05 - A STUDY OF SEDIMENT TRANSPORT AND BEHAVIOUR ON THE RIVER BANDON, CO. CORK, IRELAND

J. Harrington[1], J. Garcia[2], B. Batel[1], JM Salcedo[2], S. Harrington[3]

[1] *Sustainable Infrastructure Research & Innovation Group, Munster Technological University (MTU), Cork, Ireland*

[2] *Department of Mining & Civil Engineering, Technical University of Cartagena, Murcia, Spain*

[3] *AYESA, Cork, Ireland*

Abstract

This paper presents a study of sediment behaviour on the River Bandon, County Cork, Ireland over a time period of a decade from 2012 to 2023. The River Bandon with a catchment area of approximately 600 km^2 has an average flow rate of approximately 15 m^3/sec with a maximum extreme flow recorded of 384 m^3/sec. Land type and use vary through the catchment. The river has historically been prone to flooding, most dramatically in November 2009, and large scale flood protection works were completed on the river within the environs of Bandon town and downstream over the period from 2017 to 2019. This flood protection work included substantial dredging of the river-bed.

The study presented in this paper has primarily focused on the stretch of the River Bandon from the environs of the town of Bandon to the OPW Curranure gauging station (20002), which is located approximately 4km downstream of Bandon town and upstream of the maximum extent of tidal intrusion from the downstream estuary. The study includes the time period from pre- to post-construction of the flood protection work; dredging for the flood protection work focused on the river stretch from Bandon town to immediately upstream of Curranure.

Bed sediment behaviour has been assessed through a data gathering programme including bed sediment data gathered from a number of MTU installed river bed sediment traps (sediment size and volume data collected at traps within the town and adjacent to Curranure), bed sediment sampling, bed photographic records on lower flows, river bed surveys undertaken both pre- and post the flood protection works and from various records of dredging works undertaken. The field data gathered has provided input to numerical modelling work that has been undertaken to simulate bed sediment behaviour and transport; both using a simplified Parker sediment model and more advanced modelling using the USACE HEC-RAS modelling package which has been modified and adapted for this river system. This work provides insight into riverine bed sediment movement under specific flow conditions, bed sediment loadings and sedimentation patterns developed since completion of the flood protection works.

Suspended sediment behaviour has been assessed through a data gathering programme including an MTU installed continuous turbidity recorder and an automatic sampler at the Curranure gauging station. This data set has been supplemented by a long-term manual sampling programme at a number of locations along the river stretch of interest. This work has allowed assessment of suspended sediment behaviour across a range of flow conditions (including during high flow events)

and also has allowed some assessment of the short-term impacts of the dredging works undertaken on the river on suspended sediment behaviour recorded downstream at the Curranure gauging station.

This paper presents a bed and suspended sediment study undertaken over a decade on an Irish river, the River Bandon. A large-scale flood protection scheme including substantial dredging was completed within the time frame of the study. The learnings from this study will be of benefit and relevance to other river systems in Ireland.

1. INTRODUCTION

1.1 General characteristics of the River Bandon catchment

The 72km long River Bandon, located in County Cork, Ireland rises in the Shehy Mountains and discharges to Kinsale Estuary (see Figure 1). The catchment area is 608km^2 which is a relatively large sized catchment in an Irish context; the average flow rate is approximately 15m^3/sec with extreme flows of up to 384m^3/sec. The river is tidal up to approximately 15km upstream of the Kinsale Estuary and downstream of the town of Innishannon, the catchment is primarily agricultural, with tillage and pasture in the lower catchment, with three relatively large urban settlements along the river; Dunmanway, Bandon and Kinsale (see Figure 1). The river is prone to flooding, distinguished by engineering work on stretches and features a special area of conservation.

Figure 1: *The River Bandon Catchment*

Dynamic sediment movement is a significant feature of the river system within the catchment, with both bank and bed erosion and deposition visually apparent along the river from upstream of Dunmanway to Innishannon Bridge. Bed sediment transport and deposition is clearly evident (Figure 2), particularly within the environs of the town of Bandon, from upstream of the weir to downstream of the main Bandon Bridge. Shallow and exposed bedrock is also a feature through the river system. Information on the river and catchment has previously been provided by, for example, JBA (2011), Harrington & Harrington (2013, 2014) and Garcia & Harrington (2019).

Figure 2: *Examples of Sedimentation on the River Bandon*

1.2 River Bandon flood protection and dredging works

Large scale in-water sediment dredging works were undertaken in the Summer periods of 2017 and 2018 (from the 1st May to the 30th September) as part of the overall flood protection works funded by the Office of Public Works (OPW). The dredging works spanned approximately 3.6km from the weir in Bandon town downstream to O'Driscoll's Bridge with a design bed slope of 1/1000. The design drop in bed level varied from 1.9.m at the weir, to 1.7m at the Main Bandon Bridge to approximately bed level at O'Driscoll's Bridge. The completed works include pools, riffles, a thalweg and bank flow deflectors (OPW, 2012). The sediment volume dredged was estimated at approximately 290,000 tonnes. Figure 3 presents the extent of the in-water dredging works.

Figure 3: *Extent of the River Bandon Dredging Works - 2017 and 2018*

Prior to this large scale project maintenance dredging had been undertaken by Cork County Council from 2010 to 2016 upstream and downstream of the main Bandon Bridge, this work was partly in response to the extreme flood event that impacted on Bandon town in November 2009. The total sediment volume removed was approximately 10,000 tonnes (Harrington, 2019).

1.3 Sediment data gathering programme

A sediment data gathering programme was implemented over the study period. This work included gathering suspended sediment data through spot surface sampling and application of an automatic water sampler and through use of a turbidity sensor. Bed samples were also collected at a number of locations directly from the bed and also from sediment traps installed in the river bed. Figure 4 presents the full extent of the river over which samples were taken and Figure 5 presents the locations where the sampling effort was primarily focused. Sampling at the upstream locations at Ardcahan Bridge, Long Bridge and Béalaboy Bridge was limited to some initial sediment sampling. The primary sampling locations were at the Bandon Footbridge, the Main Bandon Bridge, the Bridewell Stream, the Mill Stream and at O' Driscoll's Bridge. In addition, sediment data was collected on a long term basis at the Curranure OPW Gauging Station (immediately downstream of O' Driscoll's Bridge) where an automatic water sampler and a turbidity sensor were installed as shown in Figure 6.

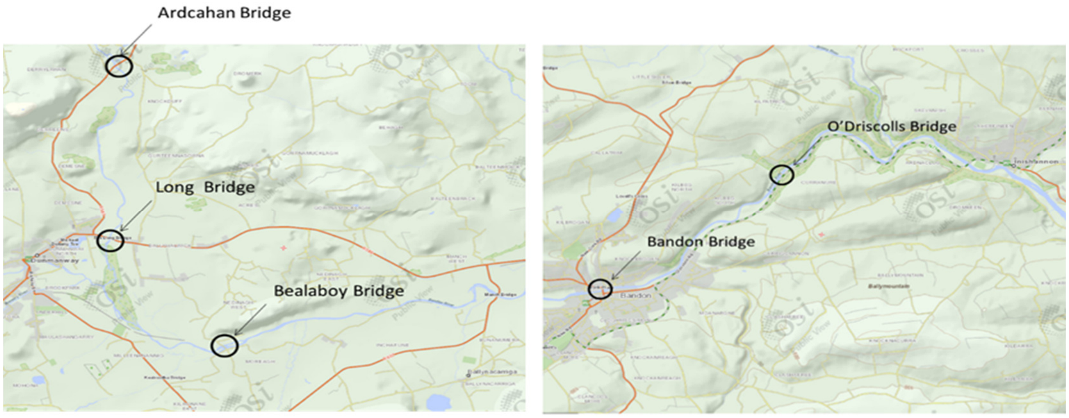

Figure 4: *Sediment Sampling Locations on the River Bandon*

Figure 5: *Primary Sediment Sampling Locations*

Figure 6: *River Monitoring Installation at Curranure Gauging Station, River Bandon*

2. SUSPENDED SEDIMENT

2.1 Approaches to collection of suspended sediment data

A number of approaches have been taken to determining suspended sediment concentration (SSC).

Suspended sediment surface spot samples were taken at a number of locations along the reach of the river (Figures 4 & 5) to establish baseline conditions and to identify higher values during the dredging events of 2017 and 2018. SSC testing was undertaken using standard methods (APHA, 1998). This work has been undertaken over the period from 2012 to 2023. Access to some sampling locations was not possible during the dredging and associated works.

An automatic water sampler was installed by Munster Technological University (MTU) at the Curranure Gauging Station in 2014. The sampler has operated regularly since to assess suspended sediment conditions and specifically high flow events and during the dredging works.

MTU installed a turbidity sensor at the Curranure Gauging Station location in 2010. This sensor records turbidity on a continuous 15-minute basis. Previous work, for example Harrington & Harrington (2013), showed that turbidity was a suitable surrogate for SSC at this location allowing conversion of turbidity to SSC using a developed equation.

Maintenance of the automatic sampler and turbidity installation has remained a challenge in this energetic river environment. For example, the automatic water sampler and the turbidity sensor were significantly damaged and required replacement due to the flood events of December 2015 and January 2016; the installation was out of operation for approximately 6 months.

2.2 Spot sampling for SSC

Various (Harrington & Gamble, 2016; Harrington, 2019) have reported on the spot sampling work undertaken. In summary SSC levels remain low on lower flows, typically less than 10 mg/l and this does not appear to have changed since the large-scale dredging works were completed.

Elevated SSC values were found on occasion when sampling coincided with higher river flows where values in excess of 100 mg/l were recorded. High SSC values were also found during the period of dredging works. For example, at the Bandon Footbridge values in excess of 700 mg/l were recorded in July, 2018, at the main Bandon Bridge where values in excess of 100 mg/l were recorded in June and July, 2018 and at O’ Driscoll’s Bridge where values in excess of 550 mg/l were recorded in August, 2017.

2.3 SSC during high flow events

The automatic sampler has been used over a wide range of river flows and during some significant flood events. Data has been gathered for 92 separate events in the period from October 2015 to May 2023. For each event flow rates and SSC values were recorded. Maximum flow rates ranged from 4.6 to 96 m^3/sec; the maximum SSC found was 509 mg/l.

One event for example, where the sampler was pre-programmed to operate during a predicted high flow event was on the 5th/6th December 2015. This event became the second highest flow event recorded on the River Bandon with a maximum flow rate of 275 m^3/sec. The sampler flooded during this flood event and the samples collected were unfortunately corrupted.

Table 1 presents data on a selection of sampled events including flow rate and SSC. A suspended sediment loading analysis was undertaken by combining SSC and flow rate data to estimate the loadings from these individual events. For example, a flood event on the 15th December, 2016 yielded an estimated suspended sediment load (SSL) of 331 tonnes over a 24 hour period (with the bulk of the loading predominately on the rising limb of the hydrograph). An indicative analysis of the truncated data from the flood event of the 5th December, 2015 indicated a total SSL potentially in excess of 1000 tonnes.

The loadings indicated above for individual high flow events can be compared with annual SSL estimates developed by Gamble & Harrington (2016) indicating annual SSL rates on the River Bandon of approximately 2,000 to 3,000 tonnes. This highlights the disproportionate impact that high flow events may have on suspended sediment loading.

Table 1: *Suspended Sediment Concentration Results for Some High Flow Events*

Date	Q_{min} (m^3/sec)	Q_{max} (m^3/sec)	SSC_{min} (m^3/sec)	SSC_{max} (m^3/sec)
04/12/2015	47.06	76.39	28.27	110.26
05/12/2015	93.58	275.08	30.07	137.28
22/08/2016	14.01	25.6	10.65	33.03
04/10/2016	31.59	48.6	5.42	35.25
12/11/2016	13.37	25.21	2.19	16.88
15/12/2016	31.16	69.58	6.94	253.26
06/01/2017	34.64	48.43	5.2	43.43
20/10/2017	83.15	96.02	33.04	105.56
24/01/2018	38.60	46.47	2.69	21.89

It may be noted that hysteresis (rising and falling limb variation) on high flows was identified and has previously been presented for the River Bandon by Harrington & Harrington (2014).

2.4 SSC during dredging events

The automatic sampler was programmed to operate specifically during dredging events to assess the potential impacts on SSC due to dredging activity. Data was gathered during an initial trial dredging event in September 2016 undertaken upstream of the Curranure gauging station, during Summer 2017 when extensive dredging was undertaken within the environs of Bandon Town and again during Summer 2018 when extensive dredging was undertaken through the river system. The dredging in Summer 2018 coincided in particular with some extreme low flow conditions.

The SSC signal during the trial dredging events in Summer 2016 showed, on occasion, some temporary increase in SSC (to a maximum of approximately 40 mg/l) after dredging with SSC decreasing quite quickly to ambient levels. Five sets of samples were gathered. Sixteen sets of samples were collected during the main dredging works in the environs of Bandon town and upstream of O' Driscoll's Bridge in Summer 2017 over a 2-month period. Figure 7 presents SSC and flow rate data (samples were taken on an hourly basis). These results show that SSC values became elevated after dredging commenced but returned to ambient levels relatively quickly. Peak SSC values all exceeded 50mg/l, were found to generally exceed 100 mg/l and on a number of occasions exceeded 200 mg/l, and with a maximum value found of 600 mg/l. The durations for which the SSC signal exceeded certain values were also determined with one indicative exceedance value being that of the 25 mg/l from the original Freshwater Fish Directive; durations of exceedance for 25 mg/l ranged from 3 hours to 18 hours. Flow rates were generally relatively low through the period of the work and only exceeded 30m^3/s on one occasion indicating that flow rates were generally not an influencing factor with the impact from the dredging works being the dominant factor.

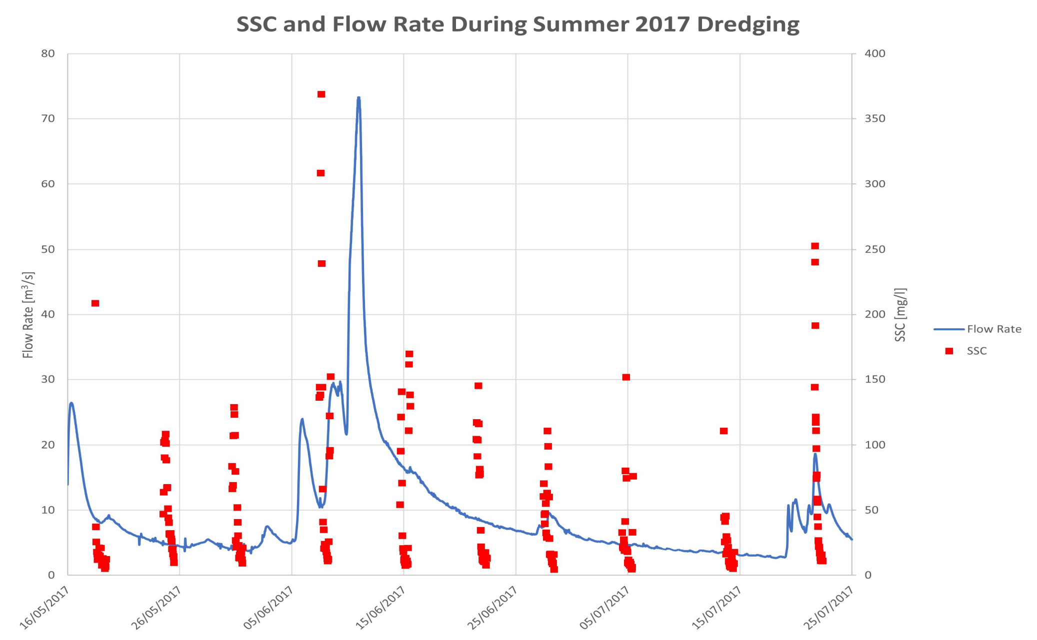

Figure 7: *Suspended Sediment Concentration and Flow Rates for the Summer 2017 Dredging Events*

Eight sets of samples were taken over the Summer of 2018 with generally lower peak SSC values recorded relative to the values recorded in Summer 2017. An SSC value in excess of 100 mg/l was recorded on two occasions with a maximum value of 200 mg/l recorded. These increased SSC values were again directly attributable to the dredging works as the flow rates were exceptionally low and less than 5 m^3/sec for much of that Summer period.

3. BED SEDIMENT

3.1 Approaches to collection of bed sediment data

A number of approaches were taken to gathering bed sediment data.

Bed sediment samples were taken at specific locations along the reach of the river (Figures 4 & 5) from 2012 to 2018. Sediment samples were collected when conditions allowed, sampling within the context of Health & Safety requirements, generally using a grab sampler and in places using a piston type core sampler where bed conditions allowed. Sediment testing was undertaken using the relevant British Standard.

A range of bed sediment traps were purchased or designed and manufactured, and installed in the river bed between February 2014 and June 2015 in an attempt to trap movable bed sediment and assess bed sediment movement. These attempts were initially unsuccessful for a number of different types of trap as sediment was not trapped and in some cases scouring around the trap occurred. The fourth iteration led to successful collection of bed sediment, using a suitable double compartment bed trap design. This type of sediment trap was then installed and initially embedded into the river bed at five locations; upstream of the Bandon Footbridge, downstream of the main Bandon Bridge, at the Mill Stream, at O' Driscoll's Bridge and immediately upstream of the Curranure Gauging Station. This trap is shown in Figure 8, both in the laboratory and installed in the river. Sediment was subsequently collected on a range of occasions from these traps. Over time these traps were either buried during dredging works, washed away or deliberately removed, and by 2019 only one trap remained in-situ, the trap located immediately upstream of Curranure.

Figure 8: *Sediment trap – in the laboratory and installed in the river*

The challenges associated with this type of work in a river environment cannot be understated, particularly the safety aspects associated with entering the river and operating the sediment trap. The time and human resource commitment involved has been substantial.

3.2 Spot sampling of bed sediment data

Various project reports (Harrington, 2014; Harrington & Gamble, 2016) have reported on the bed sediment data collected at the locations shown in Figures 4 & 5 (and prior to the main dredging works of 2017 and 2018). This sampling work confirmed the coarse nature of the surface material with D_{50} values primarily in the range from approximately 5 to 30mm, but with larger sizes recorded. Any clear and definitive sediment patterns by location or in a longitudinal downstream direction could not be concluded on although finer bed sediment was generally found in the most upstream catchment location at Ardcahan Bridge.

3.3 Bed sediment trap data

3.3.1 Sampling Effort from October 2016 to March 2017

A substantial effort and analysis of bed sediment trapped was undertaken in the period from October 2016 to March 2017. For this specific work sediment was collected from traps located upstream of the Bandon Footbridge, downstream of the Main Bandon Bridge and upstream of the Curranure Gauging Station. This work focused on determining the size of the movable sediment and attempting to estimate potential sedimentation rates.

Table 2 presents, for example, a field type summary of some of the collected field data including dates and times of trap deposition, and mass collected. This programme of work was undertaken in an attempt to determine bed sedimentation/loading over specific periods of time. In general, predicted river flow events were identified that might lead to sediment trap deposition and the sediment traps were then monitored. Once sediment deposited in the traps and the flow rate had reduced sufficiently to allow safe entry into the river, the traps were emptied and the sediment was tested and the data analysed. The sediment data consisted of sediment size data and sediment mass accumulated. River flow data was also assessed for the period of sediment trap accumulation.

Table 2: *Field type summary notes of bed sediment trap operation*

Date Filled	Date Checked	Location	Visual Observations in Trap		Height of Sediment in Box (mm)	Max Flow @ Bandon Bridge (m^3/s)	Sediment Mass Collected (kg)
			Upstream Box	Downstream Box			
14/12/2016	15/12/2016	Footbridge	Half Full	Empty	75	47.12	7.20
		Bandon Bridge	Full	Starting to Fill	150		31.99
16/12/2016	19/12/2016 (emptied)	Footbridge	Small Increase	Empty	25	64.00	2.40
		Bandon Bridge	Full	Full	150		27.99
21/12/2016	22/12/2016	Footbridge	Small Amount	Empty	30	18.33	1.73
		Bandon Bridge	Small Amount	Small Amount	25		10.15
24/12/2016	05/01/2017	Footbridge	No Change	Empty	-	18.72	-
		Bandon Bridge	Half Full	No Change	150		5.07
07/01/2017	11/01/2017 (emptied)	Footbridge	Full	Half Full	150	37.59	37.30
		Bandon Bridge	Full	Nearly Full	150		42.62
27/01/2017	30/01/2017	Footbridge	Full (emptied)	Full (emptied)	150	-	54.90
		Bandon Bridge	Full	Full	150		61.21
		Curranure	Full	Nearly Full	150		52.30
30/01/2017 to 22/02/2017	22/02/2017 (emptied)	Footbridge	Half Full	Empty		72.88	4.85
		Bandon Bridge	-	-			-
		Curranure	-	-		-	

As outlined this process was particularly challenging due to the safety aspect of entering the river and moving bed sediment to the river bank and also in emptying the traps manually in a flowing water environment. River flow rates during the bed trap accumulation events varied from approximately 10 m^3/sec to over 80 m^3/sec. On occasions when it was not possible to empty the trap immediately visual observations were undertaken to estimate the mass deposited in the trap. In the case of the peak flow rate of over 80 m^3/sec event, for example, all the traps filled during this single event.

Some results from this work and generally consistent for the different trap locations included:

- D_{50} values varied from 8 to 25mm with some of the movable sediment trapped having significantly larger dimensions
- D_{50} values recorded for the upstream trap compartment were generally larger than for the downstream compartment.
- There was no clear pattern on the movable sediment size at any particular trap location.

More specifically at the footbridge location the D_{50} value decreased for sequential trap filling suggesting a supply limited aspect for larger sediment over the period of months of the study. The data at this location also generally showed that fine sediment was mobilized initially and entered the traps first for specific trap filling events (and was primarily found in the lower layers of the sediment traps). At the main Bandon Bridge location however, the D_{50} value actually increased for sequential trap filling in contrast to the location further upstream at the footbridge. The D_{50} values found were lowest at the Curranure trap location; no other distinct patterns of sediment deposition were found at this location.

3.3.2 Sampling effort at the sediment trap upstream of the Curranure Gauging Station

Another sampling effort focused on the remaining active bed sediment trap located immediately upstream of the Curranure Gauging Station. This work has been ongoing since 2019 and has involved tracking sediment movement and associated peak river flow rates for individual events at the Curranure sediment trap. For this work the priority was to assess sediment transport with associated event flow rates. This data collection has formed part of the numerical model calibration. The approach taken was that the flow condition potentially leading to deposition in the trap was identified and after each event the trap was visited, emptied and where possible sediment was collected for analysis.

Twenty seven different events have been assessed. For fifteen events the trap filled completely. The maximum preceding flow rates for these events ranged from 41 to 216 m^3/sec. Eleven other events involved partial trap filling and one event involved no trap filling (where a relatively low flow event was deliberately identified). For partial trap filling the maximum event flows varied from 19 to 46 m^3/sec. Trap filling did not occur for the maximum flow event of 45.7 m^3/sec. For the events involving partial trap filling, sediment size was determined with D_{50} values for the trapped sediment in the range overall from 3 to less than 10mm (where sediment finer than 2mm was excluded). Data for the partial trap filling events is presented in Table 3 (with a 100% flow rate exceedance of 10 m^3/sec). Figure 9 presents the flow record over the study period and with the time of the trap events shown.

It is important to note the substantial time and human resource commitment involved in the monitoring and gathering of sediment from this sediment trap, and from the earlier work in 2016 and 2017 (see Section 3.3.1).

Table 3: *Selected sediment trap data at Curranure (January 2017 to August 2023) – partial trap filling*

Date	**Collected Sediment [kg]**		**Event Duration [hrs]**	**Q [m^3/s] 50% exceedance**	**Q [m^3/s] 0% exceedance**	**D_{50} [mm]**	
	All	**>2mm**				**All**	**>2mm**
30/07/2020	8.89	7.1	93.75	23.5	42.3	4.67	6.51
6/08/2020	6.83	5.3	107.75	21.2	45.7	4.48	6.72
30/09/2020	4.4	3.7	64.75	18.4	35.2	6.86	7.52
29/03/2021	3.66	3.3	95	17.5	30.6	6.75	7.11
21/08/2021	-	-	5	10.5	10.7	-	-
18/04/2022	6.84	5.9	94	20.9	44.9	4.58	4.91
29/06/2022	4.75	3.9	44.75	25.8	45.2	2.53	3.56
08/09/2022	1.97	1.6	66.5	23.4	41.8	2.67	3.28
11/09/2022	0.97	0.8	69.5	31.72	39.32	2.68	3.15
10/10/2022	0.29	0.2	36.75	24.89	27.35	1.88	2.61
16/02/2023	2.47	1.9	38	13.7	19.1	4.91	6.59
08/05/2023	3.11	2.5	63.5	16.1	24.1	6.03	7.25

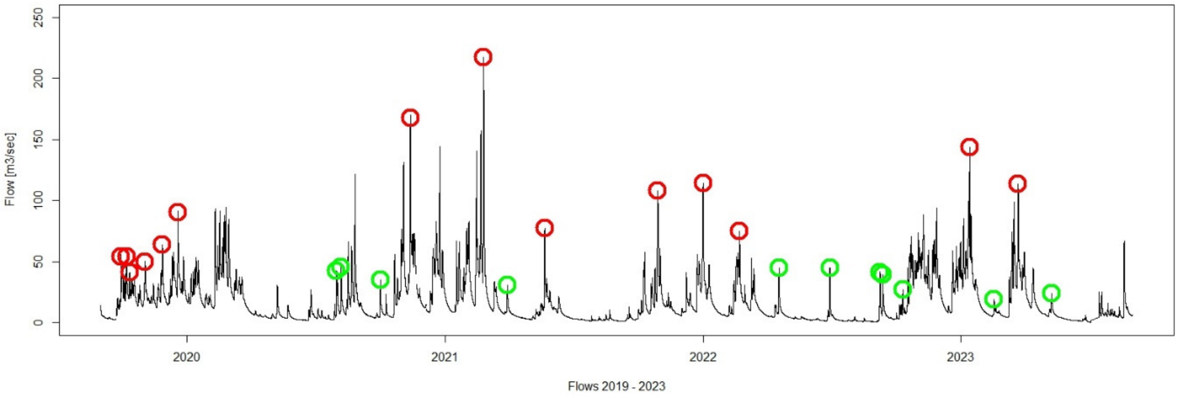

Figure 9: *Flow rates (August 2019 to August 2023) with trap events identified (red - trap full; green - partial trap filling)*

3.3.3 Some conclusions on bed sediment movement

The analysis for the sediment trap at Curranure shows that filling of the bed trap occurred for all events where the peak flow exceeded approximately 50 m^3/sec and for flow rates as low as 41 m^3/sec. Field observation suggested very limited trap filling at less than 30 m^3/sec but some trap filling has been experienced with maximum event flows as low as 20 m^3/sec. Additional information from the previous sediment trap analysis work at other trap locations presented shows similar results (albeit for a more limited data set) where partial trap filling was experienced at the Footbridge and Bandon Bridge when the event maximum flow rate exceeded 18 m^3/sec. It may be noted that an analysis of incipient movement of the bed sediment (Harrington & Gamble, 2016) has been undertaken for the River Bandon using the slope break analysis approach developed by Park (2015). This work using the field data at the Curranure gauging station indicated that incipient bed movement occurred for a flow rate range of from approximately 10 to 14 m^3/sec (Harrington & Gamble, 2016). This result is generally consistent with the sediment trap field results found.

It is recognised that the sediment bed dynamics in this river system are complex but this work provides indicative flow rate values and associated bed sediment behaviour for the River Bandon.

3.4 Analysis of River Bandon bed surveys

Two post dredging works surveys were undertaken in September 2020 and November 2021 by Wills Bros and Murphy Geospatial respectively. These surveys covered from the main weir and fish pass to downstream of the main Bandon Bridge (see Figure 10). Survey results have been assessed and are presented in Table 4; net sedimentation of approximately 1900 m^3 was found over this 14-month period. The largest volume of deposited material occurs between the weir and the footbridge. Deposition also occurs in the vicinity of the Bandon Bridge, both upstream and downstream. Some erosion was found in the remaining cross-sections between the bridges and downstream of Bandon Bridge.

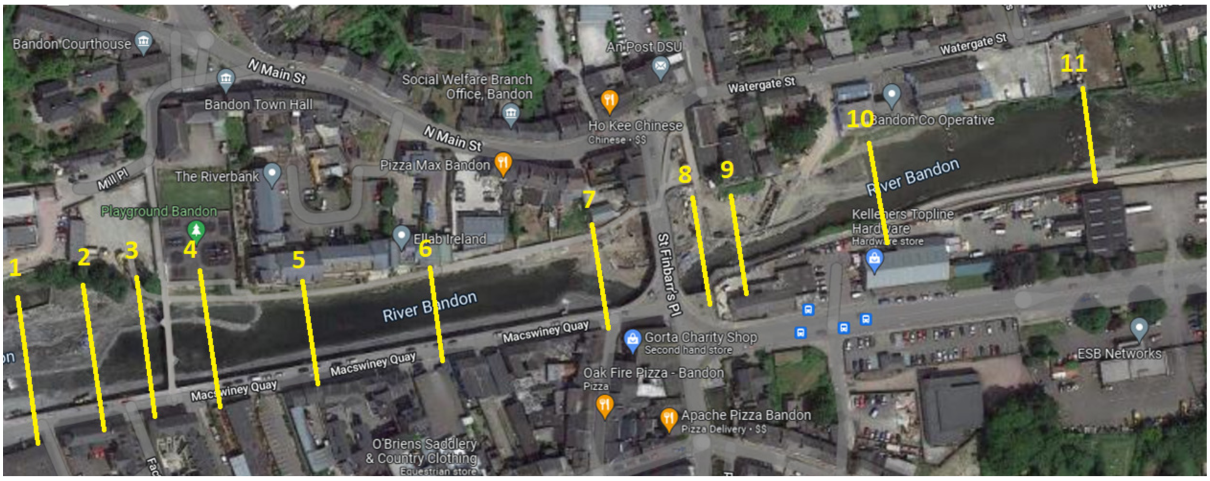

Figure 10: *Extent of River Bandon bed survey – common coverage*

The analysis includes for upstream river sourced sediment and also gravel material that flushed out of the fish pass, this was visually evident immediately downstream of the fish pass. An analysis was undertaken to assess the potential contribution of the fish pass sediment to the overall volume of deposited sediment and based on the dimensions of the fish pass. This analysis indicated the volume of river sourced sediment at approximately 1100 to 1700 m^3 (assuming a loss of 80% to 20% of the total gravel within the fish pass). Visual observation of the fish pass indicates that most of the gravel was removed and thus we estimate the effective river sourced sedimentation in the range from 1100 to 1200 m^3.

Table 4: *Estimated sediment deposition (blue) or erosion (red) volumes from Sept. 2020 to Nov. 2021*

Cross Section	Sediment Volume [m^3]
0-1	329.17
1-2	838.80
2-3	480.13
3-4	502.98
4-5	264.00
5-6	-285.65
6-7	-187.05
7-8	168.75
8-9	56.00
9-10	-111.65
10-11	-157.50
Total	**1897.97**

Field observations through experience and a photographic record (see Section 3.5 below) indicate that increased sedimentation and bed movement was not marked in the hydrologic year of September 2021 to August 2022. However, field observation and data collected more recently in June 2023 indicates that substantial additional sedimentation has occurred in the period since August 2022. This is evident, for example, on the northern bank from the weir to downstream of the footbridge (we estimate additional sedimentation up to 1,000 m^3) and also upstream of the weir and running parallel to the fish pass (we estimate additional sedimentation of between 1,500 and 2,000 m^3).

A review of the flow exceedance record at Curranure Gauging Station confirms this sedimentation pattern. This is in conjunction with the work presented above based on field data which identified that substantial bed sediment movement/bed trap filling occurs above 50 m^3/sec. Harrington et al. (2022) presented an analysis that indicated the relatively stable nature of the sediment behaviour over the hydrologic year 2021/22 based on the relationship between bed trap filling and river flow rates.

Table 5 presents the flow exceedance record for recent years at Curranure. The proportion of larger annual flows provides some evidence to support the relatively stable behaviour of the sediment deposits over the 2021/2022 period. In 2021/2022 flow rates >50m^3/sec were exceeded 2.4% of the time while the average % exceedance over the previous 3-year period was 7.2%. Flow rate exceedance over 50 m^3/sec in 2022/2023 was 9.4% reflecting the increased sediment transport observed over the year. A similar pattern is observed for flows >20m^3/sec.

Table 5: *Flow Rate Exceedance Data at the Curranure Gauging Station (2017 – 2023)*

	Flow [m^3/s]								
	> 20	**> 30**	**> 40**	**> 50**	**> 60**	**> 70**	**> 80**	**> 90**	**> 100**
Year	% Time								
2017/2018	29.7%	16.8%	9.6%	4.4%	3.1%	2.0%	1.6%	1.1%	0.6%
2018/2019	25.3%	16.9%	9.7%	6.3%	4.0%	2.9%	1.7%	1.1%	0.6%
2019/2020	38.4%	20.7%	10.2%	5.3%	3.0%	1.6%	1.1%	0.4%	0.1%
2020/2021	29.2%	19.1%	13.9%	9.9%	6.6%	3.7%	2.4%	1.9%	1.5%
2021/2022	16.4%	9.6%	5.6%	2.4%	1.1%	0.8%	0.7%	0.5%	0.3%
2022/2023	32.6%	25.1%	16.9%	9.4%	4.5%	2.5%	1.6%	0.8%	0.3%

3.5 Bed photographic record

A photographic record of the river and the bed has been developed over the course of this work, primarily in the river reach through the town of Bandon on lower water levels when sedimentation patterns are most evident. Harrington et al. (October 2022) presented a photographic record indicating the zones of deposition consistent with the November 2021 survey, confirmed the dynamic nature of bed sediment behaviour and generally indicated the return of sediment deposition patterns to pre-dredging works behaviour. Sedimentation patterns remained relatively stable from September 2021 to August 2022 with additional sedimentation experienced in the period August 2022 to July 2023. At the time of writing some of the current large 'store' of sediment located upstream of the weir will eventually be transported downstream on future higher flow events.

3.6 Overall sediment loadings

Bed load transport behaviour is complex and depends on, among others, catchment characteristics and hydrology, sources and source location of sediment, temporal and spatial nature of sediment supply, biological characteristics, river channel and river bed characteristics.

Bed load transport on the River Bandon is intermittent and varies spatially and temporally and is primarily driven by the higher flow rate events. There are a number of indicators of sediment loading. Maintenance dredging undertaken by Cork Council indicated an average annual sedimentation rate of approximately 850 m^3 over a length of 300m (Harrington et al., 2021). The estimated average volume deposited between the two bed surveys was approximately 1000 m^3 annually over a distance of approximately 500m. The volumes deposited upstream and downstream of the weir in the year since August 2022 were approximately 1500 to 2000 m^3 and 1000 m^3 respectively. These values might indicate potential annual bed loadings in the years of sediment movement into these locations from less than 1,000 to 2,000 tonnes/year. Addditional sediment trap analysis presented in Harrington

(2019) suggests that bed load as a proportion of suspended sediment load might be substantial on high flows and potentially in excess of 30%.

4. SEDIMENT MODELLING

4.1 Introduction

Sediment modelling work has been undertaken based the simplified Parker Sediment Model (Parker, 1990) and the US Army Corps of Engineers (USACE) HEC-RAS 6.3 numerical model (USACE, 2022).

Previous modelling applications have been outlined and presented, for example, in Harrington (2020). Additional modelling is ongoing based on the availability of two sets of post-dredge bed surveys.

4.2 General Description of Model Application

4.2.1 Parker Model

The Parker model (Parker et al., 1990) is a substrate-based transport relation with developed spreadsheets Acronym1 and Acronym2 in Visual Basic for application to estimate gravel bedload transport rates thus providing an estimate of the volume bedload transport per unit river width based on the surface geometric mean diameter and the grain size distribution. The Parker model uses the formative flow, q_w, also known as the dominant discharge, to estimate the discharge by dividing the 10% flow exceedance value by the width of the river channel.

We originally applied the model (before bed surveys were available) to predict potential sedimentation post the dredging works and downstream of the weir. This simplified model assumed a rectangular channel without hydraulic structures. The model was applied using the available bed sediment data and the formative flow for the period 1975 to 2020; it predicted sedimentation of approximately 3,000m^3 over a 5-year period.

4.2.2 HEC-RAS Model

The development and application of a HEC-RAS numerical model to the River Bandon has been previously presented by Harrington et al. (2020a and 2020b) and included model calibration and validation for hydraulic conditions based on substantial data analysis. Sediment calibration and validation analysis presented was based on the available sediment field data set. The model was originally applied to predict sediment transport on the river using the post-dredge bed profile. The model included the hydraulic structures in the river reach. Quasi-unsteady flow was selected for the modelling analysis with flow series boundary conditions provided by the OPW flow data recorded in intervals of 15 minutes. The upstream sediment boundary condition used a sediment input per unit volume approach using HEC-RAS generated values with the sediment input dependent on the upstream boundary inflow. The sediment transport function used was the Mayer-Peter and Muller with the Wong & Parker correction and the use of Thomas Exner 5 sorting method. This sorting method used a three-layer bed model that forms as an independent coarse armour layer, which limits erosion of the deeper layers. Sediment bed gradation data used in the HEC-RAS model reflected the bed sediment data gathered from field work. The model was calibrated using sediment trap data from traps near the Footbridge and Curranure where sediment data was available for a number of flow events in January 2017 and November 2018. Predicted model sedimentation volumes relative to actual sediment trap data were generally within approximately 25% with a better model fit at the Footbridge than at Curranure. These results were considered generally appropriate in the context of the modelling assumptions made and in the dynamic river environment.

We originally applied the HEC-RAS model for the available flow data for the period 2006 to 2018 to predict potential sedimentation in the period post-dredging (assuming similar flow conditions). This modelling work indicated a sedimentation volume in excess of 4,000m^3 over an initial 5-year period.

An updated River Bandon HEC-RAS profile has since been developed to reflect some limitations in the previous model and to also more accurately reflect the changes to the river since the Bandon flood relief scheme was completed. The riverbed surface was modelled using the original design plans and the survey undertaken by Wills Bros in September 2020 which is the most recent survey usable for modelling purposes. The new profile includes the area upstream of the weir, the new fish pass, the new weir and the flow deflectors downstream of the weir. This new profile has been combined with the original profile (from downstream of O' Driscoll's Bridge) to achieve sufficient modelling length for sediment transport simulations. The riverbanks necessary to develop the new HEC-RAS bed profile were modelled for 800 m downstream of the weir based on an additional topographic survey of the riverbanks and the surrounding area.

4.3 Model Application - Comparison to Bed Survey Data

The Parker model was re-applied with the availability of two bed surveys, the September 2020 survey used as the baseline and the model was then run from September 2020 to November 2021, allowing comparison between the model output and the actual November 2021 bed survey. The analysed flow record for this time period yielded a formative flow q_w of 1.437 m^2/s. The flow rates over the time period are presented in Figure 11. This application of the Parker model estimated a net sedimentation volume of approximately 800 m^3.

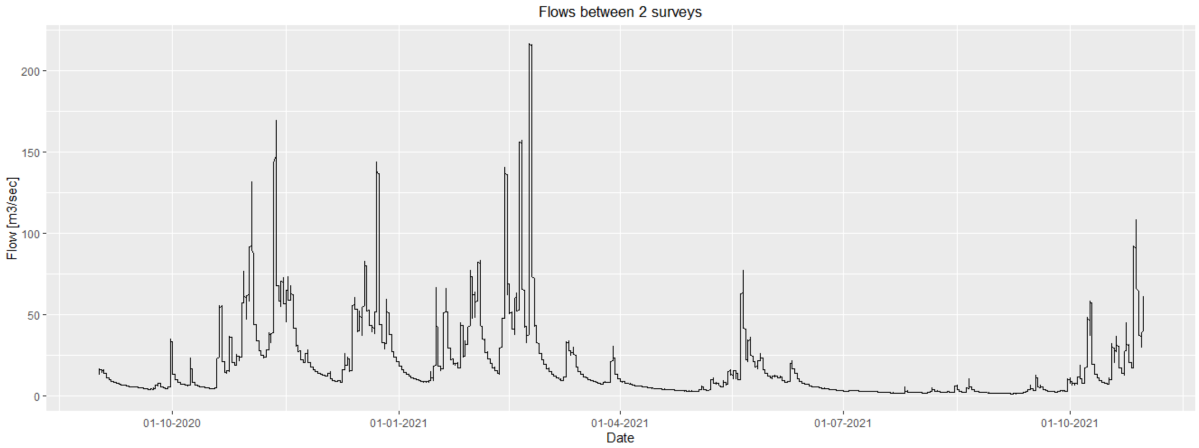

Figure 11: *River Bandon Flow Rates over the time period between bed surveys*

The updated USACE HEC-RAS model has also been applied to this stretch of river for the 14-month flow period with an estimated net sedimentation volume of approximately 1200 m^3.

The actual measured sedimentation volume is estimated at 1100 to 1200m^3. The HEC-RAS model provides a good initial estimate; the Parker model underestimates the sedimentation volume.

Development work is on-going to refine and apply the HEC-RAS model. This ongoing work highlights the challenge associated with developing a robust numerical model for sediment behaviour for this river system.

5. CONCLUSIONS

This paper presents work undertaken on the River Bandon which has involved extensive investigation into sediment behaviour based on river surveying, sediment sampling and monitoring and modelling including for both the pre-dredging and post dredging river environments.

Suspended sediments have been monitored and analysed. Baseline SSC values are generally less than 10 mg/l with significantly elevated levels experienced during high flow events with values in excess of 500 mg/l recorded. High flow events contribute disproportionately to the overall suspended sediment load. SSC levels were recorded during the dredging events from 2016 to 2018 with maximum values up to 600 mg/l experienced. These elevated levels returned relatively quickly to ambient levels and were directly attributed to dredging.

The maintenance of the installation in a relatively high energy river at Curranure has been an on-going challenge, for example the installation suffered extensive damage in the flood events of the winter of 2015/2016. By comparison maintaining a similar installation on the nearby River Owenabue in a lower energy environment has proved much less problematic.

Bed sediment monitoring, sampling and analysis has been undertaken at specific locations including from sediment traps. Trap data has been analysed for sediment size, sedimentation volumes and bed transport river flow relationships. Incipient bed load transport appears to commence at less than 15 m^3/sec, bed load transport appears to commence at around 20 m^3/sec with substantial bed load transport in excess of approximately 50 m^3/sec. For purposes of potential transferability to other river systems and based on the HEC-RAS modelling, the 15m^3/sec flow rate corresponds to a shear stress of approximately 1.3 Pa, 20 m^3/sec to approximately 1.6 Pa, 30 m^3/sec to approximately 2.1 Pa and 50 m^3/sec to 2.6 Pa. Bed sediment continuity is evident, bed trap filling is ongoing and bed sediment supply limitation has not been identified.

The successful trapping of bed sediment proved challenging. Initial attempts using commercially purchased or our own designs proved unsuccessful. The final double compartment trap design proved successful. In this case the trap was inserted and embedded into the river bed (and flush with the bed) with scour protection around the trap. This provided the necessary embedment to maintain the trap in position. The double compartment allowed some analysis to be undertaken on the initial stages of sediment transport. The two boxes within the trap were designed to be removable. The loss of bed traps over the period of the study was outside the control of the project. This type of field work involves a significant resource commitment and the health and safety requirements are onerous. It may be concluded that although such a data gathering process has its challenges it has provided valuable data and the approach taken is transferable to other river systems.

Post-dredge bed surveys have been analysed with substantial sedimentation in the period between surveys from September 2020 to November 2021. A photographic record and field observation indicates limited sedimentation for the remainder of the 2021/2022 hydrologic year but with substantial sedimentation in the hydrologic year 2022/2023; at the time of writing a substantial ‘store’ of sediment is available for transport and entry into the reach immediately downstream of the weir. A general correlation between river flow records and sedimentation patterns has been identified.

The simplified Parker model has been applied to investigate sedimentation behaviour. The HEC-RAS model has been hydraulically calibrated and also calibrated for sediment using sediment trap data and then applied to investigate sediment behaviour. An updated HEC-RAS model more accurately reflecting site conditions (including the fish pass and weir) has been developed and modelling work is on-going.

6. ACKNOWLEDGEMENTS

The authors wish to gratefully acknowledge the funding received from the Office of Public Works to support this work. The authors also wish to thank AYESA (formerly Byrne Looby Ltd.) for their assistance and support throughout this work.

The authors wish to thank the Munster Technological University (formerly Cork Institute of Technology) research team who have contributed to this work over the years including John Clancy, Nicholas Norris, Kevin Motherway, Stephen Finn, Stephen Falvey, Kieran O' Sullivan, James Hickey, John Gamble, Laurence Lomasney, David Noonan and Ross O' Sullivan and also the technical team of Gabor Szacsuri, Jim Morgan, Maggie Shorten and Liam Jones.

7. REFERENCES

APHA (1998), Standard Methods for the Examination of Water and Wastewater, 20th Edition, Clescerl, L.S., Greenberg, A.E., Eaton, A.E., Eds, American Public Health Association, IBSN:978-0872232356.

British Standard BS 1377-2:2022 Methods of test for soils for civil engineering purposes. Classification tests and determination of geotechnical properties.

Gamble, J. (2016) Analysis and Modelling of Sediment Transport on the River Bandon, MEng Thesis, Cork Institute of Technology, Ireland, September 2016.

Gamble, J., Harrington, J. (2016) *Sediment Transport Modelling on the River Bandon*, Civil Engineering Research Association of Ireland Conference 2016 (CERI), pp. 631-636, NUI Galway, August 2016.

Garcia, J.T, Harrington, J.R. (2019) *Fine Sediment Modeling During Storm-Based Events in the River Bandon, Ireland,* Water 2019, 11(7), 1523; https://doi.org/10.3390/w11071523

Harrington, J. (2014) Sediment Monitoring Programme on the River Bandon, submitted to OPW, August 2014.

Harrington, J. (2019) Field Monitoring, Modelling and Assessment of Dredging Works on the River Bandon, submitted to OPW, March 2019.

Harrington, J., Gamble, J. (2016) Monitoring and Assessment of Proposed Dredging Works on the River Bandon, submitted to OPW, September 2016.

Harrington, J., Garcia, T.J., Szascuri, G., Batel, B., (2020a) Sediment Monitoring & Behaviour for Post-River Improvement Works on the River Bandon, submitted to OPW, March 2020.

Harrington, J., Garcia, T.J., Szascuri, G., Batel, B., (2020b) *Monitoring, Modelling and Assessment of Sediment Transport on the River Bandon, Ireland*; Civil Engineering Research Ireland (CERI) Conference, pp. 618-623, Cork Institute of Technology (Online), August 2020, ISBN 978-0-9573957-4-9.

Harrington, J., Garcia, T.J., Szascuri, G., Batel, B., (2021) Sediment Monitoring & Behaviour for Post-River Improvement Works on the River Bandon, 2nd Draft Interim Report, submitted to OPW, October 2021.

Harrington, J., Garcia, T.J., Szascuri, G., Batel, B., (2022) Sediment Monitoring & Behaviour for Post-River Improvement Works on the River Bandon, 3rd Draft Interim Report, submitted to OPW, October 2022.

Harrington, J., Harrington, S.T. (2013) *Sediment and Nutrient Behaviour on the River Bandon, Ireland*. River Basin Management VII, 2013: p. pp. 215 – 226.

Harrington, S.T., Harrington, J.R (2014) *Dynamics of suspended sediment flux on the rivers Bandon and Owenabue, Ireland*, Int. J. Sus. Dev. Plann. Vol. 9, No. 6, 861–873, 10.2495/SDP-V9-N6-861-873.

Harrington, J., Lomasney. L., (2016) Field Monitoring, Modelling & Assessment of Dredging Works on the River Bandon, submitted to OPW, October 2016.

Harrington, J., Lomasney, L. (2018) *Suspended sediment and bed sediment transport on the River Bandon, Ireland,* Civil Engineering Research Association of Ireland Conference 2018 (CERI), UCD, August 2018.

Hickey, J. (2014) Suspended Sediment and Nutrient Behaviour on the River Bandon, MEng Thesis, Cork Institute of Technology, Ireland, September 2014.

JBA Consultants (2011) Bandon Flood Relief Scheme Final Hydrology Report, Ireland, 2011.

Lomasney, L. (2022) Sediment Transport on the River Bandon, Co. Cork, Ireland, MEng Thesis, Munster Technological University, Ireland, April 2022.

Office of Public Works (2023) *Hydro-Data. Station Location: Bandon & Curranure*. Available from: http://www.opw.ie/hydro/.

Office of Public Works (2102) Bandon River (Bandon) Drainage Scheme – Design Drawings, June 2012.

Park, J. (2015) Coupling Fine Particle and Bedload Transport in Gravel-Bedded Streams, PhD Thesis, University of California, Berkeley, USA, Spring 2015.

Parker, G. (1990a) *Surface-based bedload transport relation for gravel rivers. Journal of hydraulic research,* 28(4), 417-436.

Parker, G. (1990b) *The" acronym" series of Pascal programs for computing bedload transport in gravel rivers*. St. Anthony Falls Hydraulic Laboratory, University of Minnesota.

US Army Corps of Engineers (2022) HEC-RAS River Analysis System. Institute for Water Resources Hydrologic Engineering Centre (2022).