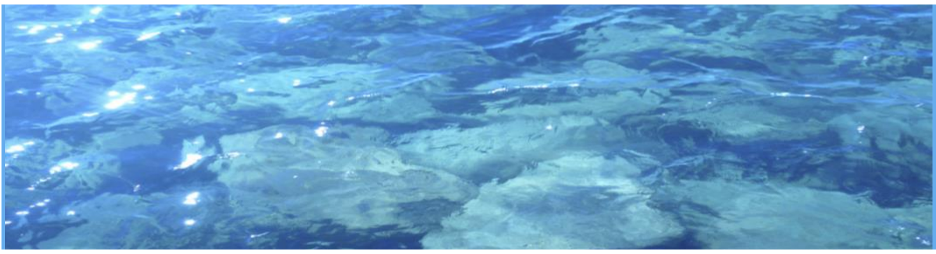
SOMERSET DRAINAGE BOARDS CONSORTIUM

Dredging Trials Monitoring Programme November-December 2016

Report AmbSDBC02

March 2017



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Executive Summary

A trial dredging project and associated programme of environmental monitoring was successfully undertaken over the period November 2016 to February 2017. A primary objective of the project was to improve our understanding of the natural sedimentary regime of the upper Parrett estuary, in order that any sediment management strategy that may be developed is optimally designed to work with nature. The principle finding is that a seasonal alternation of sedimentary processes is found in the upper estuary. There is a spring/summer/ autumn influx of marine fine sediment (moving in suspension), concentrated over a few hour period around high water on the highest spring tides. At these times of strong sediment delivery, suspended solids concentrations in the upper estuary water can reach 25 g/l. At all other times ebb flow reinforced by river flow scours sediment back down towards the sea. High river flow through the winter prevents the penetration of even the highest spring tides into the upper estuary, thus preventing winter accumulation of marine sediment. At times of river dominated flow, suspended sediment rarely exceeds 0.5 g/l. The seasonal balance between the (scouring) fluvial/ebb influence and the less frequent high spring flood tide supply of marine sediment (accumulation) dictates the net sedimentation situation. There may be significant inter-annual variability in this balance due principally to different peak river discharge conditions between the years. In 2016-17 winter river flow causes persistent scour that deepened the whole upper estuary channel system by 10-20cm. Spring/summer/autumn spring tide influx of mud must produce accumulations deeper than this, to produce the long-term net year by year build-up of mud that is seen in the upper estuary reaches. The sediment that builds up comprises primarily coarse silt, with some clay and finer silt, and up to ~15% fine sand. The bed sediment that forms under these conditions is remarkably dense and strong compared with normal estuarine mud.

Nature acting by itself establishes a slowly varying equilibrium relationship between these processes of erosion and deposition. However optimum channel-section scour is only attained after a long period of river flow erosion. This is the crux of the problem from the flood prevention stance, as the natural clearance of the channel section only takes place during and after the occurrence of overbank flooding. Dredging is therefore being undertaken to take the estuary cross-section area out of 'regime' (equilibrium) so that it is ideally prepared to effectively conduct out to sea the highest occurring floods. This channel cross-section area enlargement will however encourage sediment deposition, both by reducing the effectiveness of fluvial/ebb scour, and by encouraging inland penetration of the sediment rich marine water under high spring tidal action. Optimising dredging effectiveness maximises the cost benefit of this activity. To achieve this three analyses have to be made.

1. Hydraulic modelling that can identify the downstream point beyond which dredging has little effect on floodwater transmission (definition of minimum dredge reaches)
2. Establish the optimum timing for the dredging operations (e.g. inter-annual frequency)
3. Identification of dredge method that operates most cost effectively.

Point 1) is not addressed in this study, but the information generated here will feed into the analysis. Point 2) requires a long-term monitoring system to be set up to provide diagnostic information on the inter-annual variability of the net sediment flux through the upper estuary, which is a recommendation of this study. Point 3) was a major objective of this study. Two experimental dredging systems were trialled, a WID (Water Injection Dredger, high productivity) and a Farrell (cutter on an hydraulic arm, high precision). If it transpires that accurate shaping on the channel cross sections is a primary concern, with large amounts of side-slope cutting, then the Farrell is the best tool. If simple deepening of the thalweg is required, the high productivity of the WID makes it the best method. Both methods simply discharge the cut spoil into the water column to become dispersed by natural processes.

During the study much effort was put into measuring the processes of sediment dispersion downstream from the dredger, to ensure that the dispersing flows did not simply redeposit the dredged sediments further downstream. The processes of sediment dispersion varied between the method, and also according to whether marine (tidal) or fluvial processes were dominant at the time (river discharge).

Under low river flow conditions, the WID can only work for a limited period on the early ebb tide, due to the poor water depth and landward flow at other times. Under these conditions the high productivity of the WID system tended to swamp the low volume of water passing the dredger, producing a dense fluid mud layer on the bed downstream of the dredger, often persisting all the way through the monitored reaches. For this reason and also for the very low dissolved oxygen conditions sometimes seen in the bed layer, the use of the WID at times of low river flow is unlikely to be the most practical option.

Both with the WID under higher river flow conditions, and with the Farrell (lower productivity), less dense plume conditions were generated. The water column real-time monitoring undertaken showed that most of the time the dredged spoil was washed seawards through the monitored channel reaches. Bathymetric surveys showed that natural river scour prevented the long-term accumulation of any of the dredged mud as far north as Black Bridge, just downstream of the M5 motorway. Given that the lower reaches of the estuary contain a large reservoir of mud that feeds the process of (spring tide) pumping of mud into the upper estuary, it is probably not important to be concerned in detail about the ultimate sink sites of the dredged material.

Through all the channel reaches from Burrowbridge to the M5 motorway, between November 2016 and February 2017, it was calculated that some 32,000m^3 of mud was dispersed seaward. Only some of these reaches were dredged and logically applying non-dredged area losses to all the reaches it can be calculated that river action alone would have removed some 24,000m^3, thus attributing 8,000m^3 to the dredge activity. The winter of 2016-2017 did not see particularly high river flows, and significant inter-annual variability in the capacity of the river to scour itself should be expected. Critically, using a WID/Farrell system for dredging must be seen as a method of supplementing the natural processes of scour, and should aim to take place a) as early as possible in the winter (to maximise post-dredge river scour) and b) always at times of high river flow (to ensure optimum initial dispersion). In the same vein, spillways and sluices should be designed and operated to maximise the natural scouring power of the Tone and Parrett freshwater discharges

No serious environmental concerns emerged during the monitoring that was undertaken.

The conclusions of the study noted that an alternative to dredging (enhancing scour) might be the reduction of the supply of fine sediment to the upper estuary reaches (reducing accumulation). Although such an option would not normally be open, the plan to build a tidal barrier across the lower Parrett estuary, if operated correctly, could be a practical and economically attractive alternative solution to the maintenance of the upper estuary channel flow capacity. It is recommended that this possibility be carefully investigated.

Other recommendations made involved improved future monitoring (river flow gauging, bathymetric survey methods, sediment flux monitoring), the potential usefulness of uncovering archived data on the Parrett mud system held at HR Wallingford, and the need for further consideration/study to provide a better understanding of optimum channel profile shape and dimensions for both maximising flow capacity and minimising sedimentation.

Dredging Trials Monitoring Programme November-December 2016

1. Introduction

1.1. Background

As part of long-term planning for flood management on the Somerset Levels, the role of the River Parrett (Figure 1) as the prime western drainage conduit to the sea is under consideration. The river runs between artificial levees in its lower course, restricting its capacity for natural channelling of flood waters. The same reaches are affected by tidal action, the estuarine flow feeding sediment into the zone from the large and dynamic mud reservoir of the upper Bristol Channel. Historically the combined problem of confined channels and high sedimentation rates has been addressed by human intervention, through an active programme of dredging. This cost was affordable in the days of cheaper labour and navigational use of the Parrett, the latter ceasing between the 1930s (to Burrowbridge) and 1971 (closing of Bridgwater docks). Since closure, dredging activity has significantly reduced, this change and the resulting silting of the river channel potentially being an important contributory factor to the severe flooding seen across the Levels in the last decade.

Alleviation of the flooding problem on the Somerset Levels is the responsibility of the newly formed Somerset Rivers Authority (SRA), working closely with the UK Environment Agency (EA) and the local drainage boards (Somerset Drainage Boards Consortium, SDBC). The SDBC has taken on responsibility for the channel dredging aspects of the project.

Pioneer[1] dredging of key sections of the lower Parrett south of the M5 (from about 2km south of the motorway, Figure 1) in 20014-16 used backhoe technology, with diggers reaching from the banks or mounted aboard floating pontoons. Spoil was taken ashore, and used to widen/heighten the levees or to spread on agricultural land. This dredging method proved very expensive, and rates at which natural processes refill the excavated zones dictate that a more economical form of dredging has to be found if the practice is to be sustainable. Confirmation of this situation, and exploration of the potential for future cost-effective (sustainable) maintenance dredging strategies are both therefore required.

To this end a programme of experimental dredging and monitoring of effects was undertaken during November and December 2016 [2]. The trials were run by the SBDC, and this report addresses the monitoring undertaken during this project. The monitoring focussed on the ~2km of channel between Burrowbridge and Westonzoyland, which contained the <1km Experimental Dredge Zone (EDZ) as shown in Figures 1 & 2.

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[1] Pioneer term used instead of the normal capital or maintenance classification to denote dredging of deposits which are not natural, but which have laid undisturbed for decades.

[2] The main period of experimental dredging and monitoring finished on 2nd December 2016. After this date the presence of the dredging plant in the estuary was taken advantage of to deepen a further <1km section of channel between the EDZ and Westonzoyland, Figure 2. This dredging was only partially monitored.

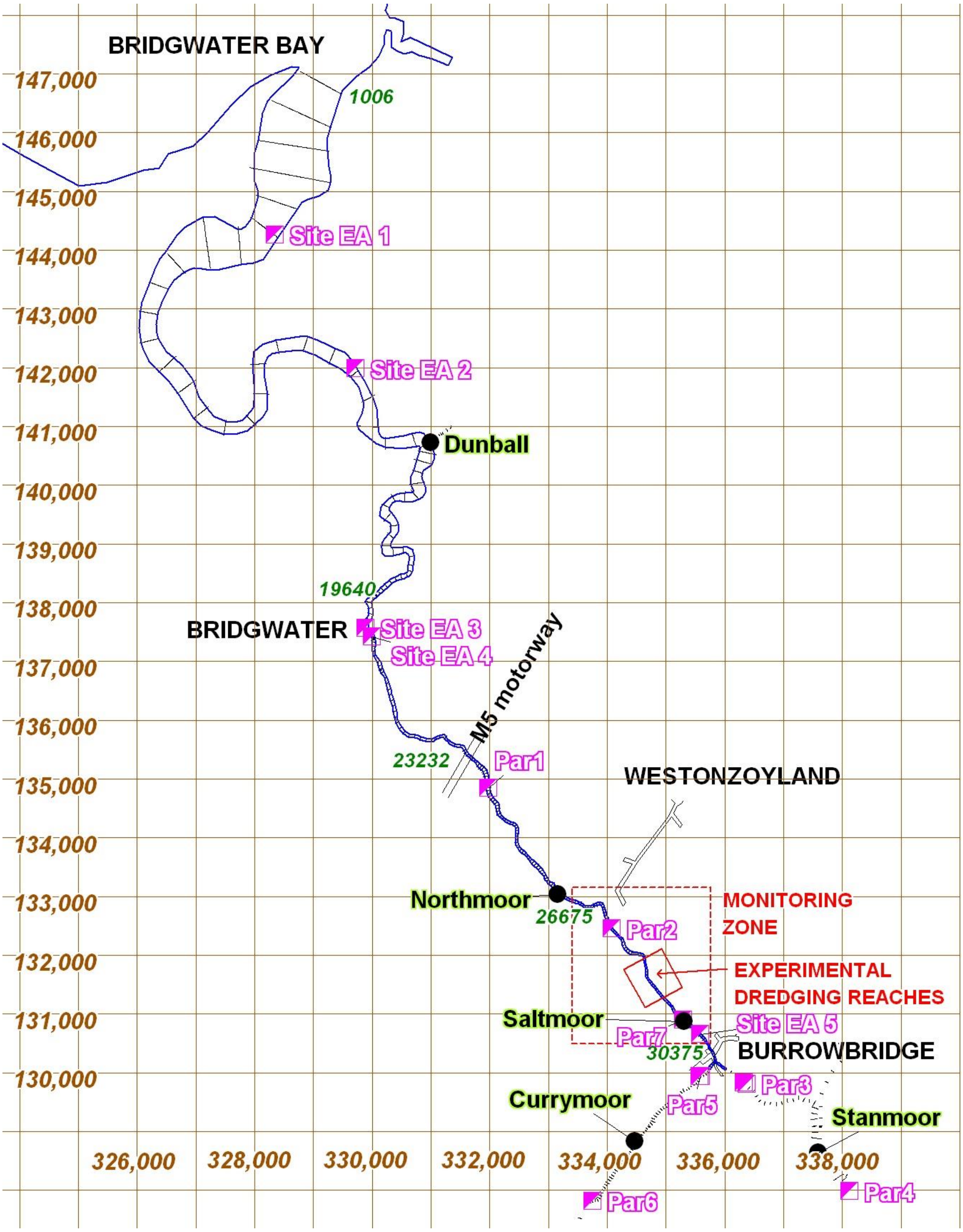

Figure 1. Locations

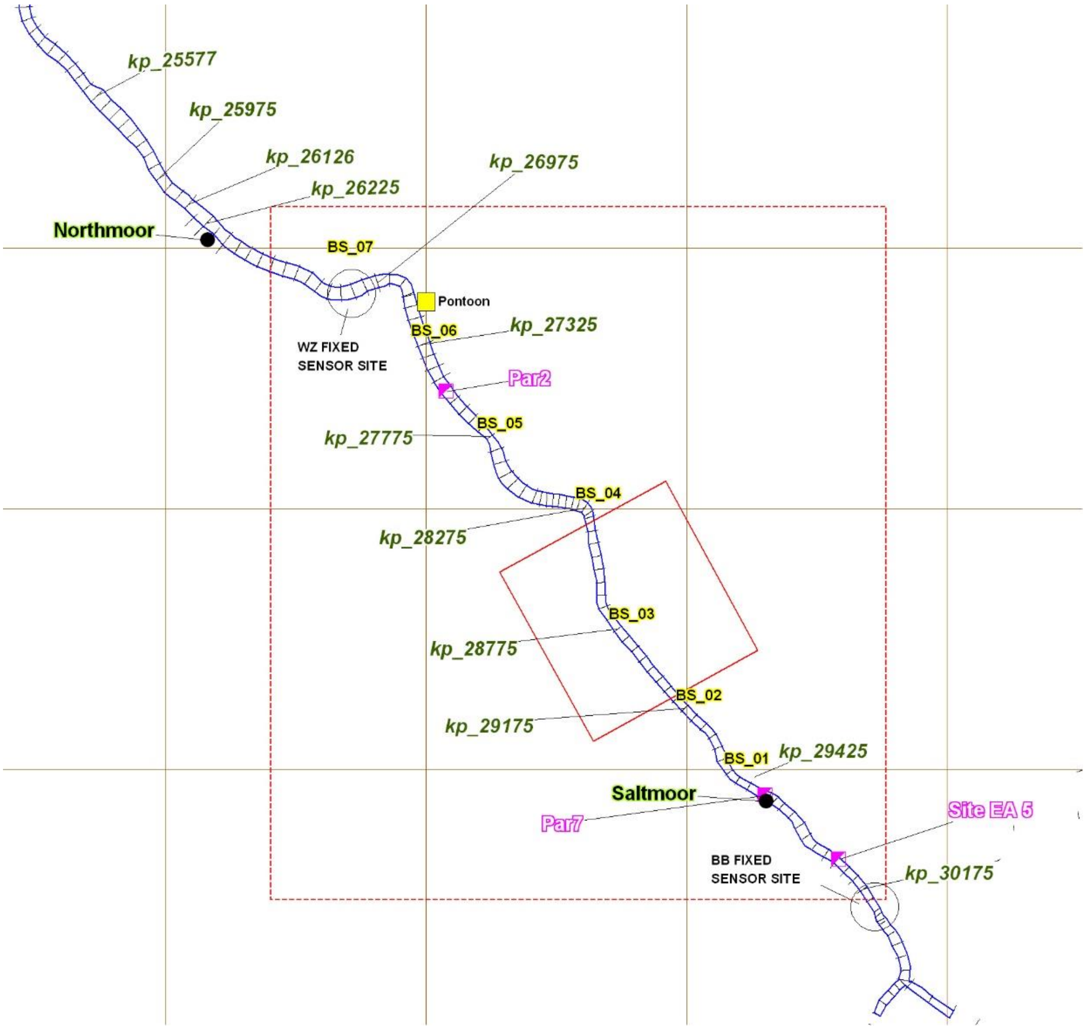

Figure 2. The monitoring zone

Figure 3. The BORR with the WID T-pipe pumping but elevated above the water surface.

The experimental dredging used two methodologies neither of which involved transport of spoil away from the river for disposal/reuse. The dredging created dense suspensions of the excavated material, which were naturally carried seawards by the (ebbing) tidal flow, augmented by the river discharge. The dredging was undertaken by Van Ord UK Ltd, using the vessel BORR (Figure 3).

Water Injection Dredging (WID). A T-pipe with downward pointing nozzles is fastened to the end of a pipe that can be lowered below the dredger, the inboard end being connected to a low pressure (~1bar) pump which forces water into the T-bar. The T-bar is lowered to be a short distance above the bed, parallel to the bed, and water is injected at low pressure into the bed while the vessel moves slowly along. The bed is stirred up into the lower water column, creating a dense suspension, which is carried away by the ambient flow. The WID method lacks precise dredge control, but is capable of very high productivity when bed sediments are unconsolidated and fine.

Farrell Dredging. A circular cutter rotates in a plane parallel to the bed, and is connected to a pump which sucks up water and sediment cuttings into a pipe. The pipe terminates at the water surface alongside the dredger, the dense slurry being discharged into the surface layers of the ambient flow to be dispersed naturally. The cutter head is on the end of a jointed hydraulic arm, which (via computer/GPS control) can be moved from side to side across the watercourse providing a precision trimming facility. Farrell dredging provides a very accurate cut but progresses more slowly than the WID method.

The methodology and dredge hardware used is described more fully in Appendix 1 (Van Ord specifications).

1.2. Monitoring Objectives

The monitoring programme has five broad objectives, most of which are addressed in this report:

1. Provide further understanding of the natural processes of water and sediment movement through the upper estuary of the River Parrett, in the form of a conceptual model [3] of the system, that will inform future planning and sediment-management-strategy development.
2. Protect the environment[4] from adverse effects during the trials and to enable assessment of any potential environmental impacts of long-term adoption of these methods.
3. Measure the effectiveness (productivity and precision) of the dredging plant (addressed in detail elsewhere).
4. Identify and quantify the processes of sediment dispersion downstream from the dredger
5. Identify the short term changes effected by the dredging (channel morphology and sediment composition)
6. Trial optimum methodologies for a long term monitoring programme.

A future (seventh) objective will be a longer-term assessment of the changes effected by the trials (Objective 5 after many months). This will be principally concerned with the rates at which sediment deposits re-accumulate in the trial-dredged reaches (bathymetry surveys and visual observations).

[3] A conceptual model provides a descriptive framework for the organization of knowledge about the elements and interrelationships within a system, serving as a guide for observation and interpretation. Importantly, conceptual models can define the envelope of reality that mathematical models (of the necessarily simplified system) must reproduce.

[4] See report: Parrett and Tone Hydrodynamic Maintenance Dredging Trials 2016. Environmental Impact Assessment (including HRA and WFD). Parrett Internal Drainage Board (on behalf of the Somerset Rivers Authority) 17 October 2016 (final version)

1.3. Secondary Data Sources

A substantial amount of research has been undertaken in past years, examining water and sediment flow in the River Parrett and linked environments. The key reports relied upon through the monitoring study are as follows.

The Unit of Coastal Sedimentation based in Taunton studied fine sediment circulation of the inner Bristol Channel in the 1970s and 1980s. They identified a system of settled muds, stationary suspensions and mobile suspensions, with mud moving between these states according to the lunar cycle of tidal energy. From the point of view of influence on the Parrett estuary sedimentary system their findings can be summarised in the following two report[5] extracts.

The turbidity maximum extends from Watchet in the Bristol Channel to well above "The Shoots," which is the upstream limit of this study. As a direct result of the energy cycles and availability of erodible fine sediment, the suspended solids concentrations are high and variable ranging from <O. 1 to >200 g l^{-1} . Based on water volume and suspended sediment mass computations in this region, preliminary estimates (unpublished) show that on spring tides of the order of 17 million t of fine sediment is suspended in the water column whilst on neap tides some 50% of this sediment settles to the bed to form dense stationary layers.

The plan distribution of average suspended solids data shows a zone of marked lateral concentration gradient along the main channel of the Severn between "The Shoots" and the Holm Islands and extending across the Inner Bristol Channel to the English coast near Watchet. This suspended solids front occupies a narrow zone at the surface and bed on spring and neap tides. The concentration on the English side of the front was consistently higher, >4.0 g l^{-1} at the bed on spring and neap tides, than on the Welsh side, where it is generally <0.5 g l^{-1}.

The same studies showed that Bridgwater Bay contains some 500M tonnes of mud as settled deposits, some of which are eroding and others accreting, and which must play an important source and sink roles in the regional fine sediment circulation system. These fluid and settled mud deposits are likely to be the primary source of the sediments that are mobile in the Parrett estuary.

HR Wallingford have undertaken several studies of the River Parrett system. The first study (unreported as data went into a physical modelling exercise) was conducted in 1977/78 in relation to proposals to construct a tidal barrier at Dunball, and involved field studies of water and sediment flow conditions between the estuary mouth and Bridgwater. These results are partially reported in a 1986 study[6] looking at dredging options for the Parrett, when some further field measurements were taken from Bridgwater to the tidal limits. Later studies of the Parrett undertaken by HR Wallingford [7] [8] [9] have not involved field measurements. Two further general HR Wallingford reports [10] [11] contain useful references to some of the above data as well as describing the latest thinking on mud suspensions.

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[5] KIRBY, R. , and W. R. PARKER. 1983. Distribution and behaviour of fine sediment in the Severn Estuary and lnner Bristol Channel, U.K. Can. J. Fish. Aquat. Sci. 40 (Suppl. 1): 83 - 95.

[6] HR Wallingford 1986. River Parrett Dredging Study. Report EX 1428.

[7] HR Wallingford 2016. Somerset Levels and moors Flood Action Plan. Dredging Study for the Rivers Parrett, Tone and Brue. Report MCR5576-RT001-R02-00

[8] HR Wallingford 2001. River Parrett Flooding Appraisal of Possible Solutions. Phase 1. Review of Agitation Dredging. Report EX 4433

[9] HR Wallingford 1996. River Parrett Dredging research Strategy. Report EX 3480.

[10] HR Wallingford 1993. Impact of Climate Change on Water Quality. Report SR 369

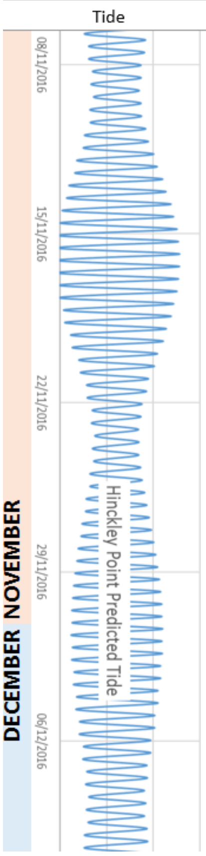
[11] HR Wallingford 2012. Methods for Predicting Suspensions of Mud. Report TR104.

In 2008 and 2009 the Environment Agency commissioned studies to examine the flux of sediment through the upper estuary, undertaken by Partrac Ltd/Black & Veatch. For two one-month periods (mid-November to December 2008, mid-August to September 2009) instrumented frames were placed at seven sites in the Parrett low-water channel in the reaches above the M5 motorway (sites identified in Figure 2). Although some data were lost due to frame failure, clogging with weed etc, some good baseline information was captured [12] on current velocities, sediment transport and channel morphology.

Sediment samples from the bed of the Parrett at five sites (Figure 1) were analysed for particle-size characteristics in both March and August 2016.9 (EA data). A laser sizing system was used.

2. Methods

2.1. Dredging timetable



Date		Dredging Activity	Monitoring Activity	
7	M			
8	Tu			
9	W	*Jetty and pontoon installed*		
10	Th		BS	*Initial bed sediment survey*
11	F	*Dredger launched at Dunball*		
12	Sa			
13	Su			
14	M	*Dredger on site. Berth dredged.*	1	*Pre-dredging WQ survey*
15	Tu	*1 hour WID. South reach*		
16	W	*1.25 hours WID. South reach*	2	*1st dredger plume survey*
17	Th	*1.25 hours WID. South reach*		
18	F	*2.5 hours WID. South reach*	3	*2nd dredger plume survey*
19	Sa			
20	Su			
21	M			
22	Tu			
23	W	*Farrell fitted*		
24	Th	*Farrell fitted*		
25	F	*2.5 hours Farrell dredge. North reach*	4	*3rd dredger plume survey*
26	Sa	*Spuds adjusted*		
27	Su			
28	M	*6 hours Farrell dredge. North reach*	5	*4th dredger plume survey*
29	Tu	*6 hours Farrell dredge. North reach*		
30	W	*4.5 hours WID . North reach*	6	*5th dredger plume survey*
1	Th	*2 hours Farrell dredge. North reach*		
2	F			
3	Sa			
4	Su			
5	M		7	*Post-dredging WQ survey*
6	Tu	*Processing*		
7	W			
8	Th		BS	*Final bed sediment survey*
9	F			

Table 1. The dredging and monitoring timetable.

Dredging and monitoring activities are detailed in Table 1. Before the 20th November, low river discharge dictated that dredging could only take place for a few hours on the early ebb after high water (HW) spring tides. After that date the river discharged increased to the point that dredging was possible at most times.The experimental dredging was undertaken along two reaches of the estuary, totalling about 800m, between Kp [13] 28300 and 29100 (BS02 to BS04 in Figure 2). The

[12] Partrac Ltd. March 2009 & September 2009 SEDIMENT BUDGET REPORT (River Parrett/Tone) Reports P1022.05.D021v01 & P1022.05.D026v01

[13] A system of kilometre posts (Kp) starting at the estuary mouth (Steart Island) and following the thalweg has been in use for previous Parrett estuary projects and is relied upon here.

northern part of this section (separated by the bend) was undertaken using the WID method alone, the southern part using the Farrell cutter but also with the WID for one day.

As an extension of the planned experimental dredge, from 12-16th December the channel between the north edge of the EDZ and the pontoon at Westonzoyland (Figure 2) was dredged using combined Farrell (side slope) and WID (channel floor) methods. Thirty-three hours of active dredging took place, with up to 11.5 hours of dredging in one day (river level was high enough to enhance ebb flow). On the final day (16th) the WID method was used to undertake a single 'cleansing' path all the way from Burrowbridge to Westonzoyland.

2.2. Bathymetry

A standard set of transects have been used for estuary bathymetry surveys over the years. These are spaced 50m apart through the upper estuary, the spacing widening in the lower estuary (Figures 1 & 2). The profiles are identified by their Kp chainage (in metres) from the estuary mouth [13]. A secondary profile numbering system is also in use, identified by profile number north of the confluence of the Tone and the Parrett. As the latter site is located at Kp 30575, this secondary profile identifier can be derived from the equation:

Profile number =1+((30575-Kp)/50) The EDZ therefore contains profile 30-45.

AP Land Surveys Limited conducted a set of surveys along these transects in October 2016. The survey was restricted to upstream of Kp 25575 (profiles 1-101). These data have been used as baseline information for the dredge monitoring. The surveys were undertaken on foot or in a small boat using a pole mounted RTK DGPS. AP Land surveys conducted a post-dredge survey at some of the profiles during late December 2016. Every profile inside the EDZ (30-45) was resurveyed and every third profile outside the EDZ between profiles 1 and 87.

Storm Geomatics were commissioned to undertake a pre-dredge survey of the estuary reaches between Black Bridge (downstream of M5 motorway) and Burrowbridge using combined multibeam (below water level) and scanning laser (above water level) techniques. The survey was however completed on the 16th and 17th November, at which time dredging had just started. The survey was undertaken by Shoreline Surveys Ltd using an Odom Teledyne MB2 (200kHz) multibeam (nominal accuracy $\pm$0.05m) and a Velodyne Puck VLP-16 Laser (nominal accuracy $\pm$0.01m). Positioning during data capture used a Trimble SPS 855 GNSS receiver using corrections from the Trimble VRS NOW service. A post-dredge survey of the same reaches, using just the multibeam, was undertaken during the week of the 13th February 2017.

For completeness the spring 2014 (pre pioneer dredge) bathymetry dataset has been included in the analyses. This (pole and ADCP method) data set comprises most of the estuary.

All data were entered into a (MapInfo) GIS system and gridded for analysis.

2.3. Fixed-point Autonomous Sensors

WATER QUALITY sensors (two) were installed on the 20th October 2016 and were retrieved on the 16th January 2017. The sensors were located near Westonzoyland (WZ, downstream end of monitoring area) and at Burrowbridge (BB, upstream edge of monitoring zone) as shown in Figure 2. They monitored conditions in the surface ~0.5m of the water column, the BB sensor being suspended from a bridge and the WZ sensor mounted in an anchored floatation system. Data were logged at 15 minute intervals and transmitted via the internet to cloud storage/PC access. Each unit contained a YSI 6600 V2 Sonde with the following sensors:

Optical Backscatter (turbidity) with a wiper Type 6026. This optical sensor was withdrawn in approximately 2002 and is characterized by relatively small optics, a factor that results in minimal penetration of the light beam into the sample which allows an improved ability to cope with higher turbidity conditions than more modern (standardised) sensors. All optical backscatter systems suffer from the limitation of continuing to provide (spurious) data above a maximum turbidity condition. This limit is be pre-defined by the manufacturer in terms of NTU but due, to the natural variability in TSS (total suspended solids) and NTU relationships, the limit can be difficult to identify in the field. The upper limit of the 6026 sensor is 4000 NTU.

Temperature & conductivity. Salinity is calculated from these two values using a standard formula.

Dissolved oxygen, which is automatically combined with temperature and conductivity data to be reported both as an absolute value and % saturation.

The sensors functioned very well throughout the monitoring period, being subject to downtime due to stranding and weed clogging for only a few days in total (worst case was the dissolved oxygen sensor at Westonzoyland which failed on the 4th January 2017 and was not replaced). Comparison with manual profiled data showed good correspondence of values, but it is recognised that although there is only weak vertical variability in water temperature and salinity, strong vertical gradients in turbidity and dissolved oxygen occurred at key times, which these near-surface sensors did not see. Turbidity calibration information for the sondes are provided in Appendix 2.

WATER LEVEL data was provided by the EA and Proudman Oceanographic Laboratory (POL). The EA maintain sensors at five sites pertinent to the survey (Figure 1). Data are logged at 15 minute intervals and are logged and accessible via the internet. POL maintains the tidal stage recorder at Hinkley Point at the western extremity of Bridgwater Bay, data again being available via the internet. As there is a slow and range-dependent progression of the tidal wave along the narrow Parrett estuary (with associated variability in high water times), all tide times have been referred to low water at Hinkley Point.

2.4. Manned Water Quality Surveys

A manned water sampling system was used from a boat on seven days of the nineteen day monitoring period (Table 1). The system was deployed from the Van Ord support vessel CHALLIS 2 (Figure 4). Although monitoring was successfully achieved using this vessel, its length, beam and draught were too large for the environment, restricting its ability to turn in the narrow channel (reducing the periods of time monitoring could be continued for) and propeller disturbance was potentially a major source of local turbidity.

The CHALLIS 2 had a small derrick at the stern which allowed deployment of a water profiling system. Water depth during the survey was always less than 5m, allowing the profiling system to be hand-hauled. The system contained the following equipment:

A Valeport 'Owen' Water Sampler (Figure 5). This is a 1m long 5cm diameter tube that is suspended horizontally in the water column, a system of fins keeping it aligned into the flow. Feet fitted to the base of the sampler allow it to securely rest on the bed for sampling 10cm above the bed when required. On release of a messenger down the supporting rope the tube can be automatically closed, trapping a water sample. The Owen tube can be quickly brought into the vessel and supported vertically in a metal frame, allowing a settling test to be undertaken. The latter is achieved by initially withdrawing a water sample from the base of the tube (total concentration) then taking subsamples at 10cm depth from the top of the tube at 5 and 10 minute intervals. Comparison of the TSS content of the three subsamples shows the rates at which the coarser elements of the suspended solids are settling out. The Owen tube was also used just to take water samples for calibrating the optical turbidity sensors also being deployed.

Two sondes were mounted on the Owen tube as illustrated in Figure 5, sampling as closely as possible the water flowing through the tube.

Figure 4. The CHALLIS 2 workboat showing the derrick used for the Owen tube.

Partech 740 turbidity meter. This sensor was mounted on the port side of the Owen tube (Figure 5). The unit is a short-beam transmissometer, measuring optical attenuation (cf optical backscatter). These systems are capable of measuring turbidity to much higher levels that OBS units, and the 740 reliably measured turbidity up to 20,000 NTU. Importantly the 740 gave a 'beyond full scale' signal once light extinction had occurred, unlike the OBS sensors. Unfortunately the 740 had no facility for data logging, simply a cable to a hand-held display unit. Therefore readings were just taken at the surface and on the bed, with note taken at the level at which light extinction occurred (both on ascending and descending casts). Unlike OBS sensors, there is not a near-linear relationship between light attenuation and turbidity.

YSI ProDSS Sonde. This unit was mounted on the starboard side of the Owen tube. The unit is cable-connected to a hand-held display unit, but also data is logged internally. Logging was set to record all data values at 1s intervals, and was simply switched on at the beginning of each survey and off at the survey end. Log time accuracy was checked daily. Surface and bed readings were logged simultaneously with the Partech 740 observations. The sonde contained the following sensors.

- Depth below water surface (by pressure, calibrated to atmospheric pressure)
- Temperature
- Conductivity/salinity
- pH

- Turbidity (OBS) that gave spurious (low) data in turbidity levels above 2000NTU (see Appendix 1)
- Dissolved Oxygen (reported both at absolute concentration and % saturation).

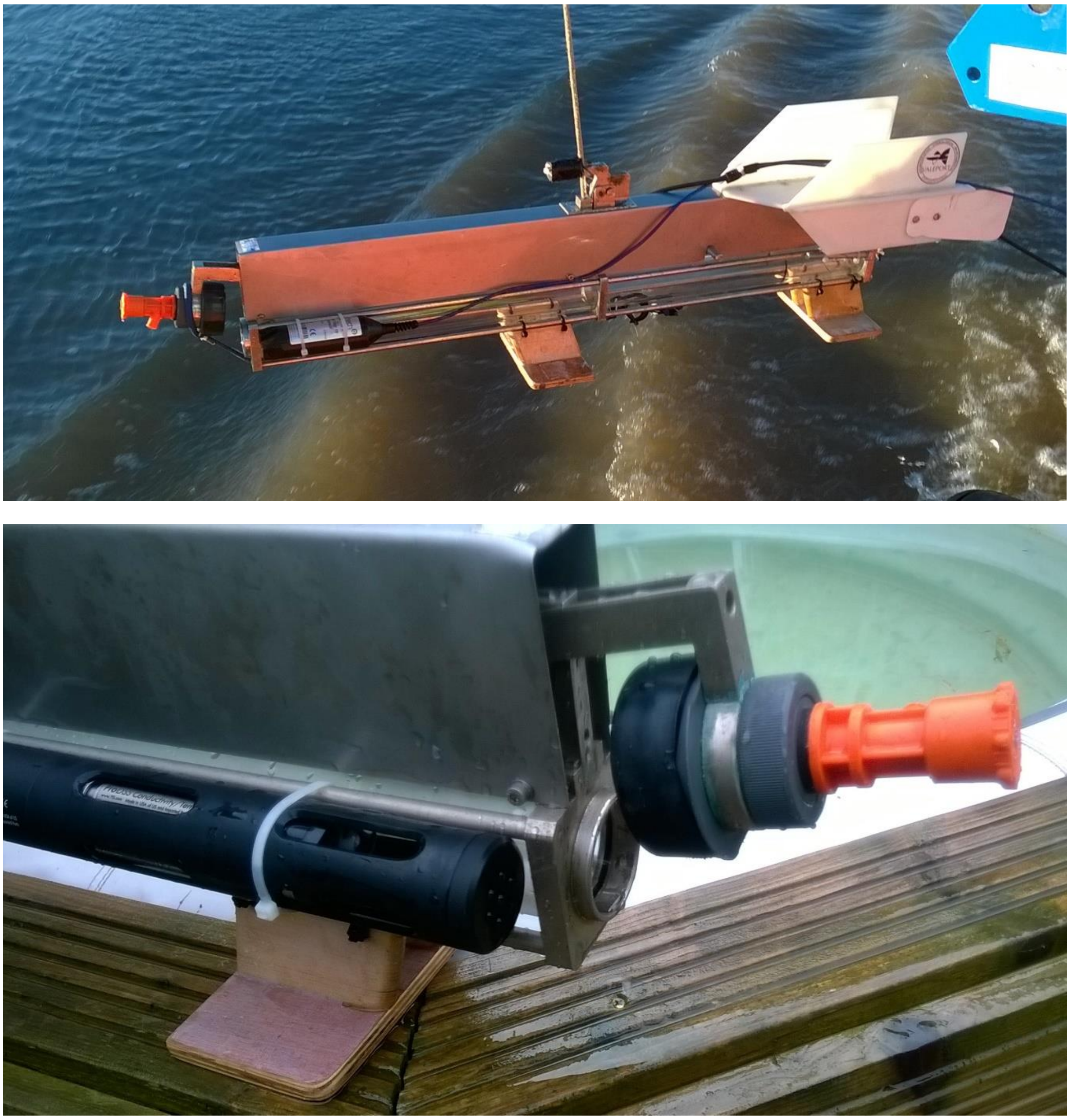


Figure 5. The Owen tube and attached sondes.

ALGIZ 10X handheld ruggedised PC fitted with DGPS (EGNOS). The position system was initiated at the beginning of each survey and logged the vessels location constantly at 1s intervals through the day. The synchronicity of the ALGIS and YSI ProDAA clocks was checked daily, and the two logs combined to provide one data record. Times when the ProDSS was not immersed were simply removed from the record on the basis of water depth (<0.1m).

One simple data collection strategy was mostly used during the monitoring of the dredge plume. All monitoring took place from local HW through the ebb tide. The CHALLIS 2 never anchored, profiling always took place in the channel centre, facing upstream with the skipper using the engine to hold position against the 1-2 knot current. The CHALLIS 2 initially took up station astern of the dredger and a water column profile was taken with the Owen tube and attached sensors. A drogue (moving with the surface ~0.5m) was thrown overboard at the start of the profiling and was carried seawards by the current. Once the profile was complete, the Owen tube was lifted from the water, the boat turned, and the Owen tube lowered back into the water at about 0.8m depth. The boat then slowly motored downstream until it caught up the drogue. The Owen tube was lifted aboard again, the boat turned (on passing the drogue) and the same plug of water (approximately) was profiled again. This process was repeated (about 5 times) before ceasing at the seaward end of the monitoring zone. Thus both point profiling and towed fixed depth observations were made. From time to time a water sample was taken for calibration purposes (the exact closure time of the tube being logged for relation to the sonde data). Up to 5 times per survey a settling test was conducted, mostly immediately astern of the dredger or at the most downstream location (for logistical reasons). Typically three or four such transects were monitored on one ebb tide (transects taking just over one hour to complete).

A simpler approach involving less profiling was adopted during the before and after dredging surveys, when little vertical variability was encountered in the water column. If for logistical reasons the CHALLIS 2 had to spend time alongside the landing Pontoon at Westonzoyland, profiling and continuous (set depth) records were also observed from that static position.

Calibration/settling water samples were filtered in the lab within seven days of collection. Cellulose nitrate 0.2um pore membranes were used. Because of the high TSS concentrations and the absence of saline water (maximum salinity of 3 observed for short time) washing through of filter cakes with distilled water was not undertaken. The highest concentration samples required dewatering using the membranes, then being washed into porcelain weighing boats for weighing (due to the volume of the filter cake). Balance precision was 4dp gram. All results can be seen in Appendix 2.

2.5. Bed Sampling

An estuary bed sediment survey was undertaken at the beginning and end of the monitoring period (Table 1). Sampling was undertaken from a small inflatable boat, allowing navigation of the channel at very low water levels (maximum intertidal exposure). Seven sites were visited, spaced at about 400m intervals through the monitoring zone (Figure 2). At each site the condition of the banks/ intertidal was photographed and samples of the bed sediment were taken from immediately above the water margin on both he left and right banks, and from the channel centre using a small (0.05m^2) van Veen grab (Figure 6).

The shear-strength of the intertidal mud at the water's edge (dry) was measured using a shear vane designed for normal estuary mud [14]. This instrument (Figure 6) measures the shear resistance of the surface 10mm of an intertidal mud deposit, and can be used in the range 1-1.3kPa. In the event, and surprisingly, many of the sediments tested exhibited strengths greater than 1.3 kPa.

[14] P. Bassoullet, P. Le Hir 2007 In situ measurements of surficial mud strength: A new vane tester suitable for soft intertidal muds Continental Shelf Research 27 (2007) 1200–1205

Figure 6. Inflatable dinghy, grab and shear vane used for the bed surveys.

With most samples it was possible to collect the mud undisturbed by inserting a 100ml volume core. This set-volume sample allowed determination of the *in-situ* bulk/dry density of the deposits.

Particle size analysis was undertaken for all samples. Sediment was initially wet sieved at 63um. The coarser fraction was dried at 105^{o}C then dry sieved (0.5 phi sieve interval). The fine fraction was quantitatively subsampled using a stirrer/syringe system. One fraction was dried to determine total weight <63um, ground and stored for possible future use. Another fraction was pre-treated with hydrogen peroxide to remove organics, dispersed with sodium hexametaphosphate and the particle-size determined using the pipette method. This methodology is based on BS1377, adapted for marine rather than soil conditions. Silt and clay content analysis is based on sedimentation principles (cf optical measure of grainsize used in laser analysis). Mineralogy of the sand fraction was examined under the microscope.

3. The Receiving Environment

3.1. Morphology

The estuary channel through the monitoring zone is a sinuous channel (Figure 2) of simple cross-section, the sinuosity taking the form of short and straight reaches separated by often sharp bends, reflecting its man-made origin. The channel thalweg varies between +3 and +1.5m ODN through the zone and the bank crestline stays constant around 8m ODN (Figures 7 and 8). Much of the riverbank is artificial levee. Through the monitoring zone the width between bank crests generally increases from 30 to ~45m, and the cross-section area from about 85 to 120m^2. There is however considerable variation in these dimensions through the zone, with narrower, smaller area profiles tending to occur on bends. The low water channel is a metre or so deep at times of low river flow, with a zone of periodically inundated mud and vegetation (Figures 3, 4 and 8) extending upwards on either bank for some 5m vertically. This zone is invaded to some level by the tide for short periods over spring tides, but only reaches bankfull levels during severe river floods.

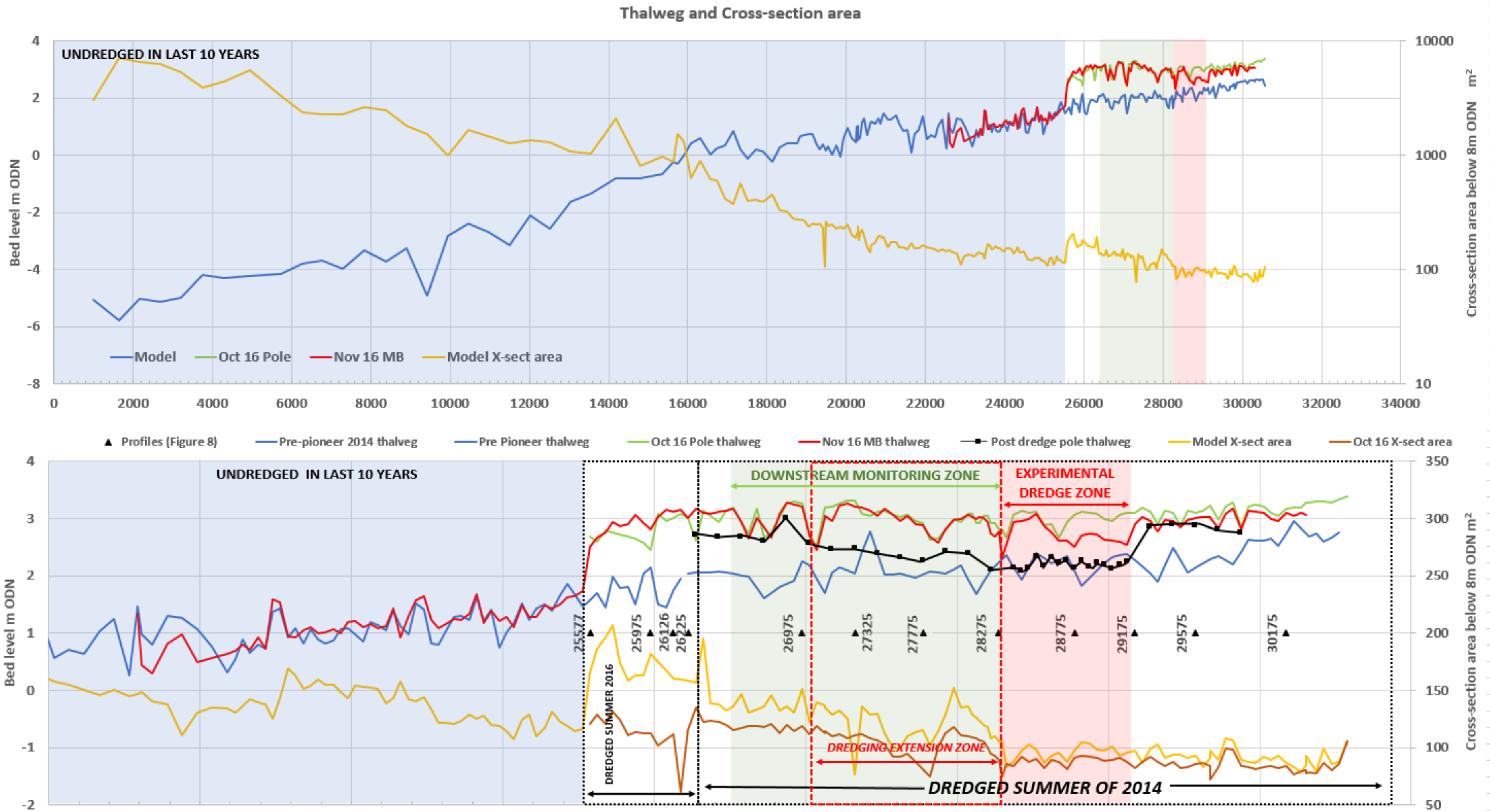


Figure 7. Long-sections of the Parrett estuary from various surveys. Top: whole estuary. Bottom: Upper reaches, including the EDZ and monitoring zone. For the 'Model' cross-sectional area data, all points including and upstream of kp 25577 (prof.101) are based on design profile data, below this point the 2014 survey data are used (explaining the marked apparent change at that kp). Cross-section areas are measured to bankfull (~+8mODN) levels.

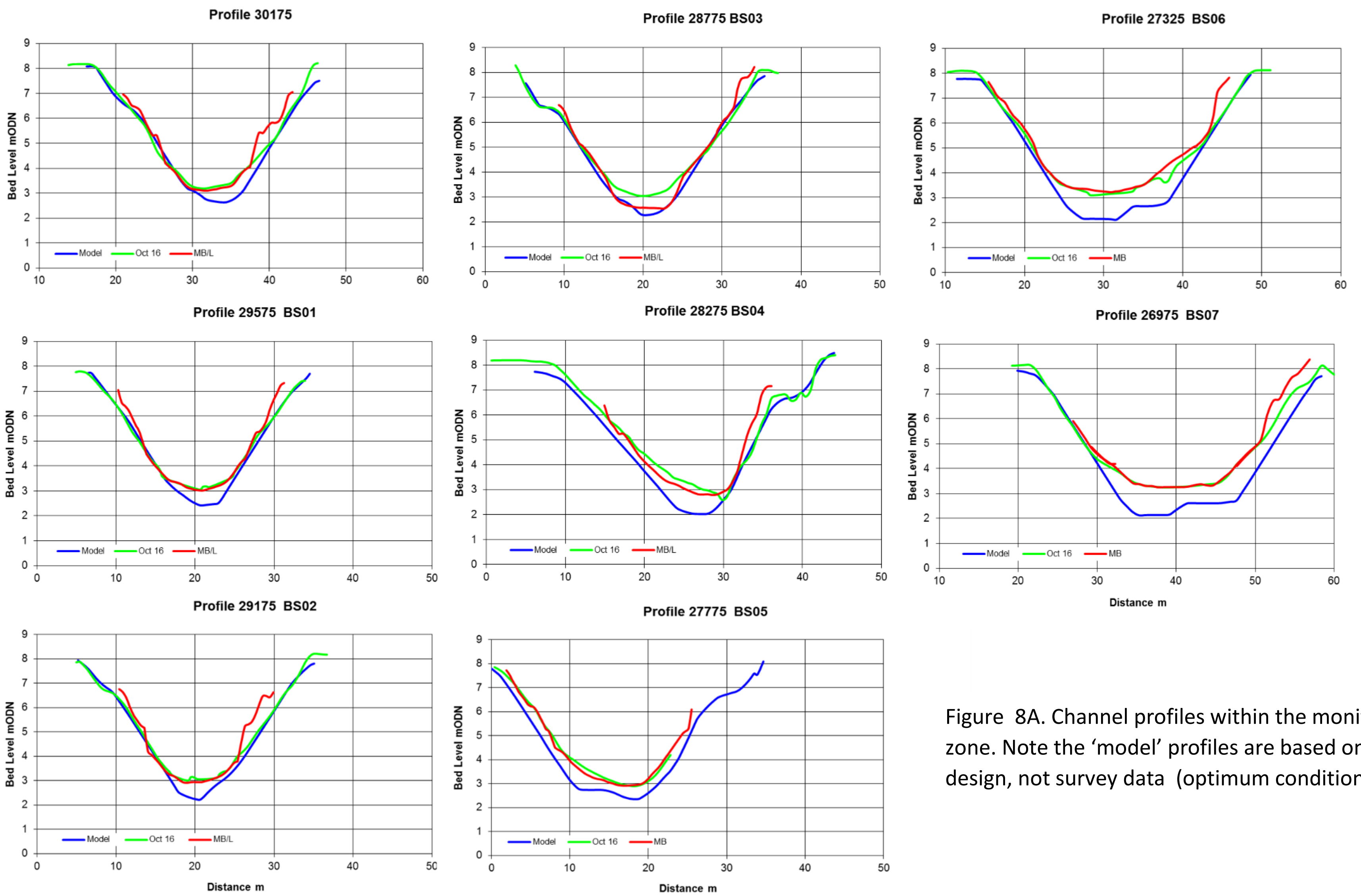


Figure 8A. Channel profiles within the monitoring zone. Note the 'model' profiles are based on design, not survey data (optimum condition).

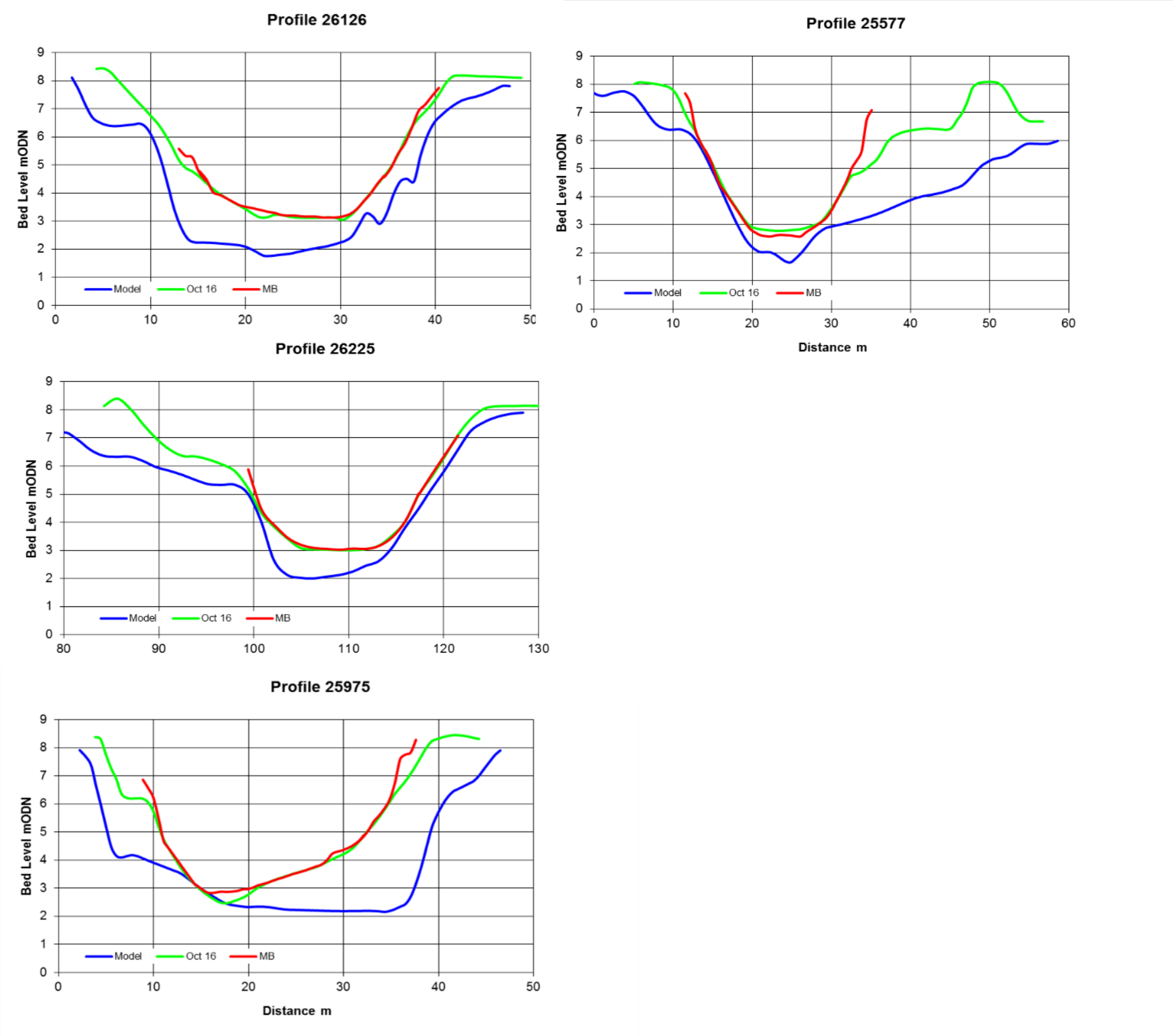


Figure 8B. Channel profiles in the reaches immediately downstream of the monitoring zone.

Rock armour reinforces outer bends, and dredging and other maintenance works ensure that the river does not laterally migrate out of the confining levees. The cross-sectional area of the channel does vary through time however, being subject to natural seasonal and inter-annual fluctuations in bed level in response to alternating cycles of erosion and deposition. Bathymetric (pole) surveys undertaken at 6 monthly intervals from April 2015 to October 2016 through the monitoring reaches (Figure 9 [15]) show a clear pattern of deposition (reduction of the cross-sectional area) through the summer months and scour (enlargement of the cross-section) through the winter months. The channel was largely free of dredging activity during this period, though the changes seen (primarily net deposition, Figures 8 and 9) probably reflect response to the unnatural widening of the channel sections resulting from the pioneer dredge activity in the summer of 2014 [16].

[15] Data and figure provided by R Kidson, SDBC.

[16] There is evidence that although the pioneer dredging increased the cross-sectional areas of the channel, the thalweg depth actually decreased by ~0.5m in the northern parts of the dredged reaches, reducing the thalweg gradient. R Kidson, SDBC, *pers com.*

In Figures 7 and 8, the red (November 2016 multibeam) profiles generally agree well with the green October (pole survey) data below +5m ODN, the deepening between surveys seen in the upper reaches of the EDZ reflecting the fact that dredging of this area had already commenced at the time of the November survey. Variations seen above +5m ODN are due to the inability of the laser data to discriminate vegetation from sediment, therefore limiting the combined multibeam/laser technology from mapping complete profile cross-sectional areas.

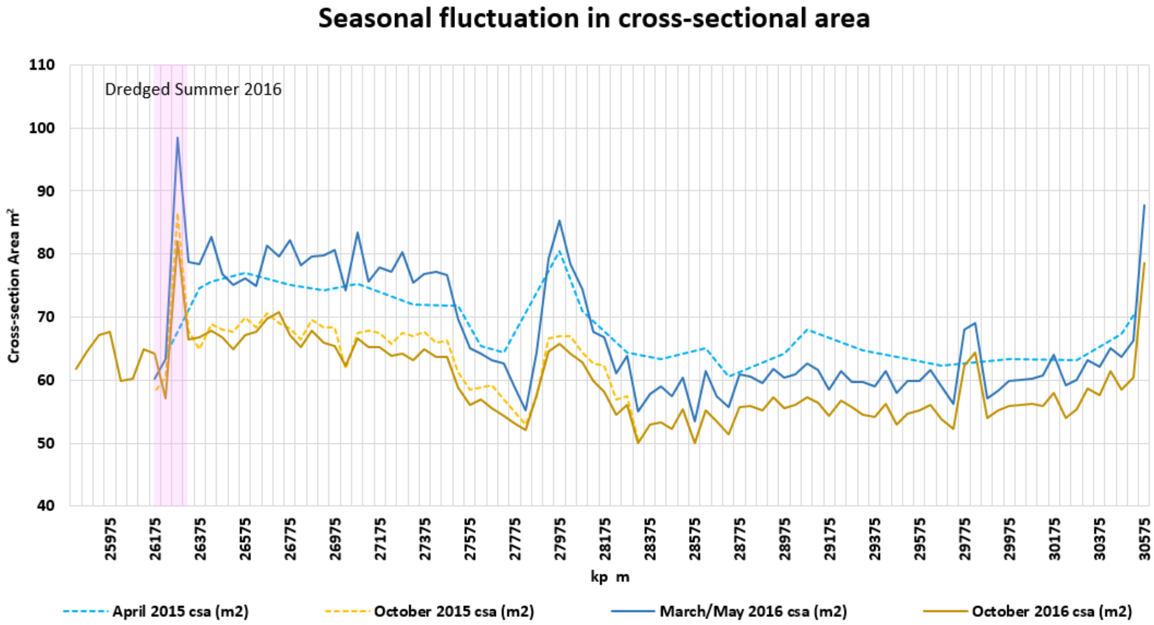


Figure 9. Natural seasonal fluctuations in channel cross-section.

3.2. Bed Sediment Characteristics

Clay and fine-silt sized sediment dominates the mud suspensions of the inner Bristol Channel [4]. Bed sampling and particle-size analyses (PSA) along the Parrett estuary in March and August 2016 (EA data) suggest both a longitudinal variation in the particle-size characteristics of the sediment, and a seasonal variation of those characteristics (Figure 10), viz:

- The sand content of the bed increases landwards, and during the winter. At the mouth sand content is <10%, increasing inland to reach 20-40% at a distance of about 20 km from the mouth, decreasing slightly again towards Burrowbridge, where the sand content was measured at 10% in late summer and 30% in late winter.
- The clay content of the mud fraction tends to decrease landwards, from 20-10% in late winter and 30-20% in late summer, the clay content seeming to build slightly through the summer.
- Coarse silt replaces fine silt landwards, with little apparent seasonal variability. At Burrowbridge, coarse silt is the dominant component of the bed.

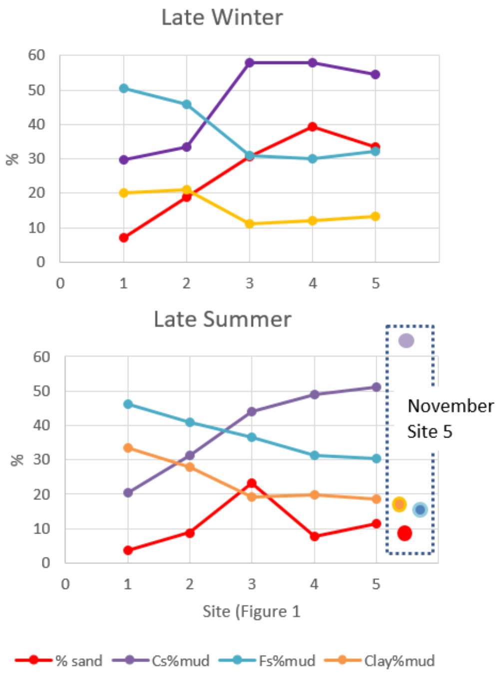
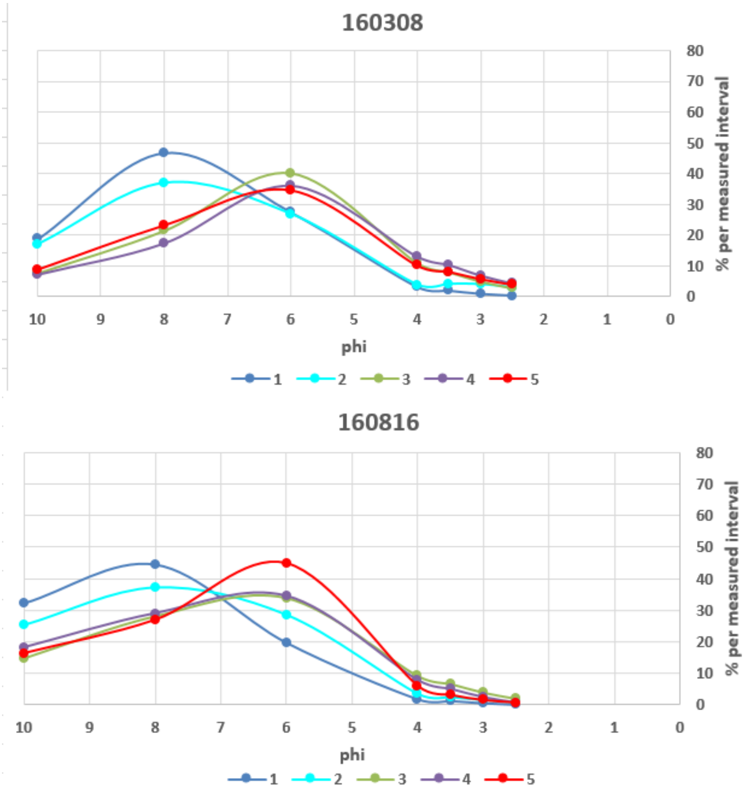


Figure 10. Particle size characteristics of intertidal bed samples along the Parrett Estuary in March (top) and August (bottom) 2016. For site locations see Figure 1. Site 5 equates to the present monitoring zone (upstream end).

%sand = % material >63um in total sample
Cs%mud = % coarse silt (>16um) in the mud (<63um) fraction
Fs%mud = % coarse silt (16-4um) in the mud (<63um) fraction
Clay%mud = % coarse clay (<4um) in the mud (<63um) fraction

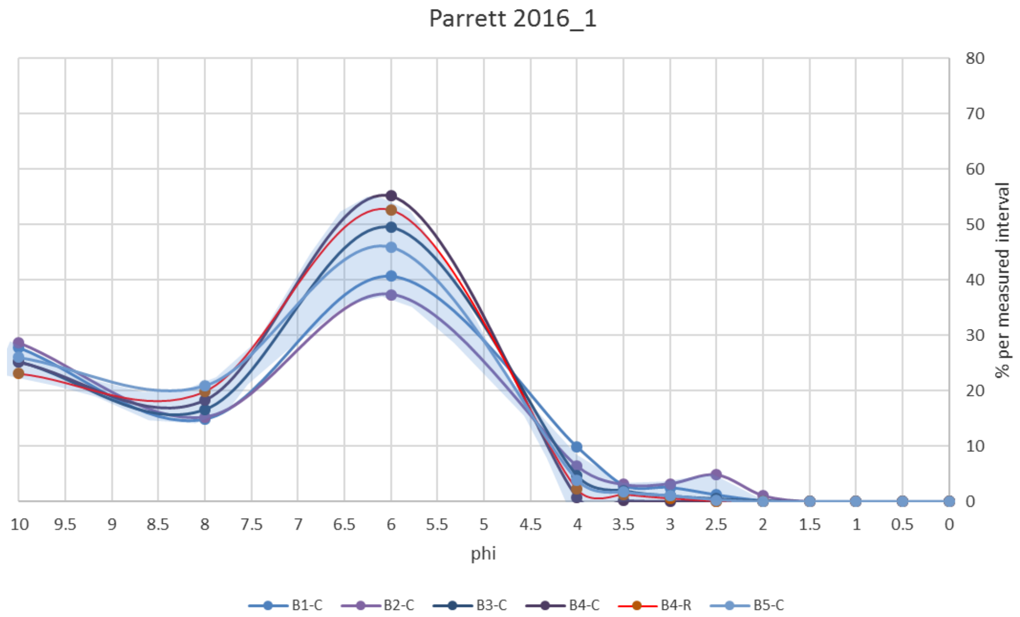
The averages (for the same sediment fractions) of all the 21 samples collected in mid-November at the initiation of the monitoring programme are shown in the lower graph of Figure 10. They correspond well to the EA site 5 data, although showing an even greater dominance of the coarse silt fraction. The latter difference may be an artefact of the different PSA methods used. The EA PSA data are presented as frequency distribution plots in Figure 11.



PHI	mm
1	0.500
2	0.250
3	0.125
4	0.063
5	0.031
6	0.016
8	0.004

Figure 11. 2016 EA data presented as frequency distributions

The frequency distributions for the 21 samples collected at the initiation of the November monitoring are plotted in Figure 12. It can be seen that they correspond well with the EA plots, and they also fall into two distinct groups, corresponding (with slight overlap) to channel centre samples and bank samples (the blue shaded area is the envelope of the plots in the upper graph, for comparison purposes). Summary data for the two groups are given in Table 2. Careful examination shows that within both groups there is a slight increase in the dominance of the coarse silt population (phi=6) from site B1 (landward end of the monitoring zone) to Site B7 (seaward end), contrary to the whole-estuary trend. Otherwise there seems no consistent longitudinal gradient in the bed sediment characteristics through the surveyed zone. Sand is sometimes present as minor fine/very-fine sand particle population, but normally forms just the coarse toe of the silt particle population.



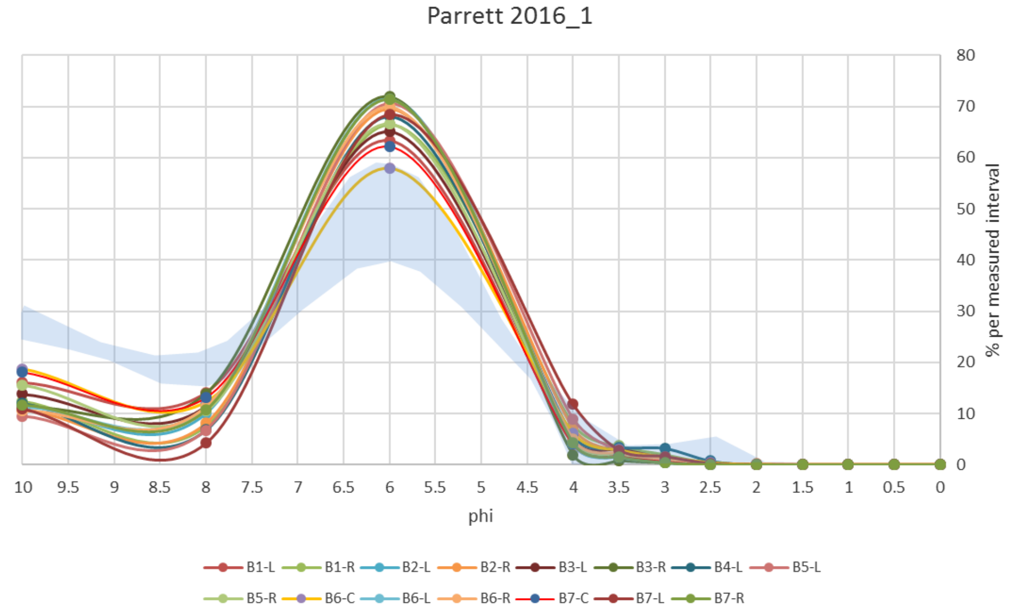


Figure 12. Discrete frequency distribution plots of the PSA data from the initial monitoring bed survey. C=channel centre, L=left bank, R=right bank (looking seawards). See Figure 10 for phi.

	Field Sample ID	% sand (2mm-63um)	% silt & clay (<63um)	% of siltclay coarser than 16um	% of silt/clay finer than 4um	Dry Density t m^3	Bulk Density t m^3	Shear Strength kPa
BANK GROUP	B1-L	6.5	93.5	67.7	17.2	0.7	1.42	1.50
	B1-R	13.8	86.2	77.0	14.3	0.77	1.48	1.50
	B2-L	6.9	93.1	76.7	12.5	0.73	1.45	0.90
	B2-R	11.7	88.3	78.6	12.2	0.79	1.49	1.50
	B3-L	9.7	90.3	72.1	15.3	0.70	1.43	1.08
	B3-R	3.1	96.9	74.2	11.4	0.71	1.44	1.50
	B4-L	13.1	86.9	78.3	13.9	0.72	1.45	1.50
	B5-L	13.1	86.9	81.3	10.9	0.78	1.48	1.50
	B5-R	7.4	92.6	71.8	16.8	0.65	1.40	1.20
	B6-C	11.0	89.0	65.1	21.1	0.69	1.43	
	B6-L	6.1	93.9	76.0	12.0	0.77	1.48	1.50
	B6-R	8.4	91.6	76.2	11.5	0.68	1.42	1.20
	B7-C	6.6	93.4	66.6	19.4	0.62	1.39	
	B7-L	16.5	83.5	81.9	13.0	0.75	1.47	1.10
	B7-R	6.3	93.7	76.2	12.4	0.71	1.44	1.05
	Average	*9.3*	*90.7*	*74.6*	*14.3*	*0.71*	*1.44*	*1.31*
	St Dev	*3.7*	*3.7*	*5.1*	*3.1*	*0.05*	*0.03*	*0.23*
CHANNEL GROUP	B1-C	16.6	83.4	48.8	33.3	0.52	1.33	
	B2-C	18.7	81.3	46.0	35.2	0.49	1.30	
	B3-C	8.4	91.6	54.2	27.6	0.49	1.31	
	B4-C	1.2	98.8	55.9	25.5	0.55	1.34	
	B4-R	4.3	95.7	55.1	24.2	0.72	1.45	
	B5-C	7.1	92.9	49.5	28.0	0.54	1.34	
	Average	*9.4*	*90.6*	*51.6*	*29.0*	*0.55*	*1.34*	
	St Dev	*6.9*	*6.9*	*4.0*	*4.4*	*0.09*	*0.05*	

Table 2. Summary PSA, density and shear strength data for the two sediment groups on the initial survey. Note the shear vane could only read to 1.3 kPa so 1.5 kPa values shown here indicate 'failure not reached'.

Comparing the two (bank and channel) groups it can be seen that there is:

- No variability in the relative sand/mud composition between groups
- A large variation in the relative contribution to the mud fraction of the coarse-silt versus fine-silt/clay fractions, the bank group containing much higher coarse silt and lower clay.
- Higher density in the bank group sediments compared to the channel group. This looks to be a function of the differing silt/clay compositions of the two groups (see density/PSA correlations plotted in Figure 13).

- Three samples do not fall clearly into either group. Sample B4-R is a relict sediment collected from an eroding, armoured outer-bend cliff, and can be explained by not being a product of the present day sedimentary regime. Samples B6-C and B7-C are from seaward end of monitoring zone, where the channel profile widens considerably, and extensive channel shoaling is occurring (Figure 8A). These two samples may therefore flag an important change in the channel floor sediment regime that begins to occur at this chainage.

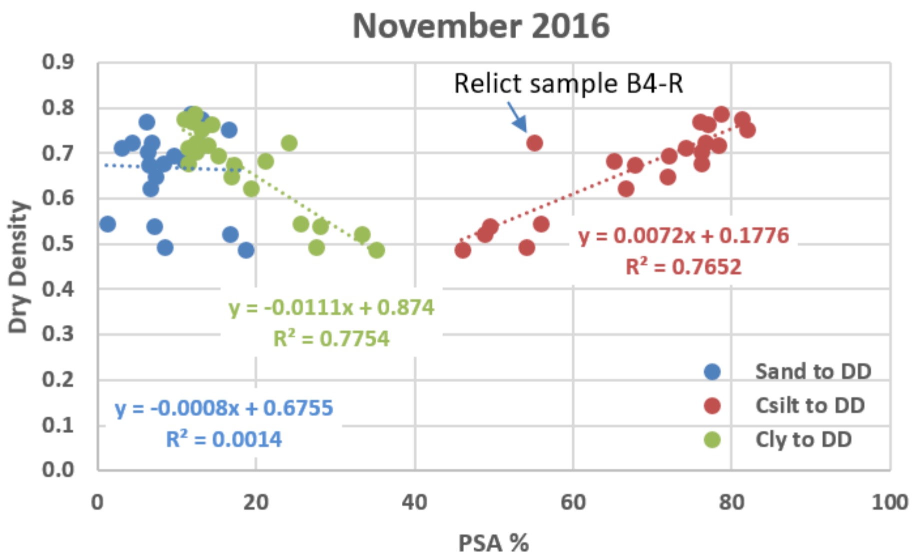


Figure 13. Sediment density to particle-size interdependencies, initial bed survey.

Shear strength data are available for bank data only. The shear vane used could only measure up to 1.3 kPa so values recorded as 1.5 kPa simply indicate that failure did not occur. The values (mean at least 1.3 kPa and lowest value seen 0.9 kPa, Table 2) are surprisingly high for natural estuary mud deposits. Analysis showed no, or very poor, correlation between shear strength and density or any of the PSA characteristics. This lack of correlation suggests that history (consolidation/drying time) is probably the primary control of shear strength. It was not feasible to make shear strength measurements on the inundated channel floor, however the appearance of the grab samples also suggested a high degree of consolidation/shear strength, comparable to the bank values.

The visual observations on the intertidal mud surfaces made during the bed sampling survey are reproduced in full in Appendix 3. The following key features emerged:

- At the landward end of the monitoring zone reeds often come down to the water's edge along much of the length of the banks (Figure 14 A). Bare sediment 'bays' are present between reed zones, and are quite steep in places. The bays become larger and more frequent going seawards. At the furthest seaward extremity of the survey area the reeds are rarely present along the LW mark, and wide, shallower angle bare mud zones typically dominate (Figure 14B).
- At the landward end of the monitoring zone the sediment surfaces are not smooth and tend to be criss-crossed with both lateral (90° to the river axis) and longitudinal features (Figure 14C). The latter probably form as micro-cliffs at the water's edge during higher stage levels, or are very minor slump faces. The origin of the former is unclear; they seem to be degrading features and could either be formed as downslope rain-wash rills, or be the remnants of transverse bedforms (likely a mix of both origins).

Figure 14. Photographs of key intertidal bed features, pre-dredge survey

Figure 15. Site BS04 Left bank, showing transverse ripple marks and micro-cliffing.

- Further south, the transverse bed features become stronger in many places and are clearly ripple marks (Figures 14B & 15, wavelength of about 20cm). Drainage seeping from the bank is guided by, and enlarges, the ripple troughs. The ripples tend to be symmetrical, not suggesting a direction for the formative flow.
- No evidence of active slumping on a large scale (few minor features).

3.3. Fluvial Discharge

Freshwater passes through the region on its way to the sea in a complex fashion involving the main watercourses (Tone and Parrett), sluices and spillways, floodplain water storage areas, bypass channels and pumping stations (Figure 16). As a result of the complexity of this system there is a paucity of data available to describe (statistically and as time series) the throughflow of fresh water.

Water levels are recorded at many sites on the river, the five relied on in this study are plotted (in green) in Figure 1. The recorders at Saltmoor and Northmoor pumping station best represents water levels at the landward and seaward ends of the monitoring zone respectively. Data are available 2012-2017 (plotted in Figure 17). The lower edges of the blue dot zones represent water level attributable to river discharge alone, and show clearly the periods of peak river discharge between December and March each year. The upper edge of the blue dots shows the monthly peaks of the effects of the highest lunar tides, and (in winter time and occasionally during other seasons) the river flood peaks.

All the estuary stage data are plotted in Figure 18 (A, B & C, November 16, December 16 and January 17 respectively). For each month of data at the Northmoor and Saltmoor sites an analysis has been undertaken to determine the Base River Flow (defined as the lowest water level found between one hour before and six hours after LW at Hinkley point, shown in centre graphs of Figure 18). This plot is probably the best available representation of levels representing true river water flow through the Parrett. Some patchy EA river discharge data are available and are used to annotate the base flow in Figure 18A (November, 5-40m^3 s^{-1}). During December and January river discharge probably varied between 10 and 20 m^3 s^{-1}. It is possible that the slight increases in Base River Flow levels seen (during all three months) to coincide with the periods of spring tides are the result of incomplete escape of tidal waters from the uppermost tidal reaches per tidal cycle, but rainfall events may also be the cause. Minor stage events were recorded in the upper catchment areas on the 9th November and the 10th - 15th December and also in January, possibly explaining these base flow variations. The same graphs show the normal persistence of a low tide steady downstream head of water between the Saltmoor and Northmoor sites, of up to 0.5m at times of low river flow reducing to 0.2m or less at times of higher river flow.

Figure 16. The Parrett and Tone: Drainage routes, spillways, pumping stations and water storage areas. The Severn Estuary is to the north (top).

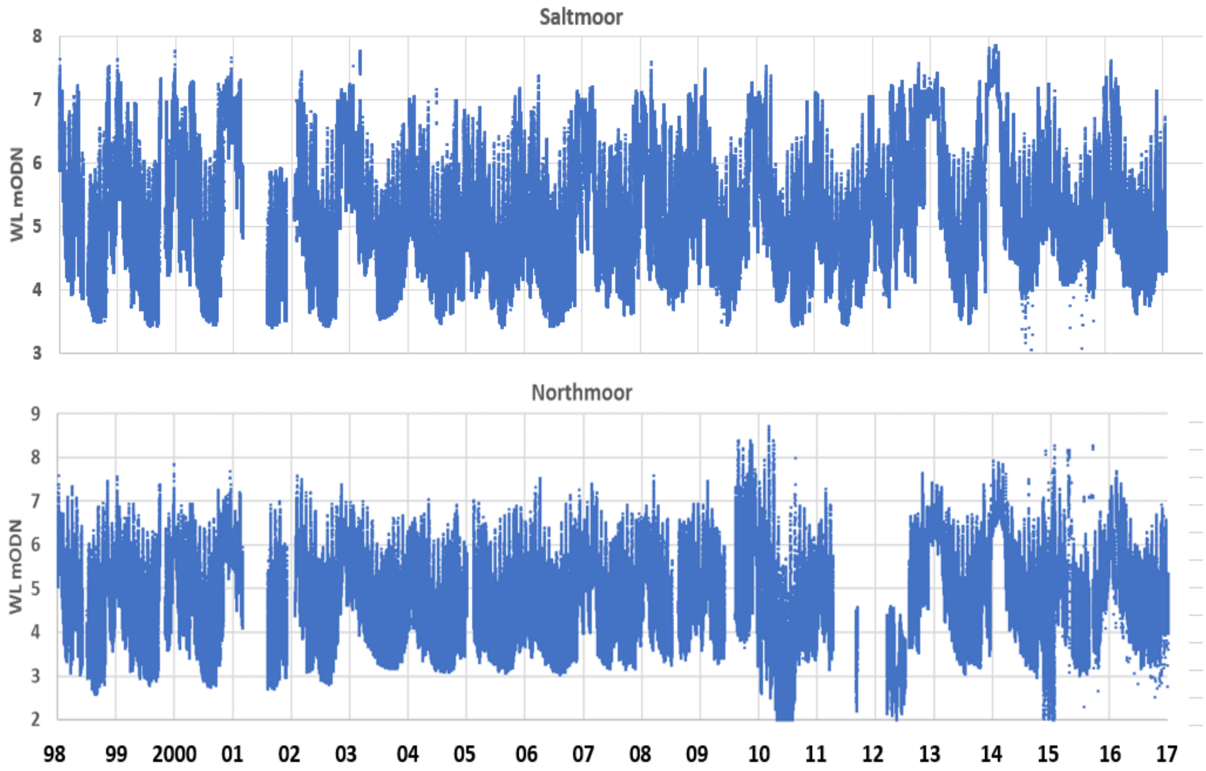


Figure 17. Water levels recorded at Saltmoor and Northmoor Pumping Stations 1998-2017. (These data seem to contain some sensor malfunctions at low water levels).

3.4. Tidal Regime

The Bristol Channel has a very large tide range, with some 14m recorded between the highest and lowest tides. The standard tide levels for Hinkley Point, the gauge at the western edge of Bridgwater Bay, are given in Table 3.

	m CD	mODN
Highest astronomical tide	13.02	7.12
Mean high water springs	11.83	5.93
Mean high water neaps	8.91	3.01
Mean low water neaps	3.59	-2.31
Mean low water springs	0.92	-4.98
Chart Datum (CD)	0	-5.9
Lowest astronomical tide	-0.19	-6.09

Hinkley High Water Level =
*0.5255 * (tide range) + 0.1876*
$R^2 = 0.9718$

Table 3. Tide levels at Hinkley Point and high water level to tide range correlation equation.

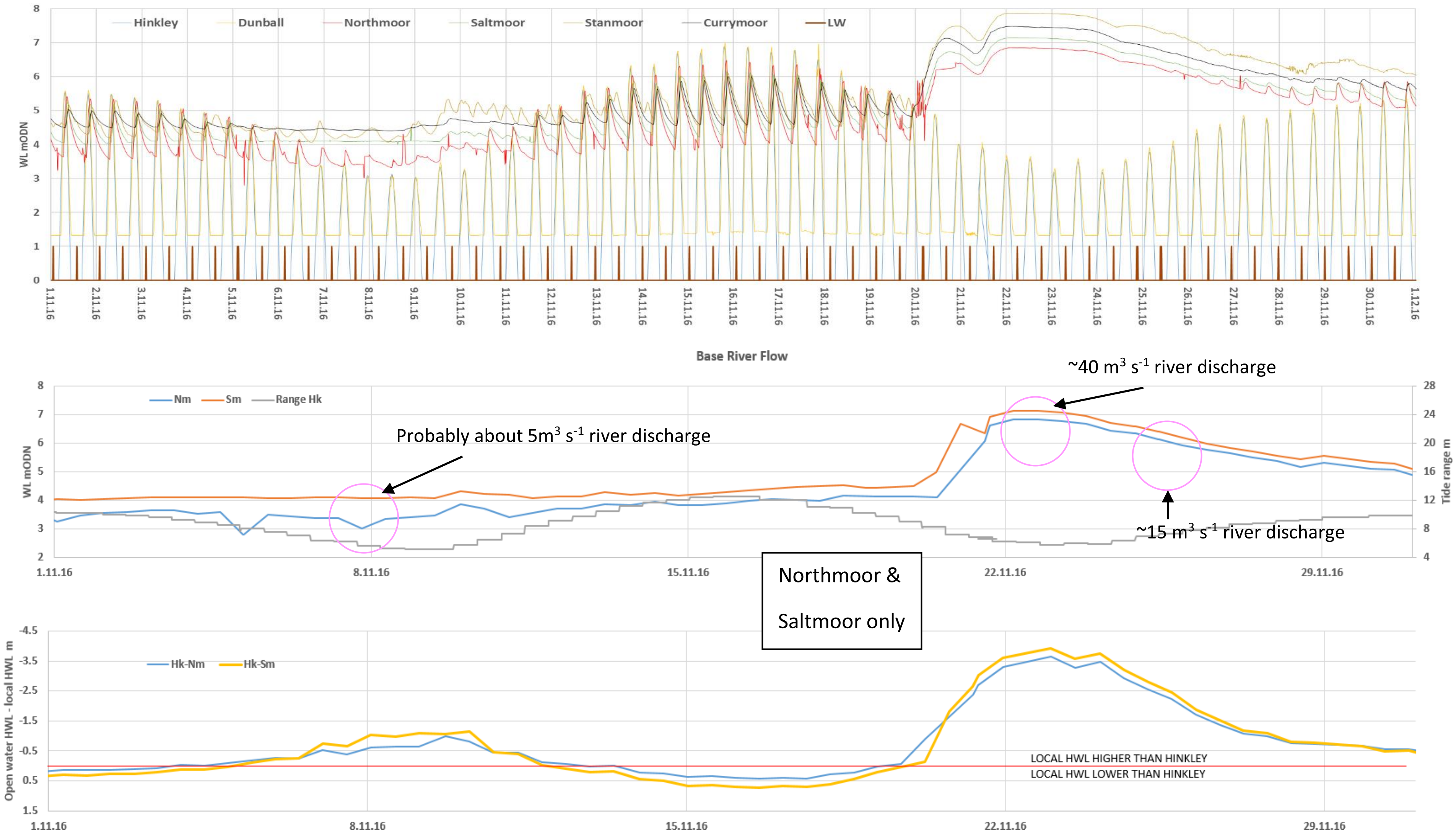


Figure 18A. November 2016 estuary water levels. Top: stage records from all sites. Middle: Base River Flow. Bottom: HW level differences on Hinkley

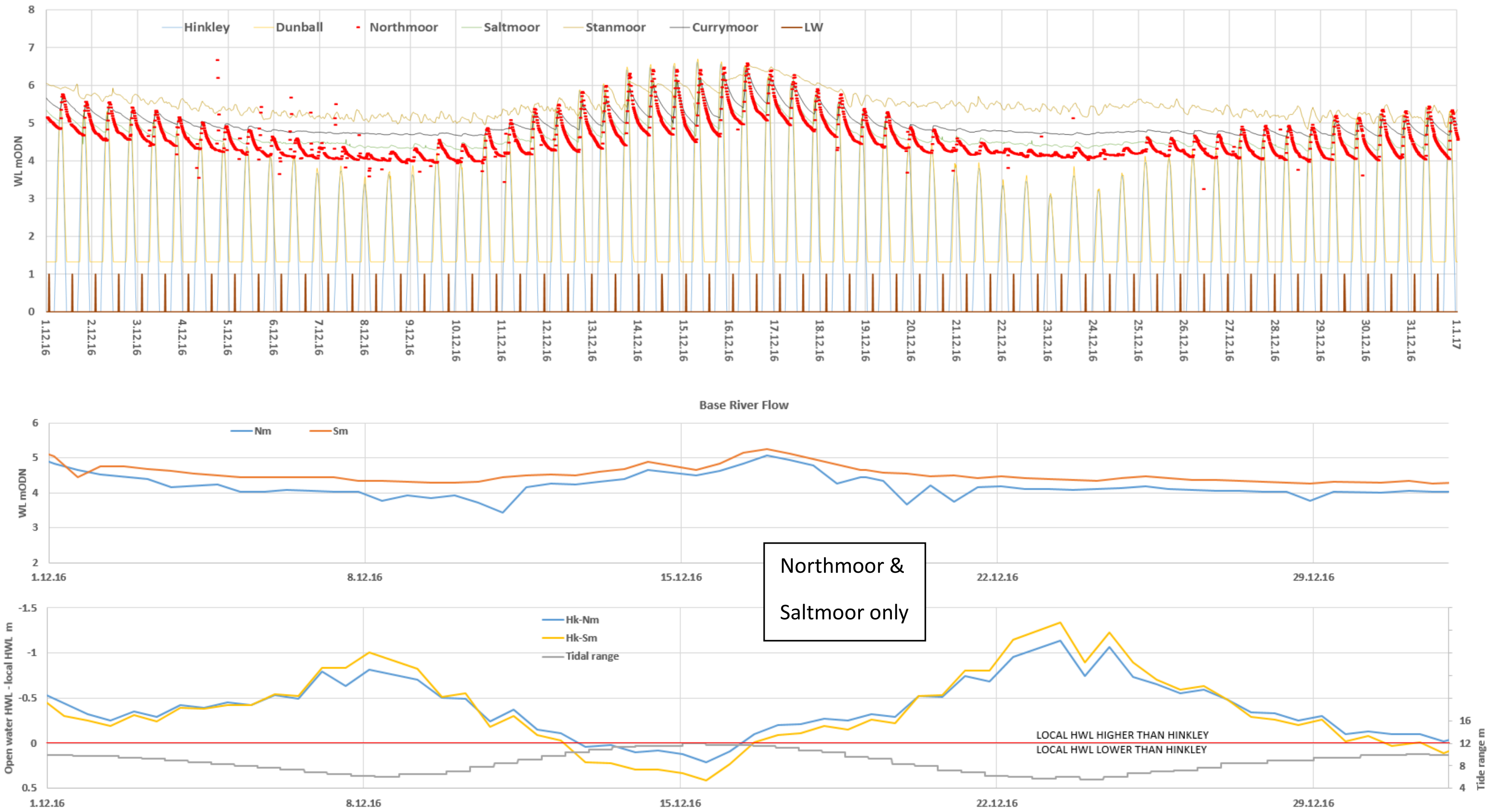


Figure 18B. December 2016 estuary water levels. Top: stage records from all sites. Middle: Base River Flow. Bottom: HW level differences on Hinkley

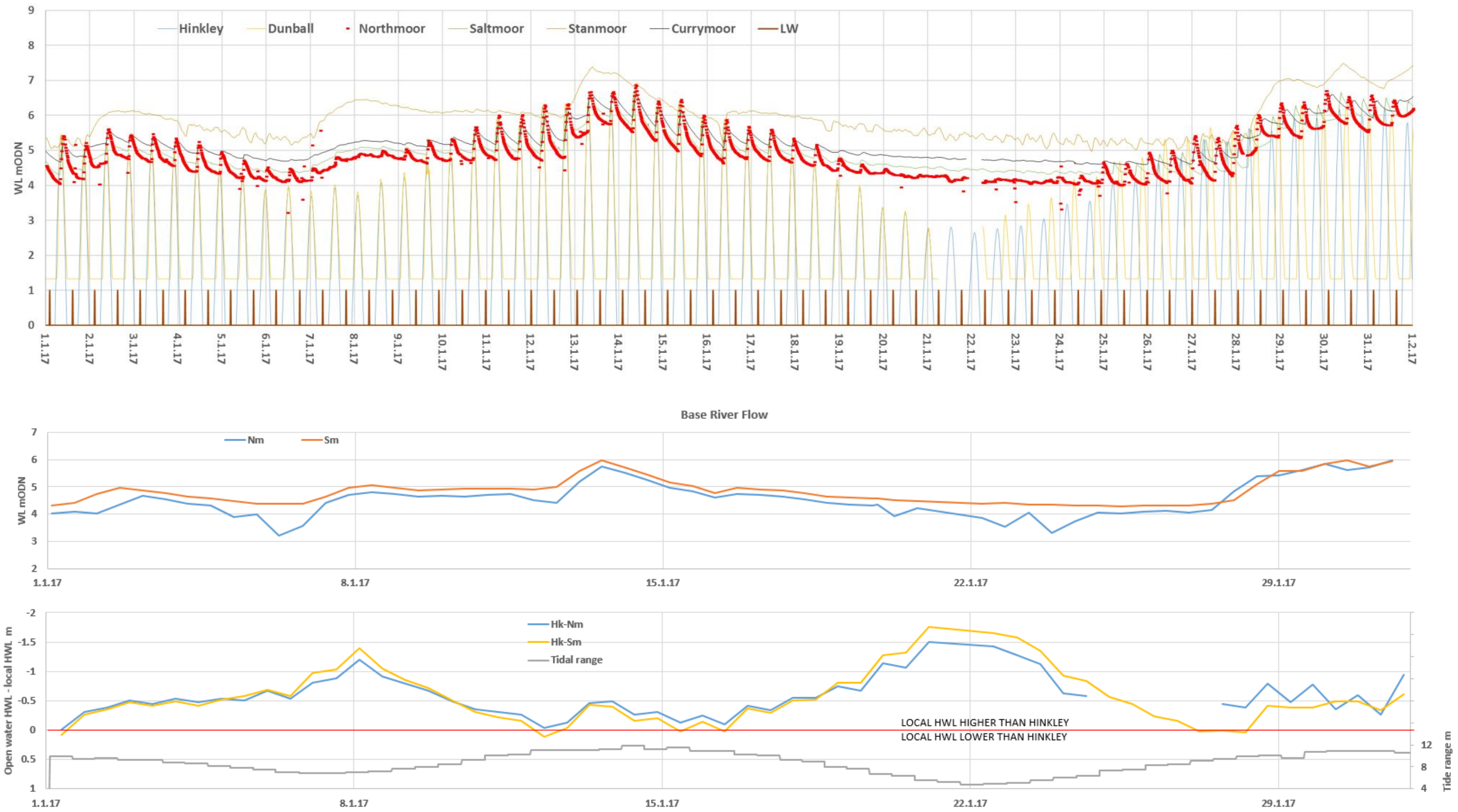


Figure 18C. January 2017 estuary water levels. Top: stage records from all sites. Middle: Base River Flow. Bottom: HW level differences on Hinkley.

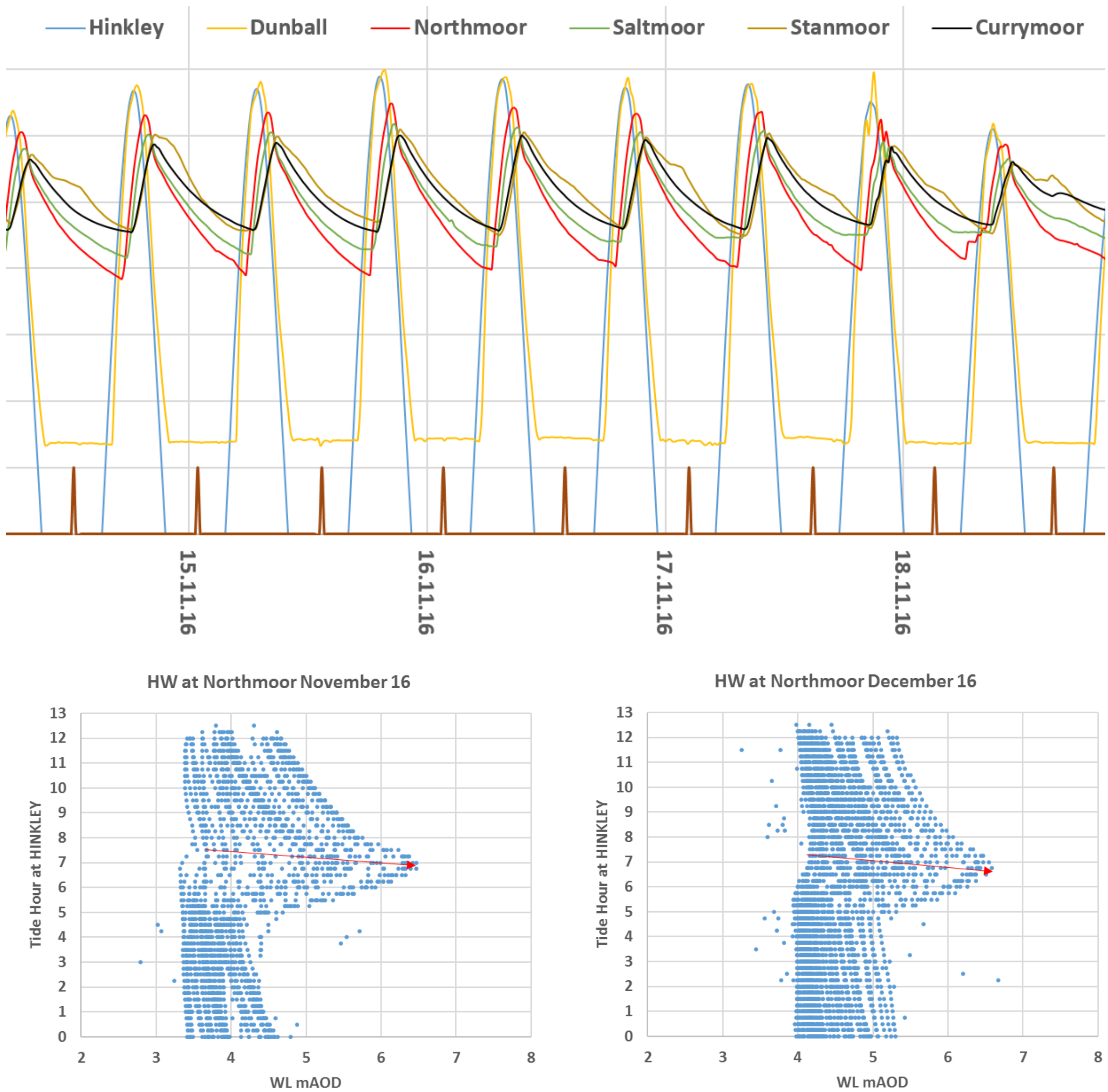


Figure 19. Detail plots of compared levels and timings of the tidal curve in the upper estuary.

Recorded water levels in the estuary through the survey period, November, December 2016 and January 2017 are shown in Figure 18A, B & C respectively. Figure 19 (top) shows an expanded part of the November data plot. The levels seen are a combination of tidal and fluvial effects, less so in December and January when river discharges were lower than the November peak flow..

The combination of high tidal range and a long narrow morphology strongly modifies the form of the tide as it progresses up the Parrett estuary. Figures 18 &19 data demonstrate the following features of the progression:

- The tide-level curve is asymmetrical, with a steeply rising flood limb and a long drawn-out ebb limb. On spring tides the flood typically begins about 2 hours before local HW and the ebb occupies the remainder of the (~12.5 hour) tidal cycle, with the water level still falling until the start of the flood. This situation sometimes generates a small bore at the beginning of the flood, with a ~0.3m high wave progressing upstream.

- There is a lag in the local time of HW as the tide wave moves up the estuary, with a spring tide one hour difference between HW at Hinkley Point and HW at Northmoor, and a 2 hour lag between Hinkley HW and HW at the tidal limits (Stanmoor recorder on the Parrett and Currymoor recorder on the Tone). This lag time can increase by a further half-hour on neap tides (Figure 19 bottom graph).
- As the thalweg bed level at Northmoor is ~+2.5m ODN, and on low flows there is always at least 0.5m of water in the river (water surface at +3m ODN), neap tides (Table 3) are only just felt at this site, and hardly any semidiurnal effects at all are seen at Saltmoor where levels are ~0.5m higher. Low neap tide HW takes the form of a backing up of river flow rather than the passing of the landward-flowing front of the rising tide. The bottom graphs in Figures 17 and 18 show the local high-tide water level (at Northmoor and Saltmoor) compared to the level reached at Hinkley Point. It can be seen that when the tidal range at Hinkley is less than about 8m, the high water condition in the monitoring zone (between the Northmoor and Saltmoor sites) is one of backing up of river water, with the Saltmoor HW level greater than that at Northmoor. At higher tidal ranges the HW level at Northmoor is greater than that at Saltmoor, consistent with the passing of the crest of the tidal wave and some dissipation of its energy between the two sites. This model of the (low river discharge) tidal mechanism and lag times is summarised in Figure 20. High river discharge modifies this model, increasing water levels relative to Hinkley and reducing lag times (to as low as ~30 minutes).

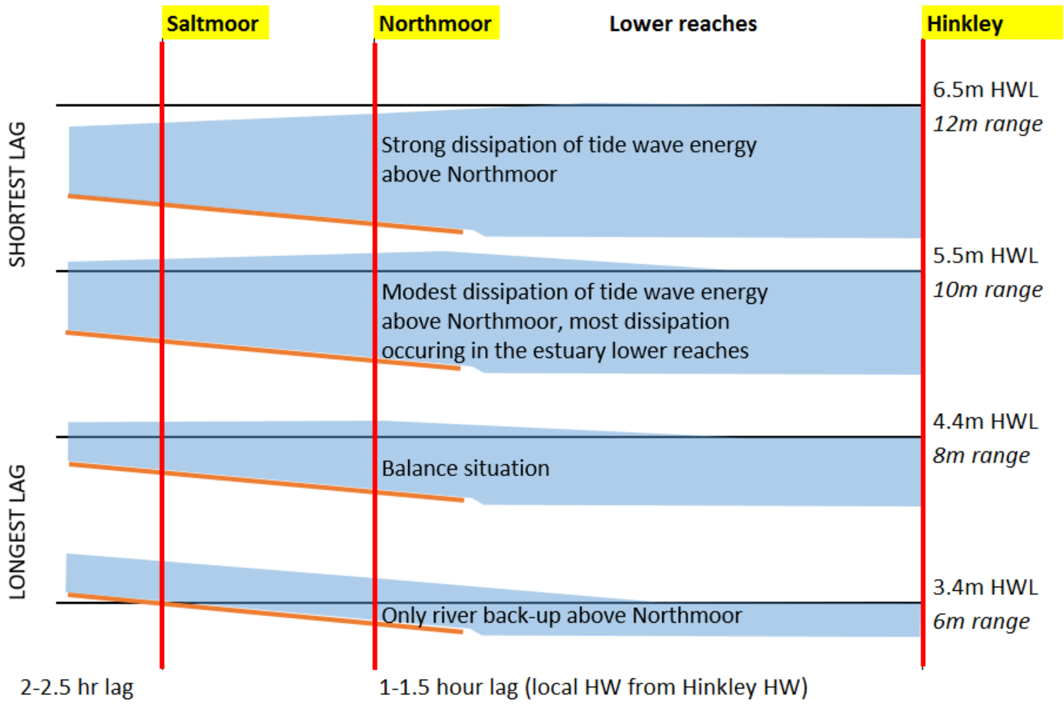


Figure 20. A model of high tide levels reached in the upper Parrett estuary compared to offshore tide levels, illustrating the changed drivers of water level elevation between spring and neap conditions.

In November at the Westonzoyland autonomous near-water-surface WQ sensor the mean and median salinity values were 0.50 and 0.47 respectively. The minimum salinity was <0.01 and was seen at the time of peak river discharge. Higher than the median salinity values were seen once the tidal range at Hinkley rose above about 11m, that is on high springs. The values rose through the flood, peaking at HW, with the greatest value (7.92) coinciding with the highest tide (16th). Manned monitoring was undertaken the same day commencing exactly at HW in the centre of the experimental dredging zone. Values recorded were generally around 1.5, rising to 2.9 near the bed on one cast. At the Burrowbridge permanent sensor site the equivalent mean, median, maximum and minimum salinity values through November were 0.44, 0.47, 1.01 and <0.01 respectively.

In December no manned surveys were taken over high spring tides. The Westonzoyland sensor recorded mean, median, maximum and minimum salinity values of 0.52, 0.47, 2.0 and 0.02 respectively, very similar to the November data except for the maximum value (spring tide maximum ranges were lower in December, Figure 18). The equivalent values from Burrowbridge were 0.51, 0.47, 0.68 and 0.01.

The salinity data collected during November and December (with low river flow for much of the period) indicate that these upper reaches of the Parrett estuary lie above the zone of saline water intrusion. No marked salinity stratification was observed, and maximum values were low (reaching 7 at times of very low river flow and highest annual tide range). Data collected during July and August 2008 at Partrac sites 1-7 (Figure 1) show similar/lower salinity values (Table 4). Maximum tidal range at that time was probably slightly lower than conditions seen in November 2016, and minor freshwater flood peaks were also reported

Site	Salinity (PSU)		
	Minimum	Maximum	Average
Site 1	0.20	3.39	0.30
Site 2	0.20	0.34	0.27
Site 3	0.20	0.41	0.30
Site 5	0.17	0.26	0.23
Site 6	0.17	0.26	0.23
Site 7	0.20	0.31	0.25

Table 4. Salinity statistics July/August 2008 at the Partrac sites (Figure 1).

Tidal currents were not directly recorded during the November-December 2016 monitoring. However average current speeds could be roughly determined from the time it took the drogues to pass though the monitoring reaches during manned monitoring exercises (Section 2.4). Drogue runs were made during a ~3 hour period immediately following local HW. Mean velocity could be determined over a 1.5 to 2km set of reaches. The results are plotted in Table 5. Fastest velocity (1.2 m s^{-1}) was encountered in the period immediately following HW on the day of the highest spring tide and very low river flow. Spring tide/low river flow velocities observed at other times lay in the range 0.56 – 0.96 m s^{-1}. The lowest velocity seen was on the 25th November during the period of peak river flow, when no tidal effects were evident (Figure 17). Both the latter runs showed velocity values of ~0.46 m s^{-1}. These slower flows at higher river stage are consistent with the lower water surface gradient that persists under these conditions (Figure 18 middle graph). During the declining river flood limb velocities increased again to 0.69-0.78m s^{-1}.

These data are very consistent with observations made by Partrac in 2008, at two sites (in and below the monitoring zone, Figure 1) and at 1m above the bed. These data are reproduced in part in Figure 21. The plots show peak velocities at high water, declining slowly through the long ebb period, then dropping to near zero just before the beginning of the flood tide. Ebb values on spring tides were around 0.8m s^{-1}, consistent with the drogue tracking results. On neap tides velocity maxima drops to about 0.6m s^{-1}. At the end of the period shown there was a minor river flood event, during which the strongest velocities were seen (reaching ~1m s^{-1} at site 2, within the monitoring zone). This increase in velocity contrasts with the marked reduction in velocity seen in November during a much more substantive river event. It is possible that this difference relates to differing water-depth to channel cross-section areas between minor and major flood events.

Date *Nov*	**Run**	**Velocity** *m/s*	**Condition**
14	1	0.8	Spring tide, very low river
16	1	1.2	Highest spring tide, very low river
	2	0.62	
18	1	0.56	Spring tide, very low river
	2	0.96	
25	1	0.46	Peak river flow
	2	0.47	
28	1	0.78	Declining but high river flow
	2	0.78	
	3	0.69	

Table 5. Reach-averaged water velocities from drogue tracking.

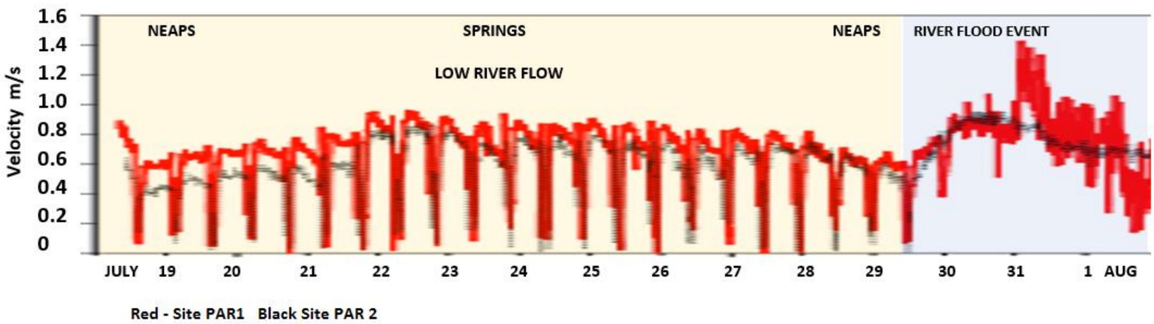


Figure 21. Partrac water flow data for late July 2008 at sites within and downstream of the monitoring zone (Figure 1). Velocities recorded at 1m above the bed.

3.5. Human Activity

As covered in Section 3.3, this system of watercourses is very much under human control. Maintenance bank works and dredging to maintain depths and channel cross-sections is one aspect of that control, with changes occurring over timescales of years and decades. Water diversion however, through use of sluices and pumps, will change on an hourly-through weekly timescale. During the November-December 2016 monitoring period, there was a two day period (21-22nd Nov) when the Parrett spillways overflowed, followed by approximately 7 days, when most of the main Pumping Stations were operational..

3.6. The Natural Sediment Regime

The bed sediment survey undertaken clearly shows that a) cohesive sediment dynamics will dictate the sediment transport processes that occur in this area and b) once in motion, processes of sediment suspension (rather than bedload transport) will dominate. Some rolling of material along the bed (gravel particles, highly consolidated mud clasts/balls) may occur at times of highest flow velocities, but they are likely to play a minor role in the sedimentary regime.

Data on the natural suspended sediment regime have collected as follows.

- Autonomous surface water turbidity recorders (WZ and BB) were deployed on 20th of October and ran until 14th November before dredge works commenced
- The same recorders ran from 19th December until 16th January 2017. The latter data set can be regarded both covering the dredge recovery period and (if there is no noticeable post dredging level of effect) the natural system. These data are initially and cautiously examined here on the basis of the latter premise.
- Manual turbidity profiling was run on the 14th November, the day before dredging commenced, and also on the 5th December, a few days after the completion of dredging. Again the latter day of data may show dredge recovery effects, but are initially examined in this section.
- Partrac data are available from 2008-9.

PRE-DREDGING

The manual turbidity profiling data are considered here first, as they provide insight into how much vertical variation in turbidity is present, and therefore how representative the surface water sensors are of the full situation. The survey was undertaken on the 14th November, with low river flow, tidal range 11.6m (high spring), HW at Hinkley 5:53 GMT (6.26m OD) and HW at Northmoor 07:00 GMT (6.04m). Monitoring began at 8:15 and ran through until 12:30. For the first two hours the vessel was stationary alongside the pontoon at Westonzoyland, during the next 1.25 hours a drogue-track run was made through the monitoring zone, and the final hour saw stationary observations alongside the pontoon again. Observations at a fixed height in the water column (~0.8m below the water surface) are plotted in Figure 22 and profile data in Figure 23.

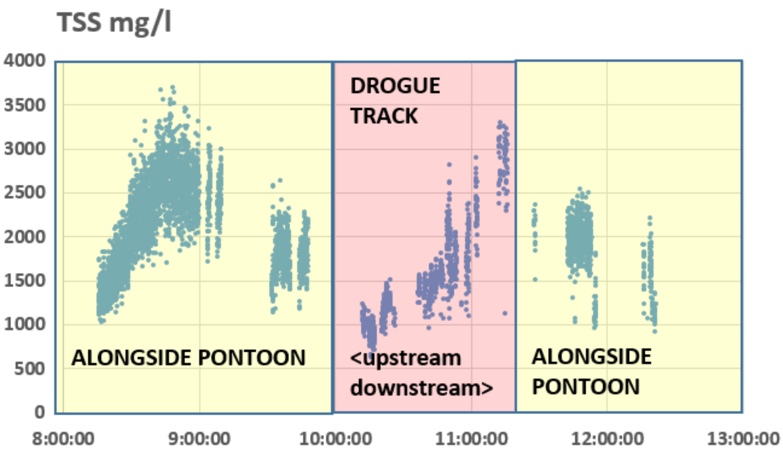
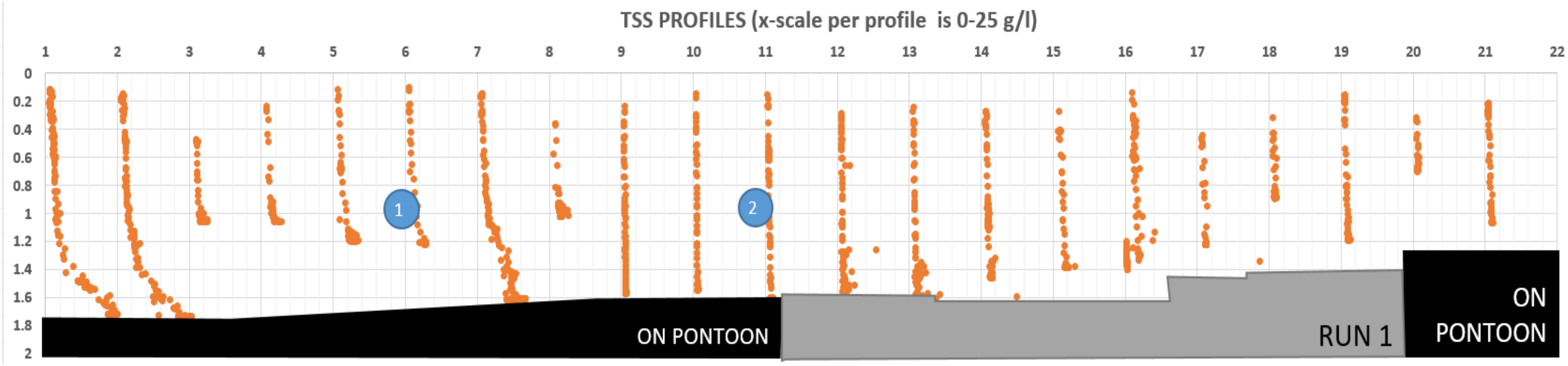


Figure 22. Pre-dredge Total Suspended Solids (TSS) data, 14th November 2016, observations at a set depth (time vs TSS plot).

Mean = 1980 mg/l
Median = 1958 mg/l
Maximum = 3700 mg/l
Minimum = 542 mg/l



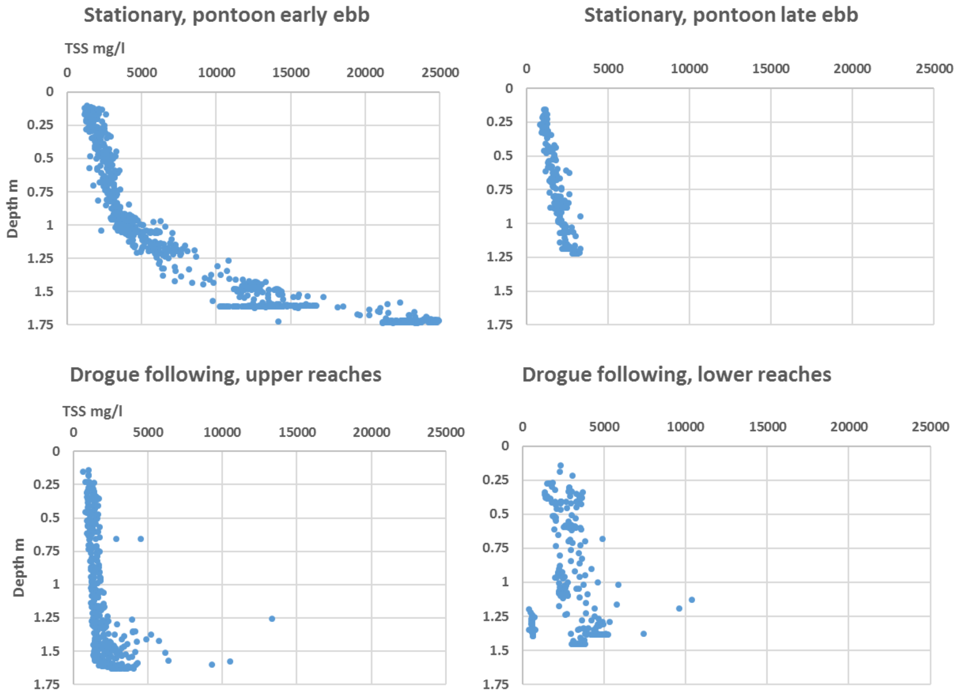


Figure 23. Pre-dredge Total Suspended Solids (TSS) data, 14th November 2016, profile observations (y-axis is depth in metres).

Top: All profiles in time sequence. Middle: All readings while moored alongside the pontoon, divided into early and late ebb datasets. Bottom: All drogue tracking data (following the same plug of water as it moves down the estuary), divided into upper and lower reaches.

Numbered blue circles are water samples taken for TSS calibration.

mg/l	Mean	Median	Max	Min	StDev
Stationary Early Ebb	9369	5973	25654	1171	7560
Stationary Late Ebb	1982	1967	3333	862	586
Drogue upper reaches	2013	1601	37364	652	1953
Drogue lower reaches	2805	2798	46662	391	2799

The key observations arising from this dataset can be summarised as follows.

- Only ebb tide conditions have been observed, and on a high spring tide.
- The mean-median TSS values lie in the range ~2-9 g/l, with minimum values around 500mg/l and maximum values exceeding 25 g/l.
- TSS levels increased through the early ebb, peaking at around 2 hours after local HW then decreased, quickly at first then slowly, through the remainder of the ebb.
- There was a strong vertical gradient in the TSS profile, with near-bed values being between 2 and 10 times higher than the near-surface values.
- During the first part of the ebb, there was a steady increase in TSS towards the bed, consistent with mud erosion occurring from the bed with particles being mixed up into the flow. In certain profiles during drogue tracking (mid ebb) in the upper reaches, the TSS profile gradient was less marked in the upper water column but there was a strong step in the lower profile with high near-bed TSS observed. In strongly flowing water this step feature is suggestive of active bed erosion.
- The set-level drogue following (Figure 22) showed that TSS steadily increased through the monitoring area as the followed plug of water moved through the zone, again demonstrating that erosion was occurring.
- In conclusion, it seems the reaches through the monitoring area were subject to active bed erosion through this spring tide ebb flow, with erosion peaking about 2 hours after local HW. Due to strong vertical TSS gradients, total TSS seen by a near-surface sensor will underestimate the sediment load being carried.

Time-series plots for the WZ and BB autonomous surface water sensors for the pre-dredge period are shown in Figure 24. The TSS data from this plot have been analysed and replotted as tide-hour graphs, grouped by lunar (spring-neap) tidal range (Figure 25). The summary statistics, grouped by spring/neap/higher river flow periods are given in Figure 26. The salient features of the suspended sediment regime that emerge from this late autumn data-set can be summarised as follows.

- The timeseries data (Figure 24) show at first glance that much more sediment is in motion over spring tide period and neaps, and at WZ compared to BB. This observation is quantified in the statistics if Figure 26.
- The spring tide periods at WZ have mean/median values of 300-900 mg/l (figure 26), comparable to the surface values from profiling data (Figure 23). Maximum TSS values as both WZ and BB reach only 10000 mg/l, less than half of near-bed values seen in profiling, due to the vertical variability in TSS. Differences between manned/autonomous datasets will also be due to the fact that both flood and ebb periods are included in the autonomous dataset, but the profiling data only covered the initial phase of the ebb tide.
- Neap tide mean/median values are significantly lower than the spring tide values, have a range of 50-500mg/l (WZ and BB, Figure 26), suggesting that bed erosion is less effective over neap tides.
- The small river flood event seen early in the period (Figure 24, within a neap period) produced a TSS peak but mean/median values were around 500 mg/l at WZ, indicating that minor flood events are not as effective at causing bed erosion as spring tides, but are more effective than neap tides.

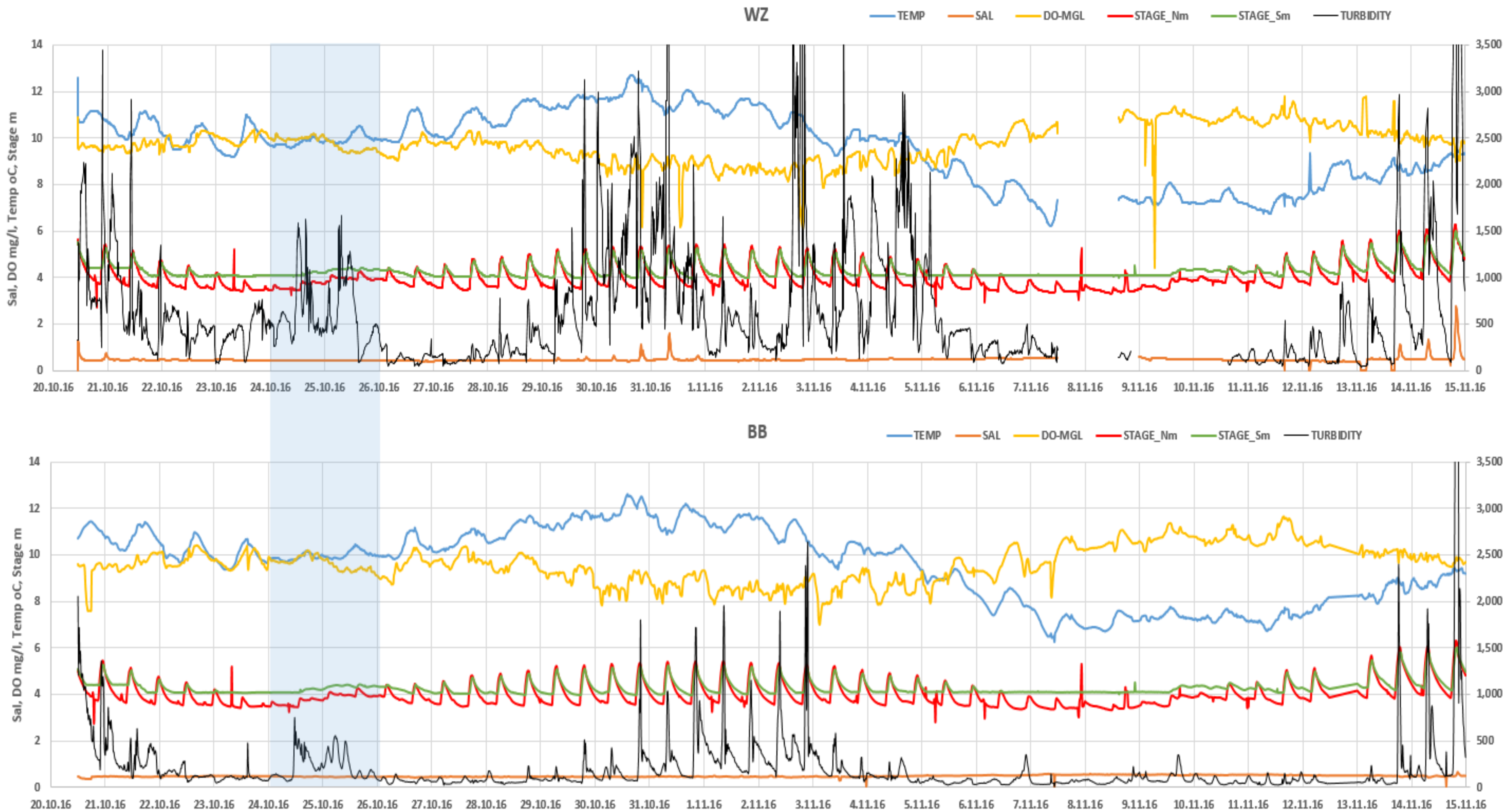


Figure 24. Westonzoyland (WZ) and Burrowbridge (BB) surface water sensor data for the pre-dredge period (20th October to 14th November). Blue shaded area is a minor river flood event.

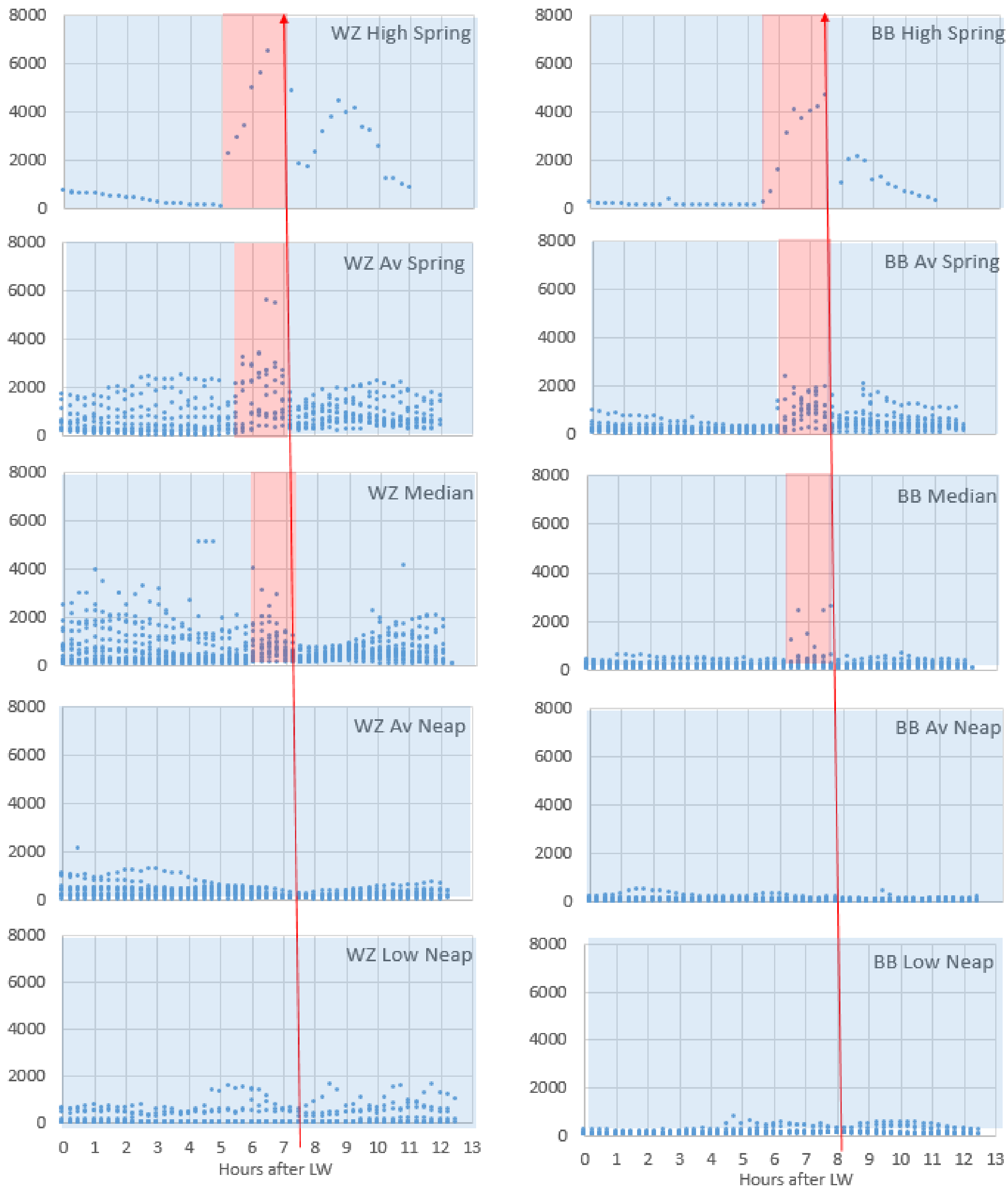
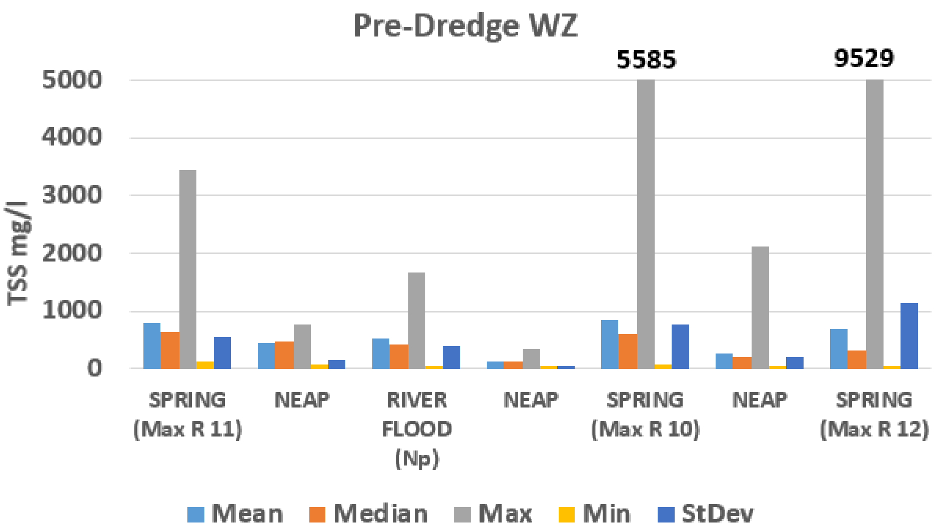


Figure 25. Pre-dredge surface water sensor TSS data (WZ & BB) tide-hour plots grouped by spring-neap condition. The red line is HW. Red shading is upstream water flow, blue shading is downstream water flow. Y axis is TSS mg/l.

The four spring neap groups correspond to tide ranges (top to bottom) >12m, 10-12m, 8-10m, 6-8m and <6m (see Figure 20).

	Mean	Median	Max	Min	StDev
SPRING (Max R 11)	781	627	3443	116	565
NEAP	437	462	769	78	158
RIVER FLOOD (Np)	520	433	1666	54	399
NEAP	122	119	343	53	52
SPRING (Max R 10)	849	594	5585	72	775
NEAP	260	199	2129	61	198
SPRING (Max R 12)	690	302	9529	42	1126



	Mean	Median	Max	Min	StDev
SPRING (Max R 11)	390	243	1835	57	356
NEAP	105	105	476	48	39
RIVER FLOOD	212	170	751	33	150
NEAP	66	62	110	24	22
SPRING (Max R 10)	233	145	2608	32	276
NEAP	73	63	352	6	49
SPRING (Max R 12)	336	91	10254	24	879

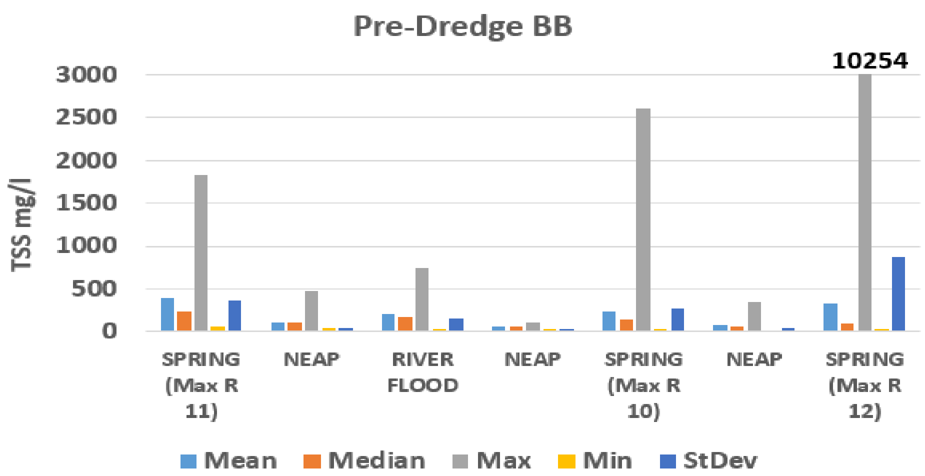
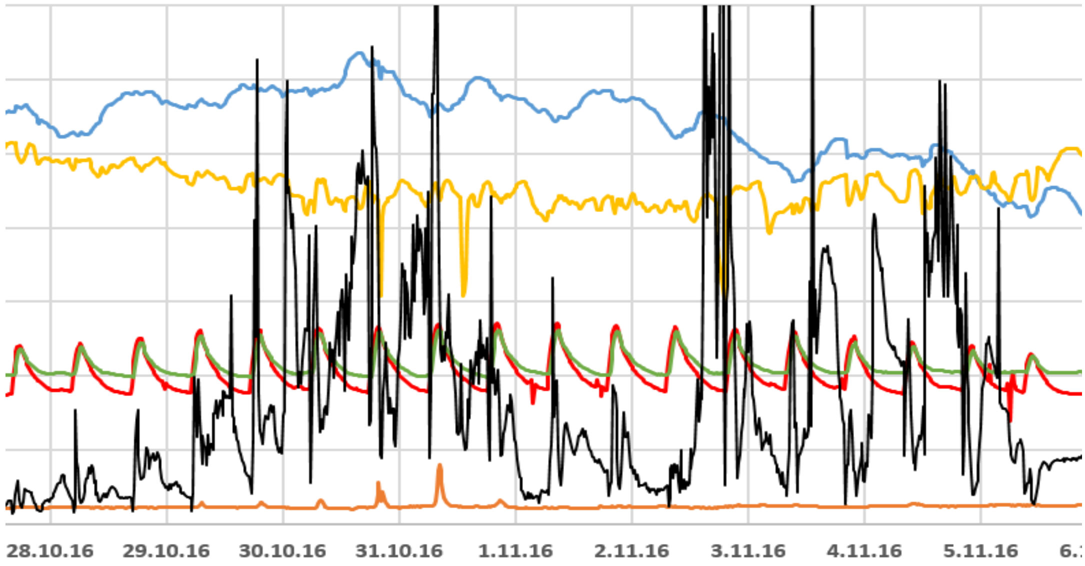


Figure 26. Summary statistics for pre-dredge TSS conditions for WZ (top) and BB (bottom). Neap to spring differentiation is based on 8m range at Hinkley Point. R=range.



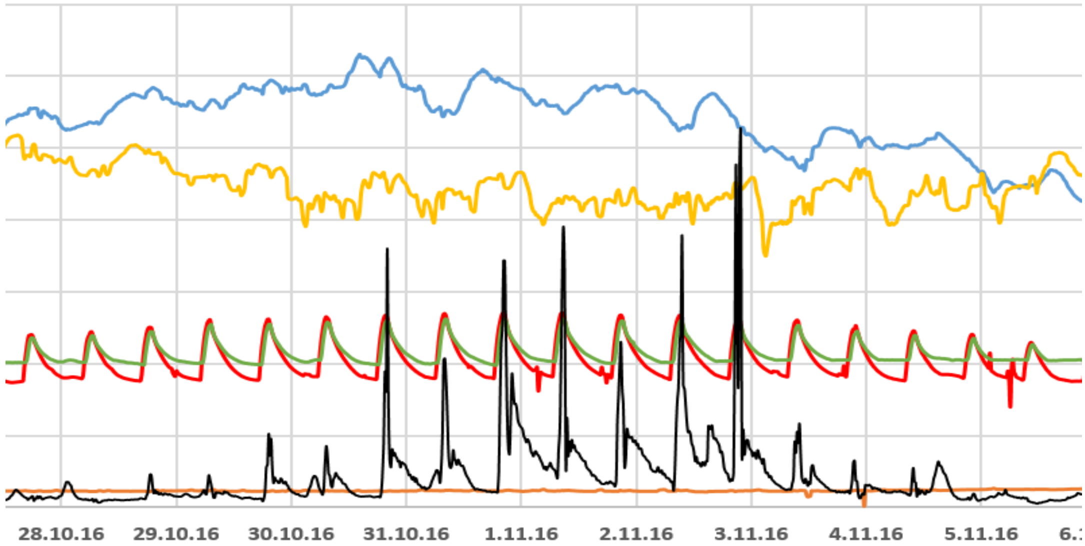


Figure 27. Enlargement of the peak spring tide zone of Figure 24, WZ (top) and BB (bottom).

- Comparing TSS statistics for the WZ and BB sites (Figure 26) the latter values are nearly all substantially lower than the former, typically by a factor of two. At times when water flow is seawards then this difference is consistent with the monitoring zone undergoing erosion. At times when landward flow occurs (short flood tide on springs), the difference is suggesting that substantive accumulation is occurring. The net flux of sediment will be a balance between these two conditions varying with space and time through the zone.
- The tide hour plots (Figure 25) provide some insight into this equilibrium. Through neap tides the flow through the monitoring reaches is nearly always seawards, even at times of low river flow. So sediment can only be carried seawards. But TSS levels are not high (rarely exceeding 1500 mg/l), so the potential for sediment transport is lower. However concentrations at WZ are clearly higher than at BB, so slow erosion through these reaches persists. On spring tides a period (maximum ~2 hours) of strong landward-going flow occurs immediately before HW. However on normal spring tides, the TSS levels seen during this

flood seem little different to those persisting through the much longer ebb period, suggesting that erosion is still the dominant process. Only on the top spring tides is it clear that the TSS concentrations on the flood are greater than on the ebb, with a suggestion that accretion processes may be dominating.

- The presence of this top spring tide situation can be clearly seen in the BB timeseries (enlarged in Figure 27, bottom). Just over the seven tides on the top of springs (not a very high spring period) it is clear that there is a peak of very high suspended sediment concentrations associated with the flood tide, and much lower concentrations on the subsequent ebb. Sediment 'pumped' through this section of the river on the flood that accumulates on the bed do not seem to be strongly eroded through the ebb. This situation will be particularly pertinent to the higher side-bank slopes, not subject to the full length of ebb drainage as they dry out.
- Inspection of the same period data (Figure 27) for the WZ site shows interesting differences. Up until the 31st October a similar pumping mechanism to BB can be seen, with spikes of very high TSS associated with the short flood flow. As at BB, lesser TSS concentration is seen during the ebb, and on several occasions much lower TSS is seen on the early ebb, building through the later ebb, again indicating that only sediment at the level of the channel floor is being actively reworked by the ebb, the deposits higher on the banks staying accumulated. As the peak of spring tides is reached (1st and 2nd November) however the overall TSS levels decrease substantially, although still with flood TSS values greater than the ebb. Then by the 3rd November the overall TSS levels increase again but with no flood TSS peak, most high TSS values being confined to the ebb (seaward erosion). This situation may reflect a sediment exhaustion phenomenon, where first spring tides of each lunar cycle set in motion the available unconsolidated mud in the lower estuary reaches, pushing the sediment towards the upper estuary on the flood. This source body (of recently accumulated sediment) may have a limited volume and become exhausted. This situation would be seen in the upper reaches as a body of high flood-tide TSS concentration that progressively passes upstream through several tides, but fading out before the peak tidal range is reached. On this particular lunar cycle this plug of high TSS water passed through WZ on the flood tides from the 29th to the 31st October, and was evident at BB from 31st October to the 3rd November. The flood concentrations of suspended sediment seen at BB were normally lower than at WZ however, showing significant accumulation through the monitoring zone.

POST-DREDGING

During the period 15th November to 17th December a) substantial dredging was undertaken through the EDZ (and subsequently most of the monitoring zone) and b) a large river flood passed through the drainage basin, peaking on the 22nd November. Both could potentially have modified the suspended sediment regime condition.

A limited series of manual profiling observations were made on the 5th December (three clear days after the EDZ dredge was completed), with moderately low river flow, tidal range 7.9m (high neap/low spring boundary), HW at Hinkley 9.23 GMT (4.39m OD) and HW at Northmoor 10.30 GMT (4.81m). Monitoring began at 9:15 and ran through until 12:30 GMT. For the first hour the vessel was stationary alongside the pontoon at Westonzoyland. Then a slow set-depth (~0.8m below water surface) run was made through the monitoring zone and back (lasting just over an hour, not drogue

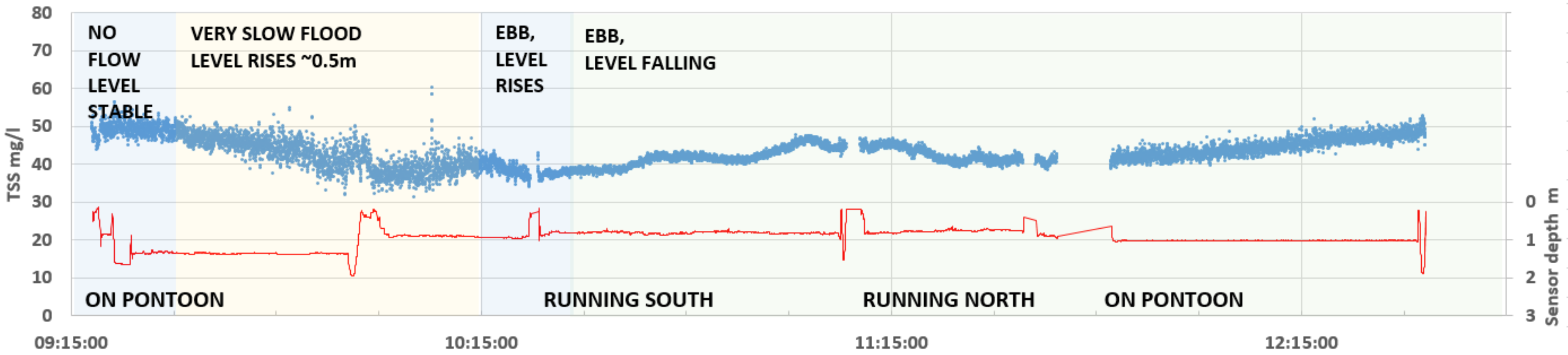


Figure 28. Set-level TSS monitoring, post-dredge survey (5th December 2016). Mean data value is 43 mg/l.

tracking), with vertical profiles at either end. Finally another hour of stationary observations were made alongside the pontoon at WZ. All the data collected on TSS are shown in Figure 28.

At the beginning of the observation period the water level was stable and there was no flow. For about 1 hour before HW time the flow almost imperceptibly move landwards and the water level rose less than 0.5m. The landward flow ceases and a slow ebb current began just before the maximum water level was reached, then the level began to fall and the ebb current slowly accelerated.

TSS concentrations remained almost constant and very low through the ~3 hour period, with values between 35 and 55 mg/l. There was no vertical variation in TSS concentration. TSS levels dropped slightly in the hour before HW, then increased slightly into the mid-ebb. Set-depth TSS concentrations showed a very slight increase in concentration towards BB, indicating some deposition from the flow at that time. This very simple situation is summarised in Figure 28.

The situation seen on the 5th December is totally different to that seen in the pre-dredge surveys, with very low TSS values. This could be an effect of the slightly higher river discharge. Or it could reflect the point in the lunar tide cycle tide (tide range 7.9m), being exactly on the balance point between constant seaward flow (neaps) or a flood tide penetration (springs), the absence of any current creating the clear water. Or it could reflect an exhaustion of erodible local sediment, as a result of both river flood scour and dredging activity. All explanations may play a role.

Time-series plots for the WZ and BB autonomous surface water sensors for the post-dredge period are shown in Figure 29. The TSS data from this plot has been analysed and replotted as tide-hour graphs, grouped by lunar (spring-neap) tidal range (Figure 30). The summary statistics, grouped by spring/neap/higher river flow periods are given in Figure 31. The salient features of the suspended sediment regime that emerge from this late autumn data set can be summarised as follows.

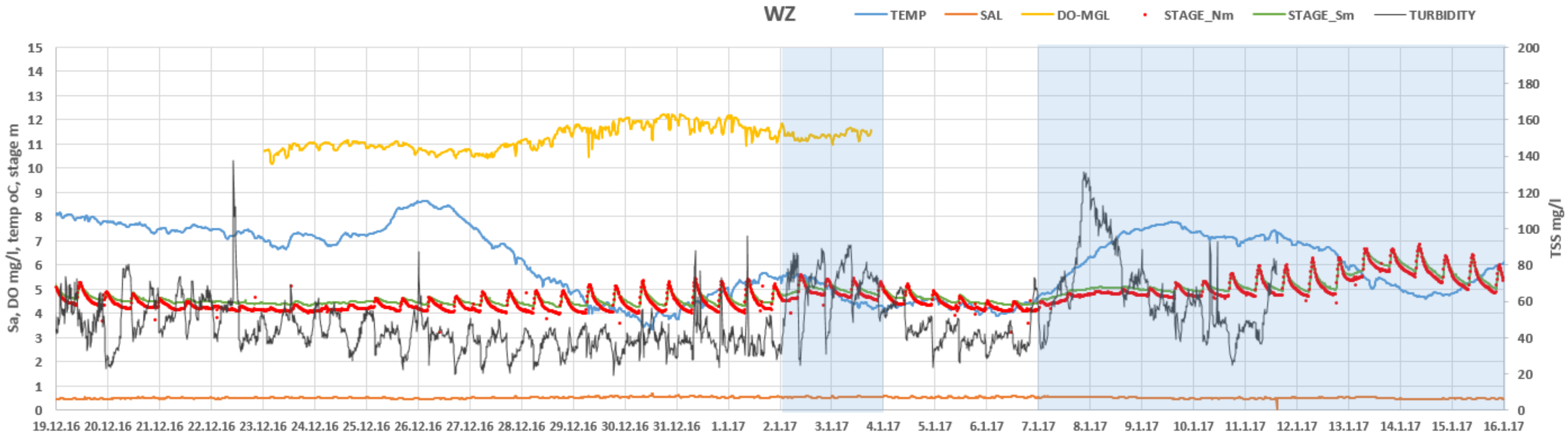
- The timeseries data (Figure 24) show at first glance that there is only slight increase in suspended sediment concentrations between neap and spring conditions at both sites, but that during river flooding events mean TSS concentrations can double and maximum values increase by up to a factor of 3 (Figure 31). The mean/median of all datasets lie in the range 30-60 mg/l, contrasting strongly with the pre-dredge situation when much higher suspended sediment concentrations were seen. At times of modest river flow there is a minor increase in the TSS levels at WZ compared to BB, indicating slight erosion through the study area, but no significant difference during the higher flood event. No flood tide TSS peak is evident on spring tides (compare Figure 30 and Figure 25). All data are summarised in the statistics of Figure 31.
- The spring/neap transition tide periods at WZ have mean/median values of ~50 mg/l (figure 31), compatible with the one day profiling data at about 1m below the surface (Figure 28 mean value of 43 mg/l).
- Although there were no tides of the higher spring range during the post-dredge monitoring period (Figure 30), comparing like energy levels (e.g. tide hour plots for median tides, figure 25 for pre-dredge and Figure 30 for post-dredge) there is huge reduction in the post-dredge TSS levels (by a factor of ~10). This may be simply due to the slightly higher river discharge compared with the pre-dredge period, but the change may be further argument for a control imposed by processes of sediment exhaustion. It is not possible to say from this evidence alone whether the potential exhaustion effect seen in these reaches is largely attributable to just the scouring action of the November river flood, or whether the dredging played an important role.

PARTRAC DATA

The Partrac data (Table 5) appear to show exactly the same (x~10) differences pre and post the first big river flood of the winter, consistent with our data showing that minor increase in river discharge and/or exhaustion effects can dramatically modify the suspended sediment regime in the upper reaches of the estuary.

	Jul-Aug 2009			**Nov-Dec 2008**		
mg/l	*Average*	*Max*	*Min*	*Average*	*Max*	*Min*
Site 1	608	3568	15			
Site 2	219	3567	38	36	39	33
Site 6/7	225	2725	41	22	28	19

Table 4. Partrac summary data for suspended sediment concentrations measured ~1m above the bed for two periods of 20-30 days (spring and neap tides). Site 2 & 7 are in the monitoring zone (Figure 1). NB. There are no data on the NTU-TSS calibration used by Partrac.



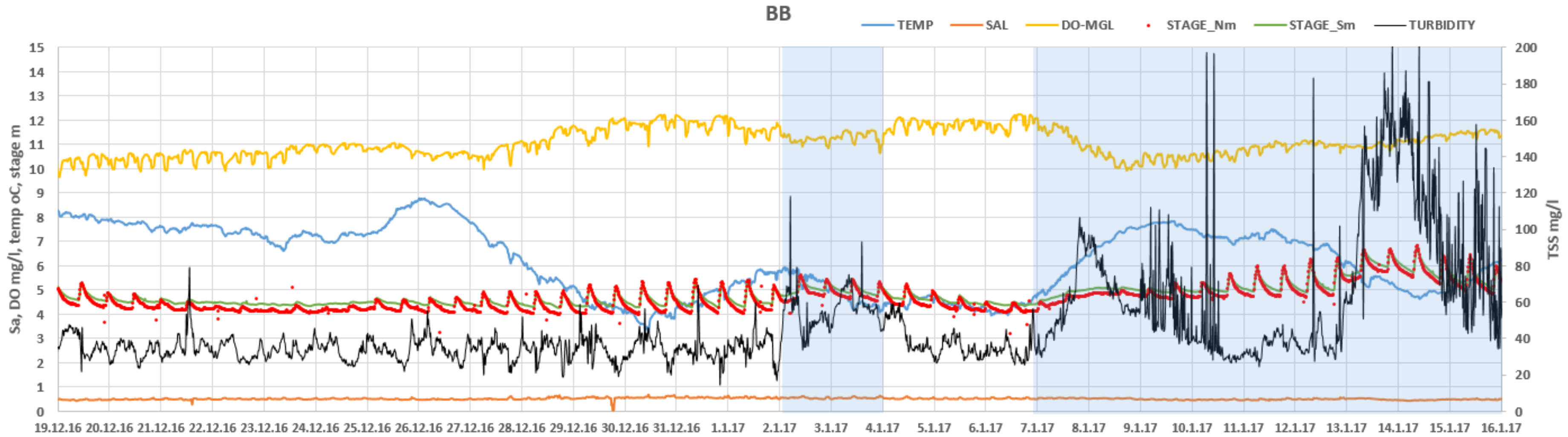


Figure 29. Westonzoyland (WZ) and Burrowbridge (BB) surface water sensor data for the post-dredge period (18th December to 16th January). Blue shaded boxes are minor river flood events. At WZ the DO sensor failed on 3/1./17 and the turbidity sensor on 11/1/17.

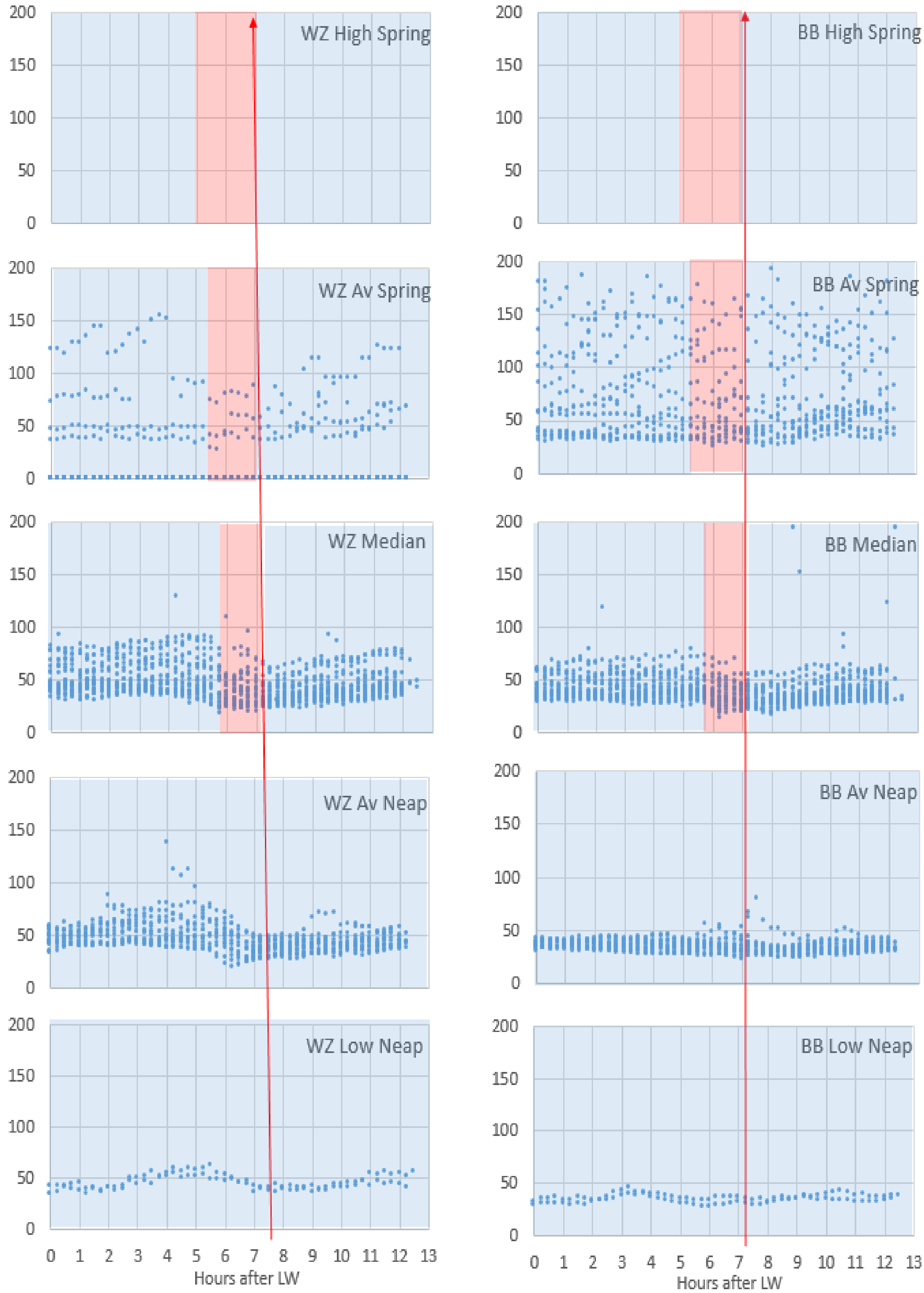
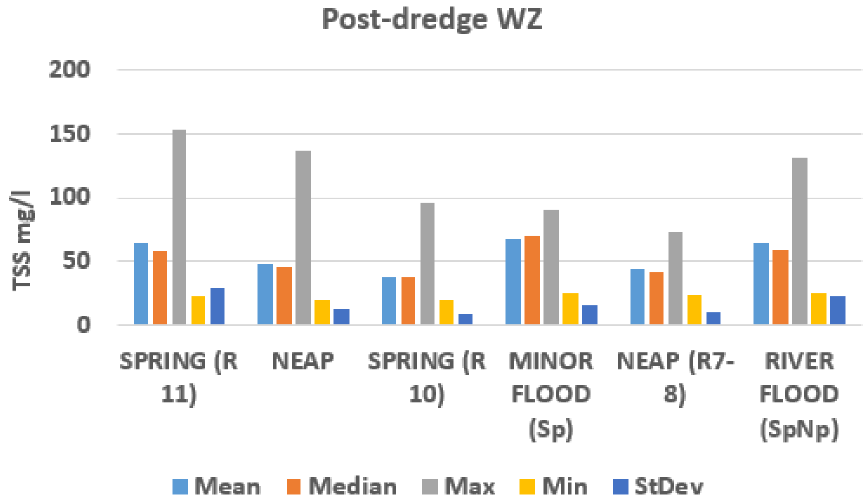


Figure 30. Post-dredge surface water sensor TSS data (WZ & BB) tide-hour plots grouped by spring-neap condition. The red line is HW. Red shading is (potential) upstream water flow (at low river discharge), blue shading is downstream water flow.

The four spring neap groups correspond to tide ranges (top to bottom) >12m, 10-12m, 8-10m, 6-8m and <6m (see Figure 20).

	Mean	Median	Max	Min	StDev
SPRING (R 11)	65	58	154	23	29
NEAP	48	46	138	20	13
SPRING (R 10)	38	38	96	19	8
MINOR FLOOD (Sp)	67	71	91	25	15
NEAP (R7-8)	44	42	73	24	10
RIVER FLOOD (SpNp)	65	59	131	25	23



	Mean	Median	Max	Min	StDev
SPRING (R 11)	44	43	192	22	14
NEAP	34	34	79	22	6
SPRING (R 10)	34	34	68	14	6
MINOR FLOOD (Sp)	55	56	118	29	11
NEAP (R7-8)	37	35	60	25	8
RIVER FLOOD (SpNp)	70	59	201	24	39

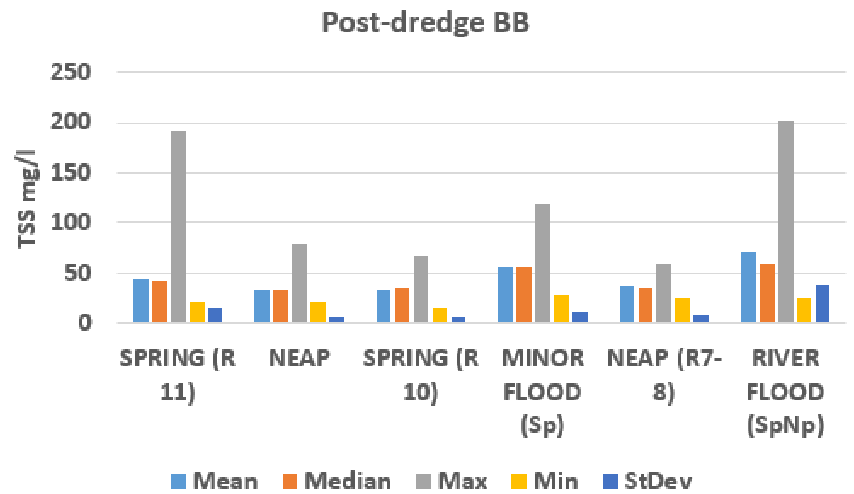


Figure 31. Summary statistics for post-dredge TSS conditions for WZ (top) and BB (bottom). Neap to spring differentiation is based on 8m range at Hinkley Point.

3.7. Water Quality

DISSOLVED OXYGEN. In all the near-surface (autonomous) measurements made the % DO in the water rarely dropped below 80%. The absolute DO value varied with temperature, but not obviously with turbidity, suggesting the latter (at natural concentrations in suspension) is not creating an oxygen demand. Absolute values only fell below 8mg l^{-1} for very short periods of time, suggesting temporary clogging of the sensor head with organic matter. All the manual profiles recorded (outside of the dredging period) also showed similarly high DO levels (no reduction with depth) except one cast, during which DO dropped to 50% on reaching the bed rose to normal values again on moving back to the water surface. There was no high turbidity associated with this event, again likely to be a spurious reading.

AMMONIA. Ammonium as N (NH4-N) concentrations generally remained below 0.5 mg l^{-1}. Small spikes in ammonia measurements (up to 3 mg l^{-1}) were observed during high spring tides. These fluctuations were closely correlated to conductivity and are a consequence of the ammonia probes being sensitive to sodium and potassium, rather than representing a real change in ammonium concentrations.

4. Geomorphometric Change

4.1. Rates and Patterns of Change

The pre-dredge morphology of the channels is described in Section 3.1 (Figures 7 & 8). Post-dredge conditions were measured using three methods:

- During dredging, control surveys were undertaken by Van Ord by running single beam echo sounder longitudinal lines run along the thalweg within the dredge zones
- Immediately after the cessation of dredging (during December) some sections were resurveyed using the pole method.
- In mid-February a multibeam acoustic survey was undertaken (re-run of the initial survey).

The three survey methods gave very comparable results. The patchy Van Ord data were difficult to combine into clear graphics, and have not been used in the analysis, beyond checking consistency. The other two data types were gridded in the GIS system to create 3-D surfaces, from which volume changes and illustrative cross-sections could be prepared (Table 5, Figures 32-34).

All the data collected showed overall scour to have occurred between October/November and December/February. Some localised accumulation occurred, notably on the lower side-slopes of the banks ('berms'), but erosion prevailed.

The multibeam survey covered the greatest channel extent, from the M5 motorway to Burrowbridge (Figure 1). Some 32,000m^3 of sediment was eroded from the channel floors and lower slopes of this section of the estuary between the November and February multibeam surveys. The estuary channel through this area has been divided into seventeen reaches of about 500m (nominal) length. These seventeen reaches can be divided into five groups (Table 5) on the basis of their modification between the two multibeam surveys.

1. Upstream of the EDZ. These two reaches were affected by both river scour and minor dredging (a single pass of the WID). Thalweg scour was the predominant mechanism of change, where a maximum of about 0.5m of deepening occurred (Figures 32 and 33). Average erosion over the period along these reaches was ~0.2m (Figure 34).

2. EDZ. These two reaches were impacted primarily by dredging but also underwent river-flow erosion. Thalweg scour was the predominant mechanism of change, where a maximum of about 1m of deepening occurred. Average erosion over the period along these reaches increased northwards, from ~0.35m to 0.55m.
3. Dredging Extension Zone (most of the original downstream monitoring zone). Van Ord surveys undertaken before this zone was dredged showed that no local accumulation of

Upstream kp	Downstream kp	Reach length m	Reach area m^2	Mean width m	Mean change m	% null (QC)	Volume change (m^3)	Erosion pattern	Dredge history
30275	29575	700	8,131	12	-0.2129	3.5	-1731	th	minor dredge
29575	29125	450	5,237	12	-0.1870	5.7	-979	th	minor dredge
29125	28675	450	4,937	11	-0.3580	5.5	-1767	th	EDZ full dredge
28675	28350	325	4,010	12	-0.5622	3.2	-2254	th	EDZ full dredge
28350	27925	425	5,948	14	-0.5208	3.2	-3098	th	Extension full dredge
27925	27525	400	5,505	14	-0.5421	4.3	-2984	th	Extension full dredge
27525	27125	400	6,990	17	-0.5037	1.9	-3520	th	Extension full dredge
27125	26625	500	9,903	20	-0.1928	2.6	-1909	th	No dredge (wide)
26625	26076	549	10,391	19	-0.2596	3.2	-2697	th	No dredge (wide)
26076	25626	450	7,486	17	-0.3235	6.6	-2422	th	No dredge (wide)
25626	25174	452	5,205	12	-0.1342	9.0	-698	bm	No dredge (narrow)
25174	24828	346	4,205	12	-0.1612	9.2	-677	bm	No dredge (narrow)
24828	24325	503	6,341	13	-0.1951	6.8	-1236	bm	No dredge (narrow)
24325	23927	398	5,418	14	-0.2264	5.1	-1226	bm	No dredge (narrow)
23927	23530	397	5,897	15	-0.2436	4.7	-1437	bm	No dredge (narrow)
23530	23081	449	6,312	14	-0.2441	4.0	-1540	bm	No dredge (narrow)
23081	22580	501	7,434	15	-0.2303	3.9	-1712	bm	No dredge (narrow)

Total erosion from all reaches **-31887**
Erosion from dredged reaches **-16333**

Table 5. Variability in bed-level change along the channel reaches. Mean level change is plotted in Figure 34 (top), th=thalweg scour predominated bm=berm erosion predominated.

dredged mud occurred through these three reaches prior to the second (extension) dredge activity. Thalweg scour was the predominant mechanism of change, where a maximum of about 1m of deepening occurred. Average erosion over the period along these reaches was the greatest seen in all areas and exceeded 0.5m.

4. No dredge zone (wide, pioneer dredged).   The channel in these three pioneer dredged reaches is wide (Table 5, Figure 33) therefore having a larger cross-sectional area. Thalweg scour predominated and although undredged, up to 0.5m of thalweg deepening was seen with average erosion of 0.2-0.3m over the period

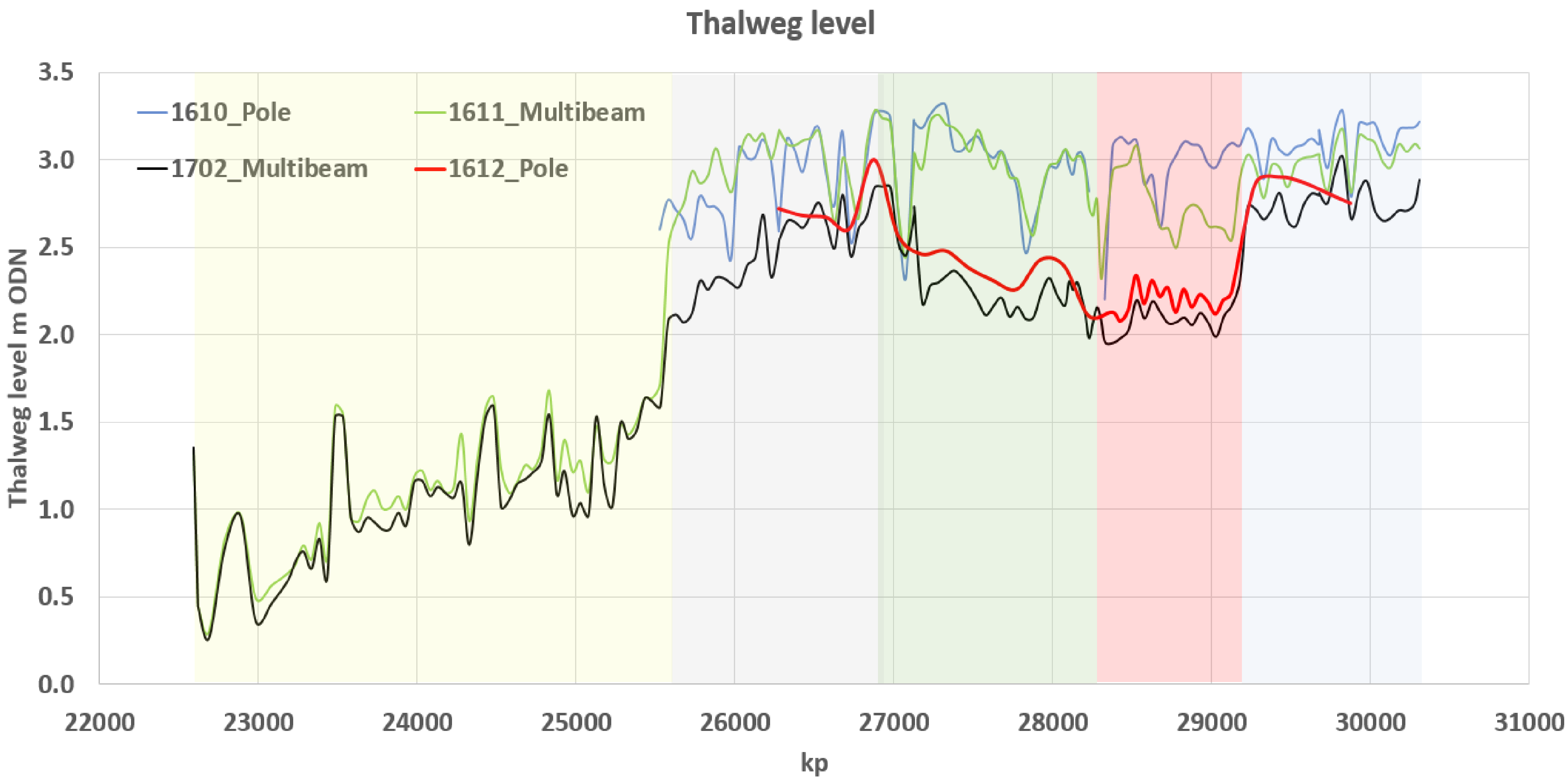


Figure 32. Comparison of pre- and post-dredge thalweg levels. See Table 5 for explanation of colour shading.

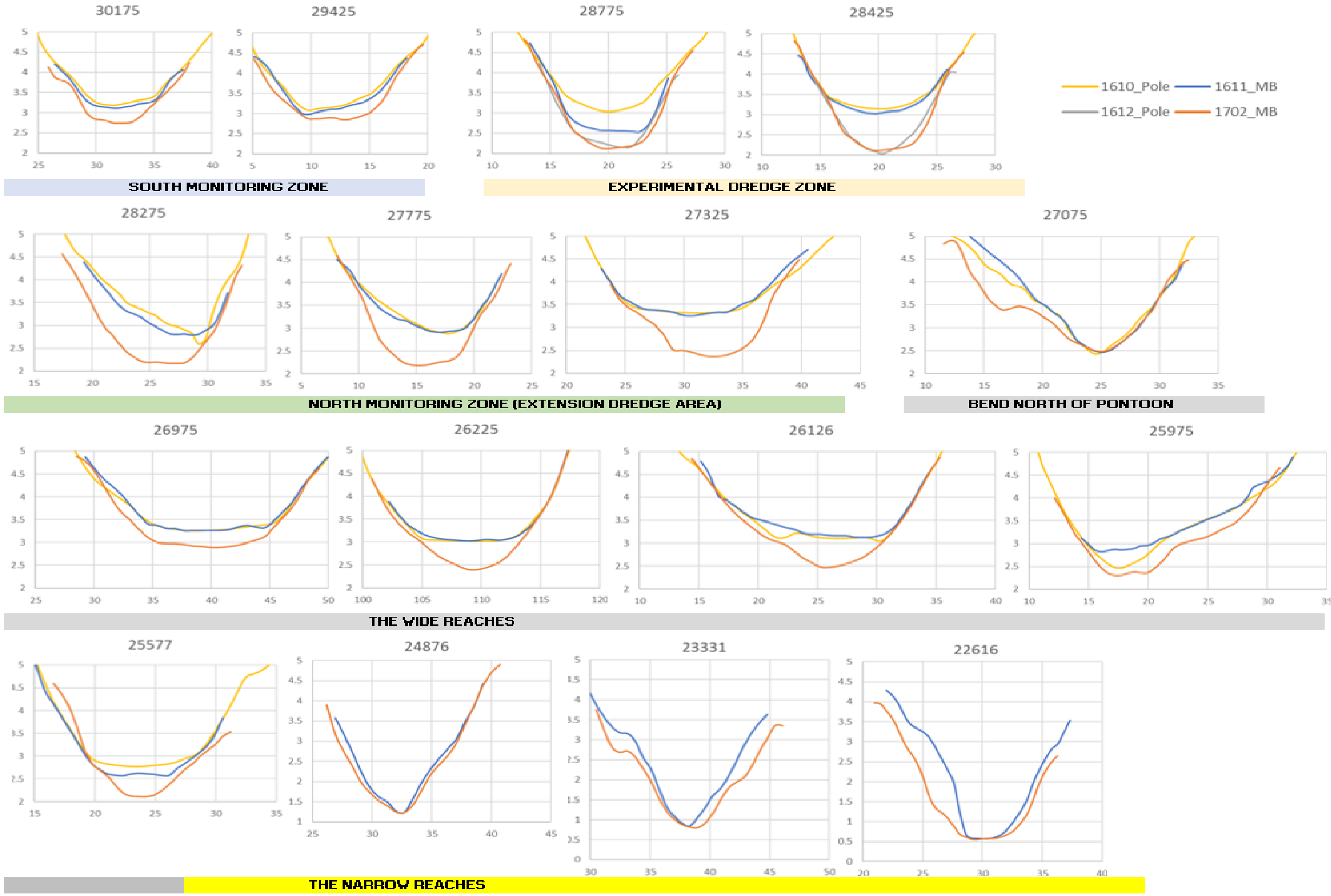


Figure 33. Illustrative cross-sections showing type and degree of change in bed levels between surveys. See Table 5 for explanation of colour shading.

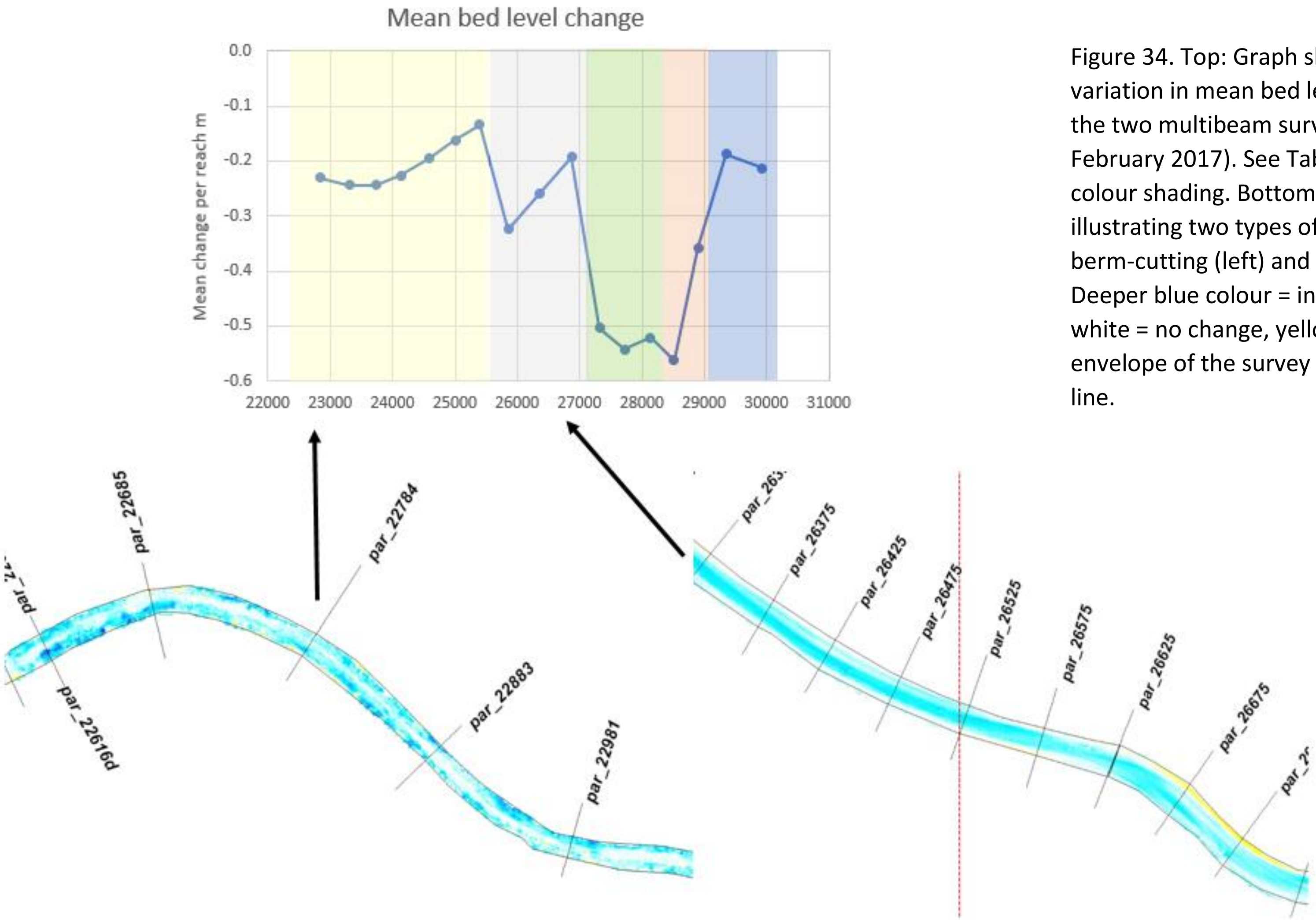


Figure 34. Top: Graph showing along-channel variation in mean bed level changes between the two multibeam surveys (November 2016-February 2017). See Table 5 for explanation of colour shading. Bottom: Channel plans illustrating two types of channel erosion, berm-cutting (left) and thalweg scour (right). Deeper blue colour = intensity of erosion, white = no change, yellow = deposition. The envelope of the survey area is shown as a grey line.

5. No dredge zone (narrow, not pioneer dredged). At about kp25500 the channel becomes narrow again (12-15m) and little erosion occurred here over the period (this local reach saw only 0.13m of mean bed lowering, Table 5, Figure 33). This pinch point appears to result from being the downstream limit of the 2014-16 pioneer dredge. Through the seven 'natural' reaches at and downstream of the 'pinch', berm erosion replaces thalweg scour as the principle pattern of erosion (Table 5, Figure 33 & 34). Thalweg levels erode only very slightly if at all (Figure 32) but mean bed lowered through the period was 0.2 to 0.3m (Figure 34), similar to the 'minor dredge' zone above the EDZ. The profiles through this undredged part of the channel are far more V-shaped than the pioneer-dredged trapezoidal sections to the south, and the profiles and erosion amount plans show erosion to be focused on the slope toes either side of the thalweg.

5.1.River Scour Compared to Dredging

As significant erosion has occurred between November 2016 and February 2017 in all of the channels monitored, it is clear that both river erosion and dredging have been responsible for scour. As will be addressed in the following section, there are several lines of evidence that clearly point to the persistence of alternating seasonal cycles of erosion and deposition in these reaches of the estuary, the erosion being driven by fluvial high discharge events.

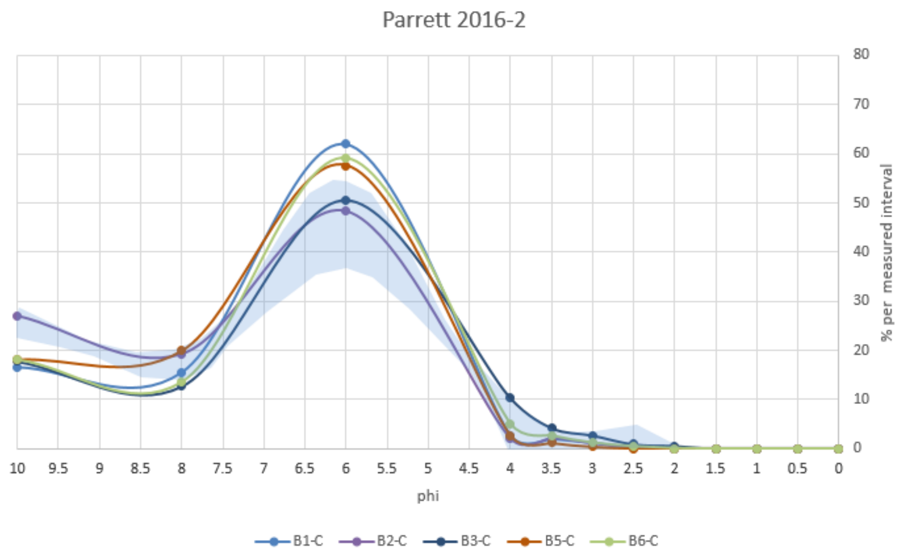
On the assumptions that a) the single pass dredge south of the EDZ had minimal impact and b) had no dredging taken place erosion inside the dredged zones would have been similar to that seen outside those zones, it can be calculated (on an area basis) that with river erosion alone these reaches would have yielded ~24,000m^3 of erosion between November 2016 and February 2017 (=average bed lowering in non-dredged areas x area of all reaches). Reality is that these reaches yielded ~32,000m^3 (Table 5), so the dredging effort (the difference) yielded 8,000m^3. The VO surveys undertaken immediately following dredging indicated dredging production to be 11,000m^3, consistent with this analysis (river scour would have naturally eroded the dredged reaches between November and January had no dredging been undertaken). Hence the dredging effort this winter increased 'natural' erosion by one third. This winter of 2016-17 actually saw quite low river discharge events compared with previous years (Figure 17) so it is quite possible that during years of really high fluvial input, river scouring might have naturally exceeded the 32,000m^3 achieved this year.

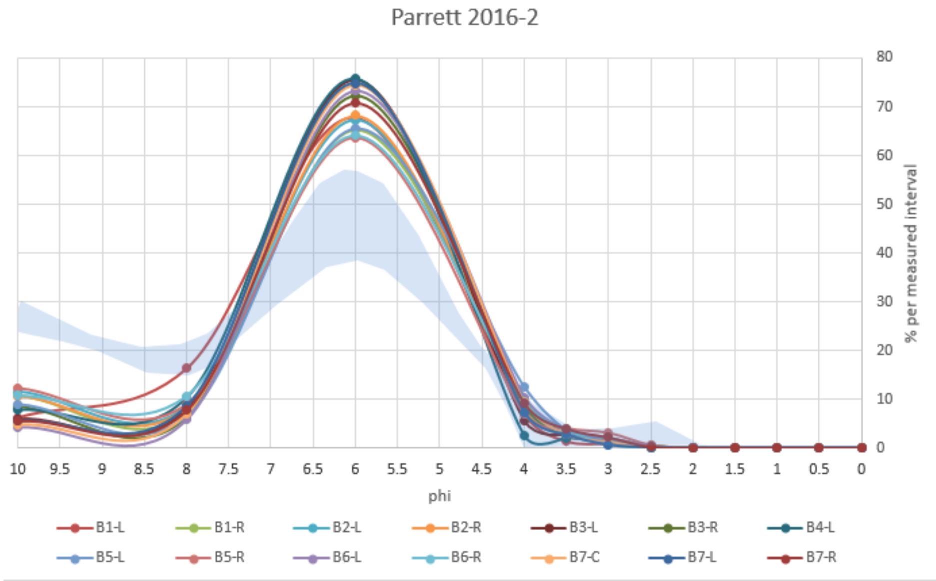
In evaluating the potential role that dredging might play in maintaining a high flow capacity channel, it would seem that an important objective is to quantify the scaling between the scouring that can be achieved by natural river erosion (taking into account the inter-annual variability) and the cleaning that can be pragmatically added by the use of dredging.

A final point to be made in this section is to highlight the potential different effectiveness of the two different profile shapes found, both for channelling flow and for promoting natural scour under river flood events. The deeper V-shaped (undredged) sections seem to encourage river flood erosion higher up on the side slopes (Figure 33).

5.2.Bed Sediment Characteristics

The estuary bed sampling survey undertaken on the 10th November (section 3.2) was repeated on the 8th December. Site locations are shown in Figure 2. Sites and methods were replicated as exactly as possible: water levels were slightly higher on the final survey so channel margin samples were taken a little higher up the bank. Sample site B4-R was not revisited as the sediment is a relict





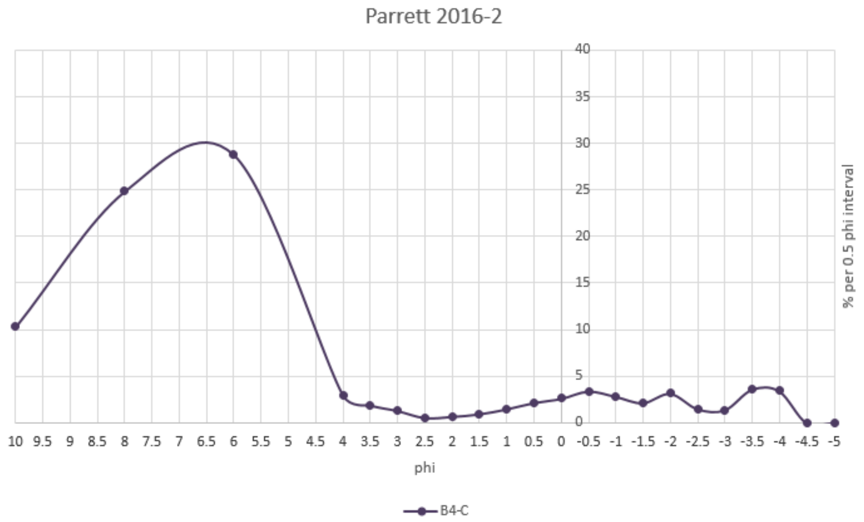


Figure 35. Discrete frequency distribution plots of the PSA data from the final monitoring bed survey. C=channel centre, L=left bank, R=right bank (looking seawards). See Figure 10 for a definition of phi.

	Field Sample ID	% Gravel (>2mm)	% sand (2mm-63um)	% silt & clay (<63um)	% of siltclay coarser than 16um	% of silt/clay finer than 4um	Dry Density t m^{3}	Bulk Density t m^{3}	Shear Strength kPa
	B1-L	0	9.4	90.6	74.9	7.0	0.8	1.51	1.50
	B1-R	0	16.4	83.6	78.1	13.0	0.79	1.49	1.50
	B2-L	0	12.4	87.6	76.9	13.2	0.78	1.49	0.90
	B2-R	0	12.6	87.4	78.1	12.3	0.89	1.56	1.50
	B3-L	0	10.2	89.8	84.1	6.7	0.75	1.47	1.50
BANK	B3-R	0	13.0	87.0	83.0	9.7	0.85	1.53	1.50
GROUP	B4-L	0	6.0	94.0	80.7	8.3	0.78	1.49	1.50
	B5-L	0	18.7	81.3	80.7	11.1	0.77	1.48	0.73
	B5-R	0	15.0	85.0	74.8	14.5	0.78	1.49	1.04
	B6-L	0	16.8	83.2	87.9	5.1	0.75	1.47	0.89
	B6-R	0	14.4	85.6	74.8	12.6	0.78	1.49	1.19
	B7-C	0	13.7	86.3	86.2	5.6	0.74	1.46	
	B7-L	0	11.0	89.0	84.0	6.2	0.77	1.48	1.50
	B7-R	0	15.8	84.2	84.1	6.6	0.81	1.50	0.95
	Average	*0*	*13.2*	*86.8*	*80.6*	*9.4*	*0.79*	*1.49*	*1.25*
	St Dev	*0*	*3.4*	*3.4*	*4.4*	*3.3*	*0.04*	*0.03*	*0.30*
	B1-C	0	6.0	94.0	65.9	17.6	0.61	1.38	
	B2-C	0	5.3	94.7	51.1	28.5	0.52	1.33	
CHANNEL	B3-C	0	18.9	81.1	62.4	21.9	0.77	1.48	
GROUP 1	B5-C	0	4.4	95.6	60.2	18.9	0.54	1.34	
	B6-C	0	9.4	90.6	65.2	19.9	0.70	1.43	
	Average	*0*	*8.8*	*91.2*	*61.0*	*21.4*	*0.63*	*1.39*	
	St Dev	*0*	*5.9*	*5.9*	*6.0*	*4.3*	*0.10*	*0.06*	
CHANNEL 2	B4-C	18	18.0	63.9	45.0	16.1			

Table 6. Summary PSA, density and shear strength data for the two sediment groups on the final survey. Note the shear vane could only read to 1.3 kPa so 1.5 kPa values shown here indicate 'failure not reached'.

		% sand (2mm-63um)	% silt & clay (<63um)	% of siltclay coarser than 16um	% of silt/clay finer than 4um	Dry Density t m-3	Bulk Density t m-3	Shear Strength kPa
BANK	**B1-L**	2.8	-2.8	7.1	-10.2	0.15	0.09	0.00
GROUP	**B1-R**	2.6	-2.6	1.2	-1.3	0.02	0.01	0.00
	B2-L	5.6	-5.6	0.2	0.8	0.06	0.03	0.00
	B2-R	0.9	-0.9	-0.5	0.1	0.11	0.07	0.00
	B3-L	0.5	-0.5	12.1	-8.6	0.06	0.04	0.42
	B3-R	9.9	-9.9	8.8	-1.7	0.14	0.09	0.00
	B4-L	-7.1	7.1	2.4	-5.6	0.06	0.04	0.00
	B5-L	5.6	-5.6	-0.6	0.2	0.00	0.00	-0.77
	B5-R	7.6	-7.6	3.0	-2.3	0.13	0.08	-0.16
	B6-L	10.7	-10.7	12.0	-6.9	-0.02	-0.01	-0.61
	B6-R	6.0	-6.0	-1.4	1.2	0.11	0.07	-0.01
	B7-C	7.1	-7.1	19.6	-13.8	0.12	0.07	0.00
	B7-L	-5.5	5.5	2.1	-6.8	0.01	0.01	0.40
	B7-R	9.5	-9.5	7.9	-5.8	0.10	0.06	-0.10
CHANNEL	**B1-C**	-10.7	10.7	17.1	-15.7	0.09	0.06	
GROUP	**B2-C**	-13.4	13.4	5.1	-6.7	0.04	0.02	
	B3-C	10.5	-10.5	8.3	-5.8	0.27	0.17	
	B4-C	16.8	-34.9	-10.8	-9.4			
	B5-C	-2.7	2.7	10.8	-9.1	0.00	0.00	
	B6-C	-1.6	1.6	0.1	-1.2	0.01	0.01	
BANK	**Average**	3.9	-3.9	5.9	-4.8	0.08	0.05	-0.06
GROUP	**St Dev**	-0.4	-0.4	-0.7	0.2	-0.01	-0.01	0.08
CHANNEL	**Average**	-0.6	0.6	9.4	-7.6	0.08	0.05	
GROUP	**St Dev**	-1.0	-1.0	1.9	-0.1	0.02	0.01	

Figure 36. Comparison of bed sediment characteristics between surveys (values Table 6 minus values Table 2). Increasing greenness reflects an increase in values between surveys, increasing redness decreasing values.

Figure 37. Sample B4-C showing presence of mud-clasts and fine gravel. Top: sediment surface seen in grab. Bottom: Gravel fraction from sample, post particle-size analysis (mud clasts dispersed).

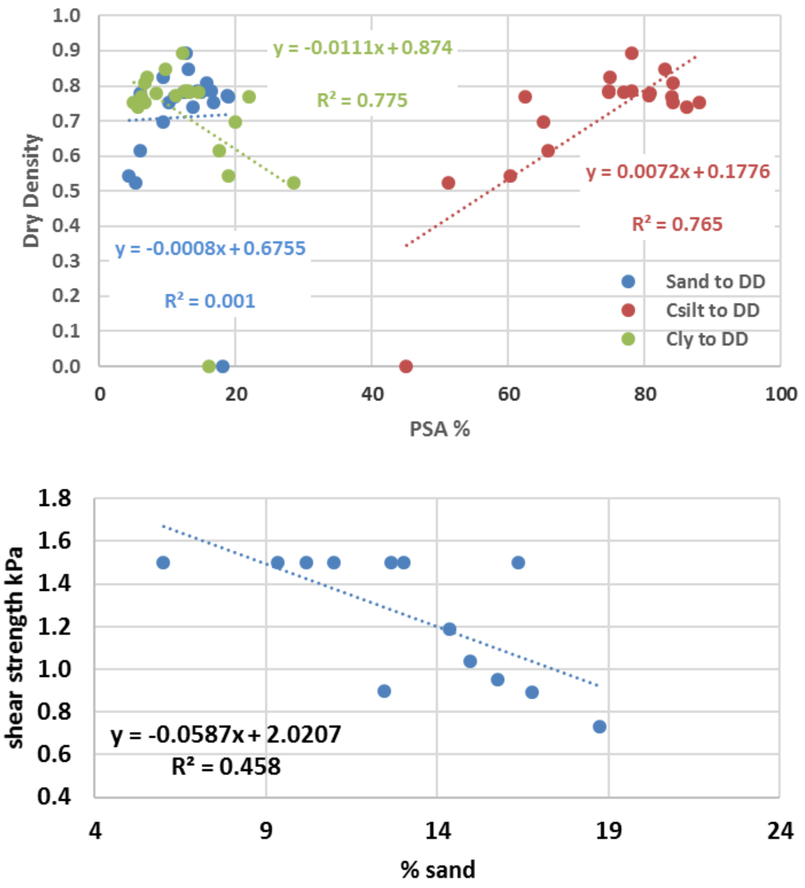


Figure 38. Sediment density to particle-size (top) and shear strength to sand content (bottom) interdependencies, final bed survey

eroding clay exposure between rock armour, and unrelated to modern channel conditions. The sampling was completed BEFORE the second (extended) dredging work took place.

The frequency distributions for the 20 samples collected in December are plotted in Figure 35. The grouping seen in the November survey remains the same, except that the channel floor sample at site 6, classed as bank group but almost between groups in November, showed characteristics of the channel floor group in December. In the figure the blue shaded area is the envelope of the plots of the channel group in November, for comparison purposes. Summary data for the two groups are given in Table 6. There seems no consistent longitudinal gradient in the bed sediment characteristics through the surveyed zone. There are modest changes in the sediment particle-size characteristics between the surveys but the basic characteristics of and differences between the bank and channel groups remain the same (former has higher coarse silt and lower clay).

The differences in the bed condition between the two surveys are shown in Table 6 (survey 1 values minus survey 2 values) where increasing colour density identifies greater degree of change. The differences seen can be summarised as follows.

- On the floor of the low water channel at Site 4 a completely new sediment type was seen. This contained 18% gravel, 18% sand and 64% mud. At the time of sample collection some of the mud was present as mud-clasts (Figure 37 top), showing recent break-up of a strongly cohesive mud bed. These clasts collapsed into mud particles on wet sieving. The actual gravel consisted of unencrusted, dull, angular to sub-rounded fine to medium gravel composed of shale and sandstone with some shell, wood and reed fragments (Figure 37 bottom).

- The sand % of the total sediment mostly increased (~4% on average) in the bank group and both increased and decreased in the channel group. The difference between sites in the channel group is interesting however because all the decrease-in-sand zones are upstream or downstream of the dredge zone. The dredge zone itself (Site 3) and the immediate lower end of the dredge zone (site 4) both showed large (10-20%, Figure 36) increase in sand content. This could be evidence that WID/Farrell dredging preferentially removes the silt/clay fraction of the bed, but sand tends to resettle to the bed locally.
- The coarse silt fraction of the sediment increased significantly at most sites in both groups (up 5-10%), although some sites saw a slight decrease. There was a corresponding decrease in the fine-silt/clay fractions.
- There was little change in sediment density (very small average increase). As in the initial survey, sediment density appears to be primarily controlled by the relative proportions of coarse silt to fine-silt/clay (Figure 38, top graph), the channel floor sediments therefore showing the lower density range compared to the banks. The general slight increase in density is consistent with the overall increase in the coarse silt fraction within the sediments.
- Seen altogether, the bank samples' bed shear strength reduced slightly, however most sites stayed at the same value as previously, and a few sites saw either quite a large reduction or increase in strength. This is interpreted as most sites having a strongly cohesive value, with local areas (in both surveys) having thin veneers of recently deposited mud accumulation. The sand content of the sediment appeared to play a stronger role in determining sediment shear strength in this final survey (Figure 38, bottom graph).

Visual observations of the intertidal sediment surfaces made during the final survey strongly indicate that the banks had been subject to strong erosion between the two bed surveys. A full description of observations made is given in Appendix 3. Images of the mud surfaces made during the survey and later during December are shown in Figure 39. Key features seen are as follows.

- In the upstream reaches of the monitoring zone, most of the intertidal mud surfaces were similar to the pre-dredge condition, being featureless or showing erosion sculpting, quite strong in places (Figure 39 A, Site B02)
- At site 3, within the dredged zone, erosion features became stronger, with micro-cliffs often separating an upper-bank featureless zone from a lower highly eroded zone (Figure 39 B, Site B03). The cliff is probably the result of water-margin erosion during (recent) higher river stage. It can be seen that the erosion of the bed reveals that the exposed sediment is strongly layered (evidence of deposition in incremental layers separated by time and/or an erosion period).
- For long sections of the bank downstream of Site B03, the cut marks of the Farrell dredger (made at time of highest river flow) were evident (Figure 39 C).
- At site B04 (lower end of dredge reach) the banks were often eroded and stepped, with crack-development leading to the release of large blocks of mud (Figure 39 D, siteB04).
- Most erosion was seen on inner-bend slip-off slopes, where large slump features had developed (Figure 39 E, between Sites B04 & B05). The slump faces again show that the exposed sediment has highly layered properties.
- On straight reaches there were wide scoured sediment surfaces, again exhibiting the stepped appearance due to sediment layering, but less prone to slumping (Figure 39 F, Site B06).


A.


B.

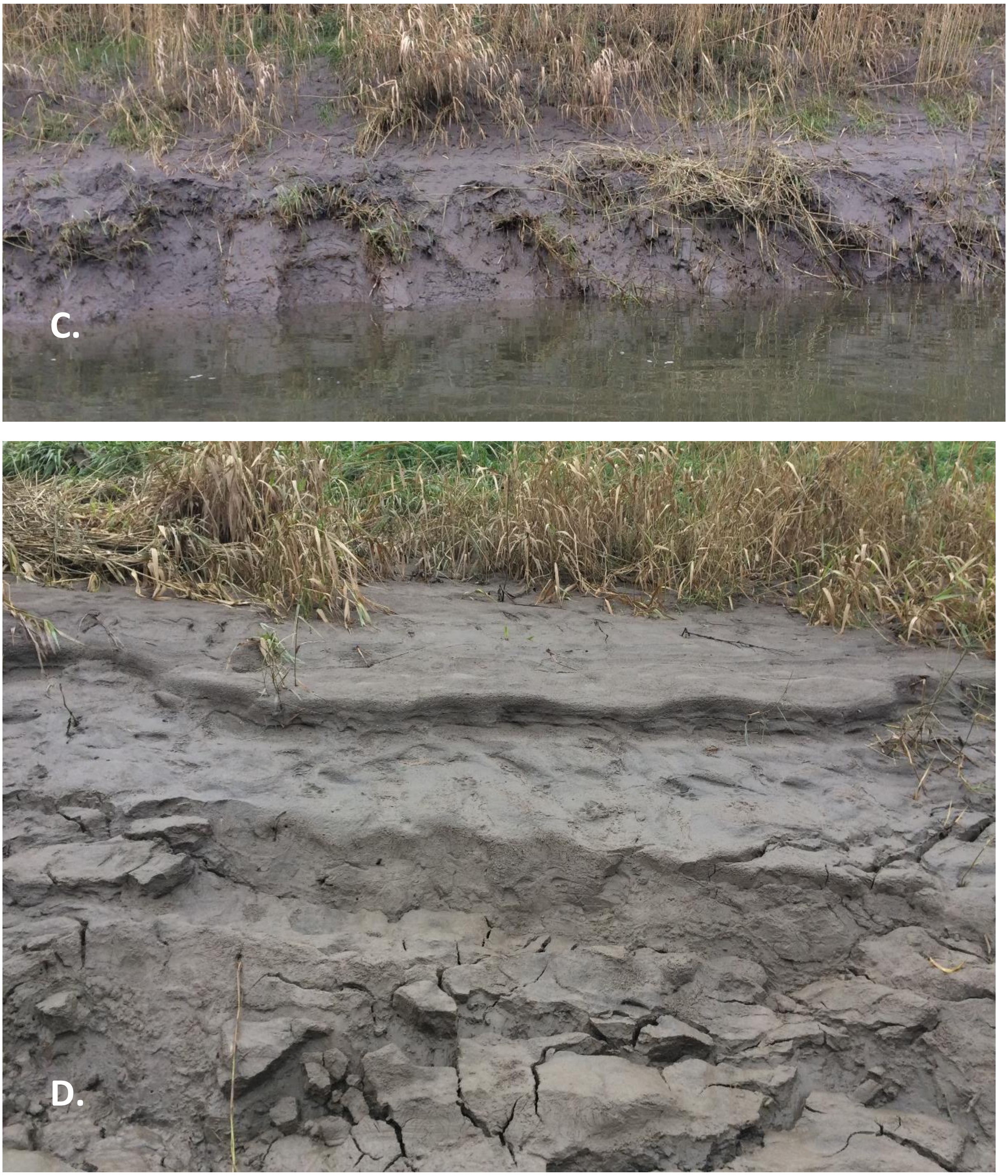


Figure 39. Photographs of sedimentary features on the intertidal. December 2016. … continues.

Figure 39. Photographs of sedimentary features on the intertidal. December 2016….. continues.


E.


F.


G.

Figure 39. Photographs of sedimentary features on the intertidal. December 2016.

- Only at Site B07, downstream of the sharp bend below the pontoon site, were the transverse bedforms (ripple marks widely seen during the initial survey) well preserved (Figure 39 E). At this point the channel has widened considerable, and the sediments on both banks and on the channel floor have some of the highest sand contents seen (11-16%, Table 6). The ripple marks are asymmetrical and clearly orientated to the formative seaward-going high river discharge.
- The inner sharp bend above Site 7 saw extreme erosion. Figure 39 F & G compare the situation in November (F) and on the 7th December (G). Very strong slumping and cliffing has occurred.

Through the dredge zone, some very large bank slumps developed through the weeks following dredging. The image seen in Figure 39 H was taken on 21st December.

From the bathymetric data (Sections 4.1 and 4.2) and from the above visual observations it is clear that most if the channel through the monitoring zone was subject to some level of erosion between November 2016 and January 2017. The (often modest) changes between the bed characteristics between the before and after surveys, therefore largely reflect the exposure of underlying deposits, the nature of which may not be related to processes active in the estuary through the monitoring period. It is therefore instructive to view the final survey as a starting point (cleanly-scoured bed left by the winter floods) and the initial survey as the end point (deposits that have built up during a spring/summer/autumn absence of river flows, dominance of marine flows and no dredging).

This approach recognises other evidence suggesting that there is a seasonal alternation of deposition and scour in the estuary, with mud building up during the summer months and being eroded in the winter. Evidence supporting this model can be listed as follows:

- Bathymetric data showing summer deposition and winter scour, with likely net deposition only over several years (Section 3.1, Figure 9)
- Turbidity data that shows both the delivery of mud from the sea on the highest spring tides and the cessation of this delivery once higher river flow sets in in the winter (Section 3.6).
- Layered properties of the estuary mud, indicating a history of alternating conditions of deposition and erosion (this Section)

On the basis of this model it is therefore useful to turn Figure 36 on its head, allowing the following observations to be made about the particle-size of the material that builds up through the (summer) low river discharge periods, compared to the residual mud deposits left behind after scouring by river floods and/or dredging.

1) The sand content of the summer accumulating material is lower than in the residual mud.
2) The summer accumulating material has more clay and fine silt than in the residual mud.

That is to say that the material that accumulates in the upper estuary through the 'summer' has particle-size characteristics more like the sediment flooring the estuary at its mouth (Figure 9), consistent with a marine source for most of the sediment in the estuary. The changing particle-size of the bed sediments in an up-estuary direction (Figure 9) may result from the effects of periodic river scour, preferentially removing the finer components (more easy to suspend a transport under modest flow conditions) from the marine-sourced material.

Finally for this section, visual evidence of post-flood/dredge bank deposit features indicates that lateral motion of sediment (slumping and sliding down the bank) may be an important aspect of cross-section scouring processes, providing a feed of material to the low-water-channel constant ebb flow. This process will tend to naturally create a V-channel section rather than a trapezoidal section. Bank deposits may be weakened while submerged at high water levels, but slumping probably continues whilst in a dry state. Dredging the toe of the bank must enhance this process.

5. Sediment Dispersion During Dredging

5.1. Trial 1 WID

The survey was undertaken on the 16th November, with low river flow, tidal range 12.49m (very high spring), HW at Hinkley 7:38 GMT (6.85m OD) and HW at Northmoor 08:45 GMT (6.42m).

Monitoring began at 9:15 and ran through until 13:15. The survey commenced upstream of the dredger which was located at the southern extremity of the southern EDZ reach, the tide was still very slowly flooding. One profile was taken. The second profile was taken just downstream of the dredger before WID activity commenced. The third profile was taken at 9.54 just after dredging commenced. Two drogue tack runs were then made during the remaining survey time. By the time the second drogue run started, the WID activity had already ceased (only 1.25 hours dredging that day). The WID dredge bar was maintained quite high above the bed, and not a large amount of sediment was dredged during this episode. All profiles and observations at a fixed height in the water column (~0.8m below the water surface) are plotted in Figure 40.

The first profile was theoretically taken from upstream of the dredger before dredging began, but with the last of the flood running from the dredger towards the survey boat. The presence of a

~1.5m thick layer of fluid mud on the bed is unlikely to be natural, and it is suspected that the WID side-ports, and energetic use of the propellers, in getting the vessel to her start location, had already initiated a lot of bed disturbance. The second profile, once the ebb had started to flow, and before dredging proper began, may better reflect the natural condition (~2 g/l surface, 10 g/l bed, cf Figure 23.).

During RUN 1 the plug of water running down the estuary comprised a well-mixed upper layer of around 15-20 g/l overlying a very dense suspension, 0.5-1.0m deep, with concentrations >20 g/l. This bed-supported fluid mud layer persisted to beyond the downstream monitoring limit. No absolute concentrations of sediment in this layer were established due to a malfunction of the Owen tube, preventing deep sampling. During RUN 2, after dredging had ceased, TSS levels reduced to ~2-3 g/l at the surface and 10-15 g/l near the bed. There were some higher levels immediately above the bed, but the fluid mud layer seen during RUN 1 has dispersed downstream from the monitoring reaches.

During both runs the TSS content of the surface water layer increased seawards as far as Kp 27.5 (the pontoon), indicating that sediment was not settling out onto the bed through these reaches but was being fed from the bed/fluid mud layer (Figure 40 lower graph). Downstream of this point however surface layer concentrations began to fall, indicating that settling was beginning to occur

5.2. Trial 2 WID

The survey was undertaken on the 18th November, with low river flow, tidal range 10.9m (high spring), HW at Hinkley 8:53 GMT (6.09m OD) and HW at Northmoor 10:55 GMT (5.86m).

Monitoring began at 11:07 and ran through until 14:30. The survey commenced immediately downstream of the dredger which was located at the northern end of the southern EDZ reach; the dredger was not operating. One was profile taken. The second profile was taken just downstream of the dredger after WID activity commenced. Two drogue track runs were then made during the remaining survey time. Dredging ceased at the time the second run ended. The WID dredge bar was maintained closer to the bed and more sediment was dredged during this episode. A stationary (on pontoon) set of observations was made from about 13:30 to 14:30. All profiles and observations at a fixed height in the water column (~0.8m below the water surface) are plotted in Figure 41.

The first profile, taken before dredging commenced, was as expected, showing apparently natural concentrations for a high spring tide (see Figure 23). As soon at the WID commenced turbidity rose and a flowing, dense near-bed suspension formed again (Profile 2 onwards), though thinner and less persistent along the reaches than during the previous trial. Owen tube samples were taken from within the fluid mud layer (points identified in Figure 41). Sample 7 at profile 10 gave a concentration value of 25 g l^{-1}, normal for a mobile dense suspension. Samples 8 (profile 2) and 4 (Profile 14) gave very high values (329 and 478 g l^{-1} respectively) more typical of a stationary (settled) fluid mud condition. A settling test conducted on sample 4 showed hindered settling conditions. It is possible that these very dense suspensions were not moving along the estuary bed.

In the water layer above the bed-supported fluid mud layer, TSS values were consistently in the range 5-10 g/l near the surface and 10-20g/l at the bed. The set-depth drogue tracking runs along the reaches below the dredging showed that on RUN1 the TSS content of the water plug dropped during the journey, indicating that sediment was settling out on to the bed. During RUN 2 TSS values stayed more constant, suggesting the suspension was stable. Once dredging stopped, TSS conditions towards the lower end of the monitoring zone dropped to ambient levels (~4 g/l) within an hour (Figure 41, bottom right graph).

5.3. Trial 3 Farrell

The survey was undertaken on the 25th November, with high river flow, tidal range 7.2m (high neap), HW at Hinkley 15:53 GMT (3.97m OD) and HW at Northmoor 17:15 GMT (6.18m).

Monitoring began at 11:44 and ran through until 15:20. The survey commenced alongside the dredger which was moored to the pontoon. A profile was taken. The survey launch then followed the dredger as it sailed to its start position at the northern edge of the EDZ. A profile was taken mid-trip (RUN 0). Observations were made astern of the dredger while it was setting up. At 13:00 dredging with the Farrell commenced, with a profile being taken immediately downstream. Two drogue tack runs were then made during the remaining survey time. Dredging ceased at the time the second run ended. All profiles and observations at a fixed height in the water column (~0.8m below the water surface) are plotted in Figure 42.

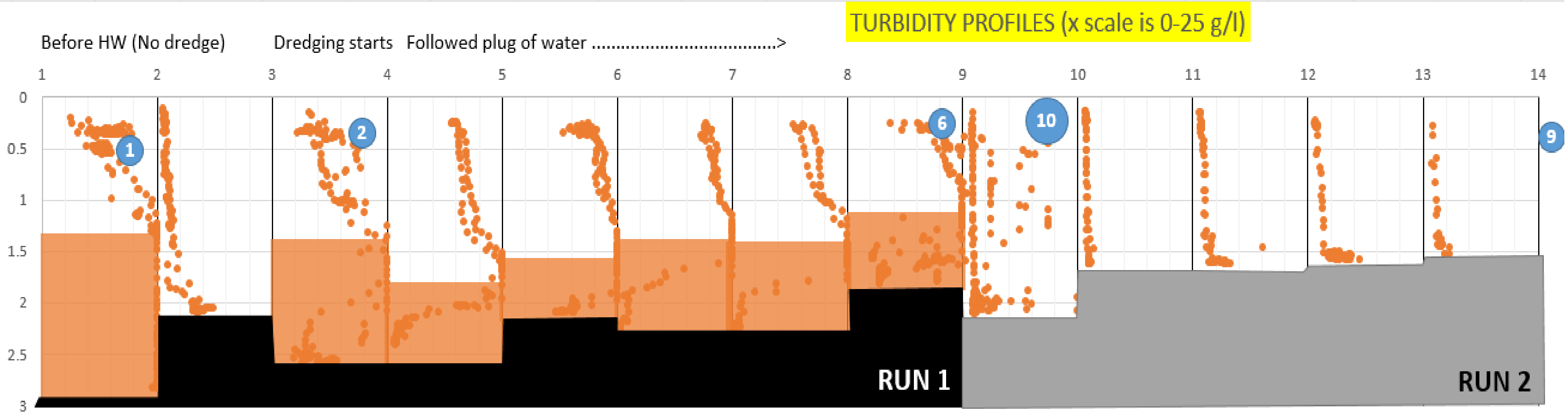
The first profiles taken showed that, due to the high river discharge, suspended sediment levels were much lower than previously seen, with ambient values being below 150 mg/l (bottom right graph Figure 42, first profile Figure 42. NOTE that the x-scale on this figure is x10 lower than in previous figures). During the initial period of getting on station and spudding in, the background TSS levels rose to 2500 mg/l, the highest concentrations to be seen that day. During the drogue tracking runs while the dredger was working downstream TSS concentration varied between 200 and 600 mg/l, with little drop in concentration with distance travelled, indicating that sediment was not falling out of suspension. The suspension was well mixed through the water column, the step of slightly higher concentrations measured at the bed possibly indicating exchange of particles between the bed and the overlying suspension, or a fine sand/coarse silt carpet flowing along the bed. TSS determinations from the various

5.4. Trial 4 Farrell

The survey was undertaken on the 28th November, with moderately high river flow, tidal range 9.2m (low spring), HW at Hinkley 5:53 GMT (4.91m OD) and HW at Northmoor 06:30 GMT (5.67m).

Monitoring began at 8:05 and ran through until 12:15. The survey commenced alongside the pontoon. A profile was taken (1). The survey launch then sailed to the dredger located at its start position within the north reach of the EDZ. The dredger had just started working with the Farrell on arrival. A profile was taken downstream of the dredger. Three drogue tack runs were then made during the remaining survey time. Dredging ceased after the time the last run. All profiles and observations at a fixed height in the water column (~0.8m below the water surface) are plotted in Figure 43.

The initial measurement made on the pontoon showed similar ambient TSS concentrations to the previous survey (Figure 43 bottom right graph, ~200-300 mg/land stable). During RUN 1, although the dredger was supposed to be pumping, TSS levels remained at the ambient concentration or lower. During RUNS 2 & 3 TSS levels increased as a result of the dredging, but not by a large amount,



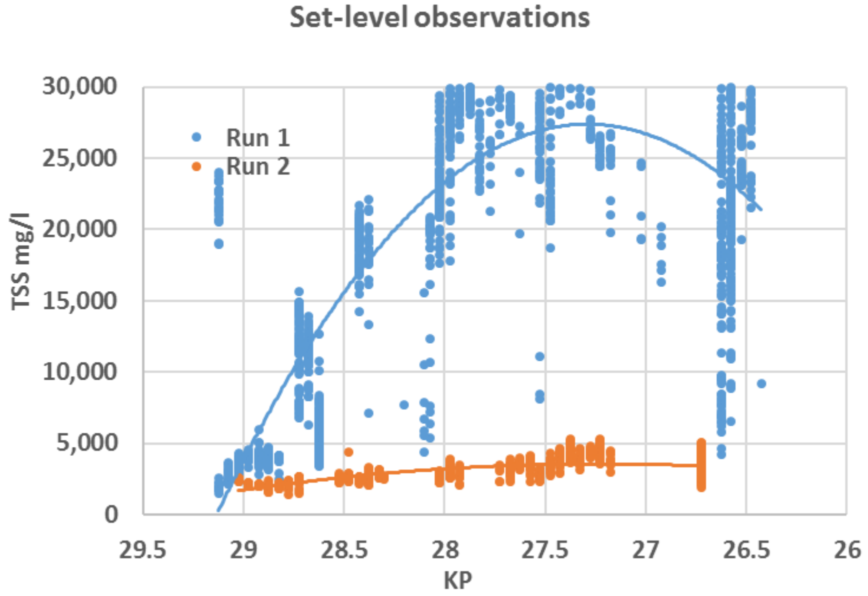
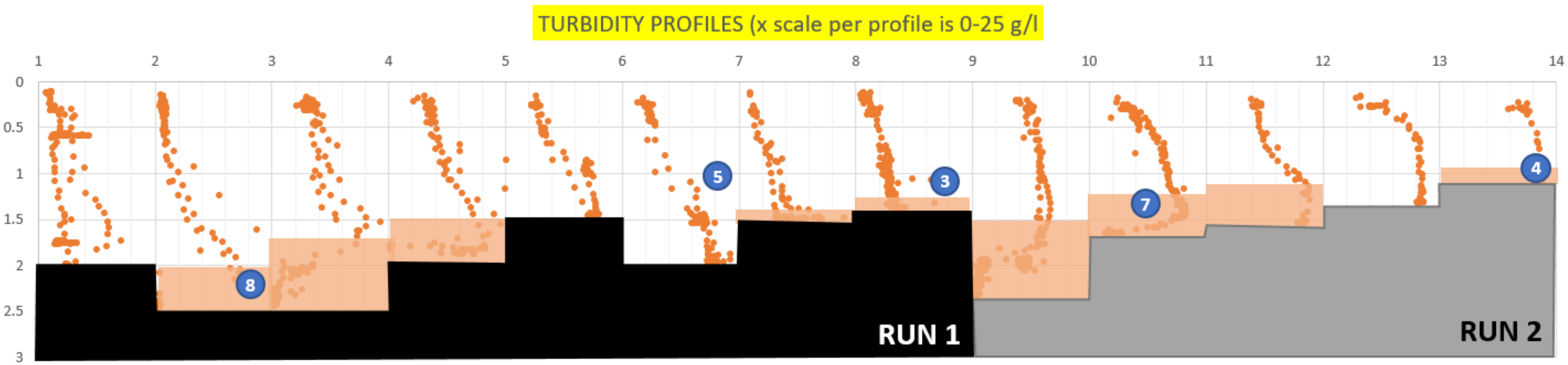
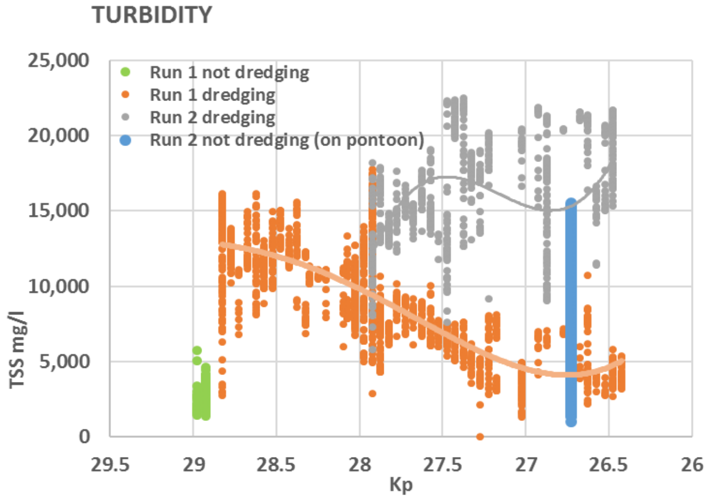


Figure 40. Total suspended solids (TSS) data collected during the first trial monitoring day (WID).

Top diagram shows successive vertical profiles (y-axis is depth below water surface in m, x-axis is TSS concentration scaled to a maximum value shown in the yellow title). Numbered blue circles are points where water samples were taken for calibration and (sometimes) sediment settling velocity measurement. Orange zones immediately above the bed indicate the presence of a layer of very dense mud suspension on the bed, as defined by the Partech transmissometer reading >20,000 NTU. YSI TSS readings seen behind this layer are spurious.

The left graph shows the constant depth monitoring undertaken between the profiles (a depth profile is given if this wasn't constant at about 0.8m). TSS value is plotted against kilometres along the estuary (Figure 1). Polynomial regression curves are fitted to these data to pick out the trends.





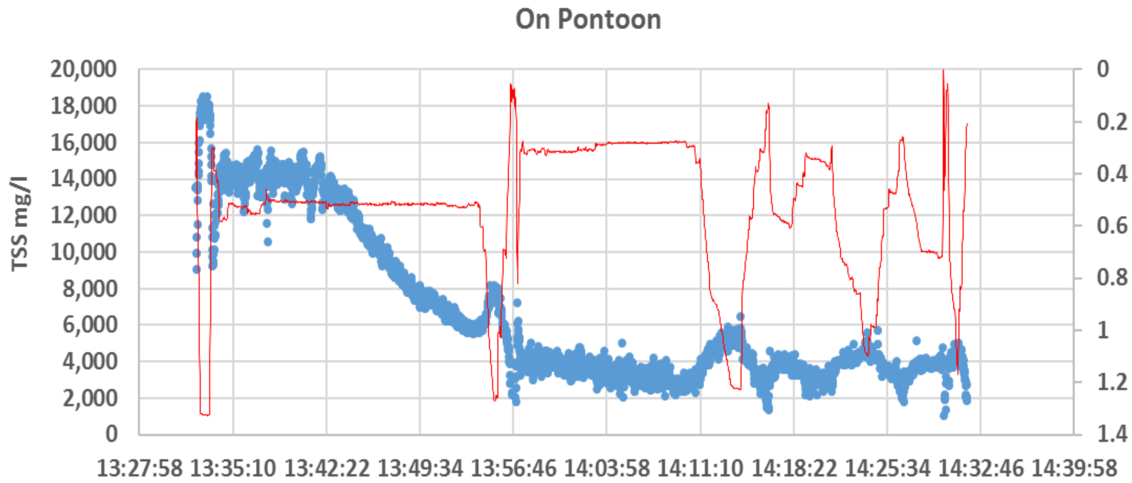


Figure 41. Total suspended solids (TSS) data collected during the second trial monitoring day (WID). For explanation see Figure 40.

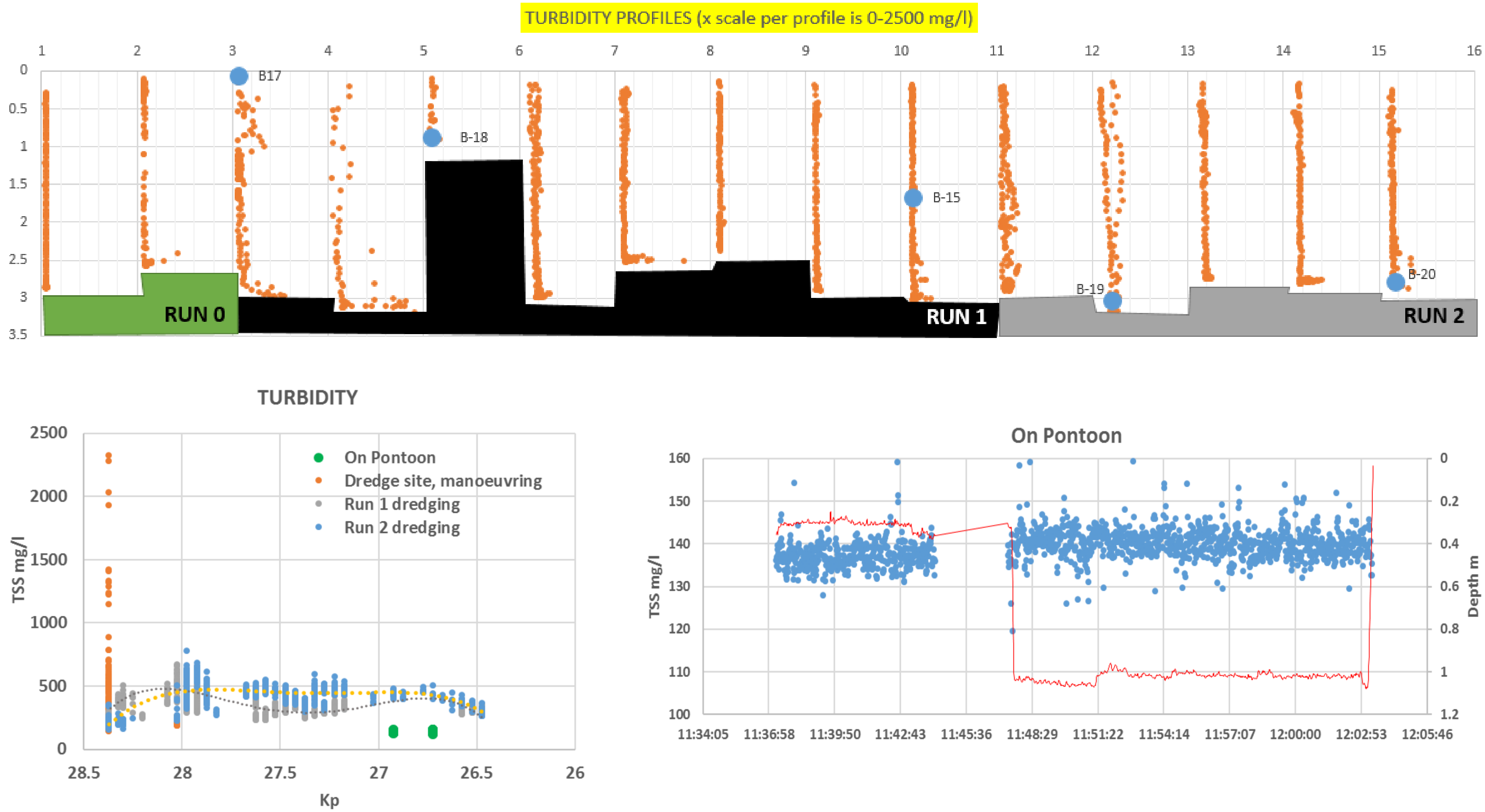


Figure 42. Total suspended solids (TSS) data collected during the third trial monitoring day (Farrell). For explanation see Figure 40.

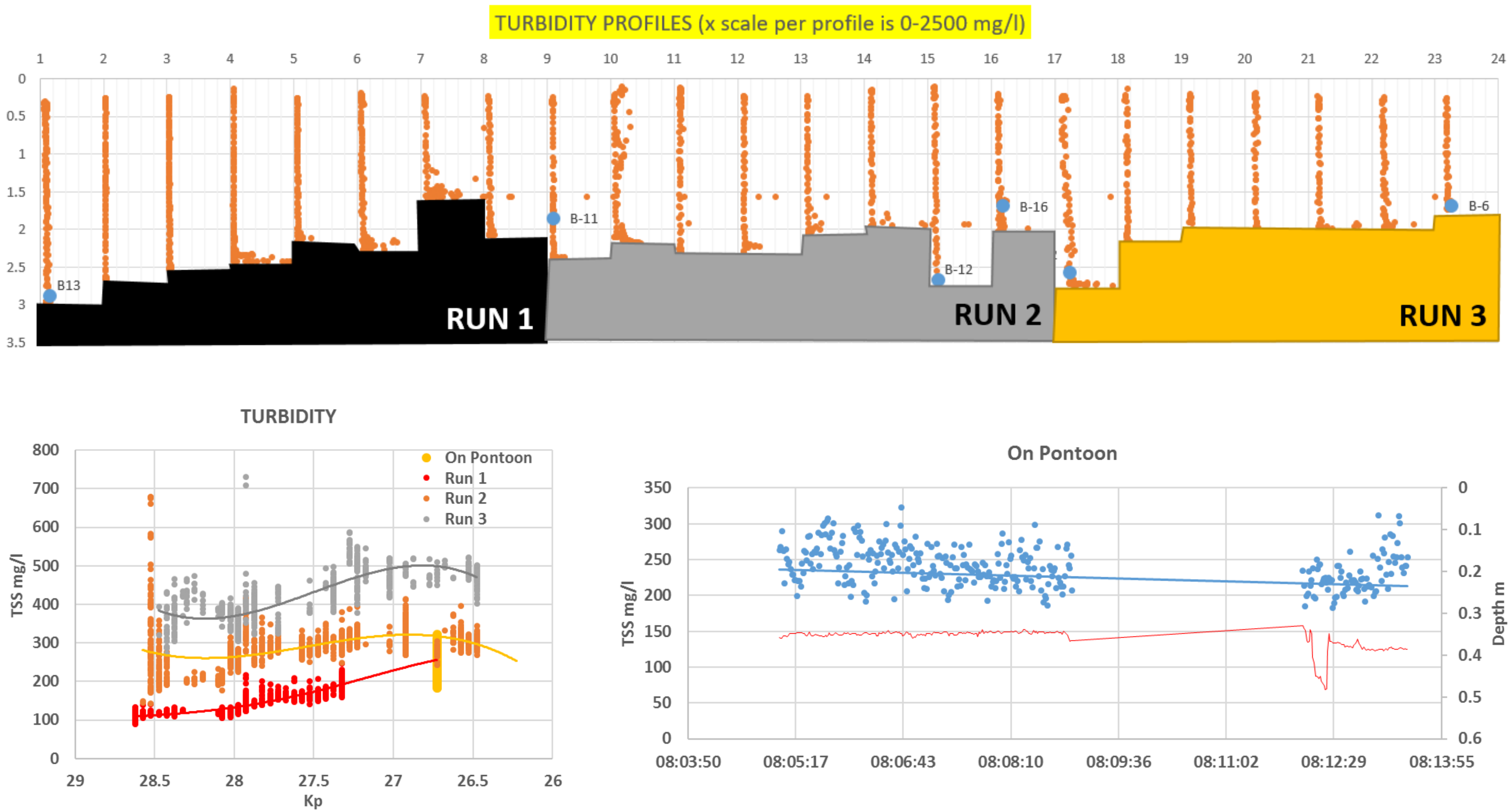


Figure 43. Total suspended solids (TSS) data collected during the fourth trial monitoring day (Farrell). For explanation see Figure 40.

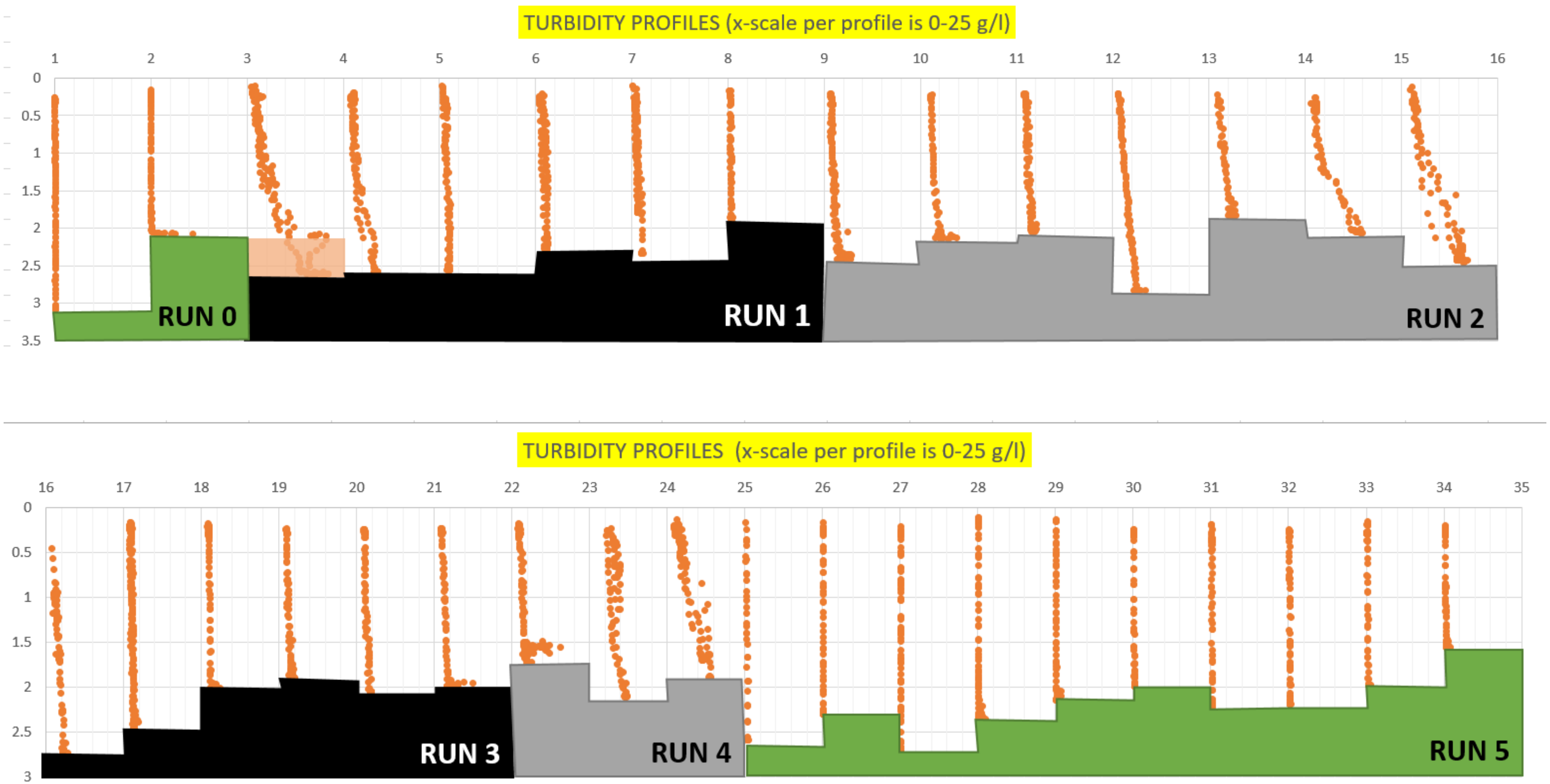


Figure 44 A. Total suspended solids (TSS) data collected during the fifth trial monitoring day (WID). For explanation see Figure 40.

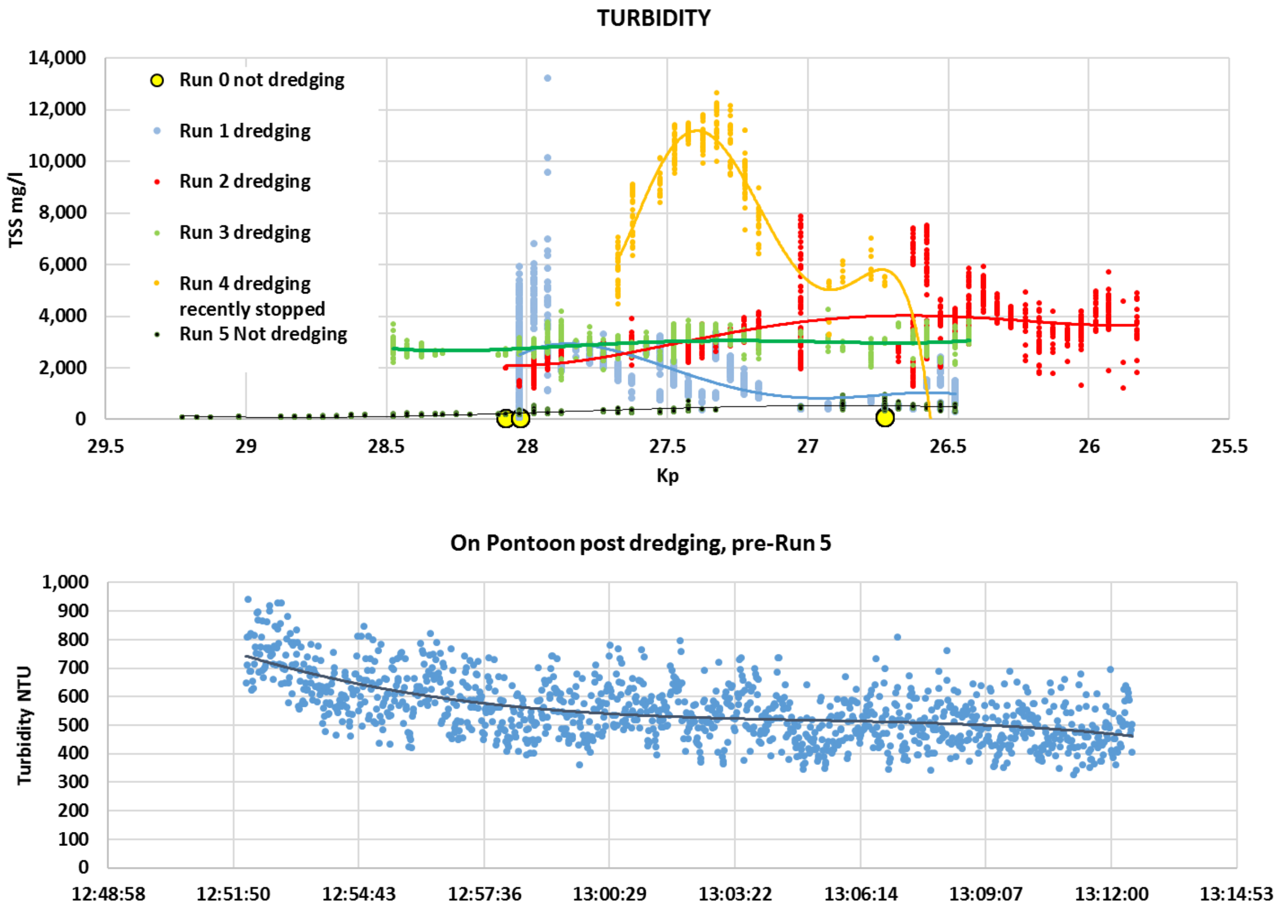


Figure 44 B. Total suspended solids (TSS) data collected during the fifth trial monitoring day (WID). For explanation see Figure 40.

reaching only about 600 mg/l maximum (Figure 43 bottom left graph). Regression lines fitted to the latter data sets show clear TSS level increases downstream of the dredger, indicating bed erosion under the natural flow rather than deposition from the dredger plume. This situation altered downstream of 27.5 Kp (pontoon site) and it would seem that particle settling began to happen below that point. Profiles (Figure 43 top) showed well-mixed conditions, but often a step increase in TSS levels close to the bed, indicating bed erosion or deposition, and/or a mobile carpet of particles with a higher settling velocity.

5.5. Trial 5 WID

The survey was undertaken on the 30th November, with moderate river flow, tidal range 9.9m (low spring), HW at Hinkley 6:53 GMT (5.30m OD) and HW at Northmoor 07:45 GMT (5.84m).

Monitoring began at 8:30 and ran through until 14:30. The survey commenced alongside the pontoon. A profile was taken. The survey launch took up position downstream of the dredger at the northern edge of the EDZ. Profile 2 was taken (no dredging). WID dredging commenced at 8:45. A profile 100m astern of the dredger was taken (3), then drogue runs commenced. Four drogue track runs were then made with the WID working continuously. Tracking stopped during RUN 4 when the WID ceased operation at 12:30. At 12:50 a short period of stationary mid-depth observations were made at the pontoon. At 13:40, a drogue track run (5) was made through the whole of the monitoring zone, the WID not having ben dredging for over an hour. All profiles and observations at a fixed height in the water column (~0.8m below the water surface) are plotted in Figure 44A&B. NOTE the x-scale on the graphs of Figure 44A are now back to a range of 0-25 g/l).

Initial profiling (RUN 0) showed ambient TSS levels to be very low (<300 mg/l). On commencement of dredging the whole water column TSS concentration rose quickly to 2-10 g/l and immediately astern of the dredger a ~0.5m thick dense mud layer (>20 g l^{-1}) was formed. This bed layer dispersed very quickly down the estuary, and the phenomenon was not seen at all during the remainder of the day's monitoring. During RUN 1 there was a strong decrease of TSS values in the water body tracked downstream (3 to 1 g/l, Figure Z11B), suggesting strong settling out to the bed. During RUN 2 this situation reversed and the form of the curve fitted to the data suggested slight erosion of the bed throughout the surveyed reaches, possibly being a mobilisation of the material that had fallen out during RUN 1. During RUN 3 conditions seemed stable in the plume throughout the monitoring zone, and during RUN 4 (when TSS values reached ~12 g/l) there was indication of strong erosion in the reaches between the dredger and the pontoon, possibly as a result of scour under the increasing velocities of the later, more confined ebb current. RUN 5 was undertaken about one hour after dredging had finished, and showed that water column TSS concentration had returned completely to ambient levels. The trendline fitted to these data along the reaches increased slightly seawards (~100 to 400 mg/l), indicating slight bed erosion. However there were no marked step increases in TSS levels close to the bed during this run, suggesting a clean bed, not clogged by unconsolidated sediment fallen out from the day's dredging, i.e. the WID process had successfully allowed all dredged material to be dispersed from the monitoring zone.

5.6 The Settling Characteristics of the Plume Suspended Sediment

The Owen tube was used on 15 occasions during the manned monitoring to determine the settling velocity of the plume suspension. The results are summarised in Table 7 and Figure 45.

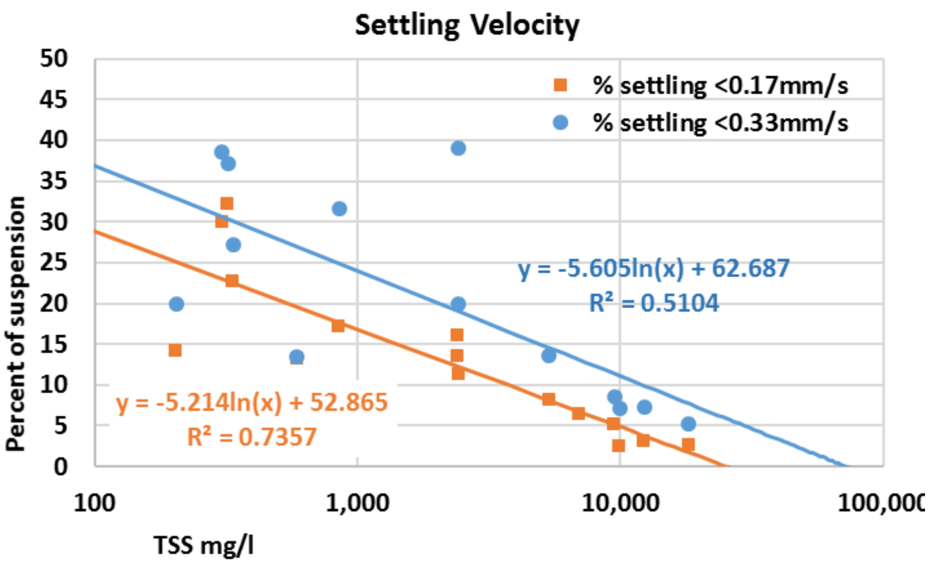


Figure 45. Relationships between sediment settling velocities and total suspended solids (TSS).

	Sample	YSI NTU	TSS mg l^{-1}	% sand	% settling<0.33mm/s	% settling <0.17mm/s
14/11/2016	1	1254	6,971	3.8		6.4
	2	786	2,428	2.0		11.3
16/11/2016	1	638	2,405	2.9	19.9	13.5
	2	1558	8,240	4.6		
	6	932	1,928	0.3		
	9	1100	5,350	6.5	13.6	8.1
	10	638	2,405	2.9	39.1	16.1
18/11/2016	3	1257	9,907	6.6	7.1	2.4
	4		478,376	4.5	0.2	0.1
	5	1705	6,838	1.2		
	7	1897	24,626	5.1		
	8		329,921	10.6		
25/11/2016	15	95	321	0.0	37.1	32.2
	17	55	161	0.0		
	18	68	336	0.0	27.2	22.7
	19	155	350	0.0		
	20	128	305	0.0	38.5	30.0
28/11/2016	2	174	473	0.0		
	6	198	700	0.0		
	11	66	204	0.0	19.9	14.1
	12	119	200	0.0		
	16	136	589	0.0	13.5	13.2
30/11/2016	1	747	1,530	0.0		
	3	308	849	0.0	31.6	17.1
	5	1164	9,488	10.1	8.5	5.1
	10	1649	18,216	6.9	5.2	2.6
	15	22	40	0.0		
	16	154	314	0.0		
	17	743	1,973	1.9		
	18	1229	3,354	0.0		
	19	1741	12,281	1.5	7.3	3.1

Table 7. Owen tube data. Yellow cells show very high TSS values and hindered settling.

The results show (the expected) strong relationship between mud settling rates and suspension concentration, the denser the suspension the higher the floc collision rates and the larger the flocs that form, with consequent higher settling rates. This model only applies at low current speeds, the shear associated with turbulence at high speeds acts to reverse this process and break up flocs. Still water does not occur during the ebb dispersion periods that have been monitored, but knowledge of settling rates is instructive as a) at modest flows with associated low vertical diffusion, particles can settle from a flow (either through the whole flow or just through the near-laminar near-bed layer) and b) it allows insight into the wider model of fine sediment dynamics in the Parrett estuary. Two standard settling velocities were measured on each experiment, and the percentage of the suspension settling slower than these velocities reported. These settling velocities were chosen as they are typical velocities for particles in the mid-silt range at normal temperatures, and therefore should relate to the Parrett sediments. The velocities (Table 7) are:

- 0.17 mm s^{-1}, which relates to a settling depth of 0.3m over a 30 minute period (the typical 'still stand' at HW on the Parrett)
- 0.33 mm s^{-1}, which relates to a settling depth of 0.6m over a 30 minute period.

At suspension concentrations of around 10g l^{-1}, in still water, about 90% of the sediment held in the near-bed 0.6m could sediment onto the bed (Figure 45). At 100mg l^{-1} only 60-70% would settle.

5.7 Autonomous Data Records from the Dredging Period

Data logged for the surface water layer at Westonzoyland (WZ) and Burrowbridge (BB) during the dredging period are plotted in Figure 46. Note this plot fits between the timeseries plots of Figure 24 and 29 (pre-dredge and post-dredge respectively). Dredge days are indicated by green blocks of shading.

At the water surface, the WID dredging of the 15th-18th November is lost in the high TSS peak naturally associated with the peak spring tide flows under low river discharge. The plot of Figure 46 is magnified in Figure 47 for this period, and shows clearly the dominance of the flood turbidity spike over the ebb turbidity levels. Only on the last tide of the sequence at WZ does the ebb dominate over the flood TSS level. The WID dredge of the 30th November, under a lower spring tide and much higher river discharge, is evident as an isolated peak at the WZ site only. The maximum value recorded (~3 g/l) agrees with the manual monitoring values (Figure Z11B). The time series data shows that ambient TSS levels were restored within about 12 hours of dredging finishing. On the Farrell dredging days (25th, 28th, 29th November and 1st December) minor peaks are evident in the TSS record at WZ. Peaks seen do not exceed ~500mg/l, consistent with the manual observations (Figures 42 and 43). Again, the timeseries data show restoration of ambient values within 12 hours of dredging ceasing.

From the start of dredging to the 11th December the only other turbidity peaks evident are between 19th and 22nd November, and coincide with the rising limb of the river flood passing through the system. Maximum TSS values reached about 1500 mg/l at Burrowbridge on the rising flood limb. By the time this water reached Westonzoyland the peak TSS concentration was in excess of 2 g/l, clearly some bed erosion occurred between the two sites. It is impossible to speculate how much of this erosion would have occurred under normal circumstances, and how much enhancement occurred as a result of the release of sediments disturbed during the dredging. Some effect of the dredging might be expected. Outside of the period of this flood limb, turbidity was very low at both BB and WZ sites, suggesting that any residual effects of the dredging on the turbidity regime must have been minor. After the 11th December a period of strong spring tides generated natural high turbidity associated with the upstream penetration of the tide. The level of turbidity generated under these processes was less that on previous spring tides (pre-dredge, Figure 24) presumably due both to the higher river condition, and sediment exhaustion due to the combined effects of dredging and the scour associated with the late November flood event. Any turbidity associated with the dredge extension period (12-16th December) was lost in the natural peak spring tide high TSS peaks.

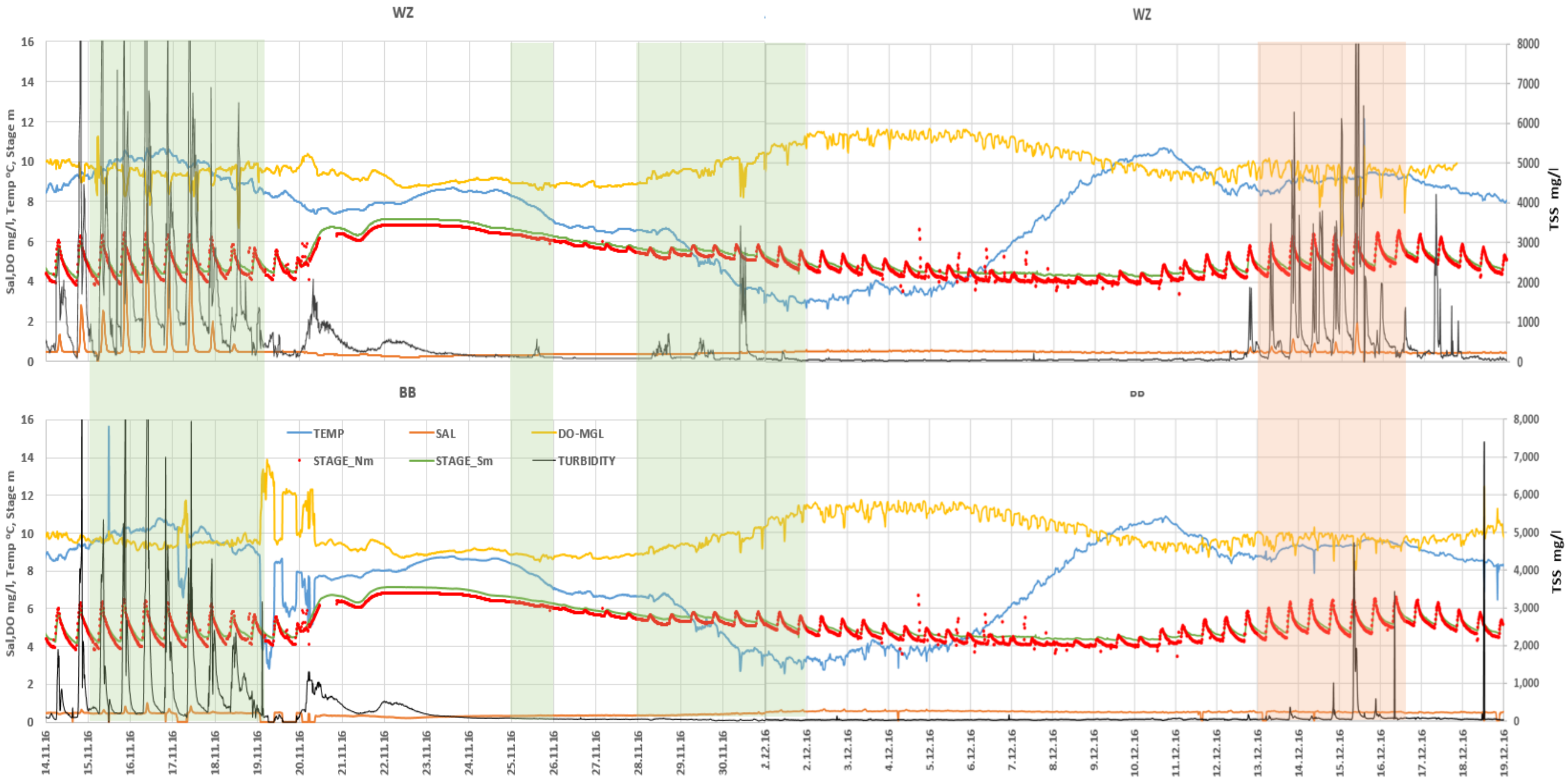


Figure 46. Autonomous monitoring data through the dredging period. Green boxes show original (fully monitored) dredge periods, pink box shows partially monitored extra-dredging period. YSI data for the 19th/early 20th November at BB are suspect (sensor became only partially submerged).

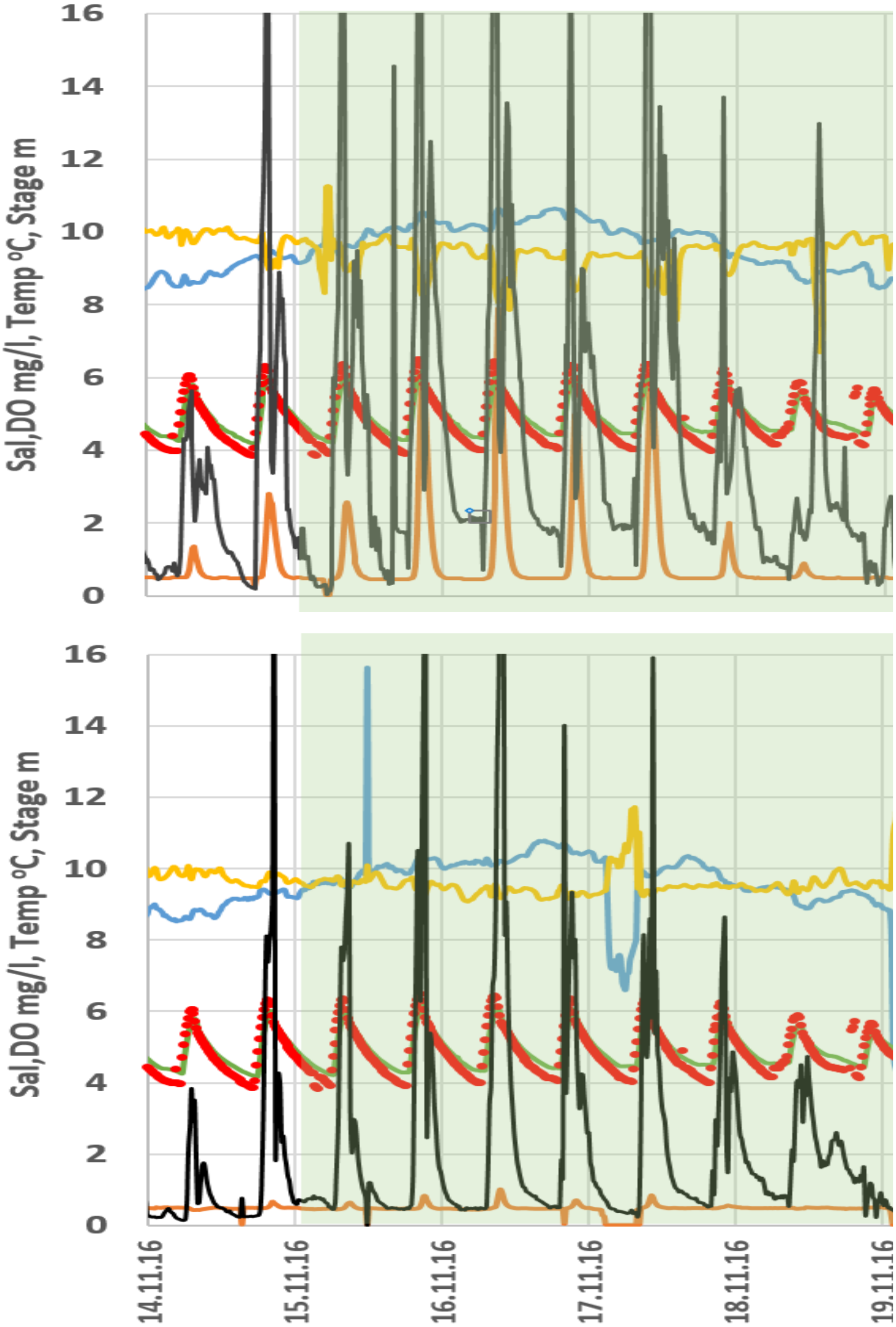
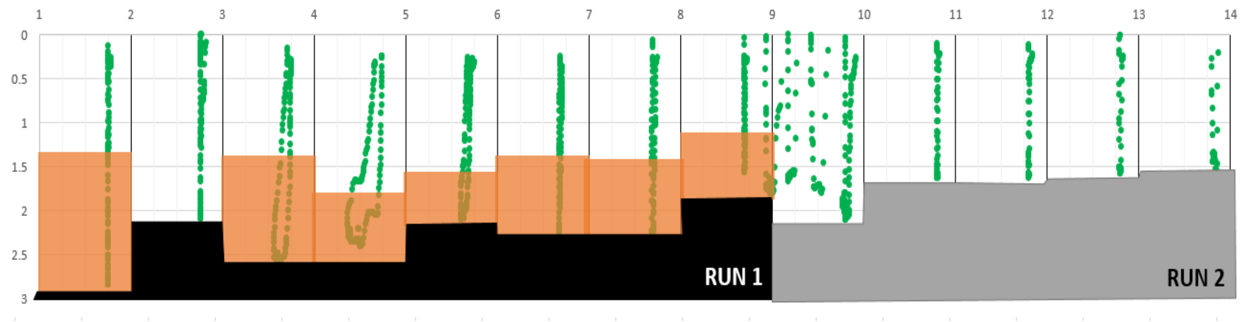


Figure 47. Zoom of part of Figure 46, covering the initial dredge period. See Figure 46 for the secondary y-axis labels (TSS mg/l). Top WZ, bottom BB.



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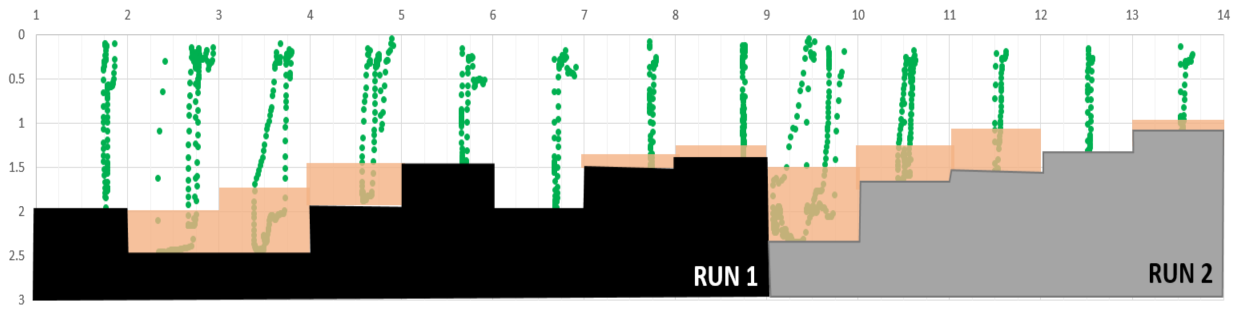

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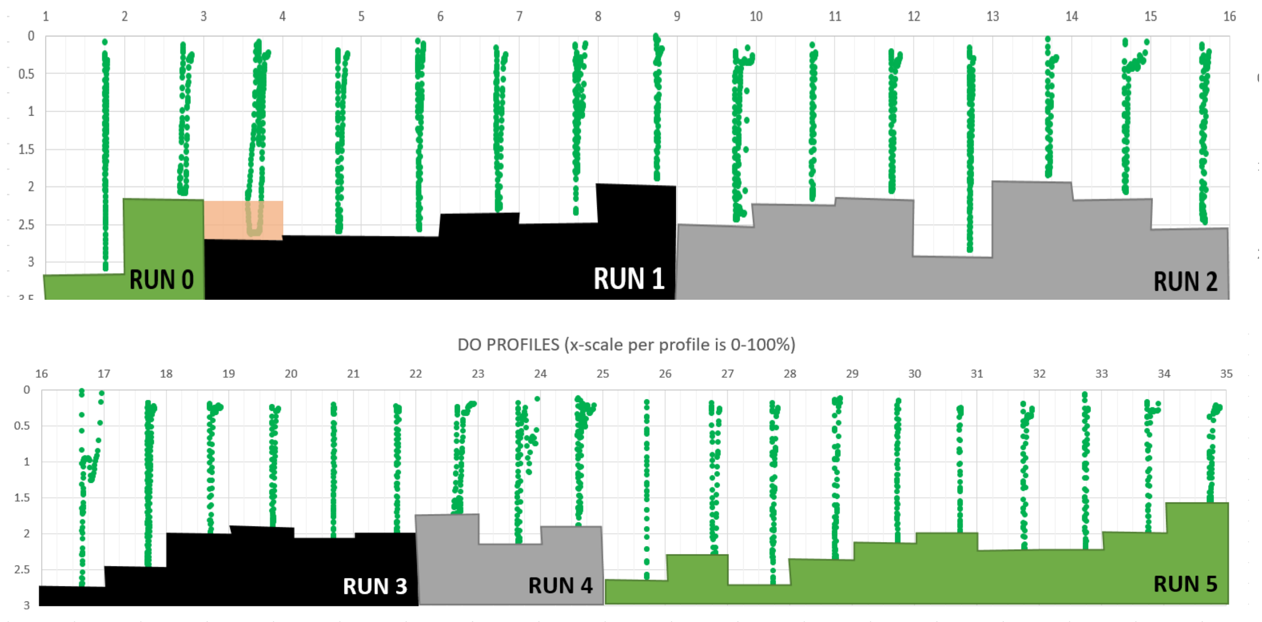

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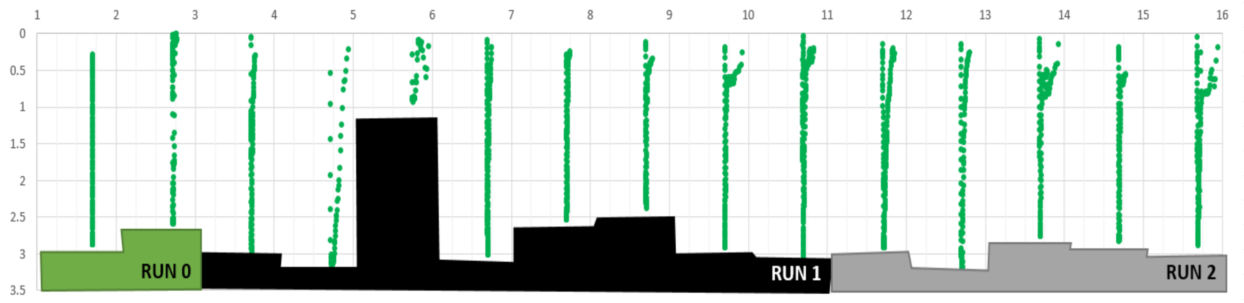
Figure 48. Dissolved oxygen profiles during the WID trials. Figure 48. Dissolved oxygen profiles during the Farrell trials. X-axis is scaled to 100% per profile, y-axis is depth below water surface.



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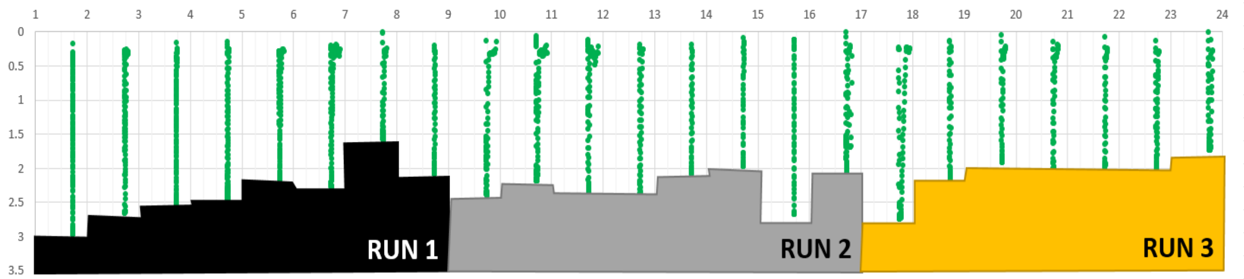

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Figure 49. Dissolved oxygen profiles during the Farrell trials. X-axis is scaled to 100% per profile, y-axis is depth below water surface.

6. Water Quality Impacts

6.1. Dissolved Oxygen

WATER INJECTION DREDGING. All the dissolved oxygen profiles observed during the WID dredging trials are plotted in Figure 48. Most of the profiles are simple, vertical and with values at around 75%, showing a normal, well-mixed and oxygenated water column. However some of the profiles that pass into fluid mud at the bed show a strong drop in dissolved oxygen on entering the layer, which takes a while to recover during the return limb of the cast. The latter is simply due to the time taken for the dense suspension to wash clean of the sensor, and the (slow) response time of the sensor. In one worst case (profile 9 on the 18th November) the DO % reached zero. The fluid mud clearly can have a high oxygen demand, as might be expected. If pools of this mud were to accumulate in trap zones along the channel thalweg, fish/eels/infauna trapped in the pre-existing bed layer could become deprived of oxygen.

FARRELL CUTTER DREDGING. All the dissolved oxygen profiles observed during the Farrell dredging trials are plotted in Figure 49. On all occasions the DO % was above 75%.

6.2. Ammonia

No discernible effects on ammonia concentrations were recorded from either WID or Farrell dredging systems.

7. Ecological Impacts

Prior to the start of the trials, the potential for the experimental dredging systems to have ecological effects was assessed in an Environmental Impact Assessment and an Environmental Action Plan was prepared, which helped establish the monitoring and mitigation requirements for the trials. Significant ecological impacts were avoided by undertaking the trials at the least ecologically sensitive time of year and by selecting dredging methods that had minimal impact on bankside vegetation and geomorphology. The potential for minor effects on water voles, fish and upper bank habitat (vegetation)[17] are discussed below.

7.1. Water Vole

River banks between Burrowbridge and Westonzoyland were surveyed for water vole signs on three occasions (Sept, Oct and Nov 2016) prior to the start of the dredging trials. These land-based surveys found no evidence water voles (burrows, feeding signs or latrines) in the monitoring zone. This is not unexpected, since the high sedimentation rates and large fluctuations in water levels, due to the tide, make these sections of the channel generally sub-optimal for water vole. Predation pressure on the banks is also relatively high and vegetation cover can be patchy, especially in the inter-tidal zone. Water vole signs are more commonly recorded in the upstream sections of the Parrett and Tone, above Burrowbridge, but rarely downstream of Burrowbridge. However, safe access to the banks for ecological surveys is also an issue and the negative survey results cannot be taken as confirmation of the absence of water vole in the monitoring zone. The post-dredge boat survey provided good opportunities to examine the lower inter-tidal zone for water vole signs, and water vole footprints were found at several locations, especially in the upstream section of the monitoring zone. During the trials, the survey boat disturbed a heron that had just caught a water vole. The heron was filmed taking off carrying the water vole, thus there is confirmation the sighting. The heron almost certainly caught the water vole on the Parrett. The boat surveys confirmed that water vole are present on the Parrett banks between Burrowbridge and Westonzoyland, albeit in very low densities. In contrast to bucket excavation dredging, which removes sediment and vegetation from the banks, it is unlikely that the experimental systems impacted on water vole, as dredging activity was focused on submerged non-vegetated areas within the channel and the inter-tidal zone. However, the use of the Farrell system for precision dredging could potentially disturb water voles, or disrupt marginal habitats, which may require further evaluation.

7.2. Fish

The channel was monitored downstream of the experimental dredging for signs of fish in distress and fish mortality. No impacts could be unambiguously linked to the dredging activity and silt plume, even when the WID generated very low oxygen levels within the liquid mud layer, during periods of low fluvial flow. The absence of any low DO impacts on fish is likely to reflect the strong stratification in oxygen concentrations, which always remained high (above 80%) in the near surface (autonomous sensor) measurements, and would allow fish to escape low oxygen water. The potential for WID to create an oxygen deficient liquid mud layer under low fluvial flows, and the time taken for the plume to disperse and DO concentrations to recover, will require further evaluation and measures may be required to minimise the potential for impacts on fish.

Only on one occasion were dead fish seen in the monitoring zone. This occurred during a WID trial on 30th Nov and included one yellow eel (approx. 30cm in length) and two small freshwater fish

[17] These sections provided by Phil Brewin, SDBC

(probably roach). The eel was recovered and examined. It had been dead a few days and had no obvious signs of external damage or disease, although the gills were extruded out though the mouth, suggesting a pressure effect as the cause of death. The eel is unlikely to have been entrained in the WID pump, since it had been dead for a few days and this was the first time the WID system had been used for more than 10 days. It is possibly that the eel had been caught by the cutter head of the Farrell, which had was used on the two days prior to the eel being found. However, the cutter head rotation speed is low and it would be much more likely to cause external damage to the eel, rather than a pressure injury, which is more typical of passage through a pump. It is quite likely that the eel and two small fish died some distance upstream of the dredging trials and floated into the monitoring zone. They were found following a period of heavy rainfall (between 19-21st Nov) and spillway flows onto the moors, when all of the principal land drainage Pumping Stations had been operating for several days.

7.3. Trees and Scrub

No trees or scrub growth were removed from the banks by the experimental dredging systems. It is worth noting that riparian vegetation surveys identified several areas where the lower vegetated sections of the banks have recently been colonised by young willow trees. This new growth of woody vegetation was most apparent on the inside of bends, where large volumes of the silt had been dredged from the banks in 2014, suggesting 'pioneer' dredging may have provided excellent conditions for entraining floating willow branches in the rapidly reaccreting sediment. The experimental dredging systems are unsuitable for controlling tree and scrub growth on the banks, and complementary maintenance methods will be needed for managing bankside vegetation, if the experimental dredging methods are adopted.

8. Conclusions and Recommendations.

A trial dredging project and associated programme of environmental monitoring was successfully undertaken over the period November 2016 to February 2017. The project addressed a series of issues.

UNDERSTANDING THE NATURAL REGIME OF SEDIMENTATION

A primary objective of the project was to improve our understanding of the natural sedimentary regime of the upper Parrett estuary, in order that any sediment management strategy that may be developed is optimally designed to work with nature. This report brings together rather patchy and inconclusive data from previous studies of the Parrett, providing a fuller and clearer conceptual model of the natural sedimentary system and explaining some anomalies that were previously apparent. Data generated in this study are fully compatible with data previously generated.

From the information gathered during this project several strong and independent lines of evidence have emerged demonstrating that a seasonal alternation of sedimentary processes is found in the estuary. Sediment influx from marine sources at times of high spring tides and low river discharge is replaced by effective seaward scouring of this material at times of higher river discharge. These two regimes can be summarised as follows.

Fluvial dominance. Sedimentary processes under the control of river flow prevail for most of the time. At times of low river flow, and when the Severn Estuary tidal range is less than about 8m (neap tides) these is no or little tidal effect the monitored area of the upper Parrett estuary. The water currents flow seaward all the time, possibly slowing with a modest rise in water level on the late flood, and no saline water is seen. At higher river discharge levels the tide is even more excluded, and during the highest river floods even peak spring tides only minorly affect local river-flow conditions. Under this fluvial regime, the suspended sediment concentration in the water is normally low, with TSS values around 500 mg/l, and in the reaches between Burrowbridge and Westonzoyland bed scour normally dominates (deduced from the observation that water turbidity generally steadily rises in concentration as the flow moves between these two sites). During river flood events scour is even more pronounced, and observed TSS values peak around 2 g/l (higher values are likely to be seen during the rising limb of the highest flood events). As a result there is little potential for sediments of (primary) fluvial origin to accumulate in these reaches, and during the winter both the channel floor and the lower side slopes of the channel are eroded, with 10-20 cm of scour being typically seen. During these periods of erosion the bed sediments tend to become sorted, with the finest particles (clays and fine silts) becoming dispersed seawards and coarse silt and sand remaining.

Marine dominance. Much higher suspended sediment concentrations are seen in the upper Parrett estuary monitoring zone during the spring/summer/autumn months (when periods of low river flow prevail) at the times of highest spring tides. These effects are seen when the Severn estuary tidal range exceeds about 11m (seen for up to about ten tides in most lunar cycles). The phenomenon results from the combination of two factors: firstly the ability of the tide to penetrate upstream as a function of the high-tide water level and secondly the massive mobilisation of settled fluid mud deposits that occurs in the upper Severn Estuary over these periods of high tidal energy, increasing the feed of highly concentrated mud suspensions into the Parrett. Mean TSS values reach about 1 g/l and maximum (near bed) values exceed 25 g/l. The distortion of the rising limb of the tide (due to the high tidal range and the long, narrow sinuous estuary morphology) creates a short (~2 hour) powerful flood (landward-going) current. In contrast the ebb is a much longer period of less energetic seaward going currents. A very strong peak of suspended solids concentrations is associated with the flood (up to ~10 g/l), and the protracted ebb also sees high turbidity, but generally lower than on the flood. Fine sediment deposits from the flood-source suspended sediment body over the short (~30 minute) high water stand, and although some of this deposit may be reworked during the ebb there is a net accumulation of mud over the tide. This process provides the primary supply of sediment to the upper estuary. The sediment is of (recent) marine origin and is dominated by clay and fine silt particles.

The seasonal balance between the (scouring) fluvial/ebb influence and the less frequent spring flood tide supply of marine sediment (accumulation) dictates the net sedimentation situation. There may be significant inter-annual variability due principally to different peak river discharge conditions between the years. A natural equilibrium between these conflicting processes will prevail, with associated channel profile dimensions and shapes. Where dredging is used, these equilibria will be disrupted and net accretion will become the norm. Under natural conditions, accumulation may be expected to dominate on the estuary lower side slopes (inundated by the sediment-rich flood tides, dry for much of the ebb and low river discharge periods) and an equilibrium maintained on the channel floor (thalweg) where prolonged ebb currents can scour away accumulations. The deposits on the side slopes are periodically scoured by the severest winter river floods, to create a natural system where the cross-sectional area of the conduit changes seasonally. This is the nub of the problem from the flood prevention stance, as the natural clearance of the channel section only takes place during and after the occurrence of overbank flooding. Vegetation may play an important role in trapping sediments on the higher bank slopes, affecting longer-term equilibria. This mechanism has not been addressed in the current study.

The sediment bed of the upper estuary that forms as the net result of the temporal interfingering of these two very different (fluvial and marine) processes is a coarse silt, with a lesser fine silt and clay content, and typically <15% very fine sand. This material moves as suspended load once set in motion, although mass-failure of cohesive mud deposits can produce large clasts of mud that may temporarily roll as bedload until disintegrated. The cycle of bed sediment formation sees (marine) fine silt and clay and lesser amounts of coarse silt and very fine sand washed into the area from the lower estuary on infrequent spring floods, and (the more easily eroded) fine-silt and clay preferentially scoured seawards again during strong fluvial flow, leaving a residual coarse silt dominance. The frequent episodes of erosion and long intertidal drying times enhance mud consolidation, and the deposits are remarkably dense and strong compared to more typical estuarine muds. The cyclic nature of the deposition and erosion created a very layered sediment, which impacts on its geotechnical properties.

Many aspects of this model remain poorly understood, or data are not available to allow robust modelling of the phenomena. An example of the former is the apparent exhaustion of mud supply over the peak spring tide periods, with flood tide turbidity peaks dying out while high energy is still available for transport. This observation suggests that at any one time the source body of available mud for transport in the upper estuary has a limited volume. An example of the latter is the absence of good data on river flow entering the system on the Parrett and Tone, making it difficult to model with any detail the progressive interchange between fluvial and marine conditions.

DETERMINING THE EFFECTIVENESS OF THE EXPERIMENTAL DREDGING SYSTEMS

Two systems were trialled, a WID (high productivity) and a Farrell (high precision).

An important objective of the study has been to Identify and quantify the processes of sediment dispersion downstream from the dredger, to ensure that the dispersing flows did not simply redeposit the dredged sediments further downstream.. The processes of sediment dispersion varied between the method, and also according to whether marine (tidal) or fluvial processes were dominant at the time (river discharge).

In the upper Parrett estuary under low river flow conditions, the WID can only work during the ~2 hour period after HW on spring tides, due to the poor water depth at other times (and landward flow on the flood). Under these conditions the high productivity of the WID system tended to swamp the low volume of water passing the dredger, suspended sediment concentrations were very high and a mobile dense suspension (>20g l^{-1}, 0.5-1m thick) formed along the bed downstream of the dredger, often persisting all the way through the monitored reaches. At times the density of this layer at the most downstream monitored site reached 0.5t m^3, the density of a settled mud deposit, so it is likely that the movement of this layer was close to stopping or had stopped, resulting in local accumulation of the dredged sediment rather than dispersion into the lower estuary. For this reason and also for the very low dissolved oxygen conditions sometimes seen in the bed layer, the use of the WID at times of low river flow is unlikely to be the most practical option.

Using the WID under higher river flow conditions, and also with the lower productivity of the Farrell system, less dense plume conditions were generated. The method used of following a body of water down the estuary clearly showed that at times there was no increase or decrease in TSS values in the water body as it passed through the reaches (suspension stable), sometimes an increase in TSS (bed eroding) or sometimes a decrease in TSS (sedimentation onto the bed was occurring(). Which model dominated at any particular time must be largely controlled by the ambient current speed. It was observed that sometimes a 'depositional' plume was followed by an 'erosional' plume, so good dispersion downstream was achieved in the longer term. Post-dredge bathymetric surveys showed that natural river scour prevented the long-term accumulation of any of the dredged mud as far north as the M5 motorway. Selecting optimum river flow conditions, to ensure both good dispersion at the time of dredging a prolonged period of subsequent downstream dispersion, would be an important aim of dredge programme planning.

Given that the lower reaches of the estuary contain a large reservoir of mud that feeds the process of (spring tide) pumping of mud into the upper reaches, it is probably not important to be concerned about the ultimate sink sites of the dredged material. Just so long as the dredged material became mixed back into the source reservoir of mud in the middle/lower reaches of the estuary, the situation cannot really be improved. Further information on the sediment regime in the mid/lower estuary would give further confidence to this statement. Much survey work in these zones was undertaken by HRWallingford in the 1970s, and although unpublished may still be available for study.

The process of lateral slumping of the side slope berms through the dredged reaches was very marked at some locations, and occurred during the weeks following the primary dredge activity. This second phase of 'natural' lateral translation of the side berm sediments down into the main channel (where the persistent seaward flow would wash the material downstream) could be an advantageous phenomenon, allowing just WID dredging of the channel floor, and a natural reaccommodation of the side slopes. The presence of high river levels and strong fluvial discharge through this readjustment period will make the cleansing process more effective.

On the wider issue of effectiveness, the dredging is being undertaken in order to take the estuary cross-section area out of 'regime' (where it is in equilibrium with average energy conditions) so that it is ideally prepared to effectively conduct the highest floods occurring. By definition, destroying this energy equilibrium will encourage deposition to occur, both by reducing the effectiveness of fluvial/ebb scour, and by encouraging inland penetration of the sediment rich marine water under tidal action. Optimising dredging effectiveness maximises the cost benefit of this activity. To minimise the cost of dredging three analyses have to be made.

- Hydraulic modelling that can identify the downstream point beyond which dredging has little effect on floodwater transmission: definition of the dredge reaches
- Identification of dredge method that operates most cost effectively (known to be systems that have high productivity and rely on natural dispersion of dredged material).
- Establish the optimum timing (inter-annual frequency, seasonal optimisation of impact) for the dredging operations

The first analysis lies outside the scope of this study, but it is flagged here as a critical piece of work to be undertaken. The most productive dredging method (second analysis) is clearly the WID system (the Farrell is precise but much slower). This study has shown that the WID can be carefully used at high productivity and with a sufficient degree of precision for maintenance of engineering safety (no undercutting of the banks). The third analysis depends totally on the continued development of a good understanding of the natural system, which will require further investigations/monitoring, ideally establishing a practical monitoring system that will advise proactively on the timing of intervention decisions rather than relying on a reactive approach.

Through all the channel reaches from Burrowbridge to the M5 motorway, between November 2016 and February 2017, it can be estimated (GIS analysis) that some 32,000m^3 of mud was dispersed seaward, into the mid/lower estuary or sea. Only some of these reaches were dredged and logically applying non-dredged area losses to all the reaches it can be calculated that river action alone would have removed some 24,000m^3, thus attributing 8,000m^3 to the dredge activity. The winter of 2016-2017 did not see particularly high river flows, and significant inter-annual variability in the capacity of the river to scour itself should be expected. Critically, using a WID/Farrell system for dredging must be seen as a method of supplementing the natural processes of scour, and should always take place a) as early as possible in the winter (to maximise post-dredge river scour) and b) always at times of high river flow (to ensure optimum initial dispersion). A better understanding of the annual inter-annual variability in natural scour processes, and similarly the spring/summer/autumn rates of sediment supply, ought to be an important input into any assessment of the effectiveness of dredging operations, allowing a scaling of the relative contributions of natural processes and pragmatic dredging intervention. A long-term programme of sediment flux monitoring in the upper Parrett estuary would be the simplest approach to provide answers to this question, and would also provide guidance on the required timing of dredging interventions.

ENVIRONMENTAL IMPACT

Geomorphologically, the pioneer dredging of recent years has put much of the upper estuary channel zone out of its natural equilibrium, and rates and patterns of sediment movement are likely to be adjusting to this impact. Future maintenance dredging impacts need to be assessed on this basis. Positively, the proposed enhancement of winter scour in order to maintain larger estuary cross-sections is enhancing a natural process rather than imposing a completely new situation. In this respect the impact on local geomorphological processes may be minimal. Two issues arise from this study:

- Keeping the upper estuary freer of marine derived sediments by enhancing scour (dredging) may modify the size and behaviour of the pool of mobile sediment in the mid-lower estuary reaches. This should be examined in future EIAs.
- Dredging may selectively resuspend and disperse different sediment particle fraction. The study has shown that natural scour retains sand and coarse silt in the upper estuary, creating a fining gradient of sediment size into the lower estuary. Results from this survey showed that the sand content of the dredged channel floors was higher than before dredging. Selective retention of coarser sediment by frequent WID activity needs to be considered as a potential geomorphological impact.

The biological impact of the dredging would primarily affect water quality, benthic ecology and upper-bank habitat.

- No significant changes in the nature or frequency of occurrence of water quality conditions have been observed with the exception of a few instances of very low dissolved oxygen levels in the on-bed fluid mud layer during the initial WID trials. The operation of the WID during low river flows is therefore not ideal practice.
- As the submerged surfaces of the upper estuary channels undergo a natural, river-scour-driven erosion each year, of 10-20cm, the short-term, local exacerbation of this system to 0.5 to 1m of scour under dredging is unlikely to have untoward impact on the benthic ecology. However, fish/eels buried in the sediment can respond equitably to slow natural scour, but may face problems when confronted by dredging. One or two fish/eel kills were noted during the dredging experiments. This issue may require further evaluation.
- During this experimental dredging there was little impact on the upper (vegetated) bank slopes as a result of dredging. If a strategy can be developed where thalweg dredging is all that is necessary, and the banks adjust themselves naturally (by river scour and/or slumping)

then this habitat should remain secure. Achieving this objective will revolve around definition of optimum channel profile shapes, a theme which has only been touched upon lightly in this study.

ALTERNATIVE STRATEGIES

The channel cross-sections in the upper Parrett estuary are naturally created as a balance between fluvial/ebb scour processes and intermittent high spring flood tide delivery of high volumes of marine mud. The flood prevention strategy this study is directed at is to assess the feasibility of upsetting this natural balance by enhancing the scour processes (using dredging) to maintain over-sized cross-sections that are always prepared to more effectively transmit peak river flood events. Another approach to maintaining this imbalance might be to restrict the peak spring flood tide delivery of sediment. A tidal (storm-surge protection) barrier is being considered for the lower Parrett estuary[18]. If this project goes ahead, with the correct construction, this gated barrier could be used to manipulate flow over the late flood tide just on peak spring tides, to prevent the upper levels of these tides occurring inside the estuary. Doing this could markedly reduce the supply of marine sediment to the upper estuary, thus effecting the required imbalance between sedimentation and scour, and helping maintain 'naturally' larger channel sections. By controlling just the late flood tide levels (as opposed to stopping a whole tide entering the estuary) this critical management ploy could be conducted with minimal environmental impact.

Assessment of the flood prevention barrier options [17] only considered a tide surge barrier (closed at low tide on the rare occurrences that a very high tide is expected) or a tidal exclusion barrier (allowing river flow out on the ebb but permanently preventing any tidal inflow on the flood, thus creating an impounded estuary lake). The (simpler) tide surge barrier is the preferred option. The report states

"A Tidal Surge Barrier would not significantly alter the present dredging and channel maintenance needs. A Tidal Exclusion Sluice would reduce dredging needs upstream of the structure by preventing the passage of silt upstream from the estuary. However, this may lead to rapid siltation downstream of the structure, which would need to be dredged to maintain navigation, and unpredictable effects on sediment transport in the Parrett Estuary. Fluvial derived sediment would still deposit upstream. There is considerable uncertainty associated with the geomorphological impact of the Tidal Exclusion Sluice. An initial study is underway to inform this, but a full assessment will be required as part of the approvals process."

The results of our study suggest that a) fluvial-derived sediment volumes are tiny compared with marine inputs and b) it would be only necessary to shut the barrier at say half flood tide at times of very high spring tides to significantly reduce the rate of fine sediment accumulation in the upper reaches of the estuary. This minimal closure time would reduce the wider concerns about the geomorphological impacts of the barrier. To achieve this capability, the additional cost on top of the basic Tide Surge Barrier would be to have a gate that could be closed at any state of the tide (capable of operating against strong lateral pressure).

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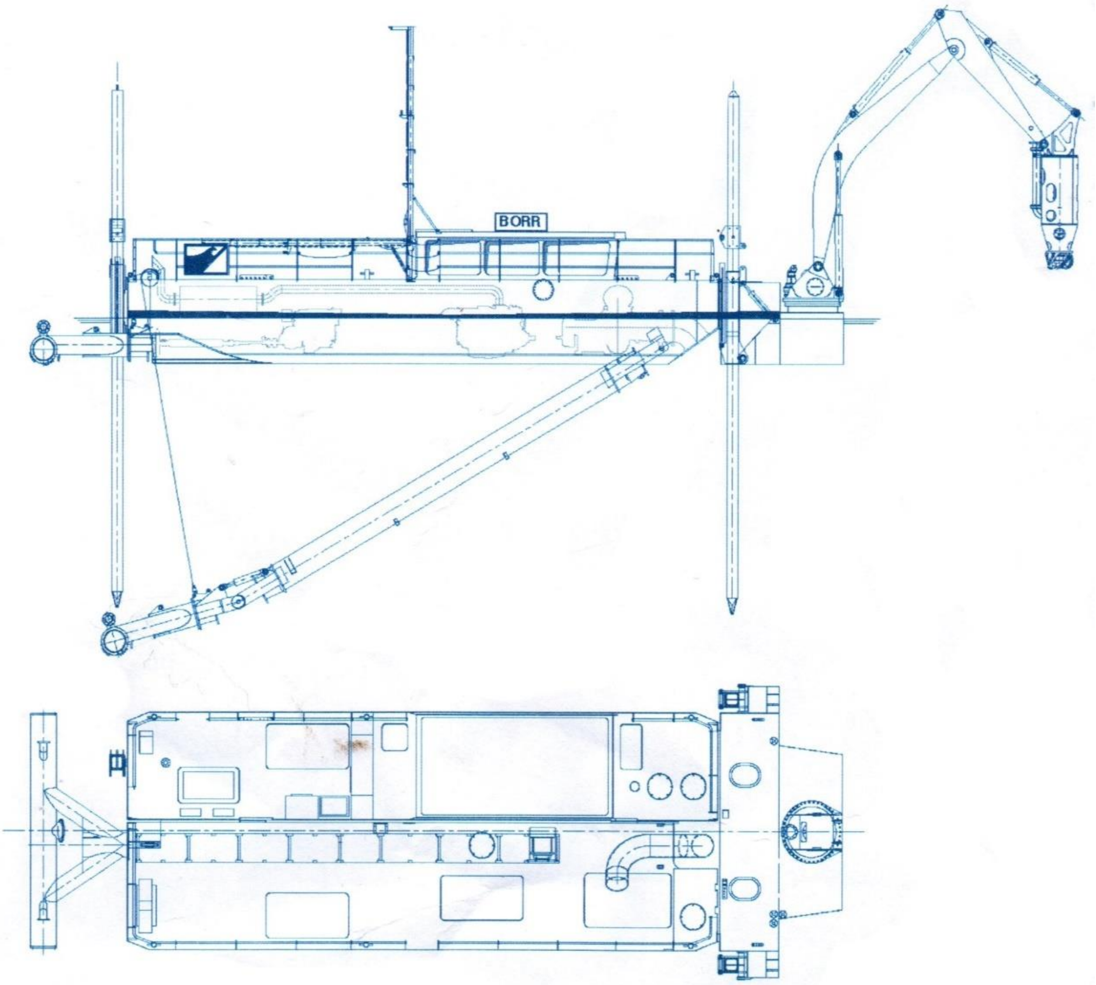
[18] Protecting Bridgwater and the Somerset Levels & Moors from Tidal Flooding Flood Risk Management Review November 2014 Black and Veatch. For EA and Sedgemoor DC

RECOMMENDATIONS

The following recommendations are made:

- Effort should be made to set-up a gauging system for real-time monitoring of fresh water discharge into the estuary through the upper tidal limits of the Parrett and Tone (Objective: allow a more detailed understanding and modelling of the interaction of fluvial and marine processes)
- Bathymetric surveys have proven a valuable tool for assessing sedimentation. There is probably no need in the long term for more than one survey per year. This should be taken at the same time each year, with the objective of identifying net inter-annual volume changes in the bed. There appears to be no difference in the accuracy between pole or multibeam surveys. The multibeam surveys provide full longitudinal coverage and allow accurate bed sediment volume changes to be made. However they provide no coverage of the upper banks, and the trialled laser method is confounded by the bank vegetation. It is therefore recommended that a multibeam survey is conducted annually in say January, when river levels are normally high and the greatest part of the channel is inundated. Pole surveys should be undertaken at the same time, on selected profiles and only by walking (upper banks) to provide full cross-section information at key points. These recommendations are made to optimise scientific and economic objectives in the medium to long term. In the short term, in the interests of continuing the twice yearly bathymetric survey pattern already established (October and April) may be the more sensible approach.
- Exploration should be made to see if the results of the extensive turbidity surveys of the estuary carried out by HRWallingford in the 1970s and 80s are archived and can be studied. (Objective: Allow further insight into natural processes of sediment transport in the mid-lower Parrett estuary)
- Detailed consideration needs to be given to optimal channel cross-section shape and area for future dredging activity. This needs to take into account the capabilities of the dredger-type, the flow-transmittance efficiency (related to flood prevention demands) and the minimisation of sedimentation. In relation to the latter, the significance of the currently seen differences in channel shape and erosion behaviour above and below kp 25,000 (pinch point generated at the seaward extent of the pioneer dredging)) needs further consideration.
- A simple monitoring system based on the continuous measurement of sediment flux (water flow and suspended sediment content) should be considered as a basic tool for predictive sediment management for the critical estuary reaches (for flood management) in the future. This would involve a monitoring site at the two tidal limits and in the vicinity of the M5 motorway. The lower monitoring system would have to be a profiling device, allowing vertical variability in turbidity (considerable at times) to be measured. The plan should be for very long-term monitoring, to evaluate thoroughly inter-annual variability in sediment flux, and to provide information for safely assessing how a minimum dredging regime can be operated (dredging to need rather than routinely).
- Discussions should be pursued with the EA to investigate the Surge Barrier Operation option for achieving reduced sedimentation in the upper reaches of the Parrett estuary.

Appendix 1. Dredger BORR Specification



Borr

Name	Borr		
Type	Water injection dredger		
Description	Borr:	Dismountable dredger, transportable on two trailers	
	Farrell:	Pontoon with spuds, hydraulic crane with clamshell or cutter unit	
Sailing and dredging area	Inland waters only		
Year of construction	2015		
Dimensions Borr	Length overall		18.73 m
	Breadth overall		5.32 m
	Moulded depth		1.80 m
Dimensions Borr & Farrell	Length overall		21.73 m
	Breadth overall		6.70 m
	Moulded depth		1.80 m
Maximum dredging depth	Borr:		14.00 m
	Farrell:		8.00 m
		with clamshell or cutter unit	

Width injection pipe	5.16 m
Propulsion	2 x 89 kW
Total power installed	460 kW
Jet pump	260 kW

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Appendix 2. Sensor calibrations

This Appendix is supplied as an accompanying Excel file << 2016-7 Parrett TurbiditySensorCals.xlsx>>

Appendix 3. Bed surveys Visual log.

This Appendix is supplied as an accompanying Excel file << 2016-7 Parrett BedSedLogs.xlsx>>