Multi-temporal Airborne Remote Sensing of Intertidal Sediment Dynamics

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ABSTRACT

Coastal remote sensing applications are regularly confined to single image 'snapshot' approaches which do not resolve the dynamic processes in the required temporal resolution. This paper reports the results of a project in which the dynamics of tidal sedimentation were monitored by multi-temporal airborne remote sensing in 10 minute time steps. The radiance data was then converted to estimates of suspended particulate matter loading by the inversion of a hydro-optical analytical model.

The results demonstrate that multi-temporal coastal remote sensing can provide information about such dynamic processes that realistically can not be obtained by field-based research methods.

Keywords: multi-temporal remote sensing, coastal monitoring, sedimentation dynamics

1. INTRODUCTION

Remote sensing approaches offer an alternative to traditional field-based coastal research methods because it is possible to collect synoptic and spatially coherent information about a surface. For example, by deploying spectral imaging sensors on an airborne or spaceborne platform the spatial heterogeneity of such a surface can then be captured. Airborne sensors are particularly suitable for monitoring coastal dynamics because they can be deployed repeatedly under favourable tidal and weather conditions. This includes monitoring and analyses of intertidal sediment dynamics.

To date, most airborne coastal remote sensing applications have had to rely on single imagery to capture sediment loading, although several studies demonstrated the potential of such approaches to measure sediment concentration [1-5]. This paper presents the results of a multi-temporal monitoring campaign of sedimentation dynamics by analysing a series of overflights that captured the inflow of tidal water into a managed realignment site in South-East England.

1.1 Field Site

This research focused on sdimentation processes at the Tollesbury managed realignment project, located at the Blackwater estuary in Essex, South-East England. The 20 km long estuary is one of a series of macro-tidal estuaries on the northern margin of the Thames estuary. The tides of the Blackwater estuary are semi-diurnal, with typical ranges of 4.1 m at springs and 2.8 m at neaps. About 13% of the intertidal area are saltmarshes. The study site at Tollesbury Fleet lies in a sheltered mid-estuary position on the northern shore and belongs to a series of managed realignment projects along the Blackwater, which includes also sites at Abbots Hall and Orplands [6, 7] (Figure 1).

The 21 ha site had been reclaimed 150 years ago and was breached again on August 4, 1995 when a 60 m wide gap was created in the outer seawall. Since then, the site has been closely monitored by the then Ministry for Agriculture, Fisheries and Food (MAFF), now Department for Environment, Food and Rural Affairs (DEFRA). The objective was to investigate biotic and abiotic changes that would occur as a direct result of seawater inundation within the area of realignment. The monitoring scheme included the measurement of long-term annual accretion at 20 transects within the site [7-10]. The availability of such additional long-term data make Tollesbury a particularly well suited research location because it offers the opportunity link observations from different spatial and temporal scales.

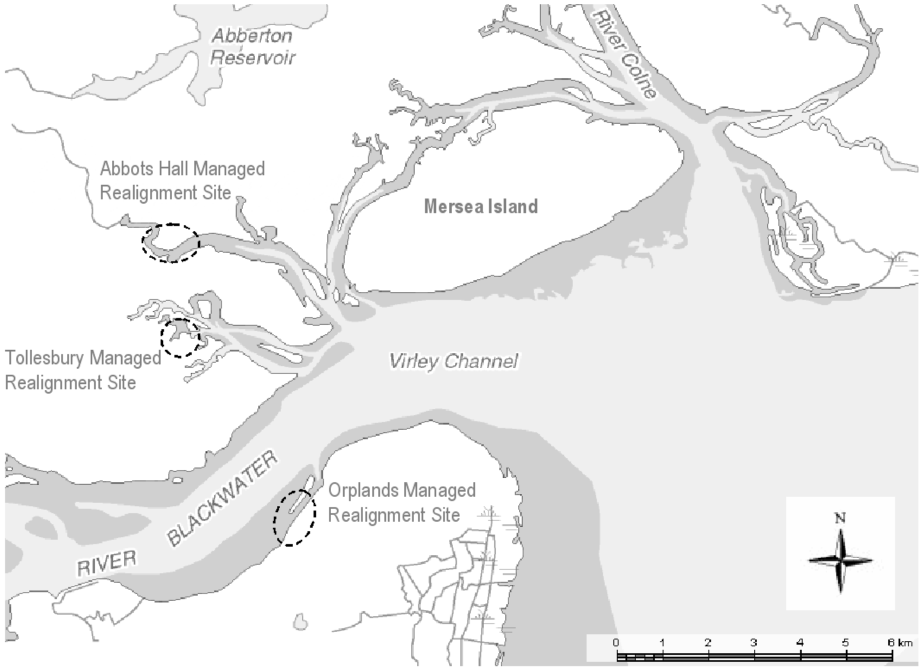

Figure 1. Location of the Tollesbury Managed Realignment site. © Crown Copyright/database right 2009. An Ordnance Survey/EDINA supplied service.

1.2 Data

The central data set for this research project was acquired on July 29, 1999 by a CASI-2 sensor on board a research aircraft that was operated by the UK's Natural Environmental Research Council (NERC). The flying campaign started at 10:05 GMT when the site was still unflooded. Subsequently, the inflow of tidal waters was monitored every 8-10 minutes until high tide (Figure 2). The CASI-2 sensor was operated in the spatial mode and the 14 channels programmed in the default ocean colour bandset (Table 1).

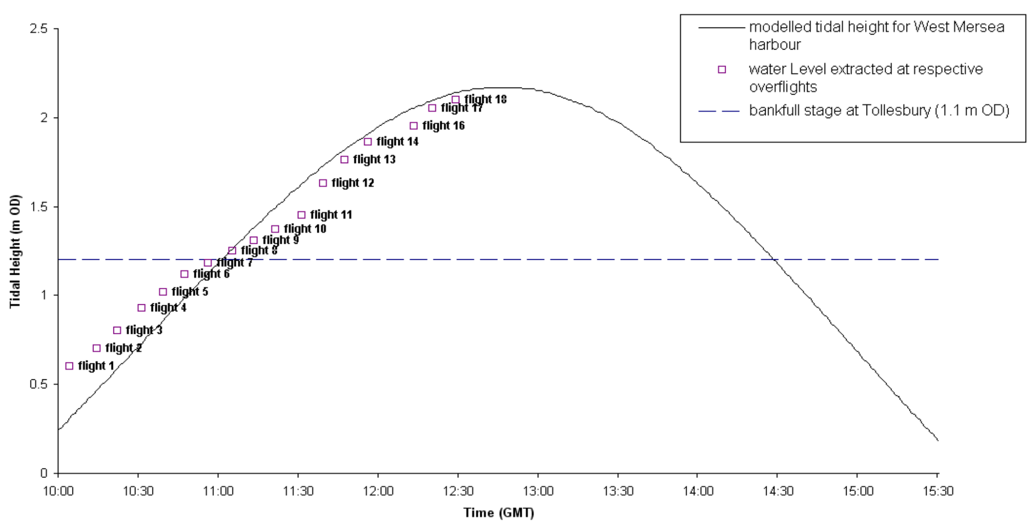

Figure 2. Timing of overflights with respect to tidal stage. The solid line displays the predicted tide for July 29, 1999 at the nearby West Mersea harbour. The squares indicate estimated water level at Tollesbury extracted from the respective images themselves with the waterline method.

The flying height of 1400 m equated to a spatial resolution of 2.8 m. The weather conditions were clear. However, no ancillary data sets on the ground were not collected because the flights were scheduled on short notice as a target of opportunity and no ground team could be organized on such a short notice.

Table 1. CASI ocean colour bandset

Band	Start nm	End nm
1	407.5	417.5
2	437.5	447.5
3	485	495
4	505	515
5	555	565
6	615	625
7	660	670
8	677.5	685
9	700	710
10	750	757.5
11	767.5	782.5
12	855	875
13	885	895
14	895	905

2. DATA ANALYSIS

Due to the absence of concurrent ground reference data it was necessary to establish a physically-based, temporally robust hydro-optical model of the estuarine waters at Tollesbury. This was done with the aid of the Water Colour Simulator (WASI). The Water Colour Simulator is a physically-based analytical model that uses non-linear optimisation procedures to analyse and simulate a number of hydro-optical parameters, including the concentration of suspended particulate matter. WASI was developed by Peter Gege from the Remote Sensing Technology Institute of the German Aerospace Center (DLR) [11-13].

WASI uses a series of analytical models that describe the physical processes of light travelling through the atmosphere, hydrosphere, and air-water interface. Although originally developed for fresh water applications WASI offers the opportunity to parameterise the model for applications in coastal environments such as those at Tollesbury.

The following WASI sub-models were parameterized, based on a data set of *in-situ* water spectra and concurrent water samples (n = 50) that were collected in spring 2001 and summer 2002. Downwelling irradiance E_d (λ), specular reflectance at the water surface $L_d^*(\lambda)$, and subsurface irradiance reflectance spectrum $R(\lambda)$. $R(\lambda)$, which is particular interest for the eventual model inversion to determine suspended sediment concentration, was parameterized as a function of the absorption coefficient a and the backscattering coefficient b_b of the water body [14, 15]:

$$R(0) = f \frac{b_{bw} + Cb_{bc} + Sb_{bs}}{a_w + Ca_c + Ya_y + Sa_s + b_{bw} + Cb_{bc} + Sb_{bs}}$$

where f is a proportionality factor that is a function of the mean cosines for the downwelling and upwelling irradiances and the ratio of the upward-scattering coefficient and the back-scattering coefficient, the subscripts w, c, y, and s stand for water, phytoplankton, yellow substance, and suspended particulate matter (SPM), respectively, and C, Y, and S stand for the corresponding concentrations. Note that both a and b_b exhibit also some dependency on the wavelength λ. This has been omitted here for display convenience.

The accuracy of the parameterised model was validated against an independent data set (n = 50) that was as well acquired by boast-based field spectroscopy. This yielded an absolute RMSE of 22 mg/l and a normalised RMSE of 26 %

(Figure 3). Measured and modelled SSC had a coefficient of determination R^2 of 0.49 ($p<.01$). Further statistical analysis showed that neither mean difference nor relative error had a significant bias. An additional validation was carried out with actual CASI airborne data collected during an additional flight campaign in 2002. The result showed that all indicators had a much higher accuracy than results from model predictions using field spectroscopy data. However, the size of the airborne CASI validations data set was very small (n = 3) which limits the statistical significance of the accuracy measures.

Model sensitivity was tested against parameter uncertainty for chlorophyll-a, yellow substance, suspended particulate matter, sunlight reflected at the water surface, anisotropy of the underwater light field, and water temperature. The analysis showed that the model was particularly sensitive to variations in reflection of direct sunlight at the water surface, and changes in the underwater light field. Both parameters are mainly a function of wave geometry that changes dynamically due to the local wave climate. Strong sensitivity exists also for negative variations of the backscattering coefficient for suspended particulate matter, b_{bs}. Little sensitivity was present to variations in the concentration of chlorophyll, yellow substance, and SPM, and water temperature which all vary substantially throughout the year. There appeared hence little inter-annual limitations to utilise WASI for the analysis of spectral data from different seasons. More care, however, seemed to be needed when analysing data from windy conditions and a corresponding dynamic dynamic wave climate.

The calibrated model was eventually applied to invert the spectral water reflectance measured by the CASI sensor to estimates of suspended particular matter (SPM) concentration. This resulted in a series of maps that indicate SPM concentration at respective overflights.

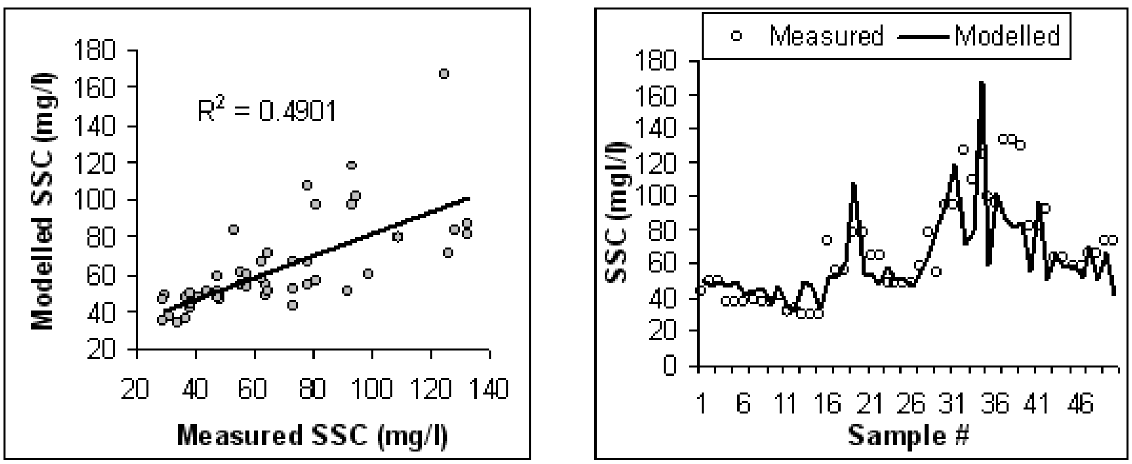

Figure 3. Accuracy of the hydro-optical model calibrated for the Tollesbury CASI data set.

3. RESULTS

The analysis of the remotely-sensed CASI data from summer 1999 by inversion of the calibrated WASI model resulted in a series of maps that show estimates of suspended sediment concentration of the incoming tidal waters with a temporal resolution of approximately 7-10 minutes. An example image is presented in Figure 4.

The ssc maps illustrate the spatio-temporal sediment patterns within the Tollesbury managed realignment project at a calm summer spring tide. Three main stages can be indentified: (i) tidal onset with increasingly infilling of outside creek network and former drainage channels inside the managed realignment project until the bankful stage is reached at overflight 8; (ii) large-scale across-mudflat inflow into the site between overflights 9 to 14 with heterogeneous scc patterns, indicating considerable resuspension of sediment; and (iii) near high tide phase between overflights 16 to 18 with more homogeneous ssc patterns.

Tidal height was estimated from a Lidar DEM and near-infrared reflectance at respective overflights using the waterline method[16, 17]. This made it possible for each overflight interval to estimate parameters such as current velocity in breach, tidal inflow, imported sediment mass, and overall sediment suspended in the site. This was then the basis for inter-overflight sediment net balances that quantified the differences between imported sediment and gain of overall suspended sediment within the site for that period. A larger gain of sediment suspended within the entire water column of the site compared to imported sediment through the breach would result in a positive balance. This would indicate a 'resuspension dominated' interval, whereas the opposite case with a negative balance could be understood to be a 'deposition dominated' phase.

The results show that the intervals until overflight 14 were resuspension dominated and the phase between overflights 14 to 17 were deposition dominated (Figure 5). This correlated reasonably well with the estimated flow velocity in the breach and associated shear-stress. Interestingly, the last interval between overflights 17 and 18 was resuspension dominated, despite experiencing a low tidal current velocity near slack water. A possible explanation for this might include sediment resuspension induced by wind-generated waves.

In addition to analysing bulk sediment budgets, the modelled ssc maps were also analysed spatially. This was done by extracting a series of sedimentological parameters at individual pixel locations. An example parameter is the amount of sediment suspended in the water column of one pixel (Figure 6). The choice for the specific locations was guide by the position of 20 transects at which long-term accretion had been monitored since the breach in 1995 [10]. This offered the opportunity to test the relationship between single tide dynamics observed from the CASI images and long-term accretions measurements on the ground.

The significance of such relationships was statistically tested by linear regression analyses and resulted in a number of statistically significant coefficients of determination (R^2) between 0.29 and 0.33. A similar test was undertaken for hydroperiod and distance to breach, respectively, which been suggested earlier by other authors as possible drivers for long-term accretion at Tollesbury[18]. However, no significant association could be established in these cases.

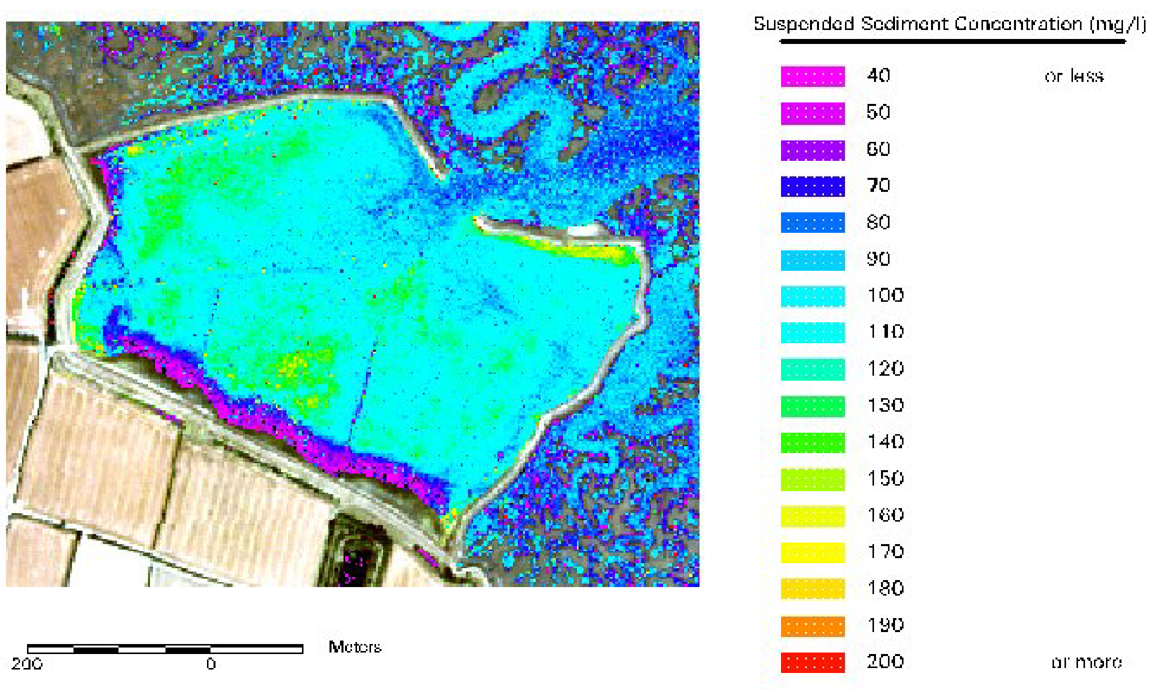

Figure 4. Map of estimated suspended sediment concentration at Tollesbury, based on inversion of spectral data from overflight 16.

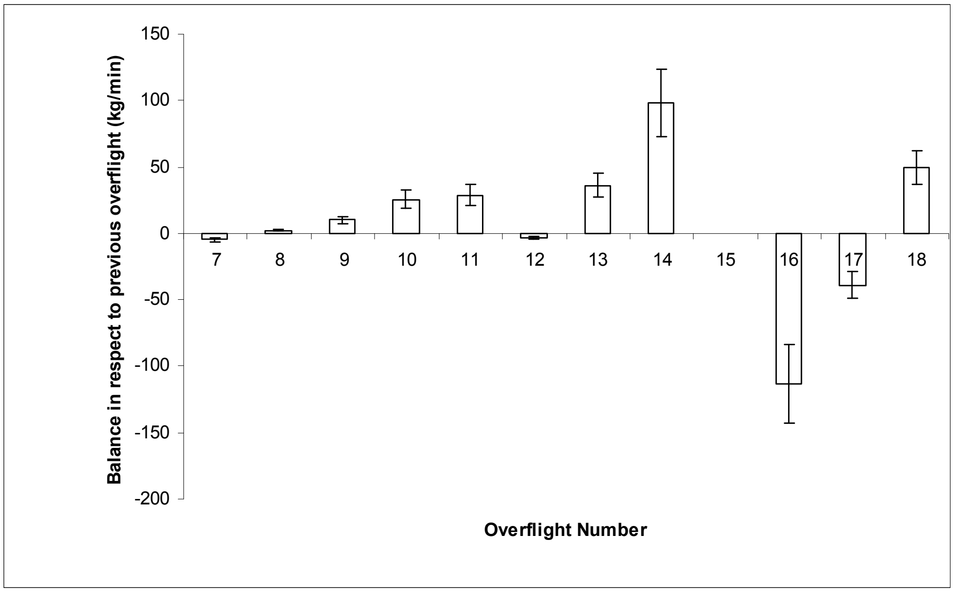

Figure 5. Sediment balance between respective overflights. Positive balance indicates resuspension dominance and negative balance indicates deposition dominance.

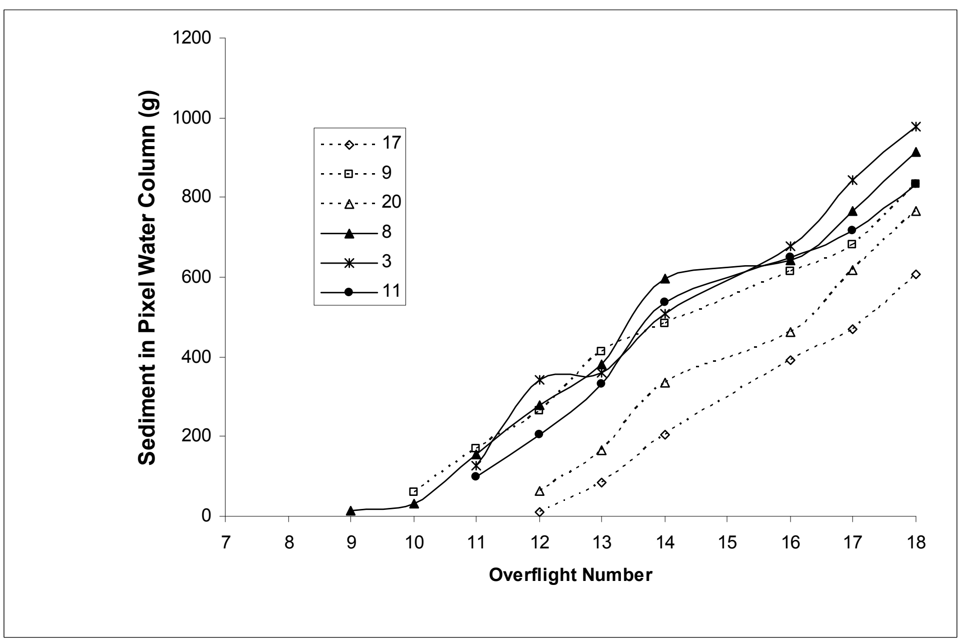

Figure 6. Time series of sediment suspended in the water column at six locations. Solid lines represent areas with high long-term accretion, dashed lines indicate low accretion locations.

4. DISCUSSION

The observed sediment patterns at Tollesbury are in general agreement with proposed conceptual models for mudflat sediment dynamics[19] as it is possible to identify stages of resuspension, transportation/relocation, and deposition/sediment settling. However, it is uncertain how far wind induced waves did influence the sites sediment dynamics at the observed tide. Overall, the dynamics identified at Tollesbury are in good overall agreement with processes reported elsewhere [19, 20].

The highly significant relationships between parameters from the period between overflights 14 and 16 and long-term measurements of accretion [8, 10, 18] show that processes observed on single tide level can robustly be linked to long-term accretion if the spatial heterogeneity of such processes can be considered. It also demonstrates the added value that can be gained by utilizing and connecting data sets from different research projects and approaches.

The statistically significant regressions data are an interesting result because sedimentation dynamics throughout the year can vary strongly. This suggests that processes have been identified during parts of a single tidal tide are at least partly driving the overall annual accretion. This supports the hypothesis that long-term accretion of mudflats in such environments is continuous and not 'event controlled' [21].

5. CONCLUSION

It can be concluded that multi-temporal remote sensing offers significant potential to capture and quantify coastal processes such as intertidal sediment dynamics that realistically can not be obtained by traditional field-based methods. Regularly, however, significant practical challenges have to be overcome before such data collection campaigns can be realised. The main obstacle for implementing remote sensing as operational research tool for monitoring dynamic coastal environments logistical problems. To make remote sensing a more integral part of the methodological suite employed in coastal research it would therefore be necessary to have unrestricted access to the monitoring equipment when weather and tidal conditions open a rare window of opportunity. This appears to be unlikely in situations where sophisticated research aircrafts have to be shared with the wider remote sensing community. It would therefore be desirable to develop a robust, low-cost, and easy-to-use system that can be deployed in the field independently. A possible platform for this might be unmanned aerial vehicles (UAV) that are equipped with relatively simple and low-cost digital multi-spectral sensors.

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