SENTINEL-2 DERIVED WATERLINES FOR COASTAL MONITORING APPLICATIONS: A NEW APPROACH FOR QUANTIFYING VERTICAL AND HORIZONTAL ACCURACIES

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ABSTRACT:

Accurate and consistent mapping of the boundary between land and water (the 'waterline') is critical for tracking coastal change and coastal management. Earth Observation satellite remote sensing provides a unique cost-effective alternative to traditional methods. Waterlines from satellites are often derived by methods based on spectral indices that lead to the separation between land and water. The validation strategy for these products requires a complex approach from accuracy assessment (quantifying error) to verification of its suitability for monitoring applications. Traditionally the accuracy of EO products is reduced and simplified to the resolution of the sensor or satellite that collects the data. However, environmental variables (sea conditions, weather, vegetation, anthropic) that may have a direct effect on the sensor and on the coastline that we are trying to monitor are not taken into consideration. Segments of Sentinel-2-derived waterlines were selected in North Bull Island for further analysis in the creation of a new benchmark dataset for understanding the waterline models of eastern Ireland. In our novel approach, we propose that horizontal accuracy assessment is performed by using the mean absolute distance between the GNSS reference line and the Sentinel-2-derived waterline. The vertical accuracy assessment was then calculated by the difference between the attributed waterline height compared with the mean GNSS elevation at the intersection points. Results were then compared with Dublin Port tide gauge height record. The development of reference validation models can allow more efficient application of satellite data for monitoring, and understanding how environmental variables affect each case study.

1. INTRODUCTION

Coastal monitoring using earth observation (EO) products, in particular satellite imagery from the ESA's Sentinel satellites, offers distinct advantages over in-situ monitoring methods such as terrestrial or airborne surveying. These advantages typically include no-cost data access, multi-temporality, high spectral resolution, rapid data access and low labour input (Tong et al., 2020). While the accuracy cannot compare with in-situ measurements, the high temporal resolution of the Sentinel satellites allows a large database of imagery (and therefore, waterlines) to be accumulated for areas along the coast (Zhao et al., 2008). A single satellite revisit time of 10 days (Phiri et al., 2020), and a combined satellite revisit time of 5 days which, at mid-latitudes, results in 2-3 days (Bergsma and Almar, 2020) something that is essential for countries like Ireland that is covered completely in clouds over 50% of the time (NASA, 2011). A large database of imagery increases the chance of having low to no cloud cover for imagery that is suitable for waterline extraction.

A satellite-derived waterline is defined as the horizontal location of the land-sea boundary as seen in a remotely sensed image. This waterline is assumed to be a line of equal elevation and can therefore be used as a topographical quasi-contour line to which a tide height may be subsequently assigned. From that, a DEM can be constructed (Ryu et al., 2008). Satellite-derived waterlines can be used as a method for estimating slopes while taking into account nearshore topography (Zhou et al., 2021). Accurate and consistent mapping of the boundary between land and water (the 'waterline') is critical for tracking coastal change and coastal management.

The waterline method is considered to be the most optimal for deriving DTM from the optical satellite imagery method of generating topographic maps of the intertidal zone (Kang et al., 2017). This method used water edges derived from remotely sensed products to construct digital elevation models (DEMs) in order to develop hydrodynamic models, study sediment transport, and monitor the intertidal zone (Mason et al., 1995).

Tong et al. (2020) extracted waterlines from Landsat single spectral bands Near Infrared (NIR) and Short-Wave Infrared (SWIR) using band rationing approaches such as the Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI) and Green Short Wave Infrared (Green/SWIR). NIR, SWIR, and Thermal Infrared (TIR) were equally effective when implemented in waterline extraction (Ryu et al., 2008). However, in images where the tide was retreating, TIR and NIR were more effective than SWIR. Heights assigned to waterlines extracted from Landsat images by obtaining co-temporal tidal gauge observation data (Xu et al., 2016).

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The objective of this paper is to expand on current validation models by looking into a holistic approach to waterline uncertainty, taking into account their application in different coastal types environments (Figure 1). The overall goal of increase the confidence level in products generated by EO for monitoring the coast. This will allow monitoring coastal areas inaccessible by traditional methods, a more efficient study from an economic point of view, and a greater number of datasets available for adaptive and predictive coastal models.

Identifying North Bull Island as a natural laboratory that serves as a benchmark for EO product validation in Ireland and along macro-meso tidal coasts and comparable environmental features around the world.

This benchmark dataset defined as BeachMark aims to be composed of a greater number of reference waterlines that cover a larger range of years. In addition to introducing new variables of the weather conditions (wind, fog, clouds, lightness), about the sea (tide, waves and currents) and related to the vegetation present in the profile of the beaches (algae, bushes, grass). All of this will be publicly available to end-users through a free-access repository.

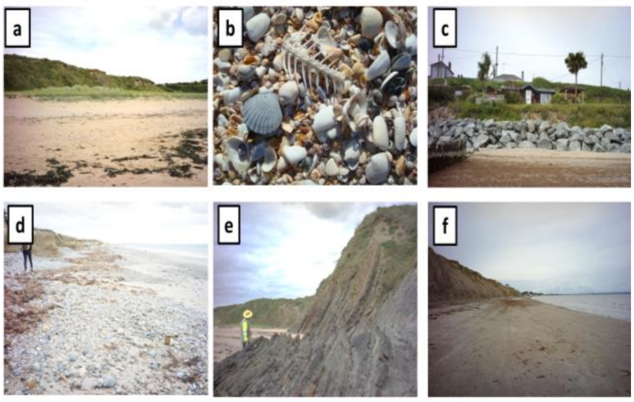

Figure 1. Different coastal types environments to test the accuracy of satellite-derived waterlines in the Republic of Ireland. (a) Sand beach, (b) bioclast beach, (c) coastal defences, (d) pebble beach, (e) rocky cliff, and (f) mud beach.

1.1 Study Area: Bull Island, Co. Dublin

Bull Island is a sand spit approximately 5 kilometres in length and 1 kilometre to 200 metres wide, created following the construction of the South Wall of Dublin Port completed in 1825 (Figure 2). Tidal changes caused by the construction of the North and South Dublin Port walls led to the deposition of sand and silt in the area. Bull Island also has an actively accreting foredune system, with current dunes measuring between 2 and 9 metres above mean sea level (Mathew et al., 2019).

North Bull Island is a protected area as a UNESCO Biosphere Reserve (Brooks et al., 2016). Additionally, the dune system has a moderate slope without any very high cliffs, preventing satellite shadow zones. Five Sentinel-2-derived waterlines were selected in this area for further analysis because it is a reference area for understanding the hydrodynamic models of eastern Ireland, widely studied by the Department of the Environment, Climate, and Communications.

In addition, North Bull Island has added value in the current situation of climate change and rising sea levels in which we live. It has become Dublin's natural barrier against extreme weather events. Monitoring and analysing its evolution with erosive and depositional zones and cycles can be key to managing the Irish coast in an efficient and sustainable way for present and future generations. Proof of the relevance that this area has in the management of the Irish coast and marine ecosystems are the several plans, reports, and research that are being dedicated to this location (Harris, 1977; Mulrennan, 1993; McCorry and Ryle, 2009; RPS, 2009; Dublin City Council, 2020).

Figure 2. Study area of North Bull Island (County Dublin, Republic of Ireland). Source: Sentinel 2 images (ESA).

2. DATASETS

2.1 Sentinel 2 optical imagery

The images from the Sentinel 2 A and B satellites are freely available from the Copernicus Open Access Hub.

The Sentinel 2 Level 2A products are the images that have been used in this research, they are composed of thirteen bands that operate from the visible to the short-band infrared (SWIR). The surface covered by each of these tiles is 110 x 110 km^2 (D'Ascola, 2022).

Another characteristic of this type of product is that images have been orthorectified. Orthorectification eliminates geometric and scale distortions in satellite images due to sensor, topographic variations, and curvature of the Earth. Level 2A products are Level-1C products in which Surface Reflectance (SR) is atmospherically corrected. Therefore, it decreases atmospheric effects (thin clouds and aerosol scattering) which improves the derived waterlines' accuracy by helping in the detection and characterization of Earth's surface changes (ESA, 2023). Five Sentinel 2 images have been used, 1 corresponding to 2021 and the remaining 4 from 2022 (Table 1).

Sentinel 2 images		
Date	**Time UTC**	**Satellite**
06/12/2021	11:44:51	2A
01/03/2022	11:43:49	2B
03/03/2022	11:33:21	2A
06/03/2022	11:43:51	2A
23/03/2022	11:33:21	2A

Table 1. Date, time, and satellite type of the five Sentinel 2 images used from Copernicus.

2.2 Global Navigation Satellite System (GNSS): location with height

Location points were measured using a GNSS Trimble solution constrained using a Virtual Reference Station (VRS) system. This methodology allows us to obtain XYZ accuracies below 5 cm. The data was collected simultaneously with the Sentinel 2 acquisition time using a GNSS pole walking along the edge between water and land (slightly on the water side). GNSS measurements were taken at 1 metre intervals.

Geopositioned measurements (X, Y), as well as height (Z - MSL), are collected together with the acquisition timestamp. This allows line post-processing in order to subset the GNSS validation segment near the Sentinel 2 acquisition time, 3 minutes before and after (6 minutes in total). The length of the waterline segment measured by the GNSS is generally around 500 meters but can vary slightly depending on the acquisition speed.

3. METHODOLOGY

3.1 Sentinel 2 waterline extraction

Satellite-derived waterlines (SDWL) represent the instantaneous boundary between land and sea at the time the satellite passes over. The waterlines were derived from EO optical data (co-registered Sentinel-2 imagery) using a locally adaptive threshold method based on spectral indices (ARGANS, 2022). The spectral index used for the extraction of the waterlines was Green Normalized Difference Vegetation Index (GNDVI) (Gitelson et al., 1996; Da Silva et al., 2022). The adaptive threshold generates the waterline using the auxiliary coastline vector as a "guide" along which a small kernel (75 x 75 pixels) frame slide. The threshold used to distinguish between land and water is the smallest value between the peaks of the histogram of index pixels inside a kernel that is smoothed to a bimodal distribution (Liu and Jezek, 2004).

The waterline vector generated presents discontinuities as a result of environmental factors such as weather, waves, sandbars, and cusps. The Marching Square algorithm is used to contour the waterlines and reduce the number of discontinuities (Paulsson, 2016; Chartock, et al., 2017 Warmerdam and Rouault, 2022); followed by canny edge detection to convert the waterlines into vector format (Liu and Jezek, 2004; ARGANS, 2022).

3.2 Horizontal accuracy assessment

Horizontal accuracy assessment has been performed by using the mean absolute distance between the GNSS reference waterline and the Sentinel 2 derived waterline. The GNSS waterlines were acquired at the same time that the satellite flew over the study area. This fact reduces the possibilities of variables (climatic, tidal, anthropic) affecting the comparisons between both datasets.

The Sentinel 2 derived waterline (vector data) is divided into points at 1 metre intervals using the tool “Generate points along lines” of ArcGIS Desktop version 10.8. The "Spatial join" tool is then used to find the nearest GNSS validation points to the Sentinel 2 determined waterline points. The Euclidian distance between the selected SDWL points and the GNSS validation points are used to calculate the Mean Absolute Error (MAE) for each dataset using the MAE formula below.

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n} | x_i - x | \qquad (1)$$

where n = number of errors
Σ = summation symbol
$| x_i – x |$ = absolute errors

3.3 Vertical accuracy assessment

The vertical accuracy assessment has been calculated by the difference between the attributed waterline height compared with the mean GNSS elevation at the intersection points. Waterlines are assumed to have a uniform height to calculate the error.

This evaluation is carried out by assigning to each waterline an average elevation that comes from the GNSS elevations at the points of intersection with the SDWL. The results obtained are compared with the values of the Dublin Port tide gauge height record located at a maximum distance of 7.5 km from waterline points (Marine Institute, 2023). The tide rates are acquired at the same time as the Sentinel 2 image (Xu et al., 2016) thanks to the measurement period of the Irish National Tide Gauge Network which records the tide every 5 minutes.

The mean heights of the GNSS waterlines obtained at North Bull Island have been calculated for 10-minute intervals whenever such measurements existed (Table 2). The 10-minute intervals have been defined by the Sentinel 2 acquisition time and the tide gauge measurement times (every 5 minutes). For example, if the waterline of 06/12/2021 was obtained at 11:44:51, the closest tide gauge measurement is taken, in this case, that of 11:45:00 as well as the subsequent and previous measurements (11:50:00 and 11:40:00).

Waterline	Dublin Port TG Height (LAT) (m)				GNSS (LAT)
Date	**Before**	**Closest**	**After**	**Mean**	**Mean**
06/12/2021	4.34	4.39	4.40	**4.377**	**4.375**
01/03/2022	3.65	3.60	3.57	**3.607**	**3.604**
03/03/2022	4.46	4.47	4.48	**4.47**	**4.452**
06/03/2022	3.26	3.32	3.36	**3.313**	**3.299**
23/03/2022	2.50	2.54	2.61	**2.55**	**2.532**

Table 2. Heights from 5 SDWL compared to GNSS reference measurements.

The mean of the tide gauge readings has been calculated averaging the 3 indicated measurements and has been compared with the mean height of the GNSS points for the time interval of the lowest tide with respect to the highest within the period of 10 minutes.

4. RESULTS

Satellite-derived waterlines prior to their application for purposes of coastal evolution must be validated to know their precision and uncertainties levels (Pardo-Pascual et al., 2018). Five SDWL corresponding to 2021 and 2022 have been validated on the following days: 06/12/2021, 01/03/2022, 03/03/2022, 06/03/2022, and 23/03/2022 (Appendix 1).

4.1 Horizontal accuracy assessment

Initial results were obtained by comparing five Sentinel 2 SDWL and the corresponding GNSS validation segments. Mean Absolute Error (MAE) is the average of all absolute errors. The polarity of the accuracy values with respect to the GNSS reference line was taken into account to know the tendency of the bias of each of the waterlines (positive values, offshore and negative values onshore). Maximum and minimum errors and standard deviations of the Sentinel 2 waterlines compared to the reference measurement are also included (Table 3).

Waterline Date	Mean Error (m)	Max error (m)	Min error (m)	MAE (m)	SD Deviation (m)
06/12/2021	16.48	26.03	7.57	16.48	3.38
01/03/2022	3.80	8.87	-1.85	3.94	2.38
03/03/2022	8.65	15.71	0.75	8.65	3.30
06/03/2022	7.54	23.46	-14.77	10.46	8.33
23/03/2022	35.70	51.44	18.36	35.70	9.38

Table 3. Horizontal accuracies from 5 SDWL compared to GNSS reference measurements.

Five Sentinel 2 derived waterlines have been compared, 4 from 2022 and 1 from 2021. The average mean absolute error (MAE) is 15.04 meters. Three of the 2022 waterlines, specifically those belonging to March 1, 3 and 6, present values lower than this average with MAE values of 3.94 m, 8.65 m and 10.46 m respectively.

The five waterlines exhibit a predominantly offshore shift compared to the GNSS validation segment. Only the waterlines corresponding to March 1st and 6th appear to shift inshore. This may be verified by looking at the minimal error values for all the waterlines, as it is these days that have negative values.

The most accurate SDWL was obtained on the 1st March 2022 with a MAE of 3.94 metres and a standard deviation of 2.38 m. This SDWL was the only one acquired with the tide going down.

The rest of the SDWL obtained by Sentinel 2A and with the rising tide include that of March 3, 2022 with a MAE of 8.65 meters and a standard deviation of 3.30 m. The least accurate SDWL was obtained on the 23rd March 2022 with a MAE of 35.70 metres and a standard deviation of 9.38. The horizontal accuracy of the 5 SDWL shows a median error of 10.5 m which is near the pixel size.

These results must be interpreted taking into account the tidal conditions in which the Sentinel 2 images used to calculate the waterlines were collected. All images coincided with a time when the tide was rising except for the day 1st of March 2022 when the best result was obtained in horizontal accuracy which coincided with the tide falling. Furthermore, the height of the tide that day coincides with the median (3.60 m) of all the tides measured between the maximum of 4.39 m and the minimum of 2.54 m registered in the Dublin Port tide gauge. Additionally, only this image was captured by the Sentinel 2B satellite; the other 4 were captured by Sentinel 2A (Table 4).

Waterline Date	Sentinel	Dublin Port TG (LAT)	Howth TG (LAT)	Tide Evolution
06/12/2021	2A	4.39 m	4.62 m	Rising
01/03/2022	2B	3.60 m	3.70 m	Falling
03/03/2022	2A	4.47 m	4.68 m	Rising
06/03/2022	2A	3.32 m	3.51 m	Rising
23/03/2022	2A	2.54 m	2.65 m	Rising

Table 4. Tidal conditions in which the 5 SDWL were obtained.

4.2 Vertical accuracy assessment

4.2.1 Height of the intersection points of the GNSS with the SDWL: The vertical accuracy has been calculated based on the average height of all points of intersection between the GNSS collected on November 5, 2022 and the points of the waterlines derived from Sentinel 2. The number of reference points on which the average height values vary are based on 128 intersection points on the waterline on 03/03/2022 to 253 points on 12/06/2021, on the waterline with the most intersection points. The values obtained from calculating the average height in LAT of all intersection points can be seen below (Table 5).

	Mean Sea Level (m)				LAT (m)
Waterline Date	**Min**	**Max**	**Mean**	**SD**	**Mean**
06/12/2021	0.658	2.410	1.335	0.246	**3.780**
01/03/2022	0.733	2.472	1.067	0.289	**3.512**
03/03/2022	0.569	2.442	1.755	0.402	**4.887**
06/03/2022	0.254	1.266	0.671	0.142	**3.116**
23/03/2022	-0.705	0.251	-0.118	0.205	**2.327**

Table 5. Lowest Astronomical Tide (LAT) reference measurements were used to calculate the vertical accuracies from the 5 SDWL at the locations of intersection.

A general pattern can be seen in the height comparison between the Dublin Port tidal gauge measurement and the average of the GNSS points. The tide gauge data are fewer than all GNSS mean values. For the five SDWLs, these differences range from 9 cm to 60 cm. Since the waterline at the end of 2021 is the one with the biggest error in this analysis, the range of discrepancies is limited to 41 cm if only the four SDWLs calculated in 2022 are taken into consideration.

4.2.2 Height of the GNSS waterlines co-temporal with the Sentinel 2 acquisition: The vertical accuracy was also contrasted using a second methodology. In this case, the average of all the height values recorded by the GNSS in the period of 10 min elapsed within the first and the last measurement of the tide gauge has been calculated. The number of heights in Lowest Astronomical Tide (LAT) used to calculate these values varies between 700 and 770 GNSS points for each of the SDWLs. This variation is only due to the speed of acquisition of the measurements since the GNSS was recorded with an interval of 1 m.

The mean of the tide gauge has been calculated between the three indicated measurements and has been compared with the mean height of the GNSS points (Table 6).

	MSL (m)	**LAT (m)**	
Date	**GNSS Mean Height**	**GNSS Mean Height**	**Mean Dublin Port TG**
06/12/2021	1.938	**4.375**	**4.377**
01/03/2022	1.160	**3.604**	**3.607**
03/03/2022	2.007	**4.452**	**4.470**
06/03/2022	0.854	**3.299**	**3.313**
23/03/2022	0.087	**2.532**	**2.550**

Table 6. Comparison of mean height values between the GNSS measurements and 3 co-temporal Dublin Port tide gauges record.

The vertical accuracy, the difference between the calculated heights of the waterline and the attributed tide gauge water level, returned an average value inferior to 3 cm.

5. CONCLUSIONS

Accuracy assessments on satellite-derived datasets are essential to provide confidence in coastal change products. The validation of five satellite-derived waterlines in a macro-tidal environment has shown a good positional alignment with the GNSS reference lines with a median error close to the image pixel size. The majority of this error is displaced to the offshore. The vertical difference between the satellite-derived waterline (tide gauge height) and the GNSS height reference lines returned a median value below 21 cm.

The development of benchmark validation models employing high-quality, accessible, and constant datasets, such as satellite data, might provide tools to communities and government bodies in coastal adaptation. BeachMark aims to become a reference benchmark dataset that end users can rely on to have greater confidence in the results obtained from EO products for coastal applications.

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REFERENCES

ARGANS, 2022. Algorithm Theoretical Baseline Document. Ref: SO-TR-ARG-003-055-009-ATBD-WL. https://coastalerosion.argans.co.uk/src/SO-TR-ARG-003-055-ATBD-WL-VNIR.pdf (6 June 2023)

Bergsma, E. W., Almar, R., 2020. Coastal coverage of ESA'Sentinel 2 mission. Advances in Space Research, 65 (11), 2636-2644.

Brooks, P. R., Nairn, R., Harris, M., Jeffrey, D., Crowe, T. P., 2016. Dublin Port and Dublin Bay: Reconnecting with nature and people. Regional Studies in Marine Science, 8, 234-251, https://doi.org/10.1016/j.rsma.2016.03.007.

Chartock, E., LaRow, W., Singh, V., 2017. Extraction of building footprints from satellite imagery. Stanford University Report.

D'Ascola, F., Cassese, M. L., Jones, M., Lugeri, N., Pesarino, V., Salmeri, A., Beck., A. L., Taji, M. A., 2022. Chapter Monitoring of the evolution of "barene" borders and the safeguard of the Venice Lagoon morphology: a contribution from the Coastal Change from Space Project results. https://doi.org/ 10.36253/979-12-215-0030-1.18

Da Silva, P. G., Sánchez, J. M., Medina, R., Beck, A. L., Taji, M. A., 2022. On the use of satellite information to detect coastal change: Demonstration case on the coast of Spain. Authorea Preprints. https://doi.org/ 10.1002/essoar.10511027.1.

Dublin City Council., 2020. North Bull Island Nature Reserve. Action Plan 2020 -2025 for the implementation of Management Objectives. Parks, Biodiversity and Landscape Services.

European Space Agency (ESA), 2023. Copernicus. Sentinel-2 MultiSpectral Instrument (MSI) User Guide. Retrieved 13th of July of 2023 from https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-2-msi

Gitelson, A. A., Kaufman, Y. J., Merzlyak, M. N., 1996. Use of a green channel in remote sensing of global vegetation from EOS-MODIS. Remote sensing of Environment, 58(3), 289-298. https://doi.org/10.1016/S0034-4257(96)00072-7

Harris, C.R., 1977. Sedimentology and Geomorphology. In: D.W. Jeffrey, (Ed), The North Bull Island, Dublin Bay, a modern coastal natural history. The Royal Dublin Society. Dublin.

Kang, Y., Ding, X., Xu, F., Zhang, C., Ge, X., 2017. Topographic mapping on large-scale tidal flats with an iterative approach on the waterline method. Estuarine, Coastal and Shelf

Science, 190, 11-22. https://doi.org/10.1016/j.ecss.2017.03.024. pp 11-22.

Liu, H., Jezek, K. C., 2004. Automated extraction of coastline from satellite imagery by integrating Canny edge detection and locally adaptive thresholding methods. International journal of remote sensing, 25(5), 937-958.

Marine Institute., 2023. "Irish National Tide Gauge Network." Retrieved 11th of July of 2023 from https://erddap.marine.ie/erddap/tabledap/IrishNationalTideGaugeNetwork.html.

Mason, D. C., Davenport, I. J., Robinson, G. J., Flather, R. A., McCartney, B. S., 1995. Construction of an inter-tidal digital elevation model by the 'Water-Line' Method. Geophysical Research Letters, 22(23), 3187-3190. 10.1029/95GL03168.

Mathew, S., Pellicer, X. M., Caloca, S., Monteys, X., Zarroca, M., Jiménez-Martín, D., 2019. Bull Island: Characterisation and development of a modern barrier island triggered by human activity in Dublin Bay, Ireland. Irish Geography, 52, 75-100. https://doi.org/10.2014/igj.v51i2.1378

McCorry, M., Ryle, T., 2009. A management plan for North Bull Island. Dublin City Council, Dublin.

Mulrennan, M. E., 1993. Changes since the Nineteenth Century to the Estuary-Barrier Complexes of North County Dublin. Irish Geography, 26(1), 1-13. https://doi.org/10.1080/00750779309478714

NASA, 2011. Earth Observatory. Retrieved 10th of July 2023 from https://earthobservatory.nasa.gov/images/49687/ireland.

Pardo-Pascual, J. E., Sánchez-García, E., Almonacid-Caballer, J., Palomar-Vázquez, J. M., Priego De Los Santos, E., Fernández-Sarría, A., Balaguer-Beser, Á., 2018. Assessing the accuracy of automatically extracted shorelines on microtidal beaches from Landsat 7, Landsat 8 and Sentinel-2 imagery. Remote Sensing, 10(2), 326.

Paulsson, H., 2016. Geospatial Processing in the Cloud.

Phiri, D., Simwanda, M., Salekin, S., Nyirenda, V. R., Murayama, Y., Ranagalage, M., 2020. Sentinel-2 data for land cover/use mapping: A review. Remote Sensing, 12(14), 2291.

RPS, 2009. Environmental report of the draft Dublin city development plan 2011-2017 Strategic Environmental Assessment. Dublin City Council, Dublin.

Ryu, J.-H., Kim, C., Lee, Y.-K., Won, J.-S., Chun, S. S., Lee, S., 2008. Detecting the intertidal morphologic change using satellite data. Estuarine Coastal and Shelf Science. 2008; Volume 78, pp 623-632. 10.1016/j.ecss.2008.01.020.

Tong, S., Deroin, J.-P., Pham Thi, L., 2020. An optimal waterline approach for studying tidal flat morphological changes using remote sensing data: A case of the northern coast of Vietnam. Estuarine Coastal and Shelf Science. 236. 106613. 10.1016/j.ecss.2020.106613.

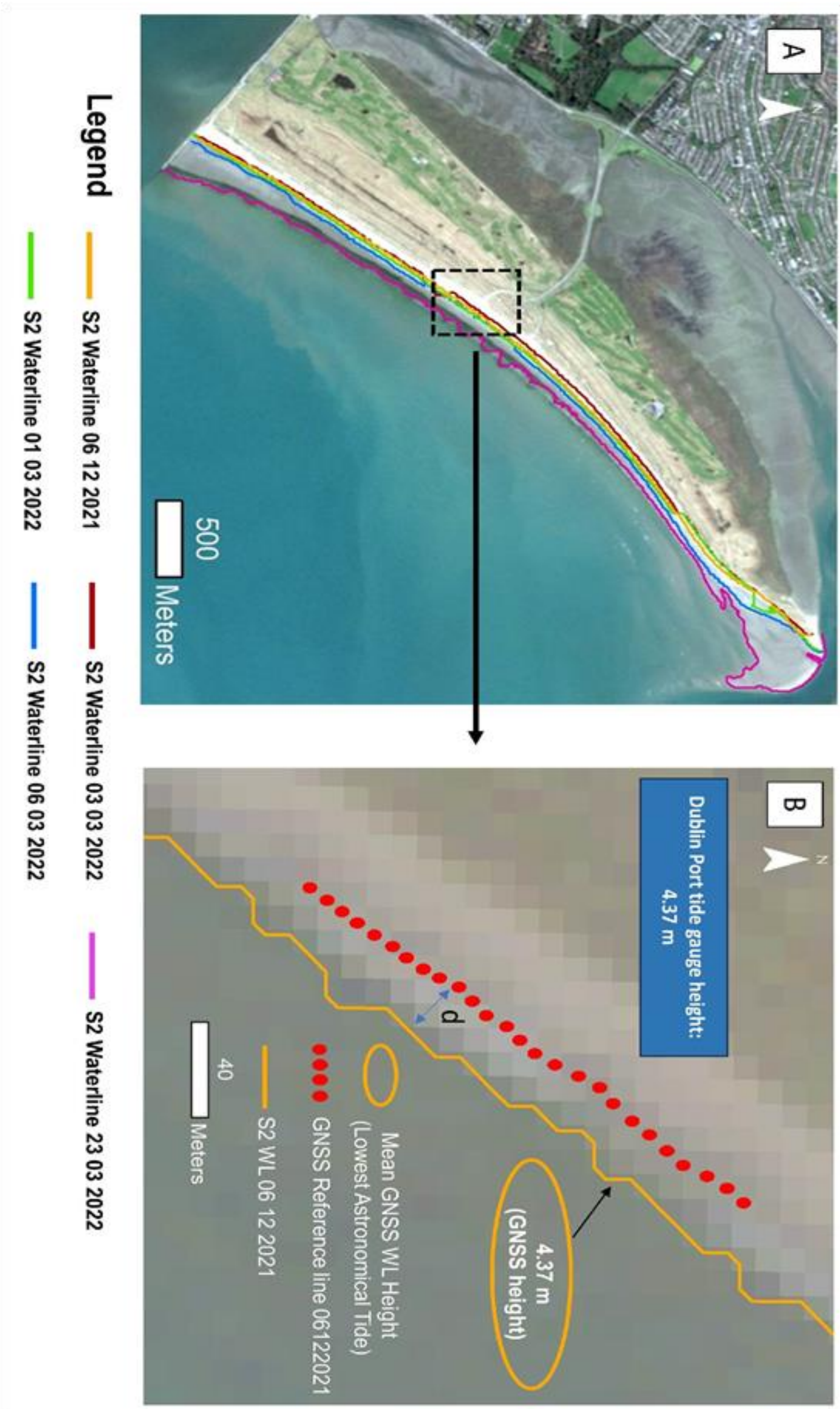
Warmerdam, F., Rouault, E., 2022. A. o. gdal_contour. GDAL documentation, Retrieved 21st February 2022 from: https://gdal.org/programs/gdal_contour.html

Xu, Z., Kim, D. J., Kim, S. H., Cho, Y. K., Lee, S. G., 2016. Estimation of seasonal topographic variation in tidal flats using waterline method: A case study in Gomso and Hampyeong Bay, South Korea. Estuarine, Coastal and Shelf Science, 183, 213-220.10.1016/j.ecss.2016.10.026.

Zhao, B., Guo, H., Yan, Y., Wang, Q., Li, B., 2008. A simple waterline approach for tidelands using multi-temporal satellite images: A case study in the Yangtze Delta. Estuarine, Coastal and Shelf Science, 77(1), 134-142.

Zhou, Y., Zhang, D., Cutler, M. E., Xu, N., Wang, X. H., Sha, H., Shen, Y., 2021. Estimating muddy intertidal flat slopes under varied coastal morphology using sequential satellite data and spatial analysis. Estuarine, Coastal and Shelf Science, 251, 107183.https://doi.org/10.1016/j.ecss.2021.107183.

APPENDIX



Appendix 1. Left image (A) contains the 5 Sentinel 2 derived waterlines under study projected onto a Sentinel 2 image corresponding to March 23, 2022 in the North Bull Island area (Dublin, Republic of Ireland). Right image (B) shows the horizontal accuracy assessment between the satellite-derived waterline on December 6, 2021 and the GNSS reference line measured cotemporally. Image B also shows the vertical accuracy assessment between the mean height of the satellite-derived waterline extracted and Dublin Port tide gauge.