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# The use of small-Unmanned Aerial Systems for high resolution analysis for intertidal wetland restoration schemes

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# Abstract

Coastal and estuarine wetlands provide a range of important ecosystem services, but are currently being damaged and degraded due to human activities, reduced sediment supply and sea level rise. Managed realignment (MR) is one approach used to compensate for the loss of intertidal habitat, however saltmarshes in MR sites have been recognised to have lower biodiversity than natural environments. This has been associated with differences in the physical functioning including the sediment structure, reduced hydraulic connectivity, and lower topographic variability such as the abundance of intertidal creek networks. Intertidal morphology, including creek networks, play an important role in supporting and regulating saltmarsh environments through the supply of sediment, nutrients and water, and in draining intertidal marshes. However, there is a lack of empirical data on the formation and evolution of topographic features and variability in saltmarsh environments. This is likely to be due to creek networks in natural marshes already being in a state of *quasi*-equilibrium, making MR sites an ideal environment to investigate creek development. However, traditional remote sensing techniques (such as LiDAR) tend to be relatively expensive, infrequent and at a coarse resolution meaning small, but important (cm-scale), changes are often missed. This study advances the ability to detect these small scale changes by demonstrating the suitability and potential applications of using the emerging photogrammetric method Structure-from-Motion (SfM) on images taken using a small-Unmanned Aerial System (sUAS). Three surveys from a rapidly changing, near-breach site were taken at the Medmerry Managed Realignment Site in July 2016, September 2017 and July 2018. A suitable degree of confidence was found between the modelled surface and independent check points (vertical root-mean-square-errors of 0.0245, 0.0704 and 0.1571 for 2016, 2017 and 2018 respectively). DSMs of Difference (DoD) analysis was performed to evaluate elevation change, with areas experiencing up to 85 cm of accretion between 2016 and 2018. However, when considering the error associated with both surveys, between 2016 and 2017, only 34.39 % of the survey area experienced change above the level of detection (LoD). In contrast, 76.97 % experienced change greater than the LoD between 2017 and 2018. Stream order analysis classified the creek networks into five orders in 2016 and four orders in 2017 and 2018, with 2016 having a higher abundance (291 in 2016 compared to 117 (2017) and 112 (2018)) and density (0.44 m/m$^2$ in 2016 compared to 0.27 m/m$^2$ in both 2017 and 2018) of creek networks. These results provide an innovative high resolution insight into the evolution of restored intertidal wetlands, and suggest that SfM analysis of images taken using a sUAS can be a useful tool with the potential to be incorporated into studies of MR and natural saltmarsh sites. sUAS analysis can, therefore, advance the management of these environments to ensure the provision of ecosystem services and to protect against future anthropogenic activity, sea level rise and climate change.

# 1 Introduction

Coastal and estuarine wetlands, such as saltmarshes, have declined globally by approximately 25 to 50 % over the last 150 to 300 years (Lotze et al., 2006), with approximately 1 to 2 % of saltmarsh lost each year (Duarte et al., 2008). This is despite the recognition in recent years of the importance and range of ecosystem services provided by these environments (e.g. Costanza et al., 1997). To compensate for the loss of intertidal habitats, a number of restoration and compensation schemes have been implemented. Managed realignment (MR) is one of the most common saltmarsh restoration schemes, and has been implemented widely across Europe and the USA. Yet, despite the relatively quick colonisation of these schemes by saltmarsh plants and invertebrates (Garbutt et al., 2006; Mazik et al., 2010; Wolters et al., 2005), MR sites commonly have different species composition in comparison to natural sites (Mossman et al., 2012), and a lower diversity of important targeted species. These differences are likely to affect the ecosystem services provided by MR schemes and have been associated with a failure to reconstruct the physical functioning and processes which occur in natural saltmarsh environments. These processes include differences the sediment structure, geochemical profiles, hydraulic connectivity (Spencer et al., 2017; Tempest et al., 2015) and topographical variability such as the density and complexity of creek networks (Lawrence et al., 2018).

In natural intertidal environments, creek networks play an important role in the physical structure and functioning of the ecosystem. Creek networks connect the upper saltmarsh to the lower elevation mudflat and the open coast, acting as a conduit for water, sediment and nutrients, regulating site drainage, dissipate wave and tidal energy, and providing habitats for fish species (e.g. Reed et al., 1999; Sanderson et al., 2001). The formation of creek networks has been studied through morphodynamic modelling (e.g. Fagherazzi and Furbish 2001), which suggest that creek formation is initially a relatively rapid process which gradually slows as creeks stabilise. However, there are relatively few empirical field studies of creek formation to validate these models, probably due to most creek networks already being in a state of *quasi*-equilibrium (e.g. Marani et al., 2003; Vandenbruwaene et al., 2012). Therefore, newly inundated intertidal environments, such as MR sites, may provide the best opportunity to study initial creek formation and evolution (Dale et al., 2018; Vandenbruwaene et al., 2012).

Studying creek formation and the topographic evolution of MR sites would provide an improved understanding of the evolution of the physical system and function in saltmarsh restoration and creation schemes, and deliver empirical data for enhanced knowledge on intertidal creek formation generally. However, there are relatively few studies that investigated these features, with most studies focusing on the movement and redistribution of sediment (e.g. Dale et al., 2017; Rotman et al., 2008). Previous studies that investigated topographic variability in MR sites (e.g. Dale et al., 2018; Lawrence et al., 2018) have relied on relatively coarse resolution remote sensing and surveying data, such as differential GPS and LiDAR (Light Detection and Ranging) datasets. In a recent study, Chirol et al., (2018) proposed the use of a semi-automated creek extraction algorithm to monitor creek development within newly inundated intertidal settings, based on LiDAR data. However, LiDAR is typically available at meter horizontal resolution, and can include a large vertical error in waterlogged (e.g. Wang et al., 2009) and vegetated areas; it has been suggested the vertical error can range between 25 to 60 cm in densely vegetated parts of the intertidal zone (Enwright et al., 2018). Given that both waterlogged and vegetated conditions are typical of intertidal marsh environments small, but important, changes in elevation which may relate to initial creek formation and topographic evolution could be missed via this approach.

One solution to these limitations was proposed by Dale et al., (2018) through the use of a high resolution digital surface model (DSM), produced using the emerging low-cost photogrammetric method Structure-from-Motion (SfM), derived from images taken by a small-Unmanned Aerial System (sUAS). Although these authors demonstrated the suitability of this technique for reconstruction of the surface geometry within an intertidal marsh setting, they failed to consider the application of multiple surveys to evaluate morphological change and development in a response to tidal inundation. Here, we present a re-evaluation of the model of Dale et al., (2018) in comparison to two further surveys, taken annually, to consider the changes in intertidal morphology at the Medmerry Managed Realignment Site, West Sussex, UK (Figure 1). Specifically, this study innovatively assesses repeat surveys to investigate the erosion and accretion of sediment, the topographic variability and evolution of creek systems at high (centimetre) resolution. This analysis has been conducted in higher resolution than has previously been possible using techniques such as LiDAR, GPS or traditional ground surveying using levels. Additionally, we evaluate the application of orthophotography and SfM derived DSMs of evolving intertidal marsh environments to describe the formation, evolution and characteristics of topographic features, such as drainage networks, which may have the potential for use not only in recently inundated sites but in older MR sites and natural intertidal settings.

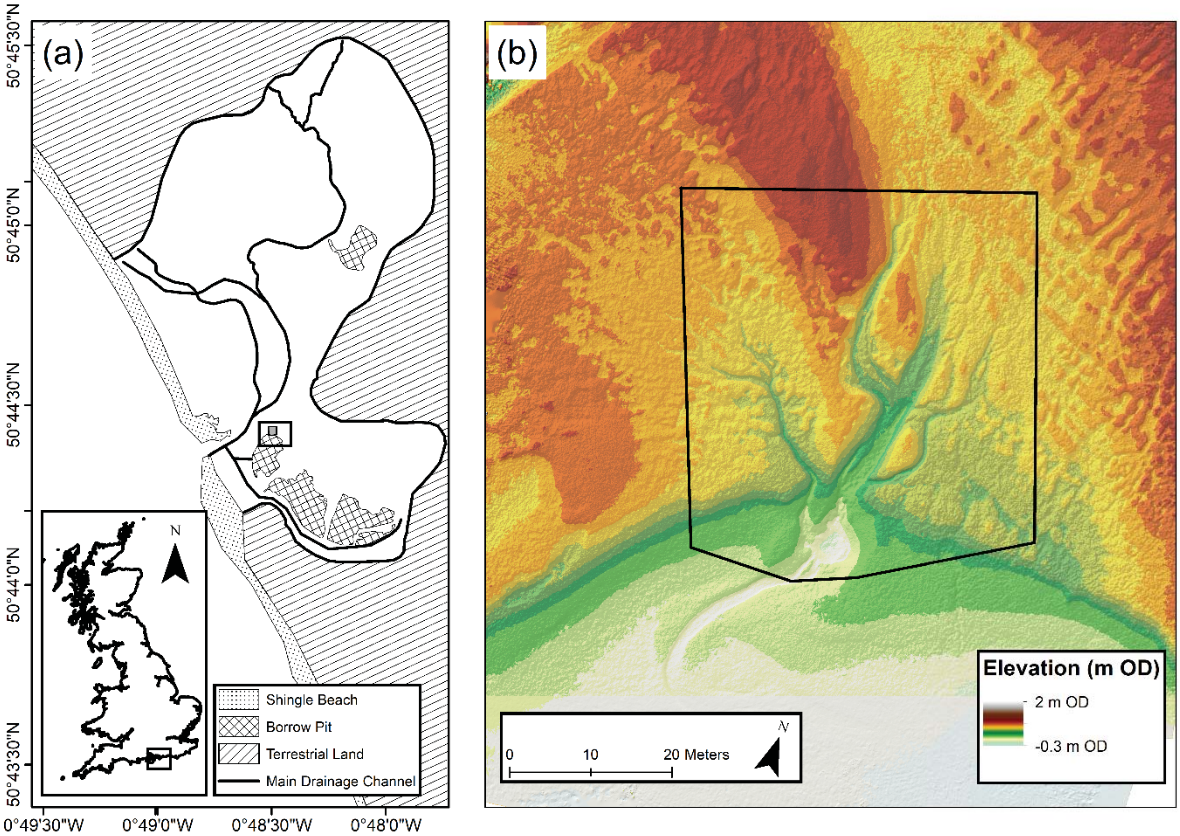


Figure 1: (a) The Medmerry Managed Realignment Site, UK setting (*insert*) and study area marked by the grey box. (b) The study area overlaying the 2017 DSM.

# 2 Methods

## 2.1 Study Site

The Medmerry Managed Realignment Site is located in the eastern Solent on the south coast of the UK (Figure 1). The site was constructed to compensate for intertidal habitat loss elsewhere in the region, and to locally improve the level of coastal flood defence, through the creation of 300 hectares of new intertidal habitat. New defences, 7 km in length, were constructed out of material sourced and extracted from within the site in order to create areas of lower elevation, known as borrow pits, to encourage a range of intertidal habitat. The site was breached in September 2013 through a single inlet cut in the former shingle barrier beach flood defences, forming a semi-diurnal mesotidal system.

Here, we present analysis of the morphological development of the higher elevation bank leading into a near-breach infilling borrow pit (Dale et al., 2017), where creeks had formed following site breaching (Figure 1) as a result of the collapse of sub-surface soil pipes (Dale et al., 2018). This site was selected as it allowed measurements to be taken in a rapidly evolving environment, and permitted comparisons to be made through a re-evaluation of the sUAS survey taken in July 2016 by Dale et al., (2018) and two new surveys covering the same 1995.91 $m^2$ study area, taken in September 2017 and July 2018.

## 2.2 sUAS Image Acquisition

For the three aforementioned surveys at the Medmerry site, aerial images were captured from sequential flights over an hour-long period using a crosshatched flight plan. A DJI Inspire 1 sUAS was deployed at a target altitude of 20 m above ground level. Images were captured using a DJI Zenmuse X3, 3-band RGB camera with a focal length of 20 mm. Surveys were conducted during consistent weather conditions (temperature 12-18 °C, wind speed 14-19 km/h, sun with minor cloud cover). A 5 m survey line spacing ensured maximum image overlap (>80 %), and complete coverage of the survey area. Ground control points (GCPs) were recorded using differential global positioning system (dGPS) measurements taken by a Leica AS19 GNSS antenna, a Leica Viva GS10 GPS receiver and a Leica CS15 controller. Raw GPS measurements were imported into Leica Geo Office (version 8.3). Network Receiver Independent Exchange Format (RINEX) correction data were obtained from Leica Smart Net UK & Ireland (http://uk.smartnet-eu.com/rinex-download_148.htm), and used to correct the raw GPS data. Leica Geo Office reported the positional quality (XYZ) for all dGPS points as <0.02 m. Seven GCPs were captured in 2016 and 2018, and nine were taken in 2017 (Table 1) for the purposes of image matching.

## 2.3 sUAS Image Processing and Analysis

Dense point clouds were produced from optimised camera locations using mild-depth filtering to ensure small and important details were preserved using Agisoft Photoscan (v1.2.5). 319 images were acquired in 2016, 318 images in 2017 and 437 in 2018. From the dense point cloud output both orthomosaic images and DSMs were produced. Previous studies have reported a central “doming” effect (e.g. James and Robson 2014), which may have been amplified in this study due to the low flight height. To minimise this effect, fisheye correction and camera alignment optimisation were applied. Additional ground check points were collected using dGPS to act as an independent assessment of model quality; six check points were collected in 2016, twelve in 2017 and ten in 2018 for the purposes of error assessment.

DSMs of Difference (DoD) analysis was performed to compare differences between the two modelled surfaces. When comparing two different DSMs, it is important to consider the uncertainties and potential error propagation between the two DSMs. It is, therefore, necessary to omit any change smaller than a specified level of detection (LoD) from the analysis (James et al., 2017). The LoD can be defined as (Lane et al., 2003):

$$LoD = \pm t\,(\sigma_{z1}^2 + \sigma_{z2}^2)^{1/2} \qquad \text{[Equation 1]}$$

where $\sigma_{z1}$ and $\sigma_{z2}$ are measures of the vertical error of the two DSMs, in this case the vertical standard deviations of error, and t is the required level of confidence (95 % used here).

Changes in topographic variability were assessed via analysis of the surface heterogeneity, also known as the rugosity, calculated as the standard deviation of the elevation in a 3 x 3 pixel moving window (after Lawrence et al., 2018). To quantify the difference in the creek networks between the two years, creeks were classified into creek orders according to Strahler (1957) stream order analysis, with the first order assigned to the smallest (source) creek with order increments with each downstream intersection. Creeks were detected and split into the corresponding order category in ArcMap (v10.5.1) as a result of the flow direction and accumulation. DSMs were filled prior to analysis to remove any sinks, and a flow accumulation threshold value of 5000 was used in order to create the creek network. The resulting creek network was visually confirmed via a comparison with the orthophotograph and the total number, total length, density (total length per survey area), average length and length of the longest creek identified for each order. Differences in total number of creeks in each order were analysed using $Chi^2$ (Pearson) analysis. The difference in creek length between each order and differences in the rugosity were analysed via Mann-Whitney U Tests as data were not normally distributed (Anderson-Darling, $p < 0.05$). Statistical analysis was performed in Minitab (v18).

Table 1: Images analysed, number of ground control points (GCPs), number of check points, resolution of the orthophotography and digital surface models (DSMs), and calculated root-mean-square error between the DSMs and check points for the 2016, 2017 and 2018 surveys.

| | Images Analysed | No. of GCPs | No. of Check Points | Orthophotography Resolution (m/pix) | DSM Resolution (m/pix) | X Error (m) | Y Error (m) | Z Error (m) |
|---|---|---|---|---|---|---|---|---|
| **2016** | 319 | 7 | 6 | 0.00658 | 0.0263 | 0.0282 | 0.0329 | 0.0245 |
| **2017** | 318 | 9 | 12 | 0.0103 | 0.0412 | 0.1043 | 0.0637 | 0.0704 |
| **2018** | 437 | 7 | 10 | 0.0112 | 0.0448 | 0.0411 | 0.0551 | 0.1571 |

# 3 Results and Discussion

## 3.1 Model Output and Accuracy

The reported resolution of the DSMs and the RGB orthorectified images are reported in Table 1. Comparisons, through RMSE values, between the DSMs and independent check points are presented in Table 1, and indicate an acceptable degree of confidence in the accuracy of the models in accordance with the range reported by Tonkin and Midgley (2016).

## 3.2 Topographic Change and Variability

The distribution of bed elevations (Figure 2) showed an increase over time, suggesting material was accreted across the study area. This is particularly the case between 2017 and 2018, when a broad, more platykurtic, distribution of elevations were observed, indicating a considerable increase in the accretion of sediment. Comparisons of the change in elevation, through DoD analysis (Figure 3), indicated that in the borrow pit at the southern end of the survey area elevation increased by up to 85 cm over the two years. This rate of accretion is more than double the annual accretion rate of 15.2 cm per year measured by Dale et al., (2017) between November 2014 and October 2015, at the same site, using an altimeter system.

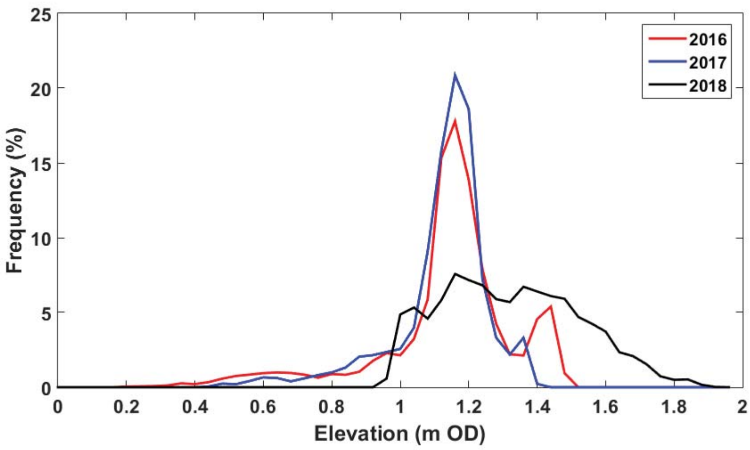


Figure 2: Distribution of elevations for the 2016 (red), 2017 (blue) and 2018 (black) DSMs.

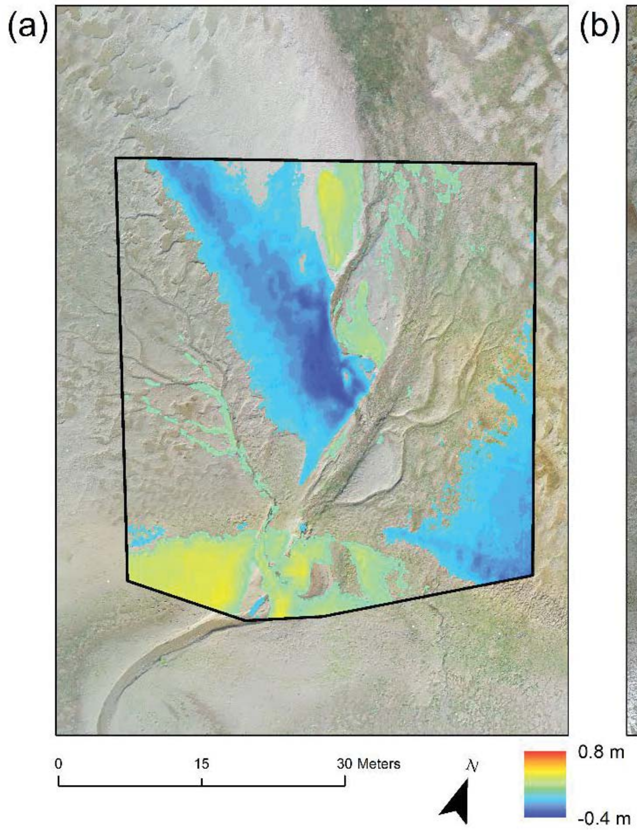


Figure 3: DSMs of Difference analysis of (a) the 2017 survey minus the 2016 survey overlying the 2017 orthophotograph and (b) the 2018 survey minus the 2017 survey overlying the 2018 orthophotograph. Blue is erosion and green to red is deposition.

On the bank, bed elevation decreased in the centre of surveyed area by 20 to 30 cm between 2016 and 2017, with the exception of a smaller patch of accretion to the north of the main areas of sediment loss (Figure 3a); given that the prevailing wind is from the southwest it is like that the eroded sediment has been remobilised, transported and deposited by locally induced wave activity. However, only in 34.39 % of the entire 1995.91 $m^2$ surveyed area was the recorded change in elevation outside the LoD. Erosion was measured in 65 % of this area, equivalent to 22.53 % of the entire survey area, whereas accretion above the LoD was measured in 11.86 % of the entire survey area.

In contrast to the 2016-2017 DoD, between the 2017 and 2018 surveys 76.97 % of the area investigated experienced a change in elevation beyond the LoD. Of this area, only 4.44 % (3.41 % of the total area) experienced erosion, which occurred within the centre of the bank (Figure 3b). Accretion was observed across the rest of the bank, with up to 80 cm of sediment being deposited on the north-eastern side of the surveyed area. This increase in sediment accumulation is likely to be the result of changes in the inlet morphology, following the processes of coastal catch up as the beach rapidly adjusts to the likely position, had it not been fixed and artificially maintained since around 1900. Moreover, Dornbusch and Mylroie (2017) estimated that prior to the beach position being fixed it was retreating at a rate of 1.5 m/year. Following site breaching the inlet cut in the shingle barrier beach has widened and rolled back. Consequently the exposure of this site to larger coastal processes and externally generated waves, opposed to waves generated within the fetch and depth limited system, is likely to have increased. The interaction between these waves and relic hedgerows and other surrounding topographical features was suggested by Dale et al., (2017) to be the source of sediment to this site, and an increase in wave energy is likely to result in increased supply of sediment.

Mean rugosity, which has been shown to correlate positively with creek density (Lawrence et al., 2018), increased (2016 = 0.0021; 2017 = 0.0024; 2018 = 0.0026) and differed significantly ($p < 0.001$) between years, suggesting an increase in topographic complexity over time. These results are indicative of an increase in surface drainage features and a reduction in the opportunity for water to pool and accumulate, which may enhance the physical, chemical and biological edaphic conditions, advancing opportunities for saltmarsh vegetation to become established (e.g. Mossman et al., 2012). Lawrence et al., (2018) compared the topography of 19 MR sites to surrounding natural saltmarshes and agricultural fields, finding that the MR sites were more similar to the terrestrial fields in terms of topographic variability. These authors also suggested that there was no relationship between age and the topographic evolution. However, results presented in this study from the Medmerry site indicate that there has been some topographic evolution as the site responds to intertidal inundation, although the rate, spatial and temporal scale of this response requires further investigation. This is particularly true of sites that have experienced different levels of pre-breach landscaping, such as ploughing or the construction of areas of lower elevation (e.g. Cotton et al., 2008), to maximise topographic variability. Comparisons of the temporal and spatial change in topography is also required, comparing both within and between MR sites, to assess the influence of different hydrodynamics and variations in the supply of suspended sediment on the topographic and morphological evolution.

### 3.3 Evolution of Creek Morphology

In 2016, 291 creeks were classified into five orders, whilst 117 and 112 creeks were divided into four orders in 2017 and 2018 respectively (Table 2, Figure 4). $Chi^2$ analysis, performed on the orders 1 to 4 as no fifth order creeks were detected after 2016, indicated a statistically significant association between the individual surveys and creek abundance ($\chi^2$ = 18.05, $p = 0.006$). A higher creek density of 0.44 $m/m^2$ was measured in 2016, compared to 0.27 $m/m^2$ measured in 2017 and 2018, suggesting that some branches have become more prominent in draining the intertidal area. This process appears to be ongoing, especially in the creek system on the western side of the study area, which was noticeably less apparent in the orthophotography and visually whilst during sampling. Only first order creek length between 2016 and 2017 differed significantly ($p < 0.001$, Table 2).

Table 2: Summary of creek order analysis for the 2016, 2017 and 2018 surveys. Significant differences in creek length between the two surveys for each order were assessed via a Mann-Whitney U Test (*p* values reported) at the 95 % confidence interval.

| | | First | Second | Third | Fourth | Fifth | Total |
|---|---|---|---|---|---|---|---|
| **Total Creeks** | **2016** | 158 | 75 | 23 | 31 | 4 | 291 |
| | **2017** | 65 | 32 | 19 | 1 | | 117 |
| | **2018** | 59 | 32 | 15 | 6 | | 112 |
| **Total Length (m)** | **2016** | 498.26 | 228.96 | 73.39 | 70.25 | 5.05 | 875.91 |
| | **2017** | 312.07 | 122.3 | 97.05 | 3.95 | | 535.37 |
| | **2018** | 310.7 | 133.18 | 69.83 | 18.06 | | 531.77 |
| **Density ($m/m^2$)** | **2016** | 0.25 | 0.11 | 0.04 | 0.04 | 0.002 | 0.44 |
| | **2017** | 0.16 | 0.06 | 0.05 | 0.002 | | 0.27 |
| | **2018** | 0.16 | 0.07 | 0.03 | 0.01 | | 0.27 |
| **Average Length (±std) (m)** | **2016** | 3.15 ± 2.99 | 3.05 ± 2.33 | 3.19 ± 2.04 | 2.27 ± 2.07 | 1.26 ± 0.81 | 12.92 ± 2.36 |
| | **2017** | 4.8 ± 3.54 | 3.82 ± 3.43 | 5.11 ± 4.21 | 3.95 | | 17.68 ± 3.73 |
| | **2018** | 5.27 ± 4.60 | 4.16 ± 4.47 | 4.66 ± 3.63 | 3.01 ± 1.72 | | 4.75 ± 4.08 |
| **Longest Creek (m)** | **2016** | 14.76 | 9.27 | 8.99 | 9.37 | 2.22 | |
| | **2017** | 16.62 | 12.57 | 17.72 | 3.95 | | |
| | **2018** | 22.87 | 16.7 | 13.65 | 5 | | |
| **Mann-Whitney U Test *p* value (length)** | **2016 - 2017** | < 0.001 | 0.603 | 0.143 | | | |
| | **2017 - 2018** | 0.893 | 0.532 | 0.89 | | | |

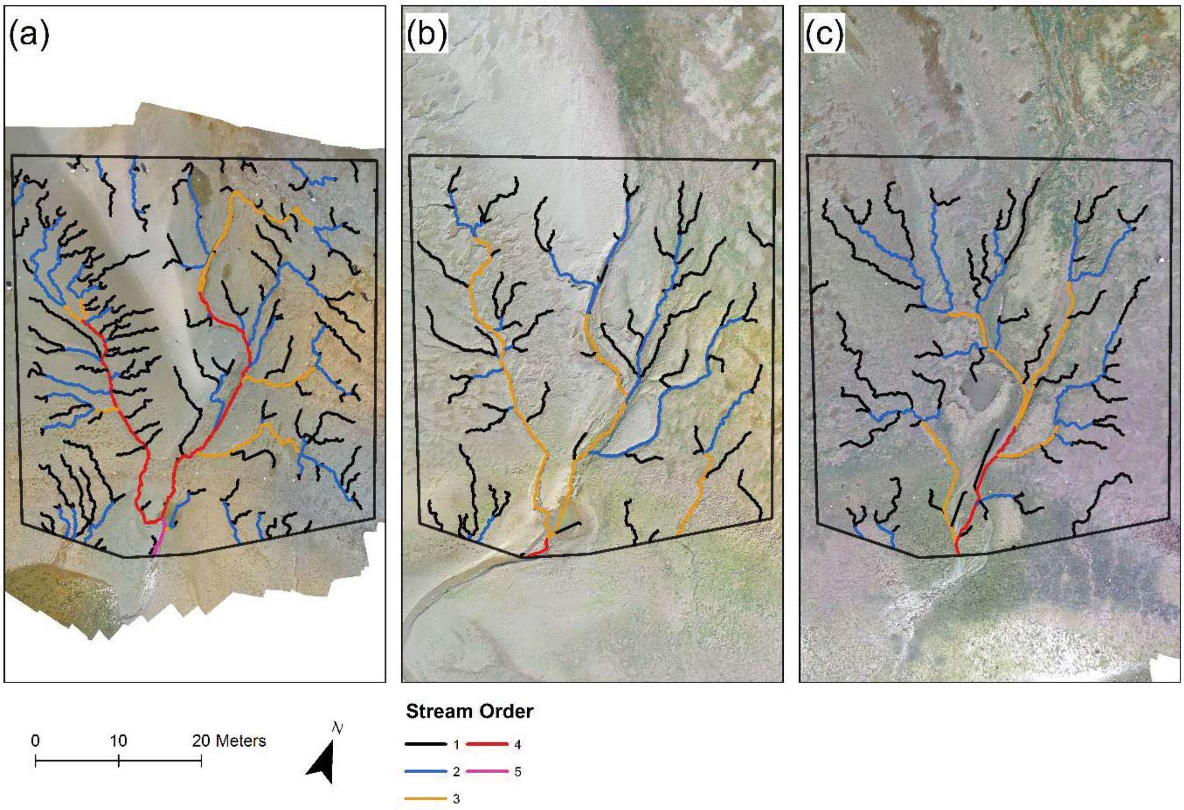


Figure 4: Stream order analysis of (a) the 2016 survey, (b) the 2017 survey and (c) the 2018 survey (after Strahler 1957). The first order (one) is assigned to the smallest (source) creek with order increments with each downstream intersection.

In 2016, a number of first and second order creeks appeared to run perpendicular to the direction of higher order (fourth and fifth order) creeks. The development of drainage features in MR sites has previously been related to the pre-existing landscape features (French and Stoddart 1992), such as plough lines, along with the sediment properties such as the drainage characteristics and the sub-surface stratigraphy, tidal energy, and the surface gradient of the intertidal zone (e.g. D'Alpaos et al., 2007; Spencer and Harvey 2012). As a result, it has been suggested that the pre-existing terrestrial topography and drainage features may be retained for many years and, in some case, remain as permanent features (Bowron et al., 2011; Lawrence et al., 2018). On visual examination of the orthophotographs from Medmerry, the perpendicular channels appear to be relic plough lines from the sites former agricultural land use; the area around the study site was last harvested two weeks before site breaching. However, the influence of these features decreased with time, with the lower order creeks detected in 2017 and 2018 appearing to have cut through the plough lines and to be considerably closer in orientation to the higher order drainage channels. Nonetheless, further longitudinal analysis is required to determine the legacy of these features in sites that are exposed to lower magnitude hydrodynamic processes and forces.

The influence different pre-breach conditions, such as plough lines, tyre tracks from site construction machinery, other pre-existing drainage features, also requires further investigation. From this, sites could be designed to incorporate these features into the post-site inundation evolution, maximising not only the sites morphological evolution but the ecological development. Consequently, the ecosystem services such as provision of habitat and flood defence provided by could also be enhanced.

## 3.4 The Potential of Using sUAS Analysis to Quantify Morphological Development and Ecological Change in Intertidal Wetland Environments

Predictive models (e.g. Allen 2000) and measurement data do exist on the topographic and morphological change in intertidal wetland environments following intertidal inundation. However, the majority of these measurement data are limited to a single point or small (cm to m) spatial area (e.g. Dale et al., 2017; Ni et al., 2014), obtained from sediment core records and do not provide a detail on the inter-annual variability (e.g. Cundy et al., 2002; Spencer et al., 2017), or have relied on remote sensing data such as aerial photography and LiDAR (Krolik-Root et al., 2015; Lawrence et al., 2018). As a result of the spatio-temporal limitations, and the vertical and horizontal resolution which may be too coarse to identify small, but important, variations in topography, the topographical evolution of MR sites is not fully understood. The use of sUAS surveys and SfM analysis, as demonstrated at the Medmerry Managed Realignment Site herein, provides an alternative method of evaluating the fine-scale evolution and morphodynamics of intertidal wetland environments to address these shortcomings. The ability of sUAS surveys to capture change at the centimetre scale over a larger area provides researchers with the ability to closely monitor the evolution of these developing systems. A further advantage of sUAS surveys in the analysis of intertidal morphodynamics is that they are relatively simple and inexpensive to deploy. This allows sUAS surveys to be used to investigate morphological evolution at multiple sites, as has been the case in LiDAR based studies (e.g. Chirol et al., 2018; Lawrence et al., 2018), but at higher resolution, increased temporal frequency and without the associated error.

Intertidal creek networks play an important role in natural saltmarsh environments as they regulate site drainage, act as a conduit for water, sediment and nutrients between the marsh and the surrounding coastal environment, and provide habitats and nursery grounds for fish species. Despite the importance of these features, previous studies into creek evolution in MR sites (e.g. Chirol et al., 2018; Lawrence et al., 2018) have relied on single topographic surveys. The use of sUAS surveying allows for repeat measurements without the time or financial costs associated with other remote sensing techniques. As a result, sUAS surveys can be used to assess morphodynamics at range of timescales (tidal, monthly, annual, multi-annual), and therefore at different corresponding spatio-temporal scales. Furthermore, the application of sUAS surveying may also be applicable to help understand vegetation development and ecosystem functioning in relation to a site's morphological development through vegetation and habitat mapping, as previously performed in other settings elsewhere (e.g. Belluco et al., 2006; Strong et al., 2017). This potential application, including multi-spectral vegetation analysis, should form the basis of future research focussed on the value and use of sUAS in intertidal settings.

The movement of sediment within these developing MR systems, presented here through DoD analysis, has been shown to be detectable using sUAS analysis providing the levels of accretion and erosion are above the survey's LoD. This is likely to be the case in newly inundated intertidal environments such as MR sites; predictive models and measurements data, including the measurements presented here, have suggested high levels of accretion should be expected as the site adjusts to tidal inundation (e.g. Vandenbruwaene et al., 2011). Moreover, given the high accuracy and precision of the DSM, it may as also be suitable for annual (or more frequent) comparisons in older and natural sites, where bed elevation may be relatively stable in relation to the hydroperiod or sediment supply could be lower (e.g. Deloffre et al., 2007; Kirby 1990). The error accounted for in this sUAS approach is considerably lower than the error associated with traditional remote sensing techniques such as LiDAR. For example, Enwright et al., (2018) reported an error of up to 60 cm for LiDAR data, compared to up to 15 cm calculated in this study. Furthermore, this technique may also be suitable for mapping marsh loss and retreat, particularly mashes that are cliffed or fragmented (Allen and Pye 1992; Baily and Pearson 2007).

# 4 Conclusions

This paper demonstrates the suitability of using sUAS and SfM analysis to monitor the morphodynamics and evolution of creek networks in restored intertidal wetlands, at a resolution that has not been possible previously. sUAS surveys are relatively inexpensive, and can easily be implemented, making them a useful tool to monitor morphological development in intertidal environments. Whilst the success of using this technique may be limited in some settings due to concerns regarding the error associated with these measurements, this error is considerably lower than the error reported using other remote sensing techniques such as LiDAR. The potential applications of using DSMs created from sUAS surveys, namely stream order, DoD and topographic analysis, are presented here from the Medmerry Managed Realignment Site. Results indicate that sediment is being imported and locally remobilised, alongside an increase in topographic variability and the development of the intertidal drainage system. From these findings, and additional studies of this nature, the importance of designing morphology prior to site breaching to ensure the successful colonisation of intertidal habitat can be quantified further. Furthermore, the evolution of established creek networks in natural marshes and intertidal wetlands can now be easily investigated in higher spatial and temporal resolution, to cm accuracy, than was previously possible. This will inform managers, engineers and policy makers and aid the management of wetland environments to ensure the provision of ecosystem services and to determine the vulnerability of these habitats from future climate change, sea level rise and anthropogenic forcing.

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## Author's Contribution

JD performed all steps in analysing and interpreting the data and writing the initial manuscript, and participated in the sUAS surveys to acquire the images.

NGB performed the sUAS surveys, assisted in model production and contributed towards editing the manuscript.

CJS performed the image processing to produce the models and contributed towards planning the data analysis.

HMB participated in the final editing of the manuscript and contributed towards the study design.

All authors have read and approved the manuscript.

## Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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