

CARDIGAN TIDAL FLOOD RISK MANAGEMENT SCHEME

Appendix 10.3 – Hydraulic Modelling Report



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FINAL

CARDIGAN HYDRAULIC MODELLING REPORT

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ABBREVIATIONS

AEP	<i>Annual Exceedance Probability</i>
EX	<i>Existing situation</i>
PR	<i>Proposed defence</i>
FB	<i>Freeboard</i>
FDL	<i>Flood Defence Level</i>
FM	<i>Flood Modeller</i>
PWL	<i>Peak Water Level</i>
RUA	<i>Residual Uncertainty Allowance</i>
SoP	<i>Standard of Protection</i>
QMDF	<i>Mean Daily Flow</i>
QMED	<i>Median Annual Maximum Flood</i>
Q100	<i>1% AEP fluvial event</i>
Q1000	<i>0.1% AEP fluvial event</i>
MHWS	<i>Mean High Water Spring</i>
T200	<i>0.5% AEP tide</i>
T1000	<i>0.1% AEP tide</i>

1. Introduction

Cardigan in Ceredigion has a history of flooding and several significant flood events have occurred in Cardigan between 2000 and 2020. The lowest lying residential and commercial properties in the Strand area have a threshold level below 3.100m AOD and are predicted to be affected by tidal events smaller than 50% Annual Exceedance Probability (AEP). Binnies has been commissioned by NRW to design a flood defence solution in the Strand area. As part of this design work, hydraulic modelling is required to:

- confirm if the proposed Flood Defence Level (FDL) of the defence (4.95m OD) provides the required standard of protection; and
- to assess what, if any, detriment results from the proposed flood defences in the Strand area of Cardigan.

2. Model Development

2.1 Data

The data from sources as listed in Table 2-1 were used in the development of the model.

Table 2-1 Model data and sources

Data	Source	Description
Topographic survey	Afon Mwldan & Afon Teifi Topographic Survey, Storm Geomatics Ltd for NRW, December 2020	Cross-section survey was used to develop the 1D model. This included details of the two bridges. Figure 2.1 shows the location of surveyed cross-sections.
LiDAR	https://datamap.gov.wales/maps/lidar-viewer/	LiDAR data (2020-22) was used to generate extended cross-sections and reservoir units to represent out of bank flows.
Coastal Flood Boundary	https://www.gov.uk/government/publications/coastal-flood-boundary-conditions-for-uk-mainland-and-islands-design-sea-levels	The Environment Agency Coastal Flood Boundary was used to create the downstream tidal boundary condition.
Typical tidal cycle	Admiralty Total Tide software	Used to obtain predicted tide cycle for the open coast near Cardigan and then used to generate different tidal boundaries as required.

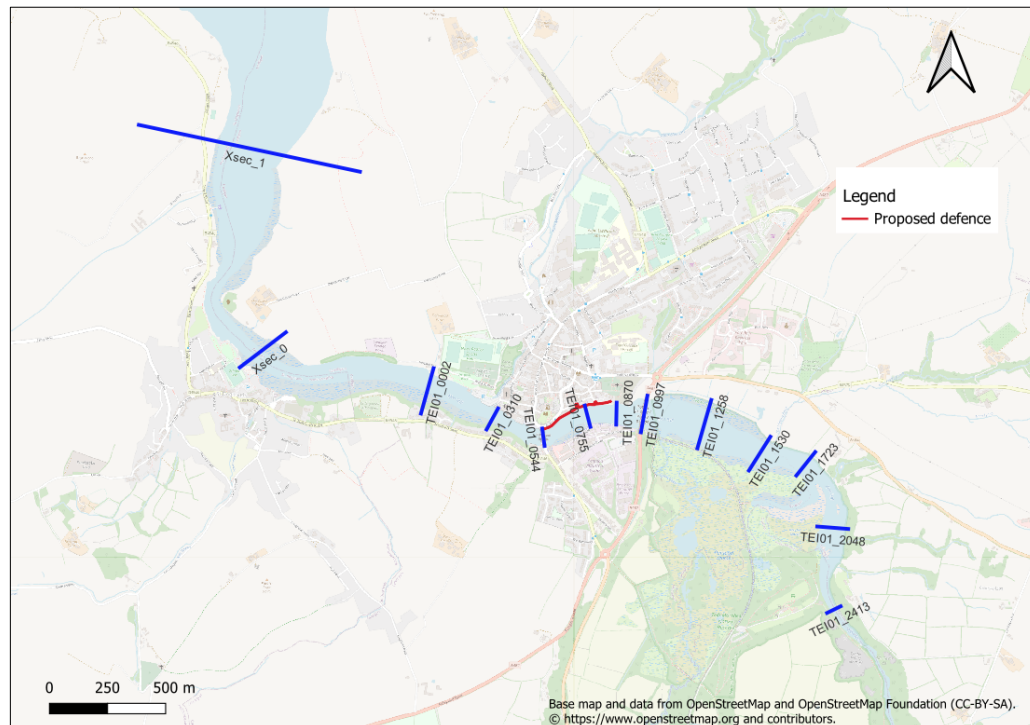


Figure 2.1 Cardigan Study Area

2.2 Software and model dimension

The hydraulic model was developed in Flood Modeller (FM) v6.1 as a 1D only model.

2.3 Model boundaries

(a) Upstream boundary

A single flow-time boundary representing the Afon Teifi is included in the model. A hydrological assessment was carried out to determine peak flows for different AEP floods.

Catchment descriptors for the Afon Teifi were obtained from the Flood Estimation Handbook (FEH) web-service. This provided catchment descriptors as far as the tidal limit, which is located around 3.5km upstream of Cardigan. Between the tidal limit and Cardigan there are several tributaries that needed to be accounted for in the flood estimation calculations. Catchment descriptors from these tributaries were also obtained from the FEH web-service. Area-weighting was then used to provide an updated set of catchment descriptors for the Afon Teifi to Cardigan. As a result, the catchment area was increased from 942 km² at the tidal limit to 968 km² at Cardigan; this small increase in area means that there was very little change to catchment descriptors from the catchment area to the tidal limit.

The FEH statistical method was applied to estimate flood flows. QMED was calculated from catchment descriptors and then adjusted using the Teifi @ Glanteifi (62001) gauging station as a donor site. The Teifi @ Glanteifi is located around 10km upstream of Cardigan and its use as a donor site reduces the estimate of QMED from 366.4 m³/s to 250.3 m³/s.

A pooling group was then generated. Following a review of the pooling group two gauging stations were removed due to having strong influence from reservoirs within their catchments, which is not reflective of the Teifi catchment. The Generalised Extreme Value (GEV) distribution provided the best statistical fit. The resulting growth curve factors and peak flows for a range of AEP floods is provided in Table 2-2.

Table 2-2 Afon Teifi Design Flows

AEP	Growth Curve Factor	Peak Flow (m³/s)
50% (QMED)	1.000	250.3
20%	1.316	329.4
10%	1.553	388.7
3.33%	1.959	490.3
2%	2.165	541.9
1%	2.468	617.7
0.50%	2.783	696.7
0.1%	3.616	905.0

The second Revitalised Flood Estimation Handbook (ReFH2) rainfall-runoff method was to generate the hydrograph shape, which was then scaled to fit to the required peak design flow.

(b) Downstream boundary

The Afon Teifi flows into the sea at Cardigan Bay, and so a tidal downstream boundary was used. The tidal boundary was derived using a combination of Admiralty Total Tide software and the Environment Agency Coastal Flood Boundary dataset (2018).

2.4 Model geometry

(a) Existing scenario

The existing model is created based on the cross-section survey (see Figure 2.1). Two sections (Xsec_0 and Xsec_1) were generated from LiDAR in the downstream sections where survey was not carried out. This was to allow the placement of the downstream boundary further towards the sea and away from the study area.

Cross section TEI01_0755 captures the existing flood wall adjacent to the Strand and Castle Street Bridge (TEI01_0544) marks the downstream end of the flood defence. There was no cross section at the upstream end of the flood defence. Therefore, cross section TEI01_0870 was created at the upstream end of the flood defence by replicating TEI01_0755 and interpolating the bed level. The existing defence levels are taken from the topographic survey.

Three reservoir units were included in the model to represent the low-lying areas of floodplain where floodwater could spill over banks and accumulate. The stage-area relationship for reservoir units was derived from LiDAR. The reservoir units were connected to the river channel using side spills. The spill section data was taken from the bank levels of adjacent river cross sections. The reservoir units and their representative floodplain area are shown in Figure 2.2.

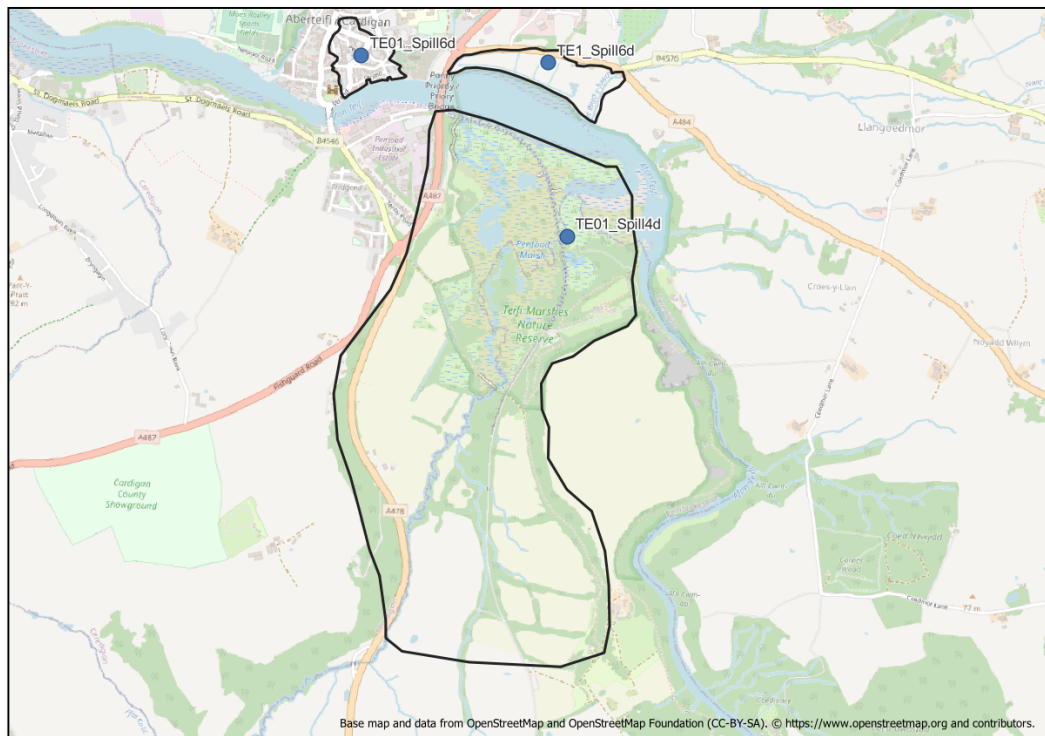


Figure 2.2 Reservoir Units

(b) Proposed scenario

The proposed model is created by modifying cross sections TEI01_0755 and TEI01_0870 to reflect the - alignment and crest level (4.95m AOD) of the proposed flood defence.

2.5 Structures

There are two bridges within the study area:

- **Priory Bridge:** modelled using a USBPR bridge unit (TEI01_0997B). The bridge has four piers with triangular faces, making up five openings. The width of openings ranges from 23.8m to 28.9m and the clearance above bed level through the central openings is over 7m.
- **Castle Street Bridge:** modelled using an ARCH bridge unit (TEI01_0538B). The downstream cross-section (TEI01_0538) has smaller area of opening compared to the upstream cross-section (TEI01_0544). Therefore, the downstream cross section would control the flow and hence it is used to represent the Bridge cross section. The bridge has five openings of varying width. The three central arches have a maximum width of around 9.7m, whilst the left-arch has a maximum width of 8.8m and the right-arch 8.4m. The heights above bed level of the arches range from 5.3m to 6.6m. There is a footbridge just downstream of the Castle Street Bridge. This is not included because the openings of the arch bridge are much smaller compared to that of the footbridge and therefore the road bridge acts as the flow control at this location.

The flow around and over the bridges is modelled using 1D spill units with spill levels taken from the survey data.

2.6 Climate Change

(a) Fluvial climate change

The Climate change uplift for peak fluvial inflows is considered based on Flood Consequence Assessments: Climate Change Allowances, September 2021 ([Flood Consequences Assessments: Climate change \(gov.wales\)](#)). For the West Wales river basin district this gives an uplift of 25% to flood flows for the 2050s epoch and 30% uplift for the 2080s epoch.

(b) Tidal climate change

The Sea Level rise allowances were considered based on emissions scenario RCP8.5 70th percentile. This was obtained from the UK Climate Projections (UKCP18) product (Sea level anomalies for marine projections around UK coastline, 2007-2100) ([Product Selection - UKCP \(metoffice.gov.uk\)](#)). Sea level rise as given in Table 2-3 for two different time frames were considered:

1. Sea level rise at the end of the 2050s epoch (i.e., 2069) was considered along with the 2050s fluvial climate change uplift.
2. Sea level rise in 2123 was considered along with 2080s fluvial climate change uplift to assess 100 years of climate change impacts.

Table 2-3 Sea level rise

Year	Sea level Rise (m)
2069	0.478
2123	0.984

3. Results

3.1 Detriment

The Existing [EX] and Proposed [PR] scenarios were simulated for different combinations of tidal and fluvial events. The peak water levels for both scenarios and the difference in peak water levels are presented in Table 3-1 and Table 3-2 for the present-day and with climate change respectively. For all present-day and climate change events, the change in peak water level is within the NRW specified detriment tolerance of 5mm. The proposed flood defence is overtopped during the 0.1% AEP flood with MHWS tidal boundary (2123 climate change).

Table 3-1 Assessment of detriment: present-day (PWL in mOD)

Event (Fluvial+ Tidal)	TEI01_0870			TEI01_0755			TEI01_0544		
	PWL: EX	PWL: PR	Change (m)	PWL: EX	PWL: PR	Change (m)	PWL: EX	PWL: PR	Change (m)
QMDF + T200	3.658	3.658	0.000	3.653	3.655	0.002	3.655	3.654	-0.001
QMED + T200	3.727	3.728	0.001	3.717	3.716	-0.001	3.710	3.710	0.000
QMDF + T1000	3.808	3.808	0.000	3.805	3.806	0.001	3.805	3.805	0.000
QMED + T1000	3.877	3.878	0.001	3.867	3.867	0.000	3.862	3.862	0.000
Q100 + MHWS	3.520	3.521	0.001	3.424	3.426	0.002	3.304	3.305	0.001
Q1000 + MHWS	4.483	4.483	0.000	4.378	4.379	0.001	4.266	4.267	0.001

Table 3-2 Assessment of detriment: climate change (2123) scenarios (PWL in mOD)

Event (Fluvial+ Tidal)	TEI01_0870			TEI01_0755			TEI01_0544		
	PWL: EX	PWL: PR	Change (m)	PWL: EX	PWL: PR	Change (m)	PWL: EX	PWL: PR	Change (m)
QMDF + T200	4.454	4.459	0.005	4.458	4.458	0.000	4.462	4.455	-0.007
QMED + T200	4.555	4.556	0.001	4.545	4.545	0.000	4.538	4.539	0.001
QMDF + T1000	4.791	4.795	0.004	4.790	4.793	0.003	4.787	4.790	0.003
QMED + T1000	4.878	4.879	0.001	4.868	4.867	-0.001	4.862	4.863	0.001
Q100 + MHWS	4.417	4.419	0.002	4.334	4.337	0.003	4.248	4.251	0.003
Q1000 + MHWS	5.273	5.268	-0.005	5.180	5.175	-0.005	5.071	5.066	-0.005

3.2 Residual Uncertainty Allowance

The RUA was calculated based on the existing guidance and is detailed in Appendix A. The following secondary variables were considered in the calculation of RUA.

- Model inflows
- Channel roughness
- Channel bed level
- Downstream tidal boundary level
- Bridge coefficient

From the calculations, a RUA allowance of 0.35m is recommended. This allowance only accounts for uncertainties in hydrological and hydraulic variables. Any other sources of uncertainties (such as settlement of embankments) should also be considered if appropriate.

3.3 Standard of Protection (SoP)

- The SoP provided by the proposed flood defence based on a flood defence level of 4.95m OD with 0.35m freeboard was assessed for different combinations of tidal levels and fluvial inflows. The results for present-day are in Table 3-3, results for climate change to 2069 are in Table 3-4. During a 0.5% AEP tide the lowest freeboard is 0.71m, reducing to 0.57m for a 0.1% AEP tide. The 0.5% AEP design standard is therefore maintained with adequate freeboard in 2069 regardless of the fluvial input (within the anticipated range of flows).
- There is no freeboard for the 0.1% fluvial event; the defence is overtopped up to a depth of 0.13m. In the 1% AEP fluvial event there is a predicted 0.78m freeboard. This is caused by Castle Street Bridge, which forms a constriction in the channel and generates a large head loss when the fluvial flows start to exceed the 1% AEP.

(a) Table 3-4 and results for climate change to 2123 are in 2123 climate change

The **2123 climate change** results are summarised below:

- During a 0.5% AEP tidal event the lowest predicted freeboard is 0.40m. This reduces to 0.07m for a 0.1% AEP tidal event. The 0.5% AEP design standard is therefore maintained in 2123 regardless of the fluvial input (within the anticipated range of flows).
- There is no freeboard for the 0.1% fluvial event; the defence overtops up to a depth of 0.32m. In the 1% AEP fluvial event there is a predicted 0.53m freeboard; the reason for the large difference between these two events is explained above.

Table 3-5.

(b) Present-day

The results from the **present-day** assessment are summarised as follows:

- During a 0.5% AEP tidal event the lowest freeboard (FB) available is 1.22m, reducing to 1.07m for a 0.1% AEP tidal event. In fluvial events, estimated freeboard is also over 1m for the 1% AEP, reducing to 0.47m for a 0.1% AEP fluvial event.
- For extreme tidal events, there is an increase of 0.08m in peak water level when increasing the applied fluvial flow input from QMDF to QMED. The fluvial input, within

the anticipated range of flows, when combined with an extreme tidal event therefore does not impact the design standard of the defences in the present-day.

Table 3-3 Standard of Protection: Present-day

Event	TEI01_0870		TEI01_0755		TEI01_0544	
	PWL (m OD)	FB (m)	PWL (m OD)	FB (m)	PWL (m OD)	FB (m)
QMDF + T200	3.65	1.30	3.65	1.30	3.65	1.30
QMED + T200	3.73	1.22	3.71	1.24	3.71	1.24
QMDF + T1000	3.80	1.15	3.80	1.15	3.80	1.15
QMED + T1000	3.88	1.07	3.86	1.09	3.86	1.09
Q100 + MHWS	3.52	1.43	3.43	1.52	3.31	1.64
Q1000 + MHWS	4.48	0.47	4.38	0.57	4.27	0.68

(c) 2069 climate change

The **2069 climate change** results are summarised as follows:

- During a 0.5% AEP tide the lowest freeboard is 0.71m, reducing to 0.57m for a 0.1% AEP tide. The 0.5% AEP design standard is therefore maintained with adequate freeboard in 2069 regardless of the fluvial input (within the anticipated range of flows).
- There is no freeboard for the 0.1% fluvial event; the defence is overtopped up to a depth of 0.13m. In the 1% AEP fluvial event there is a predicted 0.78m freeboard. This is caused by Castle Street Bridge, which forms a constriction in the channel and generates a large head loss when the fluvial flows start to exceed the 1% AEP.

Table 3-4 Standard of Protection: 2069

Event	TEI01_0870		TEI01_0755		TEI01_0544	
	PWL (m OD)	FB (m)	PWL (m OD)	FB (m)	PWL (m OD)	FB (m)
QMDF + T200	4.14	0.81	4.14	0.81	4.13	0.82
QMED + T200	4.24	0.71	4.22	0.73	4.21	0.74
QMDF + T1000	4.29	0.66	4.28	0.67	4.28	0.67
QMED + T1000	4.38	0.57	4.37	0.58	4.36	0.59
Q100 + MHWS	4.17	0.78	4.08	0.87	3.98	0.97
Q1000 + MHWS	5.08	-0.13	4.97	-0.02	4.87	0.08

(d) 2123 climate change

The **2123 climate change** results are summarised below:

- During a 0.5% AEP tidal event the lowest predicted freeboard is 0.40m. This reduces to 0.07m for a 0.1% AEP tidal event. The 0.5% AEP design standard is therefore maintained in 2123 regardless of the fluvial input (within the anticipated range of flows).
- There is no freeboard for the 0.1% fluvial event; the defence overtops up to a depth of 0.32m. In the 1% AEP fluvial event there is a predicted 0.53m freeboard; the reason for the large difference between these two events is explained above.

Table 3-5 Standard of Protection: 2123

Event	TEI01_0870		TEI01_0755		TEI01_0544	
	PWL (m OD)	FB (m)	PWL (m OD)	FB (m)	PWL (m OD)	FB (m)
QMDF + T200	4.46	0.49	4.45	0.50	4.45	0.50
QMED + T200	4.55	0.40	4.54	0.41	4.54	0.41
QMDF + T1000	4.79	0.16	4.79	0.16	4.78	0.17
QMED + T1000	4.88	0.07	4.87	0.08	4.86	0.09
Q100 + MHWS	4.42	0.53	4.34	0.61	4.25	0.70
Q1000 + MHWS	5.27	-0.32	5.18	-0.23	5.07	-0.12

(e) Summary

- The proposed flood defence level of 4.95m OD provides a minimum freeboard of 0.40m for a 0.5% AEP tidal event including 100 years of sea level rise.
- The flood defence level is also above 0.1% AEP tidal level for the same climate change scenario, although freeboard is minimal.
- The proposed defences are predicted to provide protection against a 1% fluvial event with 100 years of climate change. However, it is predicted that they will be overtopped during a 0.1% AEP fluvial event by 2069.
- Castle Street Bridge creates a significant flow constriction. During a 0.1% AEP flood, this constriction generates a large head loss across the bridge, which is the primary cause of the defences being overtopped.

4. Conclusion

4.1 Summary

A 1D-only hydraulic model of Afon Teifi at Cardigan has been built to assess tidal and fluvial flood events. The model has been used to assess the possible impact on predicted flood levels associated with the proposed flood defences along the Strand. The model has also been used to assess the standard of protection provided by the proposed defences.

The results indicate that the defences will cause no detriment in any of the tested flood events i.e., any increase in water level did not exceed 0.005m (5mm), which is within the NRW-specified detriment tolerance.

The residual uncertainty analysis (RUA) was calculated to be 0.35m from five secondary variables using First Order Error Analysis. A summary of the minimum freeboard (based on an FDL of 4.95m OD) for the 0.5% AEP and 0.1% AEP tides in different climate change epochs of the proposed defence is provided in Table 4-1. This shows that the FDL provides more freeboard than the calculated RUA for the proposed 0.5% AEP tidal event design standard over the next 100 years. It also shows the proposed defence level is above the 0.1% AEP tide level, albeit with only 70mm of freeboard in 100 years' time.

Table 4-1 Summary of Available Freeboard for Tidal Events

Climate Change Epoch	Extreme Tide	
	0.5% AEP	0.1% AEP
Present day	1.22m	1.07m
2069	0.71m	0.57m
2123	0.40m	0.07m

The proposed defence will also provide protection against the 1% AEP fluvial event over the next 100 years (with minimum predicted freeboard of 0.53m). However, the constriction presented by Castle Street Bridge means that by the 2050's epoch (i.e., 2069), the 0.1% AEP fluvial event will overtop the defence.

4.2 Assumptions and limitations

- The predicted standard of protection is based on an uncertainty analysis that considered hydraulic and hydrologic parameters only.
- The RUA assessment uses the 'Proposed' model, analysing a 0.5% AEP tidal event combined with a QMED fluvial event.
- The limited gauge data available means that no model calibration has been carried out. A calibrated model would reduce uncertainties, which would be reflected in a reduction of the RUA.
- The results from simulations used for Residual Uncertainty Analysis indicate the model to be sensitive to inflows but that it is not very sensitive to bed levels, channel roughness bridge coefficients. However, these findings are based on the extrapolation of results from small changes to parameters and does not constitute a full sensitivity analysis of the model.

APPENDICES

Appendix A: Residual Uncertainty Allowance

A.1 Introduction

As part of the flood risk study and the assessment of the SoP provided by flood defences along the Afon Teifi at Cardigan, NRW have requested that the Residual Uncertainty Allowance (RUA) is also considered. RUA is often referred to as freeboard. When flood defences are designed, a RUA is added to the modelled top water level to account for uncertainties in model parameters such as peak flow, channel roughness etc. and this forms the Flood Defence Level (FDL). The following section describes the method used to calculate the RUA following the relevant guidance¹. This assessment only accounts for uncertainties in hydrological and hydraulic parameters.

A.2 First Order Error Analysis

This method of calculating the RUA assesses the sensitivity of water levels (the primary variable) to different independent model variables. The uncertainty contributions from each independent variable are then combined to give a total estimate of the RUA. Although it is expected that the behaviour of a river system to changes in hydrological and hydraulic variables is non-linear, this method assumes that if the change is only small then that behaviour can be treated as linear.

(b) Step A – Secondary Variables

The first step is to list the secondary variables that contribute to the primary variable of interest i.e., water levels along the watercourse. **Error! Reference source not found.** describes the variables that might be considered for this model and discusses the reason for their selection or rejection for the next stage of the assessment.

Table 1: Possible secondary variables affecting the primary variable (water level)

Secondary Variable	Description	Reason for Selection or Rejection
Understanding of hydrological conditions throughout the catchment	The catchment is predominately rural catchment consisting mostly of grassland with some arable and woodland. The underlying geology is uniformly very low permeability bedrock.	SELECTED: these secondary variables essentially constitute the uncertainty of the model inflows. The understanding of hydrological conditions and availability of gauge records is wrapped up in the performance of the FEH statistical method and the uncertainty in the FEH statistical method is well documented.
Availability/length of gauging records	Glanteifi (ref: 62001) is the nearest gauging station on the Afon Teifi to Cardigan with a gauge record dating back to 1959. Its catchment area is within 10% of the total catchment area to Cardigan.	
Performance of FEH statistical method	The presence of Glanteifi gauging station will improve the performance of the FEH statistical method. The site	

¹ Accounting of residual uncertainty: updating the freeboard guide, Report – SC120014, Environment Agency, 2017

Secondary Variable	Description	Reason for Selection or Rejection
	is suitable for both QMED and pooling.	
Information on channel geometry	The topographic survey used in the model is recent having been carried out in December 2020.	SELECTED: although the survey is recent it is noted that there are areas of 'soft bed'. The tidal nature of this reach means that sediments are likely to be fine and mobile and therefore bed levels may be susceptible to changes over even short periods of time.
Information of structure geometry	Modelled structures are based on topographic survey (as described above).	REJECTED: the survey is recent and there is no reason to believe that structure dimensions have changed.
Floodplain flow interactions	Upstream of Cardigan there are some large areas of floodplain storage but as the Teifi flows through Cardigan it is well constrained in all but the most extreme events.	REJECTED: this is a simplified modelling approach that represents the storage behind flood defences and not the flow routes that may occur. Bank levels are based on recent topographic survey and storage volumes calculated using recent LiDAR giving good confidence on how and when the channel interacts with the floodplain.
Structure coefficients	There are two bridge structures on the Afon Teifi near Cardigan. Upstream is the relatively modern A487, which has a deck level well above flood levels and narrow concrete piers and modelled using the USBR bridge unit. At the town centre is located Castle Street Bridge, which is much lower and consists of 5no. arched openings and is modelled using the ARCH bridge unit.	SELECTED: Although the structures are schematised using accurate topographic survey and are unlikely to change significantly overtime, without gauge data there is some uncertainty around hydraulic performance. Changes to structure coefficients could have a localised impact on water levels.
Variations in channel roughness	Channel roughness along the Afon Teifi is low at 0.030 based on the bed being made-up of fine sediments. Bank roughness is higher at 0.060 to represent vegetation growth varying from grass to shrubs and trees.	SELECTED: The selection of Manning's 'n' is a subjective process and average channel roughness can be expected to change throughout the year with vegetation growth.
Model parameters	No unusual parameters were applied to run the model.	REJECTED: no unusual parameters applied and therefore adjustments would create unusual parameter values and more uncertainty.
Superelevation	The reach of proposed flood defence is located on the outside of a shallow bend.	REJECTED: the bend is very shallow and superelevation effects is not expected to be significant.
Downstream boundary conditions	The Teifi is strongly tidally influenced at Cardigan. For extreme fluvial events a MHWS boundary has been applied.	SELECTED: A MHWS tidal boundary is applied but as the name suggests there will be variation around the mean.

(c) Step B – Estimating Change

The second step is to estimate the change in the primary variable (water level) produced by a small change in each secondary variable. For the five selected secondary variables (refer to Table 1 above) the 'small change' made are described in Table 2 below.

Table 2: Secondary variables affecting the primary variable (water level)

Secondary Variable	'Small change' made
Model Inflows*	+5% applied to model inflow
Channel Roughness	+0.005 roughness applied to all channel sections in model
Channel Bed level	+0.05m applied to bed level of the three river sections adjacent to the proposed flood defence (TEI01_0870, TEI01_0755 and TEI01_0544)
Downstream Tidal Boundary	+0.1m increase in peak tide level
Bridge Coefficient	-5% change in calibration coefficient of Castle Street Bridge (TEI01_0538B)

**includes uncertainty of understanding of hydrological conditions throughout the catchment, availability/length of gauging records and principally the performance of FEH statistical method*

The model has been run for the proposed design standard (0.5% AEP tidal event with a QMED fluvial event) to establish the baseline. The model is then run with a 'small change' of a secondary variable, each tested independently of each other. The change in water level from the baseline is then calculated. The average (mean) impact on the primary variable (water level) has been taken from nodes adjacent to the proposed flood defence as well as the maximum change that occurs along this reach; these results are summarised in Table 3.

Table 3: Change in primary variable (water level)

Variable	Change in primary variable (m)	
	Average	Maximum
Model Inflows	0.013	0.016
Channel Roughness	0.006	0.007
Channel Bed level	0	0
Downstream Conditions	0.101	0.102
Bridge Coefficient	-0.002	-0.002

(d) Step C – Estimating Uncertainty in the Secondary Variables

The third step is to estimate uncertainty in the secondary variables. The original freeboard guidance used standard deviations to define uncertainty. The latest guidance discusses uncertainty in terms of confidence intervals. The confidence interval is not prescribed by the guidance, but notionally would be expected to be 90% or 95% and, where possible, the same interval should be applied to all secondary variables. Table 4 provides an assessment of the change in each secondary variable for the 90% confidence interval.

Table 4: Secondary Variable 90% Confidence Interval

Secondary Variable	90% Confidence Interval
Model Inflow	Design flow estimates for an ungauged catchment using the FEH statistical method results in very large uncertainty intervals. The upper value for the 95% confidence interval at an ungauged site for QMED is stated as 102% increase, i.e. the QMED peak flow estimate for the Teifi at Cardigan may be as high as 505 m³/s compared to the design flow estimate of 250 m³/s. It might be justifiable to reduce this confidence band because Glanteifi gauging station (ref: 62001) is located not too far upstream and through which at least 90% of the Teifi catchment at Cardigan flows. However, in this instance a precautionary approach has been taken and the 90% confidence interval has been set to 102%. ▪ 90% confidence interval = 102% (1.02)
Channel Roughness	Manning's <i>n</i> channel roughness in the model generally varies along the bed and bank in a range of 0.030 to 0.070. Figure 4.1 is taken from the fluvial freeboard guidance note² and shows one standard deviation of 'n' value for a range of Manning's 'n' values. If we assume an average roughness along the modelled reach of the Teifi is <i>n</i> = 0.050 this gives one standard deviation of <i>n</i> as being 0.015; two standard deviations approximates to the 95% confidence interval, therefore <i>n</i> = 0.030 has been taken as the 90% confidence interval. ▪ 90% confidence interval = 0.030 Figure 4.1 is a line graph showing the relationship between the Estimate of Mannings <i>n</i> Value (x-axis) and the One Standard Deviation of <i>n</i> Value Estimate (y-axis). The x-axis ranges from 0 to 0.14 with increments of 0.02. The y-axis ranges from 0 to 0.08 with increments of 0.01. A curve starts at approximately (0.02, 0.005) and rises to approximately (0.12, 0.065). The source is cited as US Army Corps of Engineers. Figure 4.1 Standard deviation in Manning's <i>n</i> values

² Figure 6.4 from Fluvial Freeboard Guidance Note – Research and Development, Technical Report W187, Environment Agency (2000)

Secondary Variable	90% Confidence Interval
Channel Geometry	There is no set method for estimating the confidence intervals on channel geometry. The survey applied in the model is recent, so we can have high confidence in its representativeness. However, the bed likely consists of fine sediments and may be quite mobile given the tidal influences upon it. We have assumed that a change in the bed level (cross-sectional area) of more than 20% is unlikely to occur and therefore have set the 90% confidence interval to 20%. ▪ 90% confidence interval = 20% (0.2)
Downstream Conditions	The downstream boundary conditions are based on the Coastal Flood Boundary 2018 dataset and for which confidence intervals are provided. For the 50% AEP tide, which is used in the model, the 97.5% confidence band is between 3.58m OD and 3.73m OD compared to the design tide peak of 3.63m OD. For simplicity, the higher level of 3.73m OD is taken as the 90% confidence interval, giving a maximum variation of 0.10m. ▪ 90% confidence interval = 0.10m
Bridge Coefficients	There is no guidance as to confidence intervals in regards of structure coefficients. We have accurate survey of Castle Street Bridge and the ARCH bridge unit in FM is utilised to represent it, which is based on typical arched bridges in the UK. It is, however, unlikely that the hydraulics of the bridge would be perfectly represented in the model and if suitable data existed, it would most likely require some adjustment to the calibration coefficient to provide a better match to observed conditions. We would expect the calibration coefficient to vary by more than 20% only in exception circumstances and therefore have set the 90% confidence interval to 20%. ▪ 90% confidence interval = 20% (0.2)

(e) Step D – Estimating Total Uncertainty in the Primary Variable

The formula for estimating the total uncertainty in the primary variable is given in the box below, which is an extract from the guidance for accounting for uncertainty:

Making these assumptions simplifies the analysis and supports the following practical method to estimate the primary uncertainty (R_{unc}):

$$R_{unc} = \sqrt{\left[\left(\frac{\partial R}{\partial x}\right) x_{unc}\right]^2 + \left[\left(\frac{\partial R}{\partial y}\right) y_{unc}\right]^2 + \left[\left(\frac{\partial R}{\partial z}\right) z_{unc}\right]^2}$$

where:

R is the total uncertainty in the primary source interest (at the same level of confidence as the secondary uncertainties)

$\left(\frac{\partial R}{\partial x,y,z}\right)$ are partial derivatives that represent the relationship between a small change in the components and the resulting change in the primary uncertainty; the relative size of the partial derivative 'weights' the contribution for each component

In more descriptive terms:

- The ∂R term is the change in primary variable (peak water level) resulting from a small change in a secondary variable, refer to Table 3.
- The $\partial x, \partial y, \partial z$ terms are the change in the secondary variable (represented by the percentage change to model inflow and channel geometry and by value for channel roughness and downstream conditions); refer to Table 2.
- The x_{unc} , y_{unc} and z_{unc} are the uncertainties in the secondary variables (represented by the percentage change to model inflow, channel geometry and bridge coefficients and by value for channel roughness and downstream conditions); refer to Table 4.
- The equation is expanded or contracted as required depending on the number of secondary variables assessed.

Applying the above formula using average change in primary variables provide a RUA of 0.29m. Using the maximum change in primary variables, the RUA is 0.35m, which is a more conservative estimate and is recommended for use in this assessment. The secondary variables of channel geometry, bridge coefficients and channel roughness contribute very little to the overall RUA (<1%). The uncertainty in the downstream conditions contributes to around 10% of the RUA, whilst model inflow uncertainty accounts for nearly 90% of RUA.

ADDENDUM TO CARDIGAN HYDRAULIC MODELLING REPORT

BUKL project no. 4081883

Prepared for:

Natural Resources Wales

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Revision P01



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1. Addendum

1.1 Background

This addendum to the Cardigan Hydraulic Modelling Report is prepared in response to the following comments received on the Environmental Statement (ES) during Pre-Application Consultation:

“Appendix 10.3 Hydraulic Modelling report

Overall, we are of the opinion that Section 2 does not give sufficient information to evaluate whether the model used and model set up is suitable to assess environmental impact.

More background detail should be given in Section 2.2 on the model used and its architecture to provide greater context.

We consider that Section 2.3 does not adequately explain the boundary conditions and how tidal conditions are implemented through the model. While the document mentions that tides were implemented at the downstream boundary, no details are given as to whether that boundary is forced with elevation alone or a combination of elevation and velocity. If the former, we seek clarification, on how are tidal velocities catered for in the model. We advise that the actual locations of the up and downstream boundaries be included on a map.”

Comments in the model architecture and boundary conditions are addressed under headings 1.21.3. The appropriateness of using a 1D hydraulic model for the hydromorphological impacts for the WFD Compliance Assessment are detailed under heading 1.4.

1.2 Section 2.2 – Model architecture

The hydraulic model was developed in Flood Modeller (FM) v6.1 as a 1D-only model. It incorporates surveyed channel cross-sections and key hydraulic structures, including Cardigan Bridge and Priory Bridge, extending from the upstream extent of the Teifi Marshes Nature Reserve to the Cardigan Sewage Treatment Works. Additional cross-sections were derived from LiDAR DTM data to extend the model downstream into the estuary and adequately represent tidal propagation. A flow-time (QT) boundary was applied at the upstream model extent to represent fluvial inflows from the Afon Teifi, while a head-time (HT) boundary was applied at the downstream extent to represent a range of tidal conditions.

The location of the upstream and downstream boundary located at section TEI01_2413 and Xsec_1 respectively is shown in Figure 1-1.

1.3 Section 2.3 – Boundary conditions

Fluvial inflows were applied using ReFH2-derived design hydrographs, while cyclical tidal levels were applied at the downstream boundary. The tidal profile was obtained from Admiralty TotalTide data. For fluvial events, downstream tidal conditions were based on Mean High Water Springs (MHWS) levels. For tidal events, peak tide levels were derived from the Coastal Flood Boundary Dataset, with the appropriate storm surge shape applied. Example boundary conditions are provided in Figure 1-2.

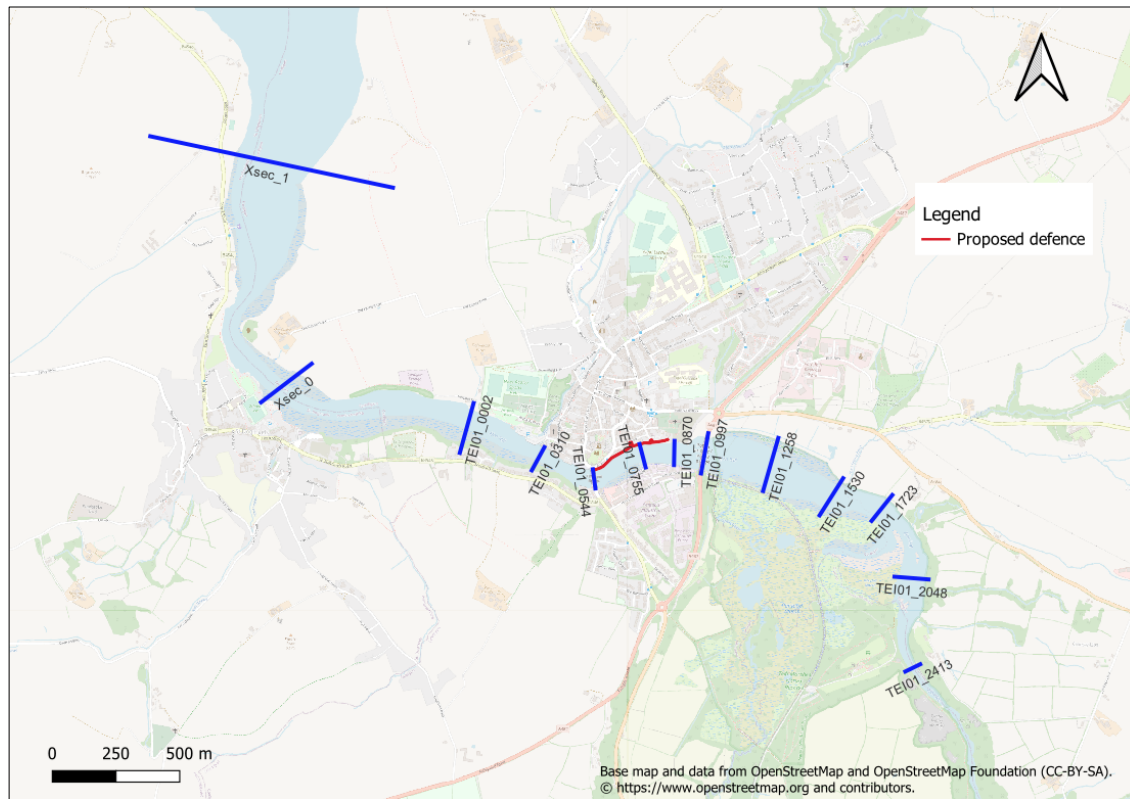


Figure 1-1: River section locations

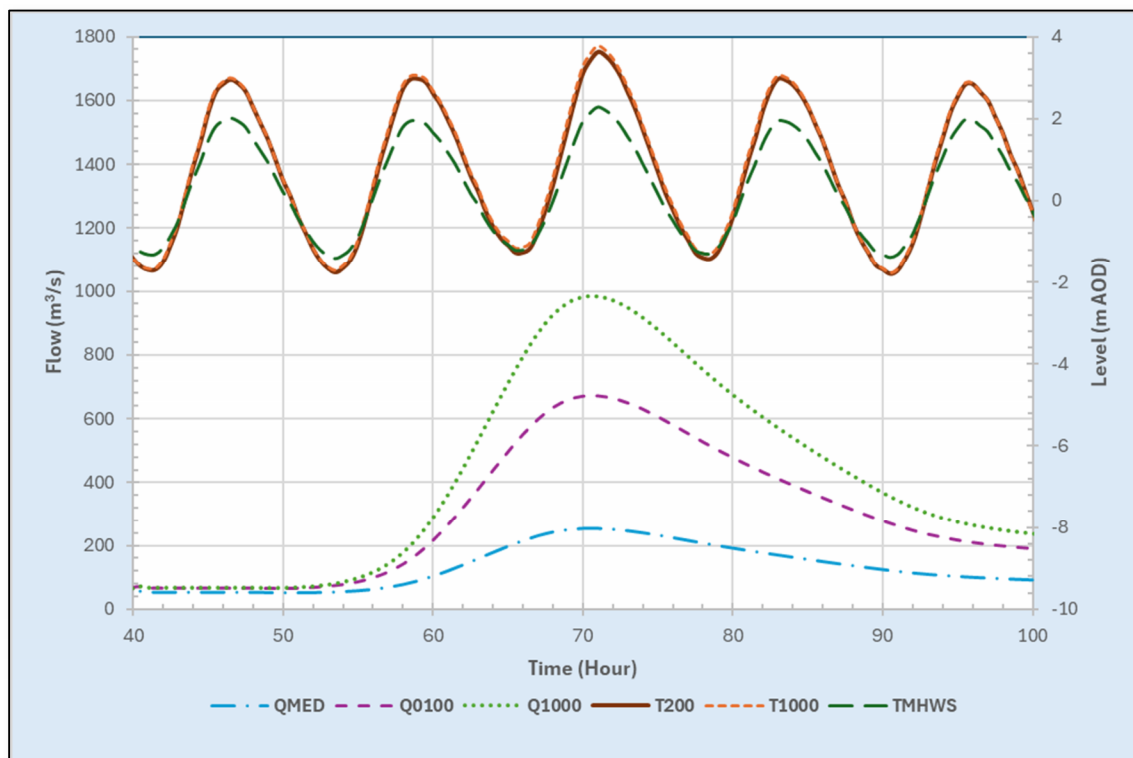


Figure 1-2: Fluvial and tidal boundaries

1.4 Appropriateness for WFD Compliance Assessment

The Flood Risk Assessment for the project has been developed using ESTRY-TUFLOW 1D-2D linked hydraulic model to accurately represent overland flow paths and floodplain volumes in the assessment of flood risk.

The application of 1D hydraulic modelling is considered suitable for assessing the baseline and impacts on hydromorphological supporting elements for the WFD Compliance Assessment, and ES Chapter 10: Water Environment. The WFD detailed assessment scope was agreed with NRW to include:

" 1D hydraulic model will require additional scenarios to be run, including:

- *Fluvial inflows of Q50, Q1 and 1 in 2-year events; and*
- *Tidal boundary conditions of highest astronomical tide, lowest astronomical tide, mean high water springs and mean low water springs.*

— Review geomorphological survey data against the 1D model hydraulic outputs and provide an interpretation of how the Scheme will impact the quantity, structure and substrate of the bed based on bed shear stress calculations.

— Review the geomorphological survey and baseline understanding of hydrodynamics in the Zone of Impact against the proposed works and modelling outputs. Provide an evidence-based interpretation of how the Scheme will impact the hydrodynamics.

— Review the geomorphological survey data against the proposed works and modelling outputs. Provide an evidence-based interpretation of how the Scheme will impact the structure of the intertidal zone."

For this assessment, steady-state fluvial flow scenarios are applied in combination with unsteady-state tidal boundary conditions, which enables an assessment of changes to in-channel hydromorphology. As the highest astronomical tide and 1 in 2-year fluvial flows result in minimal out of bank flows, a 1D-2D linked model would not provide increased detail and a 1D model is deemed suitable for our assessment. The 1D model is based upon the same topographic survey information as the 1D component of the 1D-2D linked model.