FAST
FORESHORE ASSESSMENT
USING SPACE TECHNOLOGY

Sediment dynamics and stability

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Content

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Executive summary / Abstract

The objective of the FAST project is to develop a Copernicus downstream service based on (Sentinel) satellite data and in situ data to assess the function of wetlands in reducing flood risk and erosion. This requires an assessment of the erodibility and stability of foreshores, as well as knowledge on how saltmarshes function and develop, in order to predict their future status, and hence their flood defence value over longer time-scales. While detailed results on sediment and marsh dynamics are presented in particularly Deliverable 5.2, this Deliverable 3.6 serves to lists publication output of the project related to the study of vertical and lateral sediment dynamics of foreshores and marsh range changes and their drivers. The potential for implementation of products and services related to sediment dynamics and stability in the Copernicus downstream service is discussed.

Scope

The EU FAST project aims to assess the biophysical characteristics of foreshores using space technology, as part of a Copernicus downstream service, the MI-SAFE package, for flood defence and erosion risk reduction. In this report, Deliverable 3.6 (D3.6), we give an overview of the publication output relating to sediment dynamics and marsh range changes using both in situ measurements and satellite imagery. The report builds on work reported in detail in internal Deliverables D3.9 (geo-spatial data, including the Earth Observation based products now included in the MI-SAFE package), D4.7 (in situ data) and D5.2 (application prototype rules). While this report focuses on *understanding* sediment dynamics and marsh range, potential of this knowledge for products and services in the MI-SAFE package is discussed.

1. Introduction

Foreshores and floodplains deliver several services, such as increasing sedimentation, reducing erosion and attenuating waves that mitigate flood risk. Including foreshores and floodplains in levee design and safety assessments may result in considerable cost reductions for flood risk management. The EU FAST (Foreshore Assessment using Space Technology) project aims to develop a new Copernicus downstream service, called the MI-SAFE package that includes the use of foreshores as part of nature-based flood defences.

As for all flood risk assessments, we need to know the properties of the system in its current state, but also how this will change over the design life of flood protection measures (typically circa fifty years). Incorporating nature in flood defences can be beneficial for ecosystem services but it also introduces additional temporal dynamics and spatial variation to parameters relevant for engineering.

We can distinguish several time-scales of foreshore change. Small-scale changes, on a tidal, monthly or yearly scale in, for example, bed level can best be assessed using in situ measurements. Long-term (decadal) changes in foreshores, either in vegetation or elevation, can be assessed using for example the Landsat satellites, as they have a large temporal extent (circa 30 years), but only reasonable spatial resolution. Year-to-year variation, seasonal variation and events, such as storms, can be assessed using, for example the Sentinel satellite data from the Copernicus Earth Observation programme, or very high resolution imagery, including sequential aerial photography or drone imagery.

In the project, spatial data products are developed based on (Sentinel) earth observation data to gain spatial information on the biophysical characteristics of foreshore and floodplain characteristics (as described in internal deliverable D3.9). In the MI-SAFE viewer, a number of products now relate to sediment dynamics and stability. The tool includes information on vegetation status (presence/absence and biophysical characteristics of vegetation, such as Leaf Area Index, derived from Sentinel-2 data) and vegetation dynamics (such as seasonal variation in LAI derived from Sentinel-2 imagery and vegetation change in the period 1986/1989 to 2013/2014 derived from Landsat satellite imagery. In addition, it includes information on bathymetry and topography retrieved from satellite imagery (such as intertidal elevation based on a large set of Landsat and Sentinel-2 imagery). In situ measurements are performed at eight pilot sites in Europe to validate, calibrate and complement these data (as described in internal deliverable 4.7). Generalized model rules are then applied to predict wave attenuation characteristics over the foreshores based on the information of foreshore characteristics (as described in internal deliverable 5.2).

However, the morphological response of the foreshore to physical forces, such as currents and waves, and its dependence on, for example, sediment supply, is also relevant for coastal protection. In order to be able to predict the future development of the system, and hence, safety levels, an understanding of the morphodynamics of the system is required at different spatio-temporal scales.

In this report, we list publications in whole or partly carried out as part of the EU FAST project, addressing foreshore dynamics and stability and the drivers of foreshore change.

2. Short-term bed level dynamics from in situ SED sensors

The SED sensors were developed by NIOZ to collect continuous measurements of bed level to gain insight in intertidal sediment dynamics. It is a stand-alone device based on light sensitive cells (i.e., phototransistors), suitable for continuous measurements of bed level dynamics, with multiple measurements per minute (Figure 2.1). The vertical resolution of the instruments is 2 mm. Hu et al., (2015) described the instruments, approach and the accuracy of the SED sensor in detail. The full published article in which the sensors are introduced can be downloaded here:

- http://www.sciencedirect.com/science/article/pii/S0169555X15300118
- http://www.vliz.be/imisdocs/pub/66/277266.pdf

Figure 2.1 Left: front side and back side and an enlargement of the logging section of the SED-sensor (Hu et al., 2015). The light sensitive cells are located in the measuring section, and the head. Middle: a SED-sensor on the mudflat. Right: a SED-sensor in the marsh, Paulinapolder, the Netherlands, April 2014.

Willemsen et al. (in prep.) developed a method to process the data collected with the SED sensors. The SED sensor data can be processed without adding any contextual data, such as water levels or day- and night time, allowing for automated processing. The SED sensor obtains data using multiple sensitivities; all sensitivities were used for processing the data, to increase data coverage during dusk and dawn. The raw data was processed by approximating the signal with an arctan function (Figure 2.2). A manual for processing the data is provided by Willemsen (2017).

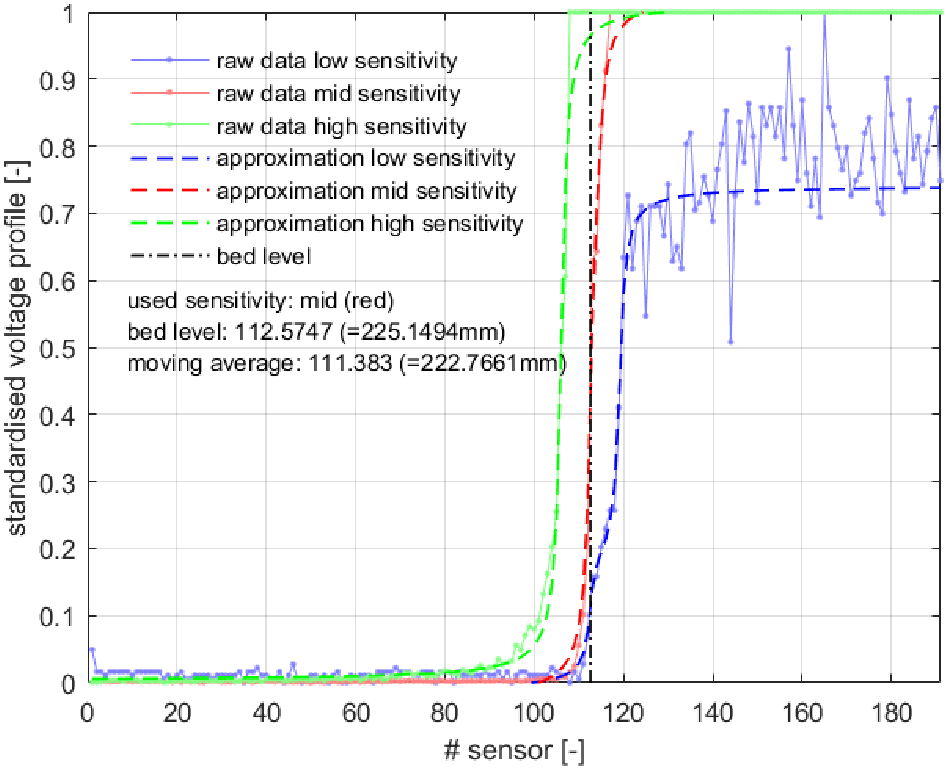

Figure 2.2 Raw data (continuous lines) obtained by the SED sensor for three different sensitivities. The raw data is approximated by an arctan function (dashed lines). The bed level is found at the mid sensitivity measurement (red).

The sensors are applied by Hu et al. (2017) to distinguish between bed level changes resulting from current and wave induced stress on intertidal mudflats. Hu et al., (2015) and Hu et al. (2017) address the sediment dynamics of the contrasting mudflats at Zuidgors and Baarland in the macrotidal Western Scheldt, the Netherlands (Figure 3.1), based on SED sensor measurements collected for circa one year, prior to the EU FAST project. The mudflat at Baarland is sheltered from waves by a seaward shoal, whereas the mudflat at Zuidgors is exposed to relatively large waves induced by prevailing south-westerly winds (see Figure 3.1 for locations). By combining the SED sensor measurements with measured and modelled wave and current bed shear stress, Hu et al. (2017) found: (1) a general steepening trend on both tidal flats, even with contrasting wave exposure and different bed sediment grain size; (2) daily morphodynamics level increases towards the sea; (3) tidal forcing sets the general morphological evolution pattern at both sites; (4) wave forcing induces short-term bed-level fluctuations at the wave-exposed site, but similar effect is not seen at the sheltered site with smaller waves; (5) storms provoke aggravated erosion, but the impact is conditioned by tidal levels. This study thus provides insights in the pattern and drivers of daily intertidal bed-level dynamics, thereby setting a template for future studies. The full published article can be downloaded here:

- https://hdl.handle.net/10.1038/s41598-017-07515-y
- http://www.nature.com/articles/s41598-017-07515-y.

Within EU FAST, in situ measurements conducted with SED-sensors at the field sites show vertical movement of bed level of the marsh and mudflat. In the case study sites in Spain, the Netherlands and the United Kingdom (and with a different field design also at a site in Romania), transects with 5 to 7 Surface Elevation Dynamics (SED) sensors were set-up to measure vertical bed level dynamics at the interface of the marsh and mudflat. For validation of the method, erosion pins have been used to record bi-monthly changes in local surface level. The erosion pin is a very thin metal rod (i.e., to prevent scouring) with a height marker on top, and a ring around the pin. The pin is pushed into the sediment, till the marker is at a fixed height above the sediment and with a metal ring placed around the pin on top of the soil surface. Every two months (bi-monthly), the erosion pins are harvested, and the distance from the marker to the soil surface and the ring buried into the sediment are measured. After each measurement, the erosion pins were re-installed. Three pins were deployed per SD-sensor location. In addition, samples were taken for sediment grain-size. Samples were also taken for chlorophyll-a concentrations of the sediment (from the upper 1 cm of the bed), as a proxy for stabilising benthic diatoms.

Willemsen et al., (2017) analysed the SED sensor data collected in EU FAST at the sites Zuidgors and Paulinapolder, as well as data from the sites Hellegat and Rilland collected in the NWO Be Safe project. The SED sensor data collected at Paulinapolder and Zuidgors show a clear temporal (seasonal) and spatial pattern of bed level changes (see for example data in Figure 2.3 for Zuidgors). The variability in bed level decreases from the sea to the vegetation edge and increases a little going into the vegetation at all sites. Zuidgors shows a more positive variability in spring and summer and more negative variability in fall and winter, while Paulinapolder shows a more equally distributed variability. In general most variability is shown in spring. The full abstract by Willemsen et al. (2017) can be downloaded here: http://library.wur.nl/WebQuery/wurpubs/515556.

Willemsen et al., (in prep.) aim to provide quantitative insight in bed level variation by relating the continuous SED measurements to dominant physical (i.e., wave gauges) and ecological (i.e., chlorophyll-a levels, as a measure of stabilisation by benthic diatoms) processes, combining information from the same four sites. The analyses have provided valuable insights in the processes that determine the width of the salt marsh. In wave-exposed sites, such as Zuidgors, the marsh width appears to be limited by sediment dynamics, whereas in sheltered sites, such as Paulinapolder, inundation duration is the main driver. These findings from the Dutch sites are now broadened to a European perspective, by analysing the patterns and drivers in the other sites, using the new script developed by Willemsen et al. (in prep.).

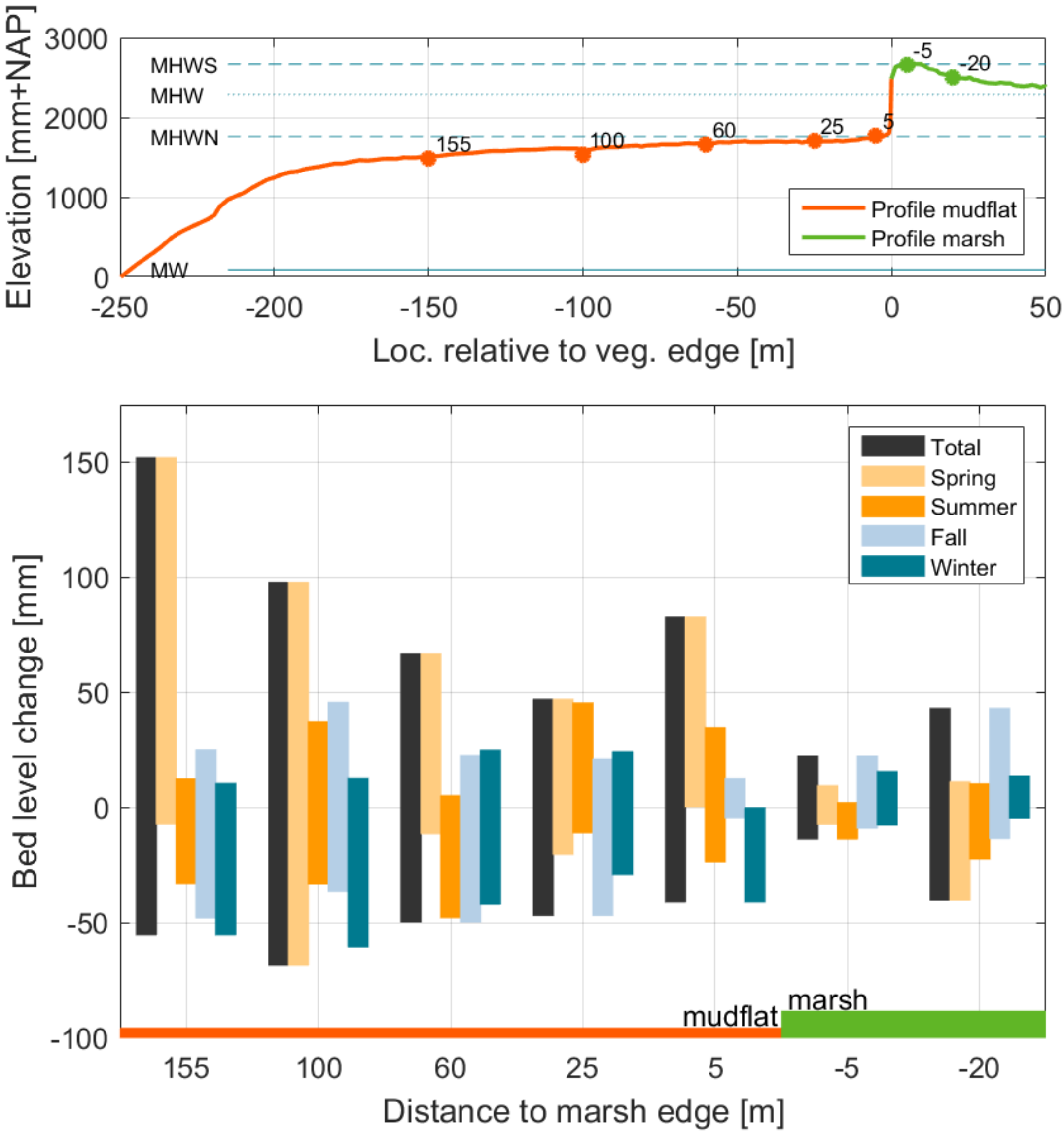

Figure 2.3 Seasonal sediment dynamics at Zuidgors (Western Scheldt, NL), 2015-2016. The initial cross-shore profile from the mudflat (orange) until the marsh (green), with the measurement locations, shows a cliff in between marsh and mudflat (top panel). The maximum and minimum bed level change was calculated for the different seasons (spring, summer, fall and winter; bottom panel). In general largest positive bed level variation (sedimentation) was measured in spring, while largest negative bed level variation (erosion) was measured in fall and winter.

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3. Marsh stability from Earth Observation and wave tank experiments

Wang et al. (2017) investigated the drivers of marsh cliff retreat in the Western Scheldt, southwest Netherlands, including the two EU FAST case study sites at Paulinapolder and Zuidgors. A summary of the article is given below. The full published article can be downloaded at https://dx.doi.org/10.1002/2016JF004193.

Salt marshes are valuable ecosystems that provide important ecosystem services. Given the global scale of marsh loss due to climate change and coastal squeeze, there is a pressing need to identify the critical extrinsic (wind exposure and foreshore morphology) and intrinsic factors (soil and vegetation properties) affecting the erosion of salt marsh edges. In this study, we quantified rates of cliff lateral retreat (i.e., the eroding edge of a salt marsh plateau) using a time series of aerial photographs taken over four saltmarsh sites in the Western Scheldt estuary, the Netherlands, i.e. Paulina, Zuidgors, Hellegat and Waarde (Figure 3.1). In addition, we experimentally quantified the erodibility of sediment cores collected from the marsh edge of these four marshes using wave tanks. Our results revealed the following: (i) at the large scale, wind exposure and the presence of pioneer vegetation in front of the cliff were the key factors governing cliff retreat rates; (ii) at the intermediate scale, foreshore morphology was partially related to cliff retreat; (iii) at the local scale, the erodibility of the sediment itself at the marsh edge played a large role in determining the cliff retreat rate; and (iv) at the mesocosm scale, cliff erodibility was determined by soil properties and belowground root biomass. Thus, both extrinsic and intrinsic factors determined the fate of the salt marsh but at different scales. Our study highlights the importance of understanding the scale dependence of the factors driving the evolution of salt marsh landscapes.

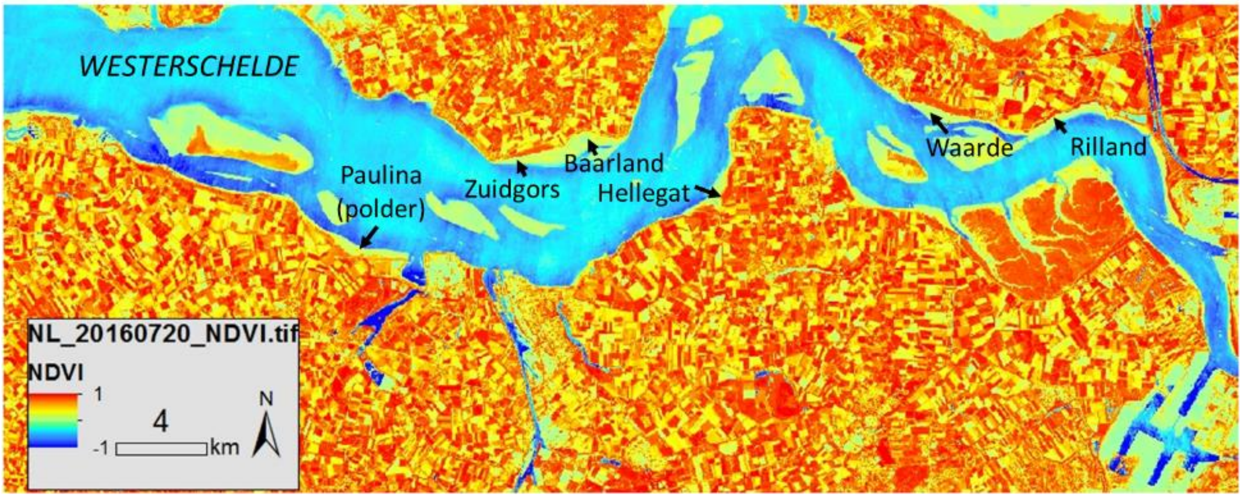

Figure 3.1 Study sites in the Western Scheldt, the Netherlands, including case study sites Paulina(polder) and Zuidgors. The image shows NDVI from a Sentinel-2 image of 20 July 2016.

4. Data-driven prediction of saltmarsh morphodynamics

Ben Evans submitted a PhD thesis at the University of Cambridge, on data-driven prediction of saltmarsh morphodynamics, as part of the EU FAST project. A summary of the thesis is given below.

Saltmarshes provide a diverse range of ecosystem services and are protected under a number of international designations. Nevertheless they are generally declining in extent in the United Kingdom and North West Europe (see e.g., Figure 4.1 for one of our case study sites). The drivers of this decline are complex and poorly understood. When considering mitigation and management for future ecosystem service provision it will be important to understand why, where, and to what extent decline is likely to occur. Few studies have attempted to forecast marsh morphodynamics at a system level over decadal time scales. There is no synthesis of existing knowledge available for specific site predictions nor is there a formalised framework for individual site assessment and management.

This project evaluates the extent to which machine learning model approaches (boosted regression trees, neural networks and Bayesian networks) can facilitate synthesis of information and prediction of decadal-scale morphological tendencies of saltmarshes. Importantly, data-driven predictions are independent of the assumptions underlying physically-based models, and therefore offer an additional opportunity to cross-validate between two paradigms. Marsh margins and interiors are both considered but are treated separately since they are regarded as being sensitive to different process suites. The study therefore identifies factors likely to control morphological trajectories and develops geospatial methodologies to derive proxy measures relating to controls or processes. These metrics are developed at a high spatial density in the order of tens of meters allowing for the resolution of fine-scale behavioural differences. Conventional statistical approaches, as have been previously adopted, are applied to the dataset to assess consistency with previous findings, with some agreement being found. The data are subsequently used to train and compare three types of machine learning model. Boosted regression trees outperform the other two methods in this context.

The resulting models are able to explain more than 95% of the variance in marginal changes and 91% for internal dynamics. Tidal range emerges as the most important predictor controlling decadal-scale marsh stability for both margins and interior regions. Position of a marsh parcel within the wider coastal system morphology is also an important control. Selected models are then queried with realistic future scenarios representing changed input conditions to predict system responses (e.g., Figure 4.2). The resulting predictions show sensitivity to all scenarios tested and a high degree of spatial detail in responses. While mechanistic interpretation of some responses is challenging, process-based justifications are offered for many of the observed behaviours, providing confidence that the results are realistic.

The work demonstrates a potentially powerful alternative (and complement) to current morphodynamic models that can be applied over large areas with relative ease, compared to numerical implementations. The comparison of statistical approaches and the insights thus gained are a valuable contribution to the development of data mining and machine learning in the field of coastal geomorphology. Such methods are shown to be of great potential value in support of applied management and monitoring interventions.

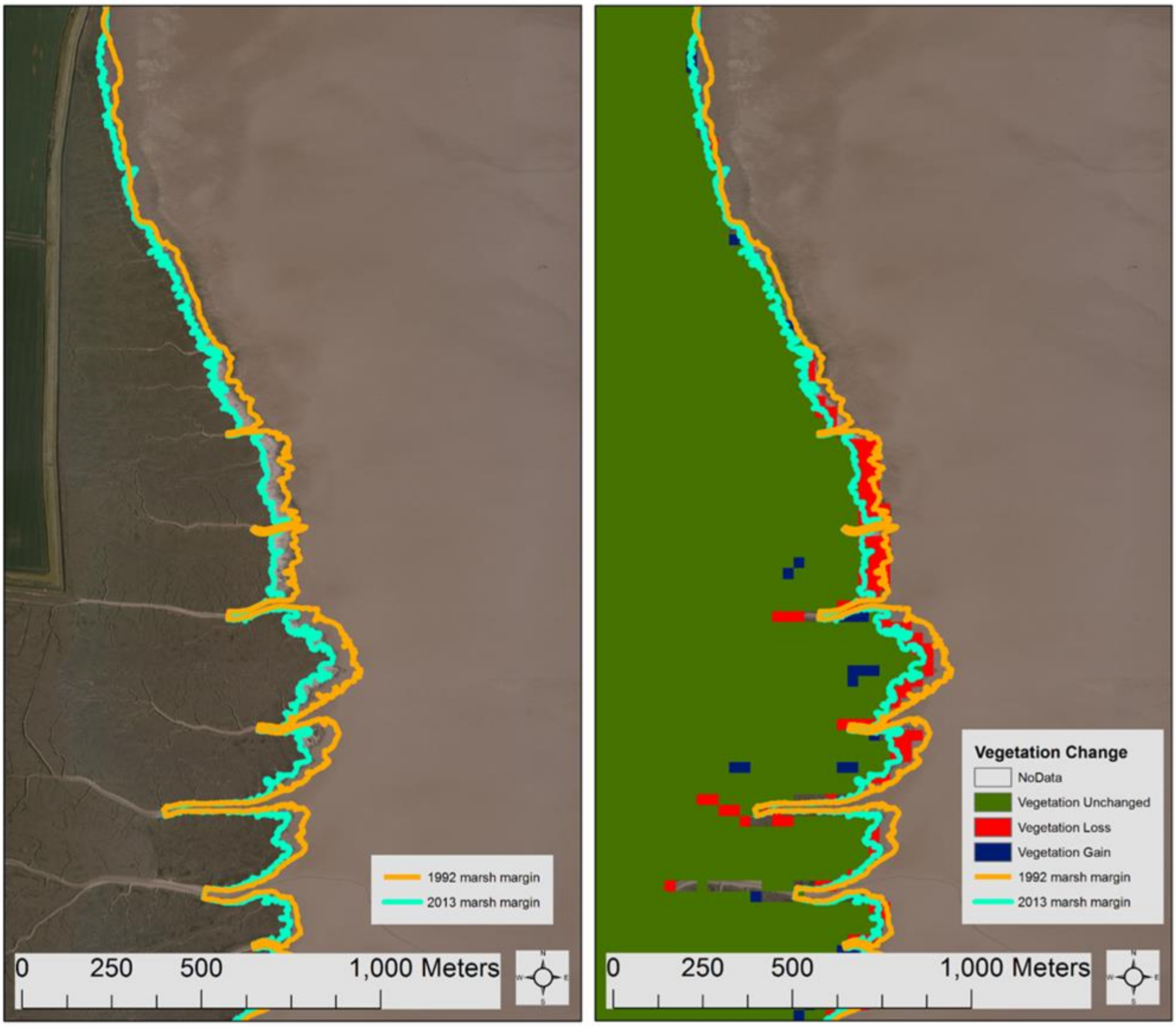

Figure 4.1 Marsh margin position at the Tillingham study site, United Kingdom, as digitised from aerial photography (1992 and 2013) and the results from the global vegetation change analysis based on Landsat satellite imagery showing sensitivity of the method where margin retreat exceeds 30m.

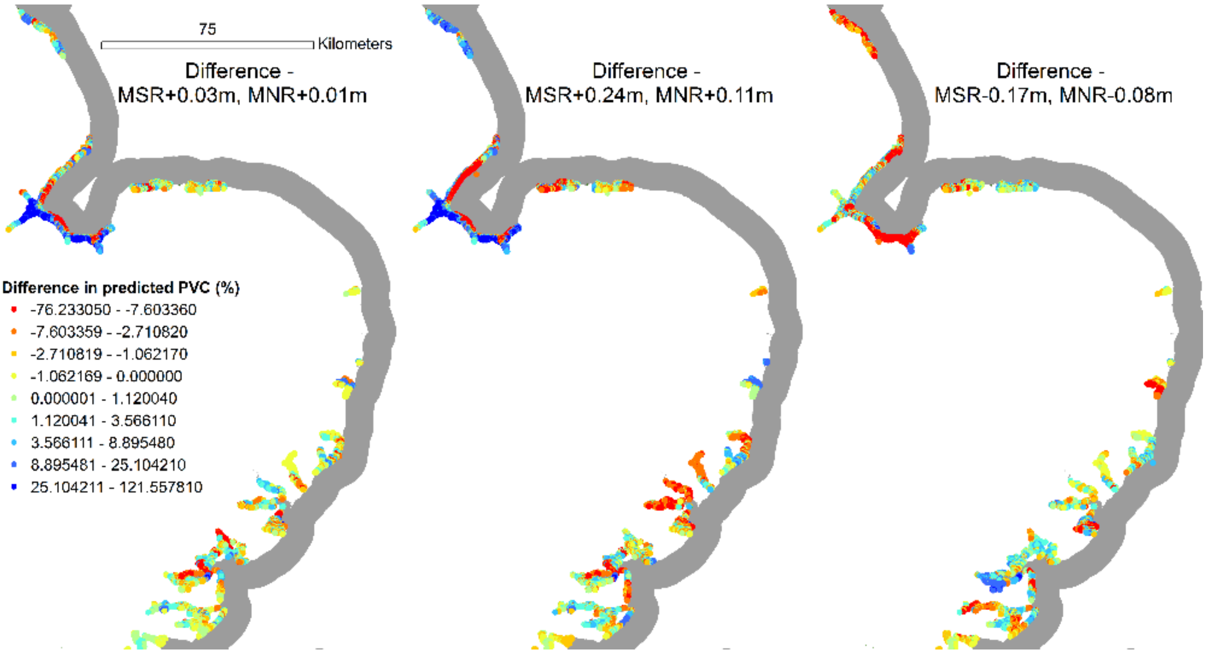

Figure 4.2 Predicted changes in rate of change in coherence of marsh interiors under scenarios of altered tidal ranges associated with sea level rise, east England, United Kingdom. PVC= percentage change in the proportion of each 30m pixel that is vegetated (over a ~25 year time period). MSR= mean spring tidal range, MNR= mean neap tidal range. Figure shows differences compared to the control run with MSR and MNR unaltered from the calibration period.

5. Long-term elevation changes from Earth Observation

Using techniques for the estimation of elevation (or bathymetry) from earth observation (EO) as developed in EU FAST (FAST-IE), it is feasible to derive ‘snap-shots’ of elevation over regular time periods, giving indications of long-term bed dynamics. Elevation can be derived from optical inversion, usually applied to single, high quality scenes, or, with a long enough time-series built up from ‘water lines’ (or other geometries) using both optical and SAR imagery, giving values in inter-tidal regions. Inter-tidal elevation can also be derived through the careful selection of images and the application of In-SAR. Indeed, these techniques have been refined, particularly with non-free sensors, to produce very high resolution commercial services with high levels of accuracy. Nevertheless, in terms of assessing long-term dynamics of coasts, the Open Access USGS Landsat and Copernicus Sentinel 2 collections are very attractive, as they form the longest continuous HR archive available (~ 30 y), are universally accessible, and potentially allow verification/reproducibility of results.

Here we demonstrate the potential of using the Landsat/Sentinel-2 collection to derive elevation and marsh extent over a 30 y timespan so as to examine long-term bed elevation changes in relation to foreshore at a case-study site in Canada. This work was carried out by Marijnissen and Aarninkhof (2017) with collaboration from Vancouver Fraser Port Authority, Environment Canada and the Ministry of Forests, Lands, Natural Resource Operations and Rural Development of British Columbia, and the EU FAST project. The high quality, independent, field data supplied by the agencies involved, and real-world nature of the challenge, made this an excellent test for the techniques being developed in the EU FAST project, providing an opportunity to refine and operationalise MI-SAFE advanced services.

The Fraser Delta is situated on the western coast of Canada, and includes parts of the highly populated metropolitan area of Vancouver and Richmond (Figure 5.1). On the western edge of the Fraser Delta lie Sturgeon and Roberts Bank Wildlife Management Areas, important brackish marshes with high ecological relevance. Human activity is intense within the region, with coastal engineering (dykes, jetties, and dredging) beginning in 1905. Recently, there has been growing concern about potential changes in the distribution of the marshes, and the possible implications this may have for coastal defence.

Using the USGS Landsat and Copernicus Sentinel-2 collections available in Google Earth Engine in combination with a Lidar survey from 2015, tidal water-level measurements at ‘Point Atkinson’ and ‘Sand Heads’, and field data on marsh presence from 1980s and 2015-2016 (B. Mason, 2016), Marijnissen and Aarninkhof (2017) evaluated variations on techniques (different indices, extracting water lines or polygons, time-ensemble averaging) for deriving bed elevation, and marsh extent (spectral unmixing versus supervised classification) using EO data. The ‘best performing’ techniques for bed elevation, evaluated by comparing the Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) against 2015 Lidar data, and deriving marsh extent, evaluated using confusion matrix statistics against field observations, were used to give indications of long-term changes.

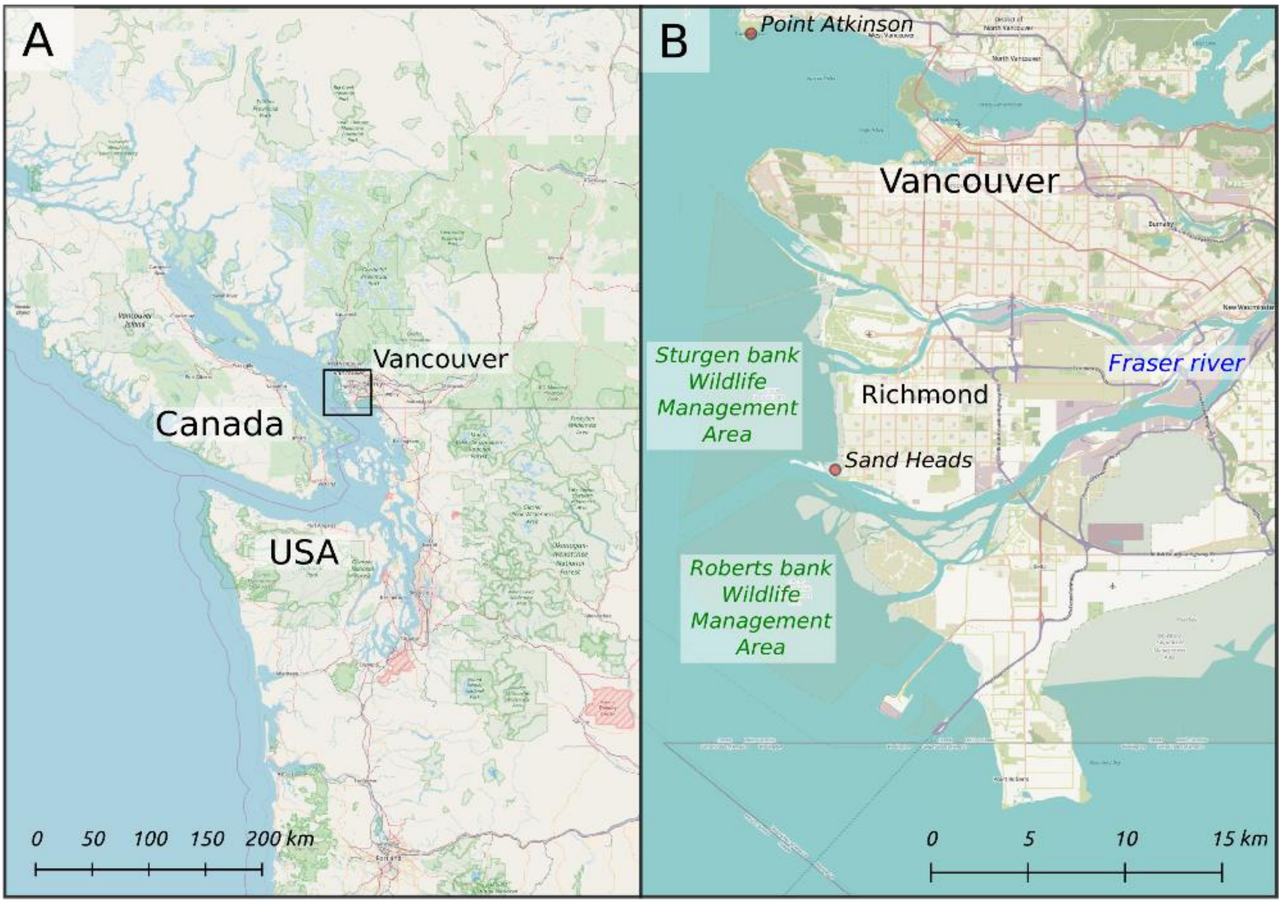

Figure 5.1 Map of Fraser Delta study site in British Columbia, Canada. A) Location of Vancouver. B) Location of Wildlife Management Areas on foreshore of Richmond. Red circles represent tidal stations. Adapted from Marijnissen and Aarninkhof (2017).

In summary, all methods for deriving elevation performed relatively well, with MAE ranging from 0.36 m to 0.73 m (Figure 5.2), which is comparable to the accuracy of Lidar in inter-tidal areas (~0.2 m). Using different spectral indices to identify water influenced the range of elevation identified, and the amount of 'noise' introduced in the final elevation product. Overall, using the normalised difference water index (NDWI; NIR, Green bands) appeared to represent a good compromise. Elevation derived from water lines, with the water level assigned from in-situ values measured at the tidal level station Port Atkinson (adjusted for minor differences observed at Sand Banks), provided higher accuracy compared to time-ensemble averaging of water indices and scaling to the highest and lowest water levels measured (the technique used in the global FAST-IE product; where min-max levels are provided by a model). Maps derived from time-ensemble averaging provided more detail, but had a consistent underestimation bias. Hence, the water-line method using NDWI was consider most accurate (RMSE: 0.53 m, MAE: 0.36 m), however the FAST-IE-advanced product (RMSE: 0.81 m, MAE: 0.73 m) was useful for visually identifying regions of change, gave similar values for relative differences in bed-level, and produced smoother across-shore transects.

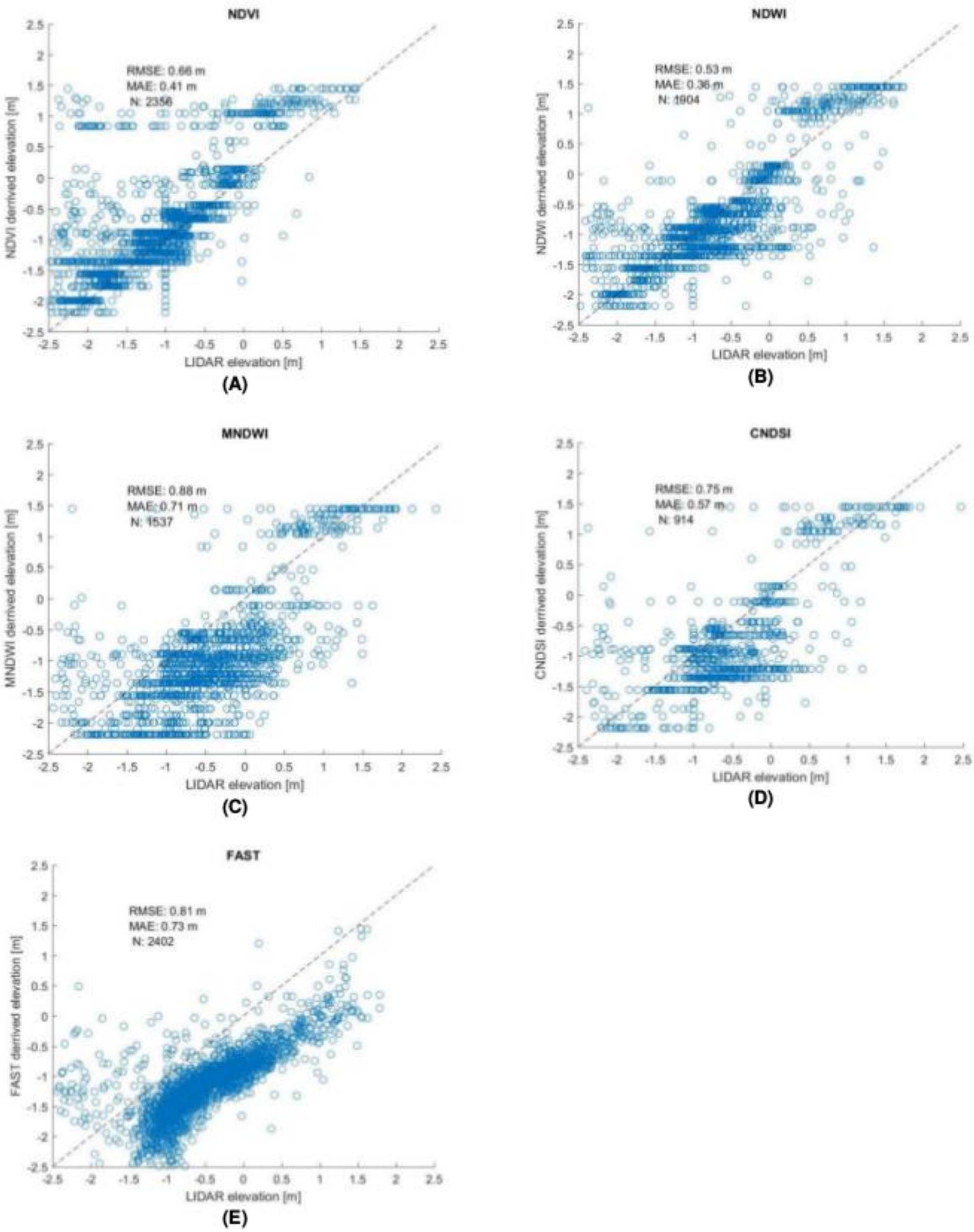

Figure 5.2 Scatter plots of the LIDAR elevations against the elevations derived from the satellite images. The water line method was carried out for the NDVI (A), NDWI (B), MNDWI (C), and CNDSI (D) indices. The FAST method (E) was carried out only once with the MNDWI. Reproduced from Marijnissen and Aarninkhof (2017).

Validation of marsh extent derived using spectral unmixing and supervised classification was made by comparing field surveys (2015-2016) that included assessment of the seaward marsh edge, and gaps within the marsh (Figure 5.3), surveys from the 1980s and 2017. Essentially both methods performed well, capturing the marsh edges observed in 2015-2016, and giving a classification accuracy of 0.9 and 0.86, respectively, compared to the extensive 1980s survey. Highlighted by the 2017 'spot' survey of regions that were problematic for classification, regions with sitting water, and the user interpretation of what is marsh and not marsh appear to contribute to misclassification.

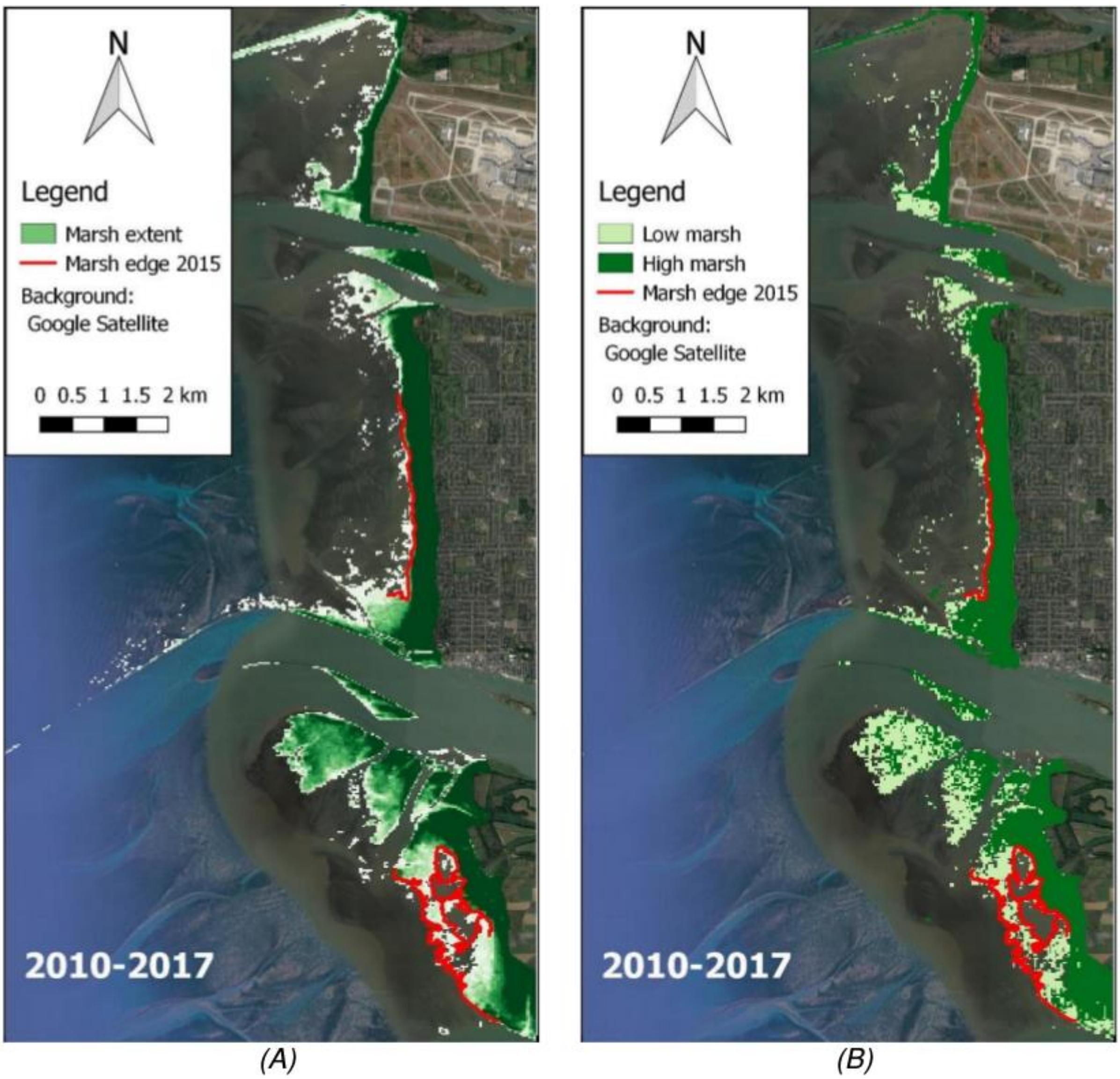

Figure 5.3 Marsh extents from the satellite analysis using (A) spectral unmixing and (B) supervised classification compared to measured marsh extents by GPS by B. Mason (2016). Reproduced from Marijnissen and Aarninkhof (2017).

Bed level changes were detected by examining 10-year intervals (Figure 5.4, only shows change between 1980-1990 and 2010-2017). A limited amount of change was detected before 2000, after which changes in the order of -0.5 m were observed, mainly in the upper region (~200 m from the dike) of Sturgeon bank, and 600 m from the dike at Roberts bank. These changes are similar to the MAE of the technique, however, combined with the other studies on the site, they give strong indications that erosion did take place and probably is the result of a process that affects the entire delta front.

The leading-edge of the marsh on Sturgeon bank receded rapidly between the periods 1980-1990 and 2000-2010 (Figure 5.5, only shows change between 1980-1990 and 2010-2017), but showed no change after 2010. On Roberts bank the outer leading edge remained stable, but the marsh was converted to mud flat during in the same period , and again after 2010 no change was detected.

Hence, the study suggests that bed-level changes appeared to lag behind the loss marsh (by one 10-year period), making it likely that marsh recession was a key factor that lead to foreshore erosion, rather than the erosion leading to marsh recession. This provides a useful focus for which to frame further research questions, i.e., what factors may have led to marsh die-off?

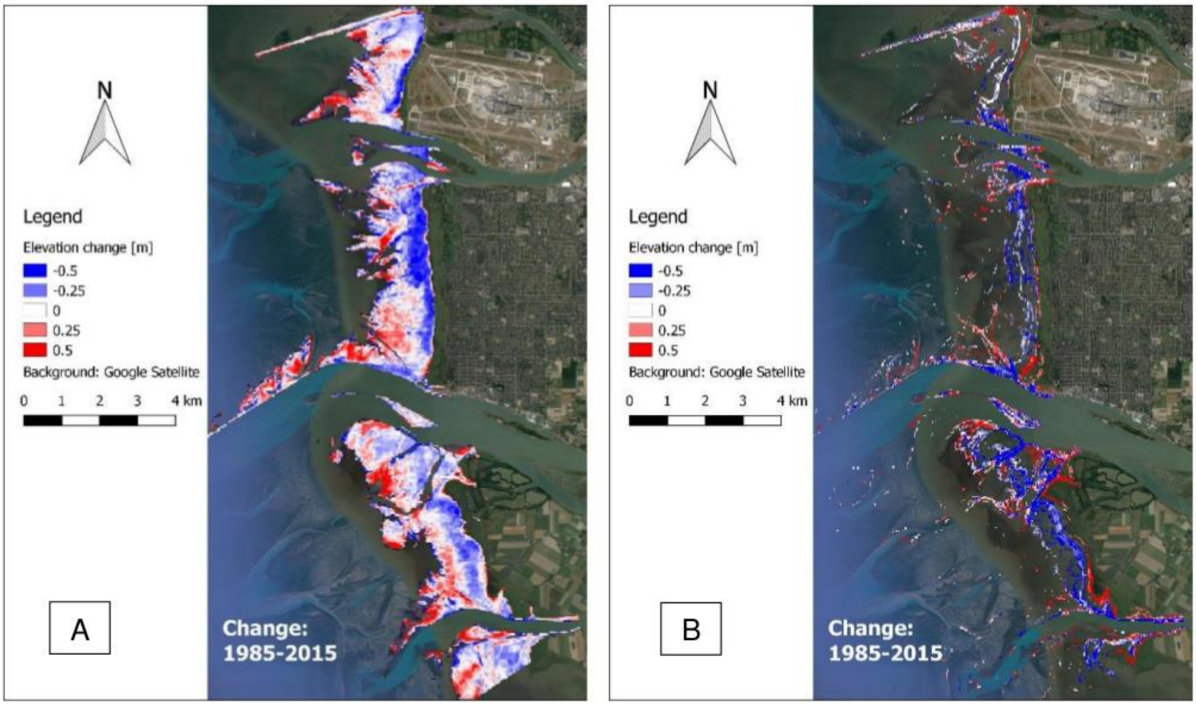

Figure 5.4 EO-derived bed level change. A) FAST-IE elevation between 1980-1990 and 2010-2017. B) NDWI waterline elevation between 1980-1990 and 2010-2017. Reproduced from Marijnissen and Aarninkhof (2017).

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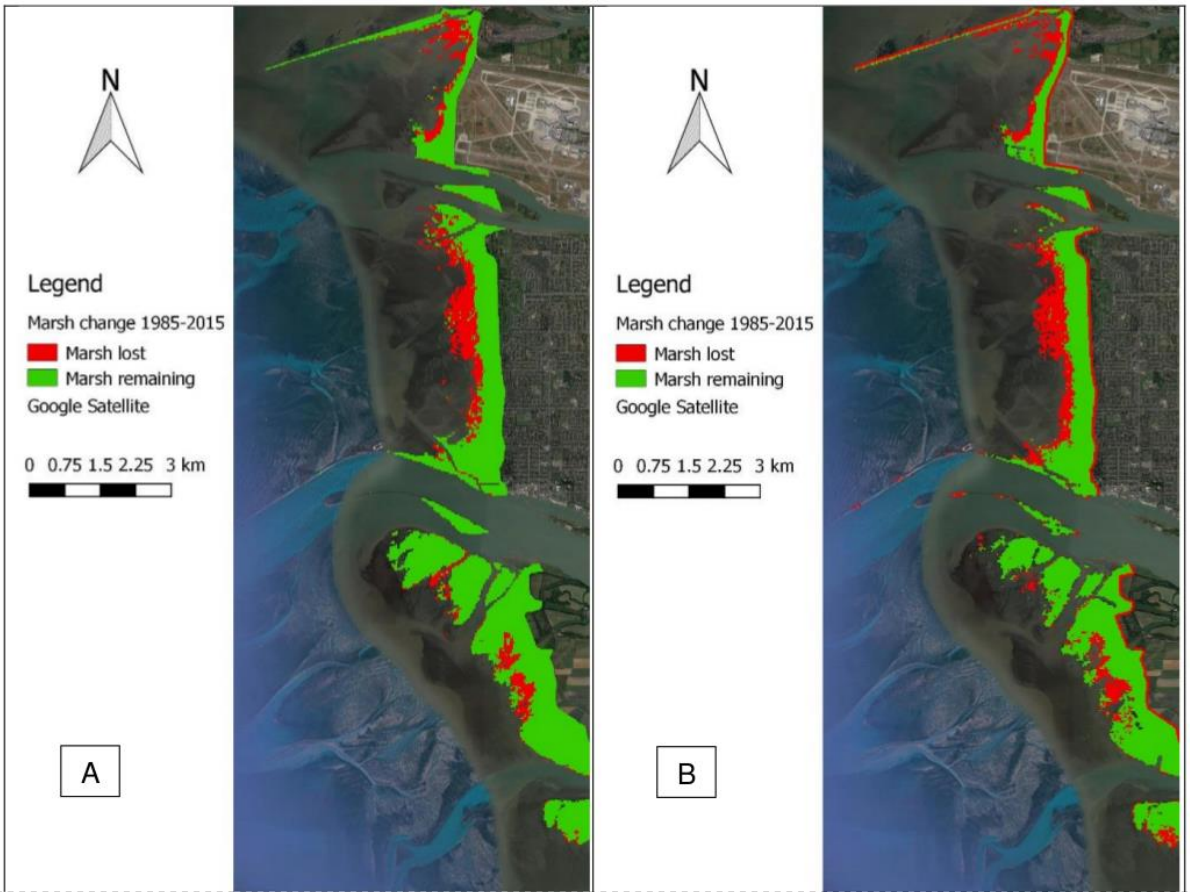

Figure 5.5 Changes in marsh extent between 1980-1990 and 2010-2017. A) from spectral unmixing. B) from supervised classification. Reproduced from Marijnissen and Aarninkhof (2017).

The advanced MI-SAFE services employed here to examine in detail long-term (30 y) bed level dynamics and marsh extent require good quality local data (time-series of water levels, accurate digital terrain model, and geospatial data on habitat types), and are thus best employed working with local data collection agencies. Using these 10 y snapshots, we are now in the process of running an XBeach model to give insight into how these changes may affect wave attenuation. The full processing chain is being operationalised and made more generic, so as to allow rapid application to other regions. Also the valuable insights gained from the testing of different techniques are being used to improve the MI-SAFE educational products; global intertidal elevation (FAST-IE) and global vegetation presence (FAST-VEG).

6. Conclusions

The status and stability of foreshores is relevant when implementing saltmarshes in flood defence strategies. In this report, we characterised the dynamics of foreshores at different spatiotemporal scales. Short-term vertical changes in bed levels have been assessed in situ using continuously measuring SED sensors, and erodibility of the sediment have been assessed in wave tank experiments. Long-term lateral changes in vegetation extent in bed levels have been assessed using both aerial photographs and satellite data. Intertidal elevation has been assessed using satellite data, and has been applied here to retrieve long-term vertical changes in elevation. Products to assess the status and change of foreshores are already included in the MI-SAFE package downstream service.

The studies presented here also address how the vertical and lateral dynamics in bed level and marsh extent are related to forcing factors, such as waves and tides. Understanding system behaviour is required to be able to predict the future development of the system, and hence, to foresee safety levels of flood protection strategies. The knowledge should then be translated to generalized predictive rules and uncertainty bands. Rules can include a physical approach, describing the relationships between sediment dynamics and wave- and current -induced bed shear stress as presented in Chapter 2, a hierarchical statistical approach as demonstrated in Chapter 3, or a predictive statistical model framework as elaborated in Chapter 4. Calibration and validation at other sites would be required to evaluate the generality of the responses.

7. Publications

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