THE EFFECTS OF FRESHWATER FLOW AND SALINITY ON TURBIDITY AND DISSOLVED OXYGEN IN A SHALLOW MACROTIDAL ESTUARY: A CASE STUDY OF PORTSMOUTH HARBOUR

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Abstract

Portsmouth Harbour was used to investigate the effects of fresh water flow and water physio-chemical properties such as salinity on turbidity and dissolved oxygen within industrialised Macrotidal estuaries. Nine sites were selected within the harbour for field sampling and data collection based on their contrasting hydrodynamic environment and accessibility from land. Sediment, water samples and water physio-chemical data were collected from the harbour once every season over a period of two years. Fresh water flow directly affects turbidity as an increase in fresh water flow leads to a decrease in turbidity. Increasing fresh water flow also leads to seaward transport of Suspended particulate matter. There is no significant migration of the estuarine turbidity maxima zone within Portsmouth Harbour due to the general low fresh water flow (average yearly flow of 0.6m^3/s) for all seasons unlike other Macrotidal estuaries. The area of intertidal flats have low dissolved oxygen ranging from about 4.5mg/L to 10.4mg/L compared to other areas within the harbour which ranged from 6.5mg/L to 12.5mg/L. This is due to the substantial amount of sediment supplied by bed forms such as runnels on the intertidal flats into receiving waters. Based on these findings, there is need for a synchronised management system within these type of estuaries.

Keywords
Suspended Sediment Concentration
Macrotidal Estuary
Estuarine turbidity maxima zone
Salinity

1. Introduction

Estuaries are seen as one of the most productive marine ecosystems in the world and crucial to the life history and development of many aquatic groups (Chapman & Wang, 2001). As a result, a lot of research have looked into water quality in different estuaries (Taljaard, Slinger, & van Niekerk, 2017; Hu et al., 2004; DiLorenzo et al., 2004; Buzzelli et al., 2004; Sanderson & Taylor, 2018; Hubertz & Cahoon, 1999). Water quality is a predominant factor of an estuary's ability to support healthy food webs (Wetz et al., 2016). The measure of water quality in estuaries is mostly done through the consideration of dissolved oxygen (DO), salinity, turbidity, temperature and nutrients status, others include organic enrichment and suspended loads (Joint Nature Conservation Committee, 2004).

DO is one of the most important parameters in coastal environments since water must contain enough oxygen to support aquatic life. The level of DO in water is generally linked to the effects of salinity, temperature and eutrophication (Li et al., 2018) and is known to be critical at a level less than 2mg/L (Mocuba, 2010). It is a known fact that dissolved oxygen decrease due to different factors, including rapid changes in temperature and salinity as well as respiration of organic matter. DO levels could also drop as a result of nutrient inputs. When nutrient loading is too high, phytoplankton can bloom and die. Bacteria and other decomposer organisms use oxygen to break down the organic matter (United States Environmental Data Report, 2017).

In sheltered estuarine environment, currents are modulated by tides, freshwater input, storm surges and local wave actions and there is significant relationship between salt intrusion length, freshwater flow and tidal range with which Pugh (2019) and McLachlan and Brown (2006) gave in-depth explanation of tides and tidal behaviour. The highly stratified estuary also known as salt wedge occurs in the absence of tidal and wave action where fresh water from the upper end of the estuary flows seaward forming a layer above the sea water (Uncles, Stephens, & Harris, 2015). This is because the freshwater is less dense than the seawater with which estimation of the density of water is derived by separately measuring salinity and temperature of water (Uncles & Mitchell, 2017). These highly stratified estuaries are more likely to occur in Microtidal regions with no tidal or wave action.

On the other hand, when the tidal range and wave action are large relative to the water depth, turbulence is produced, which subsequently leads to an intense vertical mixing at which point the water column becomes well mixed. This type of estuaries are referred to as the vertically homogenous estuary and are more likely to occur in shallow macrotidal environments.

Freshwater flow is however responsible to a considerable extent for salt water intrusion and this is known to affect the salinity experienced in an estuary.

2. Methods

2.1 Location and Description of 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 is bounded by Portsmouth city on the east, Gosport on the west and

Portchester Castle to the north of the harbour. The harbour is an unusual system in that it is heavily managed and industrialised. It has a free narrow connection to the Solent at its southern end where salt water from the sea enters the harbour and has fresh water input mainly from the Wallington River through Fareham Lake (upstream of Cams Mill, not shown in Fig. 1). It also has a free connection to Langstone Harbour to the east. Portsmouth harbour today has a length of about 8km and a maximum width of 5km at its northern end. The estuary has a tidal range at the harbour entrance of 4.5m and 2m for spring and neap tides respectively.

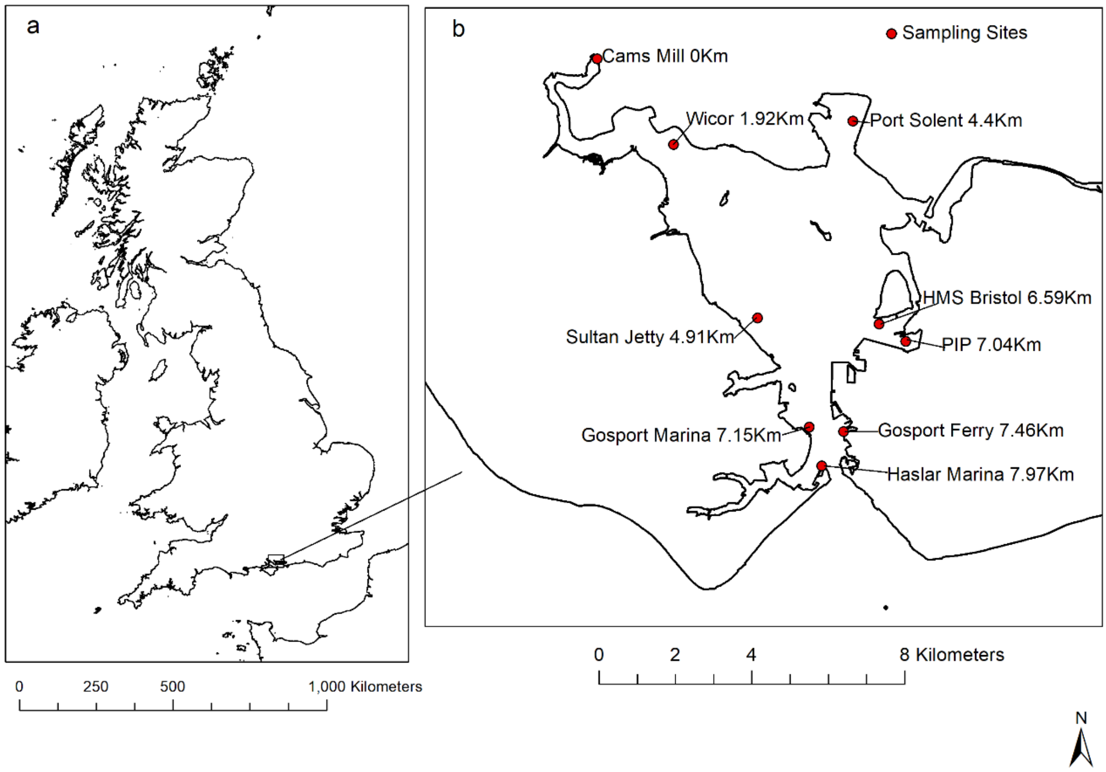


Figure 1: Map of Study area (a) shows the location of study area on a map of the United Kingdom and (b) shows the study area (Portsmouth Harbour) and the field sampling sites.

2.2 Sampling and Analysis

Nine (9) sites within Portsmouth harbour were selected for field sampling and data collection. These sites were selected due to their contrasting hydrodynamic environments, all are subtidal muds/silts, accessible from land and are situated near potential sites of PAH contamination. These sites are shown in figure 1 and their coordinates are shown in table 1. Three (3) sites were chosen out of the nine (9) sites where data logging was done between tides (flood tide to ebb tide) as shown in table 1 highlighted in the blue colour.

Table 1: Field sampling sites' coordinates

Site No	Site depth (m)	Site location	Latitude (degrees) N	Longitude (degrees) W
1	1.23	Cams Mill	50.852612	-1.167125
2	4.14	Wicor Marina	50.839310	-1.149950
3	4.2	Port Solent Marina	50.843510	-1.106180
4	3.86	Sultan Jetty	50.813225	-1.131307
5	4.98	HMS Bristol	50.813015	-1.100791
6	13.06	Portsmouth International Port (PIP)	50.811180	-1.092180
7	7.93	Gosport Marina	50.797161	-1.116882
8	7.16	Gosport Ferry (The Hard)	50.797199	-1.109248
9	8.44	Haslar Marina	50.791889	-1.115425

Sediment samples were collected from each site once over the sampling period with the use of a Van Veen grab to determine the sediment distribution within the harbour. This was subsequently stored in a refrigerator before pre-treatment for particle size analysis (PSA) was done using hydrogen peroxide (H2O2) and sodium hexametaphosphate (SHMP) as oxidant and deffloculant repectively. The Malvern Mastersizer 3000 Laser particle size analyser was finally used to analyse the sediment sizes outputting the result in an excel format.

Water samples were collected using a whale submersible pump connected to a power source (battery) and subsequently used to pump water from the water column at 100cm above bed, 100cm below surface and mid-depth between tides into 250ml reagent bottles at Cams mill, Wicor marina and Sultan jetty. The reagent bottles were stored in a refrigerator for not more than 24 hours (to reduce biological growth which could add to the sample mass) before gravimetric analysis was carried out in the laboratory to estimate suspended sediment concentrations at these sites using Fisherbrand MF 300 glass microfibere filter paper.

Water physio-chemical parameters such as salinity (measured as practical salinity), depth, temperature, pH, dissolved oxygen and turbidity were taken with a hand held YSI ProDSS CTD every season at each site. The YSI ProDSS CTD probe sensor was calibrated for depth, dissolved oxygen, salinity and turbidity using a combination of known standard calibration solution and fresh water (see ProDSS user manual, (2014)). The probe outputs were processed in excel eliminating data that were out of range before the result outputs were analysed in excel and minitab.

Relationships between parameters obtained from the YSI were assessed relative to water depth using Pearson's correlation coefficient (r), after confirming the linear relationship between the variables using scatterplot and confirming the normality of the data using Anderson-Darling test in Minitab.

The data obtained from the fieldwork and the observations made in the field helped understand the morphological behaviour of the harbour and the response of dissolved oxygen to freshwater flow. The surface current velocity was obtained from the United Kingdom Hydrographic Office (UKHO) using admiralty chart GB2361

3. Results

The results presented here are based on site physical observation and data obtained from the site from winter 2017 to winter 2019.

The main source of fresh water input into the harbour is the Wallington River at North Fareham entering the harbour at Cams Mill. The daily mean flow for the river for a year period of field sampling was obtained from the Environment Agency as shown Figure 2. The daily mean flow from January 2017 to March 2017 (winter 2017) was high compared to other seasons (see Figure 2).

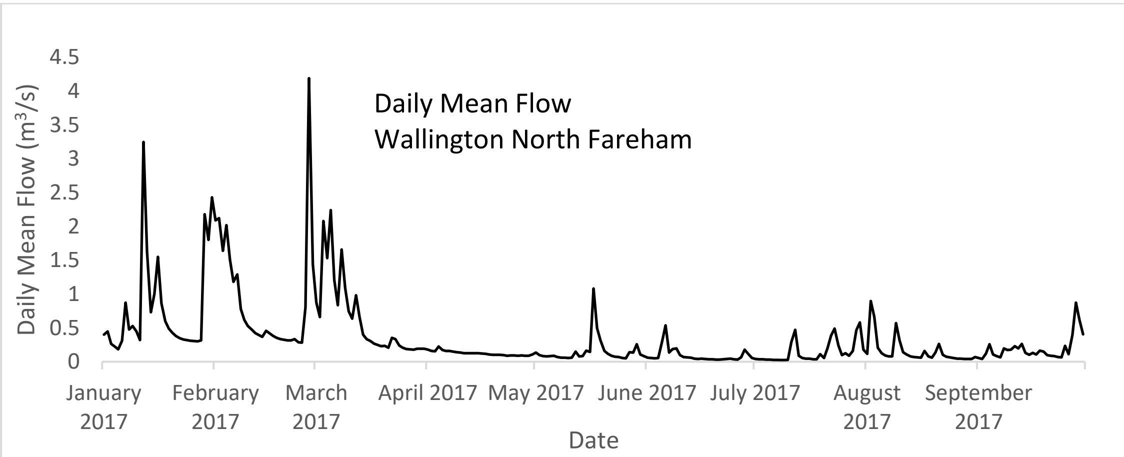


Figure 2: Flow measurement from Wallington River at North Fareham

It was necessary to assess fresh water flow to understand its impact on the water quality parameters that were assessed in this study and to understand its impact on the dynamics of sediment distribution within the harbour.

3.1 Sediment Distribution within Portsmouth Harbour

The sediment distribution within the harbour is mostly <63µm, which is a characteristic of fine cohesive sediment. The distribution of sediment within the harbour is as shown in Figure 3 from Cams Mill to Gosport Ferry.

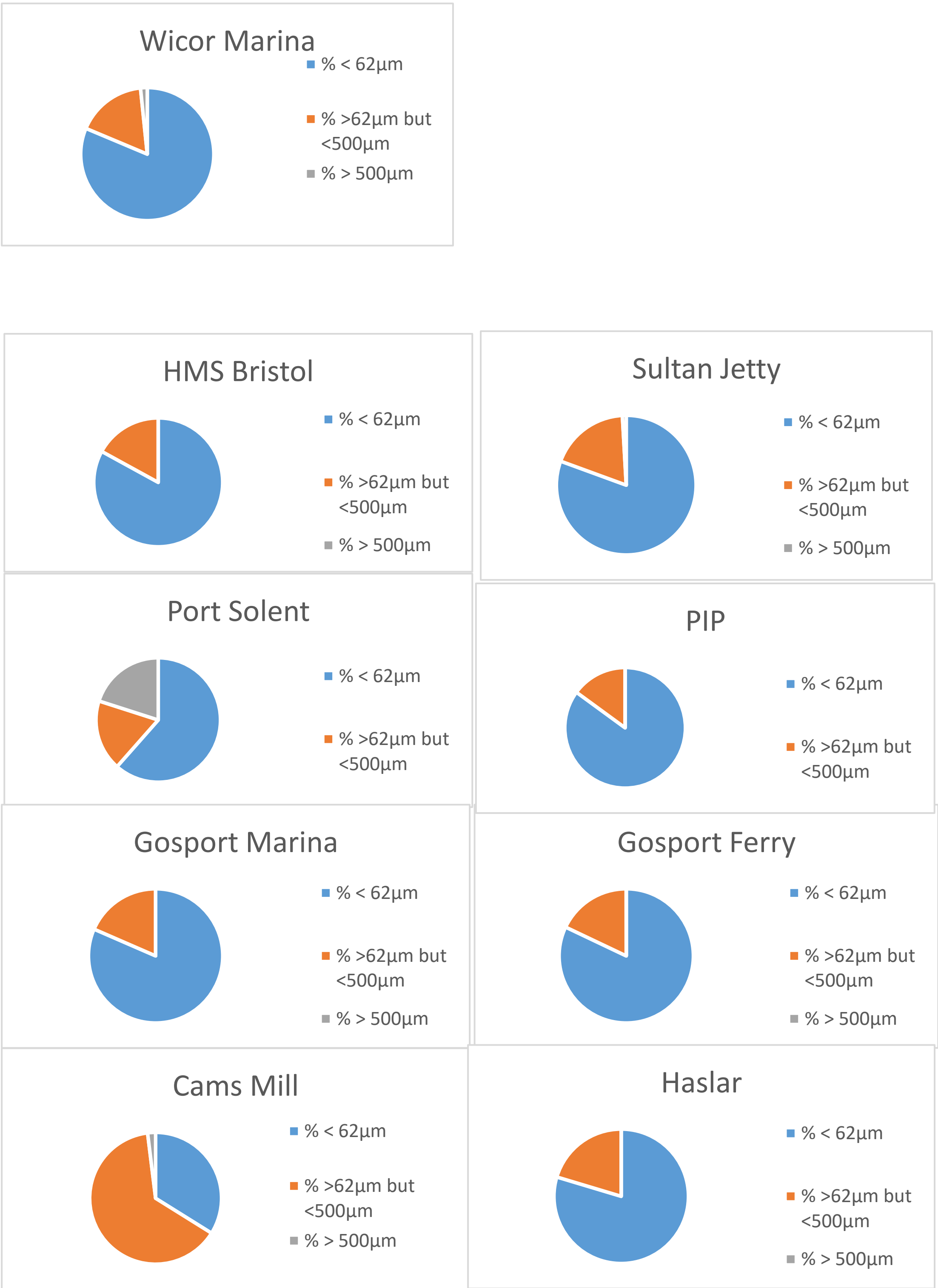


Figure 3: Distribution of bed sediment at each sampling site within Portsmouth Harbour

The majority of the sediments at each of the sampling sites were about 80% <63 µm with the exception of Cams Mill and Port Solent Marina. Cams Mill is the location of the fresh water input, which means there is constant flushing of fine sediments from that location, which may explain the sediment size distribution there. The ternary plot in Figure 4 below presents this information.

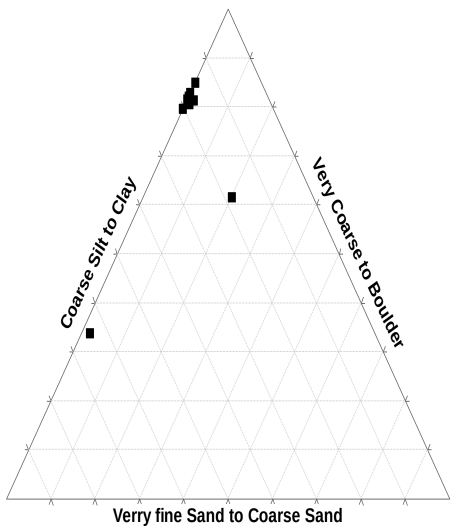


Figure 4: Ternary plot of the distribution of sediments (all sites)

3.2 Seasonal variations in the longitudinal distribution of Salinity and Turbidity within Portsmouth Harbour

The harbour is a well-mixed estuary for all seasons in agreement with shallow Macrotidal estuaries evidenced in figures 5.3a and b. The salinity follows the same pattern for all seasons and increases along the channel from fresh water input at Cams Mill to saline water input at the harbour mouth near Haslar. A maximum salinity of 35 and minimum salinity of 0.18 was measured within the harbour during the winter of 2017.

SITE	Distance (km)	Mean Salinity Winter 2017	Mean Salinity Summer 2017	Mean Salinity Autumn 2017	Mean Salinity Winter 2018
Cams Mill	0	0.18	10.05	22.86	9.86
Wicor Marine	1.92	29.61	24.11	27.91	23.34
Sultan Jetty	4.91	33.32	33.42	33.42	32.21
HMS Bristol	6.59	26.99	31.53	32.99	32.28
PIP	7.04	29.89	33.15	33.33	33.01
Gosport Marina	7.15	33.03	28.11	36.36	34.72
Gosport Ferries	7.46	32.58	32.59	32.39	33.42
Haslar Marina	7.97	27.13	31.72	35.58	33.32

SITE	Distance (km)	Mean Turbidity (NTU) Winter 2017	Mean Turbidity (NTU) Summer 2017	Mean Turbidity (NTU) Autumn 2017	Mean Turbidity (NTU) Winter 2018
Cams Mill	0	80.09	131.49	80.4	11.17
Wicor Marine	1.92	100.56	100.08	14.25	13.17
Sultan Jetty	4.91	72.32	156.91	67.44	69.89
HMS Bristol	6.59	357.29	42.99	54.34	11.64
PIP	7.04	15.6	51.69	9.29	25.33
Gosport Marina	7.15	86.61	79.65	140.09	121.88
Gosport Ferries	7.46	24.99	521.54	9.39	11.52
Haslar Marina	7.97	108.72	24.01	30.11	139.55

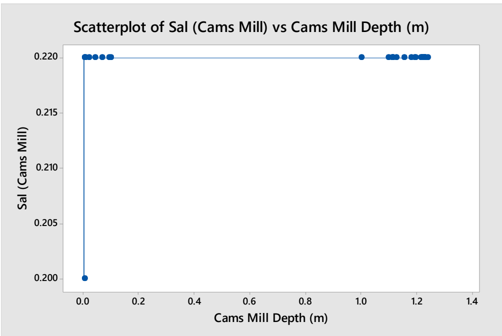
Figure 5: Seasonal distribution within the harbour from Cams Mill to Open sea for (a) Salinity (b) Turbidity

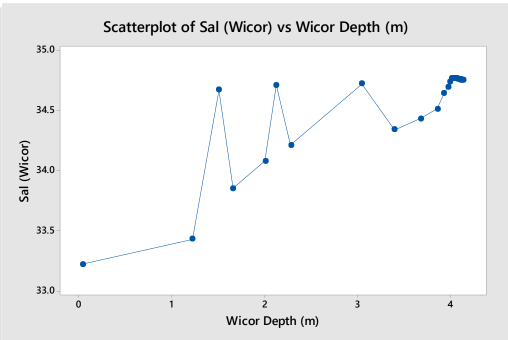
The field data show that the salinity at the fresh water input at Cams Mill was low as a result of high fresh water flow from the riverine input in the winter (See Figure 2) and increases gradually towards the estuary mouth. It nevertheless reached a point at which it was constant all the way through to the salt-water input at Haslar Marina.

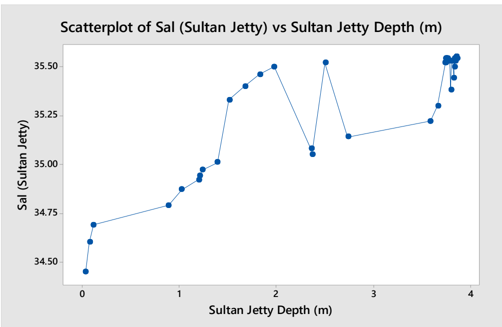
The salinity of the study area (See Figures 5a) follows the typical along-estuary salinity characteristic of an estuary as postulated by Dyer, (1997). The salinity for summer 2017 increases gradually from the fresh water input at Cams Mill and stays about the same approaching the estuary mouth. The salinity was also fairly constant vertically within the water column at each sampling site (well mixed estuary, see Figure 6).

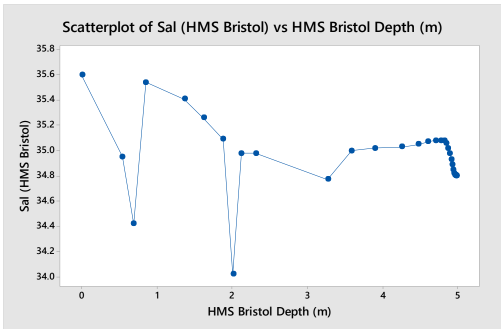
Even though the salinity measured in the autumn of 2017 follows the same pattern as that of the winter and the summer 2017 as shown in figure 5a, the salinity at the fresh water input was much higher for the autumn at 22.86. The maximum salinity measured for the autumn was 36.36 at Gosport Marina and the minimum was 22.86 at Cams Mill. The maximum salinity was 34.72 at Gosport marina while the minimum was 9.86 at cams Mill.

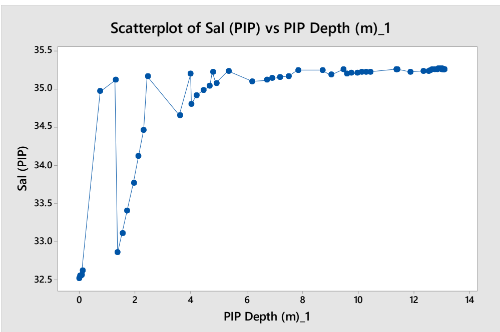
Turbidity readings along the channel were also obtained to allow assessment of the variation the amount of suspended particulate matter present in the water column within the harbour over different seasons.

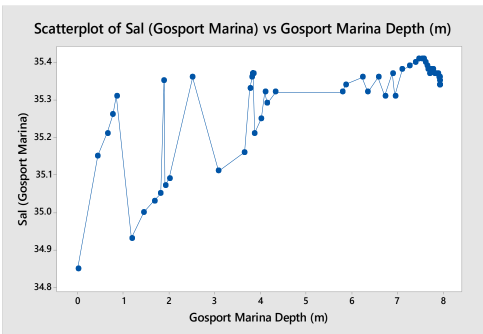












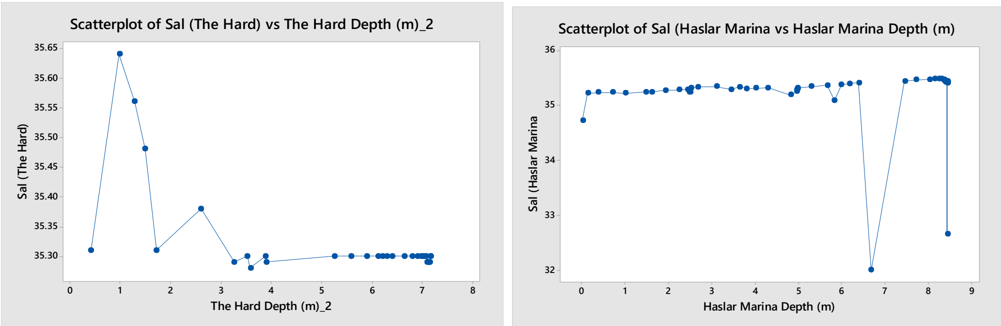


Figure 6: Depth- wise salinity for each of the site (evidence of well –mixed estuary)

The turbidity within the estuary in the winter of 2017 varies only slightly (between 70NTU and 100NTU) from the fresh water input at Cams Mill to Sultan Jetty, which is about 5km away from the fresh water input. The turbidity increases to its maximum (357.29NTU) for winter 2017 within the harbour at the Hard. This could be because of stronger currents near the harbour entrance. The presence of subtidal flat, which is sheltered from the influence of tides and waves by the Portsmouth Harbour train station restricts tidal flows and makes flushing difficult. However, there seems to be a lot of resuspension in the area based on the high level of turbidity in the water column, which could be a result of continual anthropogenic activities and increased currents near the harbour entrance.

The turbidity within the estuary changes horizontally along the channel from site to site. The maximum turbidity was measured for summer 2017 at 521.54 NTU at Gosport Ferries and the minimum turbidity was 24.01 at Haslar marina.

The turbidity of autumn 2017 was much less than that seen in winter 2017 and summer 2017. The maximum turbidity was at 140.09NTU while the minimum turbidity was 9.29NTU at Gosport Ferries as shown in Figure 5b.

The turbidity at the fresh water input was, however, higher at 80.4NTU compared to other seasons of 2017 but lower at other locations. This shows that there was more particulate matter present in the water column at Cams Mill, which reduces going further towards the saline water input. The maximum turbidity however was recorded at Gosport Marina as compared with other seasons of 2017. Unlike the maximum turbidity of winter 2017 (357.29 NTU), the maximum turbidity was much less for winter 2018 (139.55 NTU) at Haslar marina.

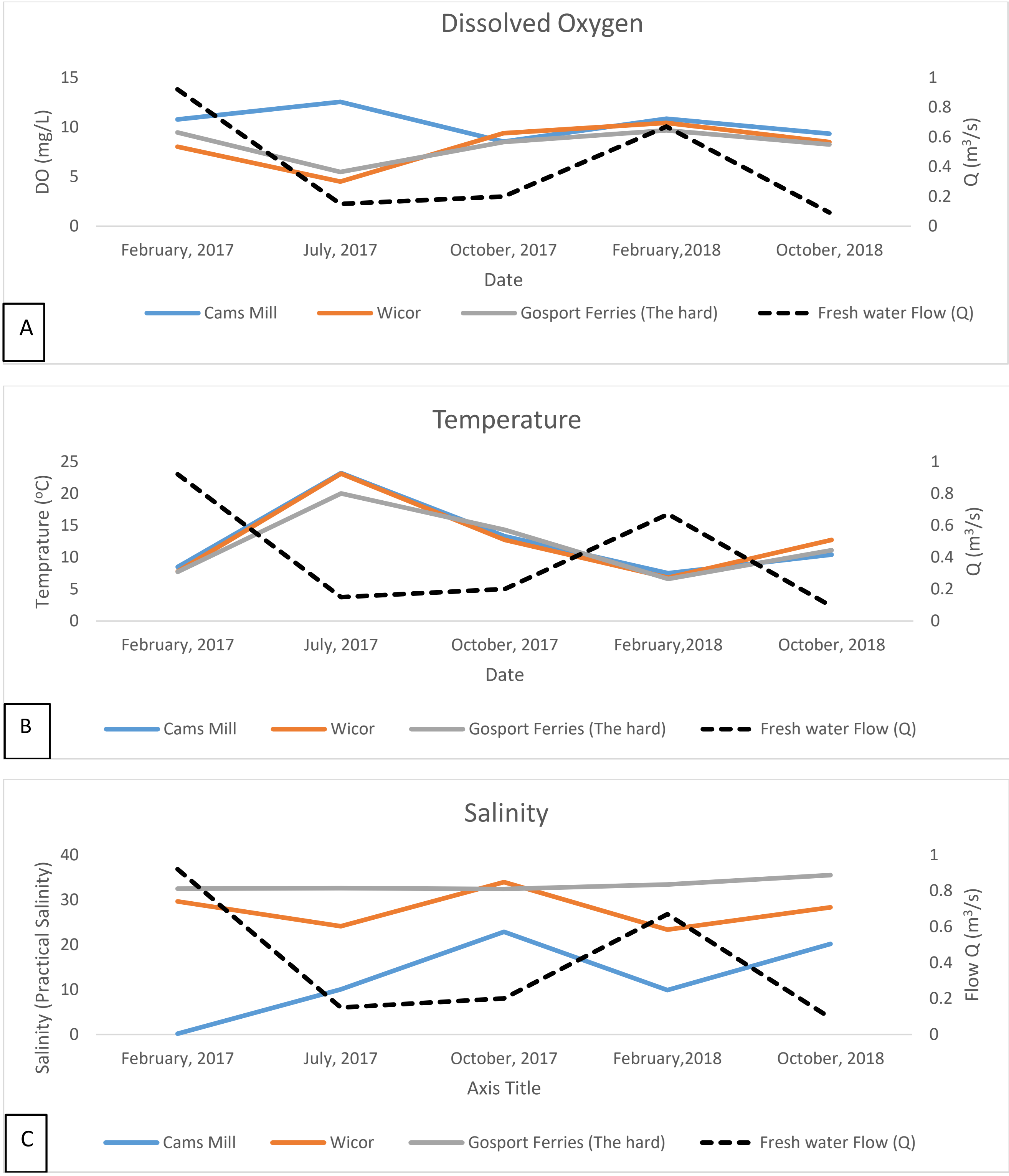
3.3. Seasonal variations in Vertical distribution of Dissolved Oxygen, Salinity, turbidity and temperature within Portsmouth harbour

In view of the results obtained, there was the need to understand variations in site-specific dissolved oxygen (DO), salinity, turbidity and temperature over different seasons.

The results presented here were for Cams Mill, Wicor and Gosport ferries. The dissolved oxygen showed similarity at both Wicor and Gosport ferries over different seasons with the exception of Cams Mill, which was substantially high in July 2017 (Summer 2017) see figure 7a.

The turbidity on this occasion was found to be high at Gosport Ferries in July 2017 with those of the other sites remaining fairly the same all season as represented by figure 7b. The temperature was found to be the same from Sultan Jetty to Wicor Marina over different seasons within the harbour with the highest temperature within the water column recorded for summer 2017 (July 2017) see figure 7c. The salinity was well distributed within the harbour as the salinity was lowest at the fresh water input (Cams Mill) and highest at the salt-water input (Gosport Ferry) as shown in figure 7d.

The trend observed here was that at the time where temperature was highest within the water column, turbidity was highest at the mouth of the harbour, dissolved oxygen was highest at the fresh water input and salinity was highest at the mouth of the estuary.


Dissolved Oxygen
DO (mg/L)
15
10
5
0
1
0.8
0.6
0.4
0.2
0
Q (m3/s)
February, 2017
July, 2017
October, 2017
February,2018
October, 2018
Date
Cams Mill
Wicor
Gosport Ferries (The hard)
Fresh water Flow (Q)
A
Temperature
Temprature (ºC)
25
20
15
10
5
0
1
0.8
0.6
0.4
0.2
0
Q (m3/s)
February, 2017
July, 2017
October, 2017
February,2018
October, 2018
Date
B
Cams Mill
Wicor
Gosport Ferries (The hard)
Fresh water Flow (Q)
Salinity
Salinity (Practical Salinity)
40
30
20
10
0
1
0.8
0.6
0.4
0.2
0
Flow Q (m3/s)
February, 2017
July, 2017
October, 2017
February,2018
October, 2018
Axis Title
C
Cams Mill
Wicor
Gosport Ferries (The hard)
Fresh water Flow (Q)

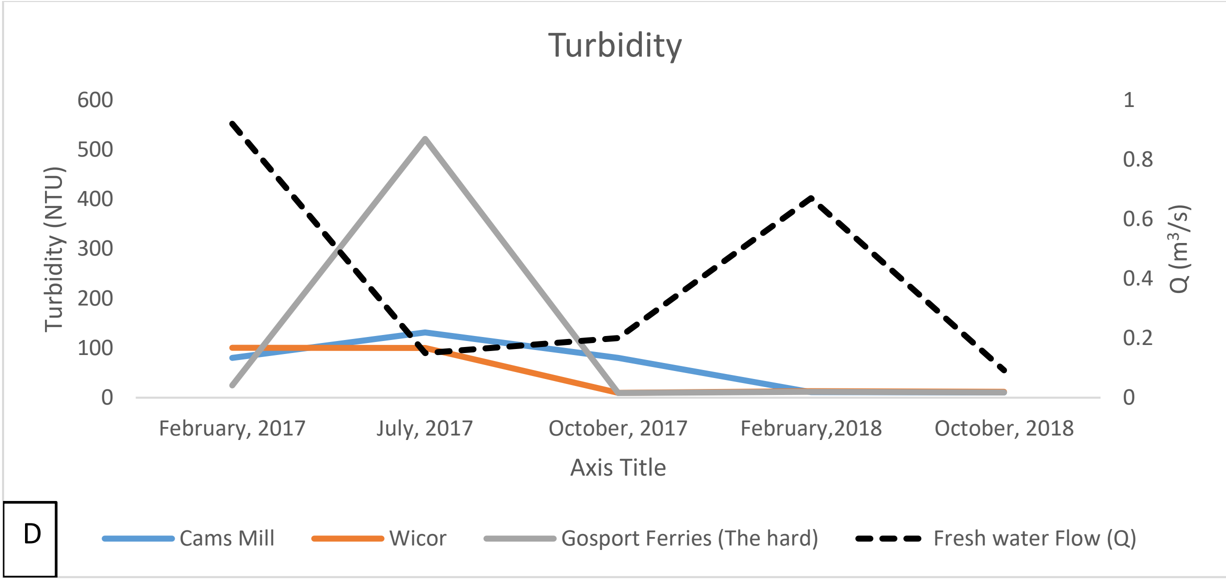
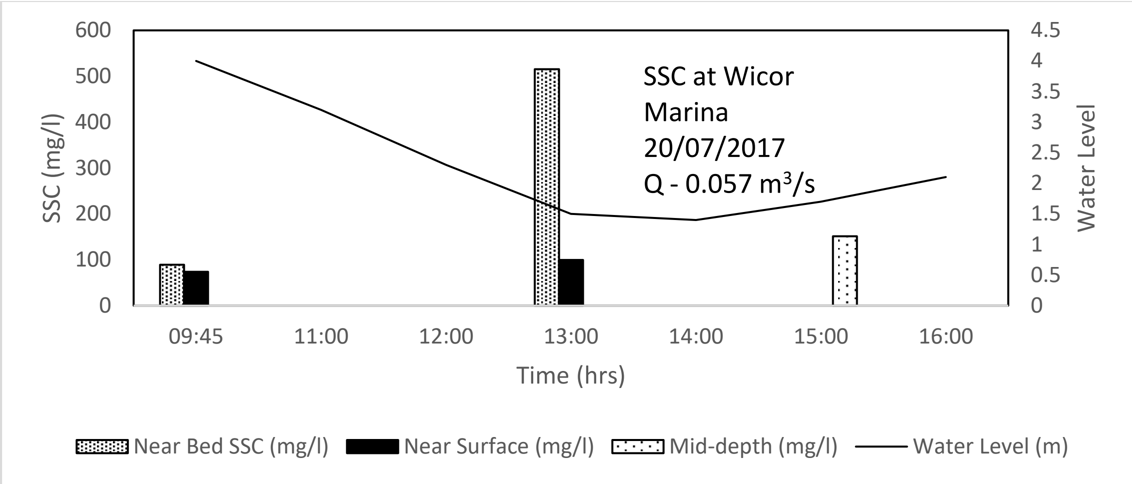


Figure 7: Seasonal variations in distribution of ((a) Dissolved Oxygen (b) Temprature (c) Salinity and (d) Turbidity with fresh water flow (Wallington river) at three different points within the harbour.

3.4. Seasonal Variability of Suspended Sediment Concentration SSC

Suspended sediment concentration (SSC) results presented here are for the three sites (Cams Mill, Sultan Jetty and Wicor Marina) where data were collected between high and low tides. The SSC data within Cams Mill were obtained at different times, because the water level at that end of the estuary was so low that it was impossible to distinguish near bed and near surface measurements. The other two sampling sites (Wicor Marina and Sultan Jetty) follow the same trend (Figure 8) in which the SSC at low water was more than the SSC at high water with the near bed concentration being more than the near-surface concentration.



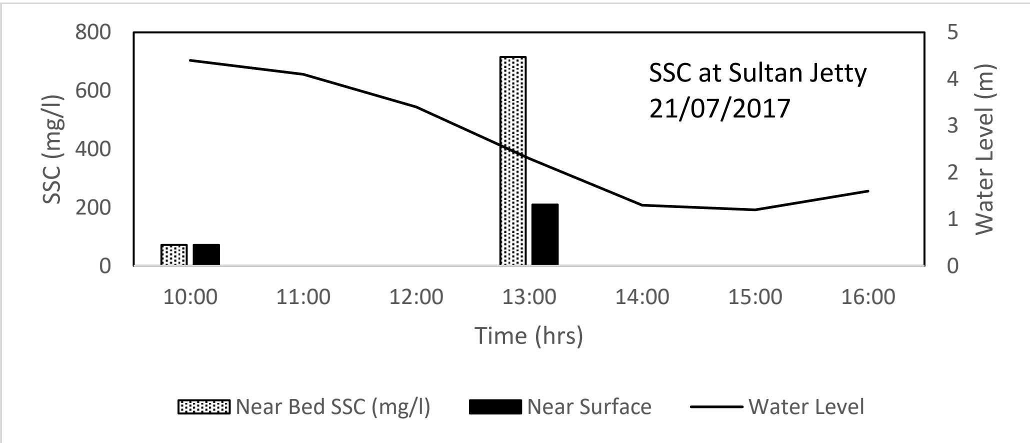
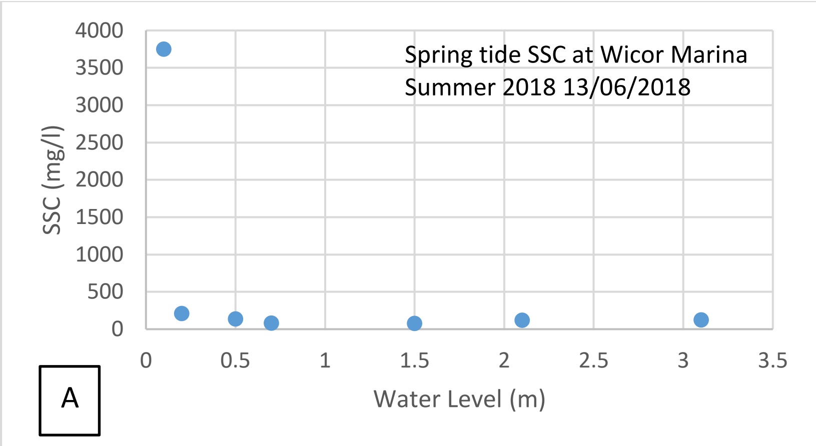


Figure 8: Vertical distribution of SSC at (a) Wicor Marina and (b) Sultan Jetty.

The SSC could also be measured through the turbidity of the water. Higher turbidity is an indication of more suspended particulate matter in the water column while the reverse is the case for low turbidity. The seasonal SSC results for Wicor Marina show that the SSC depends on seasonal changes as well as the variability in tide (either low tide or high tide and either neap tide or spring tide). The SSC at ebb tide for summer spring tide of 2018 showed a maximum concentration of 3750mg/l and the minimum was 75.6mg/l while the maximum for the neap tide was 114mg/l and the minimum was 59.2mg/l as shown in Figures 9 and 10. However, for the winter spring tide of 2019, the maximum was 104mg/l and the minimum was 20mg/l while the maximum for the neap tide was 91.6mg/l and the minimum was 66.8mg/l.



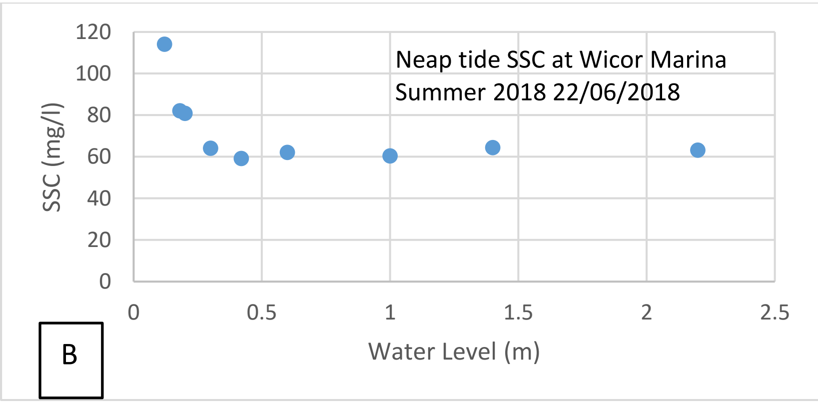
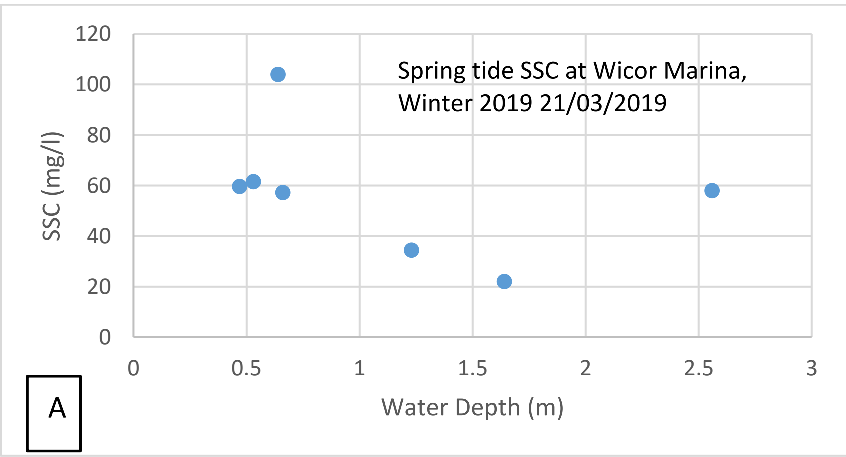


Figure 9: Depth-wise distribution of SSC at Wicor Marina for Summer (a) Spring tide and (b) Neap tide



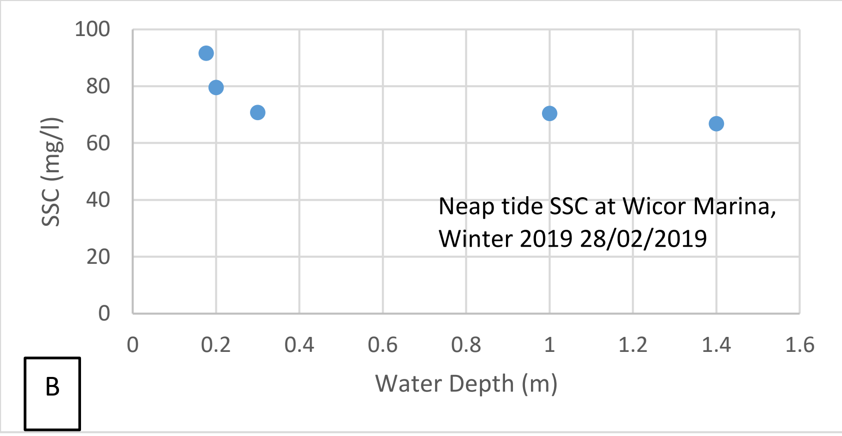


Figure 10: Depth – wise distribution of SSC at Wicor Marina for Winter 2019 (a) Spring Tide, (b) Neap tide.

This evidence shows that there is more SSC at low water in the summer spring tide compared with winter season. Just as with turbidity, this may be because of increased anthropogenic activities in the summer or hydrodynamic forcing due to spring tidal range, and it could be a combination of both factors.

3.5. Flow Velocity within the harbour

The flow velocity readings for the harbour were generally low, which made them difficult to obtain with the use of an electromagnetic current meter. The use of an Acoustic Doppler velocimetry (ADV) was not also feasible due to accessibility and safety of the sampling equipment. The flow velocity results known as tidal stream presented here were obtained from the United Kingdom Hydrographic Office (UKHO) at Gosport Ferry within the harbour over different seasons. The data shown in Figure 11 below were obtained over 24 hours for February 2017, July 2017 and October 2017.

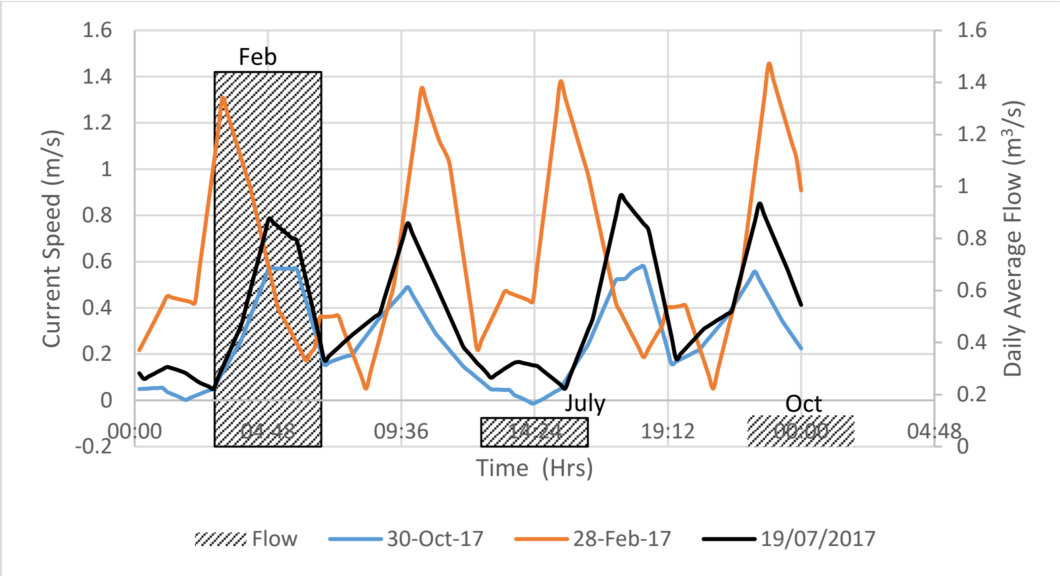


Figure 11: Current velocity readings at the harbour mouth for February, July and October 2017 (UKHO 2017) .

The current speed on the 28th of February was high compared to that in July and October 2017. The currents seen in July 2017 and October 2017 followed the same pattern with October 2017 being the lowest. Even though the fresh water flow data used for this study were obtained at Cams Mill, the current speed can be said to be related to the flow.

4. <u>Discussion</u>

Fresh water input through river runoff is an important parameter in generating gravitational circulation in an estuary (Hughes, Harris, & Hubble, 1998). The freshwater flow was highest during the winter periods at a maximum flow of about 4.5m^3/s due to high rainfall in the winter. The gradual increase in SSC is clearly linked with reduction of freshwater flow (Mitchell, Akesson, & Uncles, 2012). In the winter spring tide period, turbidity tends to increase towards the mouth of the estuary away from the fresh water input. This implies that increasing freshwater flow leads to seaward transport of suspended particulate matter.

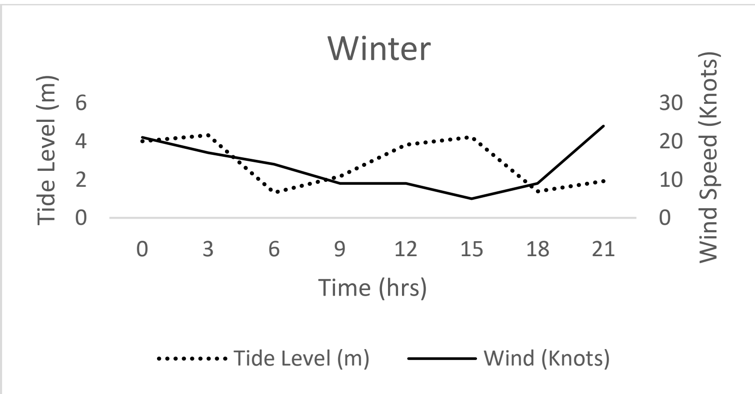
The zone of estuarine turbidity maxima (ETM) was found to be between 6 and 7km from the freshwater input for all seasons observed, this means freshwater flow did not have substantial impact on ETM zone independent of the season whereas higher freshwater flow during winter months is known to lead to a significant migration of the ETM zone (Kitheka, Mavuti, Nthenge, & Obiero, (2016); Mitchell, (2013)) which is not the case with this study. This could be due to the general low fresh water flow for all seasons observed in Portsmouth harbour, unlike in other Macrotidal estuaries (Mitchell et al., 2012).

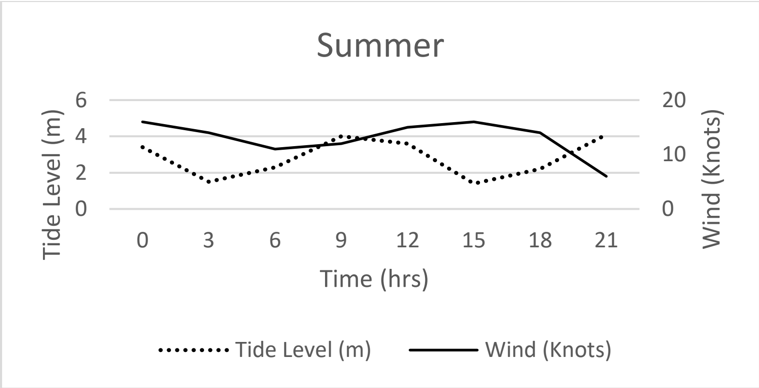
The along-channel variations in salinity and SSC in estuaries occur on time scales of both spring and neap tides. The along channel variation in salinity within Portsmouth Harbour varied slightly over different seasons mainly due to the freshwater flow at Cams Mill, the salinity within estuaries is commonly known to increase along- channel going from fresh water input to the salt water input (Dyer, 1997). The system within Portsmouth Harbour is well mixed and there was no vertical salt water and fresh water layer delineation within the water column. In other words, there was no salinity stratification within the water column due to its shallow depth. The main difference observed was at Cams Mill where the salinity was 0.18 NTU with an average daily fresh water flow of $1.44m^3/s$ in the winter spring tide and increased to 10 NTU with an average daily fresh water flow of $0.1m^3/s$ in the summer neap tide. Apart from the seasonality and tidal cycle, this difference can be attributed to the fresh water flow. The salinity was however the same at other sites for all other seasons. There is more fresh water flow in the winter as compared to summer except during periods of flood events.

The impact of tides on the distribution of salinity within a macrotidal estuary cannot be overlooked. The salinity intrusion within Portsmouth harbour is not just affected by fresh water flow but also by the tidal range and tidal cycle. Increasing tides leads to increasing salinity intrusion within the harbour. Presence of saline water, saline-induced flocculation and lower currents cause suspended sediments to settle with decreasing turbidity (Burgess, Mitchell, & Pope, 2002). This is evidenced by the increased tidal range in the summer spring tide, which led to increased salinity at Cams Mill and vice versa for the winter neap tide. Low fresh water flow with high tidal range increases salinity intrusion within the harbour.

Due to the harbour being an area of special ecological interest, the dissolved oxygen (DO) was assessed as a water quality parameter. Regions of ETM coincide with DO minimum zones (Uncles, Hooper, Stephens, & Harris, 2018). In other complex macrotdial systems it has been shown that biochemical oxygen demand has a strong influence on DO, usually due to recycling of pullted sediment (e.g. Lajaunie-Salla et al, 2017). However, in this study the location of the DO minimum was Wicor Marina. This could be because of the presence of mudflats with ridges and runnels, which supply substantial amount of sediment nutrients into receiving channels. This could also be as a result of the presence of organic matter which decays by either by chemical process or microbial action (aerobic bacteria) which further increases oxygen demand and reduces the dissolved oxygen present. It is common knowledge that DO is a product of photosynthesis, which occur in the presence of sunlight. The DO in the region of the ETM was also substantially low and similar to that at Wicor Marina. The presence of high DO in the summer at Cams Mill where there is freshwater input to the estuary shows that DO is related to fresh water flow. This further shows that DO solubility is affected by salinity and decreases with increasing salinity going from fresh water input to the salt water input within the estuary in the summer.

The observation of SSC and water level shows a relationship between SSC and state of the tides (high and low water). There is evidence of settling occurring at high water slack within the harbour from field observation, which seems to be a general case for macrotidal estuaries (Mitchell et al., 2012). There is an indication of more sediment erosion, resuspension and transport at low tide as compared to high tide which is usually due to wave action (see figure 12) which shows how tide and wind over a 24hr period for winter, summer and autumn). This is known to be the general case with shallow waters (The Open University, 1999). Other studies (e.g. Bowers and Brubaker, 2010) have shown a link between erosion and low-water exposure of sediment on intertidal zones, linked to daily sea breeze phenomena. Evidence from field survey and analysis of field data from two of the three sites within the study area showed that physical disturbance is mostly caused by wave action. The shallower neap water depths over intertidal along with lower currents in the subtidal channel make erosion from waves more likely and deposition less likely during neap events which corresponds to previous study on mesotidal estuaries by Hunt et al., (2017).





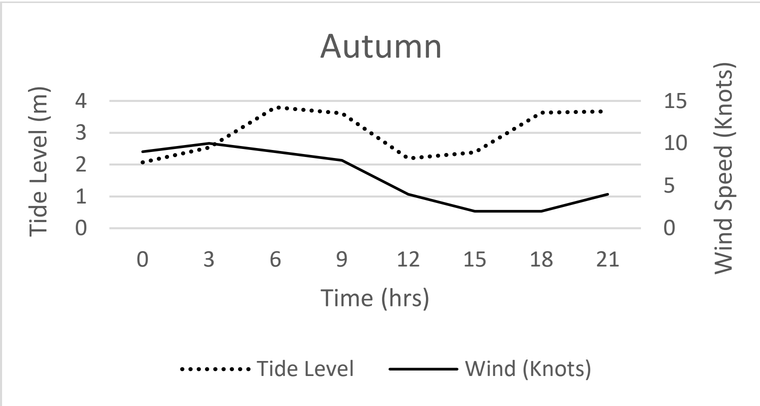


Figure 12: Relationship between wind and tide level for different season (low tide aligns with wind speed especially in the summer)

At high tides for both Sultan Jetty and Wicor marina, SSC were substantially low compared to the low tides fine sediment concentrations. The sediment concentrations from Cams Mill were not used for this analysis because there was no visible change in the water level resulting from low and high tides.

SSC also depends on the tidal range. At Wicor marina for summer 2018, there is higher SSC for the spring tide compared to the neap tide. This is because at spring tides, there is higher tidal range, which leads to faster tidal currents, and there is a longer time of flow. In the winter however, the SSC in the water column were much less for the spring tide compared to summer. This is attributed to higher fresh water flow in the water compared to that of summer. This further gives evidence of the relationship between fresh water flow and SSC.

The resuspension and erosion of sediment at any point within the estuary depends on the availability of sediment. At Cams Mill there was fresh water flushing of sediment which explains the sediment size distribution and the SSC at that point can be said to have mainly been transported and not re-suspended from the bed.

5. Conclusion

Portsmouth Harbour is representative of many industrialised heavily managed macrotidal estuaries and it is important to understand the complex balance of processes within such estuaries. The monitoring of water physio-chemical parameters was collected from 9 sampling sites along the estuary from 2017 to 2019 with SSC monitoring done mainly at Wicor marina and Sultan Jetty with which the findings of this study are presented as follows;

(1) There was no migration of the ETM zone within Portsmouth Harbour due to the general low fresh water flow for all seasons. This means fresh water flow did not have significant impact on ETM zone unlike other macrotidal estuaries.

(2) DO solubility is affected by salinity and decreases with increasing salinity. The area of intertidal flats have very low DO due to the substantial amount of sediment supplied by bed forms such as runnels into receiving waters. This subsequently increases turbidity and reduces the penetration of light at low tide. The increase in the oxygen demand in the area of intertidal flats as a result of the presence aerobic bacteria which are usually bonded to suspended sediment could also be responsible for the low DO.

(3) There is higher 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 fresh water flow. This could also be as result of increased plankton growth in the summer as this increases with increasing light availability.

Based on these findings, there is need for a synchronised management system within these type of estuaries and the effects of pontoon constructions, dredging of marina areas as well as the main channel should be assessed depending on season to reduce their impact on water quality and achieve a sustainable balance within the estuary. It can also be said from the findings that the winter season is favourable than other seasons due to high fresh water flow that leads to increased DO.

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Appendix

Table 4.2: Field sampling dates and location

Sampling Dates	Location	Data Collected
February 27th 2017	Cams Mill, PIP, HMS Bristol and Gosport Ferry	Reconnaissance survey, water physio-chemical data

February 28th 2017	Haslar Marina, Gosport Marina, Sultan Jetty and Wicor	Reconnaissance survey, water physio-chemical data
July 17th 2017	Cams Mill	Tidal cycle survey and water physio-chemical data and water samples
July 18th 2017	Haslar Marina, Gosport Marina, Sultan Jetty, Cams Mill and Wicor	Water physio-chemical data, bed sediment samples and water velocity
July 19th 2017	PIP, Port Solent, HMS Bristol and Gosport Ferry	Water physio-chemical data, bed sediment samples and water velocity
July 20th 2017	Wicor	Tidal cycle survey and water physio-chemical data and water samples
July 21st 2017	Sultan Jetty	Tidal cycle survey and water physio-chemical data and water samples
October 30th 2017	Haslar Marina, Gosport Marina, Sultan Jetty and Cams Mill	Water physio-chemical data, and water velocity
October 31st 2017	PIP, Wicor, Gosport Ferry	Water physio-chemical data, and water velocity
November 10th 2017	HMS Bristol	Water physio-chemical data, and water velocity
February 19th 2018	Haslar Marina, Gosport Marina, Sultan Jetty and Cams Mill	Water physio-chemical data, and water velocity
February 22nd 2018	HMS Bristol and PIP	Water physio-chemical data, and water velocity
February 23rd 2018	Wicor and Gosport Ferry	Water physio-chemical data, and water velocity
May 4th 2018	PIP, Gosport Ferry and Wicor	Water physio-chemical data,
June 13th 2018	Wicor	Water physio-chemical data, water velocity, water samples and runnel observation
June 22nd 2018	Wicor	Water physio-chemical data, water velocity, water samples and runnel observation
February 28th 2019	Wicor	Water physio-chemical data, water samples from runnel and main channel, water velocity,

March 21st 2019	Wicor	Water physio-chemical data, water samples from runnel and main channel, water velocity,