The Impact of Creek Formation and Land Drainage Runoff on Sediment Cycling in Estuarine Systems.

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Abstract

Field investigation and empirical analysis were used to assess the impact of tidal creeks and tidal flap gates (through which land surface runoff drains into estuaries) on sediment transport in the receiving waters downstream of the creeks and propose a semi-empirical model to assess the impact of water level rise and increased runoff flow, as may be expected under many climate change scenarios.

Results show that there is increased suspended sediment concentration (SSC) at low tide within the deeper channel downstream of the tidal flap gate. This is due to the high SSC that

is ejected by the creek because of land drainage runoff with SSC in the creek ranging from 47mg/l to 300mg/l at spring ebb tide and that in the deeper channel ranging from 22mg/l to 104mg/l. This effect was more pronounced at spring tides when the water level in the deeper channel was low. Substantial sediment is supplied by the creek on a spring low tide than a neap low tide due to higher exposure period of intertidal flats for spring low tides. The combination of creeks and tidal flap gates has the highest impact on SSC in the deeper channel at low tide and high surface runoff flow.

It is recommended that moving forward on developments around coastal areas, management authorities create more effective and sustainable drainage systems with less impact on estuarine environments to protect aquatic life and promote habitat creation for a sustainable future. Such systems whereby there are numerous drainage flaps surrounding estuaries especially in intertidal flat areas should be transformed into systems with fewer secondary effects on estuarine environments.

1. Introduction

Over time, increasing pressure on coastal areas owing to rapid development in the coastal zone regions has led to significant changes in short and long-term natural processes (Dean and Dalrymple, 2002). About 2.5 billion people worldwide (40% of the world's population) currently live within 100km of the coast adding increasing pressure to the coastal ecosystem (Sevilla et al., 2019). These developments may have direct impacts such as landfilling, dredging, and sand mining for construction or indirect impact, such as increased runoff (Reef resilience, 2016). Tidal flap gates are a typical example of coastal development with indirect impact through land drainage runoff.

The impact of exponential urban developments on the environment has been of great concern to governing bodies and environmentalists (United Nations, 2002). Due to various human activities, water bodies such as lakes, rivers, and estuaries can be affected significantly by demand for water and as convenient receiving waters for wastewater and surface runoff from urban areas (Roinas, 2015).

Tidal flap gates are used to discharge land drainage water into natural water bodies at low water while acting as part of a sea defence structure preventing the influx of seawater into upland areas at high water. They tend to be effective at controlling water flow between tidal areas (such as estuaries) and drained upland areas (Gianico and Souder 2004). At low water, tidal creeks become visible on intertidal flats directly downstream of tidal flap gates. The creek network system serves as a drainage channel by which surface runoff is discharged into natural water bodies in intertidal areas.

Tidal Creeks are relatively small-scale landforms with a low hydrodynamic energy environment without significant wave action or strong current (Healy, 2005) and are one of the characteristic zones of an intertidal flat (Torress and Styles, 2007). They are important network systems through which there is an exchange of water, nutrients, and sediment between marine and inland environments (Wang et al., 2020; Kearney and Fagherazzi, 2016). As such, it is important to understand the pressure that man-made structures such as tidal gates around the coast are putting on these systems through climate change and increasing development in coastal areas.

According to Whitehouse et al. (2000), tidal creeks are formed due to the inefficiency of the intertidal environment at draining water as the tide ebbs. Flow concentrates and dissipates by subtle variations in surface topography, creating a depression. Once formed, the flow becomes focused within the area of the depression resulting in larger bed shear stresses and increased erosion. Even though creeks develop relatively quickly In Managed Realignment (MR) schemes, they are influenced by sub-surface sedimentological conditions (such as sediment compaction and consolidation), which influence hydrological connectivity, and which in many cases will relate to historic environmental change and the former land use (Dale et al. 2018). Creeks that are known to accommodate bilateral flow develop near the shoreline with shallow gradients as drainage routes for tides, which allow the flow of water in and out through the creek depending on the gradient and sediment consolidation. In estuaries, creeks are mostly formed on intertidal flats, which are covered at high water and become exposed at low water. Shallow flows in mudflat creeks are important geomorphic agents and should be considered in the study of mudflat evolution with the presence of these landforms (Fagherazzi & Mariotti, 2012).

Understanding the impact of urban surface runoff through tidal gates into tidal creeks in estuaries is essential to making informed decisions on coastal management and improve sustainable development. There is little understanding of the role creeks play in sediment supply from intertidal areas into the deeper channel (main channel and the deeper channel will be used interchangeably from here forth) due to changing surface runoff flow and subsequently contribute to the loss of these habitats. Although a few research have looked into the effectiveness of tidal gates (Mitchell, Burgess, Pope and Theodoridou (2008) and Mitchell, Tinton and Burgess (2006)) and studies such as (Wang et al. (2020); Wolanski et al (2020); Nidzieko & Ralston (2012); Wang et al (2012); Williams et al (2008)) have looked into the hydrodynamics and sediment transport on intertidal flat, there is little understanding of the role tidal flap gates play in sediment cycling in estuaries because of the presence of tidal creeks and freshwater flow

To bridge this gap, this study used field investigation and empirical analysis to assess the impact of tidal creeks and tidal flap gates through which land surface runoff drains into estuaries on sediment transport in the receiving waters downstream of the creeks and propose a semi-empirical model to assess the impact of water level rise and increased runoff flow, as may be expected under many climate change scenarios. This will add to the existing knowledge of these landforms and inform the management strategies of these unique systems.

2. Study Area and Method

2.1 Study Area

Portsmouth Harbour is a large industrialised estuary located on the south coast of England as shown in Figure 1 and, it contains one of the four largest expanses of mudflats on the south coast (Joint Nature Conservation Committee, 2008). The harbour at latitude 50^{o} 49' 41" N and longitude 01^{o} 07' 32" W has an elevation difference of 4.1m between mean high water spring tide and mean low water neap tide at its entrance accounting for the Macrotidal nature of the estuary with the semidiurnal tidal cycle as common with UK coastal waters. Portsmouth harbour is an important area from an ecological point of view. Most estuaries in the UK are listed as Sites of Special Scientific Interest (SSSI) under the Wildlife and Countryside Act 1985 and Portsmouth Harbour is no exception to this.

The topography of the harbour is such that the expanse of intertidal mudflats can be seen at the northern end of the harbour towards the mid-section of the harbour and occupies about

30% of the harbour. Portsmouth harbour has a water depth of 12m and 0.5m at the deep channel and shallow depths respectively. This also gives an insight into the sedimentation of the harbour. Maintenance dredging is usually carried out regularly by Marinas to maintain the depth required for their boats.

The Harbour was designated a Ramsar site and SPA in 1995 (Knollys & Green, 2017) with both Ramsar and SPA sites sharing a common boundary with almost identical features. The harbour is an unusual system with a long history of naval activity and pollution which makes it a sensitive environment under intense human pressure. As such, management of the estuary is important. It is also important to understand sediment dynamics due to ecology and the potential for resuspension of contaminated sediment through constant maintenance dredging pressures from aircraft carriers and urban runoff. The Harbour was designated a Polluted Water (Eutrophic) under the Nitrates Directive in 2008, with a Nitrate Vulnerable Zone (NVZ) established in its catchment (Environment Agency, 2016).

The estuary has a free narrow connection to the Solent at its southern end where salt water from the sea enters the harbour with freshwater input mainly from the Wallington River through Fareham Lake (Onabule, Mitchell and Couceiro, 2020). The freshwater input into the harbour from the Wallington River varies between $0.018m^3/s$ and $22.31m^3/s$ as between March 1991 and October 2019 (Data from the UK National River Flow Archive For peak flow data). The harbour also has a connection to Langston harbour on the east. Portsmouth harbour of today has a length of about 8km and a maximum width of 5km at its northern end. Since Portsmouth harbour is a unique habitat, it is important to understand both the micro and macro processes in the estuary.

The sampling site (Wicor) is located northwest of the harbour is as shown in figure 1 with latitude 50° 50’ 22” N and longitude 1° 08’ 59” W. The selected study site is typical of sites around harbours where land drainage outfalls enter the harbour and Solent system.

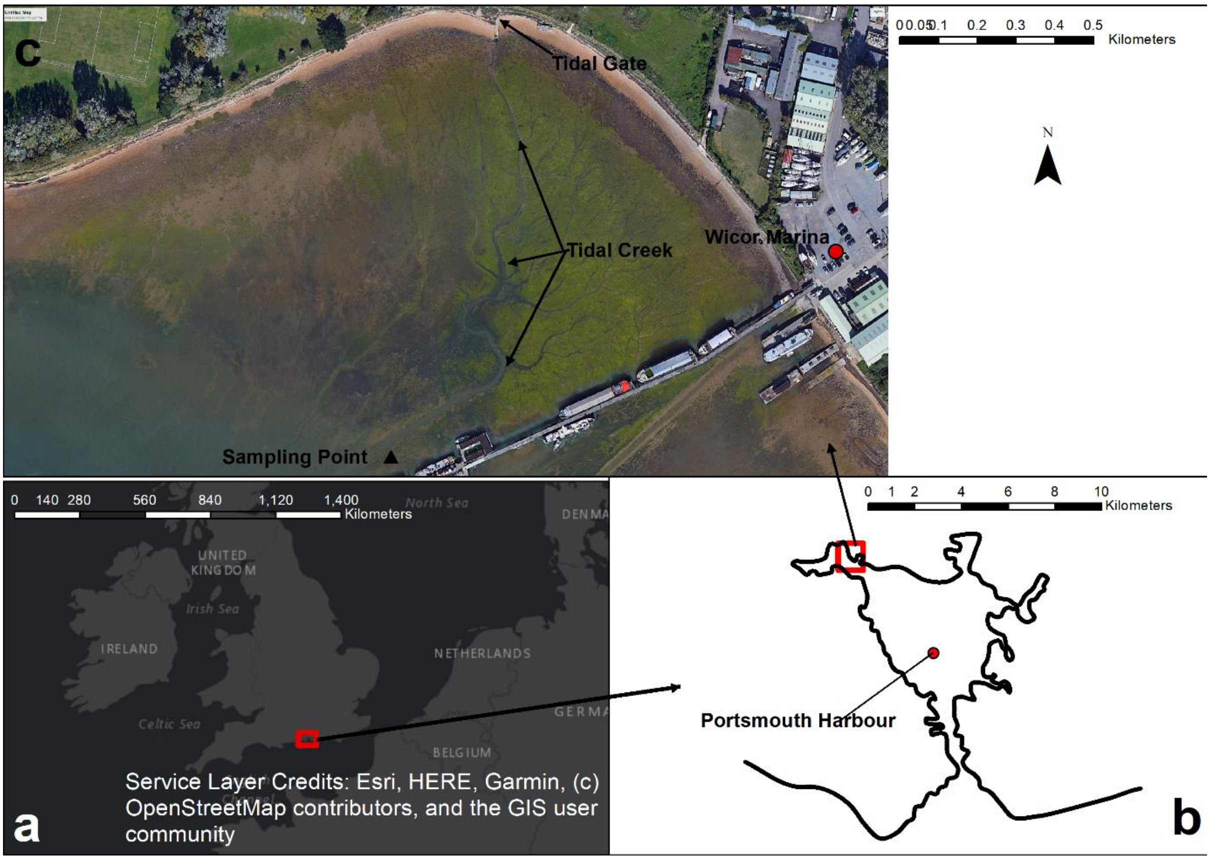


Figure 1: Location maps. (a) United Kingdom. (Base map: ArcGIS, Dark Grey Canvas.) (b) Portsmouth Harbour. (c) Wicor Marina Tidal Creek. (Base maps: Google Maps, Imagery copyright 2020)

2.2 Field Sampling

The creek observation and data collection was part of the fieldwork, which was carried out at Wicor Marina over an intertidal flat accessible through a pontoon. The data collection was carried out at low tide (sampling point indicated by the black triangle in figure 1c) in order to assess the impact of the creek suspended sediment concentration on that of the main channel (deep estuary channel) as the creeks become exposed at low water.

The field experiment was conducted over two seasons (summer and winter). The summer field sampling was undertaken on the 13th and 22nd of June 2018, for spring and neap tide respectively. The winter field sampling was undertaken on the 28th of February 2019 for neap tide and on the 21st of March 2019 for spring tide.

Water quality monitoring was carried out to assess the quality of water within the area and also to determine the source of the water gushing out of the creek at low tide.

A hand-held YSI (Yellow Springs Instrument) ProDSS CTD (Conductivity, Temperature and Depth) probe was lowered down the water column at 30mins intervals to measure physio-chemical parameters, viz salinity, depth, temperature, pH, dissolved oxygen and turbidity.

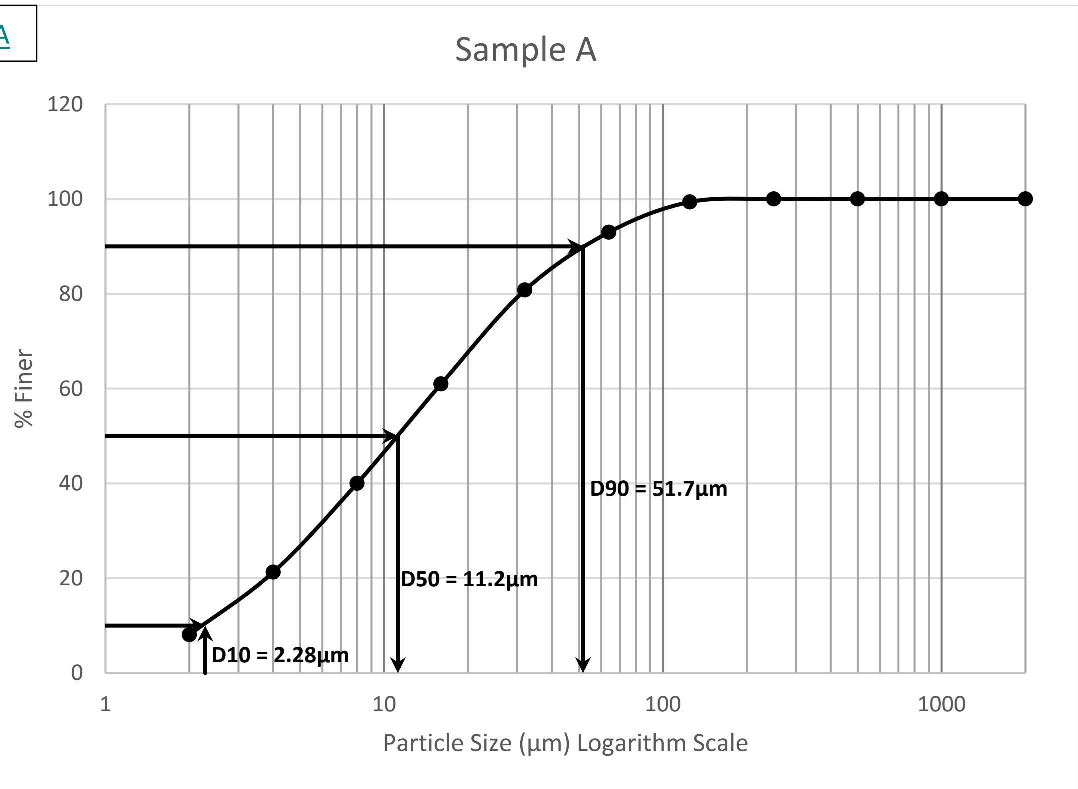
The YSI ProDSS CTD probe sensor was calibrated for these parameters using a combination of known standard calibration solution and freshwater (see YSI ProDSS user manual, 2014) laboratory analysis of surface water samples (collected in one or more 250ml reagent bottles)

The geometry of the exposed creek was directly measured using a one-meter metallic ruler.

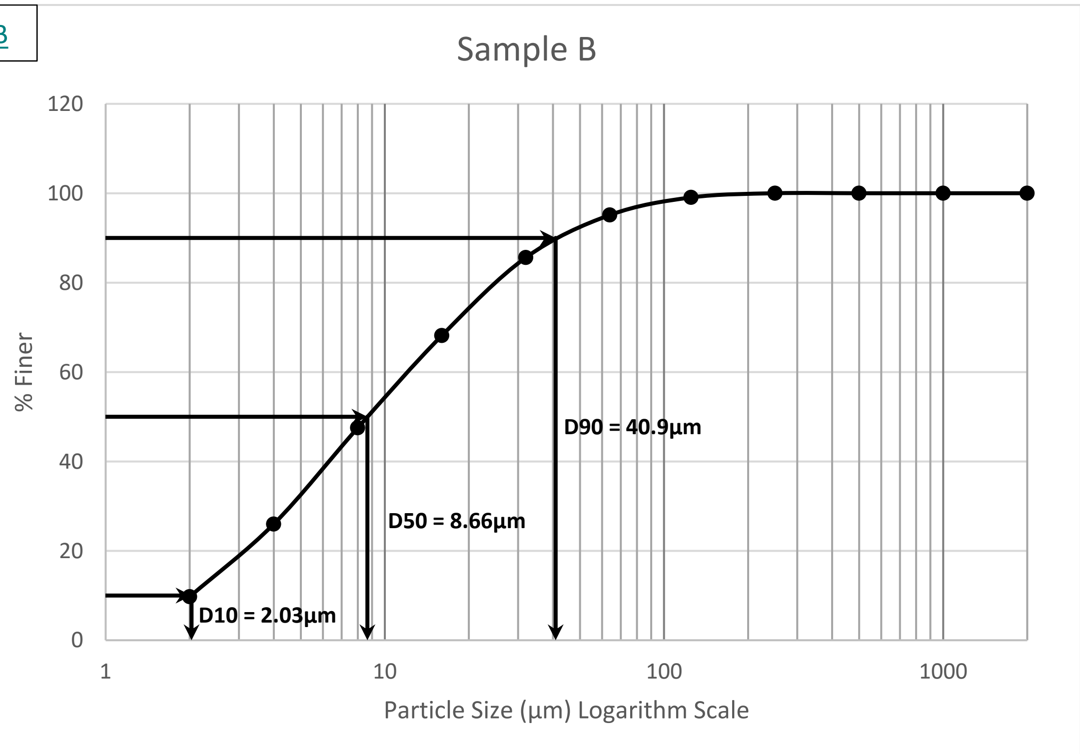
The bed sediment grain size at the sampling site was also assessed by collecting sediment samples using a Van Veen Grab and the samples were analysed using a Malvern Mastersize 3000 Laser particle analyser. The particle size distribution for the three samples is shown in figure 2.

According to Dyer (1986), $\frac{D_{90}}{D_{10}} < 2.4$ means the sediment is well sorted and $D_{90} > 35$ µm means the sediment is well mixed. The sediment samples at the site were well mixed and well sorted. As such, the average median grain size (D_{50} = 10µm) of the three samples (A, B & C) was used in subsequent analysis.

A


Sample A
% Finer
120
100
80
60
40
20
0
1
10
100
1000
Particle Size (μm) Logarithm Scale
D90 = 51.7μm
D50 = 11.2μm
D10 = 2.28μm

B


Sample B
% Finer
120
100
80
60
40
20
0
1
10
100
1000
Particle Size (μm) Logarithm Scale
D90 = 40.9μm
D50 = 8.66μm
D10 = 2.03μm

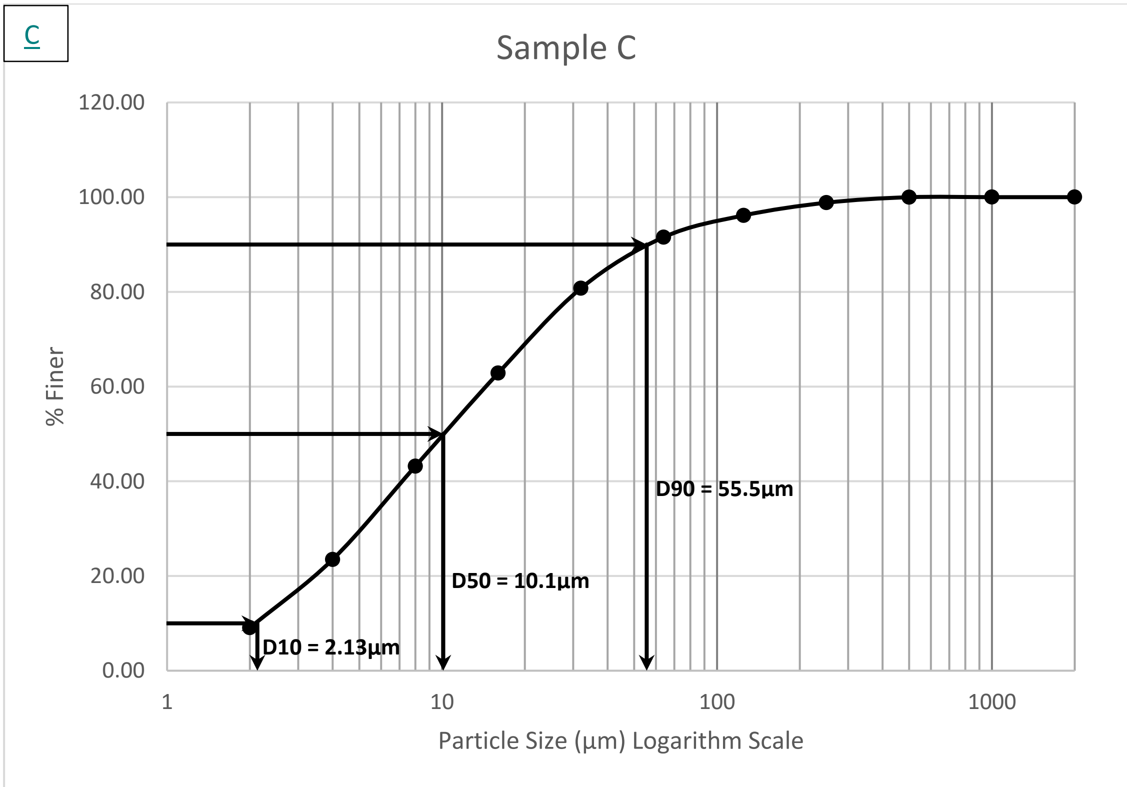


Figure 2: Particle Size distribution at Wicor (a) Sample A, (b) Sample B, (c) Sample C

2.3 Hydrodynamics

Water velocity was read using the 801 Electromagnetic current meter (EMCM) lowered into the water column at 30minutes intervals. The current meter which gives accurate readings over a wide flow range (-5m/s to +5m/s) in only 5cm of water uses a flat sensor suitable for measuring velocity in shallow waters and, have an accuracy of ±0.5% of reading plus 5mm/sec. At low water, the average velocity readings were collected in such a way that the sensor was pointed in the direction of flow . At high water, the EMCM readings were taken at three different levels in the water column, at mid- depth (established using the rod measurement attached to the EMCM), 100cm below the water surface for surface measurement and 100cm above the bed for bed measurement in the water column. This gave an understanding of how velocity varies within the water column (velocity gradient) from the water surface to the seabed

The velocity readings at high water around the creek were fairly the same at the three different points in the water column . However, the velocity increased during the transition from high to low tide particularly in the creek region, ranging from about 0.035m/s to 0.100m/s.

Water samples were collected from the water column into 250ml reagent bottles by lowering a Whale standard 12V submersible electric pump into the water column (at high water). The water samples were taken near the surface depth and suspended sediment concentration gravimetrically in the laboratory by standard methods (physical gravimetry) after filtration through a 47mm Whatman GCF filter with 0.7µm pore sizes.

The log method of estimating shear stress (Kim, Friedrichs, Maa, & Wright, 2000) was applied to this study, as the focus was on shear stress at low tide mainly at the beginning of a flood tide and the end of an ebb tide for both spring and neap tide.

The dimensionless grain diameter (D_*) was obtained using the equation given by Soulsby, (1997); This equation was used without considering flocculation.

$$D_* = \left(\frac{g\,(S-1)}{\upsilon^2}\right)^{1/3} D \qquad \text{----------------- (1)}$$

Where g is the acceleration due to gravity, S is the ratio of grain density (2650000 mg/l) to water density (1027000 mg/l), υ is the kinematic viscosity (1.0 x 10^{-6} m^2/s) and D is the grain diameter (10 µm) obtained from the particle size analysis (section 2.2).

Subsequently, the median settling velocity (ω_{50}) for cohesive sediment was estimated using equation (2) given by Whitehouse et al. (2000) equation 2 is an approach that covers both low and high-volume concentrations of sand without considering flocculation.

$$\omega_S = \frac{\upsilon}{D}\left[(10.36^2 + 1.049 D_*^3)^{1/2} - 10.36\right] \qquad \text{---------------- (2)}$$

The friction velocity u_* was obtained using the von Karman-Prandtl equation as in equation 3 (Kim et al., 2000);

$$U(z) = \frac{u_*}{\kappa} \ ln \left(\frac{z}{z_o}\right) \qquad \text{----------------- (3)}$$

Where U is velocity within the bottom few meters, z is the height above the bed, z_0 is the hydraulic roughness and κ is the Von Karman constant (~ 0.4). Equation 3 was used because of the turbulent boundary layer.

Since $\frac{u_* k_S}{\upsilon} < 5$ the flow is hydrodynamically smooth and as such the hydraulic roughness z_0 was computed using the expression shown in equation 4.

$$z_o = \frac{\upsilon}{9U_*} \qquad \text{---------------- (4)}$$

The depth average velocity for estuarine mud is computed using equation 5 as given by Whitehouse et al. (2000)

$$\bar{U} = \frac{1}{h}\int_0^h U(z) \ dz \qquad \text{---------------- (5)}$$

The bed shear stress (τ_b) was computed using equation 6 given by Whitehouse et al. (2000).

$$\tau_b = \rho u_*^2 \qquad \text{----------------- (6)}$$

Where ρ is the water density.

Finally, the suspended sediment concentration (C) was calculated using equation 7 (Whitehouse et al., 2000); This equation is used with the assumption of steady flow conditions

$$C = A_s \frac{\rho}{g} \frac{u_*^3}{h\omega_s} \qquad \text{----------------- (7)}$$

Where A_s given as 2.3 by Winterwerp et al. (1999), as cited by Whitehouse et al. (2000), is a dimensionless constant of proportionality and h is the water depth.

Sediment flux (F) was computed according to Mofjeld and Lavelle, (1988)

$$F = \int_{Z_o}^{H} U\,C\,d_z \qquad \text{----------------- (8)}$$

Where z_o is the reference height (the lowest water level in the water column), H is the highest water level in the water column, U is the flow velocity and C is the suspended sediment concentration.

The suspended sediment concentrations measured from field investigation were compared with those obtained by formulation to estimate the variance based on the formulation method.

The SSC and Net flux of sediment were necessary parameters to assess the impact of the creek on the main channel over a spring neap tidal cycle.

The critical shear stress was estimated by the formulation given by Son & Hsu (2011) as in equation 9.

$$\tau_c = \alpha_1 (M - \alpha_2)^{\alpha_3} \qquad \text{-------------- (9)}$$

α_1, α_2 and α_3 are empirical coefficients that are site-specific. The values of α_1, α_2 and α_3 used for this study are 0.3, 0.05 and 1 respectively. M is the sediment erosion coefficient and is estimated by using equation 10 given by Sanford and Maa (2001)

$$M = \rho_s \varphi_w \beta \qquad \text{-------------- (10)}$$

Where β is a local constant with units $MS^{-1}Pa^{-1}$, ρ_s is the sediment density and φ_w is the volume fraction of water.

3. Results

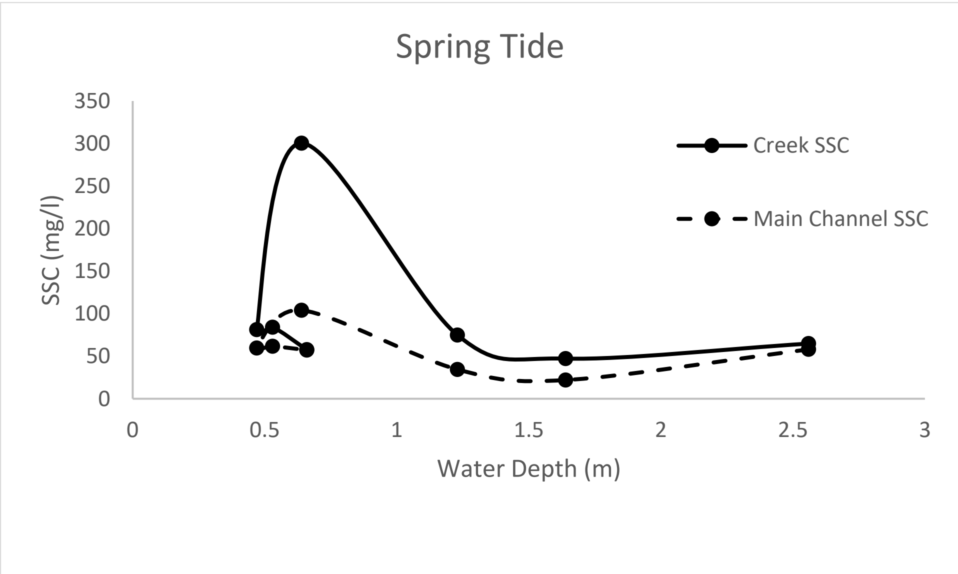
The results presented here represent the empirical model using equations 1 to 10 and analysis of field data collected at Wicor Marina over spring and neap tides at 2 to 3 hours on either side of low tide as creeks become exposed at low tide. The creek (Figure 1c) geometry varied from 1m to 2.8m irregular width and irregular depth of 0.25m to 0.75m (both depth and width measured in the field) and about 130m irregular length obtained from google earth. There is also the presence of algal bloom on the tidal mudflat which is indicative of eutrophication from nitrate (Maier et al., 2009).

3.1 Effect of Tidal Cycle on the distribution of SSC within Tidal Creek and Main Channel

The hydrodynamic condition within the study area is mainly tide and local wave action because the offshore wind at the estuary mouth had insufficient wave fetch to have an effect at the northern end of the estuary. The grain size distribution at the sampling site shows that the sediment is cohesive mud sediments with <63μm grain size distribution. The

SSC obtained from the creek was compared to that obtained from its receiving waters at low tide for both spring, neap tides, and the results are presented here. There is more SSC in the water column at spring tide than neap tide due to longer periods of flow at spring tide. This could also be because of the longer exposure period (t_{exp}) of the mudflats which supplies sediment into receiving waters.

There is an inverse relationship between SSC and water level. Figure 4 shows the spring tide SSC distribution within the creek and main channel at low tide. There is more SSC within the creek at low tide as the maximum SSC obtained within the creek for the spring tide was 300mg/l compared to that in the main channel 104mg/l and the minimum SSC obtained in the creek was 47.2mg/l and that in the main channel was 22mg/l.



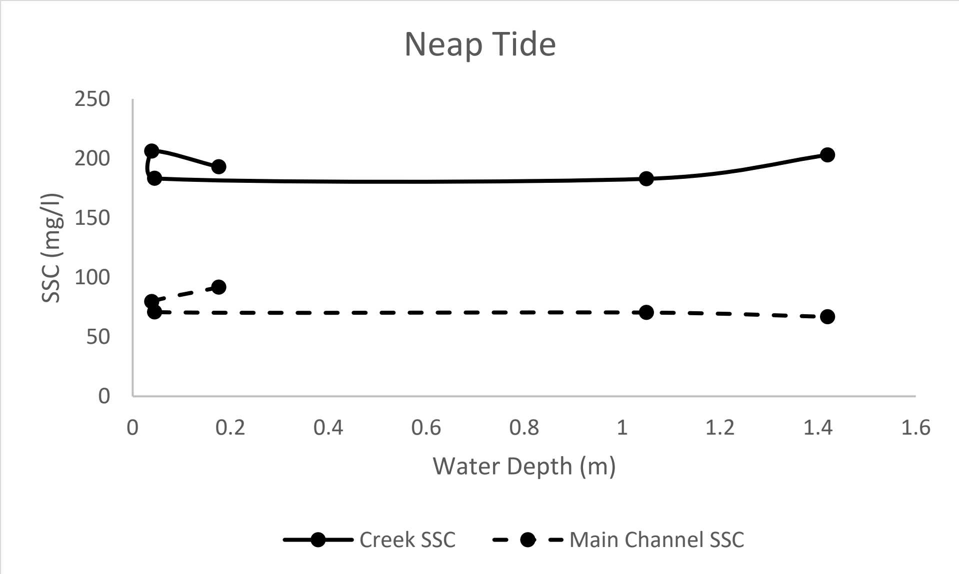


Figure 4: Measured SSC showing its distribution with water level (a) spring tide (b) neap tide

The neap tide (see Figure 4) shows the same pattern as the spring tide results with the SSC in the creek being more than the SSC in the main channel. However, the variation between water level and SSC in the neap tide was not as pronounced as that observed in the spring tide. The maximum SSC obtained in the creek was 193 mg/l compared to the maximum SSC obtained in the main channel 92 mg/l and the minimum SSC in the creek was 182 mg/l while that in the main channel was 70 mg/l. The SSC changes as the tide changes. The SSC is low at high water and high at low water (as shown in Figure 5).

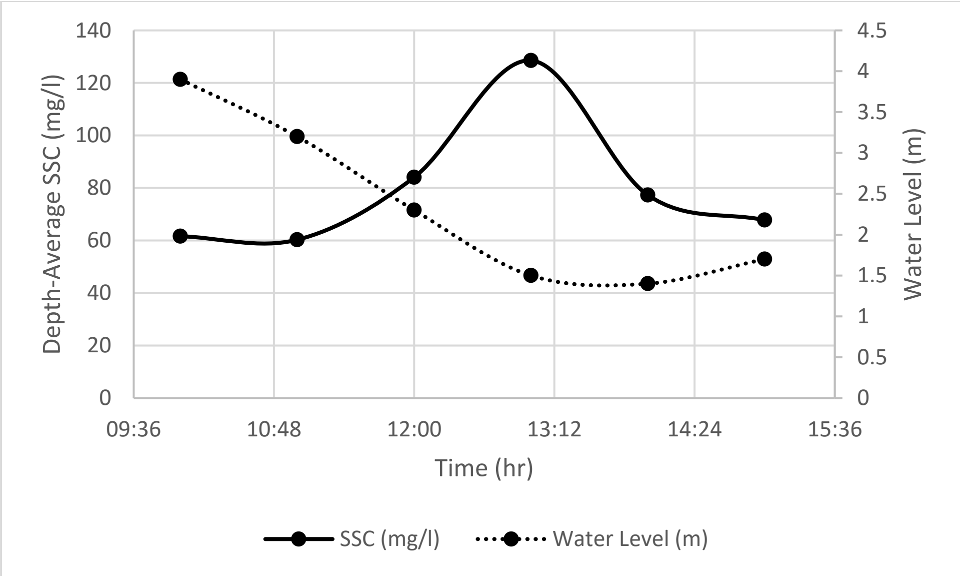
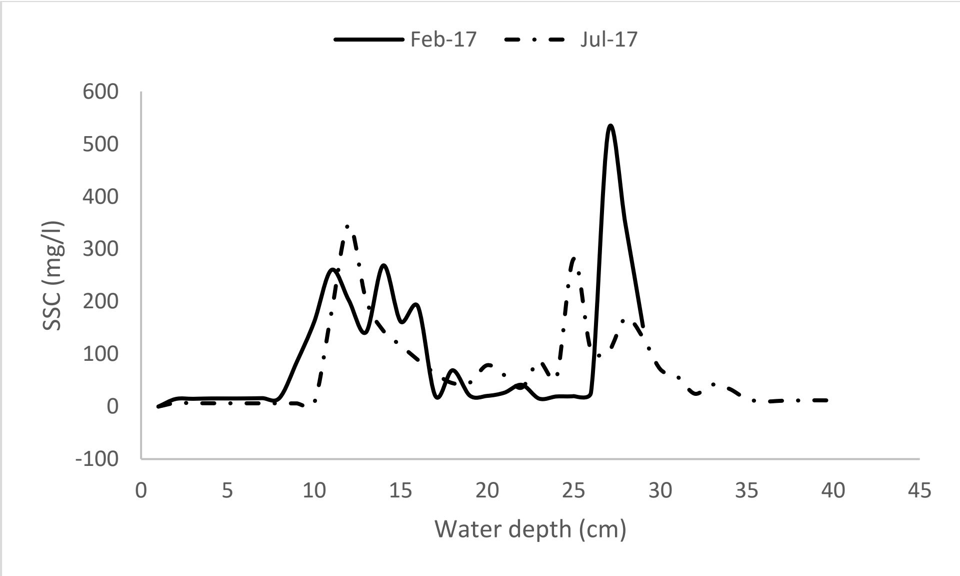


Figure 5: Depth-Averaged SSC at Wicor from high tide to low tide.

Depth wise SSC and salinity were also obtained (figure 6). The SSC at Wicor shows generally low concentration in the summer with the maximum concentration obtained in the winter. This could be because of increased runoff flow in the winter.

The depth-wise salinity at Wicor ranged between 33 and 37 (Practical salinity). Salinity was however lowest in the winter which further shows that increased concentration in the winter is because of increased freshwater flow which reduces salinity. The main freshwater input into the estuary is from the Wallington River (see Onabule et al., 2020).



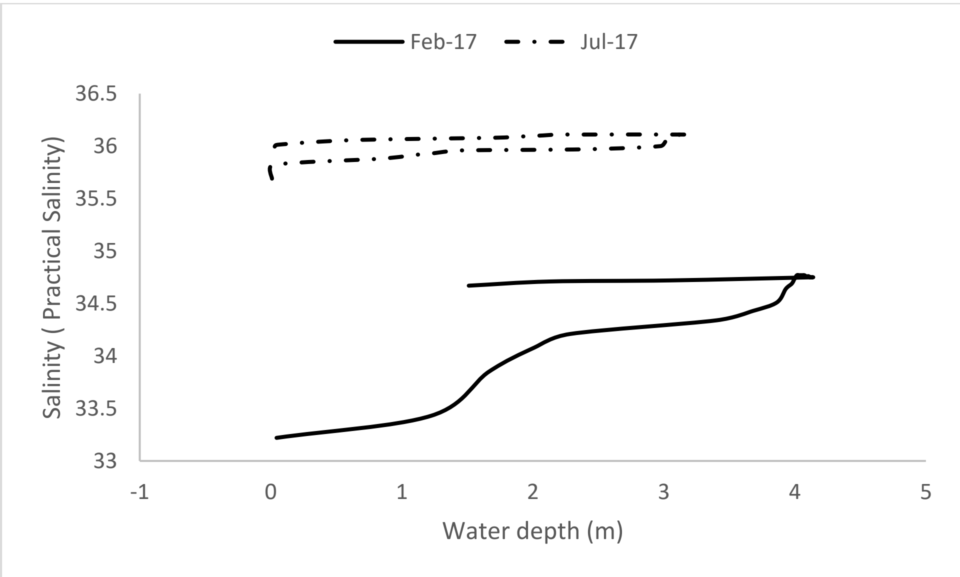


Figure 6:) (a) Depth-wise SSC and (b) Depth-wise Salinity at Sampling Site

3.2 Empirical Analysis of the Impact of creek formation on sediment transport

Following on from the effect of tidal cycle sediment supply. It was important to understand the role the creek play in the overall sediment dynamics through empirical analysis and field measurements. The formulation used to estimate the SSC showed similarity with measured data at low water but becomes less accurate as water level increases within the creek for spring tide (see Table 1).

Table 1: Sensitivity testing of the empirical formula used.

Water Level (m)	Measured SSC (mg/l)	Calculated SSC (mg/l)	% difference
1.56	64.8	8.2	87.4
0.85	47.2	18.0	61.9
0.5	74.8	36.2	51.6
0.1	300.4	323.5	7.7
0.22	81.2	109.0	34.3
0.27	84.0	82.6	1.7
0.39	57.6	50.4	12.5

However, the log profile formulation cannot be used for the computation of SSC in the main channel, as the minimum water level within the main channel of 1.2m is still quite high as compared to the creek at 0.1m. The log profile formulation used in this study is only suitable for complete low water. That is, it is suitable for the maximum low water level in the creek and not suitable for low water levels within the channel. This is because the height above the bed may not be fixed under natural flow conditions and because of the ambiguity of the bed level (Kim et al., 2000).

During high tide, it was observed that there is less movement of sediment around the creek as compared to low tide. The transport of suspended sediment at low water is visible by mere observation (as shown in Figure 7). The water level within the creek also decreases as the tide changes from high tide to low tide where they become visible. It was important to ascertain the source of the water in the creek network at low tide as such, spot samples of water within the creek was tested for total petroleum hydrocarbons (TPH) to assess potential pollution and water source using the method described by Roinas, Tsavdaris, Williams and Mant (2013). The average concentration of TPH from the water draining through the creek from upstream (tidal flap gates) to downstream (deeper channel) was 1.68mg/l and according to the United States Environmental Protection Agency, (1996), concentrations of TPH ranging from 0.7 to 6.6mg/l is an indication of road runoff. In Europe however, concentrations of TPH in road runoff according to Lundy, Ellis and Revitt (2012) is between 0.008mg/l and 0.4mg/l and in the UK, the TPH in road runoff according to Roinas, et al., (2013) is between 0.00007mg/l and 0.2mg/l. This means the use of hydraulic drainage flaps could contribute to the pollution around that area. This concentration could however also be from boat moorings around the area or a combination of both.

Figure 7: Observable distinction between existing water in the channel and the creek.

3.2.1 Shear Stress within the Creek

Shear stress plays a vital role in sediment transport and as such, the need to understand the effect of shear stress on SSC within the creek. According to the spring tide data that was collected over 5 hours (as shown in Figure 8), there is a strong correlation (r – 0.986 and p-value – 0.000) between the bed shear stress (τ_b) and SSC within the creek. Figure 8 shows that SSC increase is not significant until the critical shear stress is reached within the creek. At this point, the SSC increases substantially and reaches a point where increasing shear stress does not lead to an increase in the SSC. This is in agreement with a previous study by Wang, Yu, & Gao, (2011) with the study on the relationship between bed shear stress and SSC. Wang et al., (2011) showed that, at different stages of bed erosion, SSC increases rapidly when the flow velocity is increased but the pattern of change in the bed shear stress does not follow suit. At low concentrations, bed shear stress initially increases markedly with the increasing flow velocity. However, when the concentration reaches an apparently critical level, the rate of change in the bed shear stress abruptly slows down, or becomes almost constant, in response to further increases in the flow velocity. The critical shear stress (τ_{cr}) shown in figure 8 was estimated using equations 1, 9 and 10. Significant sediment erosion starts at the point where $\tau_b > \tau_{cr}$ which explains why the concentration starts to increase exponentially after this point in figure 8. This also shows that tides can resuspend bed sediments.

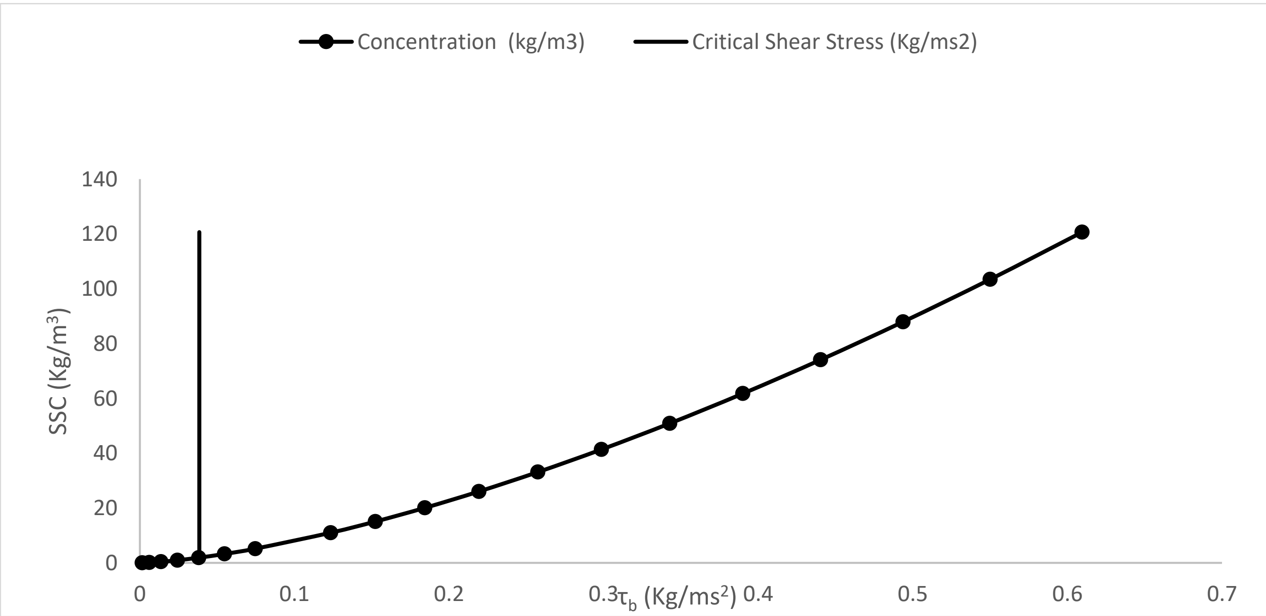


Figure 8: Relationship between bed shear-stress and SSC

3.3 Effects of Water Level and Runoff Flow from Land Drainage on Estuaries

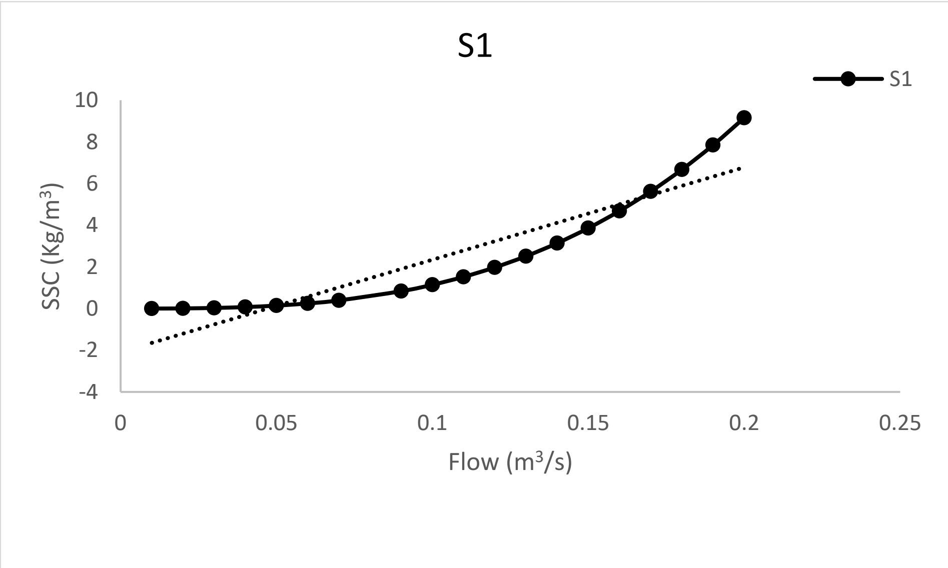
As established that creek formation and land drainage discharge plays an important role in the supply of SSC from intertidal flats into the deeper channel. It was, therefore, important to assess the effect of a combination of changes in water level and land drainage discharge on estuaries based on four different scenarios. An empirical method (equations 1 to 7 above) was used to develop a 1D model which was then analysed based on the following scenarios as shown in Figure 9.

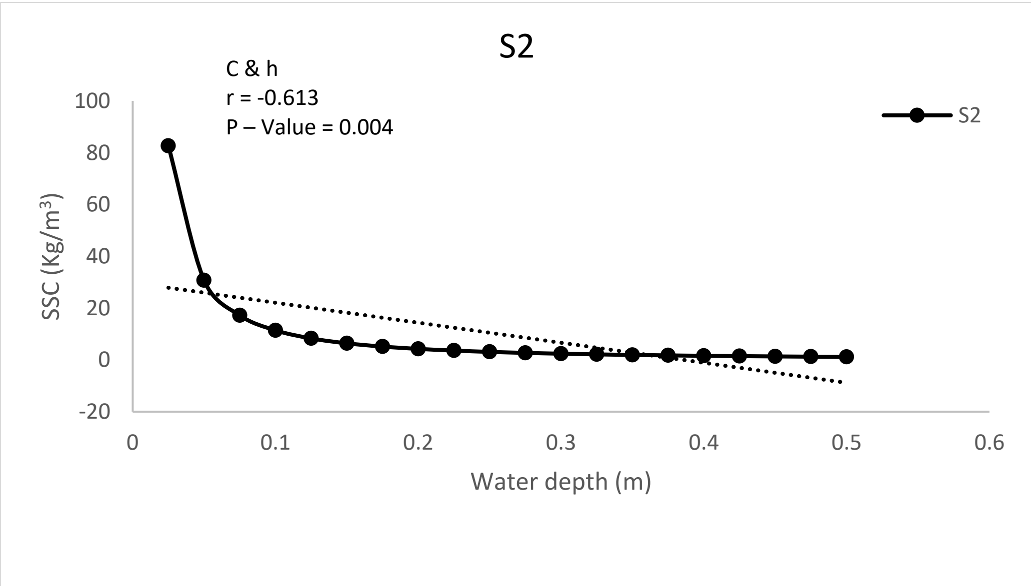
1) S1 – Increasing flow and constant depth
2) S2 – Increasing depth and constant flow
3) S3 – Increasing flow and decreasing depth
4) S4 – Decreasing depth and decreasing flow

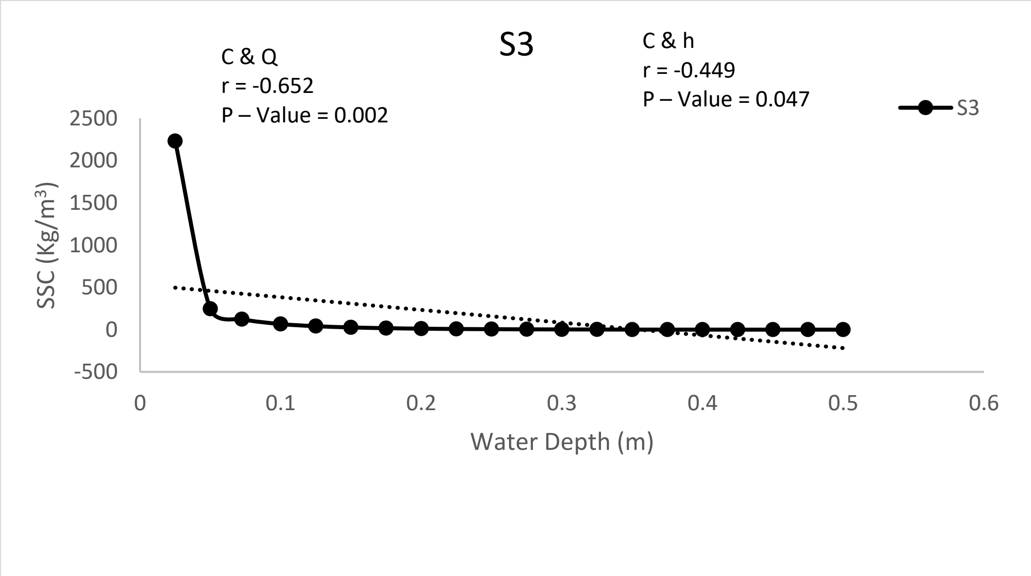
The assumed flow of 0.01m^3/s to 0.3m^3/s (typical of the sort of rates of runoff expected to discharge from many of the local land drainage outlets near the site of interest) and assumed creek water level of 0.025m to 0.5m was used for the empirical analysis.

The parameters under consideration for each scenario were tested for correlation using the Anderson Darling test. This is because all points within each parameter did not show any significant departure from normality. The Pearson correlation (r) and p-values for each scenario are shown for each combination of suspended sediment concentration (C), water depth (h) and flow (Q) in figure 9 .

The model for scenario 1 (S1 – figure 9) was developed with an assumed flow ranging from 0.01m^3/s to 0.3m^3/s and a constant water depth of 0.5m. This shows that discharge has an impact on the SSC within the creeks and as such, there is the need to reduce this effect in order to improve water quality within mudflat regions. The primary contribution to the flow within the observed creek was the tidal flap gate, which is designed to open at low water and discharge road runoff directly into the estuary main channel through a meandering creek system.







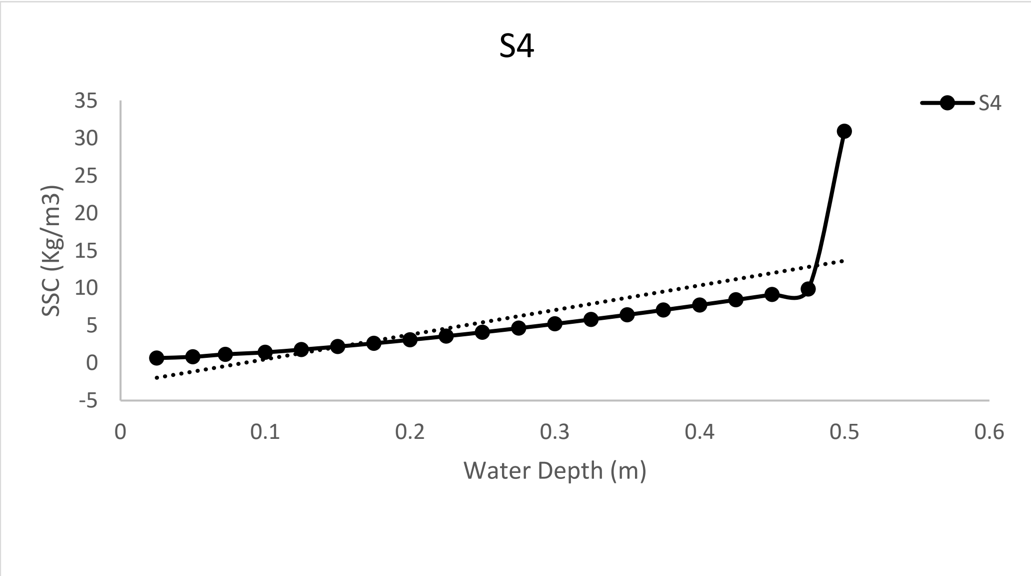


Figure 9: The effect of land drainage flow and creek water level on SSC (a) Increasing flow and constant depth (b) Increasing depth and constant flow (c) Increasing flow and decreasing depth (d) Decreasing depth and decreasing flow

The assessment of the second scenario was done with water levels ranging from 0.025m to 0.5m at a constant flow of 0.1 m^3/s (S2 – Figure 9). With increasing depth, there is a decrease in the SSC. However, more SSC would be supplied at increasing depth than increasing flow. Flow ranging from 0.01m^3/s to 0.3m^3/s and water level ranging from 0.5m to 0.025m (S3 – figure 9) was applied to the third scenario. This represents the observation made on-site as more SSC is discharged into the main channel at increasing flow and decreasing depth. The model for S3 also showed the highest SSC contributed to the main channel among all scenarios considered for this study.

Finally, the last scenario was assessed with flow ranging from 0.3m^3/s to 0.02m^3/s and water level ranging from 0.5m to 0.025 (S4 – figure 9). With decreasing water level and decreasing flow, there is also an increase in the SSC. This pattern follows the same pattern observed in S3. However, the SSC did not have as much increase.

4. Discussion

Tidal creeks are known to have different patterns of sediment cycling at different water levels (Wang et al., 2020). Cohesive sediments found in Macrotidal estuaries are highly mobile with the concentrations of suspended particulate matter (SPM) responding rapidly to changes in bed shear stress brought about by changes in current speed (Heath et al., 2017). At slack water periods, significant settling often occurs as observed in the field. The flow of water across the muddy intertidal areas described in this study is more or less steady throughout the period of low water. The morphology of a creek is significantly affected by the secondary flow that is caused by the meandering nature of the channel (Wang et al., 2020) while the intertidal morphodynamic development is affected by the unified sediment transport and associated erosion-deposition pattern within the mudflat-creek system at spring-neap tidal time scales (Xie et al., 2018). In addition, creeks undergo most of their development during late spring tide ebb discharge, and during periods of heavy rainfall run-off at low tide (Bridge and Leeder, 1976 cited by Whitehouse et al., 2000b).

The substantial amount of sediment mobilised by currents in the creek system is also a function of flow in the creek because of urban and road runoff and the period of low tide as this represents the exposure time (t_{exp}) of the creek. There is also evidence of tides resuspending bed sediments. Resuspension of bed material and erosion rates are closely related to applied bed shear stresses (Thompson et al., 2011). There is more SSC at Low tides in the summer spring tides compared to that of winter due to the higher tidal range, longer period of flow and low freshwater flow or because of increased plankton growth in the summer (Onabule, Mitchell & Couceiro, 2020). Here, high freshwater flow can mean a large amount of sediment but can also mean that the low tide does not last that long and that t_{exp} is relatively short.

The results of this study in combination with the assumptions made in the empirical model made it is possible to determine the effect of varying freshwater flow on the flux of material given the flow in the channel and the length of time for which the water drains into the main channel (figure 10).

This mode of cohesive sediment transport identified is mainly affected by tidal state, runoff discharge from land drainage and exposure period of the intertidal flat. Without these parameters, this mode of cohesive sediment transport through creeks has no substantial impact on the sediment dynamics within the main channel apart from those identified by other studies. Safe and quick disposal of land drainage water is an important means of reducing flood risk in areas upstream of the tidal flap gates (Mitchell et al., 2008). However, sustainable means of disposal of surface runoff with less secondary impact on receiving waters should be devised.

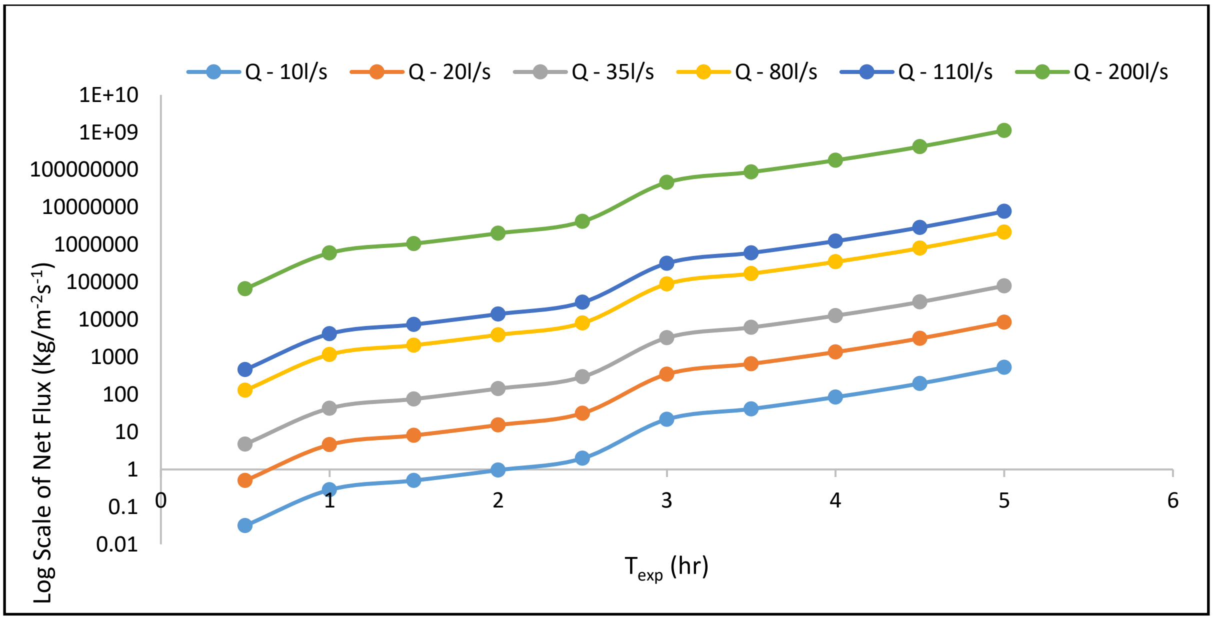


Figure 10: Contribution of time of mudflat exposure and land drainage flow on net sediment flux

4. Conclusion

This study assesses the impact of creeks on Macrotidal estuaries through the monitoring of SSC and empirical analysis. The creek geometry affects the flow velocity within it. This is because as the flow velocity increases, the bed shear stress increases which subsequently leads to an increase in SSC. There is increased SSC at low tide within the deeper channel downstream of tidal flap gates due to the high SSC that is supplied by the creek.

More sediment is supplied by the creek on a spring low tide than a neap low tide. This is because of the long exposure period of the creek experienced on a spring low tide compared to the neap low tide.

By using data to calibrate a semi-empirical scheme to assess the impact of water level and discharge from land drainage estuaries via sediment transport, it was possible to show the sensitivity of sediment supply to hydrological conditions. The combination of creeks and land drainage outfalls will have the highest impact on the main channel at low water and high flow.

It is recommended that moving forward on developments around coastal areas, management authorities should create more effective and sustainable drainage systems with less impact on estuarine environments to protect aquatic life and promote habitat creation for a sustainable future. Such systems whereby there are numerous drainage flaps surrounding estuaries especially in intertidal flat areas should be transformed into systems with fewer secondary effects on estuarine environments. A good alternative would be the use of rural sustainable drainage systems that can retain water in a pond at low water tide and releases the water directly into the estuary at high water tide. This is also a good form of alternative as they are known to reduce pollutants by capturing them. This would however have a significant impact in terms of sediment cycling and might lead to increased siltation rates at the tidal limits, in turn leading to a greater need for dredging and would also require financial investment and/or further environmental impact assessment.

There is a need to carry out studies like this within estuaries that have large expanse of intertidal flats with more prominent landforms and have the presence of tidal flap gates in their environs. This is to assess the impact they have on estuaries in terms of the sediment dynamics with which this study serves as a pilot study for other studies to be executed.

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