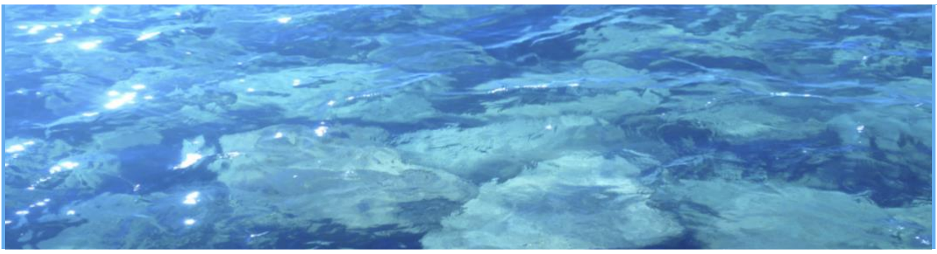
COWES HARBOUR COMMISSIONERS

Sediment Flux Measurement in the Medina Estuary Monitoring Results 2016

Report AmbCHC03a

August 2017



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Contents

Executive Summary

Measurements of fine sediment flux through and around the Medina estuary have been made for the period January 2016-January 2017. The methodology combines water flow measurements from the ABP model of the estuary hydrodynamics and field observations of total suspended solids made at four sites within the estuary. The main objectives were to determine the temporal patterns of fine sediment accumulation and erosion within the estuary (subdivided into seven polygons) and to add precision to annual (bathymetric) measurement of spatial patterns of accumulation and erosion.

Sediment flux results from the outer harbour indicate that some 6,800t of sediment was lost from the area over the year. Results from the upper estuary (above the chain ferry narrows) indicate a further ~2,600t was lost from that zone. These results are very close to measurements made from annual bathymetric surveys, and the two datasets can be readily aligned by making a 1cm adjustment to the bathymetric data in a GIS analysis.

Historically the estuary is known to naturally import mud each year, hence requiring dredging. The principle source of mud to the estuary is from winter erosion of the seabed and coast of the Wight region, providing a clay-rich material from the Oligocene clay beds that outcrop widely in that area. Significant inter-annual variability in this input can be expected and the winter of 2015-2016 showed only a modest influx and that of 2016-17 a very low influx. This situation can partly explain the net loss of sediment from the estuary during 2016. Another cause is the impact of the emplacement of the new breakwater, with modified tidal currents causing erosion as part of the readjustment of the natural system. The bathymetric data and the flux data both show enhanced erosion in zones adjacent to the new breakwater, while at the same time showing steady annual accumulation in 'traditional' sediment sink zones (marina areas and the immediate subtidal inner Shrape area). Thus the unusual net sediment flux condition (erosion) seen in 2016 reflects both a year of reduced regional supply of mud, and local erosive adjustment around the new breakwater structure.

The flux data time-series shows that the seven polygon zones show quite different behaviour through the year.

- Polygon D (inner Shrape area) shows steady accumulation throughout the year. This lack of variability/seasonality suggests the primary source of fine sediment is local (eroding harbour bed areas) and that tidally-driven mechanisms dominate.
- Polygons A & B (outermost areas) show steady erosion through the year, most likely as a result primarily of tidal forces, and in response to the emplacement of the new breakwater.
- Polygons E & C (main fairway and flood current impingement zone) show steady erosion through the year but reversing in August, when intense vessel movement may cause an influx of sediment displaced from adjacent marina areas. Polygon C erosion will result from the effect of the new breakwater; the causes of the erosion in polygon E are unclear/diverse.
- Polygon F (Cowes Yacht Haven) shows strong accumulation during winter (pre April and post September), stable between and with strong erosion during August probably as a result of intense vessel movement. The difference in mud influx rates between the two winter periods is clearly evident (2015-16 > 2016-17).

Particle-size analysis of mud taken from recent deposition zones in the estuary confirms both the paucity of influx of regional (clay-rich) material during 2016 and the abundance of fine-silt rich (locally eroded Holocene deposits) derived from enhanced erosion of the harbour bed.

Sediment Flux Measurement in the Medina Estuary Monitoring Results 2016

1. Introduction

This report is an addendum to the 2016 Medina 'fine sediment circulation' monitoring results published in March 2017 [1]. The latter report should be consulted for full details of the ongoing monitoring programme. This update uses the same data presented in the March report to calculate the flux of sediment, during the year January 2016 – January 2017, through key sectors of the Medina estuary. This work is a new and experimental approach to the monitoring, which is being undertaken with the aim of enhancing the ability for dredging requirements within the estuary to be managed on a more sustainable basis. The calculations reported here have only recently become available (July 2017) due to the need to involve mathematical modelling data [2] which were not available in March.

This report briefly describes the methodology adopted, the constraints on precision imposed by the available datasets, and provides the observed flux patterns and tonnages.

2. Methods

2.1 Approach

Four sources of information have been relied upon in measuring the flux of fine sediment through and around the Medina Estuary.

1. A mathematical model [2] of tidally-driven water flow in the Medina Estuary. This predicts volumes of water flowing through a series of key estuary cross sections (Figure 1), determined at 30 minute intervals over a full spring-neap cycle. Summary diagrams of this flow are given in the Appendix.
2. Water level (tidal stage) data from a single site in outer harbour, determined at 5 minute intervals.
3. Water turbidity data at four sites within the lower Medina Estuary (Figure 1) determined at five minute intervals. These optical measures are calibrated to gravimetric (mg l^{-1}) total suspended solids (TSS) values.
4. Bed level data (bathymetry) measured using a precision multibeam system once per year (in December).

Each of the dynamic variables (1-3 above) is related to tidal hour (measured from low water, addressing variability within the semi-diurnal tidal cycle) and to the range of each individual tidal cycle (high water level minus low water level) addressing variability within the fortnightly spring-neap cycle and seasonal variability in the latter.

Two basic assumptions have been made in relation to the dynamic variables, based upon recent field observations [3]. The first is that there is no significant vertical stratification in the estuary water

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[1] Ambios 2017. Sediment Management in the Medina Estuary: Monitoring Results 2016. Report AmbCHC03. March 2017

[2] Data derived from a rerun of the ABPmer model of water circulation in the Medina Estuary. ABPmer, 2015b. Cowes Local Model Calibration, ABPmer Report No R.2517

[3] Ambios 2016. Sedimentary Processes in the Medina Estuary May 2016 Report AmbCHC02

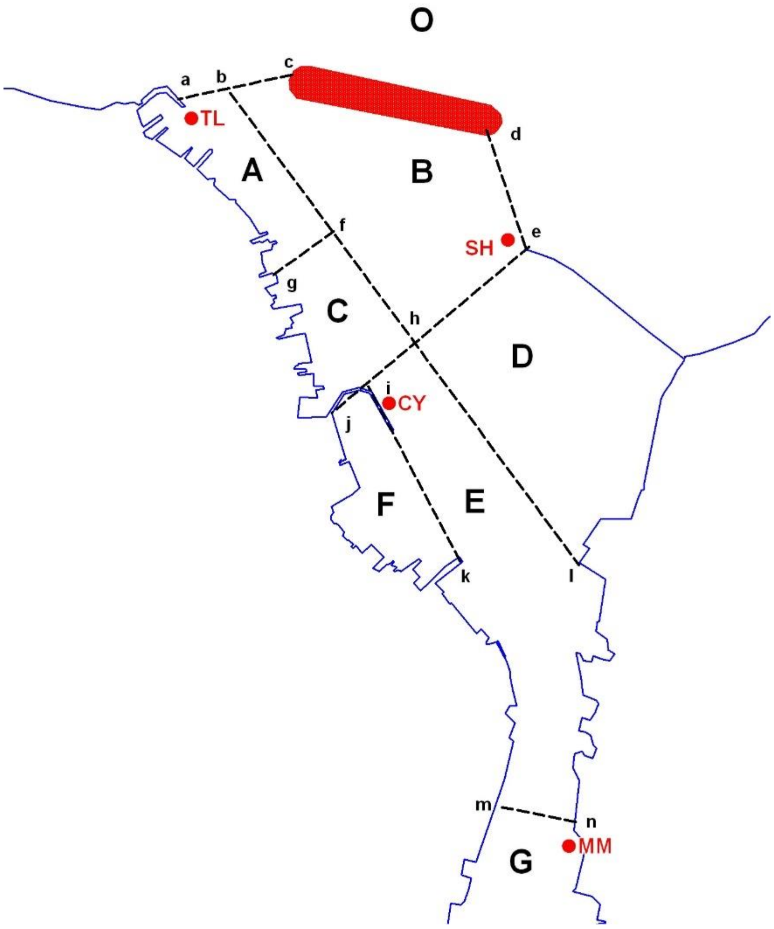

Figure 1. The lower Medina Estuary showing turbidity measuring sites (red dots), key area polygons (labelled A-G) and cross-sections (ab, bc etc) through which water flow was predicted from the ABPmer model.

column, and the second is that river inflow and wind/wave effects play a subsidiary role to tidal effects in driving the WATER circulation. With river flow for example, it is known that maximum inflow, occurring for only short periods, is about 10m^3 s^{-1}, and mean gauged river flow is of the order of 0.5 m^{3}s^{-1}. These are very small values compared to the average discharge[4] value of water through the harbour entrance of ~800m^{3}s^{-1}.

2.2 Modelled Water Flow

The ABP model runs a full spring-neap cycle simulating the two-dimensional water flow in the Medina estuary based on the period 13-29th December 2014 (full spring-neap cycle). The data from this model had been calibrated to recent velocity observations.

Six polygons were specified for the outer harbour (A-F, Figure 1) based on the known general pattern of water circulation the area. In addition the offshore zone (Area O) and the complete estuary above the chain ferry narrows (polygon G) were defined. Creation of these regions defined twelve cross-sections of the estuary (ab, bc, bf, fg etc Figure 1). The model then predicted flow through each of these sections for 30 minute periods through each of the tidal cycles in the 16 day interval. Discharges were identified as positive (flowing to the east or south) or negative (flowing to west or north). The data from each profile were then sorted by tide hour and neap-rising-springs and springs-falling-neap categories , and for each half hour interval and category a 4th order polynomial curve was fitted between tide range (x) and discharge through section (y).

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[4] Taken from the ABP model of a spring-neap cycle, with absolute values averaged.

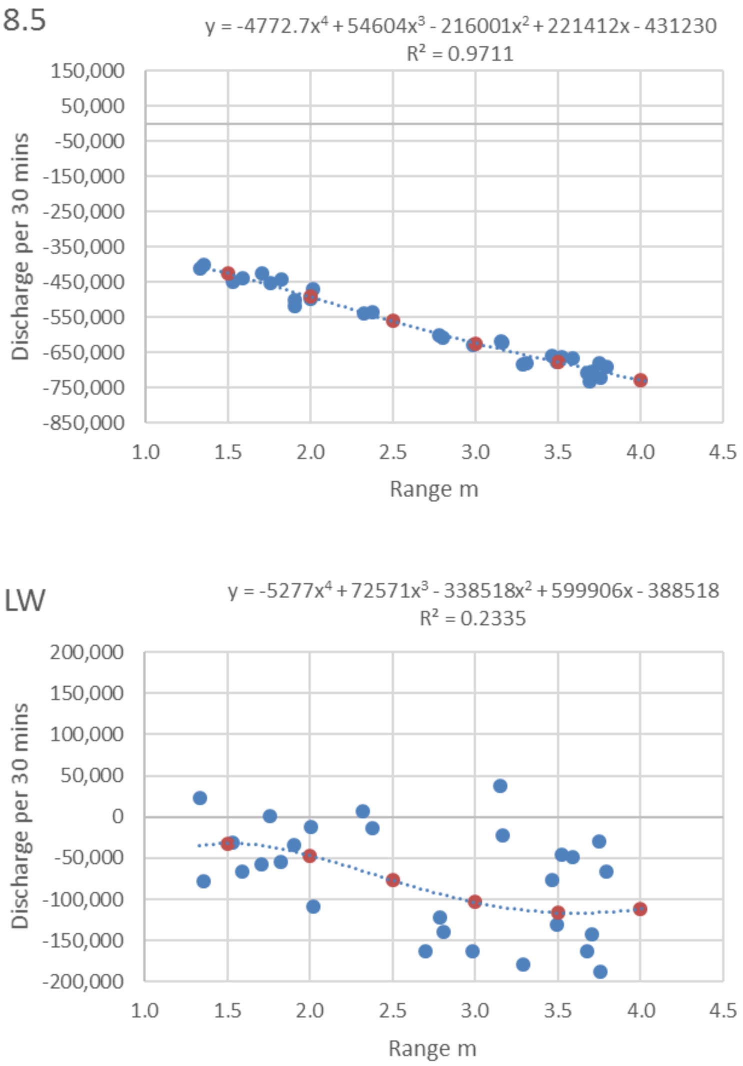

Figure 2. Examples of fitted polynomial curves for individual cross-sections, relating discharge to tidal range (shown for low water LW and 8.5 hours after LW).

Examples of a good fit (R^2>0.9) and worse fit (R^2<0.3) equation are shown in Figure 2. Worst fit simulation tended to occur around the low water period, with slowest flows, therefore poor correlations having minimal impact on precision. An Excel look-up table was created for each profile for the coefficients of the polynomial equation, so that given the range of the tide (subdivided by rising or falling spring-neap limb) and the time after LW, the half-hour discharge through the section could be readily determined.

Minor inaccuracies in these regression procedures and also in the model source data meant that a cumulative error could build in each monthly time series of water volume exchanges. This error has been treated as a near linear effect. To remove it, the water levels at LW on two tides of near-equal range near the beginning and end of each monthly data set were selected, and a (small) correction linearly applied to whole-polygon volumes in order to remove this cumulative error.

As a quality-control procedure it was possible (for polygons A-F) to apply actual tidal levels to the GIS data of the morphology of each polygon thus predicting water volume changes every half hour. The summation of the profile data volume changes for the same polygon should approximately equal this volume. Odd spikes of inaccurate data were identified in this manner, and these data ignored in favour of averages of adjacent good data points.

2.3 Total Suspended Solids (TSS) Data

An Excel workbook was set up containing all the (5 minute) TSS observations from the four sites over the one year period, together with the date, tide hour and tidal range data recorded simultaneously. The data were 'cleaned' data[1], where all spurious records (notably the effects of weed particles in the water) were replaced by 'Data Not Available' notation. For each half hour interval (after LW) an average was calculated from the (up to six) five minute readings available.

Through the year about 20% of the potential number of turbidity readings had been lost for various reasons. To infill these losses, for each month correlations were established between the turbidity concentrations recorded at the four sites. Generally these correlations show a wide degree of scatter, which lowers the precision of the flux measurement during these periods of missing data. It is hoped in future that improved turbidity measuring procedures that have been adopted will keep 'missing data' to a minimum.

In order to derive a 30 minute average TSS value for each profile (ab, bc, bf etc, Figure 1) an assumption has to be made about how the TSS values vary spatially between the four turbidity measuring sites. The (simplest) model of linear variation through space was used. Sensitivity tests were run using other models, which did not seem to make a large difference to the flux results. This is probably because there are only small variations in simultaneously recorded TSS values. If the centroid of a profile was within 50m of a turbidity measuring sight then just the data from that measuring site was used. Otherwise, the TSS concentrations from the 2 or 3 closest measuring sites were combined, weighted according to the inverse distance to the sensors (closest sensor had the greatest influence). This information is given in Table 1.

Profile	Contributing sensor sites	Inverse Distance Weighting			
		SH	TL	CY	MM
ab	TL				
bc	SH TL	130	460		
bf	SH CY TL	580	790	530	
fg	SH CY TL	555	605	610	
de	SH				
eh	SH CY	210		120	
fh	SH CY TL	580	430	610	
hi	CY				
ij	CY				
hl	SH CY MM	830		980	530
ik	CY MM			630	130
mn	MM				

Table 1. Model used for calculation of Total Suspended Solids values for each profile.

See Figure 1 for locations.

2.4 Calculation of Sediment Retention or Loss in Polygons

Having determined for each 30 minute tidal period through the year of 2016 both the water volume crossing each profile (Section 2.2) and the average TSS concentration of that water (Section 2.3) the suspended sediment flux across the section for each 30 minute period was calculated as the product of the two values. The retention or loss of fine sediment from each of the polygons A-G could then be calculated by combining the flux across each of the profile sections forming the polygon, adding the flux if it flowed into the polygon or subtracting it if it flowed out. The annual flux per polygon so predicted is shown in Table 2 (yellow area). The tonnage of sediment for each polygon has also been converted in to an equivalent volume of bed sediment, using a bed dry-density[5] of 0.7 $t\ m^{-3}$ in depositional polygons and 0.9 $t\ m^{-3}$ in erosional polygons. Data so generated allows the sediment flux results to be compared with the annual bathymetric results.

2.5 Bed Level Changes

The results of the bathymetric surveys conducted in December 2015 and December 2016 have been described elsewhere [1]. The volume of sediment that had eroded or accreted on the Medina bed between the two surveys was determined by subtracting the data-averaged values on a $1m^2$ grid from both surveys. The total area of the outer harbour surveyed (below the chain ferry, inside the breakwater) is ~$395{,}000m^2$, and above the chain ferry ~$481{,}000m^2$, the total being $876{,}000m^2$. The precision of multibeam surveys, at best, is about ±5cm. A one centimetre slice of the surveyed area therefore contains $8{,}760m^3$ of mud, or about 7,880t of (dry) sediment at a typical bed density. Estimation of total volume changes on the estuary bed over one year are therefore imprecise unless some form of calibration can be applied to finely tune the data.

On the basis of the argument that the hard, scoured seabed area in the vicinity of the chain ferry narrows is likely to be the most stable area of seabed in the estuary, the volume change was initially calibrated [1] so that the change recorded within a chain-ferry-narrows polygon was zero. This required modifying the datum of the dataset by 5cm.

In addition to monitoring bed level change, samples were taken of bed sediment at eleven sites of known sediment accretion through 2016. A small van Veen grab was used to collect the samples in June 2017, and particle-size analysis conducted using wet sieve, dry sieve and sedimentation (pipette) methods.

2.6 Reconciling Flux and Bathymetric Data

The Flux and Bathymetry methods of looking at how mud circulates in the Medina estuary have their individual strengths and weaknesses.

- Bathymetry data show clearly WHERE sediment is accumulating but cannot say when (beyond the annual period) and lacks fine precision in determining absolute volumes
- Flux data show WHEN sediment is accumulation but not where in detail (beyond between the polygons used)
- Importantly, for the whole harbour area (where both methods have 100% coverage), the use of two methods provides a check potential and also the possibility of calibration to enable an optimum quantitative estimate of total sediment budget.

On this basis, it is sensible to compare [6] the flux and bathymetry data and potentially:

1. Fine-tune the bathymetric data sediment volume changes for the whole outer harbour to the absolute value determined from the flux data and
2. Calibrate the cumulative flux data by individual polygon to the annual sediment erosion/deposition volumes derived from whole-harbour-calibrated bathymetric data.

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[5] From field data acquired during the 2015 survey. Definition of erosional or depositional condition was applied on the basis of net monthly change.

[6] Note an allowance has to be made between to total area of the flux polygons (Figure 1) and the total bathymetric surveyed area, which is significantly smaller.

Following 1), the total flux calculation for the outer harbour (Polygons A to F) is that 1,850m^3 of bed sediment was lost from the zone[7] over the year. Adjusting the bathymetry datum by one centimetre yields an equivalent volume loss from annual bed level change calculations (Table 2). Furthermore the volumes for the upper estuary agree closely once this one-centimetre mean level adjustment that has been applied (-2,324m^3 from bathymetry data and -2,907m^3 from flux data, although the latter relates to a larger area). The difference of 1cm from the previously determined mean multibeam survey level cannot be disputed on the basis of any bathymetric argument, and this fine-tune calibration has therefore been adopted (a 4cm rather than 5cm correction applied to the raw data, see section 2.5). On this basis the (very slightly updated) bathymetry-based estimate of total bed sediment volume change over the year has been adjusted to equal the (unmodified) flux-based estimate of bed sediment level change over the same period.

Following 2) (which is only possible in the outer harbour), with the exception of Area D, the spatial detail of the annual net mud budget shown by bathymetric analysis does not tally well with that shown by flux analysis. The latter appears to exaggerate deposition (by up to fourfold) in polygon E (main fairway) and erosion (or underestimates deposition) by the same amount in the other areas (erosion in polygons A, B & C and deposition in F, Table 2). Logically, the bathymetric data are more reliable, and have been relied upon for the figure of annual change, the individual polygon flux data being calibrated accordingly. The apparent inaccuracy in the local one year (cumulative) detail of the flux measurement will relate to :

1. Inaccuracies in the water circulation model
2. Incorrect assumption of linearity in TSS values between sensor sites
3. Poor correlations used to infill missing TSS data gaps
4. Insufficient sensor sites to capture important local TSS gradients.

The assumption has been made that these errors will be constant with time, and that the shape of the fine-sediment flux time-series curve for each polygon is valid although the quantities are subject to a steady cumulative error. For convenience (allowing comparison between polygons) the cumulative total of the fine sediment flux time series for each polygon has been adjusted to the bathymetric annual figure for that polygon (Table 2). This adjustment recognises the fact that the model in its current form is not representing with precision the true quantity of sediment moved between polygons, and in order to recognise that situation, adjustments have only been allowed between adjacent polygons.

Apart from improving missing data problems, little can be done to immediately address this error. As more years of flux data are accumulated, it should become more obvious which of the four potential sources of error are most serious, and improvements implemented.

Polygon G has to be omitted from this calibration process, as the bathymetric survey only covers a proportion of the whole upper estuary (to which the flux data relate). So no adjustment has been made to the flux measurement for Polygon G. Instead, an estimate of bed level change in the unsurveyed part of the upper estuary has been derived by comparing the flux tonnage for the whole upper estuary with the bathymetric tonnage for just the surveyed part of the estuary. The dredging undertaken at East Cowes Marina during the year was accommodated in this calculation, the changes quotes relating only to natural processes. The full calculations are shown in Table 2.

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[7] Shown in Table 2. Dry sediment flux tonnes are converted to volume using appropriate bed dry density values for accumulating and eroding areas, and summed to give the final volume.

POLYGONS (see Figure 1)

	A	B	C	D	E	F	All Outer Harbour (sum A-F)	G surveyed	G unsurveyed	Notes
Bathymetry Survey area m^2	31,120	97,157	32,087	104,156	106,893	24,224	395,637	480,624		*Area covered by multibeam*
Flux Polygon Total Areas m^2	33,837	97,264	35,440	113,929	112,391	31,989	424,850	480,624	990,604	*Area at HW*
Area Ratio between above two values	*x1.09*	*x1.00*	*x1.10*	*x1.09*	*x1.05*	*x1.32*				*Total area divided by surveyed area*
Bathymetry (4 cm corrected) level change m^3	-957	-2,971	-943	3,112	-3,434	2,587	-2,606	-2,324		*From GIS*
Area Ratio corrected volume	*-1,043*	*-2,971*	*-1,037*	*3,392*	*-3,606*	*3,415*	-1,850	-		*Correction for surveyed/unsurveyed ratio*
Flux m^3 bed volume equivalence	-4,509	-19,037	-3,506	3,271	20,865	1,066	-1,850	-2,907		*Applies bed dry density values to data in line below.*
Flux tonnes	-4,058	-17,134	-3,155	2,289	14,605	747	-6,705	-2,617		*Unadjusted data from flux calculations*
Ratio to bathy volume	x0.2	x0.2	x0.3	x1	x-0.2	x3.2	x1			*Ratio of bathy to flux volumes*
Volume correction applied m^3	3,465	16,066	2,468	121	-24,471	2,348	-1			*Volume adjustment if above ratio applied*
Adjustment to adjacent polygons	*From B*	*From E*	*From E*	*From E*	*To ABCD&F*	*From E*	-			
Bed volume change above chain ferry narrows								-2,324	-583	*Bathy=flux volume via estimate for unsurveyed area*
Annual bed level change cm	-3.08	-3.05	-2.93	2.98	-3.21	10.68		-0.32	-0.04	*Annual bed level change (not including dredging)*

Table 2. The reconciliation of flux model and bathymetric survey data.

3. Results

3.1 Whole Year Summary

The estuary as a whole[8] naturally lost approximately 9,000 dry tonnes of sediment during 2016, and in addition was dredged[9] of a further 20,500 m^3 of spoil. The outer harbour naturally lost ~6,800 dry t and the upper estuary (whole area above the chain ferry narrows) lost ~2,600 dry t (Table 2).

The loss from the outer harbour is very unusual, as historically (past 20-30 years) the whole estuary has naturally imported 10-20,000 wet tonnes of mud (counteracted by dredging). Inspection of individual polygon data from the outer harbour (Table 2) shows that the two historically recognised depositional zones (polygons D and F) both accumulated some 3,400 m^3 of mud, which is normal, but that this was offset by erosion of about 8,700m^3 of sediment from other areas. It is the latter (erosion) process that is responsible for the unusual annual sediment budget. Some 5,000m^3 of this erosion was found in polygons A, B & C and is therefore likely to be attributable to the modification of tidal flow caused by the emplacement of the new breakwater in 2014-5. About 3,700m^3 of erosion was found in zone E however, more remote from the known zone of accelerated tidal currents caused by the breakwater's construction, and therefore less clearly related to that recent change in the harbour morphology.

In the upper estuary, above the chain ferry narrows, flux measurements (for the whole upper estuary) showed a net loss of about 3000m^3 of fine sediment. The calibrated bathymetry data, just for the subtidal estuary north of Folly Inn, showed a loss of 2,300m^3 (after dredging has been allowed for), accounting for the bulk of the erosion in this region. This indicates that the intertidal and southernmost subtidal estuary zones lost only about 700m^3 in total. These volumes relate to <3mm lowering in the mean bed level of the upper estuary through the year.

3.2 Seasonal Variability

Examination of the calibrated sediment flux data allows time series plots to be produced for each polygon (Figure 3) and observations to be made about tidal, storm and seasonal effects in the mud transport regime. These observations are summarised as follows.

Polygon A. Western outer harbour (includes Trinity Landing and RYS)

- Steady slow bed erosion through the first half of the year, becoming stable with slight erosion in the second half. Annual mean 3cm lowering of bed levels.
- Highest erosion seen on the rising limb of spring tide periods, and only over springs later in the year.
- Storms tend to slow erosion, causing deposition at times.
- Highest erosion in August.

Polygon B. Central region of the outer harbour.

- Steady bed erosion throughout the year. Annual mean 3cm lowering of bed levels.
- Highest erosion seen on the rising limb of spring tide periods. Storms tend to slow erosion, causing deposition at times.
- Highest erosion in April and August.

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[8] Excluding the harbour approaches, seawards of the breakwater. A further ~3000t accumulated in this zone through 2016.

[9] East Cowes Marina, approximately 30,000t.

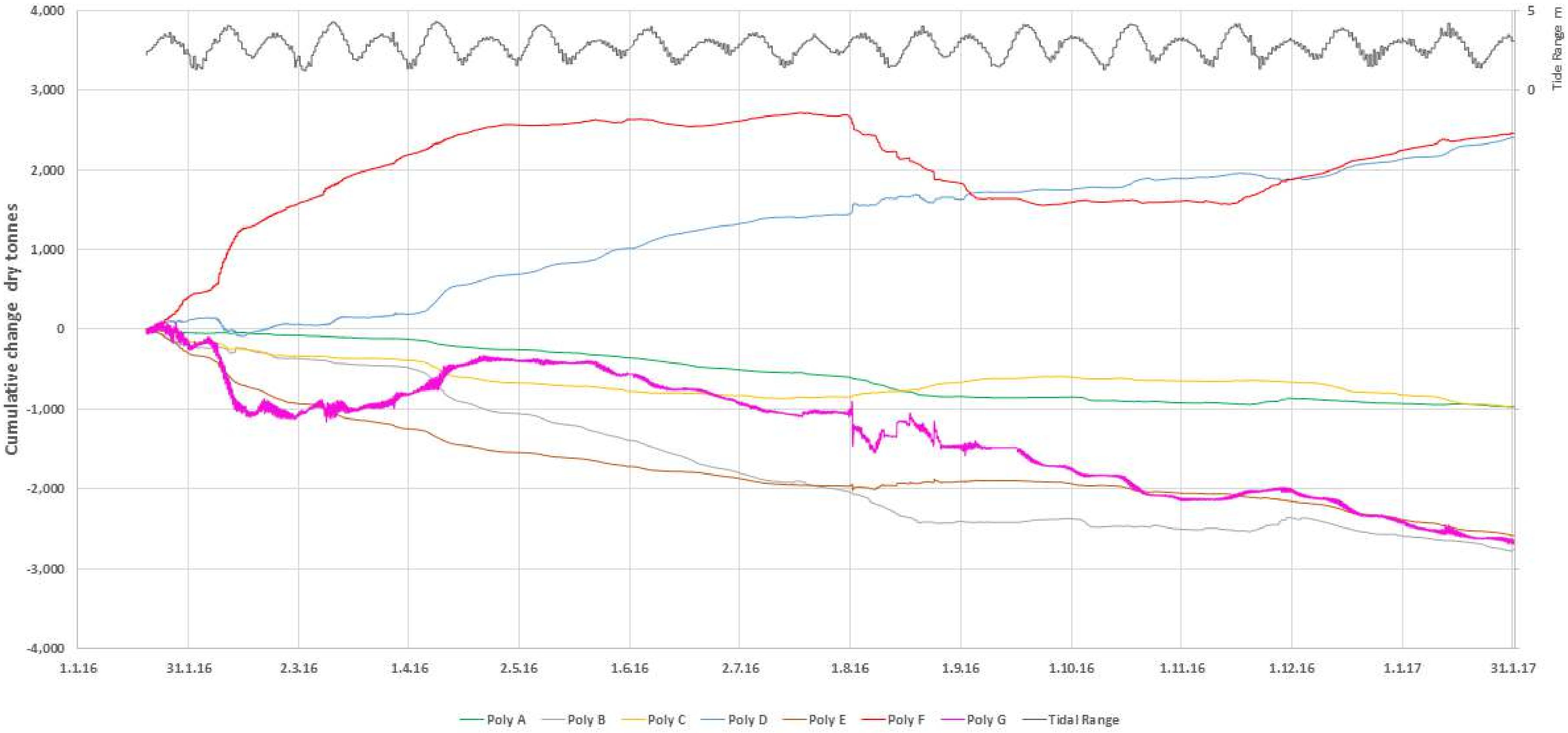

Figure 3. Time series showing accumulation/erosion history of individual polygons through 2016.

Polygon C. Vicinity of Red Jet Ferry Terminal (flood tide current impingement zone).

- Net erosion through the year, but with stable and accreting periods. Annual mean 3cm lowering of bed levels, but severe scour in the vicinity of the Red Jet turning zone.
- Most change (erosion or deposition) occurs over spring tide periods.
- Storms can cause both erosion and deposition.
- Most deposition seen during August

Polygon D. Inside Shrape Breakwater

- Steady accretion through the year. Annual mean 3cm shallowing of bed levels.
- Most accumulation throughout periods of spring tides.
- Storms tend to slow or stop deposition, but some conditions enhance deposition.

Polygon E. Main Fairway in centre of outer harbour.

- Net erosion through the year. Annual mean 3.2cm lowering of bed levels.
- Erosion strongest November-April, with slight accumulation in August and stable levels during September.
- Greatest changes seen during spring tides and during storms

Polygon F. Cowes Yacht Haven

- Strong deposition until May, then stabilising, strong erosion through August then stabilising, deposition builds again from November. Annual mean 10.7cm shallowing of bed levels.
- Highest deposition rates over spring tide periods.
- Storms seem to enhance deposition.

Polygon G (whole estuary above the chain ferry narrows)

- Strong erosion in February followed by deposition in March and early April. Subsequently slow erosion through the year. Annual mean >0.32cm lowering of bed levels.
- Deposition occurs over neap periods, erosion over spring periods.
- Storms can have variable impact on erosion/deposition in the winter, tend to have little effect or enhance deposition in the summer.

These observations reinforce the conclusions drawn in the March 2017 monitoring report, namely:

1. Sediment is primarily supplied to the estuary during the winter months from a regional (Solent-wide and adjacent offshore region) storm-produced fine sediment body. There is the potential for strong inter-annual variability in this source, and the winter of 2015-16 saw a modest mud influx and that of 2016-17 an even lower influx.
2. Sediment is mostly resuspended and redistributed within the estuary over spring tide periods.
3. Local storms play only a modest role in this process of mud redistribution.
4. In 2016 the upper estuary saw a very slow loss of mud, with deposition enhanced during neaps and erosion during springs. Most deposition occurred during the period of (regional) storm effects (February).
5. Vessel movement can play a role in redistributing mud. The bed erosion that occurred in August, particularly within the Cowes Yacht Haven (polygon F, Figure 3) can only be readily explained as a function of the high level of berthing activity during that month. No similar erosion occurred within polygon D, the other primary deposition zone, inside the Shrape

breakwater, where there are only a small number of moorings. Mud displaced from polygon F as a result of this activity can be seen temporarily accumulating in the adjacent polygons C and E (Figure 3).

(red=accretion, green=erosion)

Site polygon	Description	Area m2	1992-15 m^3 yr^{-1}	2015-16 m^3	Continuity 92-15 times	Level change 2015-16 cm	Volume by zone m^3	
17.1	Coast slope north of breakwater	70,772	729	2,016	3	2.8		
17.3	Coast slope eastern sector	25,891		-41		-0.2		
19b	East Harbour Entrance	40,949	-297	-862	3	-2.1		
12	Shrape Breakwater zone	12,492	-945	1,081	-1	8.7		
20.1	Solent shore: West Shrape	59,892	-403	-38	0	-0.1		
20.2	Solent shore: Mid Shrape	83,360		441		0.5		
20.3	Solent shore: East Shrape	40,663		1,059		2.6		
21.1	Main Fairway entrance	5,032	-106	-15	0	-0.3		**Harbour Approaches**
21.2	West of entrance Solent shore	6,910		-146		-2.1	3,495	(outside new breakwater)
14.1	West side of Fairway entrance	18,126	-653	-908	1	-5.0		
14.2	Trinity Landing & RYS	12,712	-440	-1	0	0.0		
15	West thalweg, inner entrance	7,784	-348	-537	2	-6.9	-1,446	Polygon A
17.2	Eastern fairway sideslope	5,338	-204	-158	1	-3.0		
18a	Outer harbour mid-zone	41,299	54	-1,054	-20	-2.6		
16	East thalweg, inner entrance	7,616	-238	-51	0	-0.7		
8.1a	Fairway off West Cowes	20,792	-145	-494	3	-2.4		
19a	East Harbour Entrance	17,611	-1	-874	>100	-5.0	-2,631	Polygon B
14.3	West Cowes shore private area	8,244	-75	-81	1	-1.0		
8.1b	Fairway off West Cowes	14,330	-504	-625	1	-4.4		
8.2	Shore off Fountain Quay	7,876	-194	-11	0	-0.1		
8.3	Red Jet inner	2,116	186	51	0	2.4		
8.4	Red Jet outer	1,920	-76	-275	4	-14.3	-941	Polygon C
18b	Outer harbour mid-zone	16,709	-147	-492	3	-2.9		
9.1	Venture Quay and east Small Boat Channel	27,461	304	-616	-2	-2.2		
9.2	West margin off Shrape Flats	17,300	1,050	1,680	2	9.7		
10.1	Outer Shrape Flats	11,993	71	597	8	5.0		
11	Inner Shrape Flats	34,196	-16	1,361	-88	4.0	2,530	Polygon D
8.1c	Fairway off West Cowes	35,126	-1,237	-1,977	2	-5.6		
5.1	Shepard's Wharf	8,228	-590	892	-2	10.8		
5.2	Fairway off Shepard's Wharf	4,358	16	-30	-2	-0.7		**Outer Harbour**
5.3	Fairway south of Shepard's Wharf	8,068	15	-325	-21	-4.0		(inside new breakwater)
6	Fairway off Car Ferry Terminal	11,261	-86	-749	9	-6.7		
7	Car Ferry Terminal	4,928	-47	-290	6	-5.9		
10.2	Embayment off Maritime Museum	2,576	-38	50	-1	1.9		
4	Fairway north of Chain Ferry	4,958	-5	-226	41	-4.6		
2a	North of Chain Ferry west bank	8,430	-90	-253	3	-3.0		
3a	North of Chain Ferry east bank	9,700	-107	-330	3	-3.4	-3,238	Polygon E
13.1	CYH north	8,204	-90	439		5.4		
13.2	CYH south	13,764	-165	2,008		14.6		
13.3	Corinthian YC	4,320	24	256		5.9	2,703	Polygon F
1	South of Chain Ferry channel centre	17,639	-31	-601		-3.4		
2b	South of Chain Ferry west bank	18,536	174	-224	-2	-1.2		
3b	South of Chain Ferry east bank	9,874	-1,398	-46	1	-0.5		
30.1	West bank south of UKSA	17,408	324	553	2	3.2		
30.2	Channel off East Cowes Marina Village	61,493	-284	-754	0	-1.2		
30.3	East Cowes Marina Village	35,736	-1,398	-14,607	8	-40.9		*20,500m^3 Dredged*
30.4	Medina Wharf	10,596	-144	-285	1	-2.7		
31	Estuary off Kingston Wharf	70,069	-668	-2,364	2	-3.4	-22,788	**Upper estuary (above chain ferry)**
32	Upper estuary to Folly Inn	230,627		-4,460		-1.9	**-2,288**	***(allowing for dredged volume)***
	TOTALS	**1,215,341**	**-8,219**	**-22,316**				
	ALLOWING FOR DREDGING IN 2016			**-1,816**				

Table 3. Bed level changes between December 2015 and December 2016, by estuary zone (see Figure 4 for zone location), for bathymetric survey areas only. Changes are compared to the history of change 1992-2015.

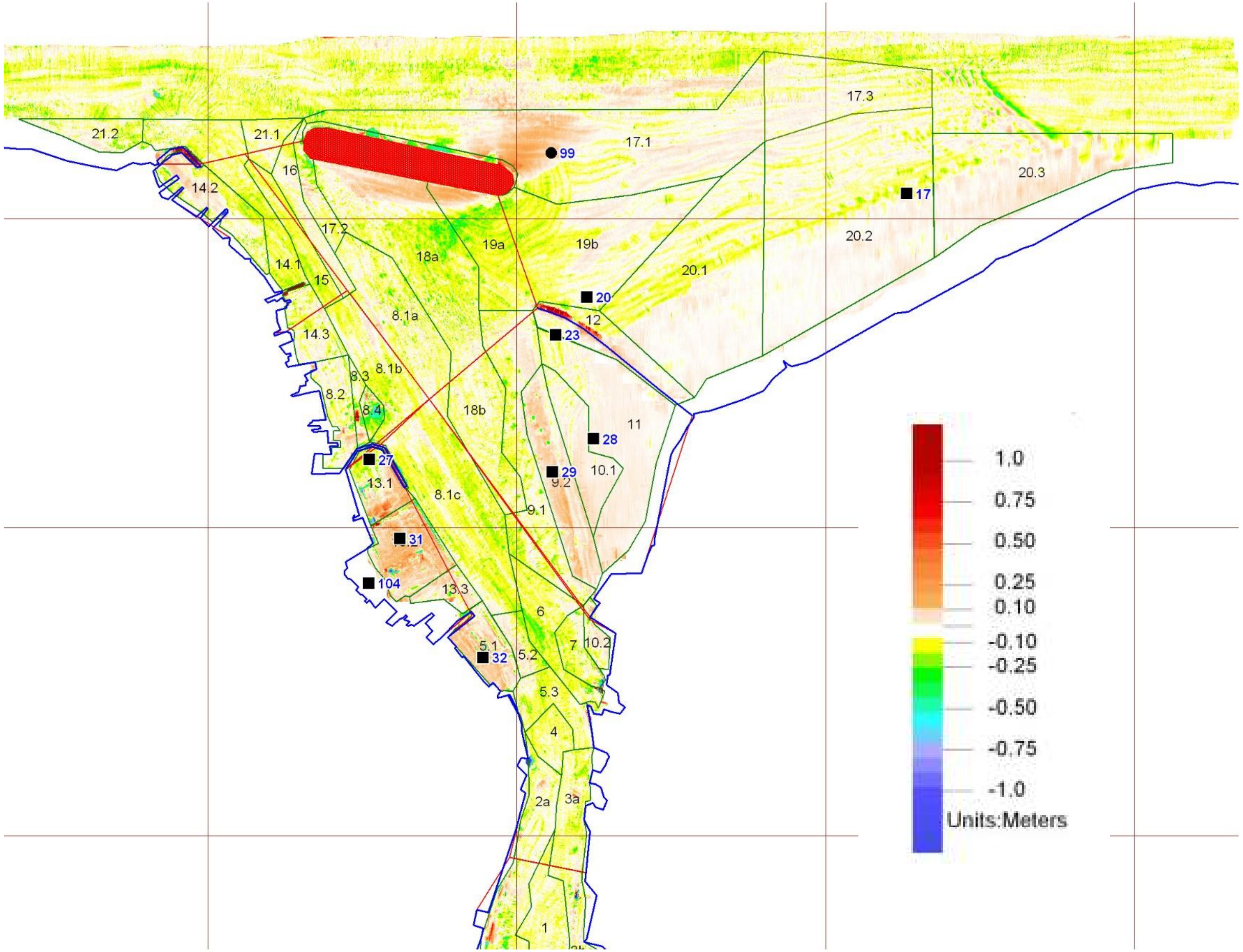

Figure 4. Chart showing change in bed levels from December 2015 to December 2016. Blue numbers are 2017 grab sites.

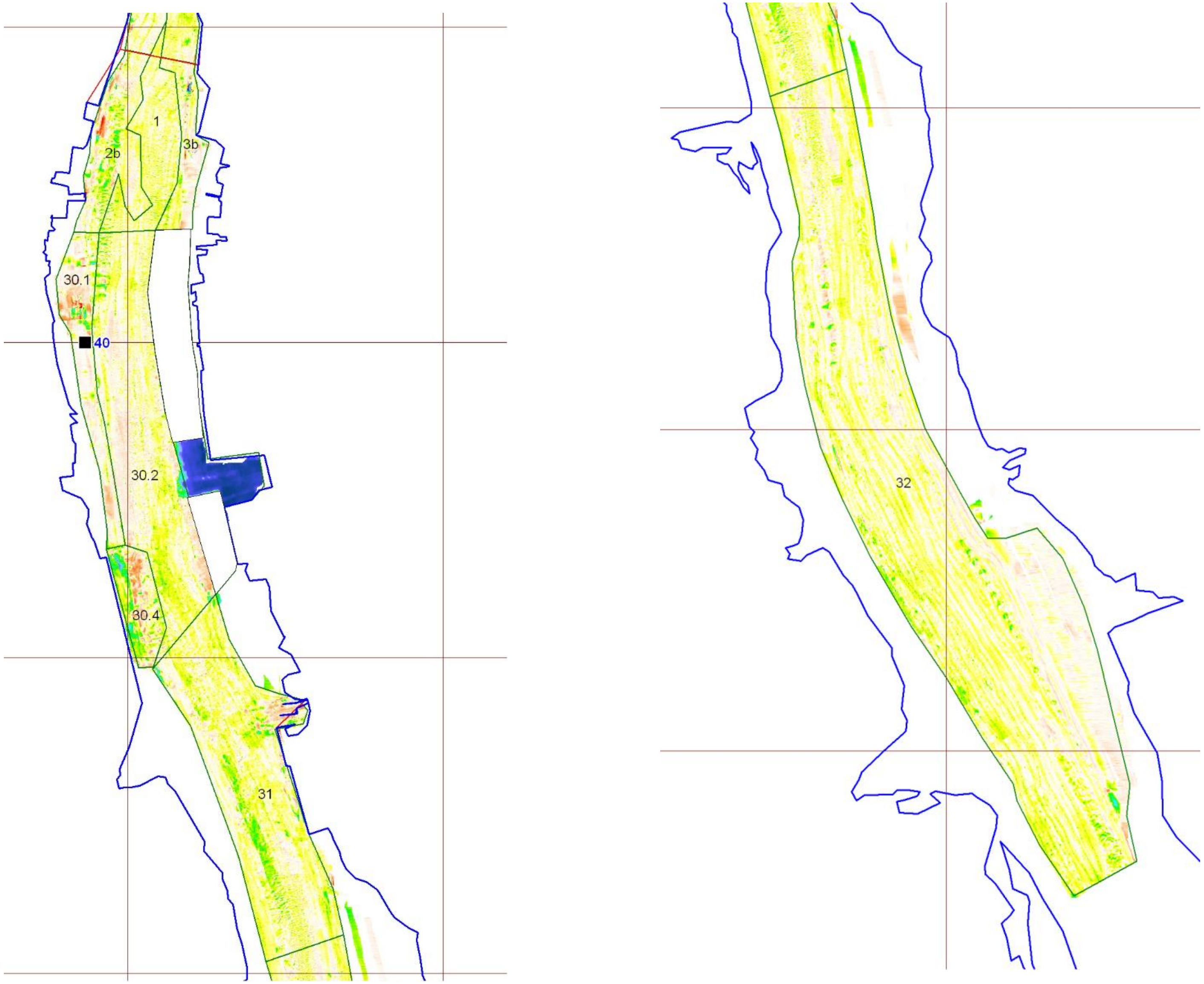

Figure 4 continued…

3.3 Local Spatial Variability

The bathymetry-change data for the year, calibrated to the flux data, show very clearly exactly where erosion and deposition are occurring. This can be seen in tabular form in Table 3, where individual small zones [10] (of similar history of bed change [1, 3]) are identified and for each the bed level changes 1992-2015 (reduced to an annual mean) and the 2015-16 changes are listed. The same 2016 data are plotted in the three charts of Figure 4.

The key 2016 accumulation areas (by bed level change) are:

• Cowes Yacht Haven south (13.2)	0.15m	2008m^3
• East Cowes Marina south of dredge (part 30.3)	0.12m	691m^3
• Shepard's Wharf (5.1)	0.11m	892m^3
• West Margin off Shrape Flats (9.2)	0.10m	1680m^3
• Shrape Breakwater Zone (with sand?) (12)	0.09	1081m^3
• Cowes Yacht Haven north (13.1)	0.06m	439m^3
• Outer Shrape flats (10.1)	0.05m	79m^3
• *Inner Shrape Flats (11)*	*0.04m*	*1361m^3*
• East Cowes Marina north of dredge (part 30.3)	0.04m	813 m^3

The key erosion areas (ordered by bed level change, ignoring the dredging) are:

• Red Jet outer (8.4)	-0.13	-275m^3
• West thalweg, inner entrance (15)	-0.07	-537m^3
• *Fairway off car ferry terminal (6)*	*-0.07*	*-749m^3*
• Car ferry terminal (7)	-0.06	-290m^3
• Fairway off West Cowes (8.1c)	-0.06	-1,977m^3
• West side of fairway entrance (14.1)	-0.05	-908m^3
• *East harbour entrance (19a)*	*-0.05*	*-874m^3*

The sites in italics in the above lists show a marked 2015-16 change to the historical pattern/rate of change (Table 3). The most notable 2016 changes to the historical rates are as follows (most, except b) relate to increased erosion):

a)	*East harbour entrance (19a). Erosion accelerated*	*x >100 fold*
b)	*Inner Shrape flats (11). Stability now deposition*	*x >50fold*
c)	*Fairway north of chain ferry (4). Erosion accelerated*	*x 41 fold*
d)	*Fairway south of Shephard's Wharf (5.3) Stability now erosion*	*x 21 fold*
e)	*Outer harbour mid-zone (18a). Stability now erosion*	*x 20 fold*
f)	*Fairway off car ferry terminal (6) Erosion accelerated*	*x 9 fold*

Items a), b) & e) in the above list are likely to be responses to the emplacement of the new breakwater. It can be seen (Figure 4) that there are significant zones of both erosion and deposition associated with the eastern end of the breakwater, as the local sedimentary system adjusts to the changed bed morphology and current patterns. Items c), d) & e) all contribute to the strong recent erosion seen in polygon E (see Sections 3.1 and 3.2). These recent changes may be related to 1) a continuing scour caused by car ferry operations, 2) recent dispersion of mud deposits ploughed out

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[10] Note some of these have been split (a, b, c) to conform better to the new flux polygons. Even with these changes, the zones and the flux polygons are not exactly contiguous, explaining some discrepancies between values.

of Shephard’s Wharf into the fairway in past years and c) some change related to the new breakwater construction.

The role of the ferries (Red Jet and car ferry) as local agents of bed scour, remain clear from their site prominence in the erosion listing above, as identified in previous reports.

3.4 Bed Sediment Character in Deposition Sites

Particle-size analysis has been undertaken on grab samples collected from eleven previously sampled sites close to key deposition zones in 2016 (identified in Figure 4). Results are plotted in Figure 5 and Table 4.

At sites 17, 20 and 27 the sea bed had a dense cover of seagrass. The sites outside the breakwater (17 and 23) contained 70-90% fine sand and a few percent gravel, the remainder being mud. The site just inside the breakwater was much muddier, with a clay-poor characteristic (PSA Group A[3]). The particle-size characteristics at these sites had changed little since 2015, indicating that any modest deposition that had occurred at these sites related to similar processes/sources as previously.

Site 99 is in an area of strong local deposition likely to be related to the emplacement of the new breakwater. A sample was not taken at this site in 2015, but comparison with the closest 2015 site showed that in 2017 the particle-size characteristics were near identical (muddy fine sand). Thus although deposition has increased, processes and sources determining the deposit appear unchanged.

Site 27 was a site of slight erosion, although within the ‘depositional zone’ Cowes Yacht Haven Marina. Although mostly (52%) composed of soft anaerobic mud, the sample also contained about 10% gravel. This material was also noted in the 2015 sample from this site, though less marked. This gravel did not have a ‘fresh’ appearance (Figure 6), suggesting that the gravel was not recently accumulated. The mud, as previously (though less markedly so), was clay-poor, dominated by fine silt (8 phi), indicative of local Holocene estuarine deposits being the prime source (PSA Group A[3]), although the deposit does not necessarily reflect 2016 conditions as it is a site of erosion.

Sample 28 was from the intertidal flats inside the Shrape breakwater, where increased deposition has taken place during 2016. The 2017 sample showed near-identical particle-size characteristics to that measured in 2015, being a clay-poor fine silt rich mud (PSA Group A) with a modest very-fine sand content. Processes and sources determining the deposit appear unchanged, even though the erosion rate has increased.

At all other sites (29, 31,32, 40, 104, all showing deposition during 2016) there has been a marked change in the nature of the mud accumulating. In 2015 these sites all showed PSA Group B or AB characteristics (clay dominated, with a dearth of particles in the fine silt fraction) indicative of (regional) erosion of Oligocene clays being the primary source. In 2017 all these sites showed the strong presence of a PSA Group A material (clay-poor, strong fine silt mode), believed to be derived from (local) erosion of the Holocene estuarine deposits that underlie the modern estuary floor. These deposits are known to be exposed on the floor of the (eroding) zone 19a[1].

The particle-size analysis findings are therefore consistent with flux measurements showing a) a poor influx of regionally derived suspended sediment during 2016 and b) enhanced erosion of the local harbour floor areas.

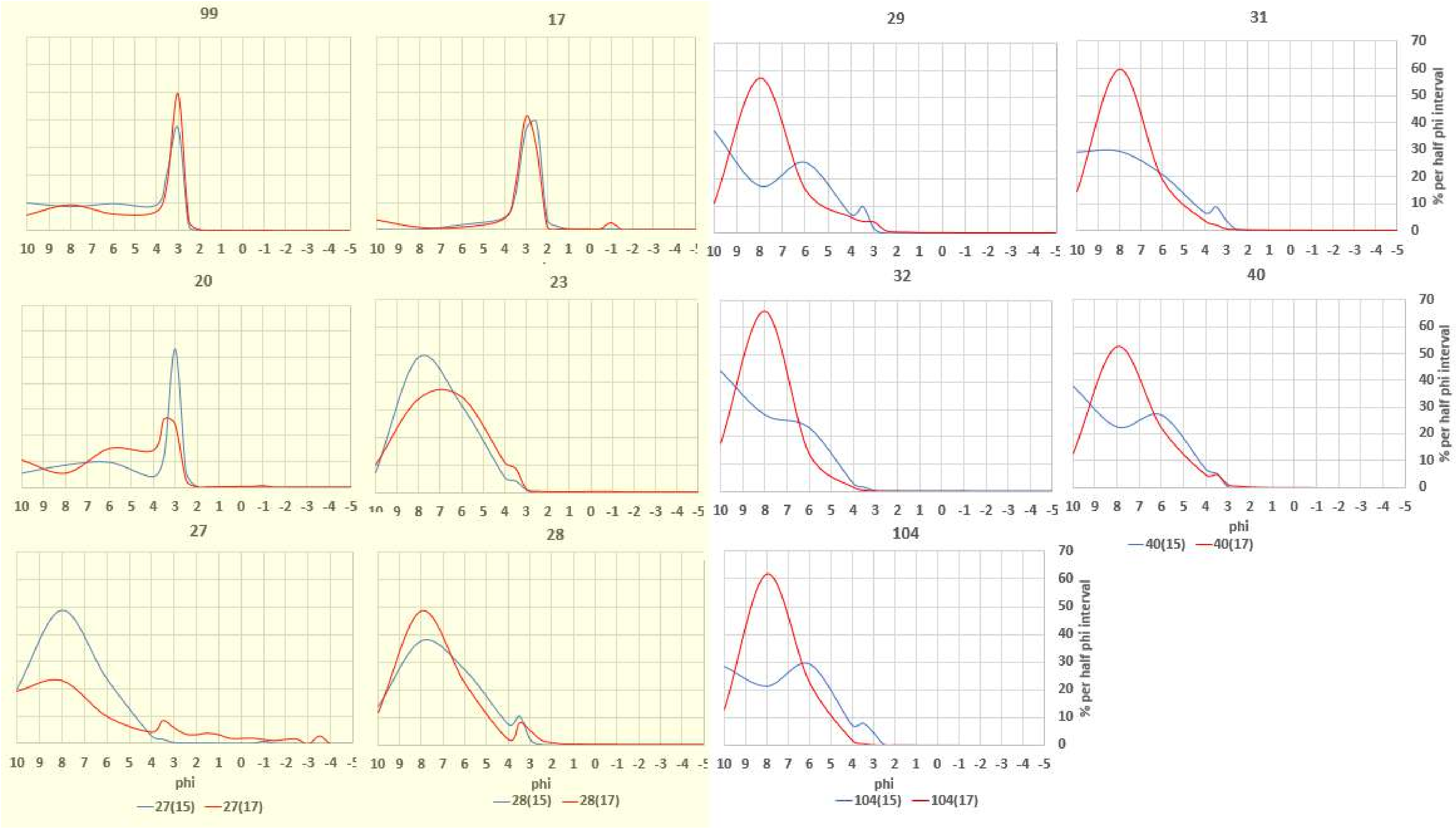


Figure 5. Comparison of particle-size distributions for bed sediments sampled at same sites in November 2015 (blue) and June 2017 (red). Site locations plotted in Figure 4.

Figure 6. Sample 27 gravel fraction.

Field Sample ID	Worksheet	% Gravel (>2mm)	% sand (2mm-63um)	% silt & clay (<63um)	% of silt/clay finer than 4um	Sand mode(s) phi
99	A	0.2	78.6	21.2	26.9	3.00
17	B	2.5	92.4	5.1	67.7	3.0 2.5
20	C	0.6	68.6	30.8	34.0	3.5 3.0
23	D	0.1	21.3	78.6	12.5	3.50
27	E	9.0	39.0	52.0	36.7	3.5 3.0 1.5
28	F	0.0	17.4	82.6	14.1	3.50
29	G	0.0	15.7	84.3	13.2	3.00
31	H	0.0	7.0	92.9	15.4	4.00
32	I	0.0	2.8	97.2	18.0	4.00
40	J	0.0	12.3	87.7	14.5	3.50
104	K	0.0	2.9	97.1	13.3	4.00

Table 4. Summary particle-size data for 2017 analyses.

4. Conclusions

Measurements of fine sediment flux through and around the Medina estuary have been made for the period January 2016-January 2017. The methodology combines water flow measurements from the ABP model and field observations of total suspended solids made at four sites within the estuary. The main objectives are to determine the temporal patterns of fine sediment accumulation and erosion within the estuary and to give confidence (precision) to annual bathymetric measurement of spatial patterns of accumulation and erosion.

Sediment flux results from the outer estuary as a whole (polygons A-F combined) indicate that some 6,800 dry tonnes of sediment were lost from the area over the year. Results from the upper estuary (above the chain ferry narrows) indicate a further ~2,600t was lost from that zone. When converted to bed volume changes, these results are very close to measurements made from annual bathymetric surveys, and can be equated by modifying the bathymetry mean level by 1cm. This adjustment cannot be argued against on the basis of any precision capability of the multi-beam bathymetric survey method, and the calibration has therefore been adopted.

Historically the estuary is known[3] to naturally import mud each year, hence requiring dredging. Previous analyses[1, 3] of the turbidity monitoring data showed that the principle source of mud to the estuary is from winter regional erosion of the seabed and coast, providing a clay-rich material from the dominant Oligocene clay beds of that wider area. The same analyses showed that significant inter-annual variability in this input can be expected, and that the winter of 2015-2016 showed only a modest influx, and that of 2016-17 a very low influx. This situation can partly explain the net loss of sediment from the estuary over the year. Another explanation is the impact of the emplacement of the new breakwater, with modified tidal currents causing erosion as part of the readjustment of the natural system. The bathymetric data and the flux data both show enhanced erosion in zones adjacent to the new breakwater, while at the same time showing steady annual accumulation in 'traditional' sediment sink zones (marina areas and the immediate subtidal inner Shrape area). Thus the unusual net sediment flux condition (erosion) seen in 2016 reflects both a year of reduced regional supply of mud, and local erosive adjustment around the new breakwater structure.

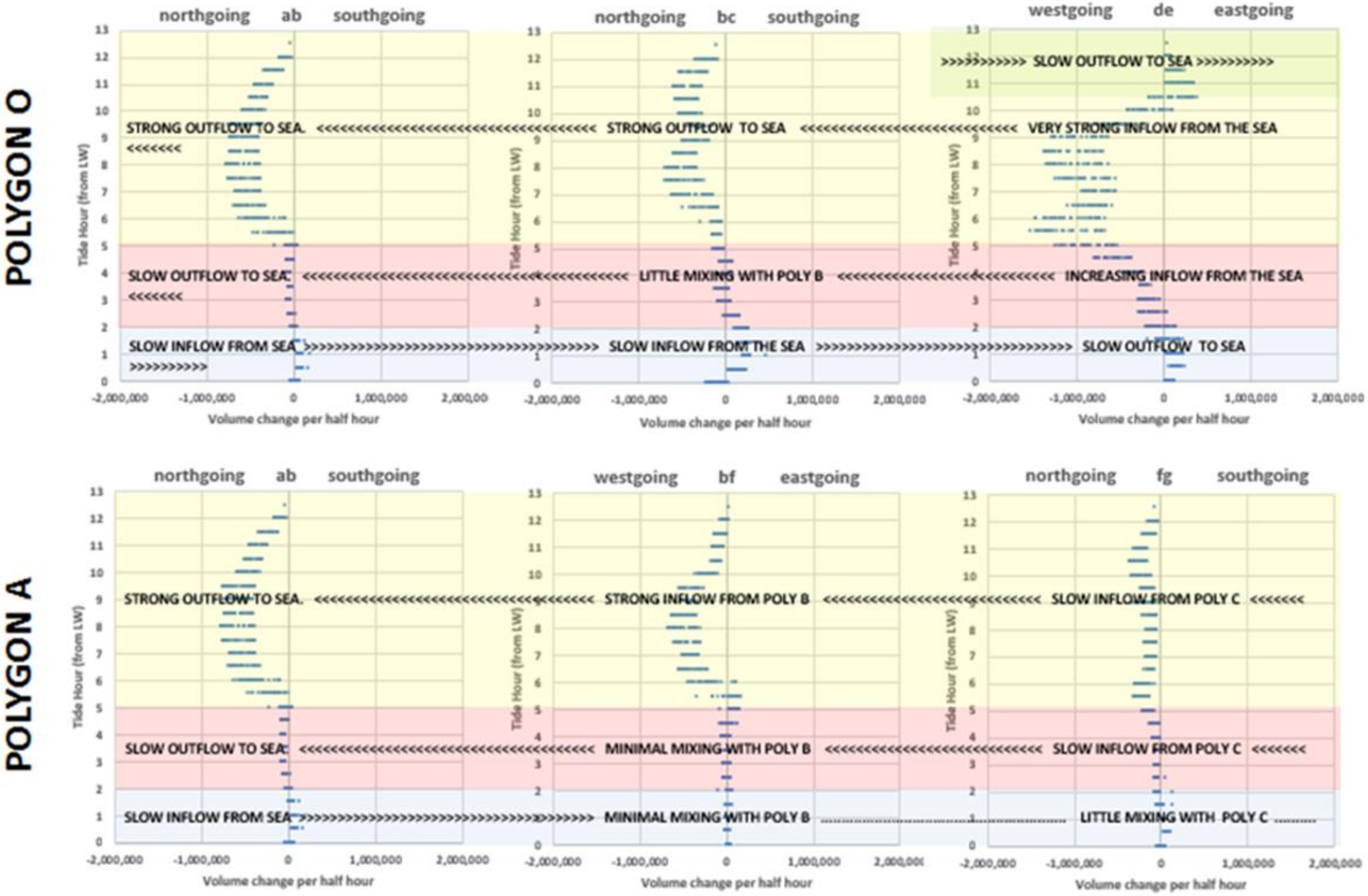
The flux data time-series (calibrated to the annual net change) shows that the seven polygon zones show quite different behaviour through the year.

- Polygon D (inner Shrape area) shows steady accumulation throughout the year. This lack of variability/seasonality suggests a local sediment primary source (eroding harbour bed areas) and a tidally-driven mechanism.
- Polygons A & B (outermost areas) show steady erosion through the year, most likely as a result primarily of tidal forces, and in response to the emplacement of the new breakwater.
- Polygons E & C (main fairway and flood current impingement zone) show steady erosion through the year but reversing in August, when intense vessel movement may cause an influx of sediment displaced from adjacent marina areas. Polygon C erosion will result from the effect of the new breakwater; the causes of the erosion in polygon E are diverse/ unclear.
- Polygon F (Cowes Yacht Haven) shows strong accumulation during winter (pre April and post September), stability in-between but with strong erosion during August probably as a result of intense vessel movement. The difference in mud influx rates between the two winter periods is clearly evident (2015-16 > 2016-17).

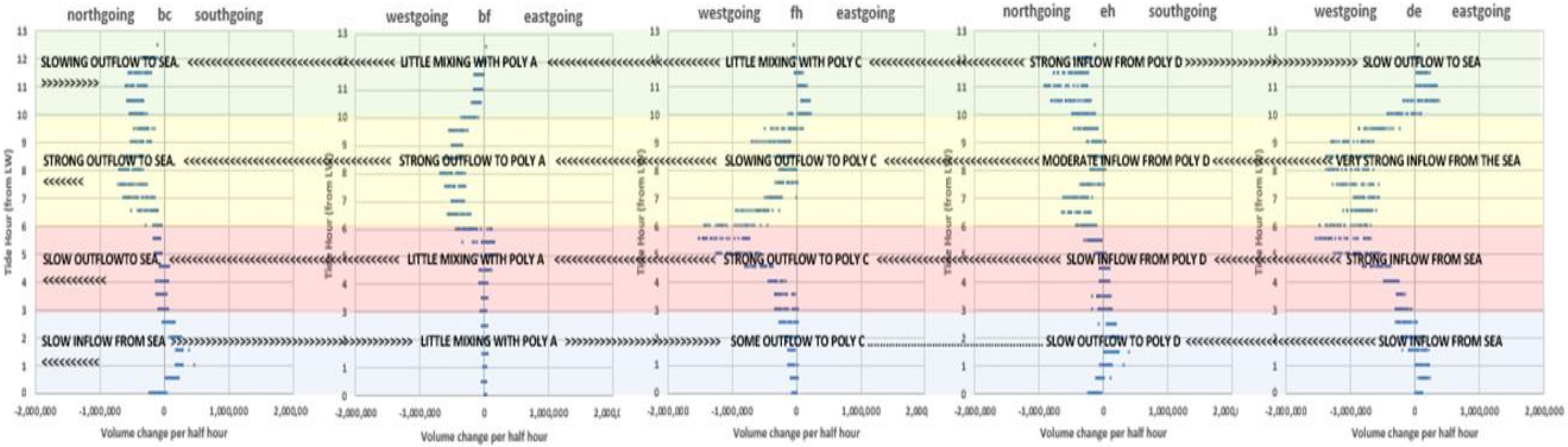
Particle-size analysis of mud taken from recent deposition zones in the estuary confirms both the paucity of influx of regional (clay-rich) material during 2016 and the abundance of fine-silt rich (locally eroded Holocene deposits) derived from enhanced erosion of the harbour bed.

Water flux diagrams have been constructed, showing typical water volume exchanges across estuary sections through the semi-diurnal cycle (Appendix). These diagrams should be a useful tool for planning Water Injection Dredging campaigns, ensuring effective routing of dredge plumes.

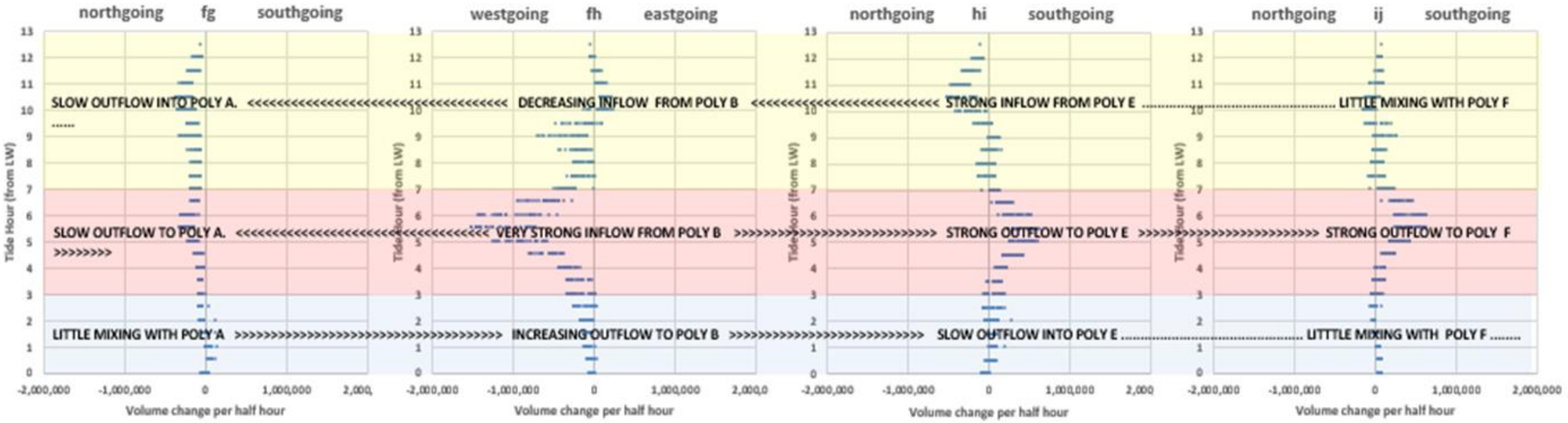
Appendix. Water flux diagrams.



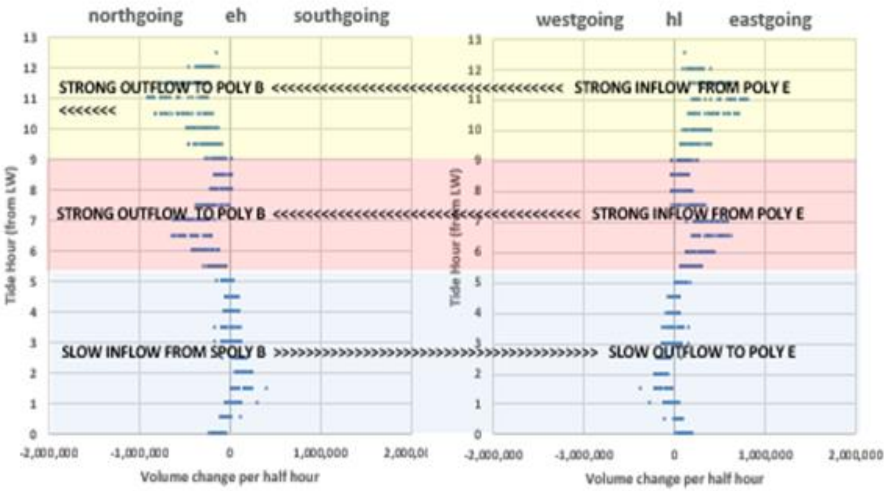
POLYGON B



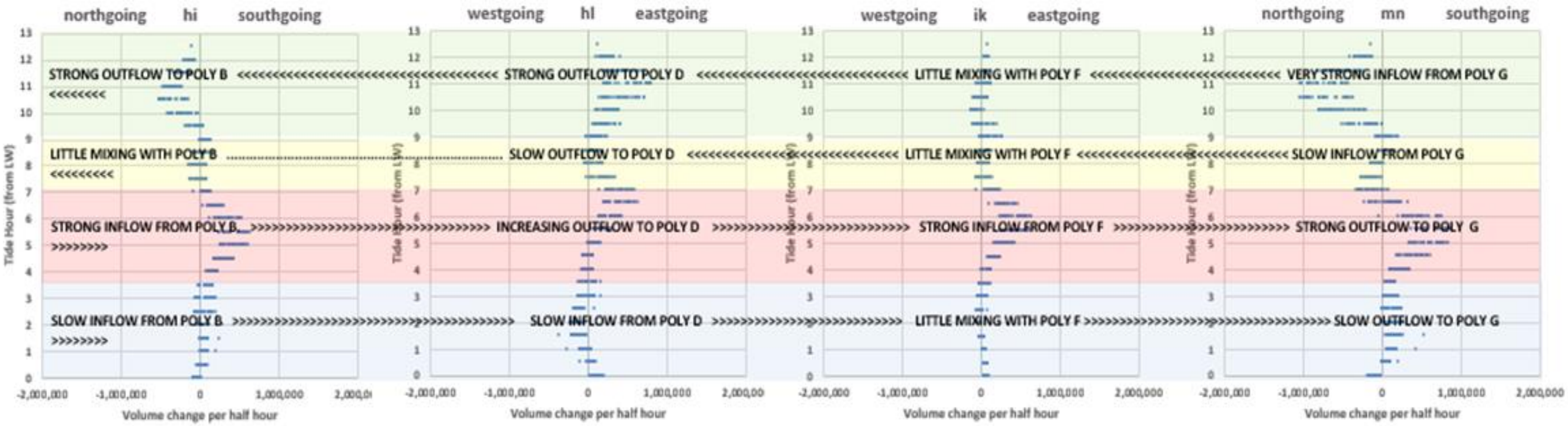
POLYGON C



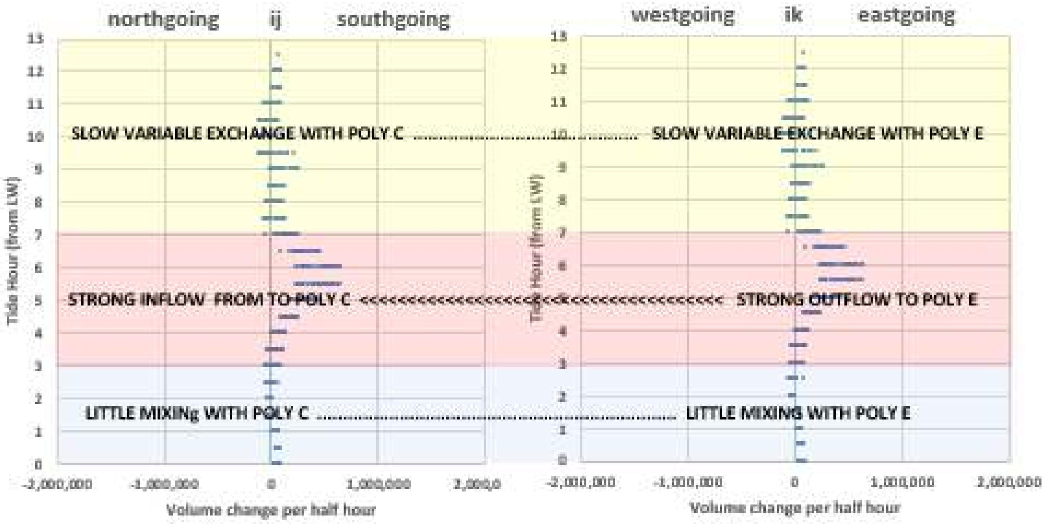
POLYGON D



POLYGON E



POLYGON F



POLYGON G