CENTRE OF EXPERTISE FOR WATERS

Dynamic Coast

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J.M. Fitton, A.F. Rennie, J.D. Hansom, F.M.E Muir

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The cover image shows: (Top) Storm waves reflecting and undermining artificial defences at Golspie, Highland. Copyright: A. MacDonald (2020). (Bottom left) coastal erosion of the beach crest adjacent to the World Heritage Site at Skara Brae, Bay of Skaill in Orkney. Copyright: A Rennie / NatureScot (2019). (Bottom right) an oblique aerial image of the Splash play park at Montrose looking north. In the 1980s the play park was set-back within the dune, due to the subsequent coastal erosion, now it is in a more exposed position relying on artificial coastal defences. Copyright: F. McCaw (2021).

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Context

Scotland's foreshore is varied and complex with differing extents of intertidal area exposed twice daily during low tides. At its narrowest it occupies almost no space against vertical cliffs and seawalls, at its widest it can stretch for several kilometres over intertidal sand banks within estuaries. Many ecosystem services are provided by the intertidal zone; including wave attenuation that provides a reduction in flood risk and coastal erosion, significant carbon sequestration within habitats that support a range of internationally recognised habitats, and an extensive range of specialist species, many of which are rare and protected. Routine monitoring of surface change for the entirety of the circa. 243,200km^2 of Great Britain is undertaken by Ordnance Survey (OS) using block captured aerial imagery. The operational constraints surrounding this huge national cyclical revision programme mean that targets are typically acquired opportunistically and not with respect to any particular tidal state. Therefore, it is rare that the time of imagery acquisition coincides with the attendant limited tidal windows and meteorological constraints necessary to monitor MLWS and the vast and rapidly changing intertidal zone. OS does plan and capture some imagery targets at specific tidal states, i.e. MLWS, in order to be able to update the intertidal zone, particularly where extensive or rapid change is known to be occurring. In Scotland, such targets are informed by the work of Dynamic Coast. Nevertheless, there are very few days in each year when tidal state, weather conditions and lighting conditions align to make such capture to MLWS possible. Therefore, such sorties are logistically challenging, relatively expensive and difficult to scale to large volumes of capture which means they tend to be limited to the highest priority areas. In England, the Environment Agency has undertaken extensive shoreline and foreshore surveys using LiDAR and SONAR and low water updates have been incorporated within OS products. Analysis in England and Wales shows that Mean Low Water has retreated landwards faster than Mean High Water and alongside sea level rise this has resulted in shoreline steepening and an increased risk of wave overtopping. More recently there is clear evidence internationally that intertidal extents are reducing in area and this has been recognised as a high priority issue internationally with Sustainable Development Goal (SDG) Indicator 6.6.1 calling for changes in the extent of water-related ecosystems over time to be monitored. To better inform management of this environment there is a pressing need to establish the current extent of the intertidal zone and monitor any changes in area over time.

Methods

The method developed by Dynamic Coast to establish intertidal extent in Scotland is called Coast X-Ray and was developed using Google Earth Engine (GEE), a cloud-based platform that allows user access to high-performance computing resources to process very large geospatial datasets. Even though this research is focussed on the Scottish context the approach taken with Coast X-Ray was to develop a method applicable globally, whatever the tidal range at that point. In the Scottish, UK and Irish context, large tidal ranges expose variable but extensive intertidal areas. These tidal extents are captured remotely from space by overpassing satellites and if the satellite overpass time stays relatively constant, different tidal states will be represented within each of the images captured. Over time, for any one location, a series of images are obtained that capture a range of tidal stages.

The occurrence of water cover within the intertidal zone is influenced by the topography and geomorphology of the area between high and low tides, with the frequency of water occurrence providing a window into this geomorphology. Figure 1 demonstrates the general relationship between water occurrence and coastal topography showing areas that are never covered by water (i.e. land) lying at elevations above the Highest Astronomical Tide (HAT) and areas that are always covered by water (i.e. sea) lying below the Lowest Astronomical Tide (LAT) elevation. The areas that are sometimes covered by water represent the intertidal zone.

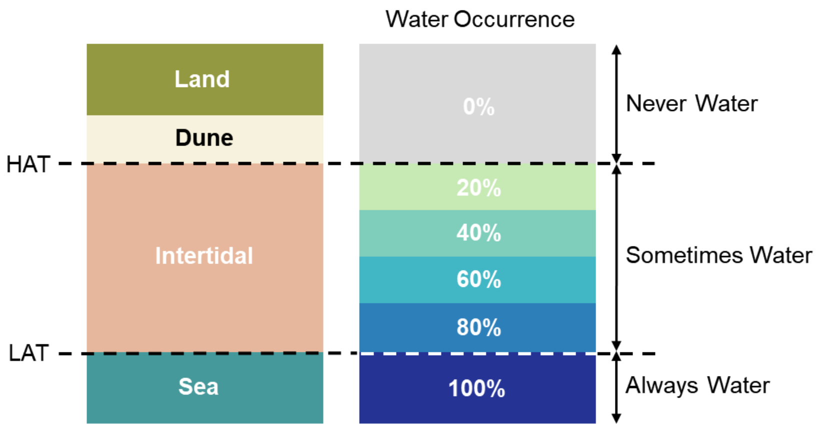

Figure 1 A hypothetical example showing the relationship between coastal geomorphology (left) and water occurrence frequency (right).

Coast X-Ray uses the Sentinel-2 satellite (EU Copernicus Programme) optical imaging, which has a revisit/overpass time of approximately 5 days. The optical data are collected as images with 13 spectral bands across the visible, near infrared and shortwave infrared parts of the light spectrum. The Coast X-Ray method applied here utilises two of the spectral bands for water identification, the green and near infrared (NIR) bands which both have a spatial resolution of 10 m.

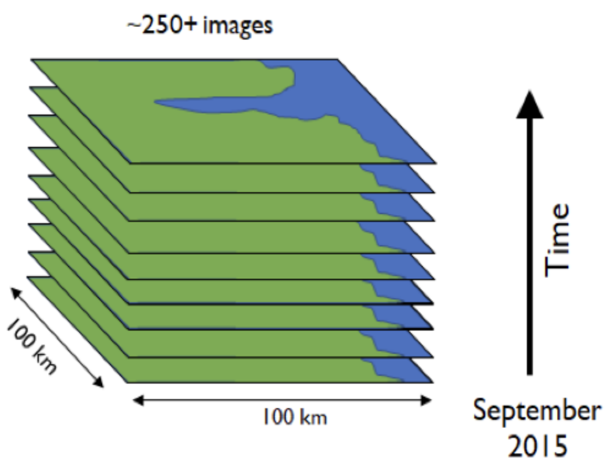

Figure 2 A representation of the 'stack' of 250 satellite scenes available within the Sentinel Back catalogue, available since September 2015.

Since Sentinel-2 collects overpass images at approximately the same time of day over locations in UK and Ireland (approximately between 11:00 and 13:00 UTC), the image capture records varying tidal extents at that time and location and can be used to build a picture of water extents over time that are controlled by the interaction of tide with the intertidal topography. In Scotland, cloud cover means that there is very often imagery that is partly, or even completely, covered by cloud or shadow that create inaccuracies within the analysis and produce errors. To limit these issues, images with extensive cloud cover and shadow were excluded from the time-series stack (Figure 2).

For each of the images within a time-series stack the water cover can be established by using a Normalized Difference Water Index (NDWI) calculated from the green and NIR bands of each image as follows:

$$NDWI = \frac{(green - NIR)}{(green + NIR)}$$

This formula creates a ratio of surface reflectance for each pixel in an image of between 0 and 1. Water produces a value close to 1, indicating very low reflectance of NIR light, with land (soil, sand, vegetation and artificial surfaces) producing a value close to 0. Coast X-Ray used 0.2 as a fixed threshold and classified any pixels with a NDWI value of greater than or equal to 0.2 as water. Each image then contains pixels that are classified as water (allocated a value of 1) or non-water (allocated a value of 0).

Processing involves reducing a time-series stack of images, that have been classified as either water or non-water, to a single image. This is done by calculating the frequency of water occurrence at each pixel in the stack by summing the water classification values. For example, in a time-series stack of 50 images, the reduced single image will have pixel values ranging from 0 to 50. Pixels that are always classified as non-water across the 50 images have a value of 0 (50 x 0 = 0). Pixels that are always water have a value of 50 (50 x 1 = 50). Pixels that are sometimes covered with water will have values ranging between 1 and 49 and are then expressed as percentages representing the frequency of water coverage.

To enable analysis to be performed at large spatial scales, the intertidal zone has been subdivided into a hexagonal grid, with each grid cell representing an area of approximately 96 km^2. The above process is run on each grid cell and amalgamated to create a national output dataset with a 10 m spatial resolution on the ground.

In order to enhance both the accuracy and the utility of the outputs to the user community, Coast X-Ray has been enhanced to link the time-stamp of each image and timing of the tidal stage at the time of data capture (see Fitton et al submitted, pre-print in annex). Using the anticipated tidal level allows targeted tideline analyses at, or very close to, MHWS or MLWS. The tidal enhancements within Coast X-Ray use the National Oceanography Centre (NOC) tidal stage model, determined at 1.5 km intervals around the coast. Time-stamping the satellite imagery data with the tidal height at the time of image acquisition allows the spatial extent and approximative elevation of the tide at that time to be shown. Establishing the anticipated elevation of the tide against observed water level on the image also allows information about the topography and gradient of the intertidal area to be more reliably determined and, potentially, order-of-magnitude intertidal pseudo-elevation models to be sequentially produced. This produces a step change in the level of information available nationally, for all foreshore, however remote or unstudied. Normally such intertidal elevation models, or digital surface model (DSMs) are only available as the product of DGPS ground survey, aerial imagery or LiDAR, all of which carry logistical challenges that impose costs that would be prohibitive to incur at a national level, and are not easily repeated. Coast X-Ray offers an alternative that is nationally and regularly updated.

Indicative results

For the UK and Ireland, Coast X-Ray Water Occurrence was generated for 1,591 hexagonal grid cells resulting in 153,000 km^2 of intertidal capture across the full Sentinel 2 data catalogue (September 2015 to September 2020). This exercise successfully delimited the national change in water occurrence, that was then validated and quality assured at several sites where the extent and changes in the positions of MHWS and MLWS had been established by Dynamic Coast and OS using conventional methods. Two of these sites are described below in order to demonstrate the use of Coast X-Ray as a change intelligence tool.

The first of these is at St. Andrews (Figure 3) where the outlet of the Eden Estuary previously existed as a single channel, shown by the MLWS grey line in Figure 3. The intertidal sand bank that extended north from the south side of the Eden estuary was used in ca 2000 & 2010 as a donor area from which sand was taken to renourish the dunes and beach on the south side. However, Coast X-Ray (2015-2020) shows two channels to now exist, this change being confirmed by the MLWS 2018 line which was extracted from bespoke OS aerial imagery collected in May 2018 and a digital elevation model. Therefore, Coast X-Ray (fast and cheap) has been able to provide the same qualitative change intelligence as a dedicated (slow and expensive) aerial survey. Both clearly show the intertidal sand bank used for dune and beach rehabilitation has now been cut-off by this new channel, key management information for any repeat of the renourishment exercise at St Andrews.

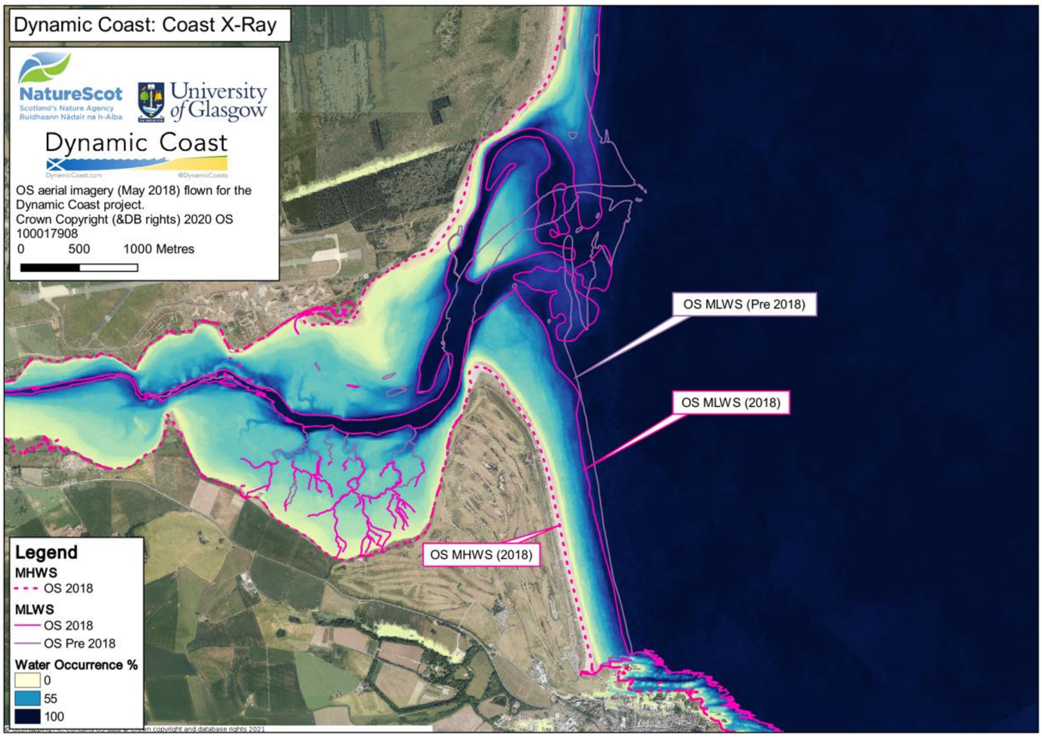

Figure 3 The water occurrence output (Coast X-Ray) derived from approximately 72 images from September 2015 to December 2018 for St. Andrews, Fife, with OS MLWS shown (unknown date). The water occurrence output shows that MLWS has migrated with the Eden Estuary channel now split into two channels. The gradient of blue areas represent higher frequency of water occurrence, with the gradient of yellow representing infrequent water coverage.

Coast X-Ray can also be used to rapidly identify areas where the OS MHWS lines require updating; for example, where offshore renewable energy cable or pipelines make landfall in remote and unsurveyed areas. The utility of Coast X-Ray is demonstrated in this regard in Figure 4 where the mouth of the North Esk in Montrose Bay has significantly changed position since its 2012 position as published by OS. The North Esk now makes a more direct exit into Montrose Bay truncating its earlier northward extending spit and producing changes to the coastal edge on both banks. This change intelligence was subsequently confirmed by a bespoke OS aerial imagery survey in May 2018.

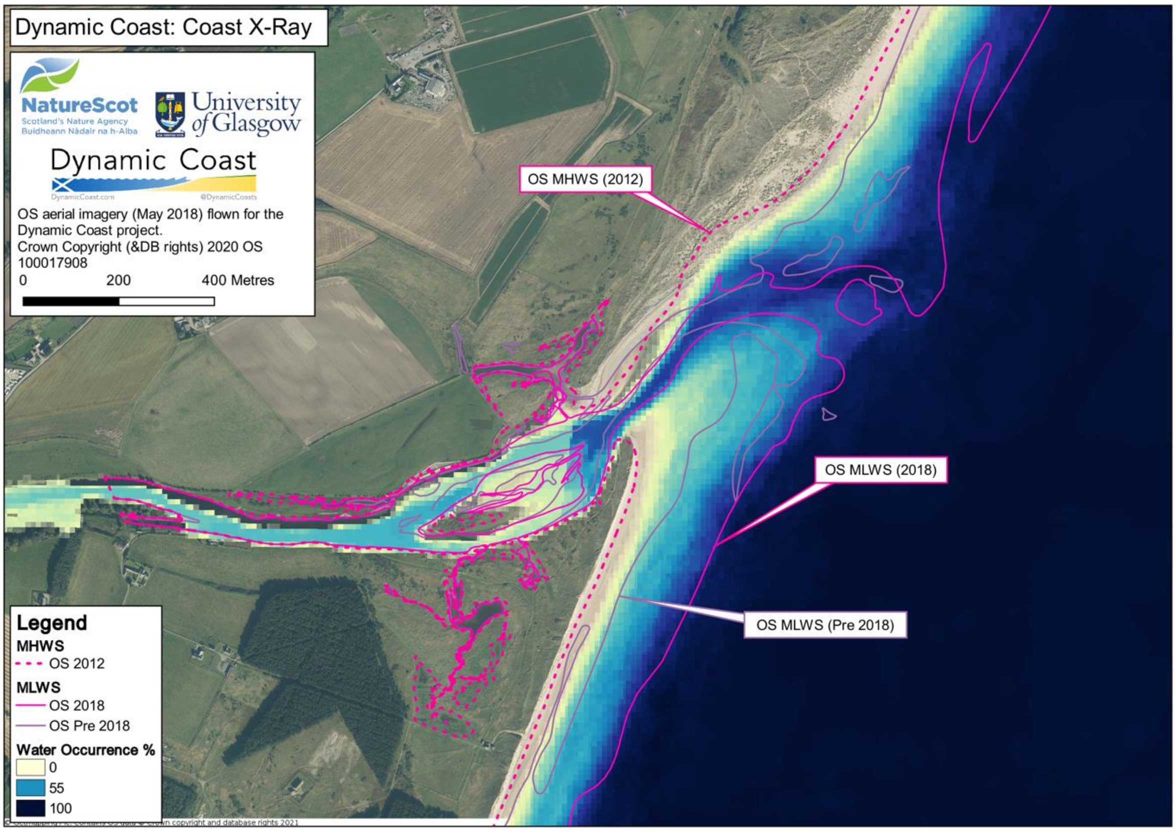

Figure 4 The water occurrence output derived from approximately 46 images from September 2015 to December 2018 at the North Esk, near St. Cyrus, Aberdeenshire. The position of OS MHWS and MLWS are shown, with the water occurrence output showing there has been movement of MHWS at the mouth of the North Esk. Blue areas represent higher frequency of water occurrence, with yellow areas representing infrequent water coverage.

The Dynamic Coast X-Ray method is a novel, cost effective and rapid way of gaining insight into the changes and extent of the intertidal areas, with validation showing positive results when compared against high resolution LiDAR data. However, it should be noted that the intertidal examples used above were flown by OS as a result of change intelligence generated by Dynamic Coast and the active collaboration between the parties. Only limited other areas have been able to be thus far subject to similar recent OS updates, although more are planned. Dynamic Coast analysis shows that 99% of the current OS MasterMap MLWS line is sourced from the 1970s MLWS line. The bulk of the Scottish intertidal zone has not benefited from detailed MLWS data collection in fifty years, this has in part been due to the hitherto absence of an effective change intelligence tool to inform which areas of MLWS actually require updating.

This highlighting the utility of Coast X-Ray in providing both change intelligence and also regular and cheaply generated intertidal extent updates.

Two further outputs are explored below based on the tidally corrected analysis. Firstly the Intertidal Elevation is available, showing the intertidal zone represented as a decile intervals of the tidal range (shown in Figure 5), and as an intertidal elevation output relative to mean sea level. Further steps are required to convert the Intertidal Elevation relative to mean sea level to Ordnance Datum; this is currently under investigation.

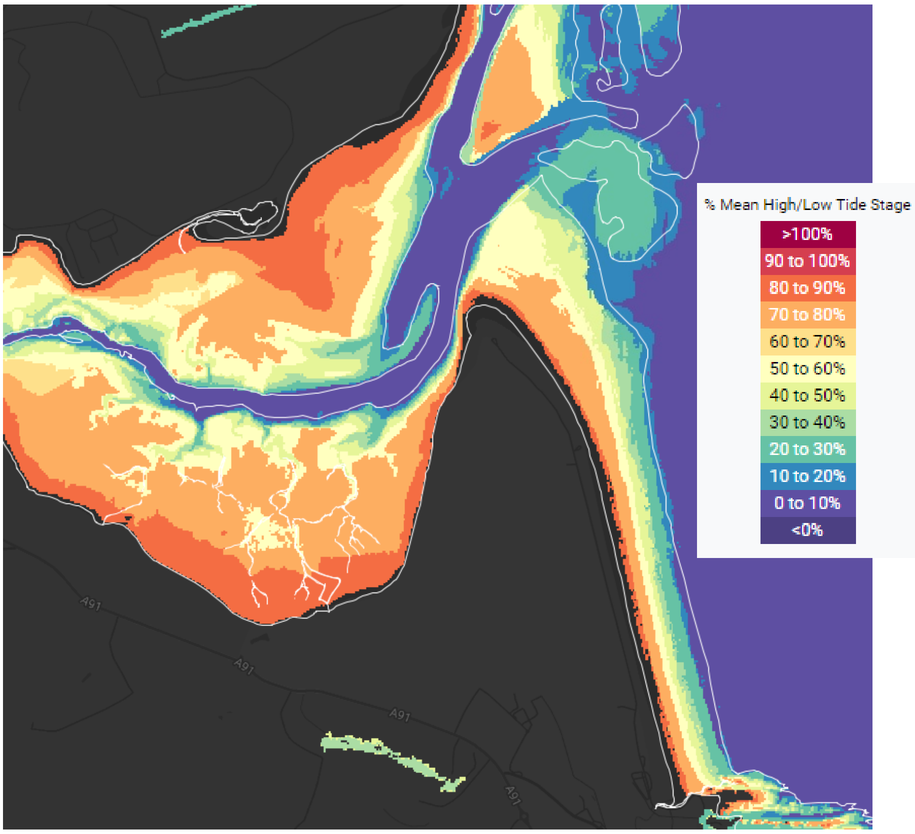

Figure 5 The Coast X-Ray Tidal Stage output shown for St Andrews Links. The low water mark occurs at the boundary between "<0%" and "0 to 10%" categories, and the high water occurs at the "90 to 100%" and ">100%" boundary, effectively making this a form of digital elevation model (if high water and low water elevations are known).

Figure 5 shows the intertidal zone, however the shading may omit high or low elevations in locations where insufficient observations have been recorded, and so introduce issues of analytical bias and sampling error. The Coast X-Ray web-map allows the user to explore the source data used within the maps in (Figure 6). Two plots are generated which show the image date and tidal level used within the analysis with the histogram displaying the number of images within each 10% of the tidal range, which provides the user with further reassurance, or warnings, that may colour subsequent interpretation.

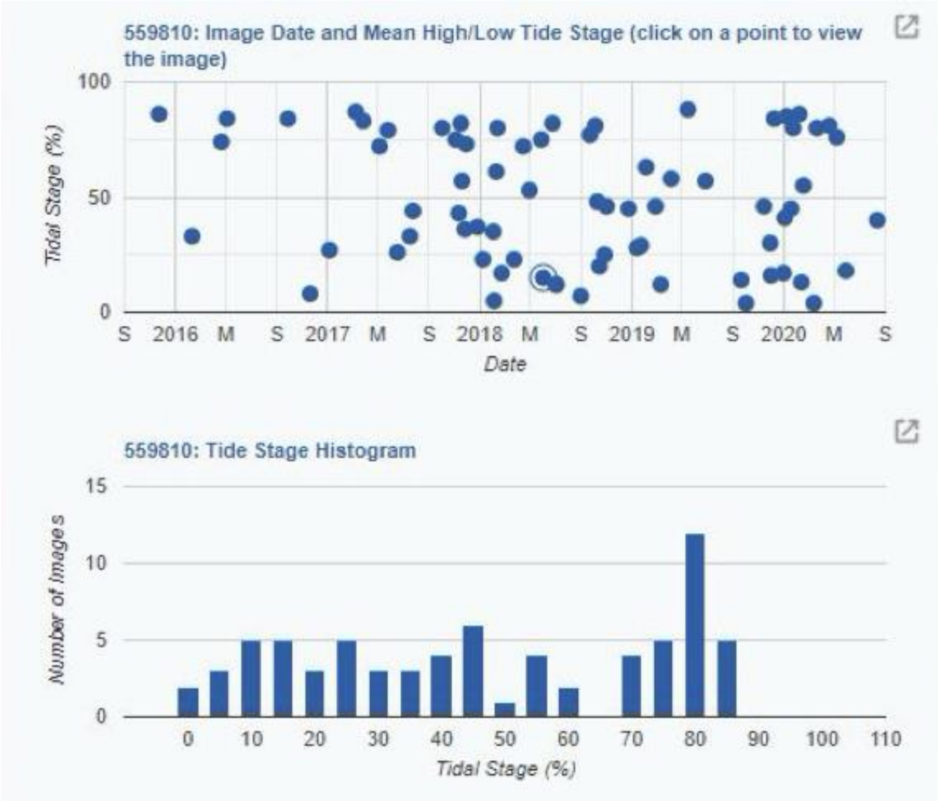

Figure 6 An example of the image charts and statistics available for each grid cell via the web map. A user can inspect an individual image by clicking on the appropriate point.

Again, within the Coast X-Ray web map the user can click on a point within the upper graph (Figure 6) which displays the actual satellite image and also to turn on 'show water' based on the NDVI analysis. Such a tool enables normally hidden topographic changes within the lower foreshore to be identified as shown in Figure 7below.

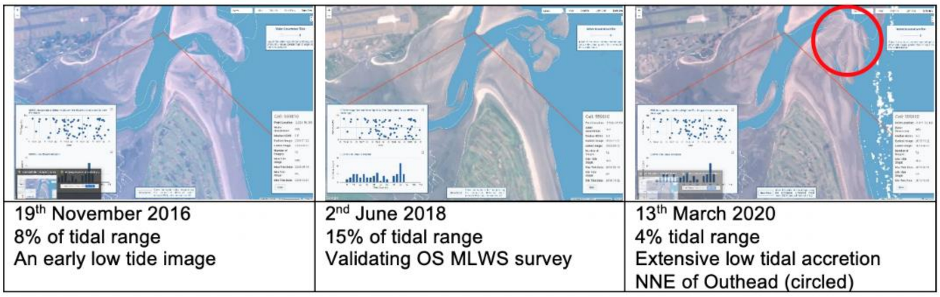

Figure 7 The apparent water extent in three images from St Andrews, used to support the identification of a new sediment extraction site.

Wider implications of this research

Since Coast X-Ray captures change in the position of tidelines nationally, it contributes to an enhanced understanding of the current and future behaviour of foreshore over a period when the pace of climate related impacts is anticipated to change more rapidly. Such change intelligence is a valuable tool for coastal and infrastructure managers, who rely on costly local assessments. Beach steepening issues nationwide can be investigated on a near real-time basis as MHWS and MLWS track landward (or seaward) at different rates. For example, this offers a step-change in the ability of managers to remotely assess the volumetric rate of change of any beach and better inform the management route forward. Coast X-Ray can provide advance notice of upper beach lowering and the potential for storm overwash that may place assets at risk of erosion or elevated flood risk. If beach renourishment is a management option, then Coast X-Ray can provide spatial changes in beach geometry, together with loss volumes and recharge volume estimates.

Since MHWS and MLWS are also administrative boundaries used by agencies for regulatory purposes, then the currency of tideline position becomes key to the effective delivery of their statutory duties, particularly in a period of uncertainty over future climate change impacts at the coast. Such change intelligence, used in conjunction with the range of information provided by other Dynamic Coast outputs, will underpin the aspirations of Government to progress the full range of adaptation options at the coast and move toward a more sustainable and resilient future for our coast and its communities. More details can be accessed in Fitton et al, (2021).

Supplementary Reports

Supplementary reports and online tools are available on www.DynamicCoast.com.

The interactive web-map is available here: https://www.dynamiccoast.com/coastxray

Reference

Fitton, J.M. Rennie, A.F., Hansom J.D. & Muir, F.M.E. 2021 Remotely sensed mapping of the intertidal zone: a Sentinel-2 and Google Earth Engine methodology. *Remote Sensing Applications: Society and Environment*. https://doi.org/10.1016/j.rsase.2021.100499

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