6 Design events

6.1 Model scenarios

Flood extents have been produced for the 50%, 20%, 10%, 5%, 2%, 1%, 0.5% and 0.1% AEP design event probabilities for the fluvial events.

6.2 Peak Flows

Peak flow estimates for design events have been estimated for Ballycarroon gauge upstream of Crossmolina. Appendix A contains details of the method and analysis carried out by the OPW design section. To fit the model calibration an additional 3% has been added to the peak flow estimates.

6.3 Future climate change scenarios

Specific advice on the expected impacts of climate change and the allowances to be provided for future flood risk management in Ireland is given in the OPW draft guidance[3], which calls for estimation of design flood parameters for two future scenarios, each intended to be a possible representation of flood conditions in 100 years time, i.e. around the year 2110:

- The Mid-Range Future Scenario (MRFS) is intended to represent a 'likely' future scenario, based on the wide range of predictions available and with the allowances for increased flow, sea level rise, etc. within the bounds of widely accepted projections.
- The High-End Future Scenario (HEFS) is intended to represent a more extreme potential future scenario, but one that is nonetheless not significantly outside the range of accepted predictions available, and with the allowances for increased flow, sea level rise, etc. at the upper the bounds of widely accepted projections.

The scenarios encompass changes in extreme rainfall depths, flood flows, sea level, land movement, urbanisation and forestry. The allowances for each of these aspects, apart from urbanisation, are set out in the brief. The sections below set out how design flood parameters for the future scenarios have been defined.

The guidance states that flood flows shall be increased by 20% and 30% respectively for the MRFS and HEFS. This change has been implemented by scaling up the flood hydrograph for each HEP and for each probability by the specified percentage.

Future scenarios have been developed as part of the hydrological analysis and are described in detail in the WCFRAM Hydrology Report for UoM 34. Table 6-1 details the changes to the hydrological boundaries for the Mid-Range Future Scenario (MRFS) and the High End Future Scenario (HEFS).

Table 6-1. Allowances for future scenarios (time horizon - 100 years)

	MRFS	HEFS
Extreme Rainfall Depths	+20%	+30%
Flood Flows	+20%	+30%
Mean Sea Level Rise	+500mm	+1000mm
Land Movement	-0.5mm/year	-0.5mm/year
Urbanisation	No General Allowance - Review on Case-by-Case Basis1	No General Allowance - Review on Case-by-Case Basis1
Forestation	-1/6Tp2	-1/3Tp2 +10% SPR3

For urbanisation the approach adopted for the Western CFRAM is to calculate future urban growth patterns based on the core strategy for each county, which is in turn passed on the settlement

3 OPW Assessment of Potential Future Scenarios, Flood Risk Management Draft Guidance, 2009

hierarchy detailed in the National Spatial Strategy (NSS)4. Although the plans and strategies do not extend to the 100 year horizon, they give an indication of where development is to be targeted for the plan period, which can be interpreted to be the likely focus of growth for the future. No distinction is made between the mid-range and high-end scenarios as regards urbanisation. Based on the region-wide analysis, an increase in URBEXT value of 20% has been applied to the flow estimate. However, in Crossmolina the catchment has so little urbanisation currently that this increase has no impact on future flows.

The likely impact of changes in forestry management practices has been reviewed across the catchment. In general, the likely changes and their impacts are so uncertain, and relate to such a relatively small catchment area that the impacts have been excluded from the development of future scenarios.

Flood extents have been produced for the 1% and 0.1% AEP design event probabilities taking a conservative approach of adding 20% flow for the MRFS and 30% for the HEFS, representing the possible impact of climate change.

Table 6-2. Current and future design flows

Design Event	Current flow (m^3/s)	MRFS flow (m^3/s)	HEFS flow (m^3/s)
50%	81.00		
20%	109.53		
10%	128.42	154.10	166.95
4%	153.31		
2%	170.51		
1%	187.83	225.40	244.17
0.5%	205.22		
0.1%	245.68	294.82	319.38

4 National Spatial Strategy for Ireland 2002-2020. The National Stationary Office

7 Baseline model results and validation

7.1 Key flood risk mechanisms and water level results at key nodes

The following gives a breakdown of the baseline flood risk and the mechanisms of flooding along the Crossmolina river, in particular where properties / buildings are at flood risk.

The following Table 7-1 presents the max 1% AEP and 1% AEP MRFS water levels at key model nodes. These nodes are used as a reference points in comparing results from the various options tested.

Public Exhibition maps for the proposed Arterial Drainage Act scheme have been prepared by Ryan Hanley. An overview of the 1% AEP and 1% MRFS AEP event results for the baseline scenario are presented in Figure 7-1.

Table 7-1. Results at key nodes - Baseline Scenario

Location	Model Node	1% AEP Max Stage	1% AEP MRFS Max Stage
Upstream property on Chapel Road	34DEEL01185	20.36	20.67
Adjacent to car park on left bank	DEEL_10808	19.38	19.58
Bridge (upstream face)	**DEEL_10722D**	**19.38**	**19.63**
Just downstream of Centra	DEEL_10594	18.75	18.98
Downstream of town	34DEEL01071	18.22	18.47

7.2 Flooding from section 34DEEL01297 and 34DEEL01185 on right bank

Flood water spills out of channel upstream of the town at Pollnacross (upstream of node 34DEEL01185) crossing the public road and flooding an area of low ground at the eastern side of the public road adjacent to the river.

A second overflow routes occurs further upstream, with flood water heading south and east onto public roads, before joining the first overflow route / flooded low lying area. Whilst no residential dwelling houses are shown at risk the flood extent does encroach on farm / outhouse buildings in this area.

7.3 Flooding from section DEEL_11388 and DEEL_11038 on right bank

Flood water overtops the wall along Chapel Street at section DEEL_11388 and flows along the road in the direction of Crossmolina town. It flows through houses located on this road and into the surrounding fields which have a lower elevation. The rest of the flood water flows into the Chapel View housing estate. Another flow path for this area is through a gap in the wall at section DEEL_11038. This is another source of flooding for the Chapel View estate and Chapel Street.

7.4 Flooding on the right bank from sections DEEL_11238 as far as the Jack Garrett Bridge on the left bank

The left bank from section DEEL_11238 as far as the upstream face of the bridge at Crossmolina town is quite low in comparison to the right bank. Water starts to come out of bank around section DEEL_11238 up as far as the bridge. This forms the main flow path on the left bank as water flows across a car park onto 'The Boreen' road and across to Bridge Street and floods the Church Street area. An obvious solution to minimise flooding on the left bank is to construct an embankment or flood walls, perhaps along the whole of the left bank (from section DEEL_11238 as far as the bridge) or alternatively an embankment at the car park. Water overtopping the bridge adds to the flood water on the left bank in the town.

7.5 Flooding in Crossmolina Town

Water overtops the bridge deck to cause flooding on the right bank as well as the left bank in Crossmolina town. There is also a gap in the left wall at section DEEL_10723 which contributes to flooding on Bridge Street and Chapel Street in the town. Downstream of the bridge, water flows out of bank at approximately section DEEL_10494 causing localised flooding. There are few receptors, with predominantly carparking and warehousing in this local area.

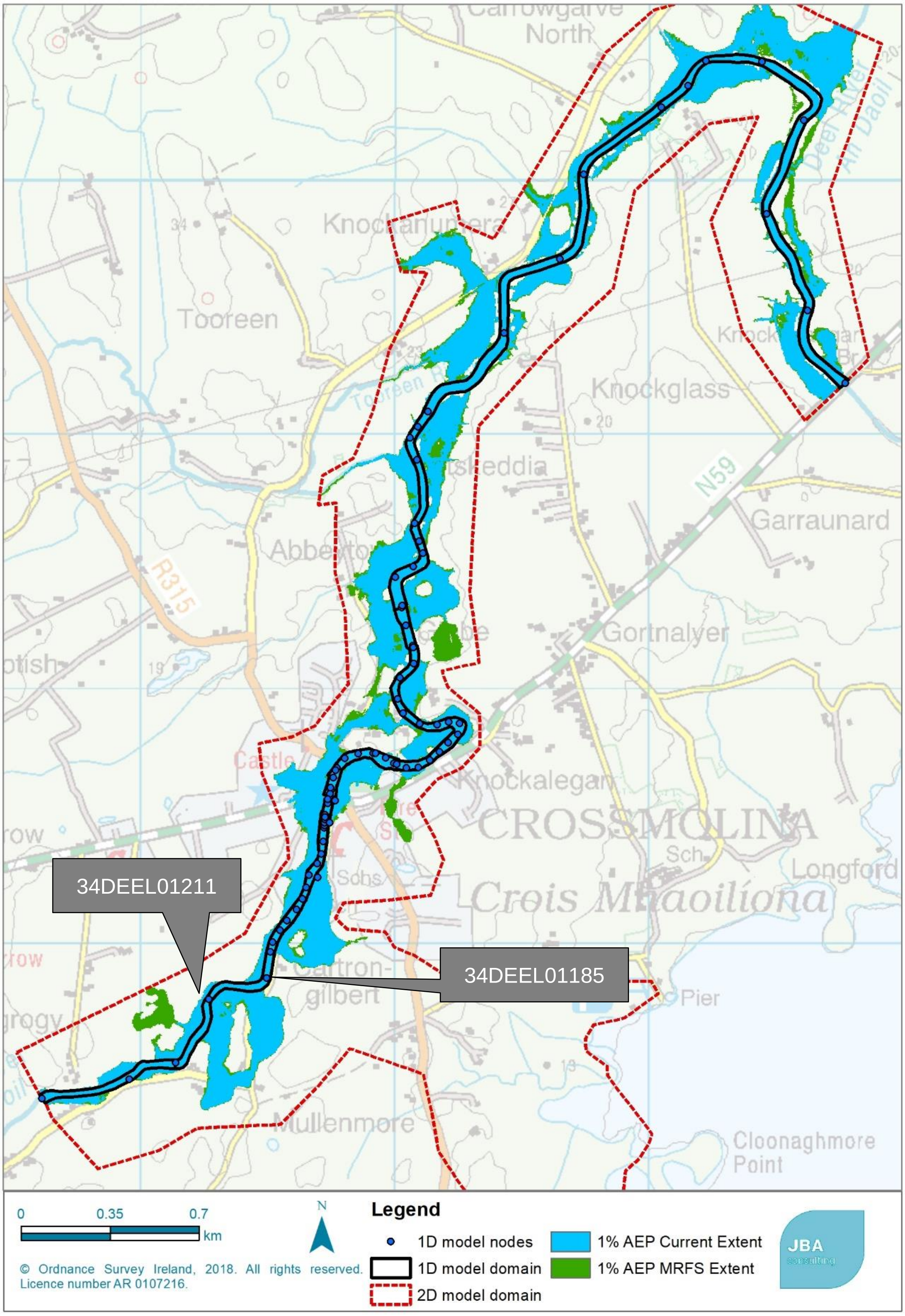

Figure 7-1. Baseline Flood extents (1% AEP & 1% AEP MRFS Events)

8 Flood Relief Options – Preliminary Assessment

A number of potential flood relief options for Crossmolina have been tested using the hydraulic model. The options selected have taken into account the appraisal provided in the feasibility report and consist of bridge replacement, flood defences, dredging, bypass channel and offline storage.

This section provides a summary of each option and describes the impact on the 1% AEP design event relative to the modelled existing risk. It should be noted that no comment on the feasibility of constructing or maintaining any of the options has been made in this report. Similarly, no commentary on the environmental or social impacts of the options has been provided. Instead, the model results have fed into the options appraisal, which is aimed at determining the most viable Flood Relief Option. The options appraisal is based on social, economic, environmental and cultural heritage factors, all of which are discussed in detail in a separate report on Options Appraisal.

The key model uncertainty, limitations and assumptions are summarised for each option in turn.

8.1 Bridge Replacement

Jack Garret Bridge is a key structure in the hydraulic model. The existing bridge restricts flow in the river channel in the higher return period events causing water to back up, increasing river levels and resulting in flooding upstream. Raising the soffit and hence road level has limitation in terms of maintaining connection with existing roads. Furthermore, flooding out of bank further upstream will still pose a risk. Replacement of the bridge alone reduces upstream flood levels but is insufficient to reduce flood risk to an acceptable standard.

Conversely containment measures on their own will be limited by the existing bridge arrangement and raising of the bridge parapet would be required to prevent floodwater flowing onto the bridge deck and beyond. Comparison of a bridge deck level of 18.67mOD and a baseline 1% AEP flood level of 19.38mOD (note this modelled flood level does not include any freeboard), indicates that a solid bridge parapet at least 1m high would be required, irrespective of the option for dredging or flood defence walls. And based on preliminary model runs a further 300mm rise in level is attributed to backing up at a solid bridge parapet. The retrofit of a solid parapet wall of this height is not considered viable and therefore replacement bridge options, with a higher soffit to increase conveyance capacity are assessed.

As replacement of the bridge alone is insufficient to provide the design standard of protection, the preliminary options assessment considers the combination of bridge replacement with the provision of walls and embankments to contain flow.

Two options were considered for the replacement bridge design as illustrated in Figure 8-1. Bridge Option 1 has the lesser impact hydraulically and is represented in the model as a single span bridge deck.

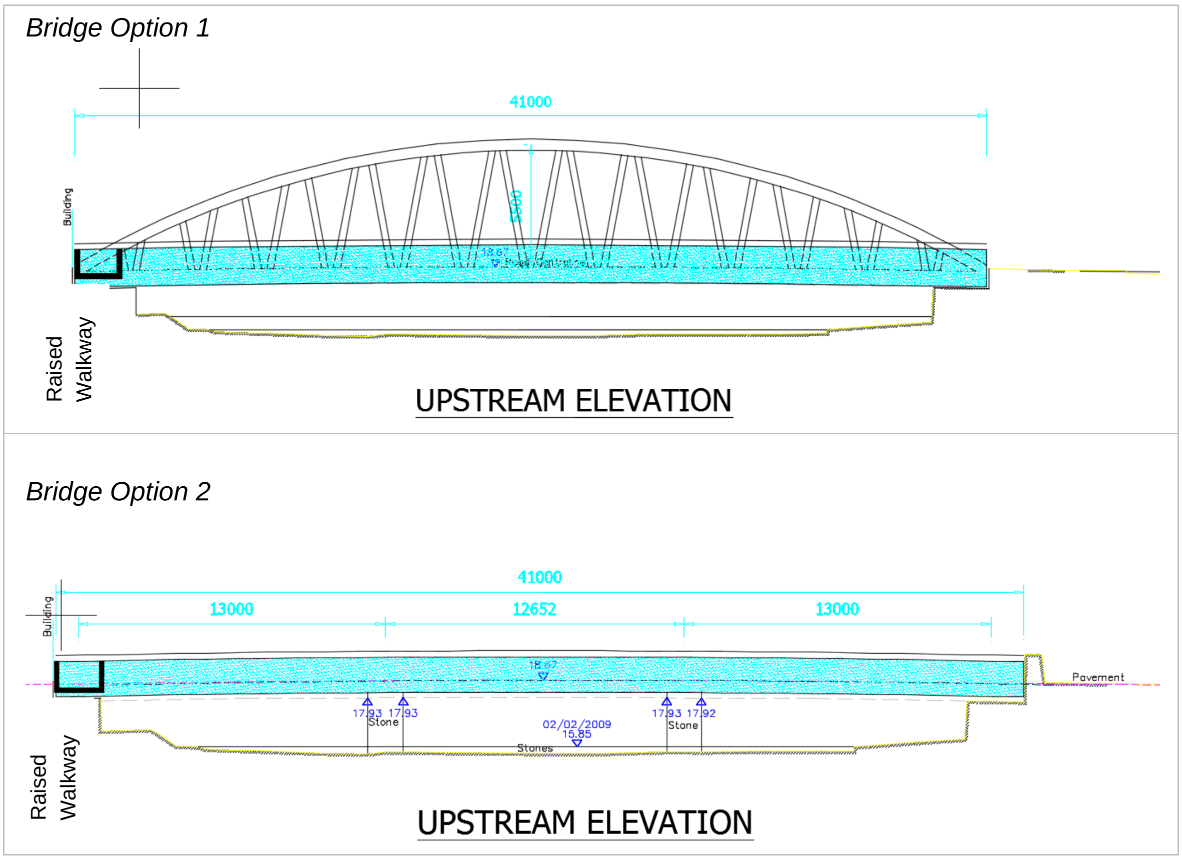

Figure 8-1. Replacement Bridge Design Options

8.1.1 Model uncertainty and limitations

The model assumes that the bridge options shall be constructed as specified in the design drawings, with key parameters, such as soffit and pier geometry as labelled. The degree of model uncertainty is similar to the representation of the Jack Garret Bridge in the baseline model. It should be noted that the model representation of the existing Jack Garret Bridge has been calibrated to flood event data.

8.2 Flood Containment

Flood containment using raised defences has been simulated by raising and filling gaps in existing walls and by adding new defence walls up and downstream of the bridge to protect local properties from flooding. The proposed standard of protection is set at the 1% AEP and this scenario enables the corresponding defence height to be determined. It also provides an indication of the magnitude of any up and downstream impacts that might result from installing this scheme.

Figure 8-3 shows the location of the proposed and existing modelled defences and walls. Of these, the existing walls will need to be assessed and possibly re-built as flood defence standard walls/ embankments. Flood containment using a combination of embankments and walls offers the potential to reduce flood risk in Crossmolina and is the primary solution suggested in the OPW feasibility report. However, the benefits of walls alone are limited due to the 1% AEP flood event overtopping the bridge deck level, causing flooding on Bridge Street when containment measures are in place.

To provide a 1% AEP standard of protection, the parapet of the bridge would need to be incorporated into the defence design and would need to be raised above the 1% AEP maximum stage, with an additional allowance for freeboard.

As discussed above (refer Section 8.1), a bridge replacement is considered in combination with the containment option. Replacement of the bridge will help reduce the required height of walls / defences. The tables below present the outputs at selected locations for bridge option 1, including for a solid bridge parapet.

The 1% AEP flood level at the bridge is 19.475mOD. To protect to the 1% AEP present day standard the bridge parapet will need to be at 19.855mOD (including 0.38m freeboard). Compared to a bridge deck level of 18.67mOD, this is a 1.19m solid parapet wall. To offer protection to the 1% AEP MRFS standard the crest of the bridge parapet will need to be 20.336mOD (1.67m high).

A longitudinal profile of model results is presented in Figure 8-2. The assessment of bridge option 2 is included in the long plot for comparison. This demonstrates that there would be an upstream impact of increasing the standard of protection to Crossmolina, as a result of backing up at the bridge at the new parapet, but that downstream water levels would reduce during a 1% AEP event. Full results are included in Appendix B.

Table 8-1. Model outputs for flood containment option with bridge option 1 including solid parapet

Location	Model Node	1% AEP Max Stage	1% AEP MRFS Max Stage
Upstream property on Chapel Road	34DEEL01185	20.47	20.94
Adjacent to car park on left bank	DEEL_10808	19.53	20.02
Bridge (upstream face)	**DEEL_10722D**	**19.48**	**19.96**
Just downstream of Centra	DEEL_10594	18.19	18.92
Downstream of town	34DEEL01071	18.19	18.42

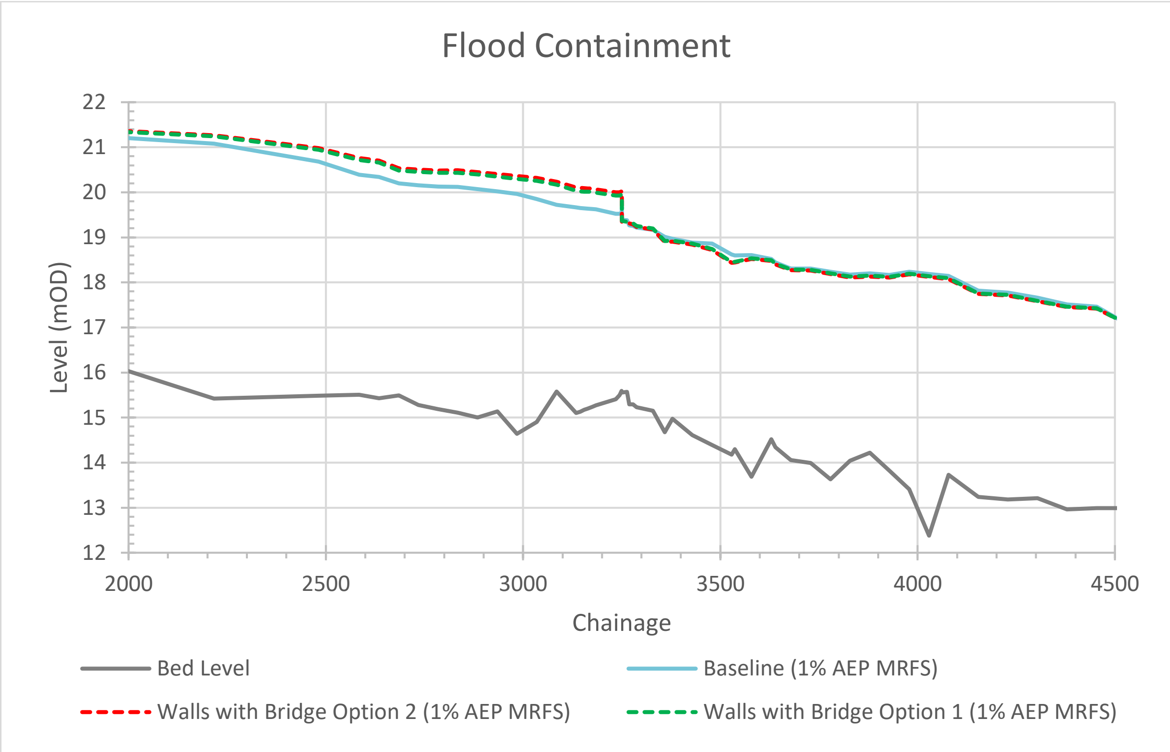

Figure 8-2. Long section plot of water levels (1% AEP MRFS) flood containment with both bridge options

Figure 8-3 shows the location of the modelled defences in relation to the resulting change in 1% AEP flood outline; all defended properties are protected and there is no major increase in the flood extent elsewhere in the town. Figure 8-4 shows the modelled flood extent from the River Deel for the undefended and defended scenarios.

The defended option has also been tested against climate change scenarios to allow the potential increase in water level under future conditions to be examined.

The flood containment solution can offer a precautionary or adaptive approach to protection against future climate change flood risk, but wall crest heights may be visually unacceptable. The adaptive approach would ensure that flood defence crest heights can be raised on the defence foundations to be constructed for the current crest height, or be adapted at minimal future cost and disturbance.

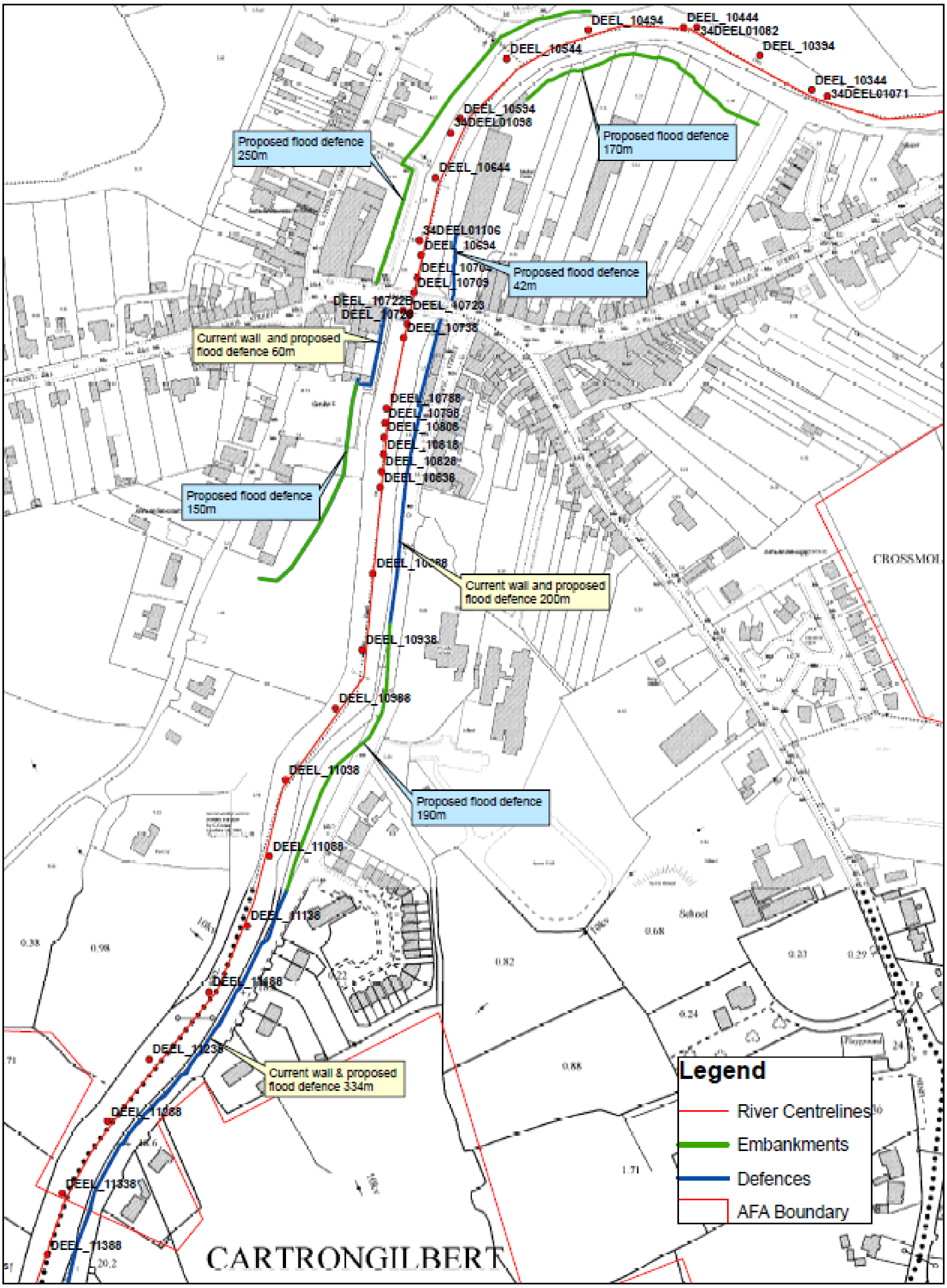

Figure 8-3. Plan of walls and embankment locations for flood containment option

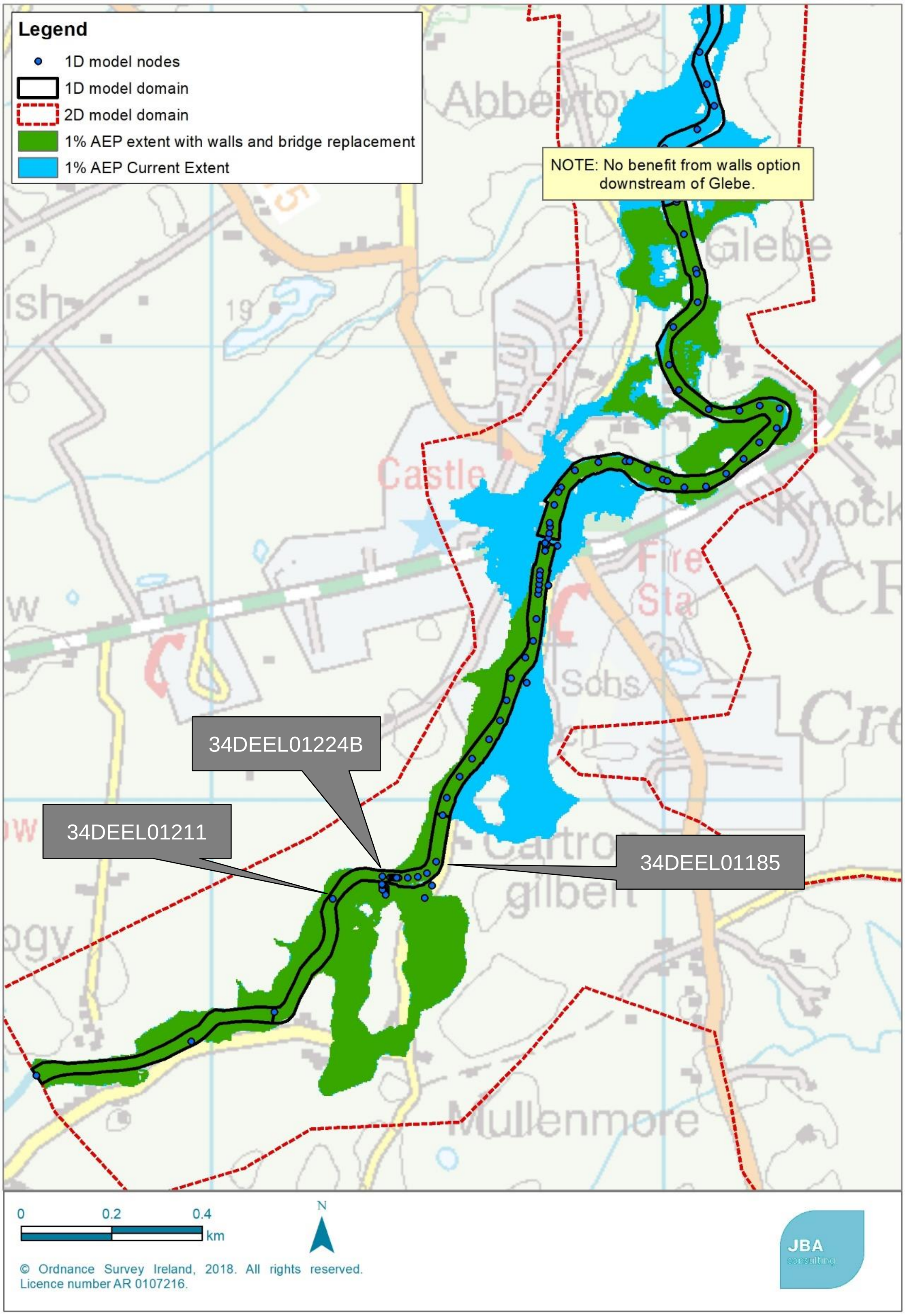

Figure 8-4. Potential area benefiting from defences with 1% AEP design standard

8.2.1 Model uncertainty and limitations

This option model assumes the alignment of flood defence walls would be as presented in Figure 8-3. The model representation uses "glass walls" along this defence alignment to determine the water level profile along the River Deel. The height of flood defences would be this modelled peak water level plus an appropriate freeboard allowance. This glass wall approach removes the need to make assumptions on appropriate wall crests and freeboard.

The model assumes that no water can seep under or through the walls, and that surface water runoff discharges freely without causing pluvial flooding behind flood defences.

Should a wall option wish to proceed, more refined modelling of the actual proposed wall crest levels would be carried out to confirm the scheme can operate as intended.

If a wall option is preferred, but under conditions of a maximum wall height, then this could be represented in a model to understand the standard of protection of specified wall crest heights. This would be an alternative to the 1% AEP design standard.

8.3 Dredging

Four dredge options have been tested (DRG1, DRG2, DRG3 and DRG4) over increasing lengths of river reach. Figure 8-5 shows the extent of these dredge options. Dredge 2 covering the extent of Dredge 1 and 2, Dredge 3 covering the extent of Dredge 1, 2 and 3, and Dredge 4 covering the full extent shown. The results of the dredge options have been provided in Appendix C. Downstream of Crossmolina town water levels are sensitive to the downstream lough level boundary. However, there is no impact in the town.

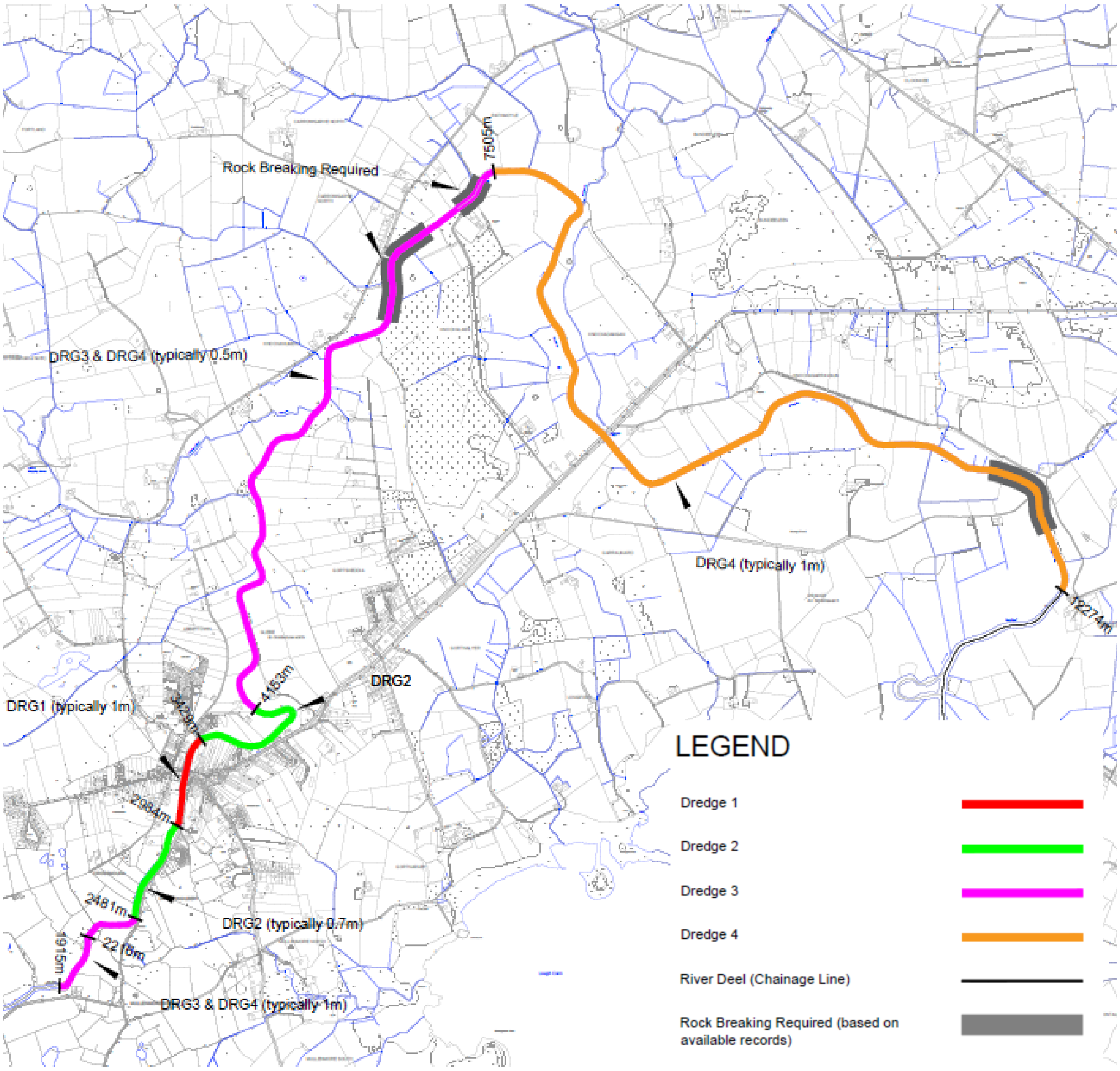

Figure 8-5: Dredge Option

Whilst the option of dredging will provide a reduction in flood levels, extensive dredging would be required to provide an adequate standard of protection.

For all dredge scenarios supplementary measures such as localised flood defence walls and/or filling in of existing gaps in walls will be required. Dredging will also require ongoing maintenance to ensure conveyance capacity is maintained over time, and such maintenance should be informed by hydromporphological assessment of catchment processes. The extensive dredge options would result in significant catchment change beyond the existing Arterial Drainage Scheme. Such extreme measures are unlikely to be acceptable environmental options as they will significantly alter river channel form and process.

Table 8-2 presents the predicted 1% AEP flood level for each dredge option at key model nodes. These results are taken from the simulation with a high downstream lake level (max recorded of 11.6mOD based on December 2015 event). This shows that dredging does not provide a standalone option to resolve the flooding issues in Crossmolina. During a 1% AEP event flow backs up at the Jack Garrett Bridge causing water to flow out of bank upstream of the bridge.

These model scenarios represent extensive and extreme dredging, which have practical limitations, including the structural integrity of the bridge and the presence of the sewer pipe below the bed downstream of the bridge.

A long plot of the results is presented in Figure 8-6.

Table 8-2. Dredge Option - 1% AEP Max Stage (mOD) at key nodes

Location	Model Node	Baseline	DRG1	DRG2	DRG3	DRG4
Upstream property on Chapel Road	34DEEL01185	20.36	20.28	19.74	19.40	19.38
Adjacent to car park on left bank	DEEL_10808	19.38	19.14	18.91	18.55	18.49
Bridge (upstream face)	**DEEL_10722D**	**19.38**	**19.14**	**18.91**	**18.56**	**18.50**
Just downstream of Centra	DEEL_10594	18.75	18.70	18.48	18.11	18.08
Downstream of town	34DEEL01071	18.22	18.21	18.05	17.68	17.59

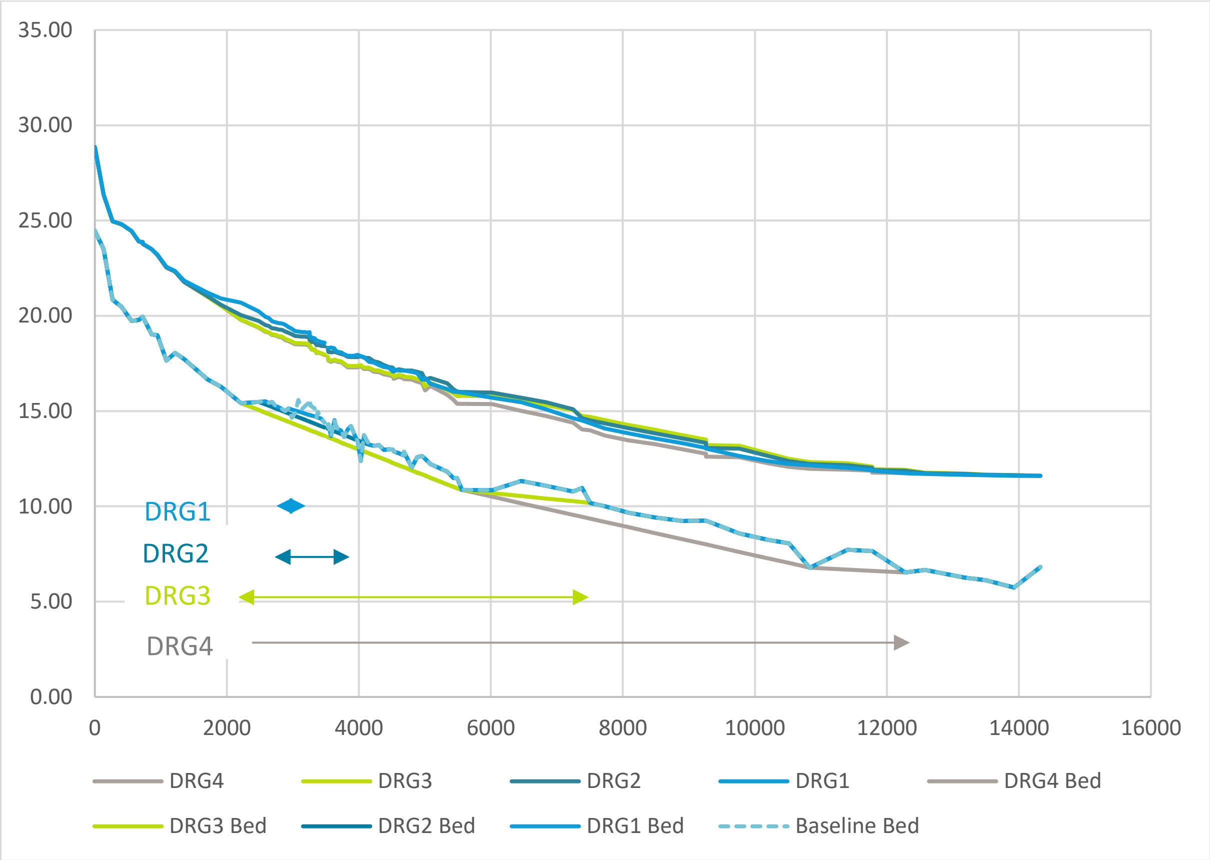

Figure 8-6. Dredge Option - long plot of results

8.3.1 Model uncertainty and limitations

The representation of dredge options in the model is based upon an assumed channel cross section profile through the dredged reach. The cross section shape in places has near vertical banks as a simplification of the final design which will need more gradual bank slopes. As such, the modelled options are likely to have a greater channel capacity than an actual dredged channel. The impact on conveyance may be less critical as channel slope and roughness also influence flow rate.

The dredging model does not take account of any additional bank or scour protection that may be required to ensure the stability of structures and river banks. Cross section roughness values in the dredging options are the same as the baseline model.

8.4 Diversion Channel

The following outlines the model development as well as providing a summary of the simulation results for the diversion channel option.

8.4.1 Option overview

The diversion option is illustrated in Figure 8-7 below. It involves the diversion of river flow upstream of the town, by allowing higher flows to overflow into an intake structure and divert along a new bypass channel, reducing the pass-forward flow in the river during extreme events and hence preventing flooding downstream in the town.

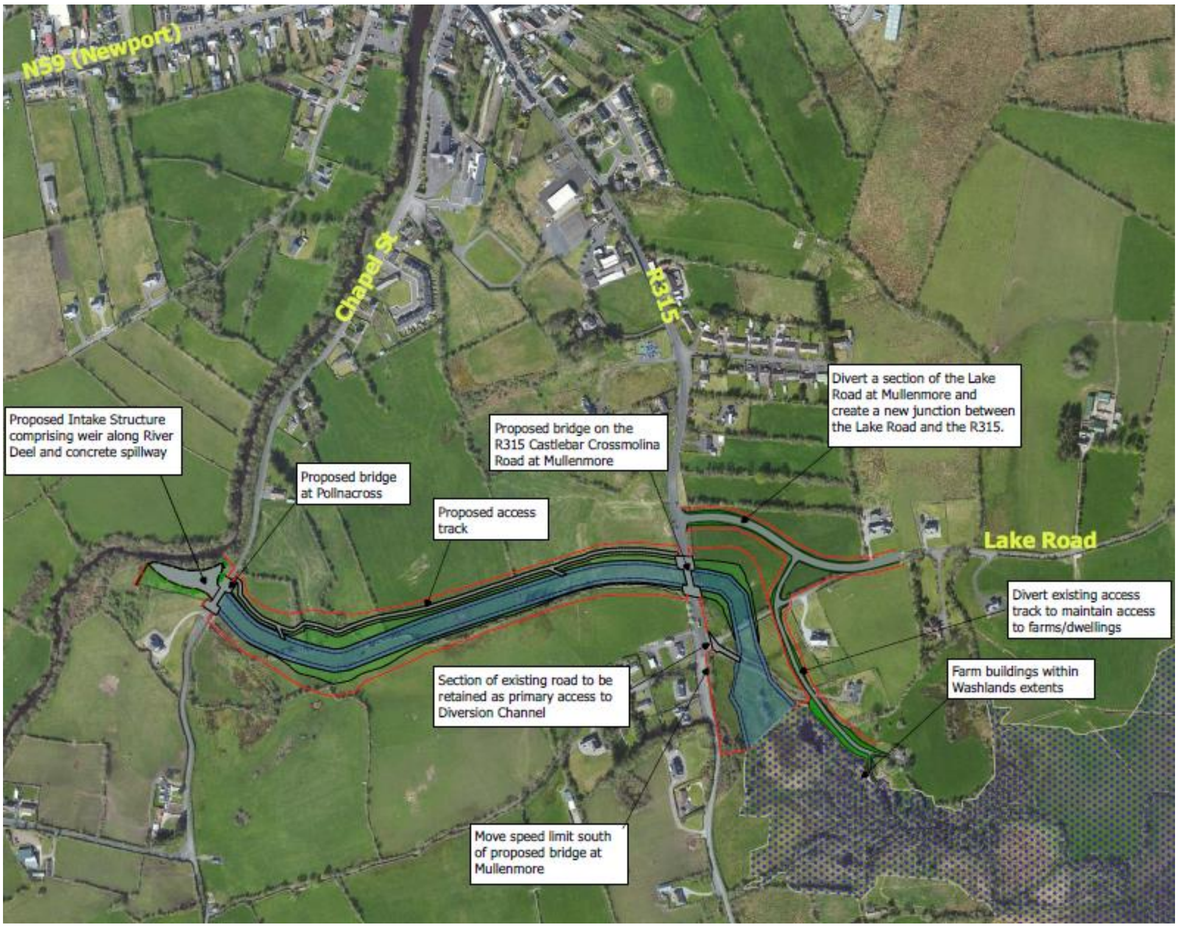

Figure 8-7: Diversion Option

8.4.2 Model development

Initial assessment of the diversion channel was completed in 1D, to optimise the intake spillway arrangement, mainly the design crest level and spillway length.

Detailed modelling of the inlet structure and diversion channel has been carried out separate to JBA modelling and is included as Appendix F - Diversion Channel Model Report.

9 Preferred option model results

Refer to Appendix F - Diversion Channel Model Report for details of the preferred option modelling.

Benefitting lands maps have been derived for the 1% AEP event using the baseline model and the outflow hydrograph from the diversion channel detailed model.

Figure 9-1 presents the maximum water level profile for the baseline and post scheme 1% AEP scenario. The peak water level exceeds the soffit of the Jack Garrett Bridge, but this does not result in any flooding of property or roads.

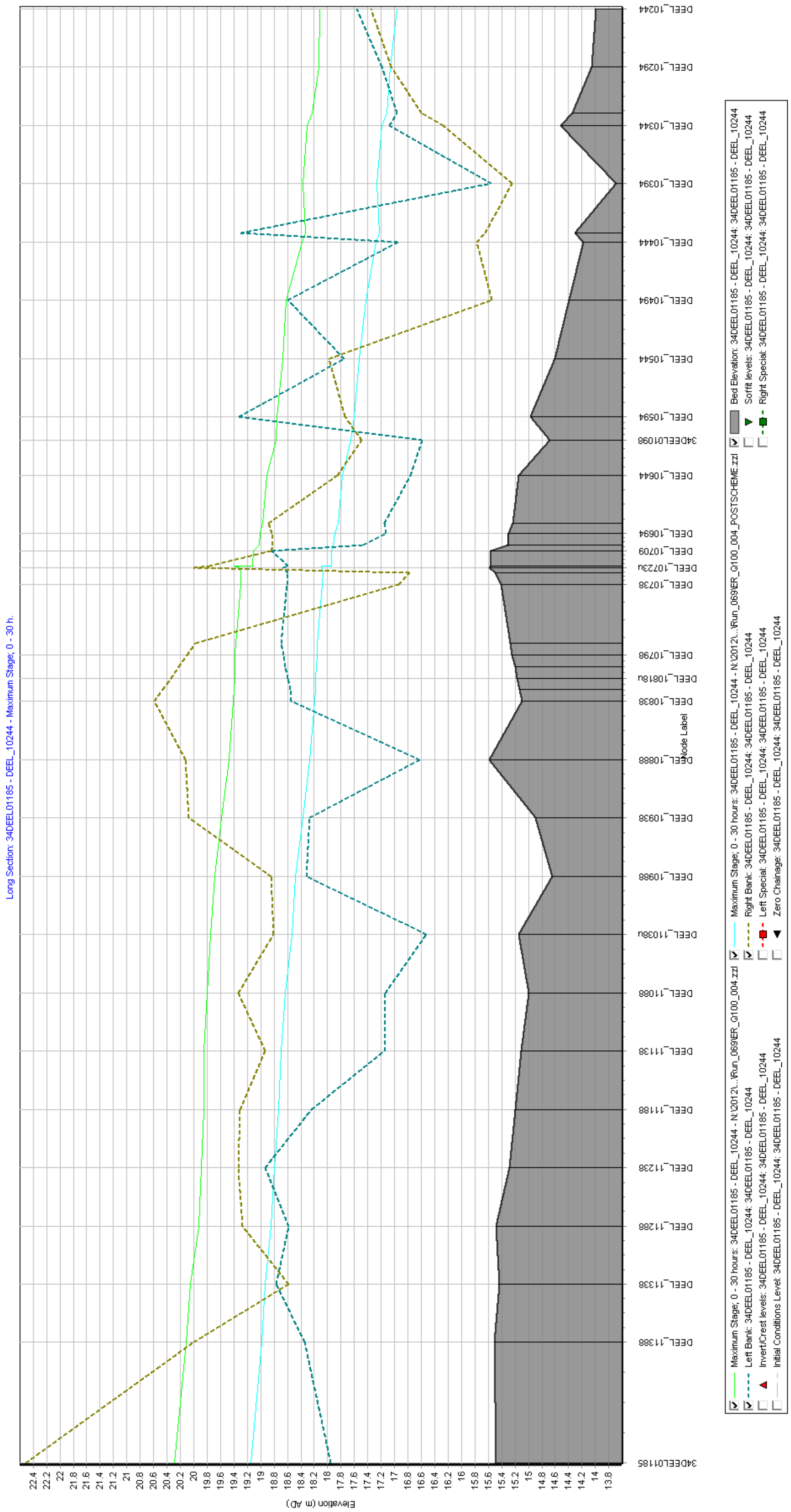

Figure 9-1. Long profile of the baseline and final diversion channel model

10 Sensitivity and Freeboard Analysis

Freeboard is a factor of safety usually expressed in height above a flood level for purposes of flood risk management. Freeboard is typically applied to compensate for the many unknown factors that could contribute to flood heights greater than the height calculated for a selected size flood, such as uncertainty of the effect of bridges, hydrological uncertainty, uncertainty in model roughness etc.

The OPW typically apply a Freeboard of 0.3m for hard defences and 0.5m for soft defences, and whilst this is appropriate in many situations, there are instances where a higher freeboard should be allowed. A specific freeboard allowance has been calculated for this scheme as follows.

$$F_B = \sqrt{\sum A_1^{\ 2} + A_2^{\ 2} + A_3^{\ 2} + A_4^{\ 2}}$$

Where:

FB is the Freeboard Allowance in meters;

A1 to A4 is the uncertainty in water level estimates for each input type.

Table 10-1 presents the input parameters with a brief description and the values used in the freeboard allowance calculation for Crossmolina, in terms of the freeboard of flood defences or resulting flood water levels in flood risk areas. The uncertainty levels were based on the sensitivity testing undertaken throughout the model development.

Table 10-1. Input parameters for freeboard calculation

Parameter	Type	Description	Freeboard allowance for post-scheme flood levels	Freeboard allowance for structures and channel as part of Diversion Channel Option
A1	Design allowance – settlement etc.	0 for hard defences such as walls 0.3 for soft defences such as embankments Taken as 0 for the diversion channel based on agreement with Ryan Hanley	0	0
A2	Roughness	An increase (10%) in roughness values based on reasonable data range	0.28	0.13
A3	Jack Garret Bridge	No significant afflux; bridge soffit above flood level. Impact of constriction in channel due to construction of single span bridge, built into design levels		-
A4	Hydrology / Flow	Using 0.5% AEP results as a test the impact of circa 10% increase in river flow	0.26	0.34
Freeboard Allowance (m)			0.380	0.360

Based on the analysis detailed above, a freeboard allowance of at least 0.380m below design flood levels is recommended for option design. Refer to Appendix F - Diversion Channel Model Report for details on the recommended freeboard allowance for structures along the diversion channel, the intake structure and the channel itself.

Appendices

Appendix A - OPW flood flow estimates at Ballycarroon

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RE: Crossmolina FRS - 34007 Ballycarroon – Executive Summary

In 1939, just a few kilometres upstream of Crossmolina Town, Hydrometric Station 34007 was installed on the Deel at Ballycarroon. The accompanying Memo… "*2016-11-22 - TJ - Station 34007 Ballycarroon - Flow Measurements & Rating Curves*" deals with developing the Flow Ratings needed to produce estimates of peak flow from the station's 64 years of Annual Maxima.

Big floods on the Deel result from high intensity rainstorms that, by nature, are of medium to short duration and quite localised. Usually, its short-lived floods have already passed through by the time a Hydrometric Team can reach the river. Despite this difficulty, in the first twelve years, six measurements were taken that ranged up to 41.34 m^3/s (January 1952). Since that, no flow greater than 27 m^3/s was measured until the recent flooding in Crossmolina Town gave a high priority to Ballycarroon station; this has provided 18 between 21.25 and 102.6 m^3/s. The resulting improved Flow Rating estimates the December 2015 peak flow to be 178.2 m^3/s. However, a comparison between the old and new ratings shows that, for a given level, the river is now running 15% less efficiently than it did half a century ago. This implies a significant change in control.

Memo… "*2016-11-22 - TJ - Station 34007 Ballycarroon - Annual Maxima & Return Period Analysis*" reports on the steps needed to produce estimates of Return Period flood flows. The lack of flood flow measurements in the middle period of the record makes it difficult to find out when the river lost its efficiency, and whether it happened abruptly or gradually transitioned over many years. The primary problem with peak-flow estimates relates to quantifying the uncertainty of those from the middle time period. This is dealt with by investigating five time-ranges and seeing the degree to which they impact the estimation of return period floods. For each chosen middle period, Annual Maxima estimates are taken to be the sliding-average of the peak flow estimate from the Old Rating and the Recent one. The five time-ranges are:

- Scenario 1 – 1963 to 1981, inclusive – Probably its greatest extent
- Scenario 2 – 1963 to 1985, inclusive – An unlikely greatest extent
- Scenario 3 – 1972 to 1981, inclusive – A likely extent
- Scenario 4 – 1975 to 1981, inclusive – The most likely extent
- Scenario 5 – 1972 to 1985, inclusive – Absolutely, its least extent

In all scenarios, the largest flood (December 2015) is 25% bigger than the second largest (October 1989), however, the third (October 1961) and fourth largest are not even 5% smaller than that one. This indicates that either the biggest flood is a truly extreme event trapped by a 64-year record or the record has not yet managed to trap enough very large events.

In statistical hydrology, the length of the flood record heavily influences the plotting positions of the biggest floods and as different estimation methods use different paradigms they produce significantly different plotting values. The impacts on return period flood estimates have been looked at by employing four different methods of estimation, namely, Gringorten, Cunnane, Median and Weibull: these are the most widely used Internationally. For each methodology, Return Period peak estimates from the five time-range scenarios only vary by between ±1 to 2m^3/s; that's less than ±1%. This means that the uncertain duration of the middle time period (caused by the lack of flood flow measurements) is not particularly significant. As the variation is small in every case and as results from Scenario 3 (the 1972 to 1981 middle period) are close to the mean, it is preferred.

The choice of method (Gringorten, Cunnane, Median and Weibull), however, does impact return period peak flow estimation. While Weibull consistently produces the biggest values, in each of the five time scenarios, they are not even 3% greater than the average of the other three methods. It also consistently provides the best 'fit' to the data; that means that its results are less impacted by how it handles the extreme floods.

An isolated extreme event along with such a large flood-gap (25%) down to the next three near-identical floods, of necessity, poses a major problem for statistical hydrology. The unreasonable level of influence that these hold on the estimation of Return Period peak flows has been looked at in two ways:

- ❖ Leaving out the three biggest events when fitting a line-of-best-fit through the Annual Maxima found that the other three methods then gave answers equivalent to the original Weibull results from the full record.
- ❖ The size-gap between the two biggest floods may mean that the record has not yet managed to trap enough very large floods. It has been assumed that an extreme flood will occur in the near future that would then be the second biggest in the record. Return Period estimates from the other three methods are then within about ±¼% of the present-day, full record Weibull answers.

These investigations confirm that the main source of difference between the methods relates to how they take the length of the flood record into account when assigning plotting positions to the biggest floods. When this influence is neutralised answers tend to present-day, full record Weibull results. Also, as Scenario 3 data is consistently the Median (with very little variation about it), the Weibull Scenario 3 estimates can be recommended (see table). This also considers the 178.2 m^3/s December 2015 flood to be an 85-year event and the 142.62 m^3/s October 1989 a 20-year.

Return Period Peak Flows

Return Period (Years)	Peak Flow (m^3/s)	Standard Error	84% Interval (m^3/s)
2	78.64	3.58	82.23
5	106.34	6.05	112.39
10	124.68	8.18	132.86
25	148.84	11.03	159.86
50	165.54	13.20	178.73
100	182.36	15.37	197.73
200	199.24	17.56	216.79
250	204.68	18.26	222.94
500	221.59	20.45	242.05
1,000	238.52	22.65	261.17

Tim Joyce, Design Section, Chartered Engineer, 19/12/ 2016

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RE: Crossmolina FRS - 34007 Ballycarroon - Annual Maxima & Return Period Analysis

1. Introduction

The Memo… "*2016-11-22 - TJ - Station 34007 Ballycarroon - Flow Measurements & Rating Curves*" has dealt with developing the Flow Ratings needed to produce estimates of peak flow from the 64 years of Annual Maxima recorded at the station while this Memo… "*2016-11-22 - TJ - Station 34007 Ballycarroon - Annual Maxima & Return Period Analysis*" reports on the considerations involved and the necessary steps to produce estimates of Return Period peak flows.

It has been found that the well-rated earliest period of the record and the most recent one require different flow ratings. These show that the river now delivers 15% less flow for a given flood level.

The lack of flood measurements makes it difficult to find out when the river lost its efficiency, and if it happened abruptly or gradually transitioned over many years; it definitely started after 1963 (most probably after 1972, perhaps as late as 1975) and likely ended before 1982 (perhaps as late as 1985). This uncertainty is being dealt with by investigating five time-ranges and seeing the degree to which they impact the estimation of return period floods. For each chosen middle period, Annual Maxima estimates are taken to be the sliding-average of the peak flow estimate from the Old Rating and the Recent one. The five time-ranges are:

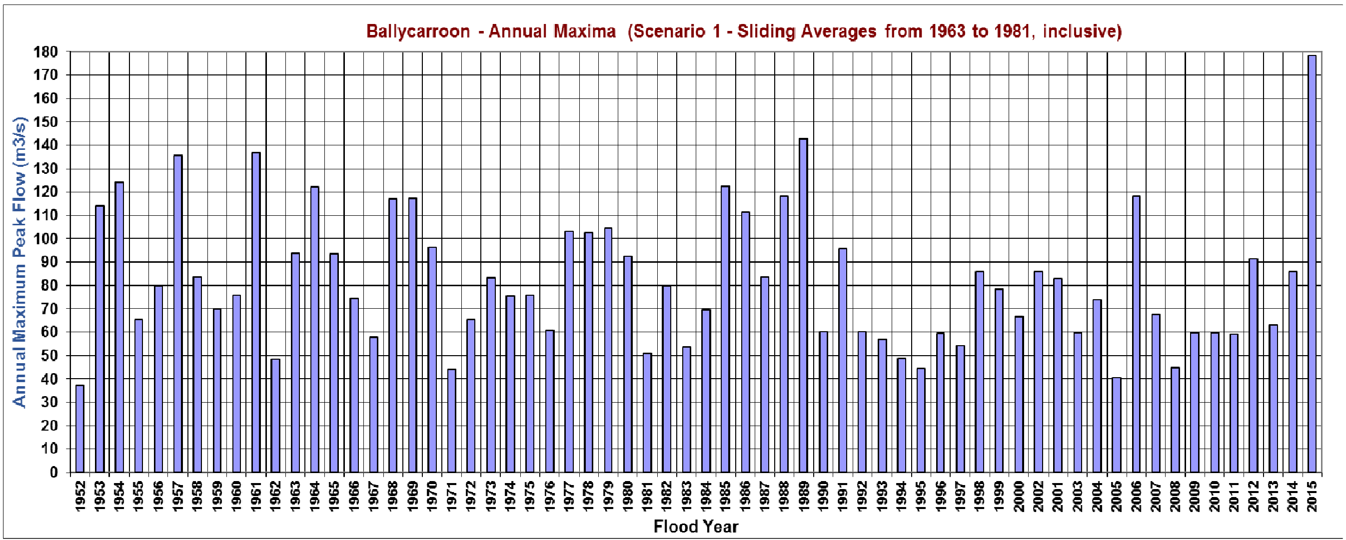
- Scenario 1 – 1963 to 1981, inclusive – Probably its greatest extent
- Scenario 2 – 1963 to 1985, inclusive – An unlikely greatest extent
- Scenario 3 – 1972 to 1981, inclusive – A likely extent
- Scenario 4 – 1975 to 1981, inclusive – The most likely extent
- Scenario 5 – 1972 to 1985, inclusive – Absolutely, its least extent

In all scenarios, the largest flood (December 2015) is 25% bigger than the second largest (October 1989), however, the third (October 1961) and fourth largest are not even 5% smaller than that one. This indicates that either the biggest flood is a truly extreme event trapped by a 64-year record or the record has not yet managed to trap enough very large events. This type of character amongst the largest floods can cause an unreasonable level of influence on the estimation of Return Period peak flows. This is being countered in three ways, by:

- Employing four different methods of estimating the Extreme Value plotting positions, namely, Gringorten, Cunnane, Median and Weibull: these are the most widely used Internationally. While Weibull consistently gives the best fit to these Annual Maxima, all four results are presented for each scenario.
- Leaving out the three biggest floods when fitting the line-of-best-fit through the Annual Maxima and seeing how this changes their return period estimate.
- Considering that another extreme flood will occur in the near future and looking at the effect this has on the estimation of the return period floods.

2. General Observations on the Annual Maxima at Ballycarroon

It may be seen from the chronological-graph of the Scenario 1 Annual Maxima (see Appendix A) that even though the less efficient Recent Rating is let influence (to a diminishing degree) all the way back to 1963, the flow regime has been noticeably mild since 1990. In fact, until the massive 178.2 m^3/s flood in December 2015, only two Annual Maxima from the 25 years make it into the top twenty; the December 2006 is just the eight biggest, while the September 1992 flood is the eighteenth. So, by 2014, the river was overdue a large flood and, even now, it still looks like the laws of probability are recommending more. This point may be supported by recognising that the 3rd, 4th and 5th largest floods come from the first eleven years of record (up to 1963). In this recent era of extreme weather, further severe floods would seem inevitable.



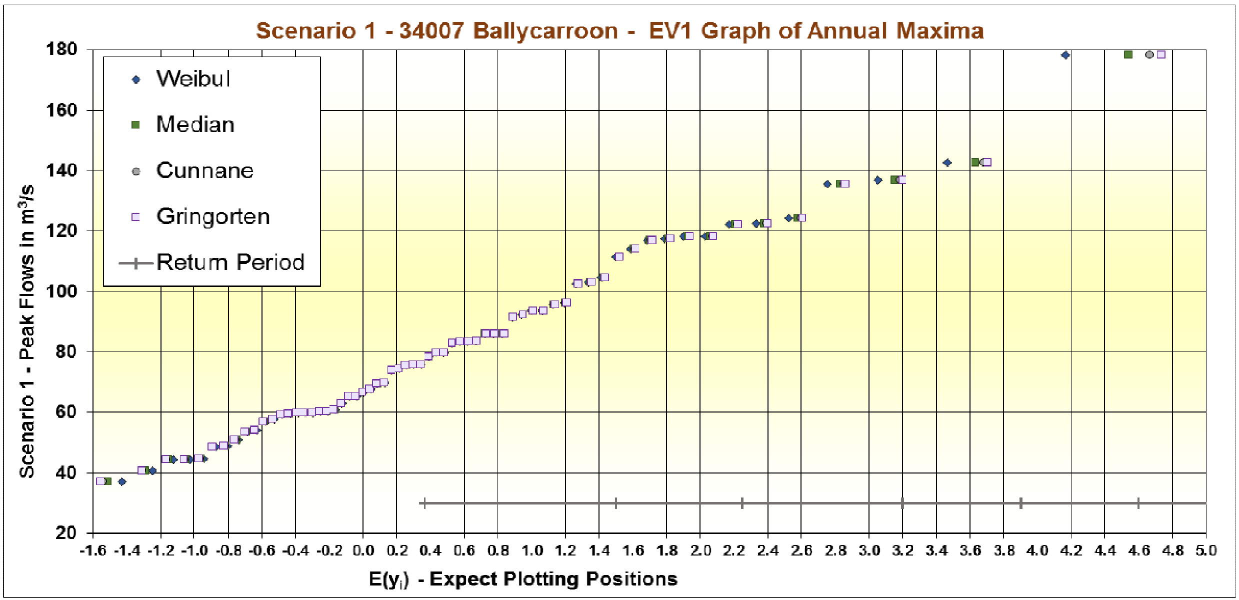
3. The four sets of plotting positions Applied to the Annual Maxima

Annual Maxima form a list of peak flows, however, there isn't a corresponding coordinate that tells of their return period. To provide an Expected Plotting Position for each maximum (that implies its return period), Hydrology appeals to statistical distributions; like the Extreme Value (EV) preferred in these islands.

A range of methods can be used to estimate Expected Plotting Positions. Amongst other things, these rely on the length of the flood record and, as they handle it differently, an unwitting bias can be brought into the estimates for the three (or so) largest floods: not surprisingly, this is most pronounced for the biggest flood and, unfortunately, that automatically defines the first estimate of its return period. Even before any analysis is carried out, Gringorten implies that the December 2015 flood is a 115-year event, Cunnane sees it as a 107-year, the Median gives it 95 years and the Weibull considers it a 65 year: a significant range that must affect the outcome of the full set of return period floods.

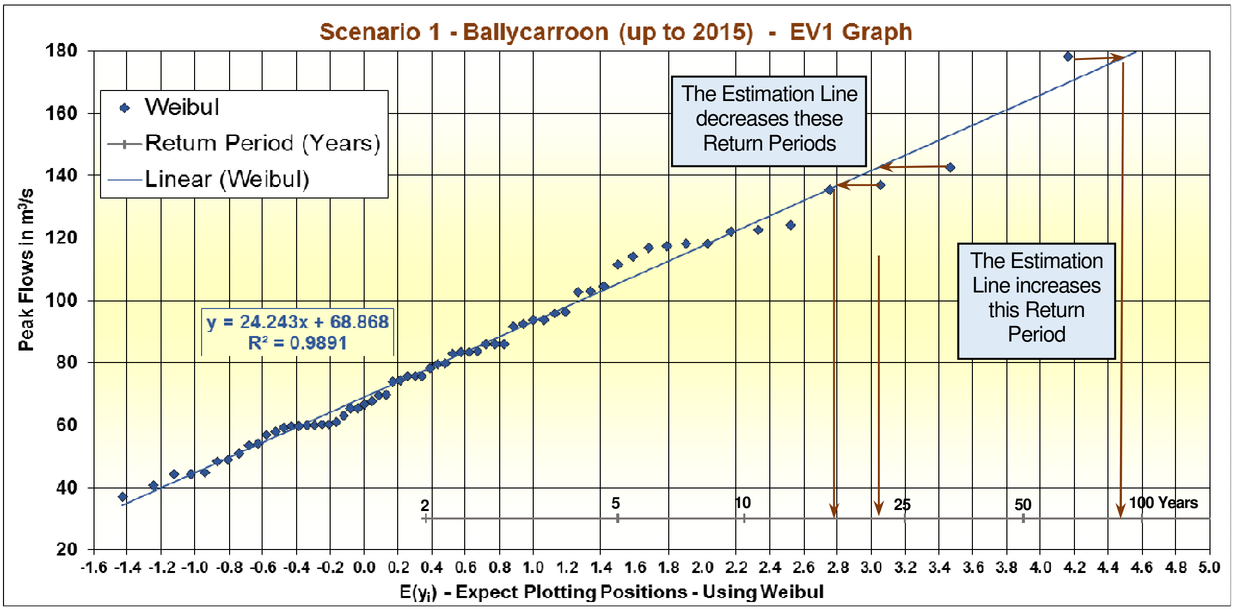
For the Extreme Value Type I (EVI), Scenario 3 floods are displayed below against each of the four sets of plotting positions. It may be seen that the three (to six) largest are dragged to the right by their plotting position. The resulting curve in the data stresses the fundamental EVI rule, namely, that the data follow a straight line pattern; this issue is considered further in Section **6**.

This effect supports the idea that the record is somewhat deficient in big floods: as indicated by the post 1990 record. In three data sets, the graph shows that the biggest flood will help push an estimation line to the right-hand-side; only the low-value of the Weibull plotting position for this flood counters the tendency.



4. Return Period for the 2015 Flood and the 100-Year Peak Flow Estimate

As Weibull gives the best 'fit' to the data throughout the five scenarios; its Scenario 1 graph is presented below. Its Estimation Line increases the Return Period of the 178.2 m^3/s December 2015 flood from the 65 years implied by its plotting position to 91, however, it decreases that of the October 1989 (from 32 to 21) and October 1961 (from 22 to 17). A record that contains a 91, 22 and 17-year events seems short of big floods. The other methods similarly decrease the Return Period of the 1981 and 1961 floods.



As discussed, the assigned plotting positions estimate that the December 2015 flood is a 115, 107, 95 and 65-year event. The EVI analysis applied to the Annual Maxima from each of the five time-scenarios produces the results in the following table. This sees return period estimates drift downwards until, in Scenario 5, they are 105, 102, 97 and 83-year; about 10 years less.

However, right across the five time scenarios, the 2015 return period estimates remain close to the value implicitly assigned to it by the plotting position of the four methods (based on its rule that takes into account the length of record).

Estimated Return Period of the September 2015 Flood					
	Plotting Position Estimating Method =>	Gringorten	Cunnane	Median	Weibull
	Return Period of the Plotting Position =>	115	107	95	65
Scenario	Range of Middle Period (incl.)	Return Period	Return Period	Return Period	Return Period
1	1963 to 1981	115	112	107	91
2	1963 to 1985	112	110	104	89
3	1972 to 1981	107	105	100	85
4	1975 to 1981	105	102	97	83
5	1972 to 1985	105	102	97	83

The 100-Year Return Period Flood at Ballycarroon				
Scenario	Gringorten	Cunnane	Median	Weibull
1	174.9	175.5	176.7	180.5
2	175.5	176.1	177.3	181.1
3	176.6	177.1	178.3	182.2
4	177.0	177.6	178.8	182.8
5	177.1	177.7	178.9	182.8

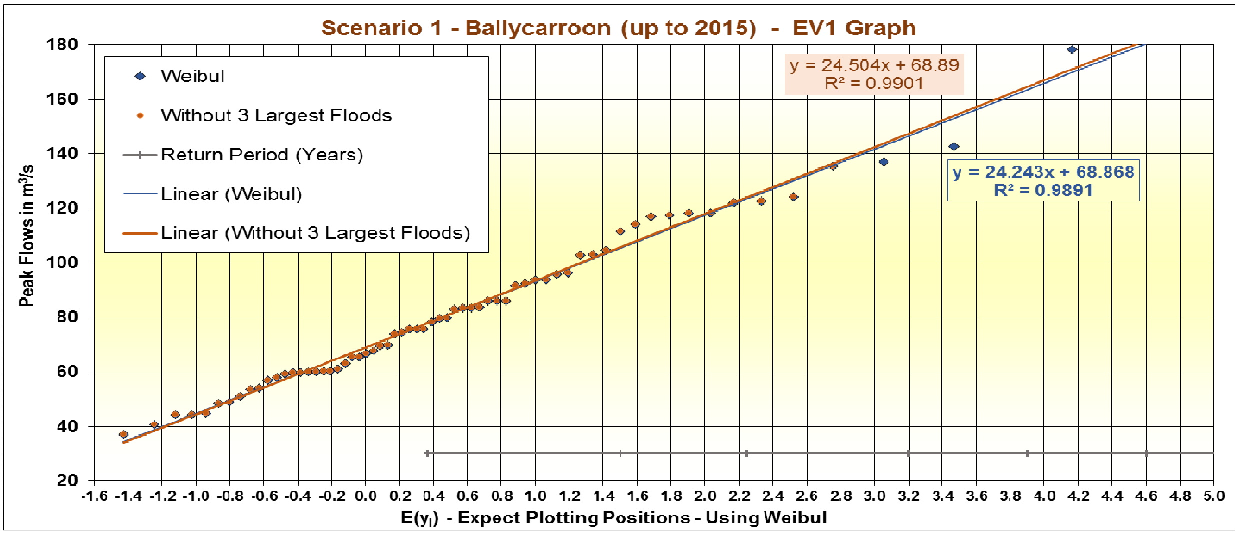
Using the first three methodologies, the above table shows that the estimates of the 100-Year Return Period Flood are remarkably close (they vary a little more than ±1% over the five scenarios). Due to its low return period for the 2015 flood, Weibull gives consistently higher results, however, in each scenario, they are not even 3% greater than the average of the other three methods.

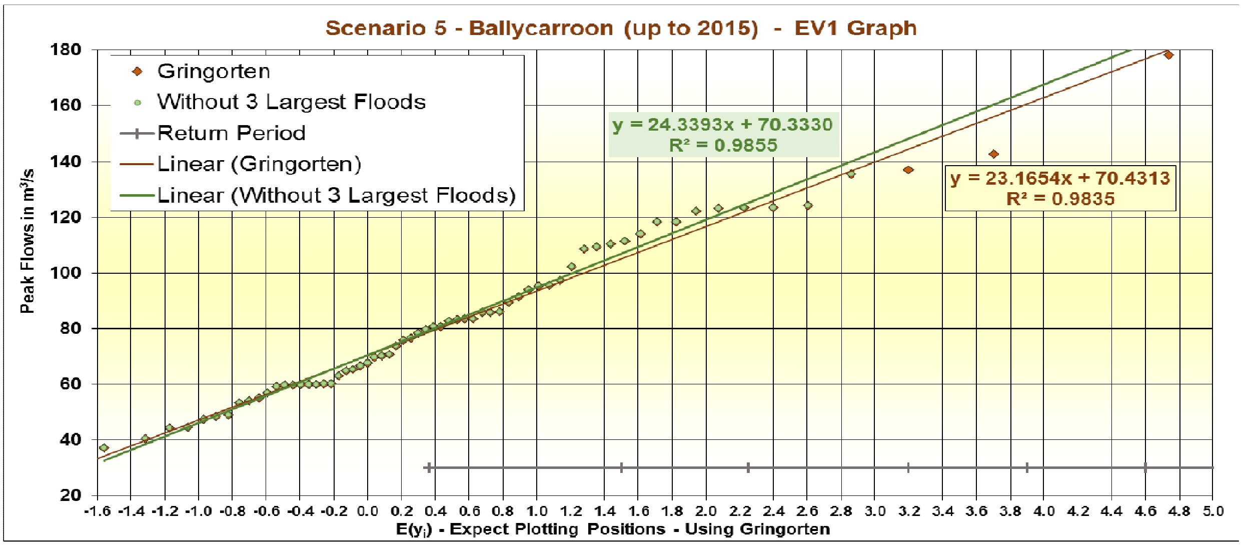
The good news is that the consequence of four methodologies applied to five different scenarios is a small range of 100-Year flood estimates. However, it still seems fair to conclude that, in flood records like Ballycarroon (where just one large flood has been trapped), it takes further investigation to arrive at a safer estimate of return periods and of the Design Flood for the Crossmolina FRS.

5. <u>Leaving out the Three Biggest Floods when fitting the line-of-best-fit</u>

Plotting positions are quite accurate for the general bulk of Annual Maxima; as there are both bigger and small floods to help define their probability of occurrence: for extreme events, the accuracy progressively drops off. The previous graphs show that, in particular, the three biggest floods are dragged to the right and that the resulting curve in the data comes close to breaking the straight line pattern needed for the EVI analysis. Leaving out these three when fitting the line-of-best-fit through the Annual Maxima will neutralise the impact of their plotting positions on return period flood estimation and improve accuracy.

As before, as Weibull gives the best 'fit' to the Annual Maxima throughout the five scenarios; its Scenario 1 graph is presented here; this also shows its original positioning of all the floods up to 2015. The difference is clearly not great; it only changes the December 2015 event's Return Period from 91 to 87-Year (its plotting position gave 65 years). For comparison purposes, the Gringorten Scenario 5 graph is also provided below; its estimate, which was 105, is now 84 years: a significant change. The table shows this pattern of reducing estimates for each of the four methods across the five time scenarios. In all cases, the December 2015 is now less than a 100 Year event and the range of estimates has narrowed.





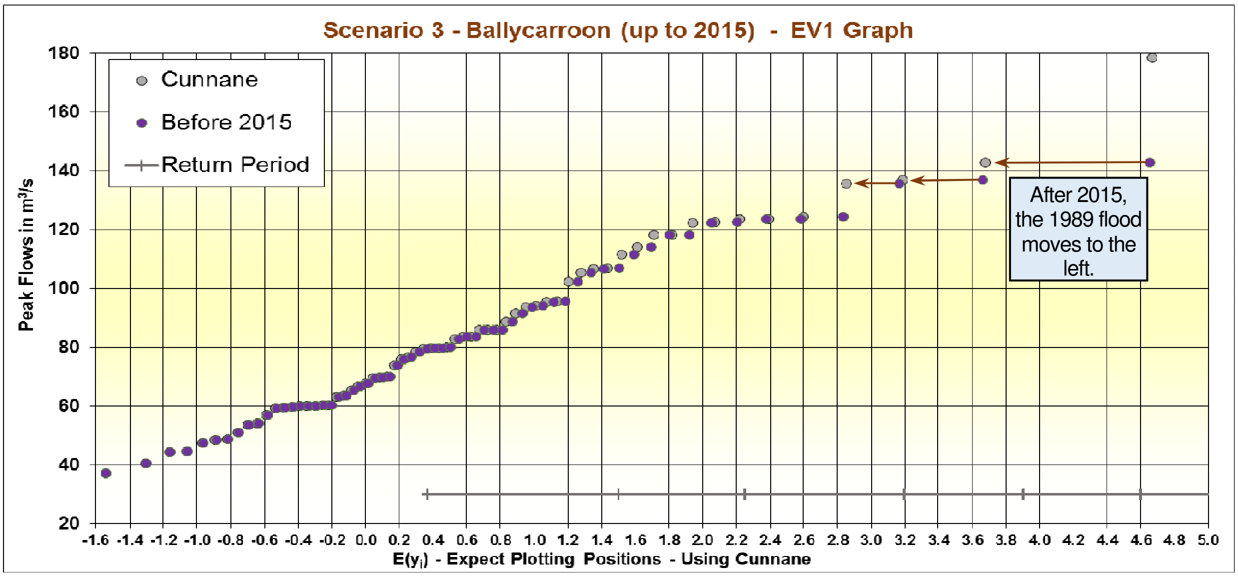
Estimated Return Period of the September 2015 Flood					
	Plotting Position Estimating Method =>	Gringorten	Cunnane	Median	Weibull
	Return Period of the Plotting Position =>	115	107	95	65
Scenario	Range of Middle Period (incl.)	Return Period	Return Period	Return Period	Return Period
1	1963 to 1981	98	97	94	87
2	1963 to 1985	94	93	91	83
3	1972 to 1981	88	87	84	78
4	1975 to 1981	85	84	82	75
5	1972 to 1985	84	83	81	75

The 100-Year Return Period Flood at Ballycarroon				
Scenario	Gringorten	Cunnane	Median	Weibull
1	178.8	179.1	179.7	182.0
2	179.8	180.1	180.7	182.9
3	181.6	181.9	182.5	184.7
4	182.4	182.7	183.3	185.5
5	182.5	182.8	183.4	185.7

The 100-Year flood estimates from the first three methodologies agree with each other to within about $\pm\frac{1}{4}$% and only vary about $\pm1\frac{1}{4}$% over the five scenarios. Also, these are now close to the original Weibull estimates (180.5 to 182.8 m^3/s). While Weibull still gives higher results, in each scenario, they are only $1\frac{1}{2}$% greater than the average from the other three methods. This coming-together of estimates is a result of being able to avoid the heavy influence of the length of the flood record on the three biggest floods and the resulting straightening of the data-curve; as the 100-Year flood estimates have gone up, risk has gone down.

6. The Case for Including Another Extreme Flood (2nd Largest)

The largest flood (December 2015) is 25% bigger than the second largest (October 1989), and the next two largest are not even 5% smaller than that one. Section **2** noticed that the flow regime has been mild since 1990 and, in Section **4**, Weibull gave its Scenario 1 estimate that the record just contains a 91, 22 and 17-year event. These may indicate either that the biggest flood is a truly extreme event trapped by a 64-year record that is causing a distortion in the analysis or that the record has not yet managed to trap enough very large events.



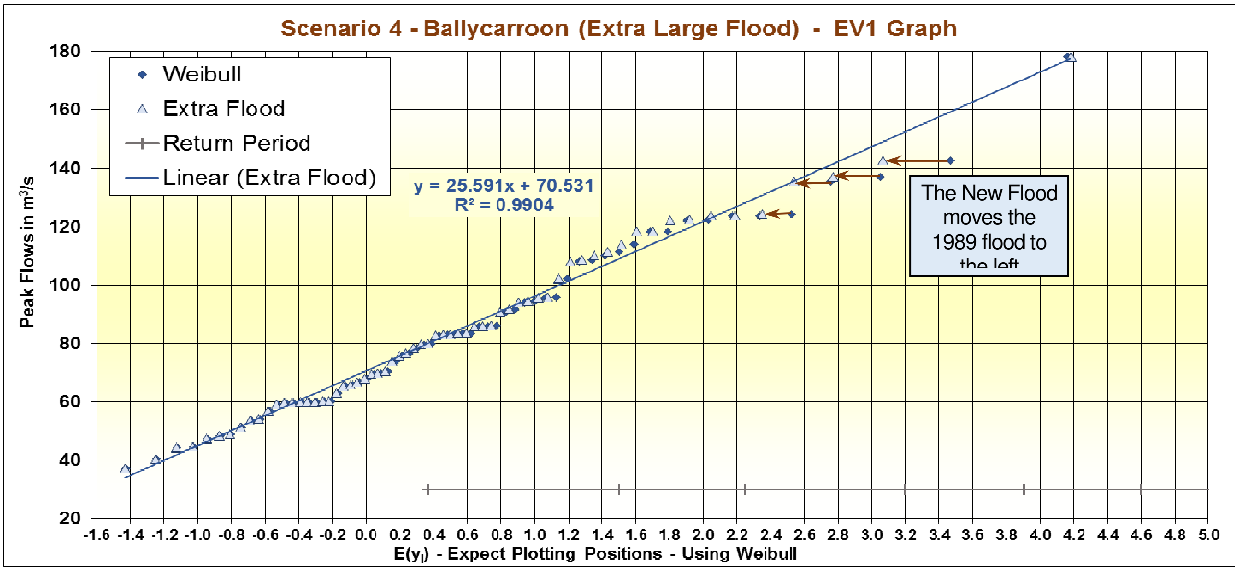
Both of these options can be explored by examining the record before the December 2015 flood had occurred. The Cunnane method applied to Scenario 3 is presented in the above figure along with the plot of the 63 years of Annual Maxima that preceded the December 2015 event shown as a separate flood-set. That earlier set shows a pronounced curvature; indicating a decelerating growth amongst the extreme events. This only happens either downstream of a very large impoundment (such as a lake or wide, flat floodplain) or because a record has not trapped enough large floods. The Deel does not have a large lake, it is a hilly catchment with minimal floodplains and, as such, can be expected to (and does) produce fast, high-peaked floods. As a minimum, catchments like the Deel are expected to produce a straight line plot (their data could curve upwards) and, as a result, previous studies concluded that the record simply had not trapped enough large floods and proceeded on that basis.

The figure also shows the impact of the December 2015 flood. It is worthwhile stating the obvious here, the biggest flood (1989) became the second biggest and was then paired with the second biggest Plotting Positions; that saw it move to the left from 4.65 to 3.68: a considerable shift. A similar, but progressively smaller, shift took place down the hierarchy of floods. This has reduced the curvature of the data set; however, as seen in Sections **4** and **5**, the 1989 and 1961 floods, and others, still lie to the right of any potential straight line.

These points put forward a case, that the impact of an additional major flood in the near future should be investigated. The difference between the two largest events allows the hypothetical flood to be the second highest in the new record.

7. Including Another Extreme Flood (2nd Largest)

As before, as Weibull gives the best 'fit' to the Annual Maxima throughout the five scenarios; its Scenario 4 graph for the New Extreme Flood study is presented here; this also shows its original positioning of all the floods. Again, it is worthwhile stating the obvious, the second biggest flood (1989) has become the third biggest and is now paired with the third biggest Plotting Positions; this moves it to the left from 3.47 to 3.07: while considerable, this shift is less than that produced by the other three methods. A similar, but progressively smaller, shift takes place down the hierarchy of floods. This has reduced the curvature of the data set to such a degree that it is now close to the minimum requirement for the Deel; a straight line (its correlation of 0.99 is impressive). This does tend to support the case that the record has not yet trapped enough very large events.



The following table presents the December 2015 return period estimates from each of the four methods across the five time scenarios. In all but one case, the flood is now less than a 90 Year event; and it could be as low as a 67-Year event.

Estimated Return Period of the September 2015 Flood					
Plotting Position Estimating Method =>		Gringorten	Cunnane	Median	Weibull
Return Period of the Plotting Position =>		117	109	96	66
Scenario	Range of Middle Period (incl.)	Return Period	Return Period	Return Period	Return Period
1	1963 to 1981	91	89	85	73
2	1963 to 1985	89	87	83	72
3	1972 to 1981	85	83	79	69
4	1975 to 1981	83	81	78	67
5	1972 to 1985	83	81	77	67

The 100-Year flood estimates are presented in the following table. The estimates from the first three methodologies agree with each other to within about $\pm\frac{1}{2}$% and only vary about $\pm1\frac{1}{8}$% over the five scenarios. As with the investigation in Section **5**, these are close to the original Weibull estimates (180.5 to 182.8 m^3/s). While Weibull still gives higher results, in each scenario, they are only about $2\frac{3}{4}$% greater than the average from the other three methods.

This time, this coming-together of estimates is a result of including an additional large flood and, as the 100-Year flood estimates have gone up, risk has gone down.

The 100-Year Return Period Flood at Ballycarroon				
Scenario	Gringorten	Cunnane	Median	Weibull
1	180.4	181.0	182.2	186.0
2	181.1	181.7	182.8	186.7
3	182.1	182.7	183.9	187.8
4	182.7	183.3	184.5	188.4
5	182.7	183.3	184.5	188.4

8. Conclusions and Recommendations

Five time-range scenarios have been used throughout this study, however, for each of the four applied methodologies in each investigation, Return Period peak flow estimates only vary by between ±1 to 2m^3/s; that's less than ±1%. As such, the lack of flood measurements in the middle-time period is not significant and, as Scenario 3 (1972 to 1981 middle period) gives results close to the mean from the scenarios, and as the variation is so small, its results are preferred.

Plotting positions assigned to the biggest floods by the four methods (Gringorten, Cunnane, Median and Weibull) do impact return period peak flow estimation (see Section **4**). In each scenario, Weibull consistently produces the biggest flow estimates, however, they are not even 3% greater than the average of the other three methods. It also consistently provides the best 'fit' to the data and that means that its results are less impacted by how it handles the extreme floods.

Section **5** looked to avoid the effects of the extreme floods' plotting positions by leaving out the three biggest ones and found that the other three methods then gave full-record, Weibull-type answers. Because the largest flood is 25% bigger than the second largest and the next two are not even 5% smaller than that one, that lead to the suspicion that the record has not yet managed to trap enough very large events. Section **7** shows that an extreme flood in the near future (that would then be the second biggest in the record) would produce Return Period peak flow estimates only 1% bigger than those from Section **5** and within about ±$\frac{1}{4}$% of the Weibull answers from the present-day record.

The closeness of the results from these two investigations confirm the observation that the main source of difference between the methods relates to how they account for the length of record when assigning plotting positions to the biggest floods. As both deliver full-record, Weibull-type answers and as Scenario 3 data is consistently the Median (with very little variation about it), the Weibull Scenario 3 results are recommended (see table). This also estimates the 178.2 m^3/s December 2015 flood to be an 85-year event and the 142.62 m^3/s October 1989 as a 20-year.

Return Period Peak Flows			
Return Period (Years)	Peak Flow (m^3/s)	Standard Error	84% Interval (m^3/s)
2	78.64	3.58	82.23
5	106.34	6.05	112.39
10	124.68	8.18	132.86
25	148.84	11.03	159.86
50	165.54	13.20	178.73
100	182.36	15.37	197.73
200	199.24	17.56	216.79
250	204.68	18.26	222.94
500	221.59	20.45	242.05
1,000	238.52	22.65	261.17

Tim Joyce, Chartered Engineer, Design Section, 19/12/ 2016

Scenario 1: Annual Maxima @ 34007 Ballycarroon (Sliding Averages from 1963 to 1981, incl.)							
Flood Year	**Date of Flood**	**Staff-gauge Level** (m)	**Estimated Peak Flow** (m^3/s)	**Flood Year**	**Date of Flood**	**Staff-gauge Level** (m)	**Estimated Peak Flow** (m^3/s)
1952	26/01/1953	1.02	37.15	**1990**	06/01/1991	1.56	60.30
1953	24/01/1954	1.96	114.08	**1991**	11/09/1992	2.04	95.70
1954	18/10/1954	2.06	124.20	**1992**	18/05/1993	1.56	60.30
1955	08/07/1956	1.40	65.40	**1993**	31/01/1994	1.51	56.87
1956	17/10/1956	1.57	79.62	**1994**	11/12/1994	1.39	48.87
1957	25/01/1958	2.18	135.46	**1995**	26/10/1995	1.32	44.38
1958	13/10/1958	1.62	83.50	**1996**	16/09/1997	1.55	59.61
1959	30/01/1960	1.45	69.80	**1997**	09/01/1998	1.47	54.16
1960	14/07/1961	1.52	75.80	**1998**	20/10/1998	1.91	85.93
1961	23/10/1961	2.19	136.96	**1999**	28/11/1999	1.81	78.34
1962	05/11/1962	1.17	48.46	**2000**	18/10/2000	1.65	66.64
1963	02/01/1964	1.77	**93.73**	**2002**	27/10/2002	1.91	85.93
1964	10/01/1965	2.09	**122.17**	**2001**	03/12/2002	1.87	82.87
1965	06/10/1965	1.78	**93.59**	**2003**	16/03/2004	1.56	59.96
1966	10/12/1966	1.56	**74.47**	**2004**	15/01/2005	1.75	73.88
1967	31/01/1968	1.36	**57.80**	**2005**	20/09/2006	1.46	40.63
1968	01/11/1968	2.07	**116.93**	**2006**	03/12/2006	2.51	118.26
1969	15/08/1970	2.09	**117.36**	**2007**	03/02/2008	1.87	67.78
1970	25/10/1970	1.86	**96.32**	**2008**	10/10/2008	1.53	44.69
1971	05/11/1971	1.19	**44.31**	**2009**	08/09/2010	1.76	59.96
1972	11/12/1972	1.49	**65.29**	**2010**	18/11/2010	1.75	59.82
1973	28/11/1973	1.73	**83.35**	**2011**	18/10/2011	1.75	59.27
1974	22/01/1975	1.64	**75.57**	**2012**	19/11/2012	2.18	91.60
1975	03/01/1976	1.65	**75.69**	**2013**	15/12/2013	1.80	63.03
1976	28/11/1976	1.46	**60.93**	**2014**	15/01/2015	2.11	86.01
1977	28/09/1978	2.01	**103.11**	**2015**	05/12/2015	3.175	178.21
1978	15/11/1978	2.02	**102.62**				
1979	26/11/1979	2.05	**104.60**				
1980	02/11/1980	1.91	**92.36**				
1981	12/03/1982	1.35	**50.86**				
1982	19/12/1982	1.83	79.84				
1983	12/10/1983	1.46	53.49				
1984	30/11/1984	1.69	69.51				
1985	01/10/1985	2.36	122.51				
1986	05/12/1986	2.23	111.56				
1987	12/01/1988	1.88	83.63				
1988	20/09/1989	2.31	118.26				
1989	27/10/1989	2.59	142.62				

Scenario 2: Annual Maxima @ 34007 Ballycarroon (Sliding Averages from 1963 to 1985, incl.)								
Flood Year	**Date of Flood**	**Staff-gauge Level** (m)	**Estimated Peak Flow** (m³/s)		**Flood Year**	**Date of Flood**	**Staff-gauge Level** (m)	**Estimated Peak Flow** (m³/s)
1952	26/01/1953	1.02	37.15		**1990**	06/01/1991	1.56	60.30
1953	24/01/1954	1.96	114.08		**1991**	11/09/1992	2.04	95.70
1954	18/10/1954	2.06	124.20		**1992**	18/05/1993	1.56	60.30
1955	08/07/1956	1.40	65.40		**1993**	31/01/1994	1.51	56.87
1956	17/10/1956	1.57	79.62		**1994**	11/12/1994	1.39	48.87
1957	25/01/1958	2.18	135.46		**1995**	26/10/1995	1.32	44.38
1958	13/10/1958	1.62	83.50		**1996**	16/09/1997	1.55	59.61
1959	30/01/1960	1.45	69.80		**1997**	09/01/1998	1.47	54.16
1960	14/07/1961	1.52	75.80		**1998**	20/10/1998	1.91	85.93
1961	23/10/1961	2.19	136.96		**1999**	28/11/1999	1.81	78.34
1962	05/11/1962	1.17	48.46		**2000**	18/10/2000	1.65	66.64
1963	02/01/1964	1.77	**93.79**		**2002**	27/10/2002	1.91	85.93
1964	10/01/1965	2.09	**122.42**		**2001**	03/12/2002	1.87	82.87
1965	06/10/1965	1.78	**93.91**		**2003**	16/03/2004	1.56	59.96
1966	10/12/1966	1.56	**74.84**		**2004**	15/01/2005	1.75	73.88
1967	31/01/1968	1.36	**58.17**		**2005**	20/09/2006	1.46	40.63
1968	01/11/1968	2.07	**117.84**		**2006**	03/12/2006	2.51	118.26
1969	15/08/1970	2.09	**118.45**		**2007**	03/02/2008	1.87	67.78
1970	25/10/1970	1.86	**97.35**		**2008**	10/10/2008	1.53	44.69
1971	05/11/1971	1.19	**44.85**		**2009**	08/09/2010	1.76	59.96
1972	11/12/1972	1.49	**66.20**		**2010**	18/11/2010	1.75	59.82
1973	28/11/1973	1.73	**84.64**		**2011**	18/10/2011	1.75	59.27
1974	22/01/1975	1.64	**76.86**		**2012**	19/11/2012	2.18	91.60
1975	03/01/1976	1.65	**77.11**		**2013**	15/12/2013	1.80	63.03
1976	28/11/1976	1.46	**62.17**		**2014**	15/01/2015	2.11	86.01
1977	28/09/1978	2.01	**105.39**		**2015**	05/12/2015	3.175	178.21
1978	15/11/1978	2.02	**105.06**					
1979	26/11/1979	2.05	**107.27**					
1980	02/11/1980	1.91	**94.89**					
1981	12/03/1982	1.35	**52.34**					
1982	19/12/1982	1.83	**81.95**					
1983	12/10/1983	1.46	**54.50**					
1984	30/11/1984	1.69	**70.30**					
1985	01/10/1985	2.36	**122.97**					
1986	05/12/1986	2.23	111.56					
1987	12/01/1988	1.88	83.63					
1988	20/09/1989	2.31	118.26					
1989	27/10/1989	2.59	**142.62**					

Scenario 3: Annual Maxima @ 34007 Ballycarroon (Sliding Averages from 1972 to 1981, incl.)			
Flood Year	**Date of Flood**	**Staff-gauge Level** (m)	**Estimated Peak Flow** (m^3/s)
1952	26/01/1953	1.02	37.15
1953	24/01/1954	1.96	114.08
1954	18/10/1954	2.06	124.20
1955	08/07/1956	1.40	65.40
1956	17/10/1956	1.57	79.62
1957	25/01/1958	2.18	135.46
1958	13/10/1958	1.62	83.50
1959	30/01/1960	1.45	69.80
1960	14/07/1961	1.52	75.80
1961	23/10/1961	2.19	136.96
1962	05/11/1962	1.17	48.46
1963	02/01/1964	1.77	94.10
1964	10/01/1965	2.09	123.61
1965	06/10/1965	1.78	95.45
1966	10/12/1966	1.56	76.56
1967	31/01/1968	1.36	59.90
1968	01/11/1968	2.07	122.15
1969	15/08/1970	2.09	123.61
1970	25/10/1970	1.86	102.28
1971	05/11/1971	1.19	47.45
1972	11/12/1972	1.49	**69.98**
1973	28/11/1973	1.73	**88.75**
1974	22/01/1975	1.64	**79.92**
1975	03/01/1976	1.65	**79.51**
1976	28/11/1976	1.46	**63.55**
1977	28/09/1978	2.01	**106.77**
1978	15/11/1978	2.02	**105.48**
1979	26/11/1979	2.05	**106.70**
1980	02/11/1980	1.91	**93.48**
1981	12/03/1982	1.35	**51.06**
1982	19/12/1982	1.83	79.84
1983	12/10/1983	1.46	53.49
1984	30/11/1984	1.69	69.51
1985	01/10/1985	2.36	122.51
1986	05/12/1986	2.23	111.56
1987	12/01/1988	1.88	83.63
1988	20/09/1989	2.31	118.26
1989	27/10/1989	2.59	**142.62**
1990	06/01/1991	1.56	60.30
1991	11/09/1992	2.04	95.70
1992	18/05/1993	1.56	60.30
1993	31/01/1994	1.51	56.87
1994	11/12/1994	1.39	48.87
1995	26/10/1995	1.32	44.38
1996	16/09/1997	1.55	59.61
1997	09/01/1998	1.47	54.16
1998	20/10/1998	1.91	85.93
1999	28/11/1999	1.81	78.34
2000	18/10/2000	1.65	66.64
2002	27/10/2002	1.91	85.93
2001	03/12/2002	1.87	82.87
2003	16/03/2004	1.56	59.96
2004	15/01/2005	1.75	73.88
2005	20/09/2006	1.46	40.63
2006	03/12/2006	2.51	118.26
2007	03/02/2008	1.87	67.78
2008	10/10/2008	1.53	44.69
2009	08/09/2010	1.76	59.96
2010	18/11/2010	1.75	59.82
2011	18/10/2011	1.75	59.27
2012	19/11/2012	2.18	91.60
2013	15/12/2013	1.80	63.03
2014	15/01/2015	2.11	86.01
2015	05/12/2015	3.175	178.21

Scenario 4: Annual Maxima @ 34007 Ballycarroon (Sliding Averages from 1975 to 1981, incl.)			
Flood Year	**Date of Flood**	**Staff-gauge Level** (m)	**Estimated Peak Flow** (m^3/s)
1952	26/01/1953	1.02	37.15
1953	24/01/1954	1.96	114.08
1954	18/10/1954	2.06	124.20
1955	08/07/1956	1.40	65.40
1956	17/10/1956	1.57	79.62
1957	25/01/1958	2.18	135.46
1958	13/10/1958	1.62	83.50
1959	30/01/1960	1.45	69.80
1960	14/07/1961	1.52	75.80
1961	23/10/1961	2.19	136.96
1962	05/11/1962	1.17	48.46
1963	02/01/1964	1.77	94.10
1964	10/01/1965	2.09	123.61
1965	06/10/1965	1.78	95.45
1966	10/12/1966	1.56	76.56
1967	31/01/1968	1.36	59.90
1968	01/11/1968	2.07	122.15
1969	15/08/1970	2.09	123.61
1970	25/10/1970	1.86	102.28
1971	05/11/1971	1.19	47.45
1972	11/12/1972	1.49	70.50
1973	28/11/1973	1.73	90.77
1974	22/01/1975	1.64	82.99
1975	03/01/1976	1.65	**82.96**
1976	28/11/1976	1.46	**65.92**
1977	28/09/1978	2.01	**110.08**
1978	15/11/1978	2.02	**108.06**
1979	26/11/1979	2.05	**108.60**
1980	02/11/1980	1.91	**94.50**
1981	12/03/1982	1.35	**51.25**
1982	19/12/1982	1.83	79.84
1983	12/10/1983	1.46	53.49
1984	30/11/1984	1.69	69.51
1985	01/10/1985	2.36	122.51
1986	05/12/1986	2.23	111.56
1987	12/01/1988	1.88	83.63
1988	20/09/1989	2.31	118.26
1989	27/10/1989	2.59	**142.62**
1990	06/01/1991	1.56	60.30
1991	11/09/1992	2.04	95.70
1992	18/05/1993	1.56	60.30
1993	31/01/1994	1.51	56.87
1994	11/12/1994	1.39	48.87
1995	26/10/1995	1.32	44.38
1996	16/09/1997	1.55	59.61
1997	09/01/1998	1.47	54.16
1998	20/10/1998	1.91	85.93
1999	28/11/1999	1.81	78.34
2000	18/10/2000	1.65	66.64
2002	27/10/2002	1.91	85.93
2001	03/12/2002	1.87	82.87
2003	16/03/2004	1.56	59.96
2004	15/01/2005	1.75	73.88
2005	20/09/2006	1.46	40.63
2006	03/12/2006	2.51	118.26
2007	03/02/2008	1.87	67.78
2008	10/10/2008	1.53	44.69
2009	08/09/2010	1.76	59.96
2010	18/11/2010	1.75	59.82
2011	18/10/2011	1.75	59.27
2012	19/11/2012	2.18	91.60
2013	15/12/2013	1.80	63.03
2014	15/01/2015	2.11	86.01
2015	05/12/2015	3.175	178.21

Scenario 5: Annual Maxima @ 34007 Ballycarroon (Sliding Averages from 1972 to 1985, incl.)							
Flood Year	**Date of Flood**	**Staff-gauge Level** (m)	**Estimated Peak Flow** (m^3/s)	**Flood Year**	**Date of Flood**	**Staff-gauge Level** (m)	**Estimated Peak Flow** (m^3/s)
1952	26/01/1953	1.02	37.15	**1990**	06/01/1991	1.56	60.30
1953	24/01/1954	1.96	114.08	**1991**	11/09/1992	2.04	95.70
1954	18/10/1954	2.06	124.20	**1992**	18/05/1993	1.56	60.30
1955	08/07/1956	1.40	65.40	**1993**	31/01/1994	1.51	56.87
1956	17/10/1956	1.57	79.62	**1994**	11/12/1994	1.39	48.87
1957	25/01/1958	2.18	135.46	**1995**	26/10/1995	1.32	44.38
1958	13/10/1958	1.62	83.50	**1996**	16/09/1997	1.55	59.61
1959	30/01/1960	1.45	69.80	**1997**	09/01/1998	1.47	54.16
1960	14/07/1961	1.52	75.80	**1998**	20/10/1998	1.91	85.93
1961	23/10/1961	2.19	136.96	**1999**	28/11/1999	1.81	78.34
1962	05/11/1962	1.17	48.46	**2000**	18/10/2000	1.65	66.64
1963	02/01/1964	1.77	94.10	**2002**	27/10/2002	1.91	85.93
1964	10/01/1965	2.09	123.61	**2001**	03/12/2002	1.87	82.87
1965	06/10/1965	1.78	95.45	**2003**	16/03/2004	1.56	59.96
1966	10/12/1966	1.56	76.56	**2004**	15/01/2005	1.75	73.88
1967	31/01/1968	1.36	59.90	**2005**	20/09/2006	1.46	40.63
1968	01/11/1968	2.07	122.15	**2006**	03/12/2006	2.51	118.26
1969	15/08/1970	2.09	123.61	**2007**	03/02/2008	1.87	67.78
1970	25/10/1970	1.86	102.28	**2008**	10/10/2008	1.53	44.69
1971	05/11/1971	1.19	47.45	**2009**	08/09/2010	1.76	59.96
1972	11/12/1972	1.49	**70.13**	**2010**	18/11/2010	1.75	59.82
1973	28/11/1973	1.73	**89.33**	**2011**	18/10/2011	1.75	59.27
1974	22/01/1975	1.64	**80.80**	**2012**	19/11/2012	2.18	91.60
1975	03/01/1976	1.65	**80.75**	**2013**	15/12/2013	1.80	63.03
1976	28/11/1976	1.46	**64.85**	**2014**	15/01/2015	2.11	86.01
1977	28/09/1978	2.01	**109.47**	**2015**	05/12/2015	3.175	178.21
1978	15/11/1978	2.02	**108.68**				
1979	26/11/1979	2.05	**110.50**				
1980	02/11/1980	1.91	**97.32**				
1981	12/03/1982	1.35	**53.45**				
1982	19/12/1982	1.83	**83.30**				
1983	12/10/1983	1.46	**55.15**				
1984	30/11/1984	1.69	**70.80**				
1985	01/10/1985	2.36	**123.27**				
1986	05/12/1986	2.23	111.56				
1987	12/01/1988	1.88	83.63				
1988	20/09/1989	2.31	118.26				
1989	27/10/1989	2.59	**142.62**				

Mr. Peter Newport,

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RE: Crossmolina FRS - 34007 Ballycarroon - Flow Measurements & Rating Curves

Introduction

The river Deel's response to rainfall is so fast that its short-lived floods make it very difficult to measure high flows. Its big floods result from high intensity rainstorms that, by nature, are of medium to short duration and quite localised. That has always made it hard to predict when one would track across the Deel and so, unless a Hydrometric Team camped out during bad weather, its flood would have already passed through by the time the Team could reach the river.

In 1939, just a few kilometres upstream of Crossmolina Town, Hydrometric Station 34007 was installed on the Deel at Ballycarroon. Over the following twelve years, flow was measured six times; but five of these are below the flood range and the remaining one (41.34 m^3/s in January 1952) just makes it into it. The station was upgraded to continuous water-level recording in September 1952 and, while a concerted effort was made in the following year, by February 1954, other than low flows, just four middle-flow measurements were captured: these only ranged from 10 to 26 m^3/s. After that, all measurements were less than 10 m^3/s until the flood of November 1989 provided a modest 25.14 m^3/s and February 2003 gave a 26.44 m^3/s.

Due to flooding in Crossmolina Town in recent years, a high priority has been given to the Ballycarroon station, and this has resulted in 18 measurements ranging from 21.25 to 102.6 m^3/s. A Flow Rating relationship for present-day conditions based on these will be a significant improvement on what was previously recent. The new data, however, shows that the river is running less efficiently than it did half a century ago. A comparison of the old and new measurement sets shows that, for a given level, the drop off in flow is about 15%. This implies a significant change in control.

The lack of flood flow measurements in the intervening period makes it difficult to find out when the river lost its efficiency, and if it happened abruptly or gradually transitioned over many years. The primary problem in estimating flood flows now relates to quantifying the uncertainty that arises from estimating peak-flows that occurred during that middle time period.

These are the subjects of this Memo… "*2016-11-22 - TJ - Station 34007 Ballycarroon - Flow Measurements & Rating Curves*" and of "*2016-11-22 - TJ - Station 34007 Ballycarroon - Annual Maxima & Return Period Analysis*".

The OD level of the station's staff gauges

To begin with, there is a longstanding issue relating to the OD level of the succession of staff gauges since 1939. For a given staff-gauge, it often happened within a span of a year or so, that two, or three, professionals ran a level survey from a local OS Benchmark along the narrow laneway to the Station and independently calculated levels for the 'zero' of the staff. These vary by as much as 0.25ft (about 0.075m). While this is not particularly large, it does change how measurements taken while that staff was in place relate to those from the other staffs: this shows up as a misalignment on level-flow plots.

At other Hydrometric Stations, where staff-zero OD levels are not in question, misalignment is dealt with by adding, or subtracting, a small amount from the flow measurement levels to bring the sets into line. Here, a simpler approach has been applied, within the historic 0.25ft variation, staff zero levels have been found that inherently produce the sought after 'fit' between the periods. These staff zero levels are presented in Table **1** (assigned values are given in 'Brown') and the alignment produced between the time periods up to 1972 is visible in Figure **1**. The new staff installed in that year remained in use for a decade; while its data is also presented, it is divided into two periods; the early one (this runs to the end of 1975) shows its continuity with the preceding data set and the remaining portion (ends in July 1982) indicates a drift to the less efficient river condition that holds today.

Figure 1 - Log-Log Plot of Flow Measurements

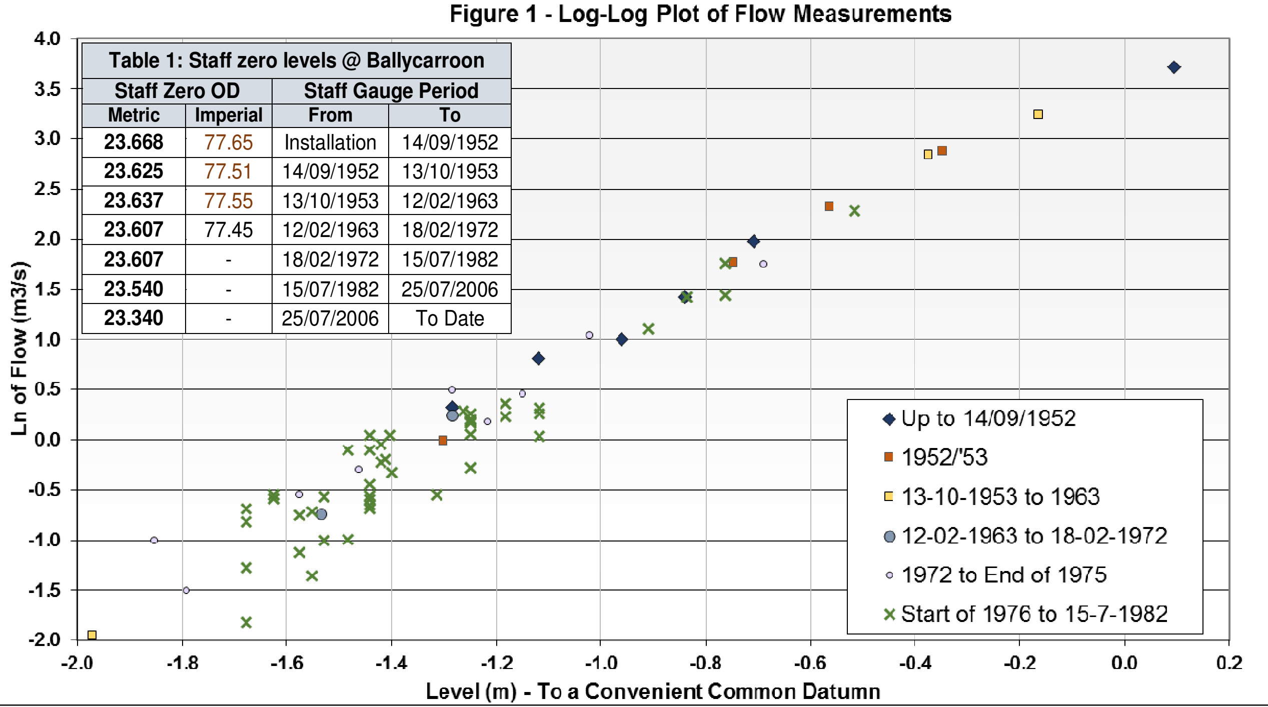

Table 1: Staff zero levels @ Ballycarroon

Staff Zero OD		Staff Gauge Period	
Metric	Imperial	From	To
23.668	77.65	Installation	14/09/1952
23.625	77.51	14/09/1952	13/10/1953
23.637	77.55	13/10/1953	12/02/1963
23.607	77.45	12/02/1963	18/02/1972
23.607	-	18/02/1972	15/07/1982
23.540	-	15/07/1982	25/07/2006
23.340	-	25/07/2006	To Date

The altered river fording point just downstream of the Station

High-energy floods on the Deel can damage fording points along the river. That has consequences for Station 34007; as it relies on the Ballycarroon ford to provide control. Probably in response to flood damage, the ford's carriageway was raised. About three decades ago, four pipes were set into the ford; most probably, to compensate for the impact of having raised the carriageway. As may be expected, there are two opposing consequences to these alterations. First, due to the four pipes, low flows run more efficiently than before and, second, when river flow outstrips the capacity of the pipes, the obstruction caused by the raised ford bites; so medium-sized flows run less efficiently than before (they need a higher level). These effects are visible in Figure **2**.

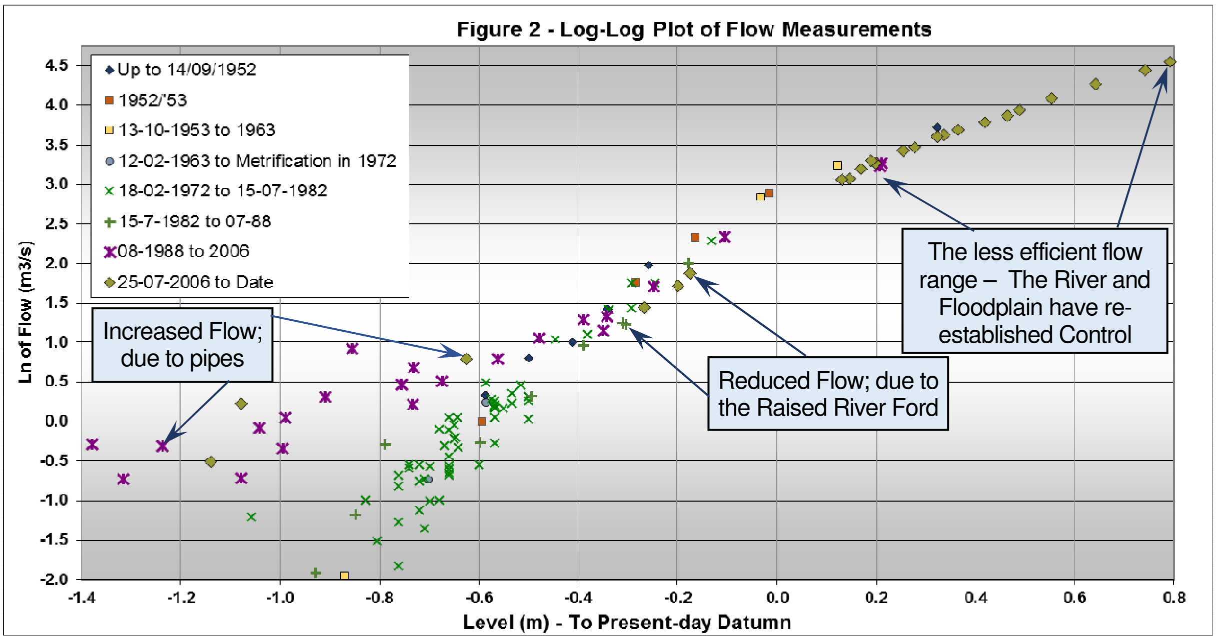

Figure 2 - Log-Log Plot of Flow Measurements

It would seem from the figure that the pipes were placed July/August 1988, however, the timing of the increase in the ford's carriageway is less clear; as it can only be judged in the middle-flow range where even reasonable sized impacts only show up as a relatively modest shift in data. This work must have occurred when the pipes were laid or before that time. The Green '+' data could take the change back to July 1982, and the preceding data period (post February 1972) also has measurements that indicate the change occurred within its time-range.

A further point needs to be added here, the raised carriageway should act as a Broad-crested Weir and, as such, Drown-out in flood conditions. The eighteen recent high flow measurements support this; as they show a less efficient river-control taking over during flood times. That means that the raised carriageway of the river-ford does not have any meaningful impact on flood levels and, by implication, on the estimation of flood flows at the station.

That then leads to the primary problem with this Station, if the river re-establishes control during floods, why does the recent flood data not show the same control as the old measurements.

Developing Flow Ratings

The old and recent data need separate relationships (see Figure **3**); the amount to be added to staff-levels to develop these ratings are presented in Table **2**. It seems that the river now delivers 15% less flow for a given flood level and, as their slopes are nearly identical (1.419 versus 1.419238), this 15% difference holds throughout the entire flood range. It can also be seen that the Old Rating holds right down into the lower middle flows while the recent one does not (see data to the left of the Green Arrow in Figure **3**: these inefficient flows are likely the result of the raised carriageway level of the river-ford.

Table 2: Amount to be Added to Water Levels Recorded on the Staff

Staff Gauge Period		Delta Level
From	**To**	
Installation	14/09/1952	**-0.197**
14/09/1952	13/10/1953	**-0.240**
13/10/1953	12/02/1963	**-0.228**
12/02/1963	18/02/1972	**-0.258**
18/02/1972	15/07/1982	**-0.258**
15/07/1982	25/07/2006	**-0.325**
25/07/2006	To Date	**-0.525**

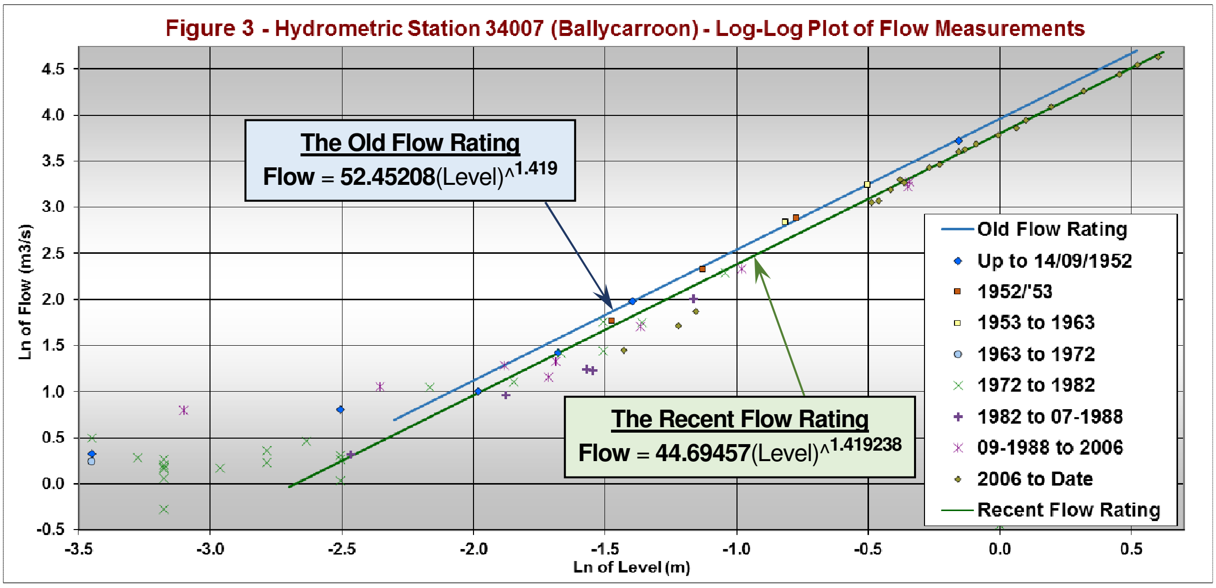

Figure 3 - Hydrometric Station 34007 (Ballycarroon) - Log-Log Plot of Flow Measurements

The River regime between 1963 and 1972, or 1975, or as late as 1982/5

This examination shows that the old rating holds up to 1963 and indicates that it, most likely, holds right up to 1972 and, possibly, even to the earlier part of the 1972-to-1982 period (see Figure **4**); but it is not possible to be certain of this. Again, the recent rating seems to hold as far back as 1982 (see Figure **5**) but, while some data between 1972 and 1982 suggest its influence, it is not possible to confirm this either. As such, there is a middle time-period (somewhere between 1963 and 1982, or later) where flow estimates carry additional uncertainty. This is dealt with in the accompanying Memo by taking a number of time range scenarios and seeing the degree to which this impacts the estimation of Annual Maxima and, in particular, Return Period Flows.

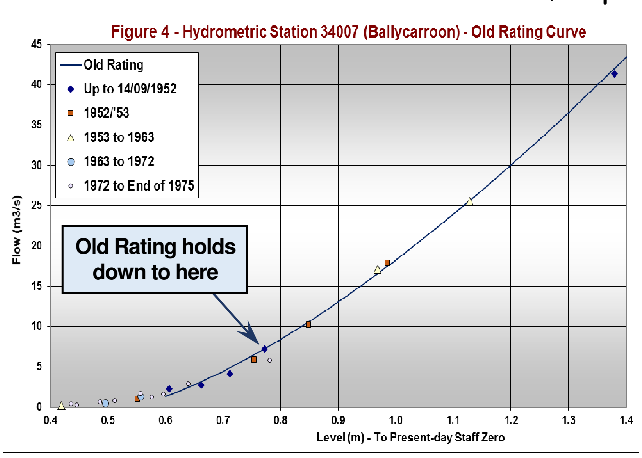

Figure 4 - Hydrometric Station 34007 (Ballycarroon) - Old Rating Curve

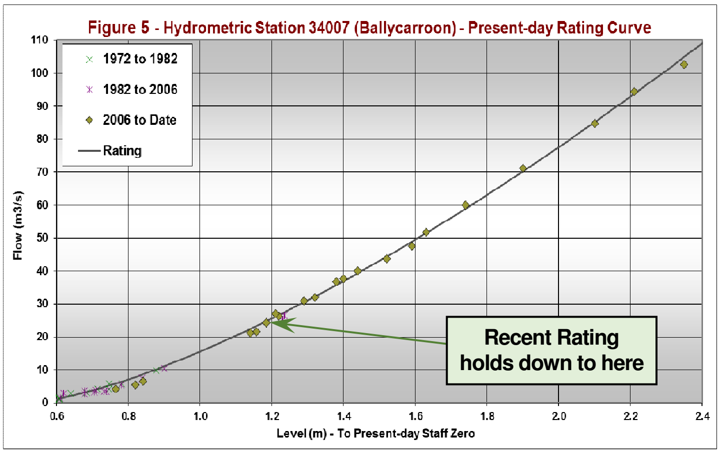

Figure 5 - Hydrometric Station 34007 (Ballycarroon) - Present-day Rating Curve

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Tim Joyce, Chartered Engineer, Design Section, 22/11/ 2016

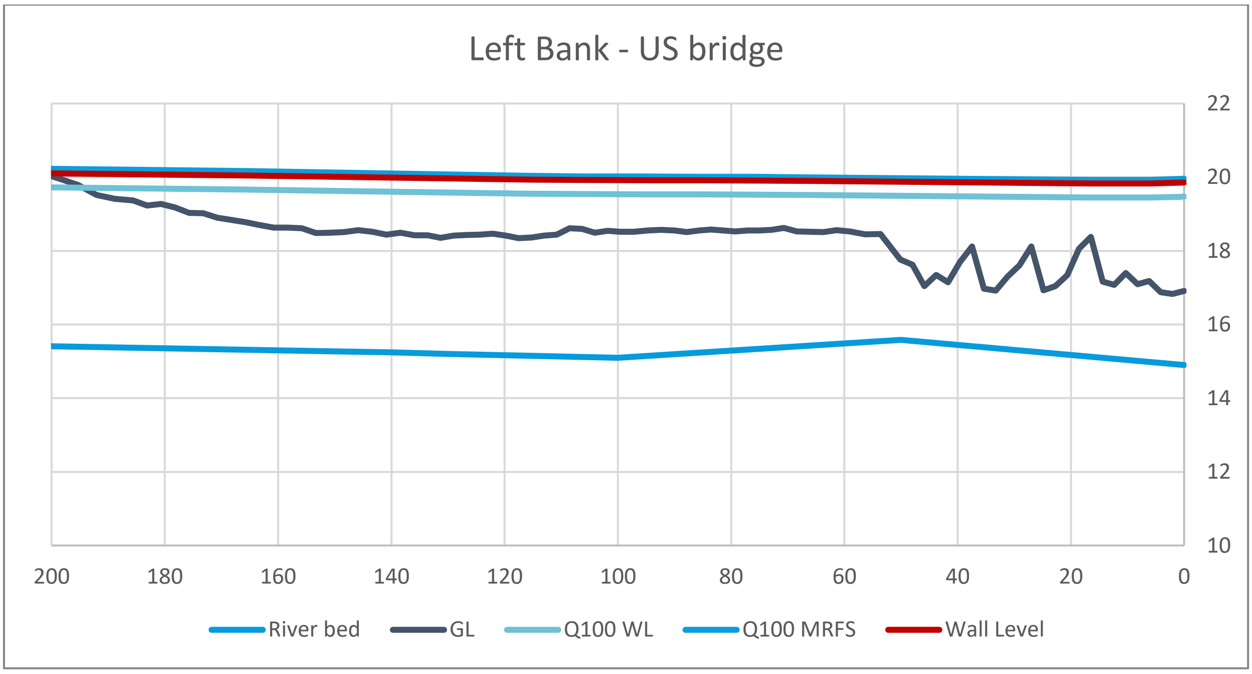
Appendix B - Wall Option Model Results

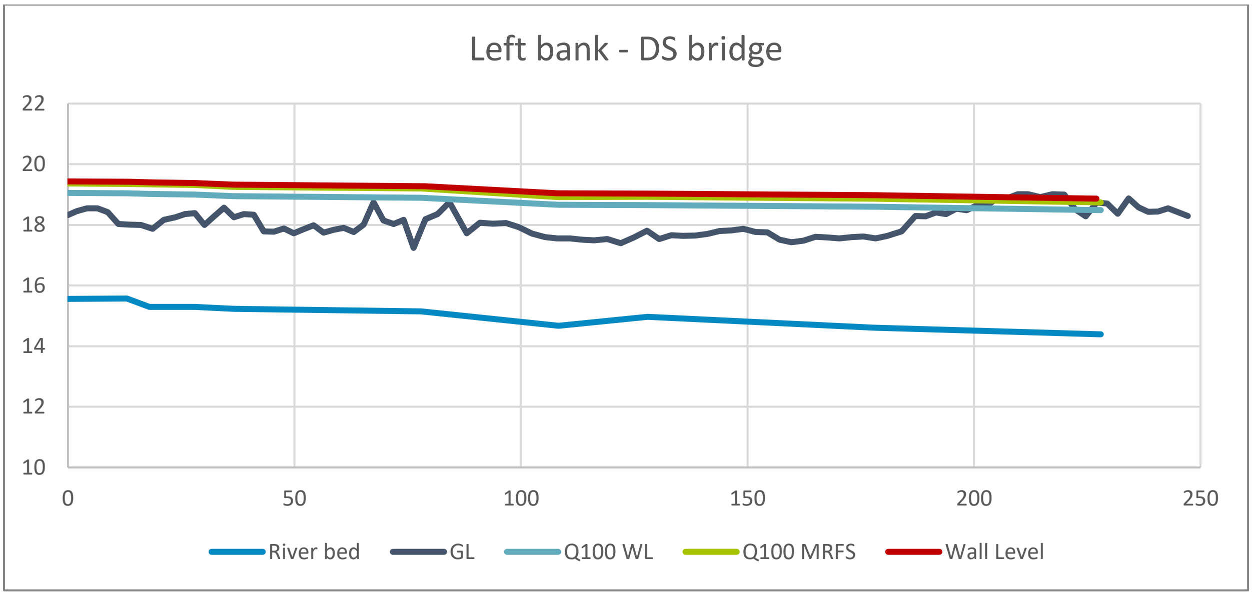
Required Wall levels

Summary of levels - Left bank

N.B. Wall chainage relates to the chainage along the wall. On left bank upstream of bridge chainage is from downstream to upstream, all other wall sections have chainage from upstream to downstream.

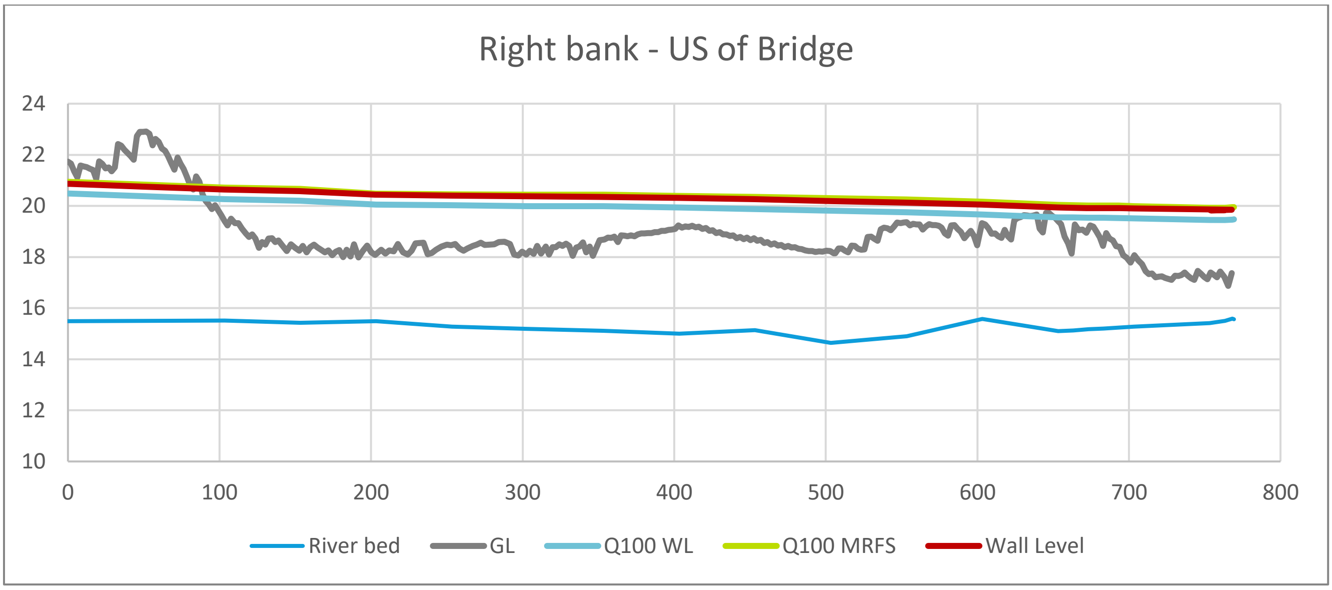
Chainage	x	y	GL	Q100 WL	Q100 MRFS	CC Impact	Wall Level (with freeboard)
Upstream of bridge							
0.00	113724.7	317569.6	16.91	19.47	19.96	0.48	19.85
6.17	113723.7	317563.6	17.18	19.45	19.93	0.48	19.83
16.44	113721.9	317553.5	18.38	19.45	19.93	0.48	19.83
66.04	113704.8	317515	18.52	19.52	19.99	0.48	19.90
74.99	113703	317506.2	18.55	19.53	20.01	0.48	19.91
85.70	113701.4	317495.6	18.55	19.53	20.01	0.48	19.91
94.78	113700.3	317486.6	18.55	19.54	20.02	0.48	19.92
106.31	113699.2	317475.1	18.60	19.54	20.02	0.48	19.92
115.27	113698.4	317466.2	18.36	19.55	20.04	0.48	19.93
165.77	113675.8	317421.3	18.78	19.67	20.17	0.50	20.05
216.00				19.75	20.25	0.50	20.13
Downstream of bridge							
0.00	113719	317584.9	18.32	19.05	19.37	0.31	19.43
13.64	113723	317597.9	18.01	19.04	19.35	0.31	19.42
18.67	113724.6	317602.7	17.87	19.02	19.33	0.31	19.40
27.99	113727.4	317611.6	18.39	19.00	19.31	0.31	19.38
36.63	113730	317619.8	18.25	18.95	19.25	0.31	19.33
78.94	113739.7	317658.8	18.19	18.89	19.20	0.31	19.27
108.06	113749.9	317679.8	17.55	18.66	18.92	0.25	19.04
127.86	113760.8	317696.4	17.81	18.66	18.92	0.27	19.04
178.29	113792.5	317735.5	17.55	18.59	18.86	0.27	18.97
227.04	113835.1	317756.4	18.73	18.48	18.74	0.25	18.86

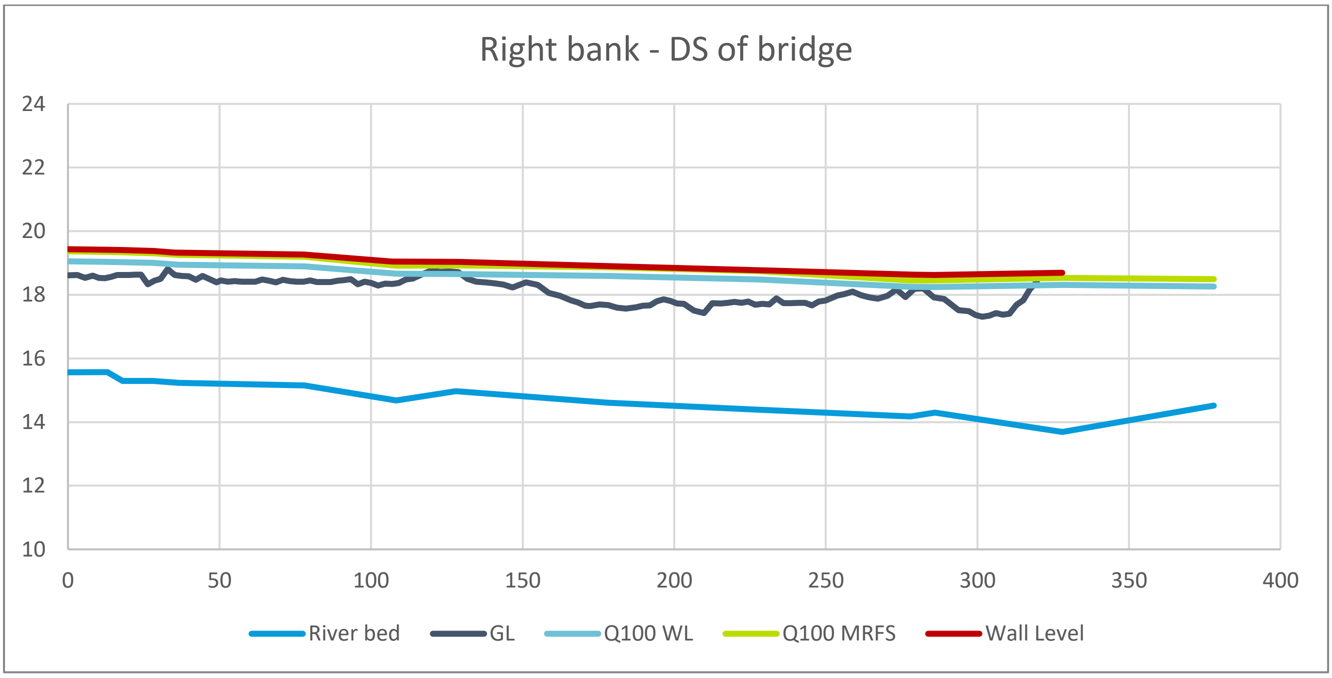

Left Bank - US bridge
22
20
18
16
14
12
10
200
180
160
140
120
100
80
60
40
20
0
River bed
GL
Q100 WL
Q100 MRFS
Wall Level


Left bank - DS bridge
22
20
18
16
14
12
10
0
50
100
150
200
250
River bed
GL
Q100 WL
Q100 MRFS
Wall Level

Summary of Levels - Right bank

chainage	x	y	GL	Q100 WL	Q100 MRFS	CC Impact	Wall Level (with freeboard)
Upstream of bridge							
0.00	113508.7	316858.4	21.73	20.49	20.94	0.46	20.87
49.55	113516.7	316907.3	22.90	20.38	20.84	0.46	20.76
103.24	113525.3	316960.3	19.43	20.26	20.72	0.46	20.64
152.61	113539.7	317007.3	18.25	20.20	20.66	0.46	20.58
202.70	113565.5	317049.3	18.08	20.05	20.48	0.43	20.43
252.83	113599.1	317084.8	18.46	20.02	20.46	0.43	20.40
302.41	113625.5	317126.1	18.10	19.99	20.44	0.44	20.37
350.89	113649.4	317167.3	18.66	19.97	20.44	0.47	20.35
402.82	113670	317214.9	19.24	19.94	20.44	0.50	20.32
452.54	113691.9	317259.5	18.73	19.88	20.40	0.51	20.26
502.81	113714	317304.7	18.23	19.81	20.35	0.54	20.19
553.48	113725.4	317353.7	19.36	19.75	20.35	0.60	20.13
603.10	113732.3	317402.8	19.32	19.67	20.30	0.63	20.05
653.31	113736.9	317452.8	19.40	19.55	20.25	0.70	19.93
662.10	113737.9	317461.6	18.13	19.54	20.17	0.62	19.92
671.98	113739.7	317471.2	18.95	19.54	20.04	0.50	19.92
682.91	113742	317481.9	18.44	19.53	20.02	0.49	19.91
693.88	113744.3	317492.7	18.40	19.53	20.02	0.49	19.91
703.57	113746.3	317502.1	18.07	19.52	20.02	0.50	19.90
767.86	113760.2	317562.5	17.37	19.47	19.99	0.52	19.85
753.91	113756.5	317549.1	17.39	19.45	20.01	0.56	19.83
762.88	113758.6	317557.8	17.22	19.45	20.01	0.56	19.83
Downstream of bridge							
0	113766.9	317574.9	18.61	19.05238	19.3653755	0.31	19.43
12.14373	113768.4	317586.9	18.52012	19.0375	19.3486538	0.31	19.42
18.15389	113768.7	317592.9	18.61999	19.0232	19.3345776	0.31	19.40
28.44206	113769.2	317603.1	18.43993	18.99997	19.3110695	0.31	19.38
35.22609	113769.5	317609.9	18.61999	18.948	19.2535477	0.31	19.33
77.68607	113780.4	317648.9	18.40997	18.88971	19.1963081	0.31	19.27
106.9125	113788.7	317677	18.34006	18.66499	18.918602	0.25	19.04
128.7534	113801.1	317694.3	18.70988	18.65525	18.9244289	0.27	19.04
181.1366	113841.5	317720.1	17.60012	18.51551	18.7593776	0.24	18.90
231.3708	113889.4	317730.3	17.7	18.3815	18.6010974	0.22	18.76
279.2561	113928.4	317707.6	18.18996	18.25375	18.4502182	0.20	18.63
285.6395	113933.3	317703.5	17.92001	18.24345	18.4558334	0.21	18.62
328				18.31042	18.535099	0.22	18.69


Right bank - US of Bridge
24
22
20
18
16
14
12
10
0
100
200
300
400
500
600
700
800
River bed
GL
Q100 WL
Q100 MRFS
Wall Level


Right bank - DS of bridge
24
22
20
18
16
14
12
10
0
50
100
150
200
250
300
350
400
River bed
GL
Q100 WL
Q100 MRFS
Wall Level

Appendix C - Dredge Option Model Results

Chainage is from upstream to downstream.

	Bed Levels					Max Water Levels 1% AEP Existing Risk (With max lough level)			
Chainage	Baseline	DRG1	DRG2	DRG3	DRG4	DRG1	DRG2	DRG3	DRG4
0	24.463	24.463	24.463	24.463	24.463	28.857	28.857	28.857	28.857
131.822	23.495	23.495	23.495	23.495	23.495	26.359	26.358	26.358	26.358
270.464	20.845	20.845	20.845	20.845	20.845	24.951	24.950	24.950	24.950
406.83	20.474	20.474	20.474	20.474	20.474	24.805	24.804	24.804	24.804
554.951	19.734	19.734	19.734	19.734	19.734	24.454	24.452	24.452	24.452
669.112	19.788	19.788	19.788	19.788	19.788	23.900	23.895	23.895	23.895
724.704	19.952	19.952	19.952	19.952	19.952	23.877	23.872	23.872	23.872
724.704	19.952	19.952	19.952	19.952	19.952	23.784	23.778	23.778	23.778
861.758	19.029	19.029	19.029	19.029	19.029	23.498	23.490	23.490	23.490
946.528	18.972	18.972	18.972	18.972	18.972	23.203	23.193	23.192	23.192
1083.624	17.648	17.648	17.648	17.648	17.648	22.565	22.539	22.537	22.537
1215.427	18.049	18.049	18.049	18.049	18.049	22.358	22.323	22.320	22.320
1352.127	17.735	17.735	17.735	17.735	17.735	21.857	21.791	21.785	21.785
1709.917	16.657	16.657	16.657	16.657	16.657	21.210	21.019	20.998	20.998
1915.402	16.269	16.269	16.269	16.269	16.269	20.909	20.576	20.528	20.528
2216.591	15.423	15.423	15.423	15.423	15.423	20.685	20.042	19.799	19.784
2481.447	15.487	15.487	15.487	15.061	15.061	20.237	19.739	19.401	19.375
2584.747	15.51	15.51	15.348	14.92	14.92	19.946	19.516	19.197	19.168
2634.747	15.43	15.43	15.28	14.852	14.852	19.877	19.464	19.136	19.105
2684.747	15.49	15.49	15.214	14.784	14.784	19.725	19.346	19.021	18.987
2734.747	15.28	15.28	15.147	14.716	14.716	19.667	19.331	19.011	18.976
2784.747	15.19	15.19	15.079	14.647	14.647	19.611	19.274	18.928	18.888
2834.747	15.11	15.11	15.012	14.579	14.579	19.600	19.271	18.910	18.866
2884.747	15	15	14.945	14.511	14.511	19.525	19.180	18.786	18.733
2934.747	15.14	15.14	14.878	14.442	14.442	19.416	19.120	18.723	18.669
2934.747	15.14	15.14	14.878	14.442	14.442	19.416	19.120	18.723	18.669
2984.747	14.64	15.086	14.811	14.374	14.374	19.308	19.032	18.653	18.597
3034.747	14.9	15.033	14.744	14.306	14.306	19.201	18.940	18.565	18.506
3084.747	15.58	14.979	14.676	14.238	14.238	19.173	18.931	18.572	18.513
3134.747	15.1	14.925	14.609	14.169	14.169	19.146	18.908	18.551	18.491
3144.747	15.13	14.915	14.596	14.156	14.156	19.144	18.907	18.551	18.491
3154.747	15.17	14.904	14.582	14.142	14.142	19.143	18.906	18.552	18.491
3154.747	15.17	14.904	14.582	14.142	14.142	19.143	18.906	18.552	18.491
3164.747	15.2	14.89	14.569	14.128	14.128	19.143	18.907	18.552	18.491
3174.747	15.24	14.883	14.555	14.115	14.115	19.143	18.907	18.552	18.492
3184.747	15.27	14.87	14.542	14.101	14.101	19.145	18.910	18.554	18.493
3234.747	15.41	14.82	14.475	14.033	14.033	19.108	18.875	18.519	18.457
3244.747	15.5	14.81	14.461	14.019	14.019	19.118	18.887	18.534	18.472
3249.747	15.59	14.8	14.455	14.012	14.012	19.134	18.904	18.551	18.490
3249.747	15.59	14.8	14.455	14.012	14.012	19.134	18.904	18.551	18.490
3250.747	15.56	14.8	14.453	14.011	14.011	19.141	18.911	18.559	18.498
3250.747	15.56	14.8	14.453	14.011	14.011	18.927	18.731	18.371	18.348

	Bed Levels					Max Water Levels 1% AEP Existing Risk (With max lough level)			
Chainage	Baseline	DRG1	DRG2	DRG3	DRG4	DRG1	DRG2	DRG3	DRG4
3263.747	15.57	14.787	14.436	13.993	13.993	18.922	18.727	18.367	18.345
3268.747	15.29	14.782	14.429	13.986	13.986	18.914	18.716	18.351	18.328
3278.747	15.29	14.77	14.416	13.973	13.973	18.898	18.694	18.326	18.303
3287.347	15.232	14.762	14.404	13.961	13.961	18.849	18.627	18.239	18.214
3328.747	15.15	14.72	14.345	13.905	13.905	18.818	18.617	18.240	18.215
3359.047	14.675	14.685	14.308	13.863	13.863	18.682	18.457	18.058	18.030
3378.747	14.97	14.66	14.281	13.836	13.836	18.697	18.484	18.108	18.081
3428.747	14.61	14.61	14.214	13.768	13.768	18.630	18.425	18.044	18.015
3478.747	14.39	14.39	14.147	13.7	13.7	18.598	18.401	17.963	17.929
3528.747	14.18	14.18	14.146	13.698	13.698	18.323	18.274	17.863	17.826
3536.747	14.3	14.3	14.08	13.631	13.631	18.299	18.108	17.700	17.657
3578.747	13.69	13.69	14.069	13.621	13.621	18.347	18.082	17.637	17.588
3628.747	14.52	14.52	14.013	13.563	13.563	18.284	18.106	17.694	17.647
3639.447	14.338	14.338	13.945	13.495	13.495	18.208	18.111	17.705	17.656
3678.747	14.06	14.06	13.93	13.48	13.48	18.101	18.053	17.637	17.585
3728.747	13.99	13.99	13.878	13.427	13.427	18.081	18.002	17.609	17.558
3778.747	13.63	13.63	13.81	13.358	13.358	17.979	17.961	17.499	17.442
3828.747	14.04	14.04	13.744	13.29	13.29	17.909	17.849	17.365	17.298
3878.747	14.22	14.22	13.677	13.222	13.222	17.902	17.831	17.365	17.297
3928.747	13.82	13.82	13.61	13.154	13.154	17.901	17.843	17.360	17.291
3978.747	13.41	13.41	13.542	13.085	13.085	17.952	17.841	17.372	17.304
4028.747	12.38	12.38	13.475	13.017	13.017	17.879	17.887	17.415	17.348
4078.747	13.73	13.73	13.408	12.949	12.949	17.831	17.804	17.287	17.212
4153.747	13.24	13.24	13.341	12.881	12.881	17.590	17.782	17.281	17.206
4228.747	13.18	13.18	13.24	12.778	12.778	17.548	17.613	17.146	17.065
4303.747	13.21	13.21	13.18	12.676	12.676	17.416	17.549	17.128	17.044
4378.747	12.96	12.96	13.21	12.573	12.573	17.306	17.416	17.023	16.930
4453.747	12.99	12.99	12.96	12.471	12.471	17.287	17.308	16.968	16.870
4516.247	12.989	12.989	12.99	12.369	12.369	17.075	17.288	16.933	16.832
4528.747	12.88	12.88	12.989	12.283	12.283	17.203	17.076	16.809	16.697
4603.747	12.79	12.79	12.88	12.266	12.266	17.138	17.204	16.897	16.792
4678.747	12.68	12.68	12.79	12.164	12.164	17.130	17.139	16.837	16.725
4683.577	12.866	12.866	12.68	12.061	12.061	17.135	17.131	16.794	16.677
4801.649	12.046	12.046	12.866	12.055	12.055	17.059	17.137	16.783	16.662
4885.077	12.573	12.573	12.046	11.894	11.894	16.997	17.061	16.682	16.543
4955.76	12.652	12.652	12.573	11.78	11.78	16.636	16.999	16.629	16.476
5005.575	12.491	12.491	12.652	11.683	11.683	16.749	16.638	16.296	16.096
5081.691	12.22	12.22	12.491	11.615	11.615	16.449	16.751	16.494	16.326
5340.225	11.83	11.83	12.22	11.511	11.511	16.154	16.450	16.113	15.846
5429.658	11.49	11.49	11.83	11.158	11.158	16.018	16.156	15.945	15.601
5491.098	11.483	11.483	11.49	11.036	11.036	16.006	16.019	15.793	15.383
5560.885	10.857	10.857	11.483	10.952	10.952	15.976	16.008	15.804	15.386
6018.631	10.845	10.845	10.857	10.857	10.857	15.704	15.978	15.786	15.370
6460.402	11.329	11.329	10.845	10.504	10.504	15.459	15.706	15.513	15.015
6831.563	11.082	11.082	11.329	10.162	10.162	15.094	15.460	15.320	14.736
7246.812	10.785	10.785	11.082	9.876	9.876	14.630	15.095	15.040	14.389

	Bed Levels					Max Water Levels 1% AEP Existing Risk (With max lough level)			
Chainage	Baseline	DRG1	DRG2	DRG3	DRG4	DRG1	DRG2	DRG3	DRG4
7381.075	10.97	10.97	10.785	9.555	9.555	14.516	14.632	14.739	14.033
7505.344	10.184	10.184	10.97	9.451	9.451	14.355	14.518	14.690	13.987
7727.415	10.006	10.006	10.184	9.355	9.355	14.097	14.357	14.530	13.713
8078.831	9.665	9.665	10.006	9.184	9.184	13.842	14.099	14.279	13.460
8482.45	9.426	9.426	9.665	8.913	8.913	13.570	13.844	14.021	13.274
8901.948	9.239	9.239	9.426	8.601	8.601	13.325	13.572	13.745	13.006
9258.252	9.259	9.259	9.239	8.277	8.277	13.067	13.326	13.495	12.767
9258.252	9.259	9.259	9.259	8.002	8.002	13.031	13.068	13.221	12.619
9762.244	8.584	8.584	9.259	8.002	8.002	12.646	13.032	13.180	12.580
10198.8	8.248	8.248	8.584	7.613	7.613	12.383	12.648	12.773	12.251
10517	8.055	8.055	8.248	7.276	7.276	12.232	12.385	12.495	12.076
10830.16	6.788	6.788	8.055	7.03	7.03	12.163	12.233	12.328	11.981
11401.21	7.722	7.722	6.788	6.788	6.788	12.026	12.164	12.252	11.926
11776.4	7.662	7.662	7.722	6.688	6.688	11.904	12.027	12.097	11.865
11776.4	7.662	7.662	7.662	6.623	6.623	11.877	11.904	11.958	11.779
12274.62	6.536	6.536	7.662	6.623	6.623	11.742	11.877	11.927	11.753
12578.51	6.663	6.663	6.536	6.536	6.536	11.703	11.742	11.769	11.718
13180.03	6.266	6.266	6.663	6.663	6.663	11.654	11.703	11.723	11.676
13493.09	6.135	6.135	6.266	6.266	6.266	11.631	11.654	11.665	11.635
13925.51	5.743	5.743	6.135	6.135	6.135	11.605	11.632	11.638	11.616
14325.8	6.816	6.816	5.743	5.743	5.743	11.600	11.605	11.606	11.603

Appendix D - Final Diversion Channel Option Model Results

1% AEP present day [5]

5 Zero and null (-9999.99) values represent nodes where no flow is present. These demonstrate that there is no flow through gaps in walls in the option.

Label	Max Flow (m3/s)	Max Stage (m OD)	Max Velocity (m/s)
34DEEL01185	95.529	19.148	1.385
DEEL_11388	95.533	18.979	1.209
DEEL_11338	95.5	18.928	1.162
DEEL_11288	95.527	18.842	1.301
DEEL_11238	95.526	18.801	1.135
DEEL_11188	93.377	18.738	1.168
DEEL_11138	86.789	18.691	1.167
DEEL_11088	72.951	18.631	1.367
DEEL_11038u	86.324	18.534	1.346
DEEL_11038L	0	18.534	0.753
DEEL_11038T	0	-9999.99	0.753
DEEL_11038	86.324	18.534	1.346
DEEL_10988	95.526	18.477	1.201
DEEL_10938	95.52	18.368	1.505
DEEL_10888	95.054	18.263	1.618
DEEL_10838	95.558	18.198	1.398
DEEL_10828	95.557	18.187	1.388
DEEL_10818u	95.557	18.178	1.372
DEEL_10818L	0	18.178	0
DEEL_10818T	0	-9999.99	0
DEEL_10818	95.557	18.178	1.372
DEEL_10808	95.557	18.169	1.353
DEEL_10798	95.556	18.16	1.335
DEEL_10788	95.555	18.151	1.316
DEEL_10738	95.552	18.079	1.39
DEEL_10728	95.552	18.072	1.346
DEEL_10723u	95.559	18.085	1.187
DEEL_10723L	0	18.085	0.977
DEEL_10723T	0	-9999.99	0.878
DEEL_10723	95.559	18.085	1.187
DEEL_10722A	95.552	18.089	1.148
DEEL_10722D	95.552	18.089	0.947
DEEL_10722E	95.552	17.948	0
DEEL_10722S	0	18.089	0
DEEL_10722T	0	17.948	0
DEEL_10722B	95.552	17.948	1.185
DEEL_10709	95.551	17.937	1.172
DEEL_10704	95.552	17.919	1.262
DEEL_10694	95.552	17.89	1.371
34DEEL01106	95.551	17.844	1.55
DEEL_10644	95.55	17.775	1.472
34DEEL01098	95.553	17.655	1.833
DEEL_10594	95.553	17.598	1.891
DEEL_10544	95.551	17.533	1.665
DEEL_10494	95.55	17.43	1.699
DEEL_10444	95.549	17.277	1.893
34DEEL01082	95.549	17.224	2.022
DEEL_10394	95.549	17.268	1.394

Label	Max Flow (m3/s)	Max Stage (m OD)	Max Velocity (m/s)
DEEL_10344	95.548	17.185	1.473
34DEEL01071	95.549	17.118	1.711
DEEL_10294	95.547	17.07	1.614
DEEL_10244	95.545	16.969	1.728
DEEL_10194	95.545	16.872	1.751
DEEL_10144	95.542	16.799	1.67
DEEL_10094	95.541	16.725	1.644
DEEL_10044	95.54	16.731	1.228
DEEL_9994	95.541	16.747	0.849
DEEL_9944	95.541	16.661	1.33
DEEL_9894	95.538	16.619	1.318
DEEL_9819	95.536	16.507	1.547
DEEL_9744	95.533	16.461	1.358
DEEL_9669	95.531	16.352	1.558
DEEL_9594	95.527	16.272	1.52
DEEL_9519	95.527	16.247	1.258
34DEEL00983	95.523	16.131	1.591
DEEL_9444	95.529	16.194	1.099
DEEL_9369	95.529	16.14	1.192
DEEL_9294	95.528	16.101	1.176
34DEEL00967	95.534	16.088	1.294
34DEEL00957	95.527	16.006	1.124
34DEEL00947	95.531	15.925	1.317
34DEEL00940	95.526	15.67	2.063
34DEEL00936	92.861	15.645	1.752
34DEEL00927	95.631	15.423	2.017
34DEEL00902	95.575	15.092	1.452
34DEEL00893	95.687	14.989	1.459
34DEEL00888	95.483	14.962	1.239
34DEEL00880	95.691	14.949	1.023
34DEEL00836	95.644	14.744	1.109
34DEEL00790	95.619	14.475	1.235
34DEEL00756	95.598	14.153	1.341
34DEEL00710	95.672	13.671	1.492
34DEEL00695	95.715	13.495	1.555
34DEEL00682	95.724	13.256	1.904
34DEEL00666	95.71	13.032	1.619
34DEEL00626	95.623	12.798	1.27
34DEEL00587	95.612	12.541	1.315
34DEEL00546	95.58	12.224	1.44
34DEEL00510A	95.563	11.993	1.276
34DEEL00510D	95.563	11.993	0.575
34DEEL00510E	95.563	11.967	0.575
34DEEL00510S	0	11.993	0.575
34DEEL00510T	0	11.967	0.575
34DEEL00510B	95.563	11.967	1.29
34DEEL00461	95.549	11.537	1.35
34DEEL00417	95.526	11.191	1.23

Label	Max Flow (m3/s)	Max Stage (m OD)	Max Velocity (m/s)
34DEEL00381	95.519	11.022	1.098
34DEEL00346	95.514	10.944	0.873
34DEEL00301	95.492	10.778	1.064
34DEEL00258A	95.484	10.55	1.396
34DEEL00258D	95.484	10.55	0.438
34DEEL00258E	95.484	10.507	0.438
34DEEL00258S	0	10.55	0.438
34DEEL00258T	0	10.507	0.438
34DEEL00258B	95.484	10.507	1.43
34DEEL00211	95.455	10.314	1.037
34DEEL00176	95.433	10.263	0.824
34DEEL00120	95.392	10.204	0.732
34DEEL00086	95.361	10.202	0.712
34DEEL00041	95.307	10.201	0.649
34DEEL00000	95.255	10.201	0.333

Appendix E - Diversion Channel Sensitivity

Manning's Roughness

The manning roughness value for the diversion channel has been set at 0.04 in the 1D model – representing a vegetated channel, predominantly grass and assumes a certain level of maintenance.

To test sensitivity to roughness, the model has been run with the following values for roughness:

- 0.06 – overgrown with light scrub, such as scattered bushes and briars.
- 0.02 – smooth channel similar to concrete lined channel or bare-earth surface.

The sensitivity analysis yielded the following results:

Range Tested	0.06	0.04	0.02
Max impact on Stage	0.52	baseline	-0.98

An additional check on the roughness was competed to inform the freeboard analysis. A value of 0.04 has been confirmed as an appropriate design value for the channel. In considering uncertainty an increase of 10% (to 0.044) has been tested and indicates a potential increase in water level of 0.13m (at the upstream end).

A decrease in roughness has an impact on velocities, with an increase in velocity up to values of 3.2m/s in the downstream reach (downstream of Mullenmore Bridge).

Bridge / channel constriction

A single span bridge is limited to a maximum span width 20m. The model geometry was modified to represent such a constriction in the channel cross sectional area. The results indicate a max rise in water level of 0.09m, due to Mullenmore Bridge.

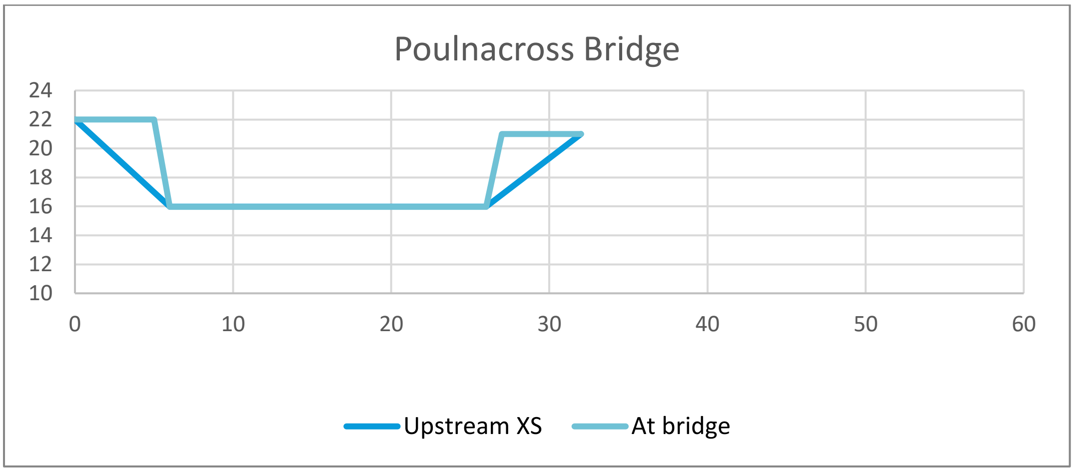
		water level results		
	chainage	no bridge	with bridges	Change in water level
DIV0200	980	18.46	18.47	0.02
DIV0097	970	18.43	18.45	0.02
Poulnacross			18.35	
DIV0095	950	18.46	18.46	0.00
DIV0072	720	18.06	18.06	0.00
DIV0049	490	17.62	17.62	0.00
DIV0026	260	16.91	17.00	0.09
Mullenmore			16.59	
DIV0022	220	16.59	16.59	0.00
DIV0012	120	16.45	16.45	0.00
DIV0000	0	16.44	16.44	0.00

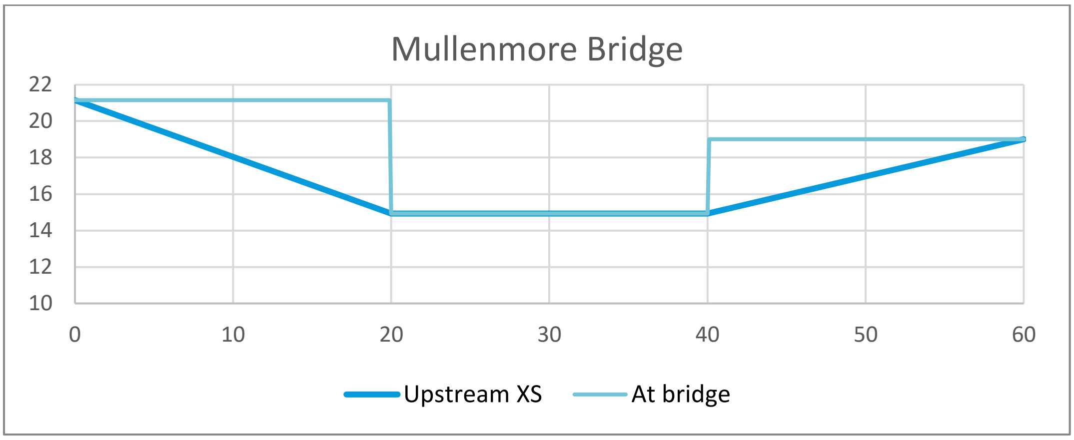
The following indicates the geometry assumed in the model with long profile levels, (downstream extent as zero chainage) and cross sections at the bridge locations.

Chainage	Bed Level
980	16
970	15.985
950	15.955
260	14.93
220	14.81
120	14.05

Chainage	Bed Level
0	13.135

The change in cross sectional area is represented in the graph below. Note that no soffit has been included and so afflux as a result of bridge soffits not represented in the model.

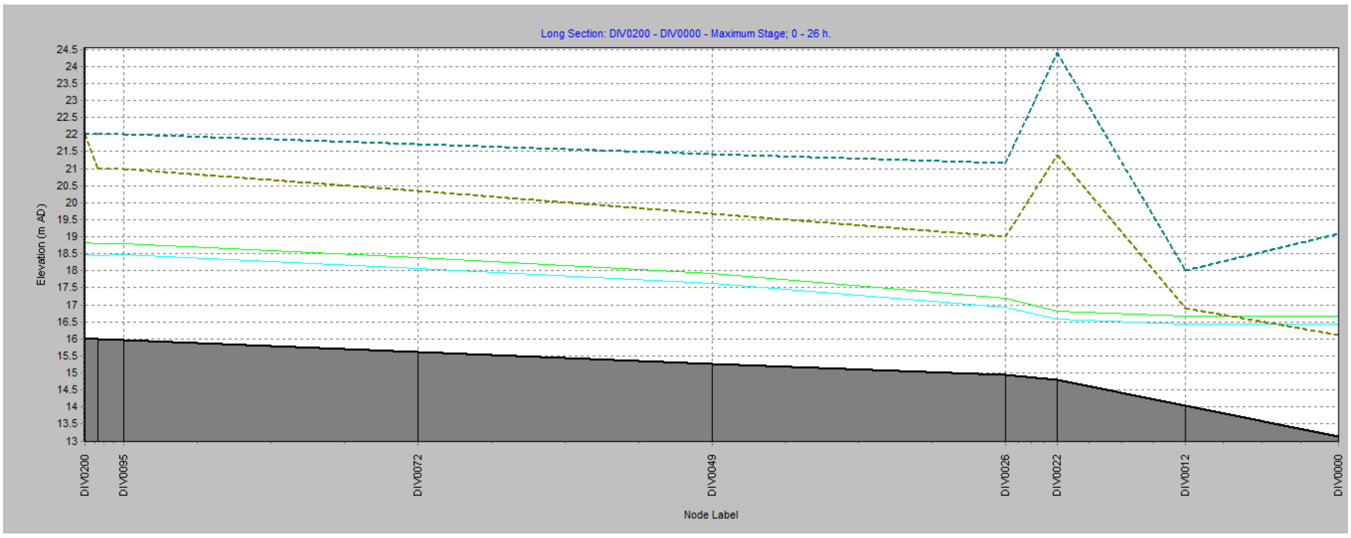




Flow

The model has been run for climate change scenario (MRFS). This is used to assess the impact on water level due to a 20% increase in river flow. The results indicate a rise in water level of 0.34m along the diversion channel.

Node	Chainage	Q100 Water Level	Q100 MRFS Water Level	Change in Water Level
DIV0200	980	18.47	18.81	0.34
DIV0097	970	18.45	18.79	0.34
DIV0095	950	18.47	18.81	0.33
DIV0072	720	18.07	18.39	0.32
DIV0049	490	17.63	17.92	0.30
DIV0026	260	16.92	17.19	0.27
DIV0022	220	16.59	16.80	0.21
DIV0012	120	16.44	16.67	0.22
DIV0000	0	16.43	16.66	0.23


Long Section: DIV0200 - DIV0000 - Maximum Stage; 0 - 26 h.
Elevation (m AD)
24.5
24
23.5
23
22.5
22
21.5
21
20.5
20
19.5
19
18.5
18
17.5
17
16.5
16
15.5
15
14.5
14
13.5
13
DIV0200
DIV0095
DIV0072
DIV0049
DIV0026
DIV0022
DIV0012
DIV0000
Node Label

Appendix F - Diversion Channel Model Report

References

2092/RP/001/A (January 2012) - Feasibility Report on the Crossmolina Flooding Problem, OPW

JBA (2014) Draft Hydrology and Modelling Report v4

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