Coastal Erosion from Space

Coastal Erosion events:

in Nerja (Spain) in Kilkee (Ireland) in St Laurent mouth (Canada)

Algorithm Theoretical Baseline Document

Ref: SO-TR-ARG-003-055-009-ATBD-SL

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Version history

Version	Date	Modification
Version 1	30/10/19	–
Version 1.1	14/11/2019	Modification from IHC feedback: - Section 2.3.2, run up information
	06/12/2019	Review
Verification by	François-Regis Martin-Lauzer	
Authorisation	Craig Jacobs	

Acronyms

CD: Chart Datum

CNES: Centre National d'Etudes Spatiales

CS: Cross-Section

CTM: Coastal Terrain Model

DSI: Datum-based Shoreline Indicators

EO: Earth observation

EPR: End Point Rate

EW: Extra Wide swath

FDBAQ: Flexible Dynamic Block Adaptive Quantization

GRD: Ground Range Detected

HAT: Highest Astronomical Tide

HRG: High Resolution Geometric

IW: Interferometric wide swath

LAT: Lowest Astronomical Tide

MHW: Mean High Water

MHWM: Mean High Water Mark

MHWN: Mean High Water Neap

MHWS: Mean High Water Spring

ML: Mean Level

MLW: Mean Low Water

MLW: Mean Low Water Mark

MLWN: Mean Low Water Neap

MLWS: Mean Low Water Spring

MSL: Mean Sea Level

OSW: Ocean Swell Spectra

SPOT: Satellite Pour l'Observation de la Terre

SAR: Synthetic Aperture Radar

SLC: Single Look Complex

TOA: Top Of Atmosphere

URD: User Requirement Document

UK: United Kingdom

WSM: Water Surface Model

WV: Wave Mode

Applicable and reference documents

Id	Description	Reference
AD-1	Requirement Baseline Document	SO-RP-ARG-003-055-006-RBD_v1.0_20190916
AD-2	Pre-processing ATBD	SO-TR-ARG-003-055-009-ATBD-PP

Contents

List of Figures

List of Tables

1 Overview and Background Information

1.1 Product requirement

Figure 1.1: An example of a range of visibly discernible shoreline indicator features, Duranbah Beach, New South Wales, Australia, © Boak & Turner, 2005

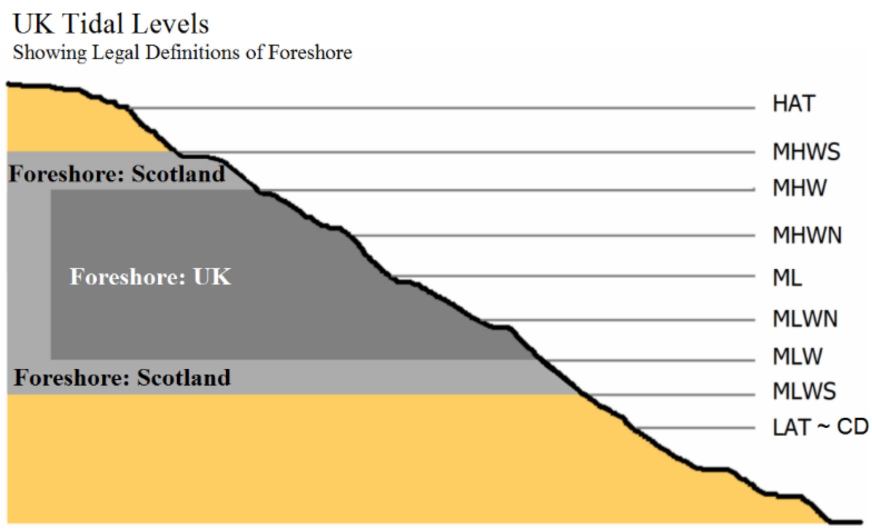

Figure 1.2: Order of tidal datums used within the UK

1.1.1 Information content quality and value

According to partners and end-users' requirements listed in the URD regarding shoreline extraction, the processor will compute datum-based shoreline indicators between the Mean High Water Spring (MHWS) datum and the Mean Low Water Neap (MLWN) datum. This will be achieved using the measured waterline and various auxiliary data including the sea state and beach slope.

A shoreline is defined as the intersection of the land with the water surface. The shoreline shown on nautical charts represents the line of contact between the land and a selected water elevation. In areas affected by tidal fluctuations, this line of contact is the Mean High Water (MHW) datum. In confined coastal waters of diminished tidal influence, the Mean Sea Level (MSL) datum is sometimes used. The shoreline is not easy to identify in contrast to the coastline, which is based on a clear morphological shift between the shore and the coast. In areas obscured by marsh, mangrove, cypress, or other type of marine vegetation, a line may be used to represent the apparent shoreline which is the intersection of the appropriate datum with the outer limits of vegetation.

A tidal datum-based shoreline indicator is determined by the intersection of the coastline profile with a specified vertical elevation. The datums are most commonly determined by the averages and extremes of harmonic tidal predictions. These elevations are measured above a fixed datum which varies depending on the country of interest and are subject to occasional updating (For example in the UK, this is either Ordnance Datum Newlyn or Chart Datum)[1]. These tidal datums can be calculated manually from the local tidal regime, however these values are usually available from a regional hydrographic organisation. Datum-based shoreline indicators are important for local authorities, they define legal spatial boundaries, are essential for nautical charting, and provide a fixed reference to accurately monitor coastal erosion rates. These lines can then be used with estimations of lateral land retreat and sediment transport volumes which go on to inform local planning policy[2].

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[1] A guide to coastal erosion management practices in Europe: lessons learned; Jan 2004, EUROSION project

[2] Helene Burningham, Jon French, Understanding coastal change using shoreline trend analysis supported by cluster-based segmentation, 2017, Geomorphology, 282

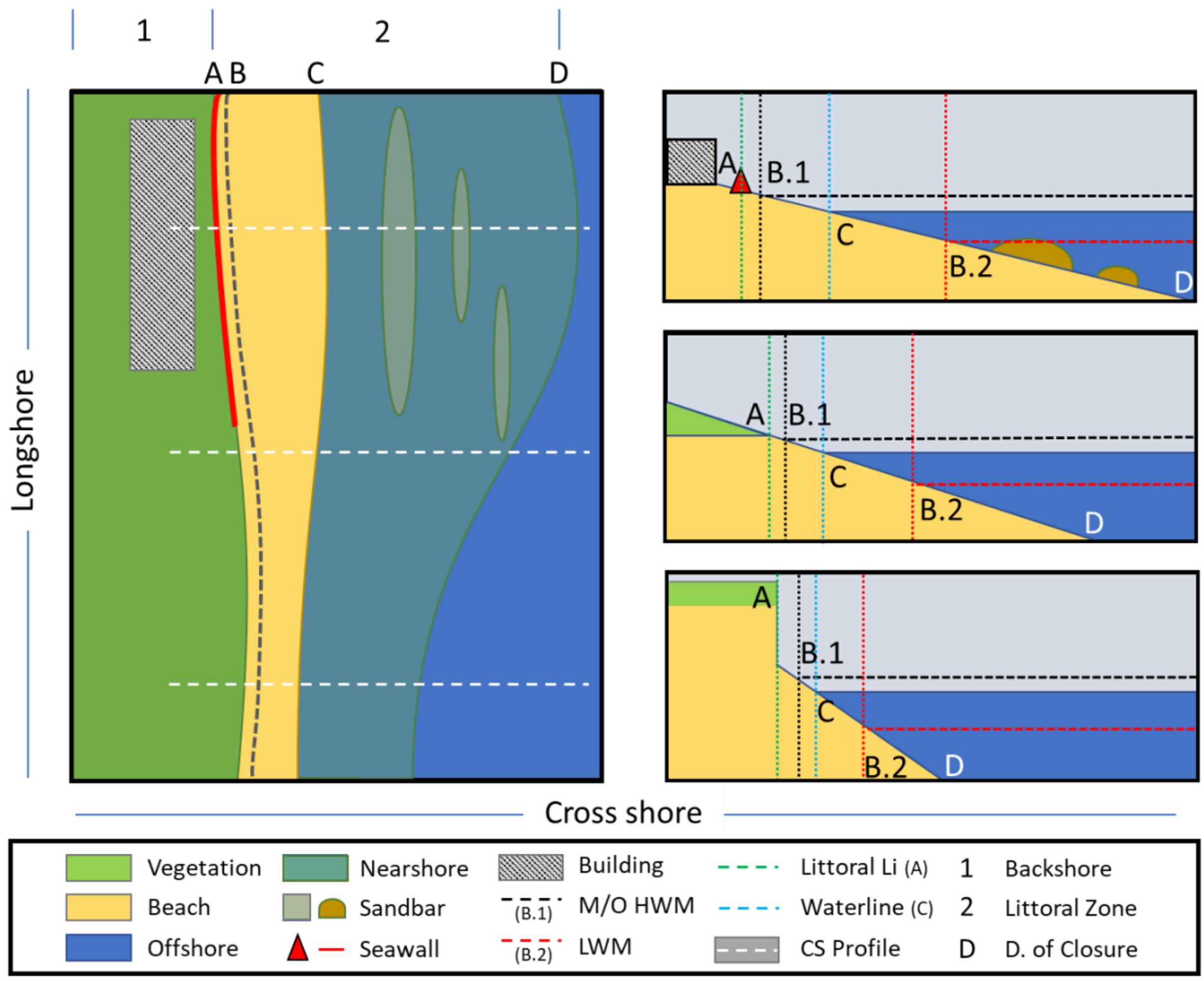

Figure 1.3: Shore and coastal features diagram

1.1.2 Product order and delivery services

A Datum Based Shoreline Indicator will be produced for each waterline, for each defined tidal datum. These are produced for each of the waterlines created by the previous processor. Lines will be produced for each location over the past 25 years. Frequency of production strongly relies on the ability to obtain accurate information on the sea state and beach morphology at the time of EO acquisition.

Output format will be as multiple polyline shapefiles compatible with GIS software such as ArcGIS and QGIS. Products will be available on a geoportal and delivery will be available by an ftp transfer.

1.2 Feasibility review

1.2.1 Satellite sensors and mission

Please refer to the pre-processing ATDB (ref: SO-TR-ARG-003-055-009-ATBD-PP)

1.2.2 Existing EO Products

Please refer to the pre-processing ATDB (ref: SO-TR-ARG-003-055-009-ATBD-PP)

1.2.3 Models specification

There are various methods to which a measured waterline can be used to generate tidal datum based shoreline indicators. For ease of conversion between the measured waterline and tidal datums, most studies suggest scheduling aerial photography / EO acquisitions when the water level is close to the target datum. This however is not always possible due to time/budget constraints or unavailability of suitable data[3]. In this case, the tidal datums can be calculated using a predetermined waterline combined with auxiliary data. The choice of methodology used to determine the datum-based shoreline indicators from the waterline will depend on the type of auxiliary data available for the area of interest.

The first possible method involves using a coastal terrain model (CTM) that contains topographic information in a narrow zone of the coast and near-shore bathymetry. Li et al (2002)[4] propose using high resolution (1 m) stereo imagery. Stereo pairs that are necessary for deriving elevation information of objects can be formed in quasi real-time; the cross-track stereo requires additional time allowing the satellite to revisit the same area from a neighbouring track. The CTM is then built by georeferencing and integrating the topographic, data, LIDAR data, and bathymetric data in the same planimetric and vertical datum. The water surface is depicted by a water surface model (WSM) that can be produced by a hydrological modelling system using meteorological data and coastal physical environmental data as boundary conditions. Then, the shoreline can be derived by a subtraction of the WSM from the CTM where the grid points with differential value of 0 represent the shoreline.

Li et al. also propose using a simplified model such as EPR (End-Point Rate) method to calculate a recession/advancing rate on each transect of the shoreline, this involves using multiple satellite optical images of the shoreline at varying time intervals. Using this imagery, the desired tidal datum can then be estimated

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[3] R. Gens (2010) Remote sensing of coastlines: detection, extraction and monitoring, review article. International Journal of Remote Sensing Vol. 31, No. 7, 1819–1836.

[4] R. Li et al. (2002) Digital Tide-Coordinated Shoreline. Journal of Marine Geodesy, Vol. 25, pp. 27-36.

by a temporal interpolation or extrapolation. However, the EPR method assumes that the shoreline position changes in one direction and linearly, which does not match the situation in the real world.

A novel method using a simplified geometric model assuming constant cross-foreshore slope can also be performed. This involves calculating the combined height of the variables which contribute to the water level above the predicted tidal height, such as wave run up and atmospheric effects. By combining these variables to the predicted tidal height, the instantaneous water level of the waterline can be estimated. Then, by assuming a constant beach slope and using the differences between the instantaneous water level and the tidal datums, the lateral distance between the waterline and the tidal datums can be calculated.

1.2.4 Auxiliary data

Various types of auxiliary are needed for extraction of the datum-based shoreline indicators.

- Sea State
    - Harmonic Tidal Prediction
    - Measured Water Level
    - Atmospheric Pressure at MSL
    - Surface / 10 m Wind Speed
    - Deep Water Wave Spectra + Direction
    - Regional rate of Relative Sea Level Rise
- Beach Morphology
    - Beach Slope.

1.2.5 Currently known issues

The most significant issue that may impact the processor is the accumulation of uncertainties created from the input waterline and auxiliary data. Primarily, the shoreline extraction processor relies on the output from the waterline processor. This carries forward errors and uncertainties as the interpretation of the waterline position is not always entirely accurate and may change depending on the type of sensor used.

Secondarily, the shoreline extraction relies heavily on accurate information of the beach slope, although this data may be available from in-situ measurements, the beach profile can be reshaped on both short and long timescales, meaning even recent slope measurements may become quickly outdated. The beach slope is also often irregular, with steepening occurring towards the backshore. This can provide a source of error when generalising the slope of the entire foreshore, as errors will occur when extrapolating tidal datums. The profile used to create an average slope must cover the entire foreshore, this is often not provided when beach slopes profiles are created from bathymetric surveys. On sandy beaches, using any bathymetric data below the point of the Lowest Astronomical Tide (LAT) instead of a measured foreshore will give an underestimation of the slope, this will result in a misplacement of the shoreline.

Uncertainty will also accumulate when using numerous parameters of the sea state. Due to a lack of in-situ data availability, some of the sea state and atmospheric conditions will be determined from model outputs, these carry significantly increased uncertainty due to their probabilistic nature. The effect of these uncertainties will amplify when used in combination (see section 2.3.4), this will reduce confidence in estimations of waterline elevation. Using a number of auxiliary data sources harmoniously will also be difficult. Issues may arise due to ensuring data continuity across a long timeseries. Any gaps in auxiliary data will prevent the processor from running effectively, ignoring any missing auxiliary terms will add significant error to the estimation of waterline elevation if an interpolation is not possible. Furthermore, this large quantity of auxiliary data may be impractical to host with the end user.

The calculations of wave run up are taken from Stockden et al. (2006) as this is the most widely cited and used set of run up equations used within coastal science. The proposed equations are derived from empirical models predominantly from sandy beaches with a limited range of parameter values (slope, roughness, wave height etc). These models may not accurately represent the wave run up of beaches outside of these parameters. Furthermore, the position of the shoreline depends on the type of waterline outputted by the waterline processor. The run up equations will represent the dry/wet boundary created from the swash. A waterline created from the land/sea boundary will represent a much more varied instantaneous position due to varying wave run up and setdown, this may cause both over and underestimations of the runup height.

1.3 Potential Solutions

Higher sampling (at least once per month or twice between storms) will increase the accuracy and precision of the shoreline estimates. In-situ metocean measurements should be utilised instead of modelled data due to the increase in accuracy and precision. Where data continuity issues arise, the missing data can be supplemented with outputs from numerical models or interpolated if the data gap is sufficiently small. To aid with accessing the large quantity of 'mismatched' auxiliary data, all datasets should be assigned the same date format and the sampling interval standardised via interpolation. A database and query system could also be produced to store and handle requests for data subsets needed for the algorithm.

1.4 Product Specifications

The algorithm will use a waterline provided from the waterline processor[5] as the primary data source, the auxiliary data will then be analysed to calculate positions of the shorelines based upon the position of the waterline. The algorithm will assume a simplified geometric model of the foreshore, assuming a constant slope across the length of each cross section analysed. The waterline will be split into a number of cross sections of varying slopes. The most significant limitation is expected to be the uncertainties accompanying the waterline and the limitation created by an assumption of uniform slope along a cross-section.

[5] Refer to document ref: SO-TR-ARG-003-055-009-ATBD-WL for more information.

2 Algorithm Description

2.1 Data Processing outline

2.1.1 *Sketch of the computer program*

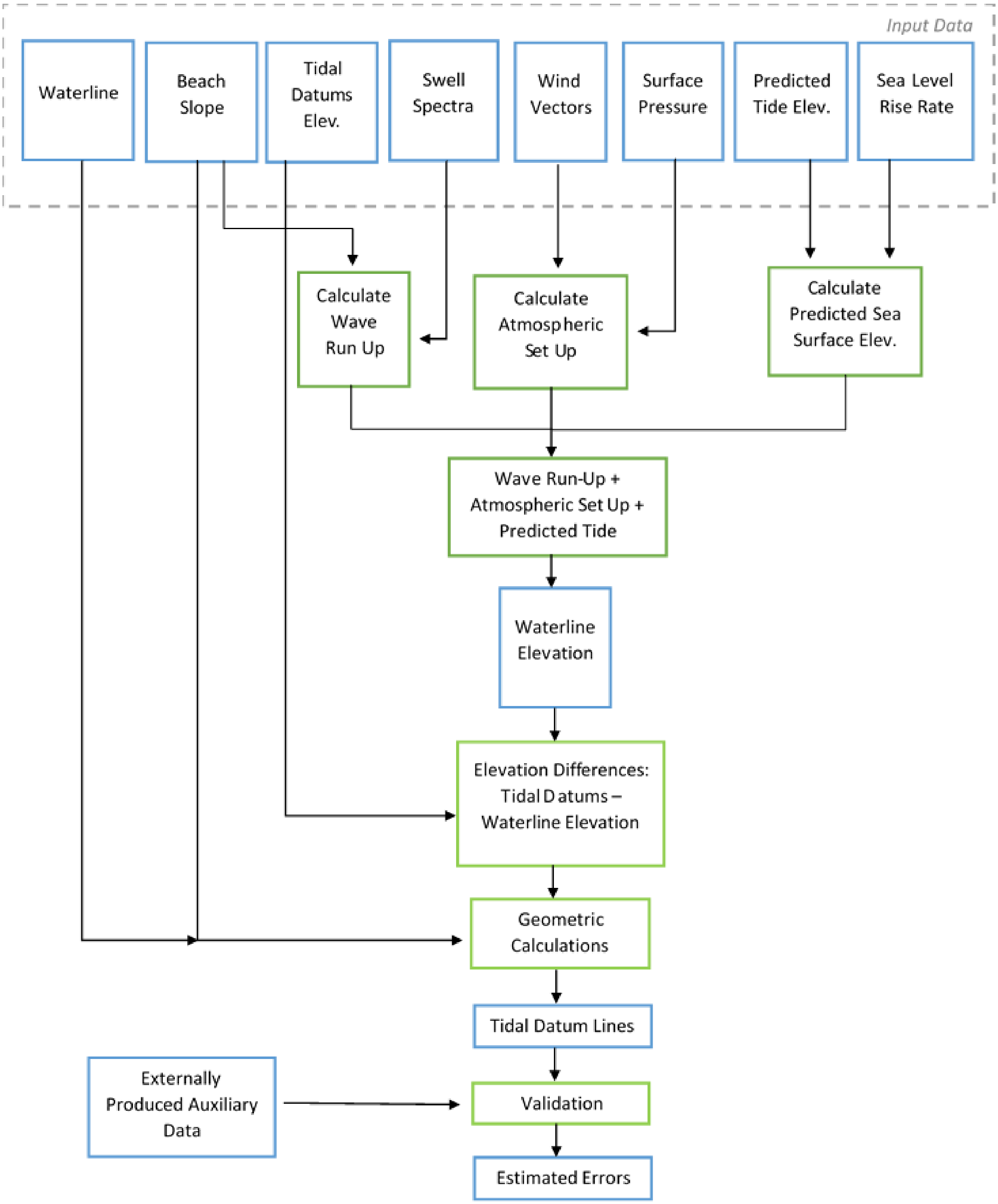

Figure 2.1: Flowchart indicating structure of the algorithm

2.1.2 Pre-requisite

The algorithm requires a waterline, The waterline must be as accurate as possible, as the algorithm does not attempt to mitigate any error in the waterline output. The algorithm also requires accurate slope information for each area, this slope must be representative of the foreshore, and not derived from nearshore bathymetry. The algorithm also needs accurate heights of the required tidal datums, referenced to the same datum as the water level data. Finally, the algorithm needs a full catalogue of metocean data, ideally this information should come from in-situ measurements rather than numerical models to reduce the impact of any uncertainties on the final shoreline output.

2.2 Algorithm Input

The processor uses the waterline as a primary input, the various pieces of auxiliary data listed in 1.2.4 are also used for calculations of the waterline elevation. Measured tidal datum waterlines provided by the user can be used later in the algorithm to validate the results.

2.3 Theoretical Description of the models in background of the procedure

2.3.1 Physical Description

The equations used to calculate the water level residual (height of water above predicted still water height) are used in engineering calculations to determine the required dimensions of protective coastal structures[6]. Therefore, there is a good level of confidence that the methodology used for the calculation of the waterline elevation is suitable for practical application. The equations are highlighted in Section 2.3.2. To run the model, the waterline is first split into sections, each section corresponds to an area of coastline with a known slope. Where the measured slope varies across the extent of coastline, slope values are interpolated across the section. Next, the combined height of the physical processes which contribute to the water level above the predicted tidal height, such as wave run up and atmospheric effects, are calculated. By combining these variables to the predicted tidal height, the elevation of instantaneous water level represented by the waterline is estimated. Using this information, vertical height differences between the measured waterline and the required tidal datums can be calculated. Next, whilst assuming a constant beach slope across the cross-shore

[6] USACE (1984) Shore Protection Manual Vol 1 & 2. Department of the Army. Washington DC.

profile, the lateral distance between the waterline and the tidal datums can be calculated geometrically. This lateral distance is then used to construct a new line parallel to the waterline corresponding to the waterline.

2.3.2 Mathematical Description and calculation procedures

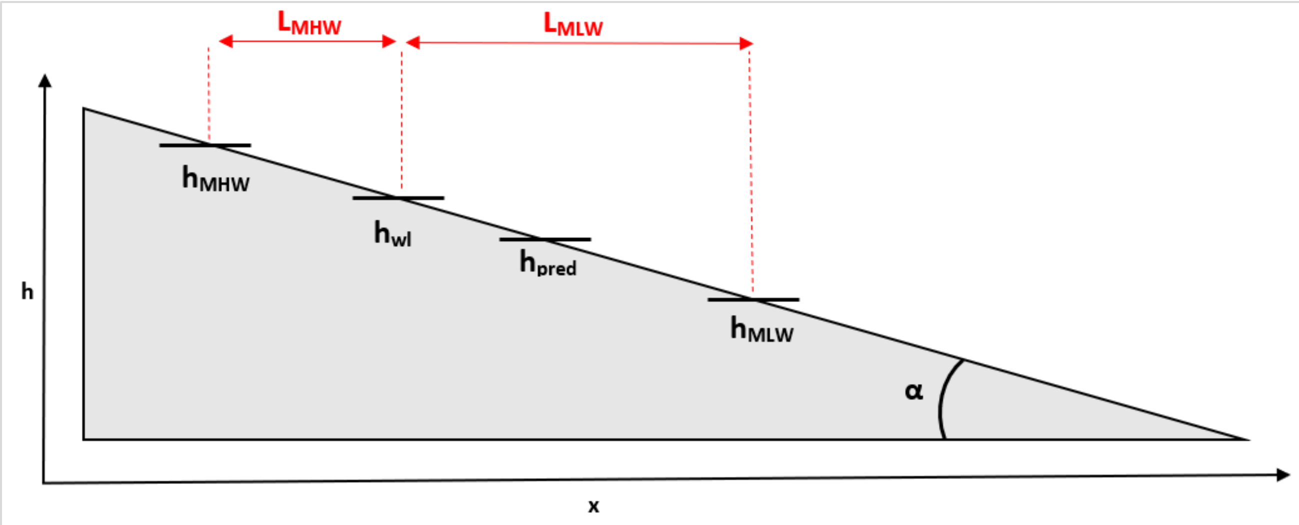

Figure 2.2: Conceptual overview of a cross-shore profile

a. Define Variables:

Slope (α) is a fixed value across the specific cross shore profile given as:

$$\alpha = \frac{dh}{dx}$$

The elevation of the tide in still water conditions (h_{pred}) at the time of the EO measurement (t_0) is given as:

$$h_{pred} = tide(t_0)$$

The change in height of the sea surface increases by approximately 1cm for every 1mbar fall in surface atmospheric pressure, this is known as the inverse barometer effect. This is given as:

PA = Surface Atmospheric Pressure (mbar)

$$h_{atm} = (1013 - PA) / 100$$

The wind setup is an additional elevation component caused by wind stress on the ocean surface. Where κ is a frictional coefficient, u_{10} is the mean wind speed at 10 m, g is gravitational acceleration

(9.81 ms^{-2}), d is the depth of the basin, x is the fetch of the wind, ϕ is the angle away from the normal between the shoreline and wind direction[7].

$$h_{wind} = 0.5\kappa \frac{u_{10}^2}{gd} x \cos(\phi)$$

h_{wind} equation is used to calculate wind setup above a lake of constant depth but can be applicable in shallow coastal environments.

The wave driven component of sea surface elevation is known as the wave run up. This is composed of the wave set up (the super-elevation of the mean water level above the still water level) and wave swash (the height of the time-varying fluctuation in instantaneous water level above the setup elevation)[8]. The wave set up $\bar{\eta}$ is given below where α is the slope, H_s is the significant wave height and L_p is the peak wave period.

$$\bar{\eta} = 0.35\alpha(H_s L_p)^{0.5}$$

The wave swash S is comprised of both an incident component S_{inc} and an infragravity component S_{ig}. H_s is the significant wave height and L_p is the peak wave period.

$$S_{inc} = 0.75\alpha(H_s L_p)^{0.5}$$

$$S_{ig} = 0.06(H_s L_p)^{0.5}$$

$$S = \sqrt{S_{inc}^2 + S_{ig}^2}$$

The wave driven component of sea surface elevation is therefore:

$$h_{wave} = \bar{\eta} + S$$

The rate of sea level rise can be used to correct historic tidal predictions if they are not already corrected. This value will also account for any land subsidence t_0 is the date of the EO measurement, t_1 is the date that the predicted tide was calculated.

$$h_{slr} = h_{msl}(t_0) - h_{msl}(t_1)$$

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[7] Bezuyen, K., Stive, M., Vaes, G., Vrijling, J., & Zitman, T. (2012). Inleiding waterbouwkunde (Collegedictaat CT2320). Delft: VSSD.

[8] Stockdon et al. (2006) Empirical parameterization of setup, swash, and runup. *Coastal Engineering 53*. Pp 573 – 588.

b. Determine the elevation of the measured instantaneous waterline (h_{wl}):

In the absence of a measured water level (tidal data only), the elevation of the waterline can be determined with the following equation.

$$h_{wl} = h_{pred} - h_{SLR} + (h_{atm} + h_{wind} + h_{wave})$$

With measured water level h_{meas} available, the elevation of the waterline is simply:

$$h_{wl} = h_{meas} + h_{wave}$$

c. Determine the lateral distance from the waterline to the chosen tidal datums:

As the slope is assumed to be constant, the lateral distance from the waterline to the tidal datum based shoreline L_{datum} is calculated as shown below. h_{datum} is the still water elevation of the target tidal datum above a predefined reference datum.

$$\frac{dy}{dx} = \alpha = \frac{h_{wl} - h_{datum}}{L_{datum}}$$

$$L_{datum} = \frac{h_{wl} - h_{datum}}{\alpha}$$

A positive value of L_{datum} implies the datum is seaward of the waterline, a negative value implies the datum is landward of the waterline.

d. Polylines are then created parallel to their respective waterline section, with the spacing between these lines proportional to the lateral distances calculated above.

2.3.3 Acceptance of the Models

Will be completed in version 2

2.3.4 Error Estimation

Estimating the error in shoreline position is essential for calculating uncertainties in erosion rates calculated by subsequent processors[9]. Below, the potential sources of error and methods of quantifying this error are highlighted.

Various sources of errors are identified. Primarily, the shoreline processor relies on the output from the waterline processor. The calculation of the waterline position is subject to accuracy and precision errors from the instrument, the satellite sensor resolution, the product pre-processing and radiometric correction. These errors will create uncertainty which will carry forward and become inherent to the shoreline. Errors will also be created from using auxiliary data. These errors occur from uncertainties in measurement and errors accumulated through the methodology. For example, the beach slope is often irregular with steepening occurring towards the backshore rather than a gradually sloping surface. This provides a significant source of inaccuracy when calculating the position of the shorelines. Errors may also accumulate when using numerous measurements of the sea state. Calibration issues and limits in measurement resolution for the various oceanographic/atmospheric instruments used to collect the auxiliary data may lead to erroneous calculations of run up and sea surface height, this in turn will affect the calculated positions for of the shoreline indicators.

Regionally, in the Atlantic, a large source of error is the discrepancy between the reference level and the tidal level at time of the EO snapshot, which is not given by any metocean forecast. In the Mediterranean, the main source of error is related to the metocean conditions, with errors created in the shoreline position of up to 10 m, if the storm surge and the wave runup are not calculated correctly. Errors can be quantified by totalling the uncertainty ranges of the measurements. For example, with a tide height of 5 m ± 0.2, a wave run up of 1 m ± 0.4 and a wind set up of 0.3 m ± 0.1. Totalling these values would lead to an expected water level at the waterline of 6.3 m ± 0.7 (assuming no h_{SLR} or h_{atm} terms). Uncertainty ranges for the auxiliary data measurements are obtained from the complimentary metadata files.

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[9] Refer to document ref: SO-TR-ARG-003-055-009-ATBD-ER

2.4 Algorithm output

2.4.1 Product content

Shoreline product will contain a continuous vector line. This line will carry information such as the quality assessment (real detected line or interpolation due to missing data), the date and time at which the original product was taken.

2.4.2 Product organisation.

Datum-based shoreline products will be organized in different directories according to the study area. For each area, partners will access the shoreline with all metadata and the instantaneous waterline from which the shoreline was calculated, refer to section 2.4.1.

2.5 Algorithm Performance Estimates

2.5.1 Test specification

Testing could be performed by using known tidal datum shoreline indicators provided by the user. Statistics of the lateral distances calculated at points between the algorithm output and the tidal datum line provided will give an estimation of the algorithm's performance and accuracy.

2.5.2 Test Datasets

Testing could use polylines provided by the user which (to their knowledge) accurately represent the shoreline position of tidal datums.

2.5.3 Verification

Will be completed in version 2, following result obtain from the processor.

2.6 Products Validation

2.6.1 Test specifications

Test specifications will vary depending on the type of validation products that can be provided by the partners.

2.6.2 Test Datasets (identification & description)

Data from the partners and in-situ surveys are needed to run tests for each location sites.

2.6.3 Validation

Will be completed in version 2, following result from feasibility study.

3 Conclusion

3.1 Assessment of limitations

The two most significant limitations are the waterline positional uncertainties and the accumulations of uncertainties associated with the auxiliary data. In microtidal regions where the spacing between shorelines is limited to several metres, datum-based shorelines may share a position within the same snapshot pixel, this leads to inherent overlap of shoreline positional uncertainty. Furthermore, the accumulated uncertainties from the auxiliary data may create shoreline uncertainty ranges larger than the spacing between shorelines. This again causes overlap of shoreline positional uncertainty.

For the processor to run, a large number of auxiliary data files must be provided, thus the processor is limited to run within the inner temporal range of the combined datasets, this limits the total range of snapshots available to be processed. Furthermore, any gaps in auxiliary data will prevent the processor from running. Therefore, locations with auxiliary data scarcity (due to remoteness/inaccessibility) may be difficult to process.

Although the processor encapsulates the majority of sea level drivers, sub-annual regional sea level variation is ignored as it is difficult to accurately quantify the contributing phenomenon. Sub-annual variations will not be present in annual mean sea level calculations and can also be difficult to differentiate from short terms atmospheric effects.

3.2 Mitigation

This will be completed in version 2, following result from feasibility study.

4 References

5 Appendix

End of Document