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Sediment Transport Modelling on the River Bandon

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ABSTRACT: In November 2009 Ireland was subject to a severe weather event, causing widespread flooding nationwide. One of the worst effected towns was the town of Bandon in County Cork which regularly floods. The River Bandon is located in the South Western River District (SWRBD) with a catchment area of 608km^2. The River Bandon offers a positive environment for biodiversity, facilitating habitats for some endangered species. The River Bandon is planned to undergo significant river improvement works.

This paper presents the findings of an extensive sediment sampling, testing and analysis programme, including for suspended and bed sediments and sediment loadings. The HEC-RAS numerical model has been developed and applied to a 7.7 km river reach from Bandon town downstream. The model has been calibrated and validated with a preliminary application to predict sediment transport conditions.

KEY WORDS: Sediment Transport; HEC-RAS; Flooding.

1 INTRODUCTION

The River Bandon, located in County Cork, and its sediment behaviour is the subject of this paper. The town of Bandon is the largest urban settlement on the river and has a history of flooding. Stretches of the river in Bandon town and downstream are planned to undergo significant river improvement works in the summers of 2016 and 2017.

Sediment samples were taken at five locations along the river. The samples were analysed for suspended load and bed load characteristics. Turbidity sensor data was also gathered and analysed. Sediment loading rates were determined.

A numerical model was developed to predict sediment transport conditions on the river.

2 BANDON CATCHMENT

The River Bandon is located in the South Western River District (SWRBD), the largest of the eight river basin districts in Ireland. It is approximately 74km long with a catchment area of 608km^2 which is relatively large in an Irish context. The river rises in the Shehy Mountains and discharges to Kinsale Estuary. The river is tidal up to approximately 15km upstream of the Kinsale Estuary which is downstream of the town of Innishannon [1]. The catchment is primarily agricultural with three relatively large urban settlements along the river; Dunmanway, Bandon and Kinsale (see Figure 1). The catchment consists of two distinct areas; the upland Bandon/Caha area which is upstream of Dunmanway and comprises of mainly mountainous areas with poor soil conditions and downstream of Dunmanway which is generally low-lying agricultural land with good soil conditions.

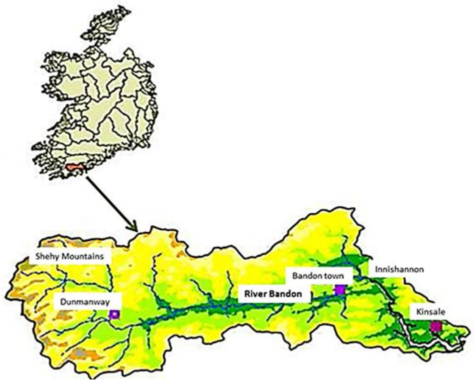

Figure 1: River Bandon Catchment

3. RELEVANT LEGISLATION

Existing European Union (EU) legislation regarding sediments is quite limited [2]. Three of the most important EU directives relevant to the work are:

- Water Framework Directive
- Freshwater Fish Directive
- Habitats Directive

3.1 Water Framework Directive (2000/60/EU)

The Water Framework Directive (WFD) (2000/60/EU) was introduced in December 2000 with the aim of preventing the further deterioration of water quality and restoring all waters to good status by 2015 [3]. The WFD uses five water quality categories which are based on the biodiversity within the relevant aquatic system.

3.2 Freshwater Fish Directive (78/659/EU)

The Freshwater Fish Directive (FFD) (78/659/EU) was enacted to ensure that freshwater bodies are capable of sustaining natural fish life. The FFD places limits on various parameters and limits the suspended sediment concentration to 25mg/l for salmonid waters [2]. This limit can be exceeded for short-term events, such as during flood and drought conditions. The FFD was repealed in 2013 (in the overall context of the WFD) leaving individual EU Member States to decide on how to assess impacts on fisheries [3].

3.3 Habitats Directive (92/43/EU)

The aim of the Habitats Directive (HD) (92/43/EU) is to conserve natural habitats of wild fauna and flora. The HD achieves this by creating Special Areas of Conservation (SAC), also referred to as European sites or Natura 2000 sites in Irish legislation; such sites are considered to be of exceptional importance for the protection of rare and endangered species.

4. RIVER BANDON – SITE CONDITIONS AND PROPOSED WORKS

4.1 River Ecology and Sediments

Sediment transport occurs naturally in rivers and is essential to maintaining habitats. Changes to land-use cause changes in the delivery of fine and coarse sediment and sediment transport can vary over space and time due to changing flows and catchment conditions. The ecological regime of a river can adapt to small changes in sediment transport over short time periods. However, excessively high levels of suspended sediment concentration can cause significant detrimental impacts, the effects on the ecosystem depend on the suspended sediment concentration level and duration of exposure. Four impact zones have been indicated with Zone 1 with suspended sediment concentration levels below 25mg/l has little or no impact on fish and their habitats. However, suspended sediment concentrations above 25mg/l have varying impacts depending on the duration of exposure. Zone 2 shows behavioural effects on fish causing population decline and/or increase in mortality rate. Zone 3 shows a physical effect on fish. In this zone fish gills and other tissue are damaged. The effect may not cause immediate death but increases the mortality rate and leads to a decline in the fish population. Zone 4 results in lethal effects on fish. With the majority killed immediately or suffer damaged tissue resulting in a large reduction in fish population and also damage to the capacity of the system to support a future fish population [4].

Bed load transport can create habitats, however, this transport also has the ability to remove and smother habitats. The movement of bed load has a greater impact on embryo and fry than on larger fish with deposition of bed load suffocating eggs and fry in spawning grounds. The build-up of sediment around fish eggs results in the water not being able to wash away the fish waste, leading to potential fish kill by poisoning [5].

The variation of habitats on the River Bandon offers a positive environment for biodiversity. Table 1 presents detail on important species on the River Bandon [6].

Table 1: Important Species on the River Bandon [6]

Species	Location	Comments
Atlantic salmon	Lower reach downstream of Innishannon	Salmon have been recorded upstream of Dunmanway
European Eels	Lower reach downstream of Innishannon	Eels have been found as far upstream as Bandon town
Lamprey	Lower reach up to Bandon town	Heavy density below Innishannon
Three-spined stickleback	Lower reach below Innishannon and upstream of Dunmanway	Recorded downstream of Innishannon

4.2 Proposed Works

The proposed river improvement works in Bandon Town and downstream are designed for a 1 in 100 year return period event [1]. Table 2 presents the proposed river improvement works with the improvement locations presented in Figure 2.

Table 2: Proposed Works [1]

Proposed Works	Area
Dredging	Bandon Weir to O'Driscoll's Bridge
Flood defence walls	Various locations in Bandon town, Bridewell river
Improvement to existing flood defences	Bridewell River, Bandon Wastewater Treatment Plant
Provision of removable flood barriers	Specific locations
Provision of rock ramp and fisheries mitigation measures	At Bandon weir
Local drainage works	Local drainage behind flood defences

Figure 2: Proposed Works

The proposed river improvement work includes the dredging of the River Bandon for 3.6km from the weir in Bandon town downstream to O'Driscoll's Bridge at a slope of 1/1000. The dredging will cause a reduction of bed level at the weir of 1.9.m, at Bandon Bridge of 1.7m, at the wastewater treatment plant of 1m and to bed level at O'Driscoll's Bridge as shown in Figure 3 [1]. Once dredging is complete, pools, riffles and a thalweg will become a feature of the improved river

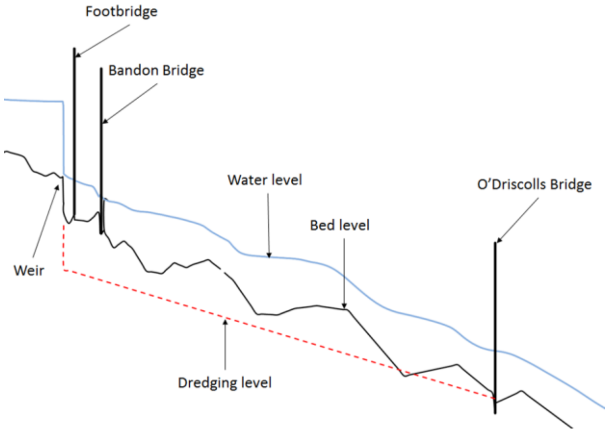

Figure 3: Proposed Dredging Levels

4.3 River Flow Analysis

The River Bandon has five hydrometric stations with two (Bandon town station and Curranure station) located within the modelled reach. An extreme flow analysis was undertaken for both stations using six different probability distribution functions. For the subsequent work the extreme flow rates determined for the Bandon station are used due to the longer term nature of the data record (see Figure 4). For this case the Generalised Logistic (GLO) probability distribution function was found to provide the best fit. Figure 4 also presents the 'outlier' 2009 flood condition.

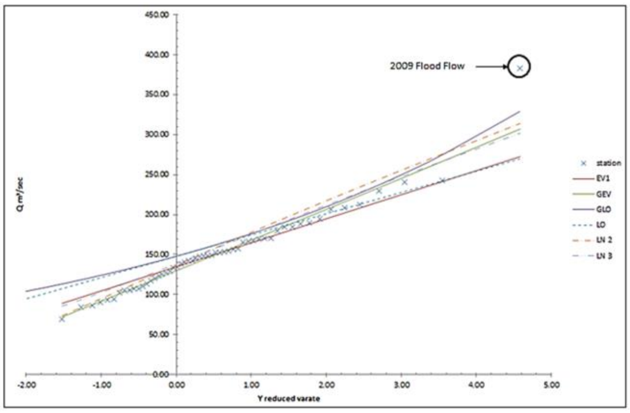

Figure 4: Bandon Station Flow Distributions

Figure 5 presents the top ten annual maximum flows recorded at the Bandon station, including the most recent 2015 event (in red). An L-moment extremal flow analysis was undertaken and the December 2015 event was found to correspond to a 1 in 35 year event, with the 2009 flood event, the highest event recorded, indicating a 1 in 100 year event.

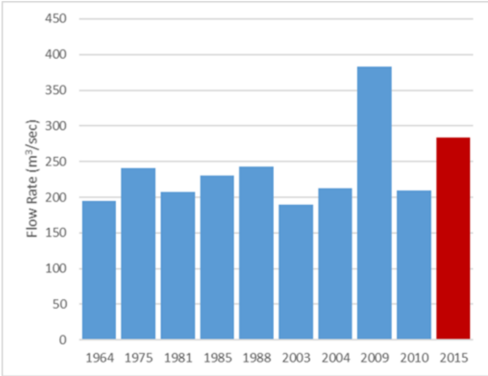

Figure 5: Top Ten Recorded Flood Events

Table 3 presents the extreme flood event analysis for both pre-2015 flows and for all flows.

Table 3: Variation in Return Period Flow Events

Return period	Pre-2015 Flow Rates (m^3/sec)	All Flows Rates (m^3/sec)	Variation (%)
2	148.0	148.0	0
5	188.6	188.3	0
10	217.3	219.8	1
25	257.8	268.1	4
30	266.5	279.0	4
50	292.0	312.1	6
100	330.0	364.4	9

4.4 Sediment Sampling and Analysis

A sediment sampling programme was undertaken at five locations along the river, as shown in Figure 6.

Figure 6: Sediment Sample Location

Suspended sediment samples were taken using both surface grab and depth integrating approaches. Water levels were recorded using the local staff gauge at each sampling location (if available) or downloaded from the OPW water level record website as necessary [7]. Water temperature was also recorded. Table 4 shows a summary of manually sampled suspended sediment concentration data. Figure 7 provides a longitudinal profile of measured values. These show suspended sediment concentration (SSC) values generally less than 10 mg/l reflecting the clear nature of the water flows observed along the river reach during the sampling work. It should be noted that suspended sediment concentrations can be elevated on high flow events.

Table 4: Summary of Suspended Sediment Concentration

Location	Suspended Sediment Concentration (mg/l)		
	Minimum	Maximum	Mean
Footbridge	0.2	11.84	2.57
Bandon Bridge	0.4	6.37	2.55
Bridewell	0.22	74.9	2.14
Millstream	1.98	9.99	3.66
O'Driscoll's Bridge	0.98	14.76	3.85

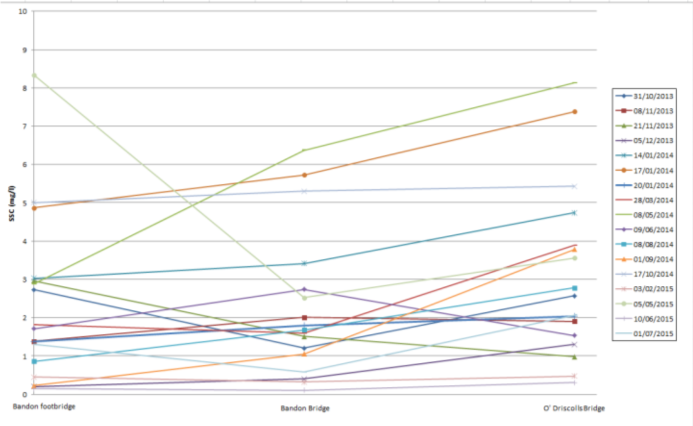

Figure 7: SSC on the River Bandon

Cork Institute of Technology installed a turbidity sensor at the Curranure Gauging Station in February, 2010. This sensor records turbidity on a continuous 15-minute basis. Previous analyses have shown that turbidity is a suitable surrogate for suspended sediment concentration at this location [8] and thus the continuous turbidity record allows conversion to a continuous suspended sediment concentration record.

The analysis has been based on applying the flow rate (Q) and turbidity as a surrogate for suspended sediment concentration (C) in the following equation (1).

$$SSL_s = \int_{t_1}^{t_2} Q_t C_t \, dt \qquad (1)$$

Table 5 presents summary seasonal and annual suspended sediment loadings (in tonnes) for 2010, 2011 and 2014, for comparison purposes. These results indicate the highly variable and dynamic nature of suspended sediment behaviour and transport within the river system. The annual suspended sediment loading varies between approximately 2,000 and 3,000 tonnes; significant variation in the seasonal loadings estimated is also clearly evident.

Table 5: Annual and Seasonal Suspended Sediment Loadings

	2010	2011	2014
Spring Loading (March to May)	85.1	243.9	1072.2
Summer Loading (June to August)	296	107.9	239.5
Autumn Loading (September to November)	862	1406.1	268.6
Winter Loading (December to February)	708	1300	1205
Annual Loading	2148	3058	2785

Bedload samples were collected by entering the water body at each sampling location and were taken when conditions allowed, sampling within the context of Health & Safety requirements, generally using a grab sampler (an Ekman Grab Sampler) and in places using a piston type core sampler where bed conditions allowed. Table 6 presents summary results.

Table 6: Bed Sediment Size Summary

Location	D_{50} (mm)	
	Minimum	Maximum
Footbridge	10.4	29.6
Bandon Bridge	3.2	33.6
Bridewell	3.9	19.1
Millstream	28.5	> 50
O'Driscoll's Bridge	28.5	> 50

5. NUMERICAL MODELLING

5.1 Numerical Model – HEC-RAS

The U.S Army Corps of Engineers HEC-RAS model (a 1-Dimensional numerical model – Hydrologic Engineering Center's River Analysis System) has been applied to numerical modelling on the River Bandon [9]. It provides for both steady and quasi-steady flow conditions, the quasi-steady flow condition is required for the sediment transport aspect of the modelling.

Calibration of the model involves an analysis for both water level variation and sediment characteristics with comparison between field data and model outputs. The aim of the calibration process is to produce a best fit of model output to observed field data. Model validation involves additional model comparison with field data and is required to provide additional confidence in the numerical model to accurately simulate field conditions

Figure 7 shows the river reach modelled from the upstream model boundary located 0.7 miles upstream of the weir in the town of Bandon to the downstream boundary at Innishannon Bridge. Short reaches on the Bridewell, Millstream and River Brinny tributaries are also modelled. The upstream and downstream model boundaries are shown including the three tributary streams (the Bridewell, Mill Stream and the Brinny).

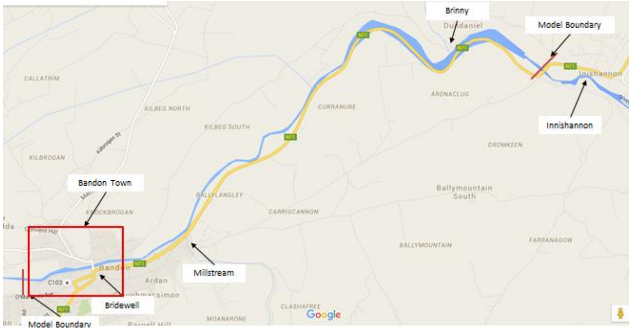

Figure 8: Numerical Model Boundary

5.2 Hydrodynamic Calibration

The hydrodynamics were calibrated at both Bandon town and Curranure hydrometric stations located within the model boundary. The calibration involves comparison of steady state water level predictions from the HEC-RAS model with water levels at gauging stations. This comparison was undertaken for a range of flow conditions for both in and out of bank flows, varying from 19 to 352m^3/sec.

The analysis involves varying the Manning Roughness Coefficient 'n' to provide a best fit between model prediction and gauged field data. The best fit is determined using various statistical parameters: Root Mean Squared Error (RMSE) (Equation 2), Nash-Sutcliffe Coefficient of Efficiency (E) (Equation 3) and the Systematic Error (SE) (Equation 4) .

$$RMSE = \sqrt{\frac{\sum_i^N (WS_{ob} - WS_{sim})^2}{N}} \quad (2)$$

$$E = -\frac{\sum_i^{nN} (WS_{ob} - WS_{sim})^2}{\sum_i^N (WS_{ob} - WS_{obavg})^2} \quad (3)$$

$$SE = \frac{\sum_i^N (WS_{sim} - WS_{ob})}{N} \quad (4)$$

where:

WS_{ob} = water surface level observed by the station
WS_{sim} = water surface level simulated by HEC-RAS
WS_{obav} = is the average water surface level observed at the station
N = number of reference measurements (data points)

The results of the model calibration analysis are shown in Table 7 for both gauging station locations. The Manning 'n' values presented are typical for rivers similar to the River Bandon. The values found for each of the statistical parameters used are considered to be appropriate for model calibration purposes [10].

Table 7: Model Calibration Analysis Results

	Manning 'n' Coefficient	RMSE (m)	E	SE (m)
Bandon Bridge	0.0348	0.0808	0.993	-0.03
Curranure	0.0339	0.043	0.997	-0.024

The model was validated for flow rates over a 12 month period from 1/10/2009 to 30/9/2010; with flows ranging from 2.6 to 184.8m^3/sec, with an average flow rate of 15.6m^3/sec. Figure 8 presents the water levels at Bandon hydrometric station. The validation of the model provided additional confidence in the calibrated model.

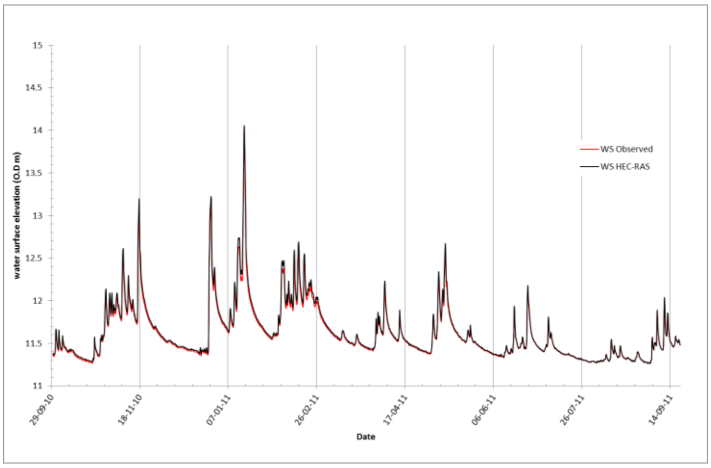

Figure 9: Model Validation for Water Level

5.3 Sediment Transport Calibration

Sediment transport data was collected over the period from 1st to 9th July 2015. Table 8 shows the measured bed load and suspended sediment load, which was estimated to have occurred over this time. This data suggests that the suspended sediment load is significantly higher than the bed load transport during this time period with the bed load accounting for approximately only 1.2% of the total load.

Table 8: Measured Sediment Transport for Calibration Period

	Sediment Load (tonnes)	
	Bed Load	Sediment Suspended Load
01-07-15 to 08-07-15	0.237	18.9

An extensive model calibration process was undertaken to determine key model parameter values. A summary of these key parameter values applied within the model and based on the model calibration and validation is given in Table 9.

Table 9: Sediment Transport Simulation - Model Parameters

Model Parameter	Value
Manning Roughness Coefficient - Bandon Station	0.0348
Manning Roughness Coefficient - Curranure Station	0.0339
Sediment Transport Function	Meyer Peter Muller
Total Rate Coefficient (C)	1.9
Power Function (P)	1.5
Critical Shear Stress $\tau*$	0.047
Time Step (Δt)	25 SECS

5.4 Model Simulation

The HEC-RAS model developed was applied to simulate flows over a 12 month period.. Results from this simulation (for the year 2011) predicted five locations with identified erosion or deposition, as presented in Figure 9. These locations correspond to the actual river locations where sediment deposition has been observed.

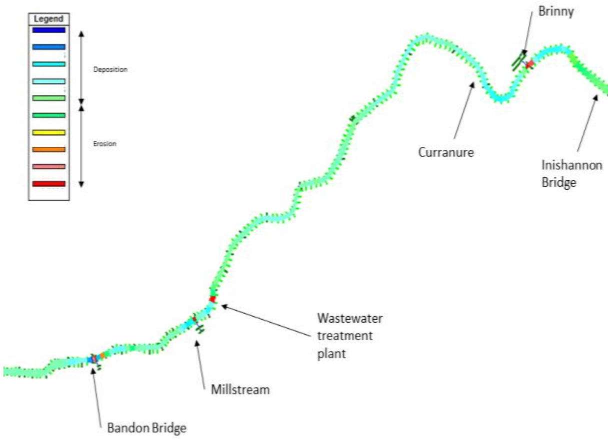

Figure 9: Identified Erosion and Deposition Locations

Total sediment transport rates at these locations were predicted from the HEC-RAS model with the results presented in Table 10.

Table 10: Predicted Annual Sediment Transport Rates

Location	Total sediment transport (tonnes/annum)	BL % of total load
Bandon Bridge	2866	7.8%
Bandon Station	2845	7.8%
Wastewater Treatment Plant	2957	7.6%
Brinny	3362	5.9%
Upstream of Innishannon Bridge	3395	5.6%

Model results indicate bed laod transport at from 5.6 to 7.8% of the total load. These results are indicative in nature and a more extensive dataset for sediment calibration purposes would enhance confidence in model results.

6. CONCLUSIONS

A suspended and bed sediment manual sampling programme has been undertaken at five locations on the River Bandon and the sediment data has been presented and analysed. Manual suspended sediment data has been complemented by continuous turbidity data gathered at the Curranure Station using turbidity as a surrogate for suspended sediment concentration. The river is characterised by low suspended sediment concentrations (< 10mg/l) with peaks during high flow events. Annual suspended sediment loadings vary from approximately 2,000 to over 3,000 tonnes.

An extremal flow rate analysis is presented for the Bandon station with the most recent December 2015 flood event estimated to be a 1 in 35 year event.

The HEC-RAS numerical model has been applied to a 7.7km stretch of the river system. Model inputs include geometric data based on a series of surveyed cross-sections, suspended sediment and bed sediment data and river flow rates.

The model has been satisfactorily calibrated for hydraulic conditions with a high level of confidence, it has also been satisfactorily validated for hydraulic conditions. The model has been calibrated on a preliminary basis for sediment transport. This calibration is based on available field data which is limited for the bed load. Additional model calibration and validation for bed sediment transport is required.

The HEC-RAS model has been applied to the river system with locations of erosion and deposition predicted. Sediment transport rates from the model have been estimated at from approximately 2800 to 3400 tonnes/annum with bed load transport estimated at from 5.6 to 7.8% of the total sediment load.

This paper presents new work on suspended and bed sediment behaviour and modelling for the River Bandon.

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