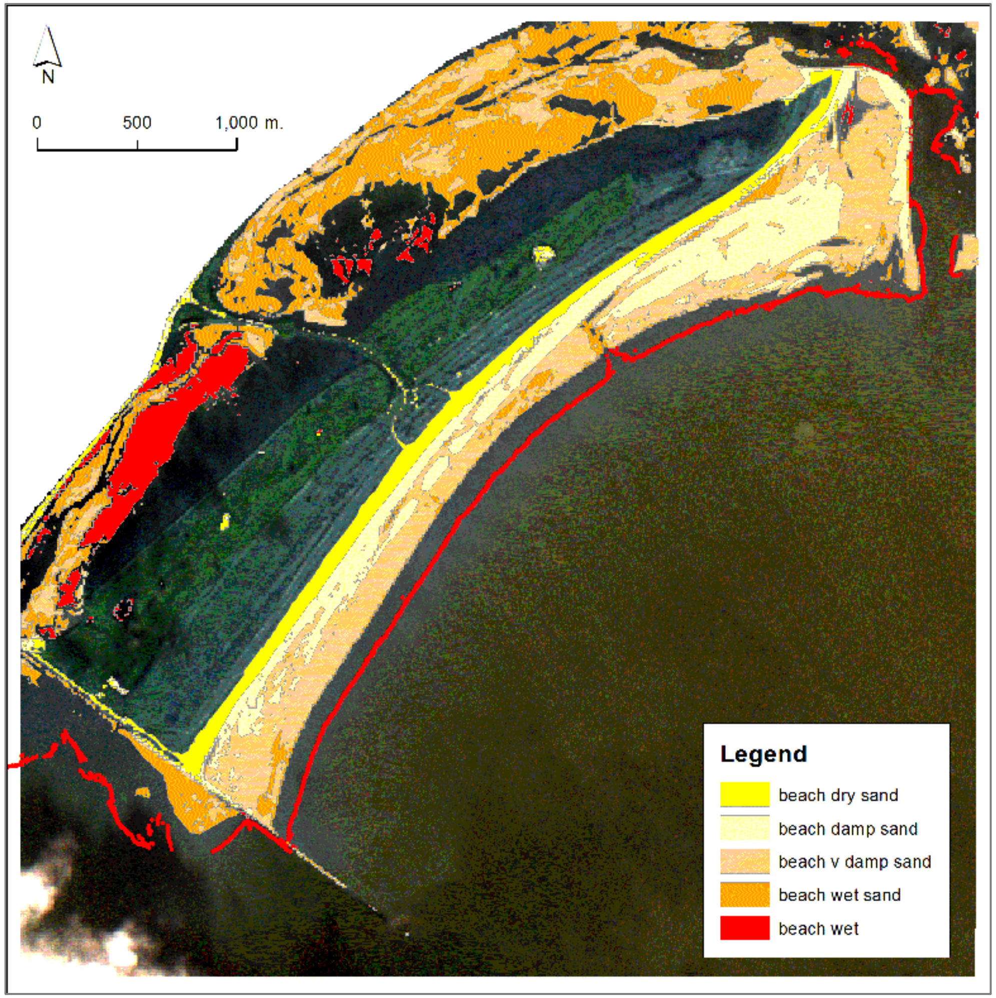


Fig 1.6(d): BEACH FEATURES **FROM 17/06/2017** OVERLAID ON 17/07/2017 ORHTO

1.5.3 Potential of model for change detection

Figure 1.7 (see overleaf) assesses model repeatability, and the capacity of the model to be applied to the assessment of intertidal feature change over inter-seasonal timescales. Please refer to section 1.5.1 for discussion of the outcomes of this assessment when viewing Figure 1.7.

Figure 1.7: Potential of the Feature Extraction algorithm for the evaluation of intertidal feature change over a longer (inter-seasonal) time-scale at the Sandymount test site (Sentinel-2 image date 25/02/2018, coincident with a tide level of -1.334 Malin OD at Dublin Port tide gauge.

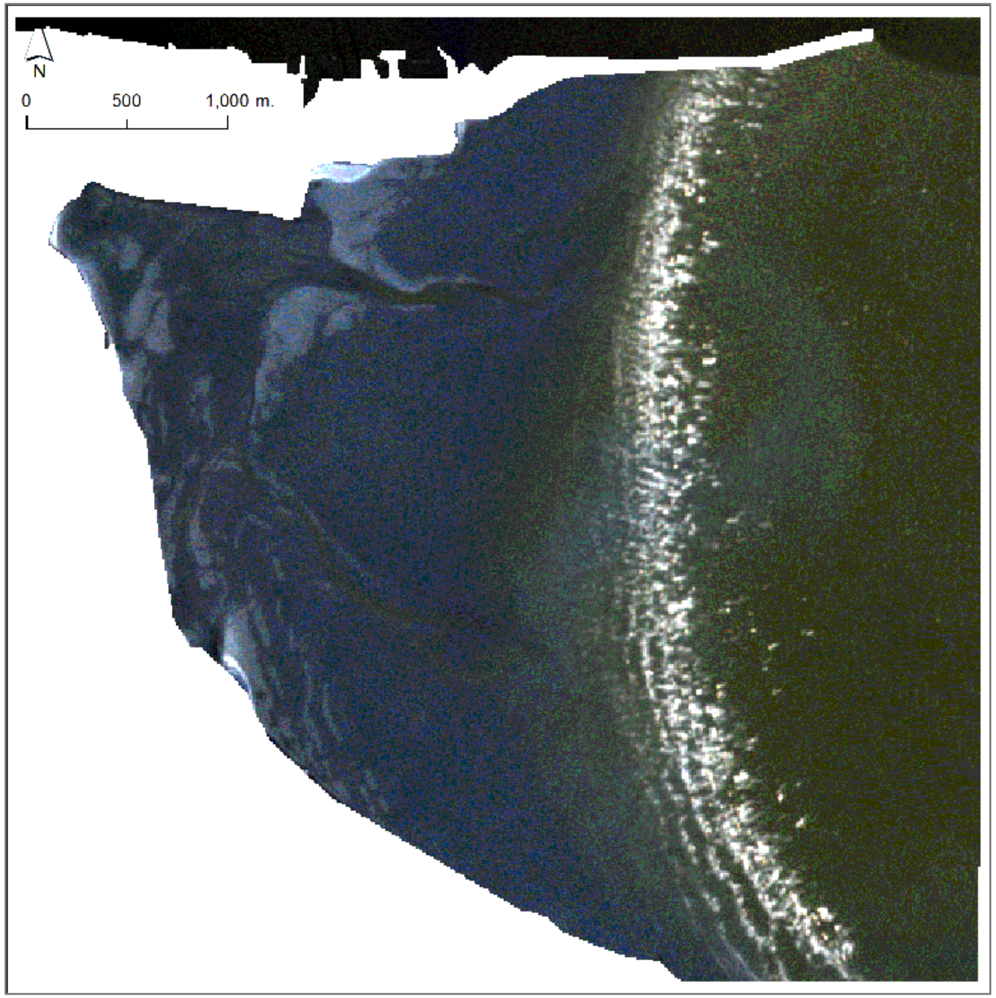


Fig 1.7(a): Sandymount S2 image composite (R,G,B,NIR) **25/02/2018**

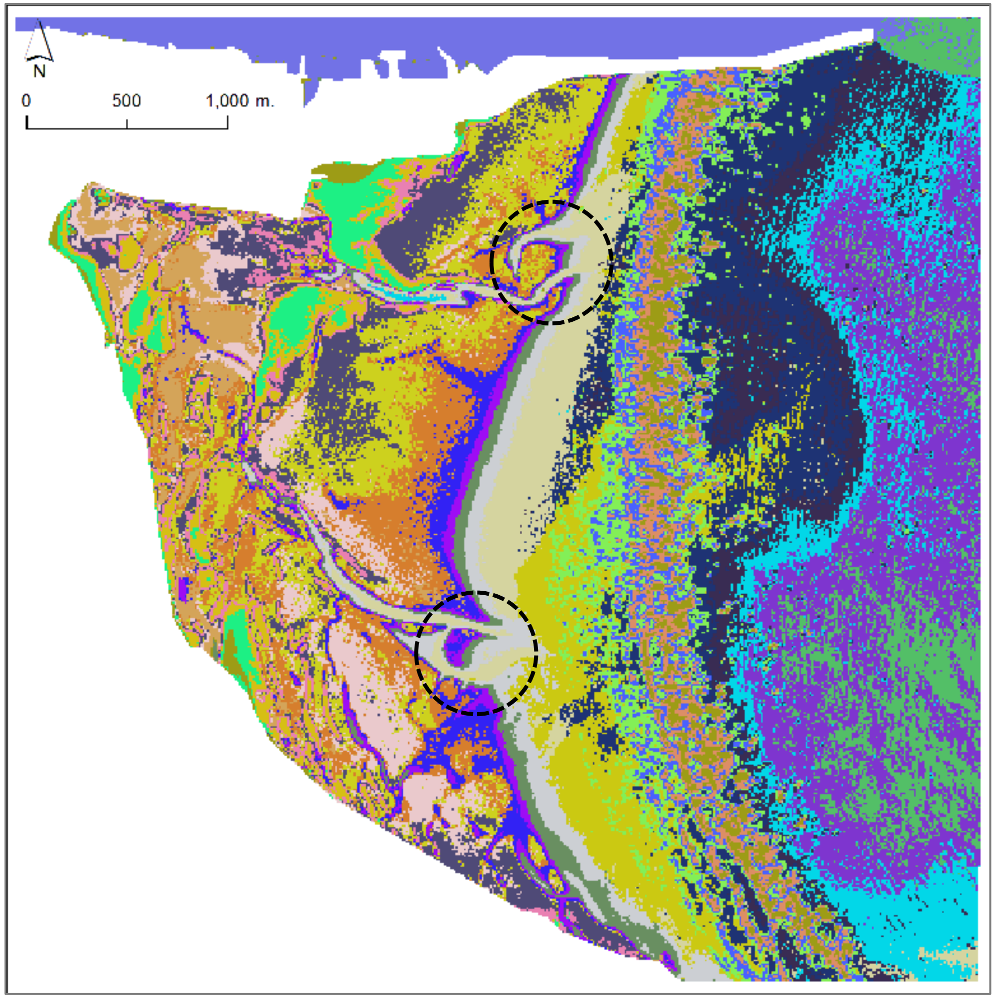


Fig 1.7(b): Sandymount ISO Cluster classes (25) of S2 image composite (R,G,B,NIR) **25/02/2018. NOTE: Dashed outlines highlight areas of subtle change.**

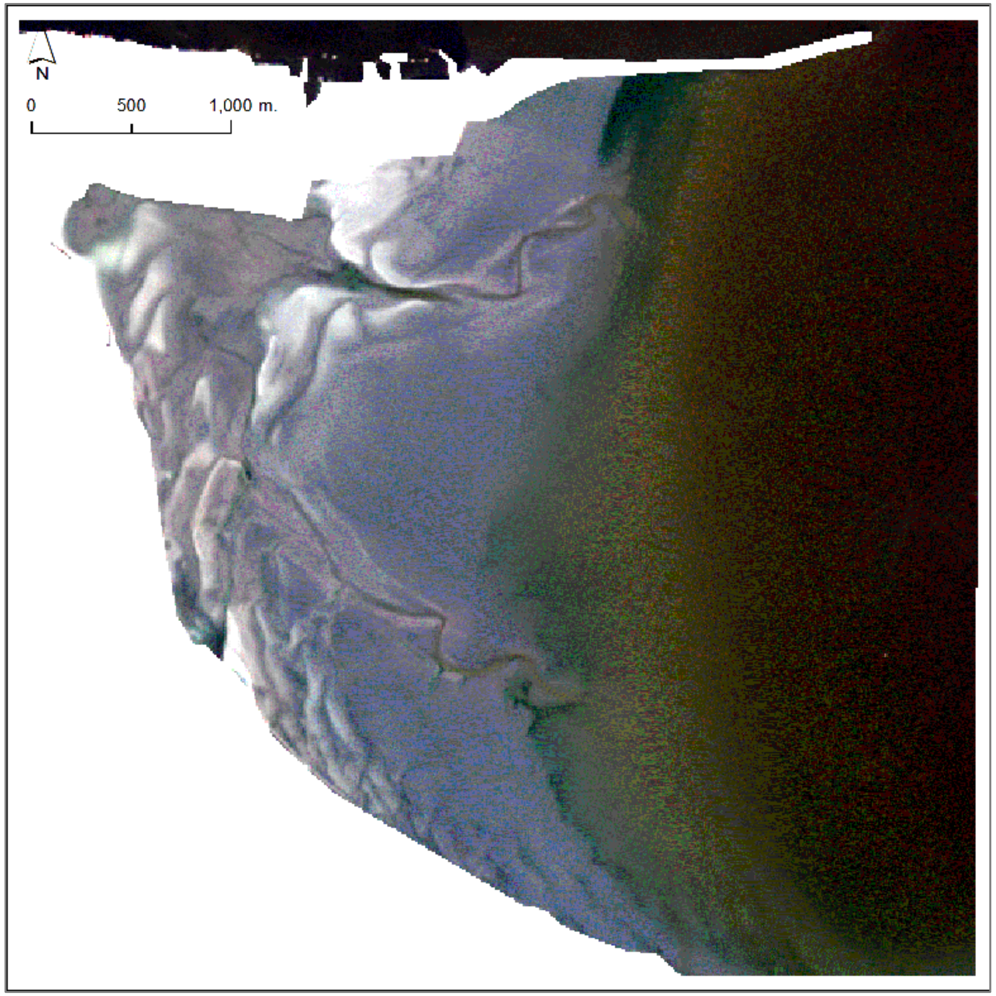


Fig 1.7(c): Sandymount S2 image composite (R,G,B,NIR) 17/06/2017

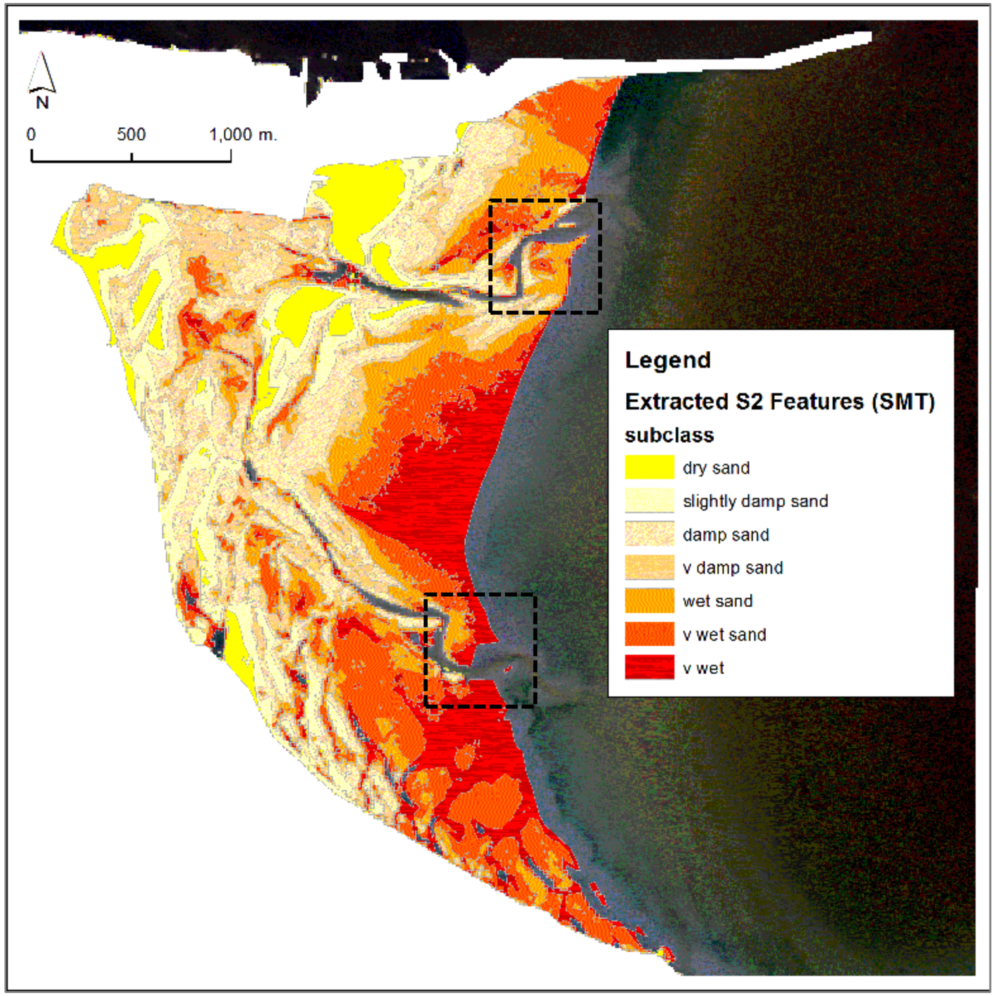


Fig 1.7(d): Sandymount S2 image ISO Cluster Dry Intertidal Polygon Features 17/06/2017. **NOTE: Dashed outlines highlight areas of subtle change.**

SECTION 2 - Shoreline extraction from Sentinel-2 imagery

SHOREX software, supplied by Universidad Polytecnica Valencia, was used for shoreline extraction. The SHOREX toolbox (Palomar-Vázquez et al., 2018) develops upon previous work from Dr Pardo-Pascual at the Universidad Polytecnica Valencia (Pardo-Pascual et al., 2018; Pardo-Pascual et al, 2012) generating vector shoreline extractions (Figure 2.1) from satellite images (including Sentinel-2). It also provides data with the potential to derive intertidal DTMs in a manner that cannot be easily achieved using water Indices mapping (Figure 2.2d & Figure 2.3). SHOREX identifies shoreline pixels from Short Wave Infrared bands (Sentinel-2 band 11), from within a series of co-registered Sentinel-2 images. Secondly, the extraction of the shoreline vertices is conducted at a subpixel level, and these are subsequently output as individual vertices in a vectorised shoreline. The operation of the software is summarised (*figure courtesy of Dr Pardo-Pascual at Universidad Polytecnica Valencia*) in Figure 2.1.

Shoreline extraction was applied to a set of 20 substantially cloud-free time-stamped Sentinel-2 images (Table 2.1). These shorelines were encoded with Malin datum elevation values from contemporaneous (5-minute resolution) tide levels recorded at the Dublin Port tide gauge. Subsequently, a GNSS validation survey was employed to verify the accuracy of sample sections of all 20 shoreline extractions. The Sentinel-2 images from which these shorelines were extracted, represented a tidal range of 3.25m, enabling the production of an intertidal Digital Terrain Model (DTM) for the Bull Island test site. The accuracies that were achieved (0.30 metres RMSE, excluding one obviously erroneous shoreline of 20 shorelines) suggest that the approach may have potential for the generation of useful intertidal DTMs elsewhere around the Irish coast, potentially overcoming the difficulties associated with generating accurate DTM data in the intertidal zone (Coveney & Monteys, 2011; Coveney et al., 2010, Coveney & Fotheringham, 2011; Coveney & Monteys, 2009). Examining this question within additional INFOMAR Priority Bays might form the basis of a useful follow-up study.

2.1 Methodological approach

- Shoreline extraction for the 20 best Sentinel images using SHOREX
- Shorelines extracted from time-stamped Sentinel-2 images (Figure 2.3) were encoded with tide heights from 5-minute tide levels (Malin OD) recorded at the Dublin Port tide gauge (Table 2.1)
- Shoreline tide-heights were validated relative to GNSS elevation, expressed relative to Malin OD by walking sample sections of each SHOREX-extracted shoreline (Figure 2.4a), using a Trimble R8 Rover, acquiring points in Realtime Kinematic (RTK) mode (Figure 2.4b) at an RMSE elevation positioning uncertainty of (RMSE <0.015m & a max elevation error of 0.031m)
- An intertidal Digital Terrain Model was generated (Figure 2.5) from the tide-encoded shorelines, demonstrating the potential to link high temporal-resolution tide height data with shoreline extraction. The approach might be usefully applied for the generation of intertidal DEM products in further Priority bays.

2.2 Deliverable products

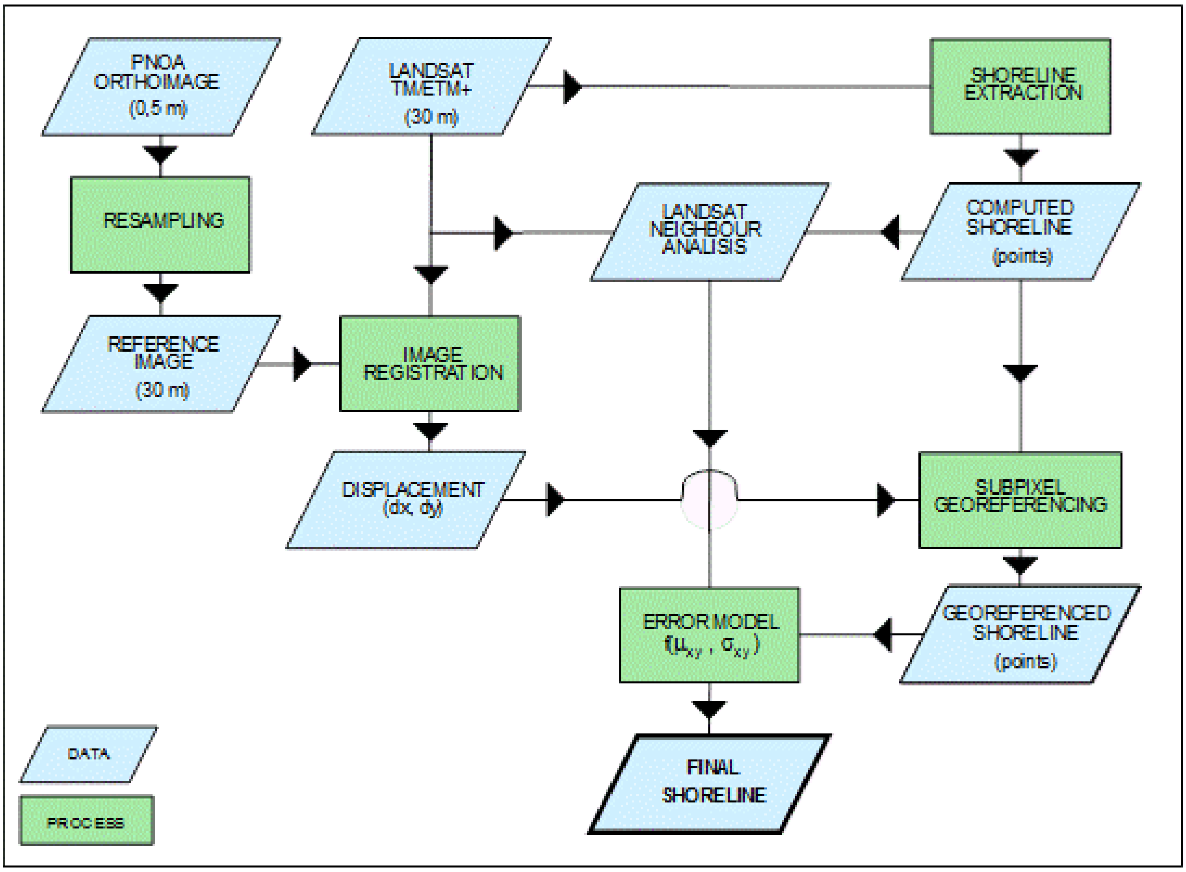
- A proven methodology that can be implemented for shoreline extraction from Sentinel-2 satellite imagery
- An intertidal Digital Terrain Model (DTM) product for Bull island, constructed from the tide-level encoded (and GNSS validated) Sentinel-2 shorelines.

2.3 Summary conclusions

Potentially useful intertidal DEMs can be generated by extracting multiple tide-defined shorelines from time-stamped Sentinel-2 imagery, attaching contemporaneous (5-minute resolution) tide levels recorded at nearby tide gauges. GNSS validation of the extracted shorelines confirmed that

RMSE elevation accuracies (Table 2.2) of 0.30m are achievable (mean elevation error 0.18m), potentially providing a methodological basis for the generation of Sentinel-2 derived intertidal DTM data for additional INFOMAR Priority Bays.

Figure 2.1: Schematic representation of the SHOREX algorithm (courtesy Dr. Pardo-Pascual, Universidad Polytecnica Valencia) to a satellite image (Sentinel-2 in this case).



2.4 SHOREX versus Water Indices

SHOREX generates an extracted shoreline from a Sentinel-2 multispectral image, utilising a variety of band combinations, including the approaches that are implemented within non-extraction water indices such as the Modified Normalized Difference Water Index MNDWI = (Green - SWIR) / (Green + SWIR) (Xu, 2006). MNDWI was applied here as an array calculation between the normalized SWIR and Green bands (Figure 2.2a and 2.2b), generating a binary raster that delineated land and water (Figure 2.2c). While the resulting binary raster could be quite easily converted to vector shorelines, the critical additional steps that are applied within SHOREX presents substantial accuracy advantages. SHOREX applies the critical additional steps of image co-registration, sub-pixel georeferencing and error modelling prior to generating a vectorised sub-pixel shoreline extraction (Figure 2.3), which can subsequently be used to derive an intertidal DTM.

Figure 2.2: Illustration of the outputs from a non-extraction MNDWI model

Fig 2.2(a): Sentinel-2 band 11 (SWIR, 1614 nm)

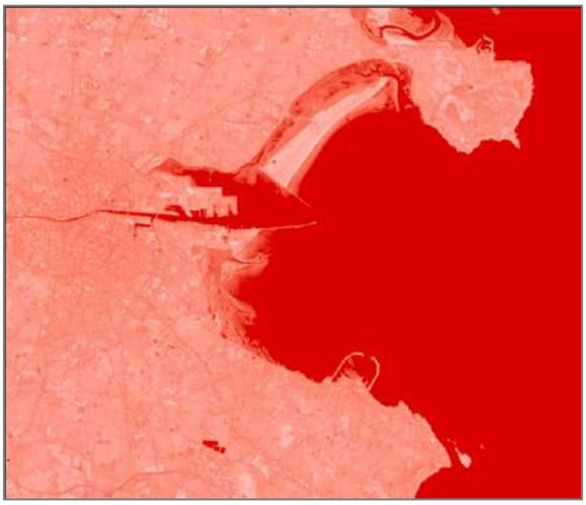


Fig 2.2(b): Sentinel-2 band 3 (Green, 560 nm)

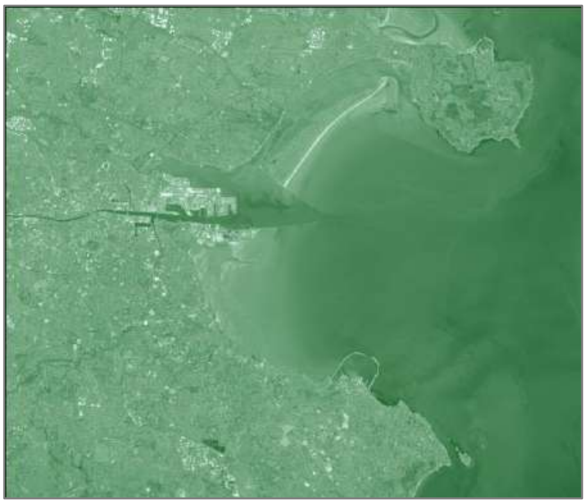


Fig 2.2(c): MNDWI from Sentinel-2 bands 3 & 11

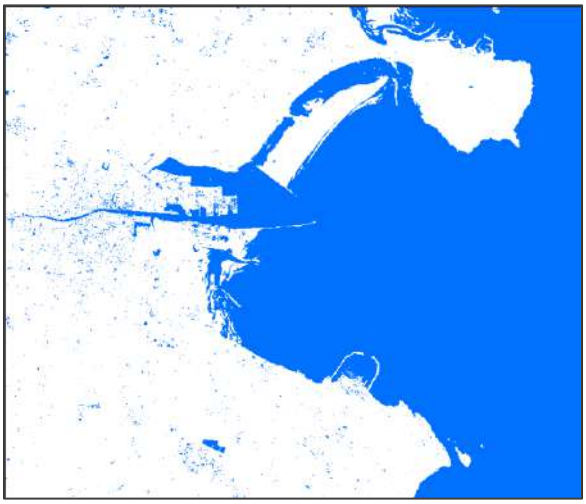


Fig 2.2(d): A sequence of 20 shorelines from SHOREX

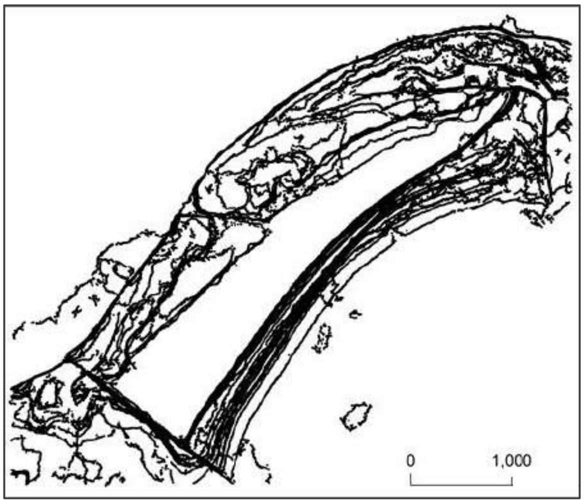


Figure 2.2 (above) briefly illustrates the critical difference between outputs from a Modified Normalized Difference Water Index (MNDWI) and SHOREX. SHOREX outputs produce a sequence of vector shorelines (not binary rasters as is the case with MNDWI). When SHOREX is applied to a sequence of satellite images and their contemporaneous tide gauge records, the resulting set of elevation-encoded shorelines can provide the basis for the generation of an intertidal DTM product (Figure 2.5).

2.5 Shoreline extraction using SHOREX Toolbox

Table 2.1: Cloud-free images used for shoreline extraction. Tide levels at Dublin Port were sourced from http://data.marine.ie/Dataset/Details/20932)

Date	Time	Filename	Instrument	Sat	Tide Dublin (m)
08/04/2017	11:33:21	S2A_MSIL2A_20170408T113321_N0204_R080_T29UPV_20170408T113407	S2A_MSIL2A	S2A	3.70
11/05/2017	11:43:51	S2A_MSIL2A_20170511T114351_N0205_R123_T29UPV_20170511T114352	S2A_MSIL2A	S2A	4.49
17/06/2017	11:33:21	S2A_MSIL2A_20170617T113321_N0205_R080_T29UPV_20170617T113319	S2A_MSIL2A	S2A	1.81
20/06/2017	11:43:51	S2A_MSIL2A_20170620T114351_N0205_R123_T29UPV_20170620T114348	S2A_MSIL2A	S2A	2.05
17/07/2017	11:33:21	S2A_MSIL2A_20170717T113321_N0205_R080_T29UPV_20170717T113326	S2A_MSIL2A	S2A	1.48
30/09/2017	11:33:09	S2B_MSIL1C_20170930T113309_N0205_R080_T29UPV_20170930T113303	S2B_MSIL1C	S2B	2.34
30/10/2017	11:33:09	S2B_MSIL1C_20171030T113309_N0206_R080_T29UPV_20171030T132927	S2B_MSIL1C	S2B	2.26
04/11/2017	11:33:21	S2A_MSIL2A_20171104T113321_N0206_R080_T29UPV_20171104T134102	S2A_MSIL2A	S2A	4.77
12/11/2017	11:43:39	S2B_MSIL1C_20171112T114339_N0206_R123_T29UPV_20171112T133854	S2B_MSIL1C	S2B	1.96
29/11/2017	11:34:19	S2B_MSIL1C_20171129T113419_N0206_R080_T29UPV_20171129T133534	S2B_MSIL1C	S2B	2.62
27/12/2017	11:45:01	S2A_MSIL2A_20171227T114501_N0206_R123_T29UPV_20171227T135533	S2A_MSIL2A	S2A	1.81
08/01/2018	11:34:39	S2B_MSIL2A_20180108T113439_N0206_R080_T29UPV_20180108T133524	S2B_MSIL2A	S2B	2.20
02/02/2018	11:33:11	S2A_MSIL2A_20180202T113311_N0206_R080_T29UPV_20180202T164512	S2A_MSIL2A	S2A	4.28
12/02/2018	11:33:21	S2A_MSIL2A_20180212T113321_N0206_R080_T29UPV_20180212T150912	S2A_MSIL2A	S2A	3.43
20/02/2018	11:43:39	S2B_MSIL1C_20180220T114339_N0206_R123_T29UPV_20180221T151310	S2B_MSIL1C	S2B	3.35
25/02/2018	11:43:51	S2A_MSIL2A_20180225T114351_N0206_R123_T29UPV_20180225T170025	S2A_MSIL2A	S2A	1.70
07/03/2018	11:43:51	S2A_MSIL1C_20180307T114351_N0206_R123_T29UPV_20180307T120807	S2A_MSIL1C	S2A	3.08
24/03/2018	11:33:21	S2A_MSIL2A_20180324T113321_N0206_R080_T29UPV_20180324T115416	S2A_MSIL2A	S2A	1.99
21/04/2018	11:43:51	S2B_MSIL2A_20180421T114349_N0207_R123_T29UPV_20180421T134219-ql	S2A_MSIL2A	S2B	2.61
12/07/2017	11:33:19	S2B_MSIL1C_20170712T113319_N0205_R080_T29UPV_20170712T113319	S2B_MSIL1C	S2B	3.74

Figure 2.3: All 20 shorelines extracted using SHOREX from the Sentinel-2 image set referenced in Table 2.1.

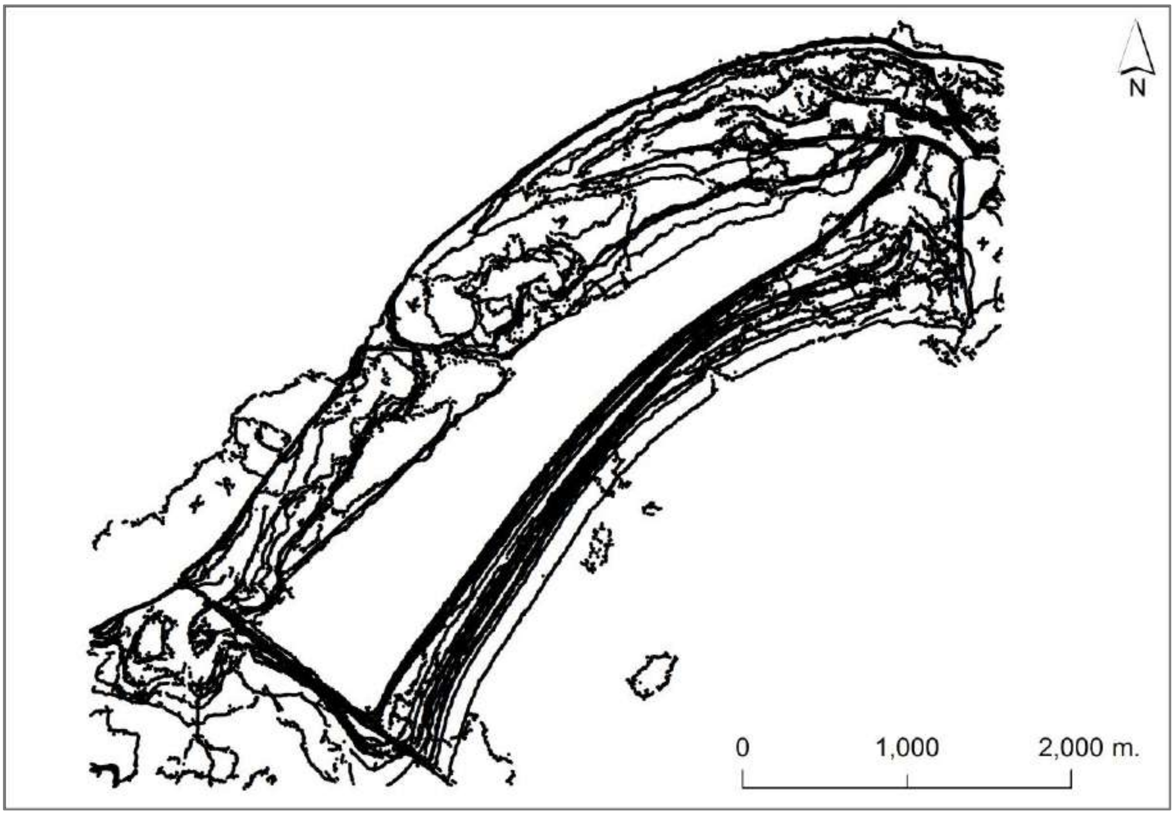


Figure 2.4(a): Sample GNSS validation transects for each of the 20 extracted shorelines.

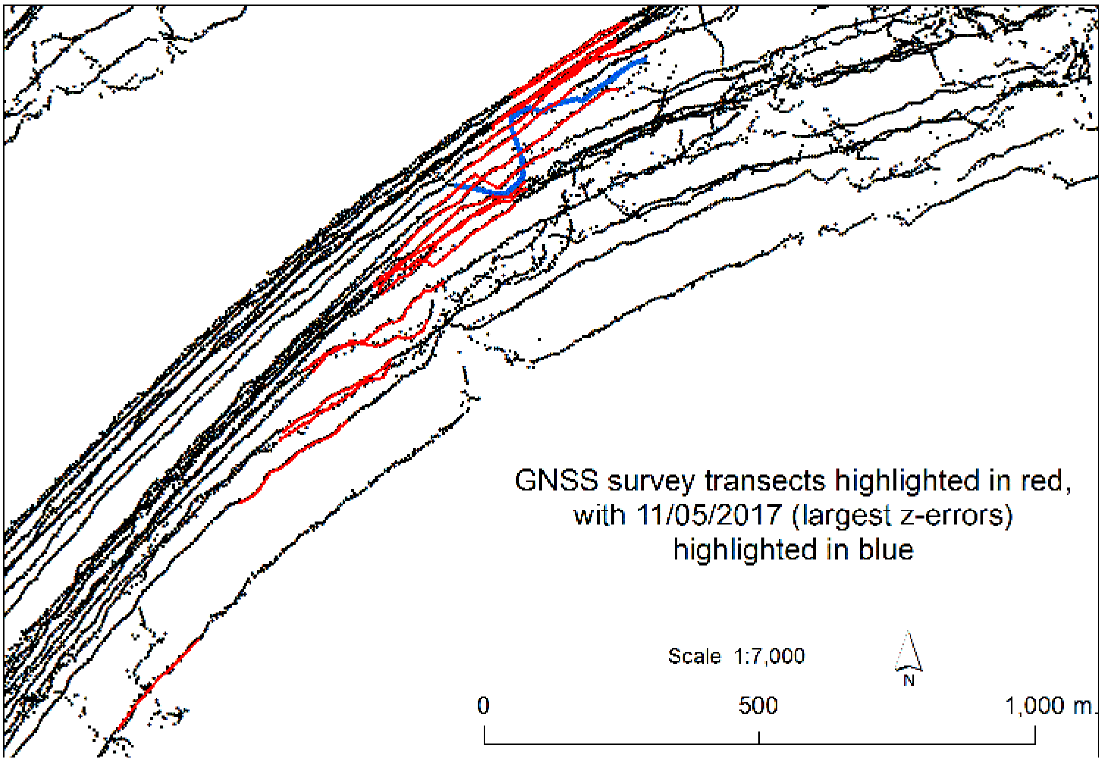


Fig 2.4(b):: GNSS validation point locations.

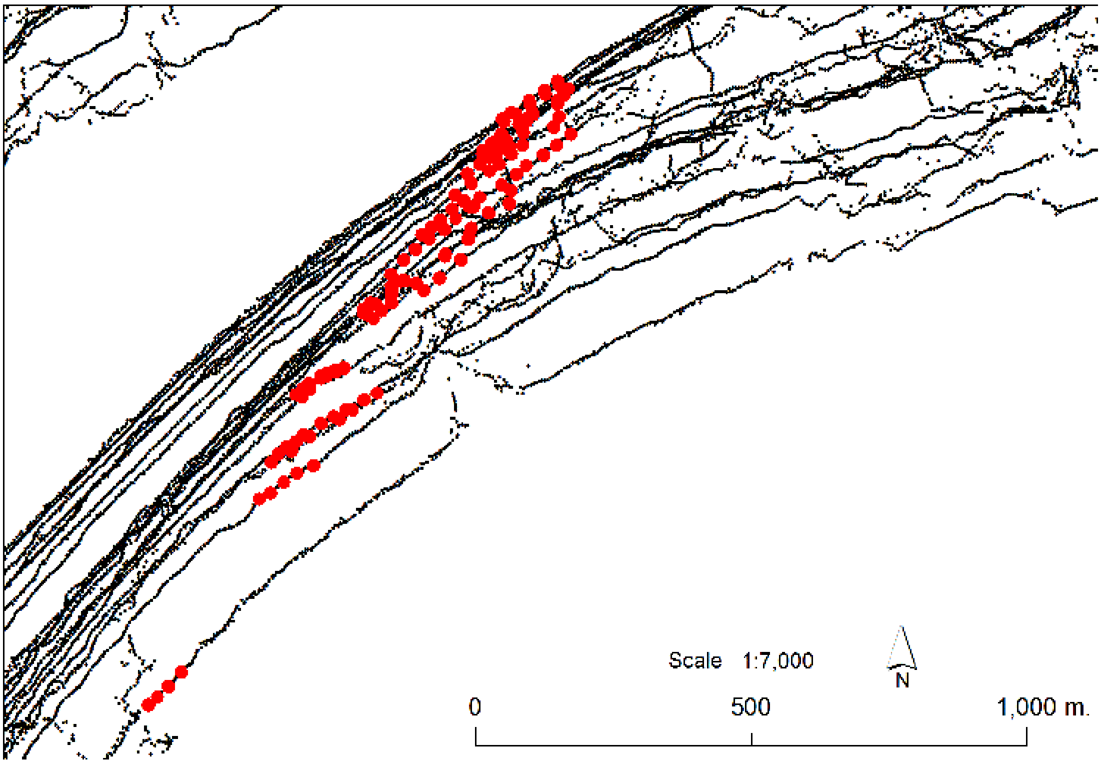


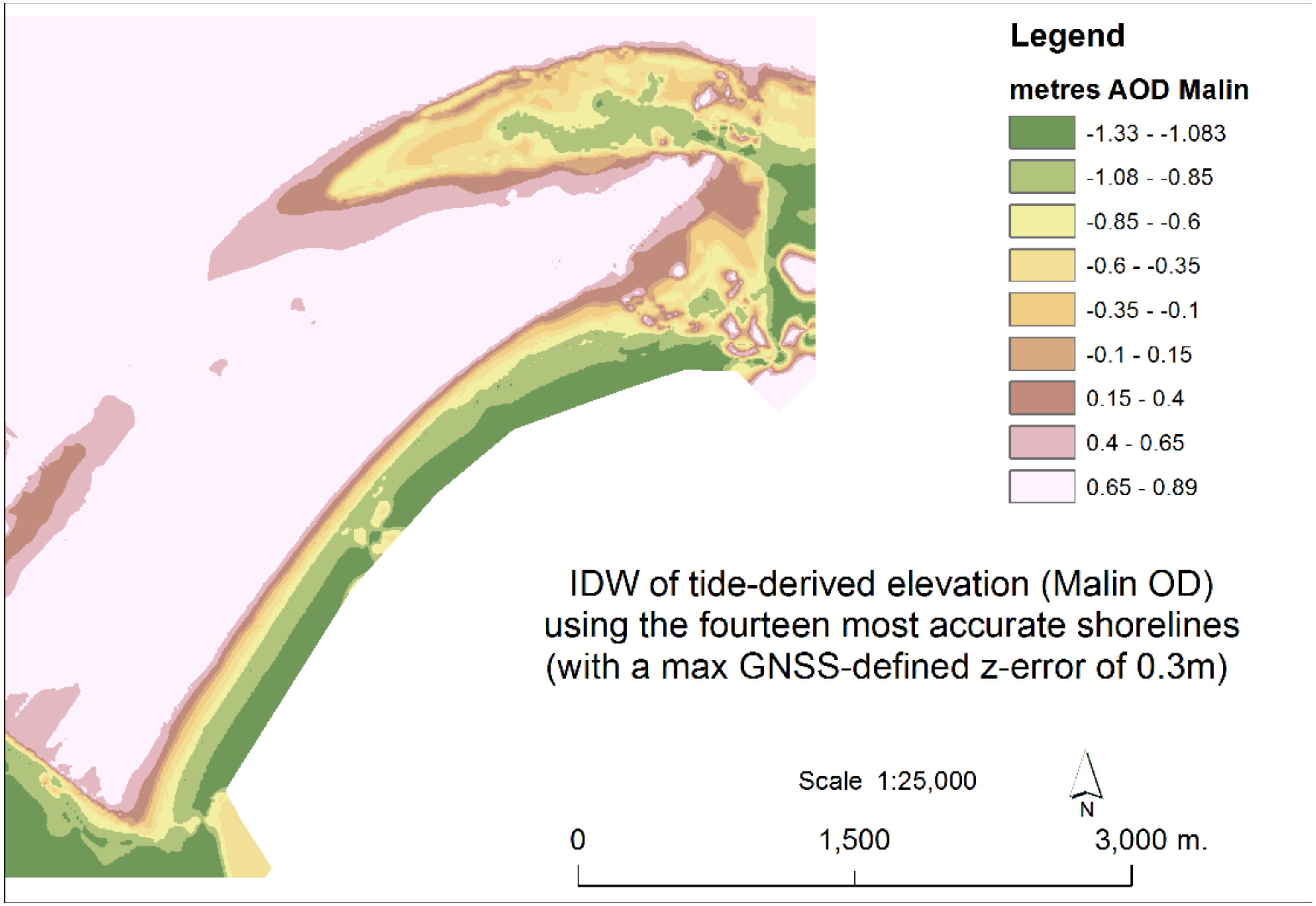
Table 2.2(a): Shoreline validation summary statistics

Summary statistic	**Error (m)**	**Point count**
Count	-	122
Ignored	-	5
RMSE	0.303	-
Median error: 0.2	0.2	-
Mean error: 0.18	0.18	-
Max error: 0.54	0.54	-
Min error:-0.02m	-0.02	-

Table 2.2(b): Validation statistics for each shoreline, outlining contemporaneous (5-minute resolution) tide levels for each time-stamped Sentinel-2 image, mean GNSS elevations (expressed relative to Malin datum) along each shoreline validation transect, number of GNSS validation points per transect, mean shoreline elevation errors, and the shoreline that was characterised by the largest elevation errors *(highlighted in bold italics).*

Shoreline date	SL time	Sat	Dublin Tide (Malin datum)	Mean GNSS elevation	GNSS validation points	**Mean shoreline z-error (mAOD)**
04/11/2017	11:33:21	S2A	1.96	1.42	5	**0.54**
02/02/2018	11:33:11	S2A	1.47	1.05	5	**0.43**
12/02/2018	11:33:21	S2A	0.62	0.72	6	**-0.10**
12/07/2017	11:33:19	S2B	0.87	0.71	6	**0.16**
08/04/2017	11:33:21	S2A	0.89	0.69	4	**0.20**
20/02/2018	11:43:39	S2B	0.54	0.51	8	**0.03**
07/03/2018	11:43:51	S2A	0.27	0.38	7	**-0.11**
11/05/2017	***11:43:51***	***S2A***	***1.70***	***0.02***	***5***	***1.68***
30/09/2017	11:33:09	S2B	-0.47	-0.05	8	**-0.42**
21/04/2018	11:43:51	S2B	-0.20	-0.41	14	**0.21**
08/01/2018	11:34:39	S2B	-0.61	-0.78	5	**0.17**
30/10/2017	11:33:09	S2B	-0.55	-0.79	6	**0.24**
20/06/2017	11:43:51	S2A	-0.76	-0.86	6	**0.10**
29/11/2017	11:34:19	S2B	-0.19	-0.86	6	**0.67**
24/03/2018	11:33:21	S2A	-0.82	-1.09	7	**0.27**
25/02/2018	11:43:51	S2A	-1.11	-1.09	6	**-0.02**
27/12/2017	11:45:01	S2A	-1.01	-1.25	8	**0.23**
12/11/2017	11:43:39	S2B	-0.86	-1.28	6	**0.42**
17/06/2017	11:33:21	S2A	-1.07	-1.38	5	**0.31**
17/07/2017	11:33:21	S2A	-1.33	-1.46	4	**0.12**

Figure 2.5: Intertidal DTM map derived (using Inverse Distance Squared interpolation) from the contemporaneous tide-levels (Metres relative to Malin OD) recorded at Dublin Port tide gauge.



SECTION 3 - Feature recognition and classification from GSI UAS imagery and DSM data.

A repeatable methodology is presented and evaluated here, which achieves intertidal feature recognition from a combination of UAS imagery and DSM data. Figure 3.1 summarises the process in the form of a flow diagram, describing the sub-component geoprocessing and spatial analysis tools that were used (*from within ArcGIS 10.x ArcInfo licence*). It also presents a schema that may be repeated in the future if/as required. The process, when applied to GSI drone data, effectively delineated tall-features from ground-features and allowed for sub-classification of intertidal, onshore and nearshore features, using elevation and spectral information.

3.1 Methodological Approach

- The UAV survey and data processing was undertaken by GSI staff and was provided (*courtesy of Ronan O'Toole, GSI*) as DSM, DTM and Normalised Difference Vegetation Index (NDVI) data (Figure 3.2a, 3.2b, 3.2c)
- A DSM-DTM difference model was generated, which was used to segregate above-ground from ground-based features (Figure 3.2d)
- The NDVI data was used to segregate vegetated (Figure 3.2e) from non-vegetated (Figure 3.2f), above-ground and ground-based features
- The vegetated, non-vegetated, above-ground and ground-based classes were then segregated based upon feature height and vegetation / non-vegetation status into seven Meta classes (Figure 3.1 & 3.2)
- These were segmented by elevation of NDVI values to define 24 distinct feature classes (Table 3.1) which included: 5 tall vegetation classes, 4 built-structures classes, 4 coastal rock-outcrop classes, 2 non-vegetated open-area classes, 4 ground vegetation classes, 4 intertidal vegetation classes, and a single nearshore water feature class (Figure 3.3).

3.2 Deliverable products

- A desktop-GIS based methodology for feature extraction from GSI drone data, utilising drone imagery and drone DTM data inputs (figure 6)
- An onshore, intertidal and nearshore feature extraction data set for Bunmahon, county Waterford.

3.3 Summary conclusions

The combined use of high-resolution drone Digital Elevation Model (DEM) data and drone multispectral data from a single GSI drone survey data set allowed for the extraction of 24 feature classes, including thirteen intertidal / near-intertidal feature classes (Table 3.1). The model was designed and applied in ArcGIS, using simple raster algebra calculations, all of which could be implemented across a wide range of remote sensing or GIS software platforms.

The approach that was developed here may be of practical interest to GSI (and other bodies) for coastal change monitoring. Useful applications might include (at a minimum) integrity assessments of coastal defences, coastal erosion monitoring, coastal & intertidal feature mapping and the validation of satellite feature extraction from Sentinel-2 data sets.

Figure 3.1: Schematic of the Feature Extraction process, describing the sub-component geoprocessing and analytical tools that were used to (*from within ArcGIS 10.x ArcInfo licence*) to generate 24 intertidal, onshore and nearshore feature (polygon) classes.

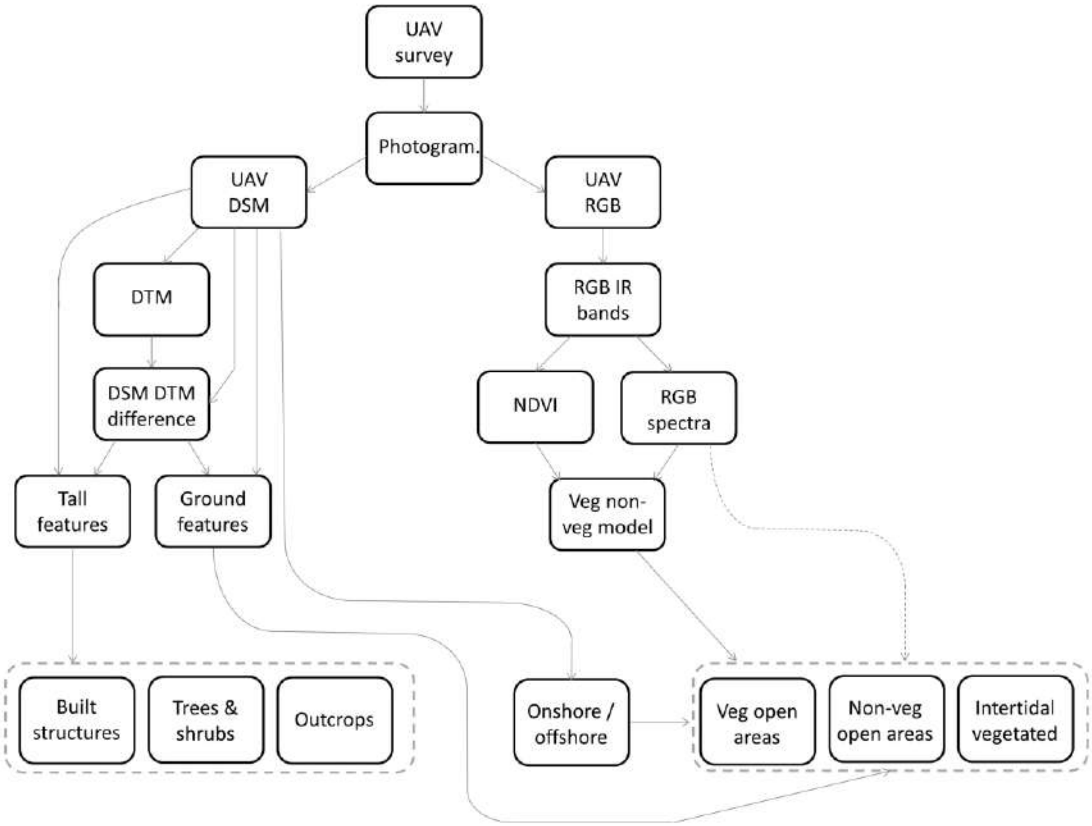


Table 3.1: Feature classes generated from the GSI drone image and DTM data sets

Meta class	Sub-class
Tall vegetation	-0.8 to 0.25m vegetation
	0.25 to 2.37m vegetation
	2.37 to 4.8m vegetation
	4.8m to 8.57m vegetation
	8.57 to 19.17m vegetation
Built structures	Low structures (<2m)
	Low buildings (2 to 3.5m)
	Mid-sized buildings (3.5 to 4m)
	Tall buildings (4 to 7m)
Rock outcrops	Outcrops (0 to 3m)
	Outcrops (3 to 7m)
	Outcrops (7 to 11m)
	Outcrops (11 to 19m)
Tidal	Up to 2m AOD Malin
Open non-vegetated areas	Paved / dark mineral surfaces
	Sand / light-toned mineral surfaces
Ground-based vegetation	0 to 0.05m vegetation
	0.052 to 0.073m vegetation
	0.0.73 to 0.084m vegetation
	0.084 to 0.095m vegetation
Intertidal vegetation	0 to 0.49m vegetation
	0.49 to 0.65m vegetation
	0.65 to 0.79m vegetation
	0.79 to 0.95m vegetation

Figure 3.2: GSI drone data components and their derived feature meta-classes

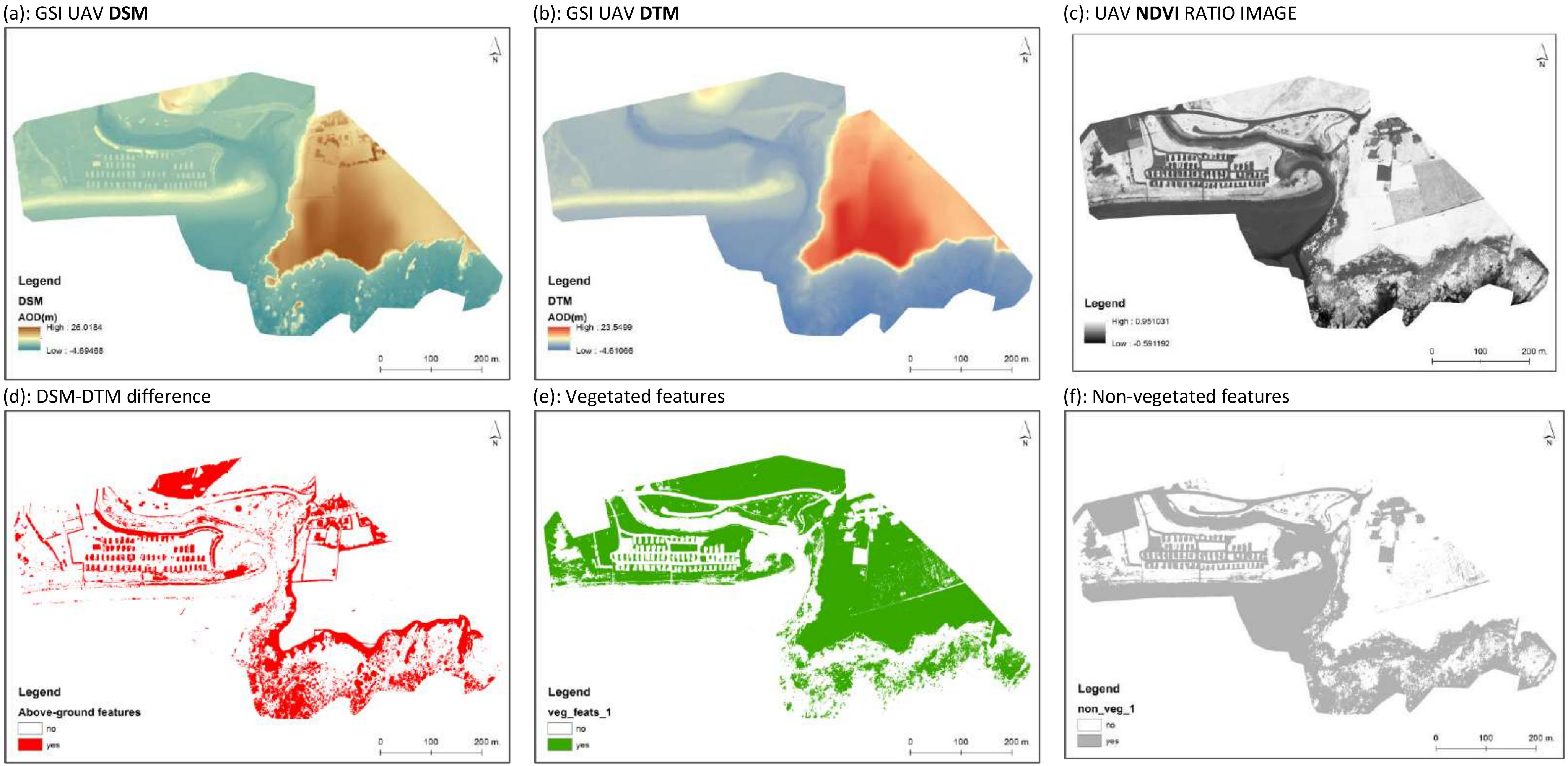
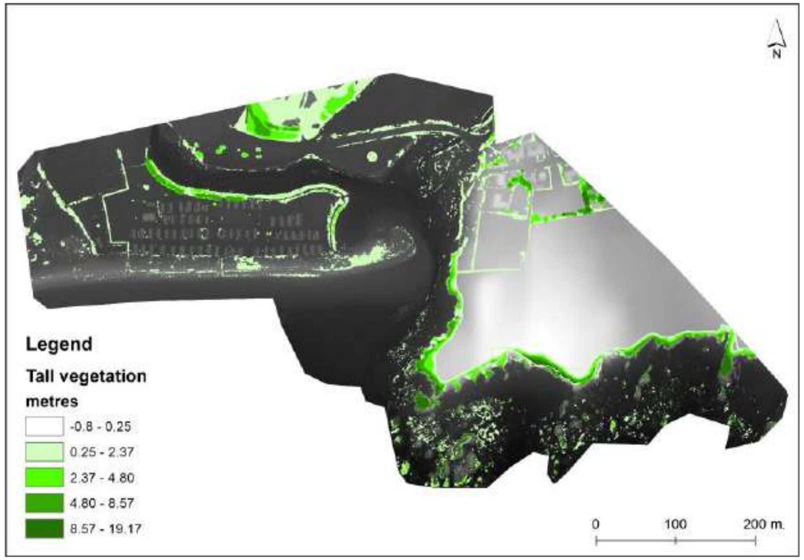
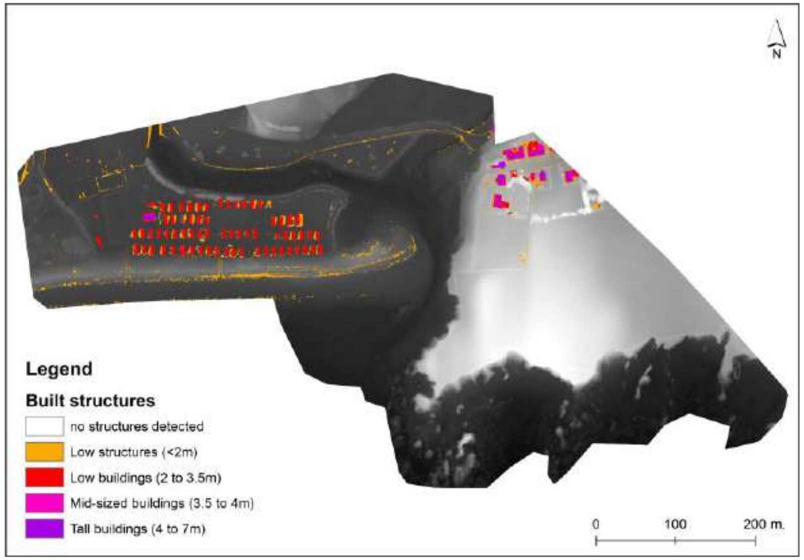


Figure 3.3: Polygonal Feature Classes derived from the GIS drone elevation-defined and spectral data Meta classes

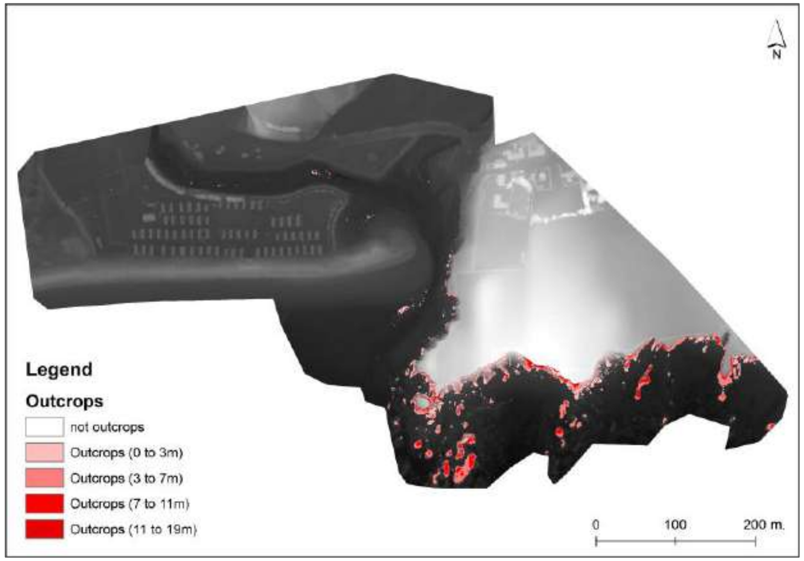
(a) Tall vegetation features



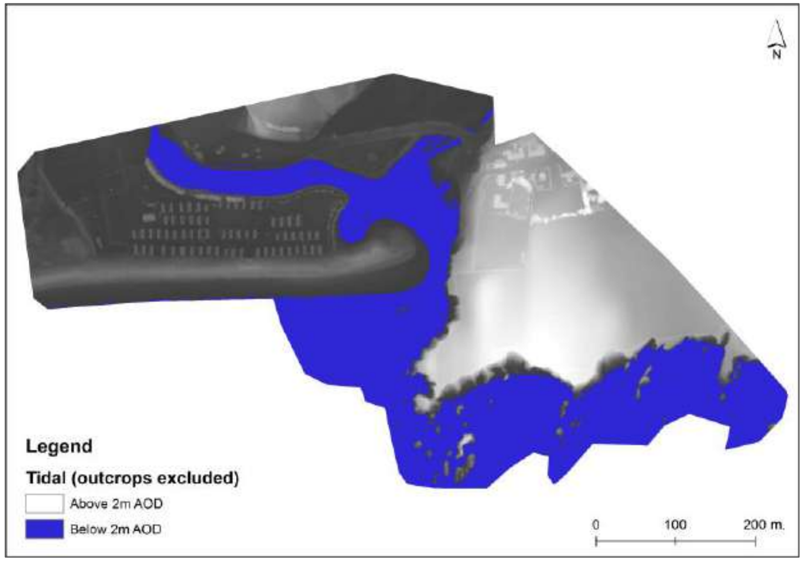
(b) Built structures



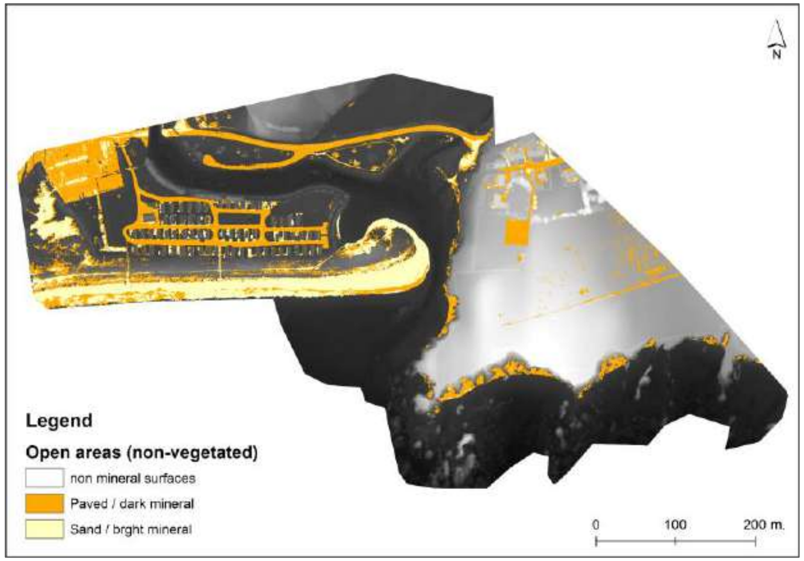
(c) Outcrop features



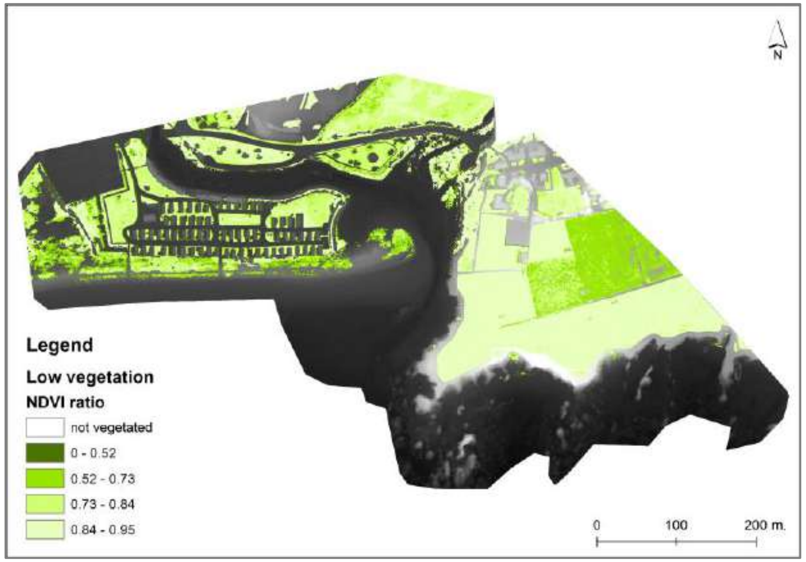
(d) Tidal extents (extracted by DSM elevation))



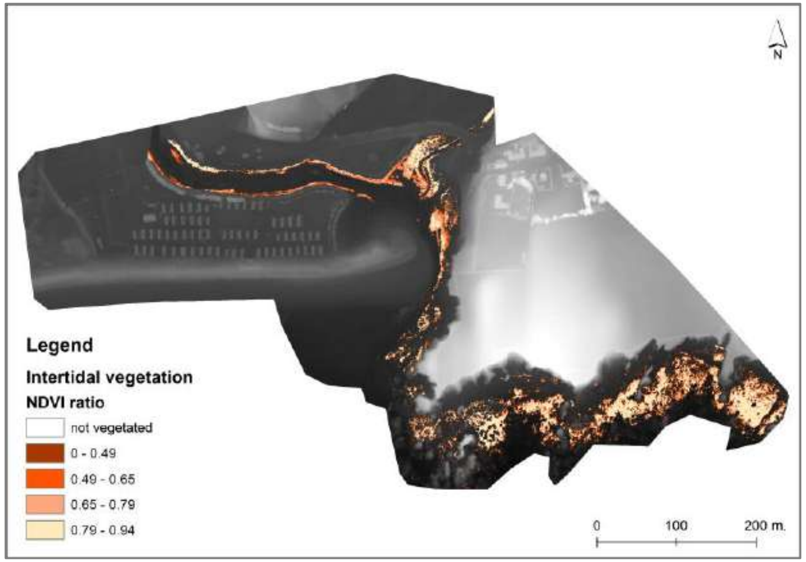
(e) Open non-vegetated features



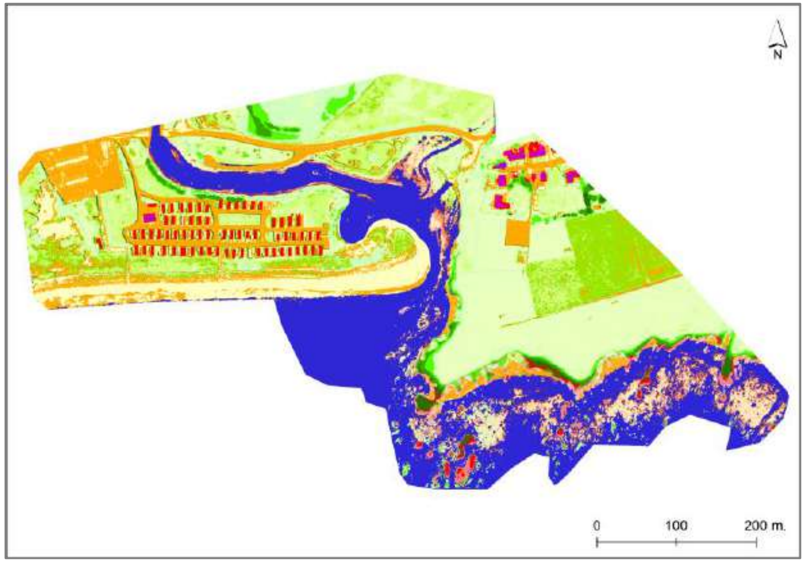
(f) Low-height vegetation features



(g) Intertidal vegetation features



(h) All features



SECTION 4 – Potential for shoreline accuracy evaluation using GSI UAS DSM data

The potential to use INFOMAR drone Digital Elevation Model (DEM) data to validate the elevation accuracy of tidal shorelines extracted from multi-date Sentinel-2 satellite images was assessed here. The existing very high-resolution GSI drone survey data for Bunmahon county Waterford was used for this assessment (Figure 4.1). The methodology implemented here was designed to be repeatable elsewhere, potentially providing the basis for the validation of Sentinel-2 intertidal DTM data (as was undertaken in section 2 of this study) in other Priority sites. The use of rapid digitising of shorelines form Sentinel-2 imagery (evaluated here as a prospective alternative to automated extraction with SHOREX) proved to be a limiting factor in terms of satisfactorily quantifying the efficacy of drone DTM data for shoreline validation. However, the use of GSI drone DTM data may likely represent a worthwhile and coherent alternative to shoreline extraction validation using GNSS only (*GNSS was applied to this end in section 2 of this report*), particularly as GSI drone surveys extend to additional Priority locations.

4.1 Methodological approach

- Eight cloud-free Sentinel-2 images were found for the drone survey site from within the entire Sentinel-2 image archive (Figure 4.2)
- Manual digitisation of apparent shorelines (Figure 4.3) was carried out for all 8 satellite images to determine the potential to extract shorelines without using SHOREX or Water Indices
- Shoreline vectors were linked to 5-minute tide levels (Malin OD) recorded at the Dunmore East tide gauge (Table 4.1)
- Shoreline tide-heights were evaluated relative to GSI drone DTM elevation (Malin OD) values (Figure 4.4)

4.2 Deliverable products

- An evaluation of the potential to use drone DEM data to evaluate the accuracy of Sentinel-2 shoreline extraction (figure 5)

4.3 Summary Conclusions

- The methodology applied could be usefully evaluated in any subsequent study of intertidal DTM generation from Sentinel-2 imagery
- The manual digitisation of shorelines from Sentinel-2 images did not provide a satisfactory basis for the generation of tide-encoded shoreline elevation values
- SHOREX or MNDWI or NDWI indices are likely produce more satisfactory results, for example if the potential for shoreline extraction from Sentinel-2 data was to be assessed for other INFOMAR Priority Bays.

Figure 4.1: GSI Drone DSM colour ramp

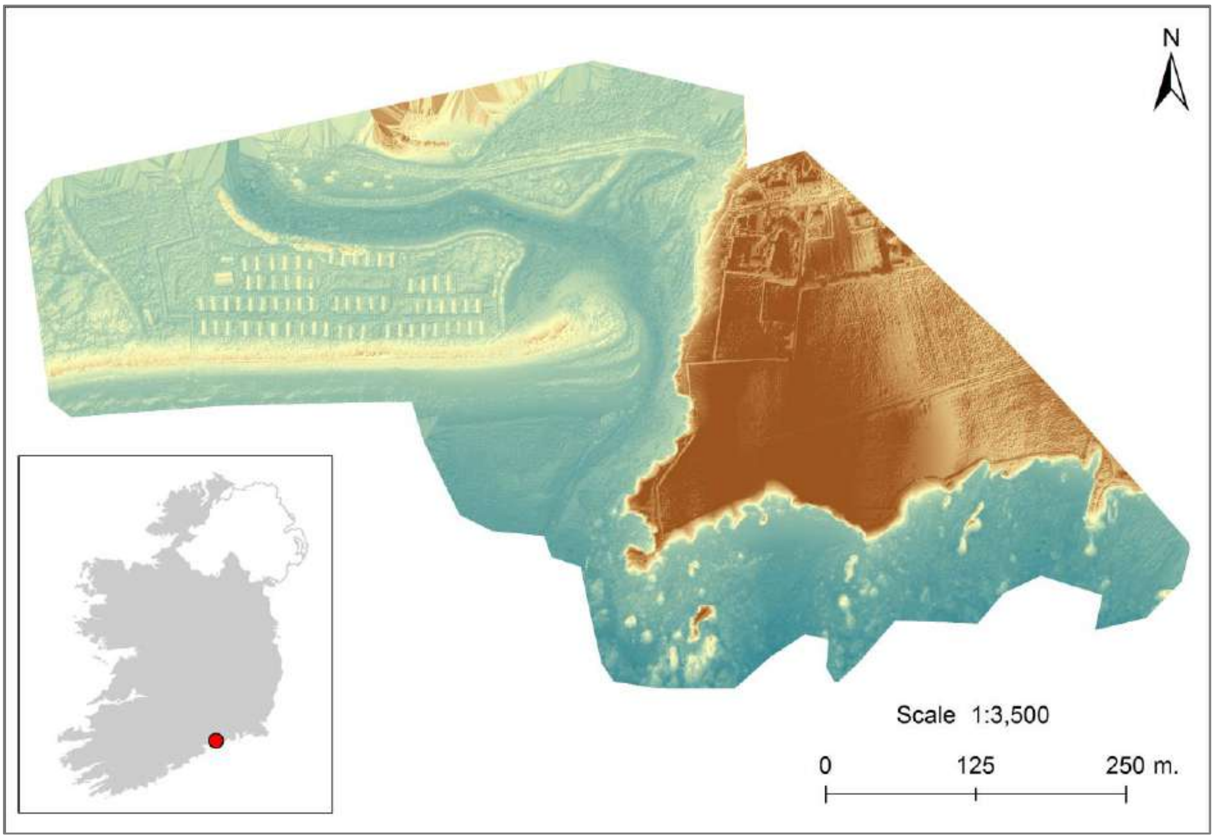
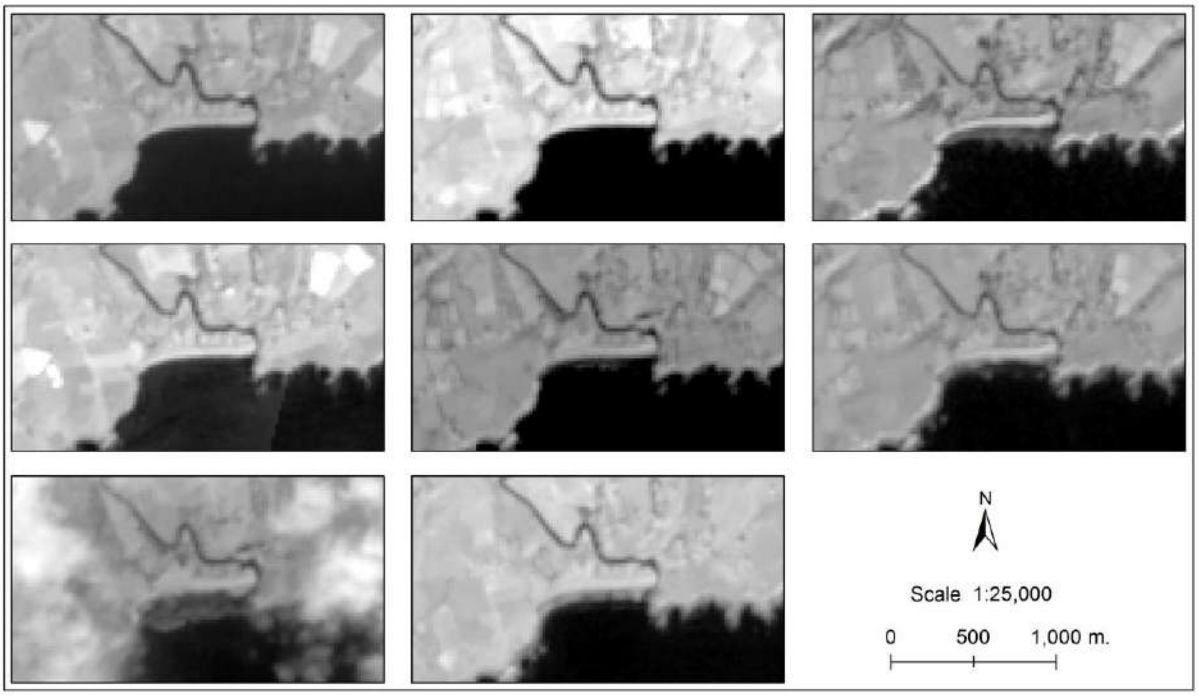


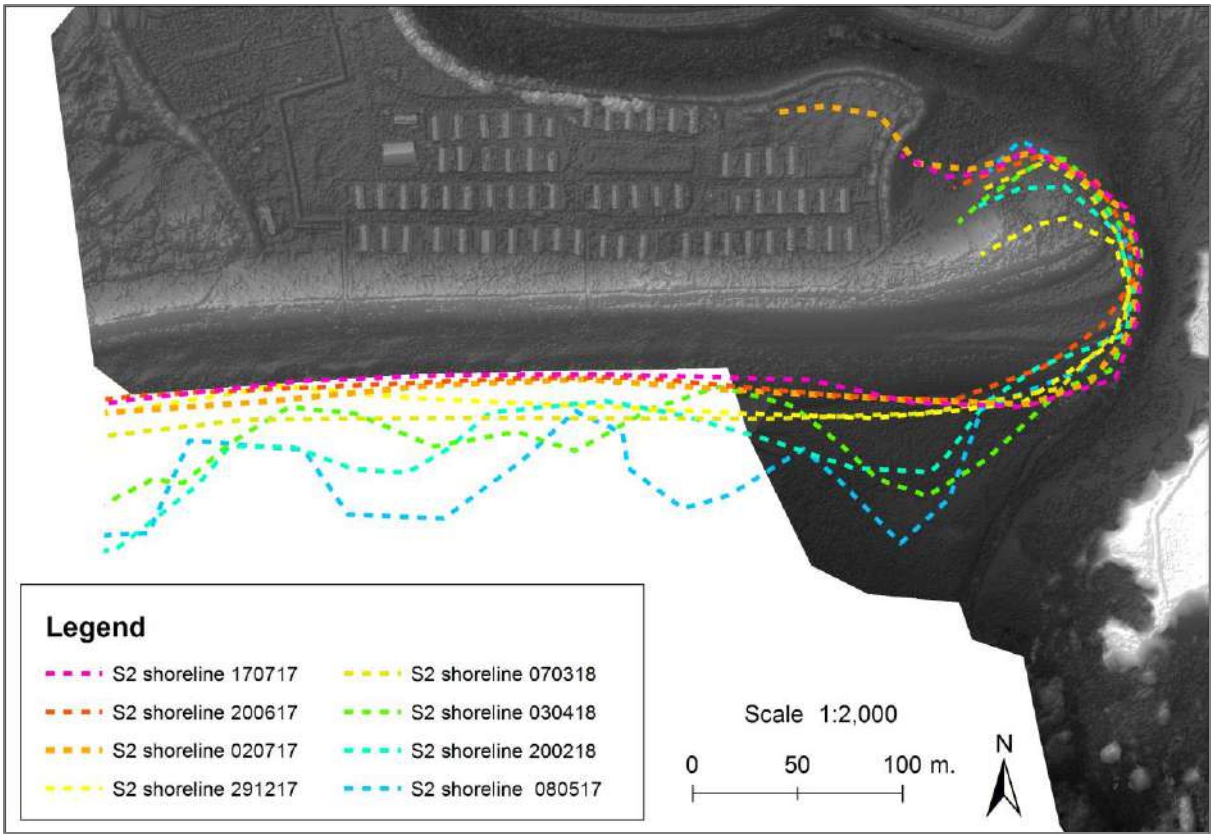
Figure 4.2: Cloud-free Sentinel-2 images for the Bunmahon drone survey site



4.4 Manual definition of shorelines

Manual extraction of visible shorelines form Sentinel-2 imagery was attempted here to assess its potential as a rapid alternative to automated extraction using SHOREX or Water Indices. While this unfortunately resulted in variable and consequently inconclusive validation results (Table 4.2), the accuracies that are now possible from photogrammetric drone DTM data (Coveney & Roberts, 2017) suggest that it has strong potential for quantifying the accuracy of Sentinel-2 shorelines.

Figure 4.3: Manually digitised shorelines



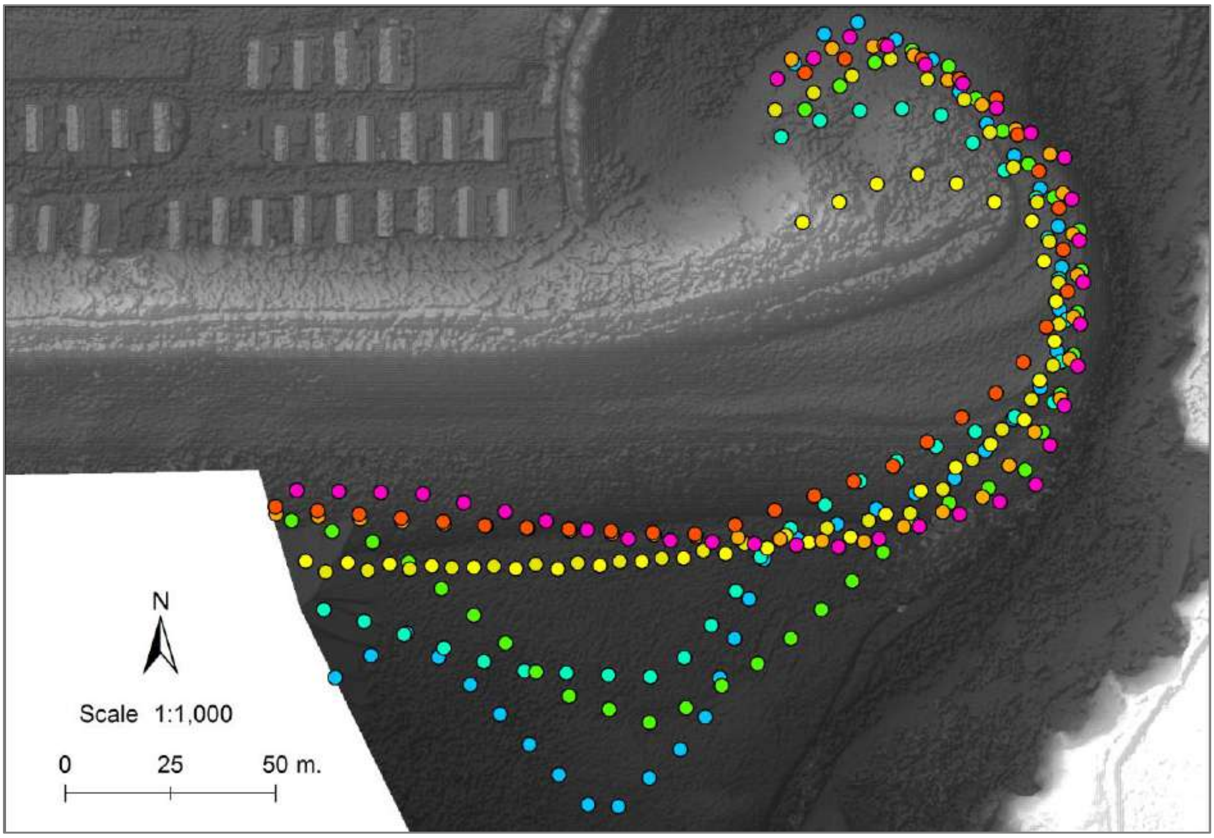
4.5 Tide records for shoreline elevation encoding

Table 4.1: Contemporaneous tide records (from Dunmore East tide gauge) for each shoreline.

S2 image date	S2 image time UTC	Tide level Dunmore East	Tide time UTC	Datum
08/05/2017	11:33:00	1.31	11:35:00	Malin
03/04/2018	11:33:00	1.81	11:35:00	Malin
20/02/2018	11:33:00	2.06	11:35:00	Malin
07/03/2018	11:43:00	2.82	11:45:00	Malin
20/06/2017	11:43:00	3.12	11:45:00	Malin
29/12/2017	11:34:00	3.25	11:35:00	Malin
17/07/2017	11:33:00	3.50	11:35:00	Malin
27/12/2017	11:45:00	3.53	11:45:00	Malin
02/07/2017	11:33:00	3.55	11:35:00	Malin

4.6 Validation of inferred shorelines using drone DTM

Figure 4.4: DSM elevation points used to validate (manually inferred) shoreline accuracy



4.7 Validation outcomes

Table 4.2: Summary elevation error statistics for the manually-inferred tide-encoded shorelines.

S2 image date	Tide level Dunmore East	Mean SL elev (z)	count	std dev	pos max err	neg max err	**Mean error (z)**
08/05/2017	1.31	0.72	38	1.26	2.14	-1.15	0.59
03/04/2018	1.81	0.87	37	1.15	2.4	-1.01	0.94
20/02/2018	2.06	1.27	33	1.55	2.63	-1.79	0.79
07/03/2018	2.82	1.20	32	1.09	3	0.19	1.62
20/06/2017	3.12	1.40	32	0.81	3.06	0.77	1.72
29/12/2017	3.25	1.79	30	2.35	3.45	-5.68	1.47
17/07/2017	3.50	1.27	35	0.86	3.56	0.41	2.23
02/07/2017	3.55	1.13	34	0.83	3.59	1.31	2.42

Summarised Project Conclusions

Section one: The 'Intertidal Feature Extraction' Toolbox developed for ArcGIS is re-usable, and could potentially form a basis for subsequent application within future GSI projects. Feature extraction from Sentinel -2 imagery offers potential for application to further INFOMAR Priority bays.

Section 2: Potentially useful intertidal DEMs can be generated by extracting multiple tide-defined shorelines from time-stamped Sentinel-2 imagery, attaching contemporaneous (5-minute resolution) tide levels recorded at nearby tide gauges. GNSS validation of the extracted shorelines confirmed that RMSE elevation accuracies (Table 2.2) of 0.30m are achievable (mean elevation error 0.18m), potentially providing a methodological basis for the generation of Sentinel-2 derived intertidal DTM data for additional INFOMAR Priority Bays.

Section 3: The combined use of high-resolution drone Digital Elevation Model (DEM) data and drone multispectral data from a single GSI drone survey data set allowed for the extraction of 24 feature classes, including thirteen intertidal / near-intertidal feature classes (Table 3.1). The model was designed and applied in ArcGIS, using simple raster algebra calculations, all of which could be implemented across a wide range of remote sensing or GIS software platforms.
The approach that was developed here may be of practical interest to GSI (and other bodies) for coastal change monitoring. Useful applications might include (at a minimum) integrity assessments of coastal defences, coastal erosion monitoring, coastal & intertidal feature mapping and the validation of satellite feature extraction from Sentinel-2 data sets.

Section 4: The methodology applied could be usefully evaluated in any subsequent study of intertidal DTM generation from Sentinel-2 imagery. The manual digitisation of shorelines from Sentinel-2 images did not provide a satisfactory basis for the generation of tide-encoded shoreline elevation values. SHOREX or MNDWI or NDWI indices are likely produce more satisfactory results, for example if the potential for shoreline extraction from Sentinel-2 data was to be assessed for other INFOMAR Priority Bays.

Re-usable Products issuing from the INTREPID Project

- A Sentinel-2 Feature extraction toolbox for ArcGIS
- A methodology that generates intertidal DTMs from Sentinel-2 images
- A feature extraction model that operates using drone DSM and image data.

Potentially useful applications

1. In terms of intertidal feature extraction from ESA Sentinel-2 imagery, potential useful applications include: coastal management and coastal change assessment arising from short-term weather events and longer-term climate variability
2. As regards shoreline extraction for 3D intertidal mapping from ESA Sentinel-2 imagery, potential useful applications include: intertidal 3D mapping for coastal management and change assessment, potentially filling a gap between onshore and nearshore 3D mapping products.
3. With respect to feature extraction from GSI drone imagery & 3D data, potential useful applications may include: coastal erosion monitoring, condition surveys of coastal defences, detailed assessment of targeted coastal features, assessment of risk to infrastructure and vulnerabilities of archaeological heritage.
4. GSI drone DTM data might be applied to evaluate the accuracy of Sentinel-2 shoreline extractions and derived intertidal DTM products.

Opportunities for subsequent research

1. Section 1: The project developed a prototype toolset that could provide the basis for subsequent GSI investigations and might usefully provide the basis for a subsequent study that focuses on a number of INFOMAR Priority Bays.
2. Section 2: The extraction of multiple tide-derived shorelines from time-stamped Sentinel-2 images (linked to 5-minute resolution Irish tide gauge records) appears to be viable for intertidal 3D mapping. The methods developed here might therefore be transferred to other Irish intertidal locations.
3. Section 3: The GSI drone feature extraction approach is designed to be repeatable, and could be directly applied to subsequent GSI drone surveys.
4. Section 4: GSI drone Digital Elevation Model data may provide a very useful method for evaluating the accuracy of shorelines extracted from Sentinel-2 imagery.

References

Coveney, S. and Monteys, X., (2011), Integration Potential of INFOMAR Bathymetric LiDAR with External Onshore LiDAR Datasets. *Journal of Coastal Research,* Special issue no. 62 (LiDAR applications), pp.19-29.

Coveney, S. & Monteys, X., (2009), Integration of INFOMAR Bathymetric LiDAR with external onshore LiDAR datasets, *INFOMAR research report INF-08-06-COV*.

Coveney, S., Roberts, K., (2017), Lightweight UAV digital elevation models and Orthoimagery for environmental applications: data accuracy evaluation and potential for river flood risk modelling. *International Journal of Remote Sensing*, 38(8-10):3159-3180.

Coveney, S. and Fotheringham, S., (2011) The impact of DEM data source on prediction of flooding and erosion risk due to sea-level rise, International Journal of Geographical Information Science, 25, 7, pp.1191–1211.

Coveney, S., Fotheringham, S, Charlton, M. and McCarthy T., (2010) Dual-scale validation of a medium-resolution coastal DEM with Terrestrial LiDAR DSM and GPS, *Computers and Geosciences*, 36, pp.489–499.

Marine Institute, (2018), Tide Gauge records for Ireland, http://www.marine.ie/Home/site-area/data-services/real-time-observations/tidal-observations-imos, accessed September, 2018.

Palomar-Vázquez, J. M., Almonacid-Caballer, J., Pardo-Pascual, J. E., Sánchez-García, E., (2018), SHOREX: a new tool to automatic and massive extraction of shorelines from Landsat and Sentinel 2 Imagery. *Proceedings of Coastlab 2018*, IHCantabria, 22-26 May 2018.

Pardo-Pascual, J. E., Sánchez-García, E., Almonacid-Caballer, J., Balaguer-Beser, A., (2018), Assessing the Accuracy of Automatically Extracted Shorelines on Microtidal Beaches from Landsat 7, Landsat 8 and Sentinel-2 Imagery, *Remote Sensing,* 10, 326.

Pardo-Pascual, J. E., Almonacid-Caballer, J., Polomar-Vázquez, R., (2012), Automatic extraction of shorelines from Landsat TM and ETM multi-temporal images with subpixel precision, *Remote Sensing of Environment*, 123:1-11.

Xu, H. "Modification of Normalised Difference Water Index (NDWI) to Enhance Open Water Features in Remotely Sensed Imagery." International Journal of Remote Sensing 27, No. 14 (2006): 3025-3033.