

YGC, Cyngor Gwynedd Council
(CGC)

Barmouth North Promenade OBC

Barmouth OBC Flood Modelling Report

REP/

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1 Introduction

Ove Arup and Partners (Arup) were appointed in September 2018 by YGC, part of Cyngor Gwynedd Council (CGC), to deliver an Outline Business Case (OBC) for coastal risk management for the Barmouth North Promenade frontage.

1.1 Location and Background

Barmouth is located in Gwynedd on the west coast of Wales, north of the Afon Mawddach estuary. The North Promenade is the northmost section of the Barmouth developed frontage, extending from residential housing estate at Heol-y-Llan to the northern extent of the promenade wall.

The frontage comprises a mixture of hard defences, including a vertical sheet piled sea wall, a concrete platform, stone blockwork revetment and precast concrete wave recurve wall units, with secondary and tertiary setback walls. The northern end of the promenade is fronted by a shingle berm, whilst the southern end is fronted by a vegetated stabilised sand-dune. There are timber groynes in a poor condition, increasingly exposed towards the north. Defences deteriorate in condition towards the northern extent of the study area with beach lowering leading to undermining of the sea wall and access steps.

Coastal flooding is experienced during storm events, with barriers deployed to prevent overland pathways through access points in secondary and tertiary setback walls.

Whilst there are no Main Rivers in the study area, sources of local flood risk were identified during a site review and walkover. A large extent of the study area is shown to be at High Risk (>1 in 30 annual chance) of surface water flooding (see Figure 6). This is supported by feedback from the public stakeholder engagement event (March 25th) (see

Figure 17). In particular there are two ordinary watercourses (non-main river) noted to flow into the study area from the east (see Figure 6). These two watercourses are ungauged and it was assumed that they discharge to the sea via flapped outfalls and / or the pumped surface water system, discussed in subsequent sections of this report.

Previous studies have been completed to appraise and justify improvements to coastal risk management, but these have been insufficient to receive support by Welsh Government.

The approach to the wave overtopping modelling is provided in a separate note (ABPmer, 2019¹).

¹ ABPmer, (2019). Barmouth North Promenade, Wave modelling, extremes analysis and overtopping, ABPmer Report No. R.3105.

1.2 Policy Context

The West of Wales Shoreline Management Plan 2 (SMP2) (2011) sets out the policy for coastal risk management. Barmouth North Promenade (shown in Figure 1) is within Management Area 24 (MA24) and Policy Unit 15 of the SMP2 Policy Development Zone (PDZ) 11. The SMP2 sets a 'Hold the Line' policy for short term (0-20 year) however to change to 'Managed Realignment' in the 20-50 year, and 50-100 year epochs.

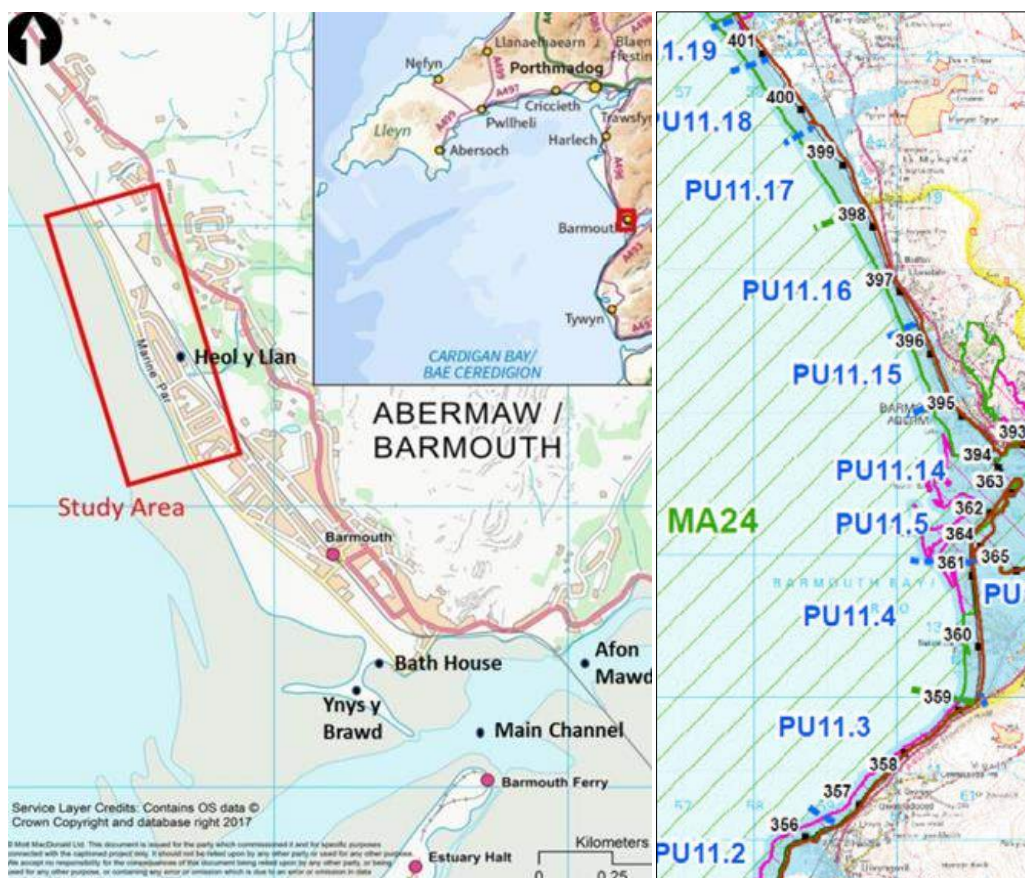


Figure 1 - Barmouth North Promenade study area [reproduced from Figure 1-1 in Barmouth North Promenade PAR Review, Mott MacDonald, February 2018], boxed insert showing Shoreline Management Plan Policy Units [Reproduced from West of Wales SMP2 Shoreline Management Plan Sub Cell 9 Baseline Location Map Policy Development Zone 11, Policy Development Coastal Area D, Royal Haskoning, 2011].

The rationale and context from the SMP2 is repeated below.

To the south the SMP2 policy for the area of southern Barmouth, Barmouth harbour and the access road to Barmouth is to Hold the Line. To the north the general policy at Llanaber Point would also be to Hold the Line. However, to the north end of Barmouth the SMP1 policy of Hold the Line is going to become increasingly difficult to sustain.

Consideration should be given to widening the overall defence system in this area. This may require nearshore or shore connected structures to reduce wave energy but is also likely to require some future realignment of the defences, quite probably with the loss of property. This would require a more integrated

approach to management, considering how the northern seafront could be developed to better advantage both in term of use and shoreline management. The SMP2 policy for the northern end of Barmouth would be to Hold the Line during epoch 1, but to change to one of Managed Realignment over epochs 2 and 3.

Whilst the Barmouth frontage through to Llanaber would be defined as three policy units, the policies need to be progressed as one overall area. The manner in which Llanaber Point is managed influences the way in which the north Barmouth frontage and the manner in which the apex between north Barmouth and south Barmouth is approached needs to be integrating management to both north and south. In all probability works will be needed to the north Barmouth frontage towards the end of Epoch 1. Planning for a more adaptive approach to management, therefore, needs to be undertaken during Epoch 1.

2 Objectives

The principle objectives of the Barmouth North Promenade OBC are to:

- Identify a preferred way forward to manage coastal risk at Barmouth North Promenade and make the case for further investment in accordance with Welsh Government guidance².
- Produce a robust OBC, informed by accurate modelling and a thorough understanding of the coastal processes and baseline conditions within this area.
- The requirement for proportionate evidencing of wider benefits, mapped against the Well Being of Future Generations Act³.

Figure 2 shows that much of the land immediately landward of the northern frontage is at risk of coastal flooding and is within either Flood Zone 2 or 3. Note that the Flood Zones extend slightly beyond the northern and southern ends of the area shown in Figure 1. Key receptors impacted by the risk of coastal flooding includes the infrastructure immediately behind the defences, pedestrians and other road users, land and property landward of the defences within the area at risk, infrastructure such as the Cambrian railway and services/utilities.

Inundation modelling is required to understand the extent of the coastal flooding and to consider the residual fluvial and surface water flood risk to inform the options assessment, and to support the economic appraisal through provision of flood depths and velocities for the assessment of flood damages.

The hydraulic modelling is required to provide flood depths for a range of return periods and epochs for flood risk management scenarios. These flood depths will be used in an assessment of flood damages to determine the economic benefits of flood risk management options as part of the options appraisal.

² Welsh Government, Flood and Coastal Erosion Risk Management – Business Case Guidance, June 2018

³ Well Being of Future Generations Act 2015 Available at: <http://futuregenerations.wales/about-us/future-generations-act/>

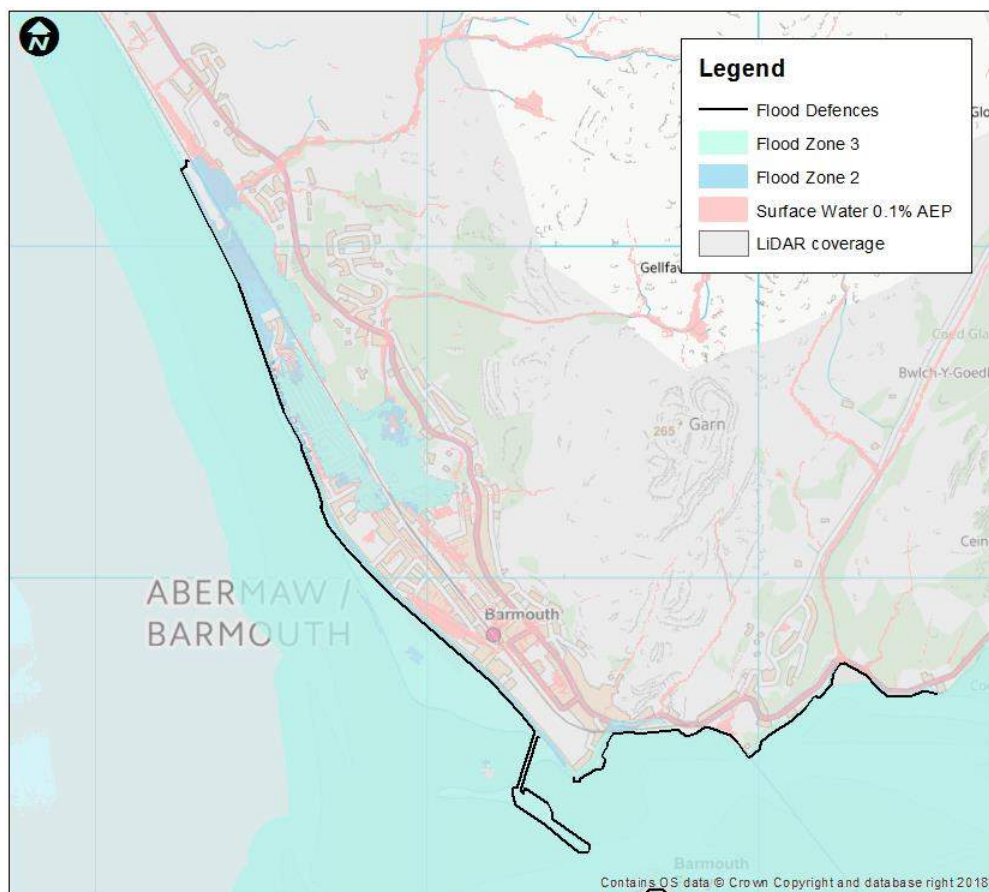


Figure 2 EA Flood Zones, Surface Water Flood Map and LiDAR coverage.

2.1 Project interfaces

Natural Resources Wales (NRW) provide a strategic oversight role for Flood and Coastal Risk Management. NRW prioritises its mapping and modelling work on a risk basis, using the Communities at Risk Register. They follow a nationally risk based and consistent approach. NRW are planning to complete coastal modelling and mapping improvements for Barmouth and Fairbourne in 2019/20⁴. Engagement with NRW was completed to exploit significant efficiencies by aligning objectives and scope where appropriate.

YGC, as Lead Local Flood Authority, take a lead in the management of local sources of flood risk (ordinary smaller watercourses, surface water and ground water). Cycle 1 Flood Risk Assessments in Wales will be reviewed as part of a detailed consolidated Preliminary Flood Risk Assessment for Gwynedd that will cover all sources of flood risk by December 2018⁵. Emerging findings were requested to inform option long-listing and short-listing however YGC advised there were no significant implications.

⁴ <https://cdn.naturalresources.wales/media/683744/wales-coastal-flooding-review-closure-report-december-2017.pdf?mode=pad&rnd=131594634380000000>

⁵ <https://www.gwynedd.llyw.cymru/en/Residents/Documents-Residents/Parking,-roads-and-travel/Flood-and-Coastal-Risk-Management/Gwynedd-PFRA-phase-1-review-questionnaire-Part-4.pdf>

3 Previous modelling

Previous studies have modelled coastal overtopping and flood inundation at a range of locations along the Barmouth frontage including:

- Barmouth North Promenade PAR – Appendix F: Overtopping Flood Modelling, Final Report, Martin Wright Associates, June 2014. Civil Engineering Solutions UK (CESUK) were commissioned to prepare a flood inundation TUFLOW model from predicted overtopping of the coastal frontage along the northern sections of Barmouth Promenade for seven return periods.

The subsequent Barmouth North Promenade PAR Review (Mott MacDonald, 2018) identified the following shortcomings with the 2014 PAR Overtopping Flood Modelling:

- A review of the wave model is required to ensure correct overtopping rates are applied.
 - The model domain did not extend sufficiently far to contain the flood cell, particularly at the north end of the study area. This is not a topographic feature and therefore flow paths towards and from the northern section of the frontage are not considered. This prevents flow paths to and from the northern section to be appropriately considered.
 - Flood extents are presented for seven return periods however sea level rise scenarios are not addressed.
 - General lack of detail in the modelling report, with no further details about model setup, calibration, validation or any sensitivity analysis.
- Barmouth Viaduct Gardens – Overtopping Assessment and Review, CESUK, March 2018. The viaduct gardens lie to the south of the North Promenade OBC study area. The overtopping study derived wave conditions and associated overtopping rates for present day climate return periods for the viaduct gardens frontage. The 1:200yr mean overtopping rate is 3.73m³/s per metre run of defence. There is no mention of inundation modelling within the report so it is assumed this was not undertaken. The ‘Discussion of Results’ chapter provides indicative return period ranges for the storms of November 2011 and January 2014, which may prove useful for validation of the North Promenade inundation model results.
 - Barmouth North Channel Options Study - Overtopping Assessment, CESUK, February 2018: (potential for reinstatement of Bar Bach channel). This study assessed the changes in overtopping that would result from re-opening a nearshore channel at the south end of the frontage between the shoreline and the current offshore breakwater of Ynys-y-Brawd that is linked to the shoreline by a concrete causeway. The channel lies towards the south of the North Promenade OBC study area. The overtopping study derived wave conditions and associated overtopping rates for present day climate return periods with and without the Bar Bach channel and identified

that overtopping would reduce with the Bar Bach channel re-opened. No overtopping was predicted for sections with wave return walls for storms from the NW sector. There is no mention of inundation modelling within the report so it is assumed this was not undertaken. However, the ‘Discussion of Results’ chapter provides some potentially useful commentary on anticipated flooding mechanisms and the presence of walls. This is only relevant to the North Promenade OBC if our inundation results show flooding could extend this far south.

4 Scenarios modelled

4.1 Development of Baseline scenario

In order to undertake an economic appraisal of potential coastal improvement measures, it is customary to compare the benefits of any ‘Do Something’ options to the baseline scenarios representing the ‘Walkaway’ (i.e. ‘Do Nothing’) and the ‘Business As Usual’ (i.e. ‘Do Minimum’). It is customary to undertake inundation modelling of all three scenarios across the present day and future epochs. However due to similarities between the baseline Walkaway and Business As Usual Scenarios, the modelling approach taken has been, conservatively, to consider the Business As Usual as the ‘Baseline’ Scenario going forward. This is discussed further below.

4.1.1 Walkaway Scenario

The ‘Walkaway’ or ‘Do Nothing’ scenario assumes that no maintenance is carried out and that any defences are allowed to progressively deteriorate. Along the Barmouth north promenade, the sea-wall and revetment have been identified to be in a poor condition, and with a continued reduction in beach levels anticipated over the next 10-year period, it has been **proposed that the residual life of the sea-wall and revetment is less than 10 years⁶**.

Due to the frequency of expansion joints (at approximately 10m centres) it is reasonable to assume that, as the wall degrades over time, any breaches in the primary sea wall will be in 10m increments. The secondary and tertiary wave walls are unreinforced masonry structures and do not currently function as effective flood defences. The secondary wall is too close to the primary wall to contain overtopping. The tertiary wall has several access points where flood boards or gates are set in place in advance of storms. Evidence from previous storm events indicates that both walls have a history of repeated failures and breaches (Figure 3). Adhoc repairs after each storm have been implemented.

⁶ Existing Coastal Defence Review technical note (Arup, 2018).



Figure 3 Storm damage to secondary and tertiary wave walls following 2014 storm surge (photo credits top left: NRW, top middle: Hugh Griffith Roberts, top right: Sam Jones, bottom left: Allison Brooker, bottom middle: Aaron Hughes, bottom right: Richard Burt Birdy).

Table 1 sets out the assumptions regarding a Walkaway (Do Nothing) scenario.

Table 1: Walkaway (Do Nothing)

Factor	2019	2069, 2119
Beach	Profile assumed as existing survey based on composite LiDAR from 2014.	Profile amended to reflect findings from coastal process study (average draw down).
Primary wall	Wall profile removed from overtopping assessment for defined stretches to reflect 'breach'.	
Secondary wave wall	Wall with aggregated drainage holes represented based on 2018 topographic survey. Removed for defined stretches to reflect 'breach'.	
Tertiary wave wall	Wall represented based on 2018 topographic survey. Removed for defined stretches to reflect 'breach'. Flood gates/board not deployed.	
Measures managing local sources of flooding	Surface water pumping station and surface water outfalls' flap valves not functioning.	

4.1.2 Business As Usual Scenario

The 'Business As Usual' or 'Do Minimum' scenario assumes that the present beach management regime will continue, with repairs to the existing defences as they become necessary. Measures to protect or replace the sheet pile section and arrest the abrasion/ corrosion are likely to be significant and not considered to be a business as usual intervention. The Existing Coastal Defence Review technical note (Arup, 2018) judged that continued loss of the structural section results in an **expected residual life of the sea-wall and revetment of less than 20 years**.

Table 2 sets out the assumptions regarding a Do Minimum scenario.

Table 2: Business As Usual (Do Minimum)

Factor	2019	2069, 2119
Beach	Profile assumed as existing survey based on composite LiDAR from 2014.	Profile amended to reflect findings from coastal process study (average draw down).
Primary wall	Wall profile reflected in overtopping assessment.	Wall profile removed from overtopping assessment for defined stretches to reflect 'breach'.
Secondary wave wall	Wall with aggregated drainage holes represented based on 2018 topographic survey. Removed for defined stretches to reflect 'breach'.	
Tertiary wave wall	Wall represented based on 2018 topographic survey. Removed for defined stretches to reflect 'breach'. Flood gates/board deployed.	
Measures managing local sources of flooding	Surface water pumping station and surface water outfalls' flap valves represented and functioning. Subsequent site visit identified that the flap valve of the northern outfall was damaged and has been removed.	

4.1.3 Resulting Baseline Scenario Modelled

The 'Walkaway' and 'Business As Usual' scenarios are sufficiently similar that the adopted modelling approach was to take the 'Business As Usual' scenario as the baseline for the present day and future epochs and to undertake sensitivity testing of the Walkaway scenario including:

- Not operating tertiary flood wall gates/boards.
- Measures to manage local sources of flooding not functioning (namely the existing pumping station).
- Breaches of the primary wave wall.

Table 3 summarises the adopted baseline arrangement for each existing risk management feature for each epoch.

Table 3: Modelled baseline

Factor	2019	2069, 2119
Beach	Profile assumed as existing survey based on composite LiDAR from 2014.	Profile amended to reflect findings from coastal process study (average draw down).
Primary wall	Wall profile reflected in overtopping assessment.	Wall profile removed from overtopping assessment for 2No. 10m stretches to reflect 'breach' (See Figure 4).
Secondary wave wall	Wall with aggregated drainage holes represented based on 2018 topographic survey. Removed for 4No. 50m stretches to reflect 'breach' (See Figure 4).	

Factor	2019	2069, 2119
Tertiary wave wall	Wall represented based on 2018 topographic survey. Removed for defined stretches to reflect 'breach' 4No. 50m stretches to reflect 'breach' (See Figure 4). Flood gates/board deployed .	
Measures managing local sources of flooding	Surface water pumping station and surface water outfalls' flap valves functioning .	



Figure 4 Breach assumptions for baseline scenario model representation.

4.2 Development of Do Something scenario

The shortlisting stage identified three Do-Something options, beyond the Walkaway/Business As Usual (Option 1) for consideration:

- Option 2 – Betterment of existing defences, including improving the primary wave wall, tertiary and secondary flood defences and refurbishment and enhanced protection to the primary defences (with the addition of a rock toe or shingle beach profile).

- Option 3 – Enhanced beach management, supported by groyne or breakwater structures.
- Option 4 – Managed Realignment – i.e. a new line of defence set back to beyond the existing defence structures.

To understand the performance of the proposed options:

- Option 2: we examined the relationship between wave overtopping and the crest level of the primary defence wall (with an addition of a rock toe or shingle beach profile) to explore options to reduce the risk of overtopping along Barmouth North Promenade. This was undertaken at two locations - Profile 1 at the northernmost extents of the frontage and Profile 7 opposite the Heol-Y-Llan Housing Estate⁷. Optimum primary defence heights were assessed, based primarily on reducing the risk to coastal overtopping, cost and amenity/visual constraints. Further improvements were considered to the tertiary wave wall.
- Option 3 and Option 4: Supported by the overtopping and inundation modelling, further studies were undertaken to understand the implications and form of Option 3 (Beach Management) and Option 4 (Managed Realignment)⁸. Different defence construction options, alignments and phasing were considered within the short-listing economic assessments through changes to the option costs. These options did not involve any additional inundation modelling.

The preferred outcome from a Do Something Option is to limit coastal inundation to levels to be decided.

Due to the high existing coastal flood risk, overtopping rates for higher wave and water level conditions (see section 7.7.2 for further information) it has not been possible to assess the coastal flood risk for all baseline return periods; this similarly applies to the Do Something scenarios.

4.2.1 Residual Risk of Do-Something Option

It is recognised that the do-something options proposed as part of the OBC only reduce the risk of coastal inundation. However, there is a surface water flood risk still present within the study area. Recognising this, the residual surface water flood risk was modelled to understand the residual implications of a scheme and support the economic assessment.

The residual risk from coastal inundation at the southern end North Promenade primary defence was considered to be minimal - the plans in Appendix A show that coastal inundation over the profiles 30 and 60 is negligible for all return periods up to the maximum modelled event in 2069 (combined 1 in 100yr coastal dominated event). The 'Do Something' inundation model therefore utilised the baseline model and inputs, and applied zero wave and tidal overtopping to

⁷ Please refer to Appendix B 2019 ABPmer's Wave Modelling Report for further information.

⁸ Please refer to Appendix I for further information.

represent the prevention of inundation from coastal sources up to the standard of protection being assessed. This is discussed further in Section 10.

4.3 Application of Wave Overtopping Profiles

The ABPmer Wave and Overtopping Modelling (see Appendix B) provided five wave overtopping profiles (Profile 1, 7, 10, 30 and 60) at different locations along the promenade. Please refer to Section 7.7.2 for further information.

Figure 5 shows the locations of each of the profiles at which wave overtopping was applied for both the baseline and do something scenarios, along with the location of the SMP2 boundary between North and South Barmouth. The figure shows that profile 7 extends slightly beyond the boundary of the North Barmouth SMP2 zone. The profile extent was based on the location of the beach dunes and their relation to the anticipated worst-case wave approach to the primary wall, it was therefore felt that location of the profile extent was justified.



Figure 5 Location of wave overtopping profile sections and SMP2 boundary. Wave overtopping applied to all 5 profiles for baseline scenarios. Wave overtopping only applied to profiles 30 and 60 for the Do Something scenarios. The North Promenade study area extends from the northern end of Profile 1 to the SMP2 Policy Unit boundary.

5 Modelled return periods and epochs

5.1 Overview of return periods and epochs

Modelling has been undertaken to support the OBC economic analysis. This required damages to be assessed to enable present value damages to be calculated for the 100 year appraisal period. A range of return periods were required to enable accurate Annual Average Damages to be estimated.

Three epochs were selected across the 100 year appraisal period in order to assess flood risk at different stages throughout the period. The epochs selected were 2019 (present day), 2069 and 2119. Model results from each epoch then contributed to the damage assessment; further details of this methodology can be found in Appendix X Economic technical assessment. For each epoch the following return periods were modelled: 1 in 1yr, 1 in 10yr, 1 in 50yr, 1 in 100yr, 1 in 200yr, 1 in 1000yr.

The main source of flooding to the OBC area is from the coast via tidal and wave overtopping of the frontage. As discussed in Section 1.1, surface water risk has also been considered which led to the joint probability approach as described below.

5.2 Joint probability approach

A joint probability approach was applied to consider the combined impact of coastal and surface water (rainfall) inputs. To derive all possible pairs of coastal and rainfall return periods that could occur concurrently for a given return period, the desk study method from the Defra / Environment Agency Joint Probability guidance⁹ was applied (see North Prom Barmouth JPA Combinations technical note, Arup 2018 for further details of the JPA analysis undertaken). This approach led to 60 combinations of coastal and rainfall inundation simulations.

Given the coastal focus of the outline business case it was agreed to rationalise the approach to joint probability of coastal and surface water flooding to reflect the study's objectives while maintaining a robust approach to support the outline business case. Table 4 presents the rationalised return period joint probability pairs.

Table 4 Pairs of coastal and rainfall return period (RP) for each combined RP for the baseline scenario.

Scenario	Combined RP	2019		2069		2119	
		Coastal RP	Rainfall RP	Coastal RP	Rainfall RP	Coastal RP	Rainfall RP
Baseline	1	1	0	1	0	1	0
		0	1				
	10	10	0	10	0	10	0
		0	10			0	10
	50	50	0	50	1	50	1
		0	50			1	50
	100	100	1	100	2	100	2
		1 (2) *	100	1 (2) *	100	1 (2) *	100
	200	200	2	200	4	200	4
		1 (2) *	200			1 (2) *	200
	1000	1000	8	1000	16	1000	16

⁹ Joint Probability: Dependence Mapping and Best Practice Technical Report FD2308, Defra / Environment Agency, 2005.

Scenario	Combined RP	2019		2069		2119	
		Coastal RP	Rainfall RP	Coastal RP	Rainfall RP	Coastal RP	Rainfall RP
Sensitivity test 0 – baseline interim return periods - SW management performance	100	10	8				
Sensitivity test 1 - Baseline with no flood gates/boards	100	100	1				
Sensitivity test 2 - Baseline with measures to manage local sources of flooding not functioning	10	0	10	0	10		
	50	0	50	0	50		
Sensitivity Test 3 - Baseline with breaches of the primary wave wall	10*	10*	0				
Sensitivity test 4 – Do-something with beach management measures	100			100	1	100	1

* Note: Available coastal flood return periods are available and so substitution has been proposed (shown within brackets).

Table Key

	Coastal dominant simulation – primary outline business case focus
	Surface water dominant simulation – to test residual risk
	Intermediate combined return period
	NNT limited return period

Within Table 4 there are several combinations which are highlighted in purple. This reflects the return periods that were initially planned to be modelled but where, owing to the Neural Network Tool (NNT) limitations¹⁰, there was insufficient data to model the coastal component of inundation. These return periods were therefore excluded from the study.

6 Climate change assumptions

The economic case requires that the economic impact of flooding is considered over the 100-year appraisal period. Section 5 shows that return periods modelled included events in 2069 and 2119. It was therefore necessary to apply assumptions regarding climate change in the flood modelling to both sea level and rainfall inputs to represent anticipated uplifts due to the effects of climate change

¹⁰ Please refer to Appendix B 2019 ABPmer's Wave Modelling Report for further information.

as recommended by Welsh Government guidance¹¹. Climate change assumptions were applied to wave overtopping calculations, which is reported separately.

6.1.1 Increases to rainfall

For the purposes of this study it was agreed to use the central estimate as highlighted in Table 5, thus 10% for 2069 and 20% for 2119. These allowances were applied to the rainfall hyetographs rather than the fluvial inflows due to the surface water nature of the study area and small catchments which are less than 1.5km² each in area.

Table 5 - Change to extreme rainfall intensity compared to a 1961-90 baseline. As with river flood flows, it is recommended that the 2080s changes are used when considering any time beyond 2115. The peak rainfall intensity ranges should be used for small catchments and urban/local drainage sites. For river catchments over 5km², the peak flow ranges should be used.

Applies across all of Wales	Total potential change anticipated for 2020s (2015-2039)	Total potential change anticipated for 2050s (2040-2069)	Total potential change anticipated for 2080s (2070-2115)
Upper estimate	10%	20%	40%
Central estimate	5%	10%	20%

6.1.2 Sea Level Rise

Tidal water levels were applied to the model, discussed later in Section 7.7.1. Allowances for climate change were applied to the 2019 baseline tidal data using uplift values in the model boundary condition database to account for the anticipated rise in sea level due to the effects of climate change. The changes to relative mean sea level were derived from Welsh Government guidance¹¹ and are shown in Table 6.

Table 6 - Sea level rise (SLR) increases to apply to tidal water levels. Based on 2008 base year.

Modelled year	Allowance applied (m)
2019	0.039
2069	0.422
2119	1.099

7 Baseline inundation model

To inform the economic case of the OBC for North Promenade Barmouth, a coastal flood inundation model has been developed. It covers the study frontages and determines flood routes, depths and extents; these have been mapped accordingly. The modelling provides flood water level, velocity and hazard information for the economic analysis of flood damages, which informs a cost benefit analysis for the OBC. The assumptions and limitations are set out below.

¹¹ Adapting to Climate Change: Guidance for Flood and Coastal Risk Management Authorities in Wales. Welsh Government, December 2017.

7.1 Model type

The 2D flood inundation model was developed as a TUFLOW 2D inundation model and has been simulated using the latest available version at the time the model build commenced (2018-03-AB).

This model represents overland flows; it does not represent flows in the underground drainage system aside from the infrastructure identified in Section 7.5 and an allowance for urban drainage losses as discussed in Section 7.7.4.

A 2D TUFLOW model is considered appropriate for representing flood inundation caused by overtopping of the frontage and surface water caused by rainfall and overtopping of rivers as it can represent overland flow routes and determine the spatial variation in flood depths, hazard and velocities across the study area which can then be mapped accordingly to support the economic appraisal.

7.2 Flood sources

The model considers the prevalent coastal flood risk from the North Promenade jointly with the risk from surface water flooding arising both from fluvial and direct rainfall sources.

Whilst there are no Main Rivers in the study area, sources of local flood risk were identified during a site review and walkover. A large extent of the study area is shown to be at High Risk (>1 in 30 annual chance) of surface water flooding (see Figure 6). In particular, there are two ordinary watercourses (non-main river) noted to flow into the study area from the east (see Figure 6). These two watercourses are ungauged and it is assumed that they discharge to the sea via flapped outfalls and / or the pumped surface water system, discussed in subsequent sections of this report.

The two watercourses were not explicitly included in the model; however, the infrastructure identified in Section 7.5 was included. Joint probability analysis was undertaken to determine the possible coastal and surface water conditions that could occur together for a given return period as discussed in Section 5.2.



Figure 6 Location of two non-main watercourses flowing east to west into study area with surface water flood risk (high, medium and low risk) areas shown in (dark to light) orange.

7.3 Model extent and resolution

The model extent was based on the study area requirements, the extent of relevant surface water catchments, and the extent of the flood cell identified using LiDAR data. To address a key limitation of the 2014 PAR modelling, the model was extended far enough north to ensure appropriate representation of flow into / out of the flood cell at the northern end of the frontage. The model was also extended inland and to the south to a sufficient distance to ensure that all potential impacted areas are included, where possible, to facilitate a robust economic assessment, and to limit artificial ‘glass-walling’ against the edge of the model.

LiDAR and Nextmap digital terrain data were used to identify the catchment areas which drain into the two watercourses within the study area. These were used to derive the fluvial inputs to the model area, and the model boundary was extended to a suitable location at which to apply these inflows (see Figure 7). Areas that do

not drain into the two watercourses but from which rainfall runoff could contribute to surface water impacts were included in the model extent. These are represented as the 'Intermediate' catchments in Figure 7.

Figure 4 shows that the model extent does not include all of the 'Intermediate B' catchment area. The extent has been cropped in this location to match the extent of the 1m LiDAR DTM, which is unavailable further inland. The use of Nextmap 5m LiDAR was considered, however the discrepancies between the two datasets were too great and caused the model to display erroneous ponding of surface water at the top of the catchment. To account for the direct rainfall 'lost' by cropping the model extent, a multiplication factor has been applied to the top of the Intermediate B catchment so that the surface water inputs to the model are representative of the entire 'Intermediate B' catchment.

The adopted model extent is shown in Figure 7 together with the fluvial and rainfall catchment areas.

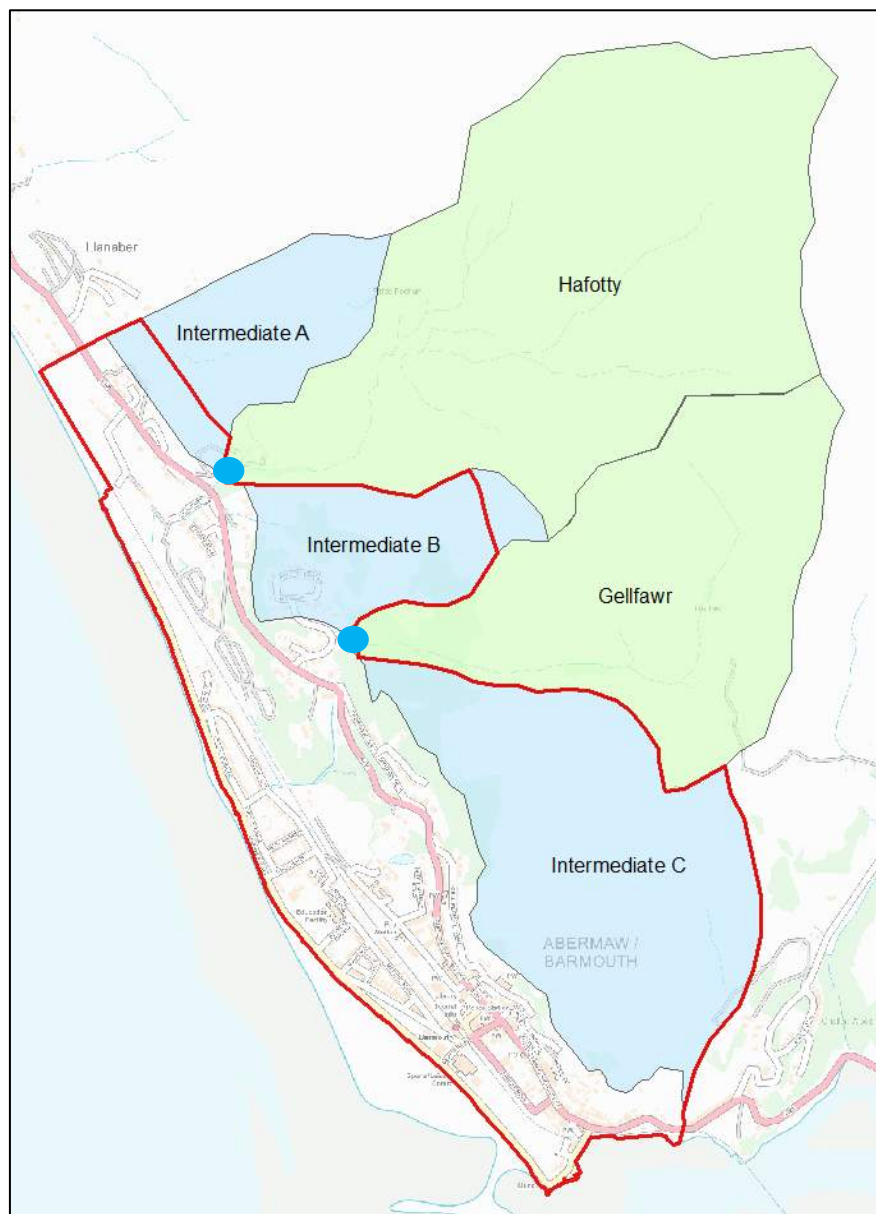


Figure 7 Barmouth 2D inundation model extent (red outline). Fluvial catchments relating to the two watercourses shown in green, with intermediate surface water 'catchments' shown in blue. Blue dots indicate the locations of fluvial inflows to the model.

The seaward boundary of the model was aligned along the existing frontage and primary (front line) defences, which it was assumed correspond approximately to the locations where waves would break during storm conditions.

The model resolution was set to 3m, which was considered sufficient to represent flow routes through the developed land behind the defences including flow routes along roads and other infrastructure. The effect of model resolution was sensitivity tested, which supported the adoption of 3m resolution (see Section 8).

7.4 Topography

The Welsh Government's composite LiDAR DTM data at 1m resolution was used to provide model elevation information. The data originates from a LiDAR survey flown in March 2014; the age is considered representative of current ground levels. Figure 8 shows LiDAR coverage of the study area and highlights the steep nature of the topography, particularly inland, with a narrow coastal platform that contains most of the built-up area of Barmouth.

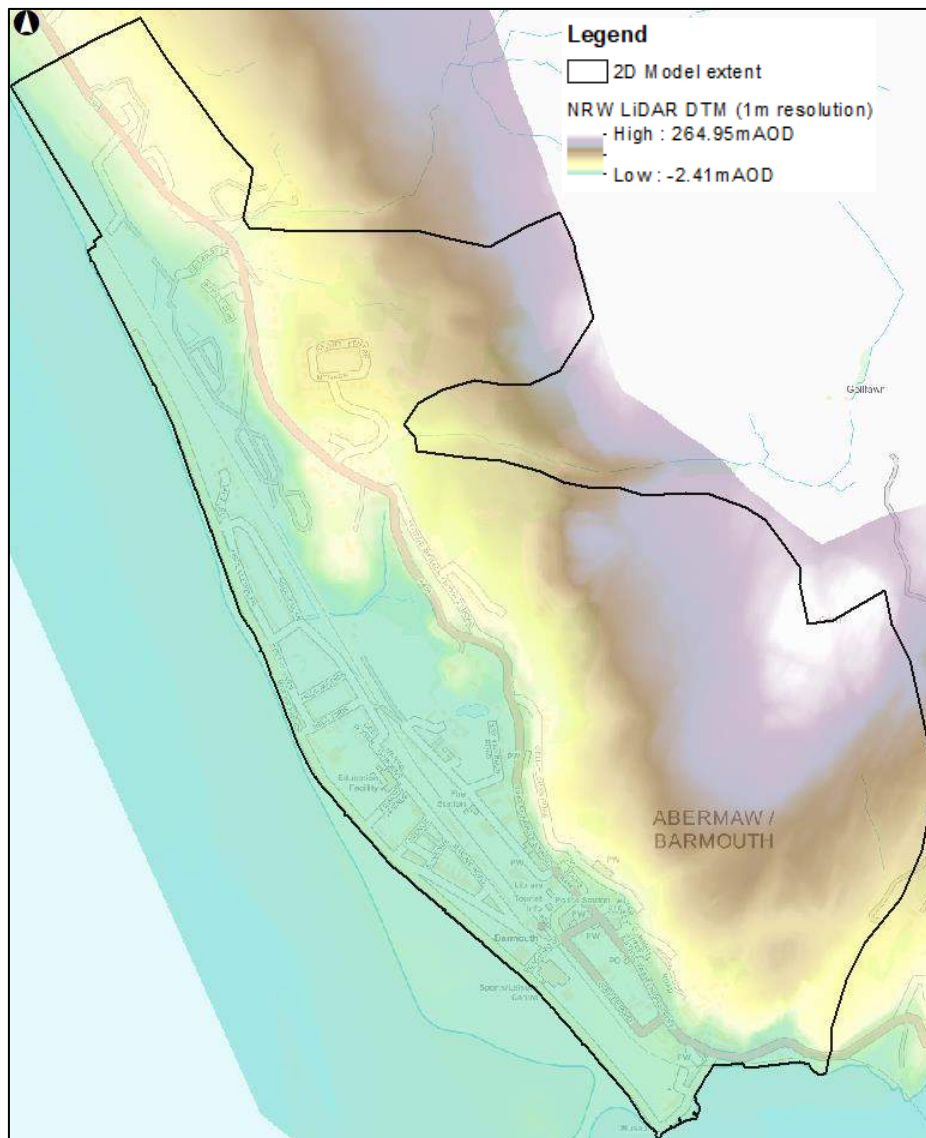


Figure 8 LiDAR DTM indicating topography of Barmouth study area.

Elevations range from 264mAOD at the top of the hill near to Cell-Fechan farm, to 3.5mAOD along the frontage at the harbour. Between the coast and the A496 the topography is relatively flat; with elevations averaging from 4m to 10mAOD, and low points of 2.8mAOD at the caravan site inland of the railway embankment. This means that any flood water that reaches these areas is likely to pond and cause inundation.

Barriers to flow were identified using LiDAR and topographic survey collected in September 2018 including the primary, secondary and tertiary walls along the northern promenade frontage, and the railway embankment. Topographic survey was collected for the three wave walls from the northern end of the promenade to the railway embankment at Viaduct Gardens. Data from the survey were used to provide crest elevation values applied to separate breaklines within the 2D model grid. Average crest levels for the primary wall ranged from 5.8mAOD in the north to 3.5mAOD in the south adjacent to the harbour.

It was assumed that the demountable defences such as flood barriers at Heol Y Llan are operated and in the closed position for all options except for the relevant sensitivity test scenario (see section 5.2).

For the railway embankment, the breakline elevation was set to the elevation of the hard ground below the ballast, which was assumed to be 300mm below the top of the ballast level. The effect of the ballast on flows was represented by setting the ballast to have a higher roughness value (Manning's 0.3).

7.5 Specific flow routes

7.5.1 Structures and outfalls

Underpasses and culverts, which provide flow routes under the railway and other infrastructure, were represented using 1D culvert elements embedded in the model, which were linked to the 2D model grid. YGC provided locations and dimensions including inlet and outlet diameter / width, elevation and height for many of the culverts, however a number were inaccessible due to their location within private land or due to being obscured by overgrown vegetation. Where these inaccessible culverts were required for the model, geometry was estimated using OS mapping, aerial imagery and LiDAR. Table 7 details culverts included in the model with their locations shown in Figure 9.

Table 7 Culvert references, locations and geometry

Culvert reference	Location	Diameter (mm)	Width (mm)	Height (mm)	Inlet invert (mAOD)	Outlet invert (mAOD)
A	Pumping station to outfall	900			1.216	1.216
B	Culvert under railway at Heol-Y-Llan		1500	1250	2.41	2.25
E	Culvert under A496 at Mynach Road		1500	1350	29.23	19.88
G	Footbridge at northern end of caravan site	450			3.392	3.321
H	Footbridge at northern end of caravan site		800	200	3.313	3.267
I	Culvert under access road within caravan site	900			3.4	3.389
J	Culvert under access road within caravan site		1600	1350	5.2	5.161
L	Culvert under access road within caravan site	300			2.699	2.68
M	Culvert and outfall adjacent to Promenade café	500			2.933	1.3
O	Culvert under A496 north of Ceilwart Lane	1500			31.88	27.66
P	Small culvert on private land near Ceilwart Ganol farm. Geometry estimated from LiDAR	500			48.73	46.83
Q	Small culvert on private land near Ceilwart Ganol farm. Geometry estimated from LiDAR	500			46.15	45.1
R	Culvert under A496 south of Ceilwart Lane	300			35.98	16.29

Culvert reference	Location	Diameter (mm)	Width (mm)	Height (mm)	Inlet invert (mAOD)	Outlet invert (mAOD)
NR1	Not surveyed - no access due to Network Rail boundary. Geometry estimated from LiDAR	500			4.02	3.84
NR2	Not surveyed - no access due to Network Rail boundary. Geometry estimated from LiDAR	300			3.75	3.65
NR3	Not surveyed - no access due to Network Rail boundary. Geometry estimated from LiDAR	300			2.53	2.506
NR4	Not surveyed - no access due to Network Rail boundary. Geometry estimated from LiDAR	500			2.27	2.26
Holding pond	Culvert from holding pond to pumping station		900	900	1.779	1.629



Figure 9 Location of culverts included in the TUFLOW model.

Two flapped outfalls were identified from OS mapping and LiDAR and included in the model as 1D tidal boundary connections at the end of culvert M and at the outfall of the pumping station discussed in Section 7.5.2. These two culverts were designated as 'CU' type culverts to represent the operation of the flap in maintaining one-directional flow. These flapped outfalls were assumed to be maintained and operational in all modelled scenarios except for the relevant sensitivity test (see Section 5.2).

7.5.2 Surface water pumping station

Part of the surface water drainage system is pumped during periods of tide locking. This pump operates under the promenade near to the Heol-y-Llan estate (Figure 10).



Figure 10 Pumping station on North Promenade.

This pump has been explicitly represented in the model using a pump in the 1D network and a control file that references specified operating rules. A total of 5 culverts were used to represent the pumping system, from the holding pond to the outfall at the beach (see Figure 11).

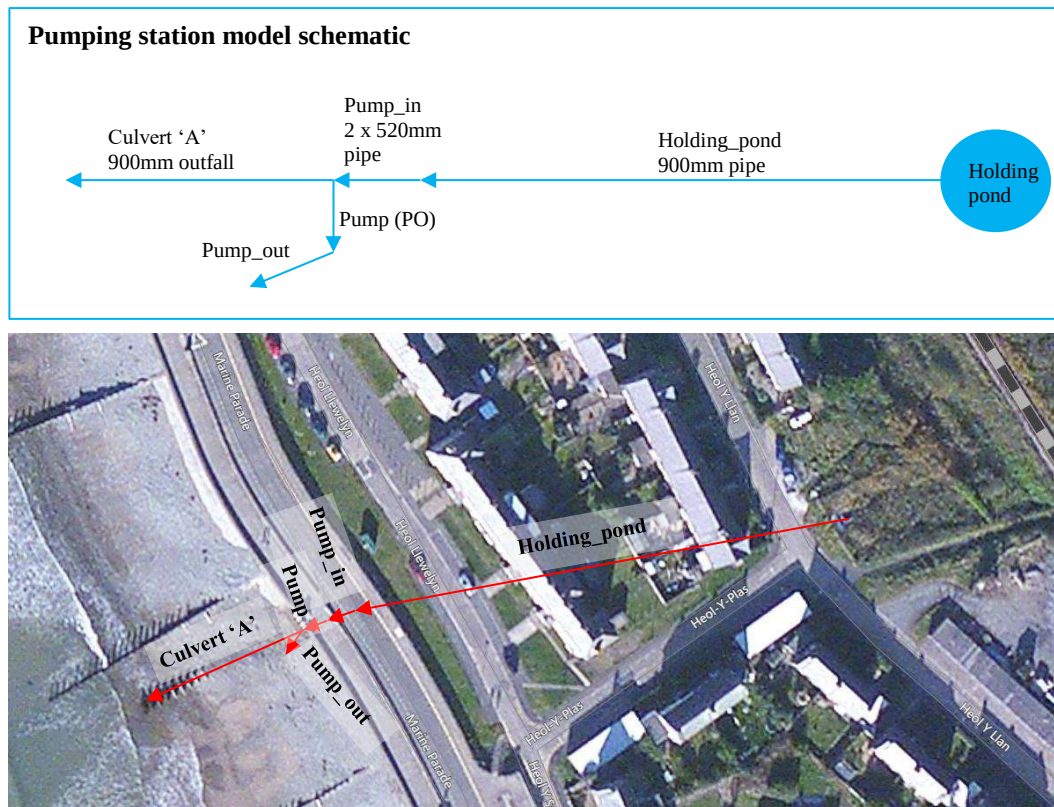


Figure 11 Location and model schematic of surface water pumping station culvert network.

The pumping station geometry was derived from LiDAR and information provided by YGC including the pumping station refurbishment report (Report ref: 2304¹²). The invert levels for the 5 culverts were assumed to equate to the information provided by the YGC culvert survey (2018) where possible, as this represented the most up to date data. These levels were available for the holding pond and outfall (pump_out / culvert A) inverts. The pumping station report also contained invert levels, however these were significantly higher than the most recent survey. It was assumed that the differences between invert levels for the 5 culverts within the system were accurate in the pumping station report and the percentage difference between these levels was therefore applied to the 2018 survey data to interpolate the intermediate culvert inverts (see Table 8).

Table 8 Pumping station network culvert invert estimation.

Culvert network ref.	Pipe number	Pipe size (mm)	Invert (2018 YGC culvert survey used for first and last value; % change from Pumping station report used to estimate intermediate values) (mAOD)	Invert from pumping station report 19981201-1265-Richard Broun Technical Report (mAOD)	(%) decrease between the holding pond and the pump inlet invert levels, and the pump inlet and outlet invert levels from the Pumping Station Technical Report.
Holding_pond	1	900	1.779	6.071	
Pump_in	2	520	1.629	5.56	8.42
Pump	1	1040	1.216	4.15	25.36
Pump_out	1	900	1.216		
Culvert A	1	900	1.216		
Downstream/outfall invert			1.152		

The pumping station was assumed to have a capacity of 208l/s with a total of 4 pumps (3 in operation and 1 on standby) where water flows via gravity at low tide with the pumps operating when the tidal water level reaches the pipe invert level (as advised via email communication from YGC in December 2018). A trigger level of 1.216m tidal water level was adopted (see Table 8), which was taken to be the invert level of the gravity discharge culvert. The default operation for the pump was set to 'off' unless the tidal water level reached the trigger level. A culvert was also included in the model to represent bypass gravity discharge as TUFLOW does not allow flow through the pump when the pump is set to 'off'.

7.5.3 Open channels

No major open channels were added to the model as it was considered that the two small watercourses were sufficiently represented in the LiDAR DTM.

¹² Refurbishment of Heol Y Llan Pumping Station Barmouth. Richard Broun Associates. December 1998 Ref: 2304 (CGC).

7.6 Representation of buildings

Fixed buildings, including static caravans, were set to a high Manning's n roughness value of 1 to represent the significant reduction in flow velocities through buildings compared to around buildings.

The baseline model was also tested with a threshold height of 150mm above ground levels applied at buildings. This resulted in lower flood depths across the property footprint but no significant difference in flood depths adjacent to buildings than using the roughness approach alone. Water levels were not sensitive to the application of threshold height and it appropriate to apply the high Manning's value only. This provided a conservative approach to estimating flood damages during the economic assessment.

7.7 Boundary conditions

In order to model coastal inundation and consider the joint probability of surface water flooding, four inflow boundary types were required:

- Tidal water levels
- Wave overtopping flows
- Fluvial hydrographs
- Rainfall hyetographs.

7.7.1 Tidal water levels

Water level vs. time tidal curves were derived for the range of return periods and epochs to be assessed (see Table 9); these were applied in the TUFLOW model along the seaward boundary of the model, which was aligned along the line of the primary defence crest; the model automatically calculates inflows into the model based on the water level and the frontage or defence level.

Table 9: Maximum tidal water levels (mAOD) for coastal return periods and epochs to be assessed.

Return period	2019	2069	2119
1:1	3.52	3.94	4.62
1:10	3.86	4.28	4.96
1:50	4.07	4.49	5.17
1:100	4.15	4.57	5.25
1:200	4.24	4.66	5.34
1:1000	4.43	4.85	5.53

7.7.2 Wave overtopping flows

Joint probability wave and water level pairings were derived by ABPmer for the range of return periods and epochs to be assessed (Table 9). The worst-case combination of water level and wave conditions were applied to the model. The method used to derive wave overtopping flows ensures there is no double

counting of flows from still water levels as the latter are automatically calculated by the flood modelling software.

Wave overtopping was analysed by ABPmer using Monte Carlo analysis and the overtopping NNT associated with EurOtop (2007) methodology. Further details of the overtopping analysis can be found in ABPmer's Wave Modelling and Overtopping Report (2018)¹³.

It was identified by ABPmer that there were numerous occurrences when a valid overtopping rate was not returned from the NNT when overtopping would be expected. The primary reason for this is the relatively low defence crest level against which very significant water level and wave conditions were examined. These conditions prevented the NNT from providing overtopping predictions as they would not generally be designed for and hence are not covered by the physical model test data that informs the NNT.

Due to these limitations, the return periods and epochs carried forward from the wave modelling to the inundation modelling were amended (see Table 10).

Table 10: Amended coastal return period and epochs to be assessed.

Return period	2019	2069	2119
1:1	✓	✓	✓
1:10	✓	✓	x
1:50	✓	✓	x
1:100	✓	✓	x
1:200	✓	x	x
1:1000	✓	x	x

For return periods and epochs where wave overtopping flows were available, overtopping hydrographs were applied to the inundation model using SA (source over area) polygons immediately landward of the primary defence line or frontage. Each polygon related to a representative beach frontage profile as shown in Figure 12.

The most northerly profile in the study area, Profile 10, represents the shingle bank between the northern end of the promenade and the property Cartrefle. This frontage is adjacent to the Cambrian Coast Railway.

Profile 1 represents the northern end of the promenade where the beach has experienced lowering, exposing the toe of the primary defence and shows a near vertical profile from the defence crest to the beach below. It was determined that profile should represent the section of frontage from the northern end of the promenade to the northern extent of the residential properties at Tai'r Heli.

¹³ ABPmer, (2019). Barmouth North Promenade, Wave Modelling, Extremes Analysis and Overtopping, ABPmer Report No. R.3105. A report produced by ABPmer for Arup, February 2019.

Profile 7 represents the middle section of the promenade that has also experienced beach lowering although to a lesser degree. The profile along this section is more sloping and represents the area between Tai'r Heli and the start of the dunes.

Profile 30 represents the section of frontage from the start of the dunes to the southern end of Black Patch car park. It was not specifically modelled by ABPmer because the dunes at this location currently provide protection to the frontage and therefore no overtopping is likely to occur during the present-day epoch (2019). Despite this, the profile has been included in the inundation model as a separate inflow section to allow us to account for changes in beach profile over the future epochs. In epochs 2069 and 2119 it was identified that the still water level would be above the current crest of the dunes for certain return periods; the profile might then be expected to tend towards the form of the adjacent profile 60. Therefore, overtopping flows representing either zero overtopping OR the adjacent profile 60 were applied to profile 30 as follows:

- 2019 – Zero overtopping applied.
- 2069 – Zero overtopping applied up to and including the 1:10yr event (note that overtopping flows were additionally not available for return periods greater than 1:100yr due to NNT limitations).
- 2119 – Overtopping flows applied for 1:1yr event only due to NNT limitations.

Profile 60 represents the area from the end of the established dunes to the breakwater. This location is south of the North promenade where there is a substantial gap in the dune system and hence an area of increased flood risk to the Barmouth frontage.

Wave overtopping flows were not applied to any frontage south or east of the breakwater as this structure affords protection from significant wave action. Tidal water levels were applied however, as the frontage has a relatively low elevation and inundation from high water levels provides a substantial contribution to the overall flood risk in the south of the modelled extent, particularly in the vicinity of Viaduct Gardens.

Overtopping of set-back defences and walls, e.g. secondary and tertiary defences, was automatically calculated in the TUFLOW inundation model based on flood water levels predicted by the inundation model. Secondary wave behaviour in flood waters landward of the frontage and primary defences is not represented within the inundation model.

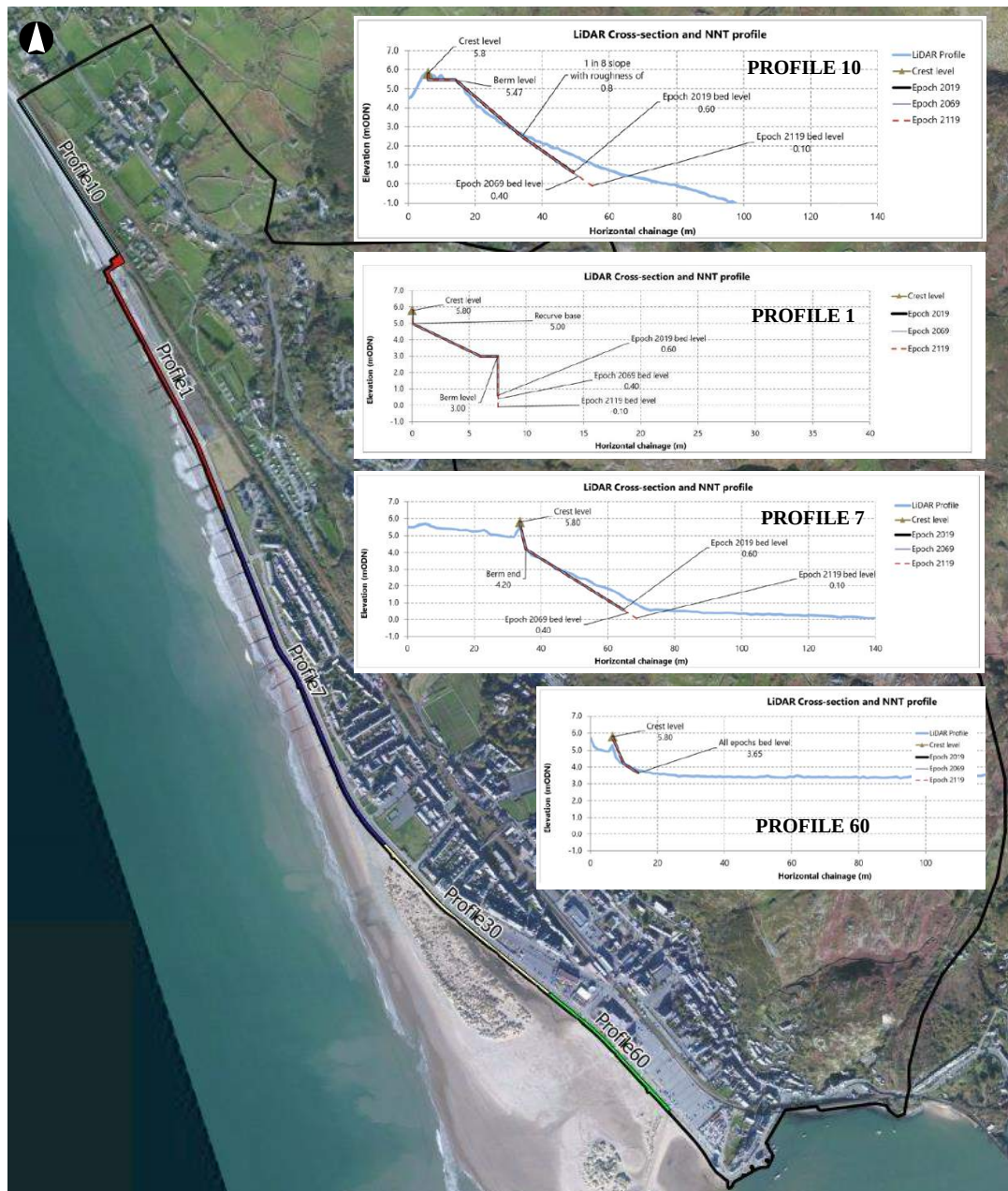


Figure 12 Location and schematisations of wave overtopping profiles. Schematisations as represented in ABPmer's Wave Modelling and Overtopping Report (2018)¹⁴.

7.7.3 Fluvial flows

Fluvial flows were derived for the two small watercourses draining into the study area from the catchments nominated 'Hafotty' and 'Gellfawr' (see Figure 7). The watercourse sources are within the Snowdonia National Park and comprise steep and narrow channels for much of their course. The Natural Resources Wales surface water flood maps³ indicate that flooding associated with these watercourses is mostly contained within the channels, only contributing

¹⁴ ABPmer, (2019). Barmouth North Promenade, Wave Modelling, Extremes Analysis and Overtopping, ABPmer Report No. R.3105. A report produced by ABPmer for Arup, February 2019.

significantly to surface water flooding once the topography flattens out near to the coast (see Figure 2), hence the use of the joint probability approach to modelling as discussed in Section 5.2.

The ReFH2 method was used to generate peak flows and hydrographs for the two watercourses. This method is based on FEH Web Service, **Error! Bookmark not defined.** catchment descriptors and FEH2013 rainfall and was considered to be suitable for this study given the small catchment size and lack of gauged data relating to these watercourses or nearby hydrologically similar catchments. The catchments were considered to be rural, with isolated buildings.

Peak flows and hydrographs were initially generated for a range of storm durations for the 1 in 10yr and 1 in 200yr flood events in order to test the catchments' sensitivity to duration and identify a critical storm duration to take forward for the main phase of modelling. Table 11 shows the peak flows for each catchments and duration.

Table 11 Peak flows for Hafotty and Gellfawr catchments for a range of storm durations.

Duration (hrs)	Peak Flow (m ³ /s)			
	Hafotty		Gellfawr	
	10-year	200-year	10-year	200-year
0.5	0.888	2.459	0.476	1.333
1.0	1.117	3.279	0.600	1.770
2.0	1.406	3.803	0.751	2.039
3.0	1.496	3.838	0.794	2.048
6.0	1.531	3.569	0.804	1.889
12.0	1.314	2.768	0.681	1.448
24.0	1.067	2.054	0.548	1.063

Following the critical storm duration analysis, the 12hr storm event was adopted as the critical storm duration. It was found that although flood depths were found to still be increasing in places for this duration, flow and water levels did not significantly increase for storm duration longer than this indicating that little would be gained from extending the model run time to utilise a longer storm duration, particularly given the focus of the current study is coastal flood risk.

In addition to the two main watercourses, peak flows and hydrographs were also required for a small intermediate catchment (designated 'Intermediate A') to the north of Hafotty at the northern end of the modelled study extent (see Figure 7). This was to represent surface runoff from the hillside which did not originate from one of the two watercourses for an area that was clearly defined by the LiDAR DTM (as opposed to the areas of the model where direct rainfall was to be applied where it was not possible to delineate individual surface water catchments based on LiDAR alone). Intermediate A flows were based on Hafotty flows and scaled based on the differences between the catchment areas which was deemed an appropriate method for a small catchment of this nature. The Intermediate A flows were applied in the TUFLOW model using a narrow SA polygon along the extent of the inland model boundary of the catchment. Table 12 details the peak flows for each return period (present-day) for each of the three 'fluvial' catchments.

Table 12 Peak fluvial flows for each catchment and return period (present-day).

Return period	12-hour storm duration peak flow (m ³ /s)		
	Hafotty	Gellfawr	Intermediate A
1yr	0.849	0.435	0.167
2yr	0.908	0.465	0.179
4yr	1.064	0.548	0.209
8yr	1.244	0.643	0.245
10yr	1.314	0.681	0.259
16yr	1.483	0.774	0.292
50yr	2.022	1.057	0.398
100yr	2.382	1.247	0.469
200yr	2.768	1.448	0.545
1,000yr	3.744	1.956	0.737

There are a number of assumptions associated with the derivation of fluvial flows; the main assumption being that the ReFH2 method and catchment descriptors are adequately representative of the hydrological conditions of the two watercourse catchments. It should also be noted that the upper catchments contain several quarries and manganese mines; the details of which, and therefore impact on flows, are unknown. For further detail regarding the derivation of fluvial flows please see the hydrological summary in Appendix D.

7.7.4 Surface water (direct rainfall)

Rainfall hyetographs were generated for all required present day return periods using ReFH2 for the Gellfawr catchment. This catchment was selected for use as it is the nearest spatially to the area over which rainfall was to be applied (and therefore likely to be most similar in topography, soil type etc). The hyetographs were applied across the remaining study area surface (see Figure 7), this includes Intermediate catchments B and C in addition to the area not identified as 'catchment') using a direct rainfall boundary in the TUFLOW model which automatically calculates surface water runoff and associated flow paths arising from direct rainfall.

The area within the modelled extent is largely rural in nature however there are also urban areas, namely Barmouth town centre and a number of small residential areas surrounding the town. It was therefore decided to apply the direct rainfall as either rural or urban depending on land classification. OS Mastermap data was used to identify building footprints, and other urban surfaces including roads and pathways, these polygons were extracted and used to spatially define the extent of the 'urban' rainfall boundary layer across which the design rainfall (without infiltration losses) was applied. An allowance for urban drainage has been added to the application of direct rainfall to urban surfaces to account for losses to the underlying drainage system. A drainage capacity of 12mm/hr was used as this has been adopted by the Environment Agency's national scale surface water flood mapping produced in 2013, currently known as the 'Risk of Flooding from Surface Water' Flood Map. The remaining OS Mastermap polygons in the study area were used to spatially define the extent of the 'rural' rainfall boundary layer across which the net design rainfall (including infiltration losses) was applied.

A range of storm durations were tested for the rainfall hyetographs along with the fluvial flows during the critical storm duration analysis for a range of durations for the 1 in 10yr and 1 in 200yr events. Following this analysis, the 12hr storm was adopted as the critical duration. Table 13 details the peak rainfall for the 12hr storm for the Gellfawr catchment across the entire range of required present day return periods.

Table 13 Peak rural and urban rainfall for each present-day return period.

Return Period	Gellfawr 12hr storm duration peak rainfall (mm)		
	Rural (net rainfall)	Urban (design rainfall)	Adjusted urban rainfall
1yr	0.111	0.319	-0.281
2yr	0.12	0.34	-0.26
4yr	0.142	0.396	-0.204
8yr	0.169	0.457	-0.143
10yr	0.179	0.481	-0.119
16yr	0.204	0.538	-0.062
50yr	0.282	0.7	0.1
100yr	0.336	0.804	0.204
200yr	0.393	0.908	0.308
1,000yr	0.539	1.152	0.552

For further detail regarding the derivation of surface water / rainfall hyetographs please see the hydrological summary in Appendix D.

7.8 Roughness

Ordnance Survey Mastermap data was used to categorise land classes in order to create a TUFLOW model materials file which is used to spatially assign appropriate Manning's n roughness values across the model domain.

7.9 Runtime options and parameters

As recommended in the TUFLOW Manual, the double precision version of TUFLOW was used to improve accuracy of surface water flows where these are generated using a rainfall boundary applied directly to the 2D domain.

A timestep of 0.5s was used, which is smaller than the value typically used for a 3m resolution model (0.75 – 1.5s). A smaller value was used to maintain model stability for surface water flows on the steep terrain.

Model runtime parameters were set to default values except for:

- Number Iterations: set to 4 (default is 2): This parameter was set to 4 to improve accuracy and reduce stability issues associated with surface water flows on steep terrain.
- Cell Wet/Dry Depth: set to 0.0002 as recommended by the TUFLOW Manual for direct rainfall models due to the substantial amount of shallow sheet flow.

8 Baseline sensitivity testing and validation

To explore the impact of assumptions in the model sensitivity testing and validation exercises were completed.

8.1 Sensitivity Testing

Sensitivity tests as detailed in Table 14 have been undertaken to test the assumptions made within the modelling process.

Table 14 Scenarios tested for sensitivity analysis.

Scenario	Combined RP	2019		2069		2119	
		Coastal RP	Rainfall RP	Coastal RP	Rainfall RP	Coastal RP	Rainfall RP
Sensitivity test 0 – baseline interim return periods - SW management performance	100	10	8				
Sensitivity test 1 - Baseline with no flood gates/boards	100	100	1				
Sensitivity test 2 - Baseline with measures to manage local sources of flooding not functioning	10	0	10	0	10		
	50	0	50	1	50		
Sensitivity Test 3 -Baseline with breaches of the primary wave wall	10*	10*	0				

* Note: Available coastal flood return periods are available and so substitution has been proposed (shown within brackets).

Table Key

	Coastal dominant simulation – primary outline business case focus
	Surface water dominant simulation – to test residual risk
	Intermediate combined return period

Sensitivity test ‘0’ modelled the intermediate 1 in 100yr return period with a joint probability of coastal 1 in 10yr and rainfall 1 in 8yr events. This was performed to confirm the assumption that the coastal dominant modelling predicted the worst-case flooding and to further explore the surface water management performance. Figure 13 indicates that the extents and depths from Sensitivity test 0 are between those modelled under both coastal and rainfall dominated events. The results demonstrate flood risk is tidally dominant and the modelling assumptions are appropriate.

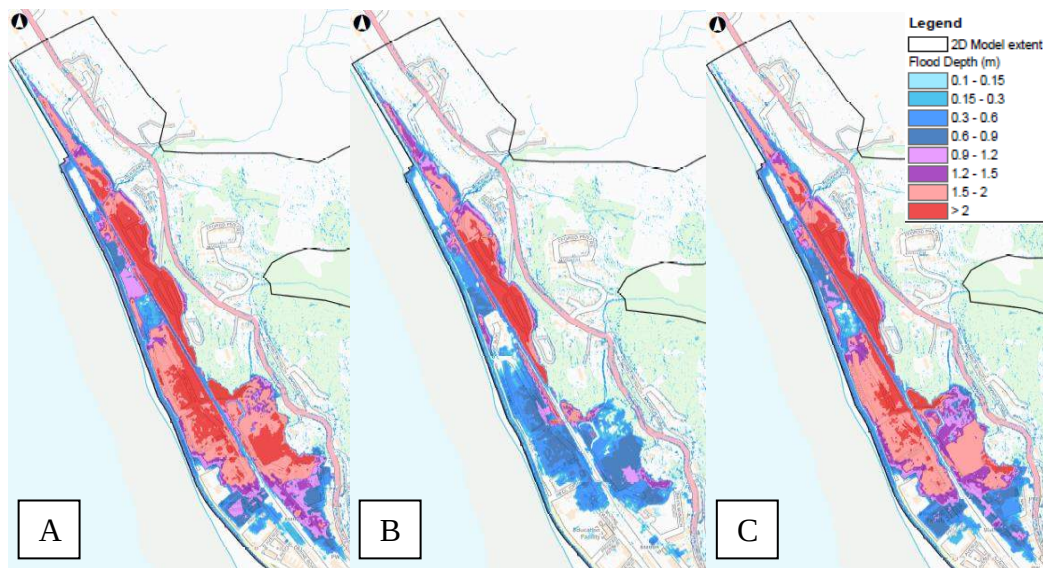


Figure 13 1 in 100yr flood depths for A) Coastal 100yr, rainfall 1yr, B) Coastal 1yr, rainfall 100yr and C) Coastal 10yr, rainfall 8yr (sensitivity test 0).

Sensitivity test 1 modelled the 1 in 100yr coastal dominated event with the flood gates and boards that are usually deployed in the secondary and tertiary wave walls removed to allow flood water to flow through the access points and gaps in the walls. The results indicated that for the area immediately landward of the promenade there was little difference between the gates being present or removed.

Sensitivity test 2 modelled the 1 in 10yr and 1 in 50yr rainfall dominated events for the present day and future epoch 2069 with the surface water pumping station not functioning. See Figures S02a to S02d in Appendix B for mapped outputs. It was observed that there was little difference between the results with the pumping station operational and non-operational.

Sensitivity test 3 modelled the present day 1 in 10yr coastal dominated event with breaches in the primary wall at the northern end of the promenade to assess the impact of failure of the wall given the concerns regarding its potential residual life (see Section 4.1). Results indicated that this may have a significant impact on flood depths and extents as shown in Figure 14.

The model was also tested to ensure that an appropriate resolution was used. Initially the model was set to run at a 2m resolution, however due to the direct rainfall approach this resulted in a simulation time of over 60 hours. To reduce this to a more practical computational time, the model was tested at both 3m and 4m resolution. It was found that at 4m the model did not suitably represent the flow paths, particularly along the promenade between the wave walls. A resolution of 3m was adopted as this was found to provide similar flood risk predictions to the 2m resolution model with an improved run time of approximately 20 hours.

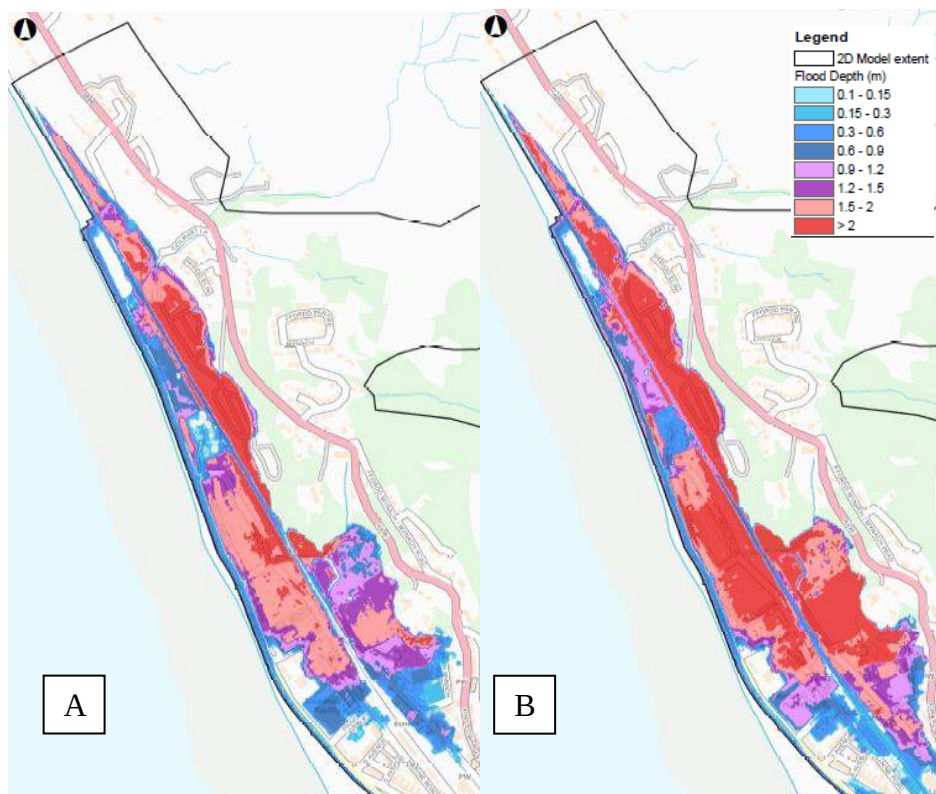


Figure 14 Coastal dominated 1 in 10yr present day flood depths for A) No breaches in primary wall and B) with breaches at northern end of primary wall.

8.2 Validation

The NRW Historic flood map indicates the impact (number of properties flooded) and extent of flooding for a storm event of approximately a 1 in 10yr to 1 in 25yr return period¹⁵ on 03 January 2014 according to NRW advice. This was compared to the 1 in 1yr and 1 in 10yr coastal dominated modelled flood extents (i.e. 1yr / 10yr coastal, 0yr rainfall joint probability) which can be seen in Figure 17. Videos and reports were also observed, for example, videos of the 2014 storm event and the Investigation Report: North Wales Flooding (NRW, 2014). These indicate that, although slightly conservative, the modelled flood extents provide an adequate representation of flooding from coastal sources along the Barmouth frontage.

¹⁵ As per correspondence from Natural Resources Wales on 19th February 2019. It was stated that “Using the class A gauge record against the CFBD it places the 2014 event in the 10 to 25 year bracket. So obviously waves are important at that point then. But haven’t been assessed before. Feeling is that the return period should not be huge.”



Figure 15 Image of the January Barmouth 2014 Storm event – looking southward towards Barmouth North Promenade



Figure 16 Image of the January Barmouth 2014 Storm event – looking northwards from Barmouth North Promenade across Network Rail, highlighting overtopping at Profile 10

During the Barmouth North Promenade public drop in exhibition on 25th March, the following points were highlighted by local residents:

- The promenade was breached, and flats were flooded in 1975/6 winter storms.
- During high tides the ditch along the railway surcharges. Previously the fire brigade attended events to provide pumping, with significant flooding in 1980s but not since surface water pumping station was installed. The flap valve of northern outfall has been removed – tidal egress is an issue.
- Watercourses inland of the railway are prone to surcharging – maintenance of culverts under railway a concern of caravan park owner.

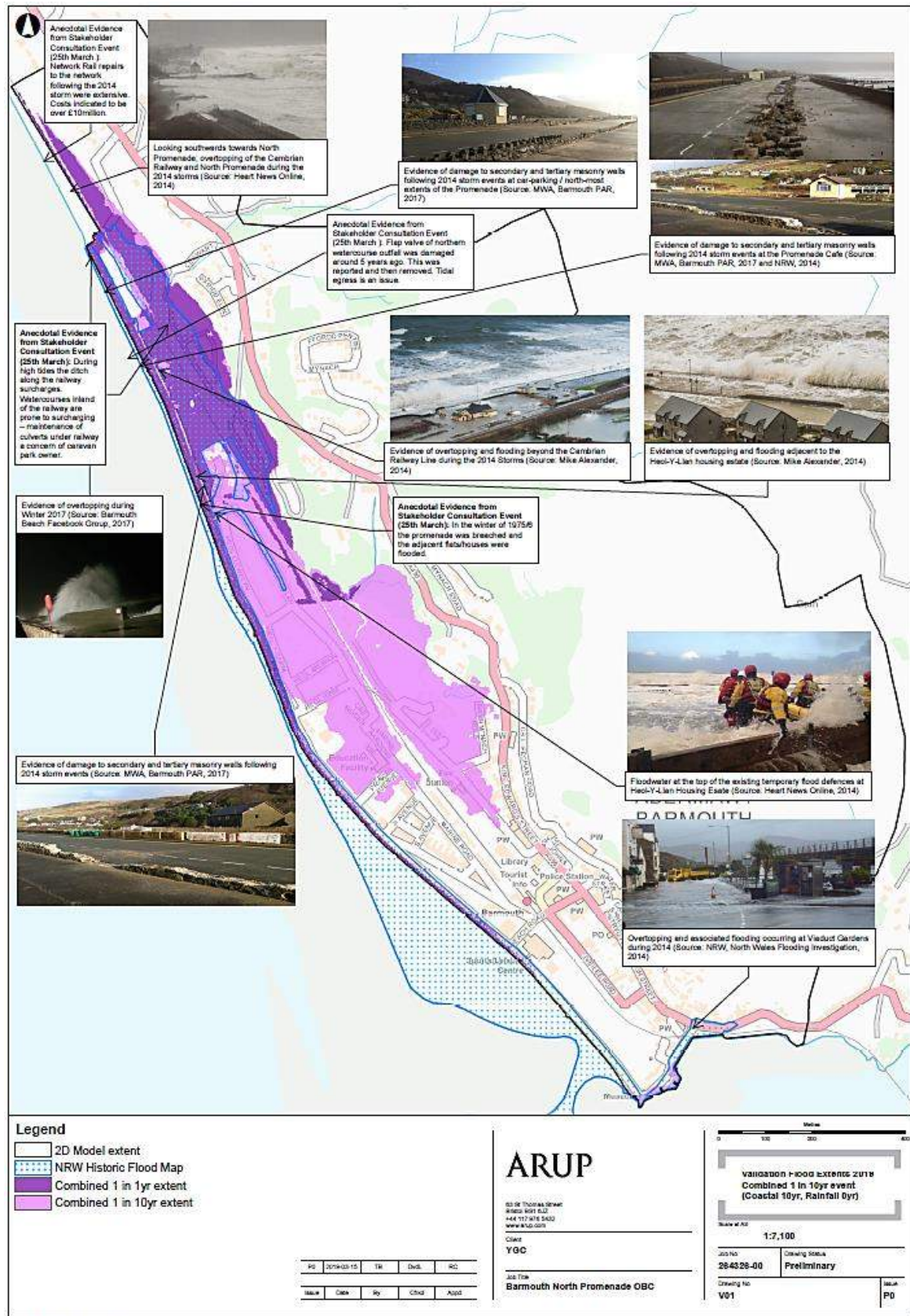


Figure 17 Comparison of 1 in 1yr and 1 in 10yr modelled coastal flood extents with the NRW Historic Flood Map. **Refer to Appendix B for full map.**

The 1 in 200yr model results were additionally compared to the NRW Flood Zone outlines (see Figure 18); these show that the modelled flood extents are similar to the flood zones although are slightly larger.

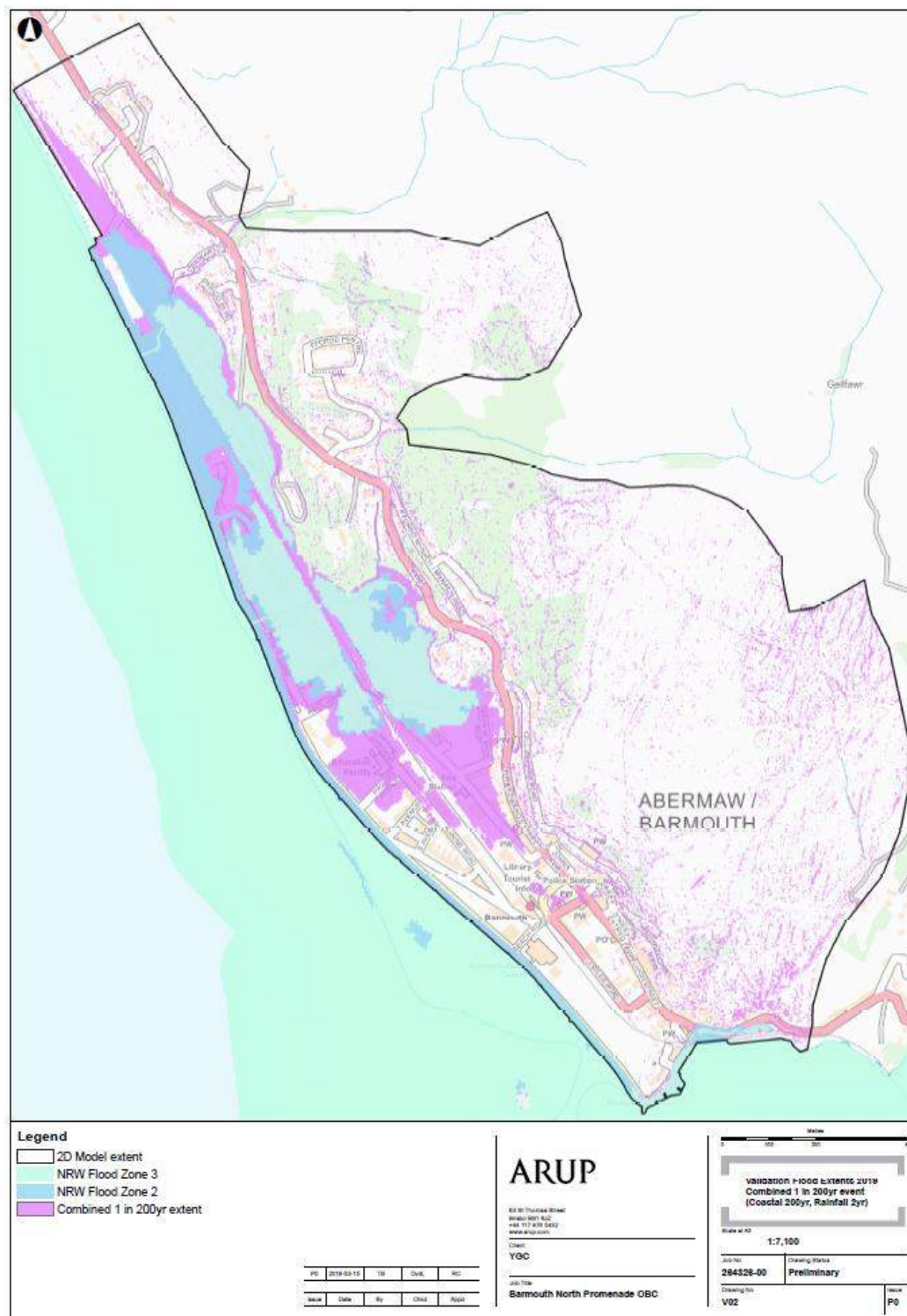


Figure 18 Comparison of the 1 in 200yr modelled coastal flood extent with the NRW Flood Zones.

9 Baseline outputs

Hydraulic modelling outputs of flood depth, water level, velocity and hazard have been produced to inform into the flood damages assessment to support the economic case. The flood depths have been mapped accordingly in Appendix A and are summarised below.

9.1 Present-day (2019) flood depths

The inundation model results confirm that the overall impacts of coastal flooding are greater than those of surface water flooding arising from fluvial and rainfall inputs for all return periods and epochs.

The present-day onset of coastal flooding is very low as flooding was observed to occur extensively at the lowest modelled event (1 in 1yr) along the northern promenade with flood depths of up to 0.9m, and up to 2m for the land between the promenade and the railway. Landward of the railway 1 in 1yr flooding was also observed at an average of 2.3m deep within the Caravan park. Surface water dominated flooding was also found commence at the 1yr event and give rise to water depths of over 1m at the Caravan park.

Flooding also commenced at the 1yr surface water event affecting properties and the road adjacent to Viaduct Gardens in the south of the modelled extent with flood depths of approximately 0.7m. Note that there was no flooding at Viaduct Gardens during the coastally dominated 1yr event. This is due to the steep hillside behind these properties and the vicinity is known to have an issue with ponding of surface water.

For all return periods above the 1 in 1yr coastally dominated event, flooding is extensive across much of the northern promenade and land to the east. The areas experiencing the deepest flooding for all return periods are the Caravan park, the area around Heol-y-Llan and land north of Maesteg and Park Road (see

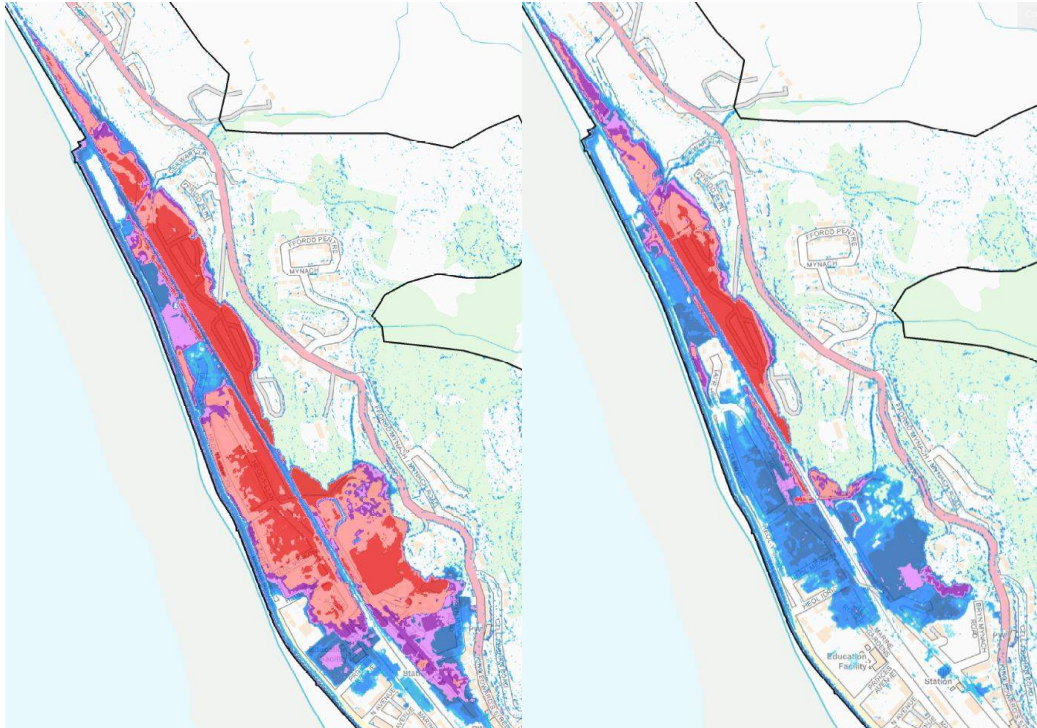


Figure 19).

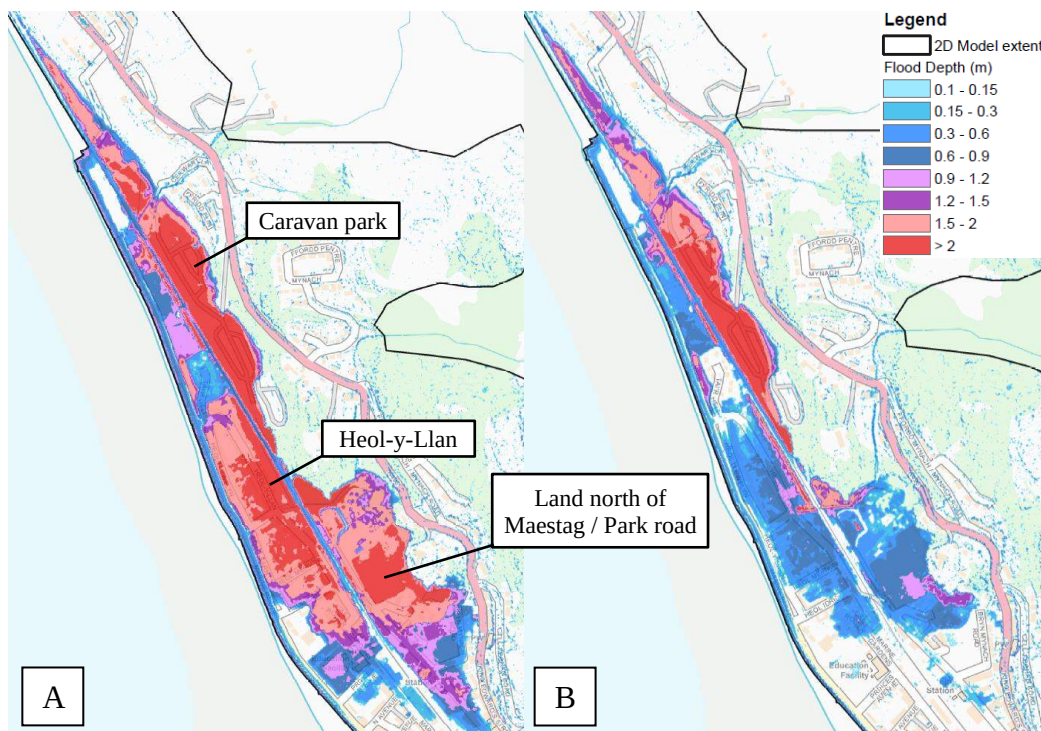


Figure 19 1 in 100yr flood depths in the area of the northern promenade for A) 100yr coastal with 1yr rainfall event and B) 100yr rainfall with 1yr coastal event.

9.2 Future epoch flood depths

Simulations were run for epochs 2069 and 2119 as outlined in Table 4, however it is difficult to compare the results directly to explore changes for equivalent flood events over time due to the decision not to model many of the surface water dominated events in 2069 prior to identifying that only the 1 in 1yr coastally dominated event could be run for 2119 due to the limitations of the NNT method (Section 7.7.2). When comparing the 1 in 1yr coastally dominated events for 2069 and 2119 the results show that for both epochs the extent and depth of flooding is greater than for the present day as would be expected given the anticipated effects of climate change. However, it should be noted that the results for 2069 predict greater flood depths than for 2119 for the 1 in 1yr event. This is because, as per Table 1 and 2, ‘Do Nothing’ overtopping hydrographs were applied to the 1yr event for 2069 to represent breaches in the primary wall. These rates were not available for 2119 due to NNT limitations which therefore used the Do Minimum overtopping hydrographs. As this only applies to one return period in the far future epoch this has a limited impact on the damages assessment given the effect of discounting and also represents a conservative approach to the damages estimated for the purpose of the business case.

The results for each epoch are therefore compared to the present day only.

9.2.1 Present-day versus 2069 flood depths

In 2069 the flood extents are predicted to be largely similar to the present-day baseline. This is due to the substantial extent of flooding under current conditions for most return periods and the constraints to flooding where the ground rises

steeply to the east of the town and frontage. The main differences are therefore increases in flood depth. When comparing the present-day and 2069 flood depths for the coastally dominated 1 in 10yr event, model results showed similar depths along the promenade with increases of approximately 0.1m at the Caravan Park, 0.2m across the Heol-y-Llan area and up to 0.3m north of Park Road. As return periods increase the differences between the present-day and 2069 results decrease; for the 1 in 100yr coastal event extents are very similar with increases in flood depth of approximately 0.05m across the promenade, Caravan park and Heol-y-Llan area.

9.2.2 Present-day versus 2119 flood depths

Model results for 2119 show increased extents and depths when compared to the present-day baseline. Figure 20 shows how extents and depths vary for the 1 in 1yr coastal event. Where extents overlap, such as in the vicinity of the Caravan park, flood depths were observed to be approximately 0.65m deeper in 2119 and up to 0.25m deeper along the promenade.

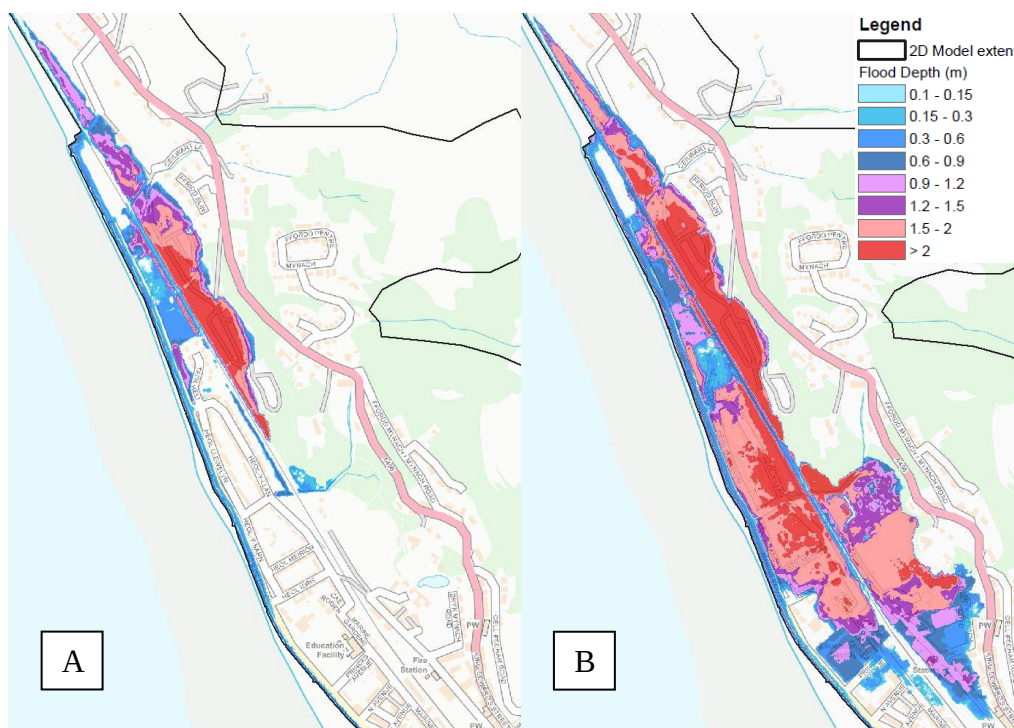


Figure 20 1 in 1yr modelled flood depths for A) Present day coastal 1yr, rainfall 0yr and B) 2119 coastal 1yr, rainfall 0yr.

When comparing present-day and 2119 1 in 10yr surface water events, the model results showed similar flood extents except for an expansion of flooding at Heol-y-Llan with depths of up to 0.5m. Flood depths are similar elsewhere except at the Caravan park where they increase by approximately 0.2m.

Figure 21 shows the increases in flood extent and depth predicted by the model between the present-day and 2119 for the 1 in 100yr surface water event. Key areas of increase in extent are along Park Road where flooding extents approximately 300m further south. There are also substantial increases in flood

extent across Tai'r Heli and Marine Gardens. Where extents overlap, flood depths were observed to increase; for example, flooding at the caravan park deepened by up to 0.35m, by approximately 0.3m along the promenade and up to 1.4m north of Park Road and in the area of Heol-y-Llan.

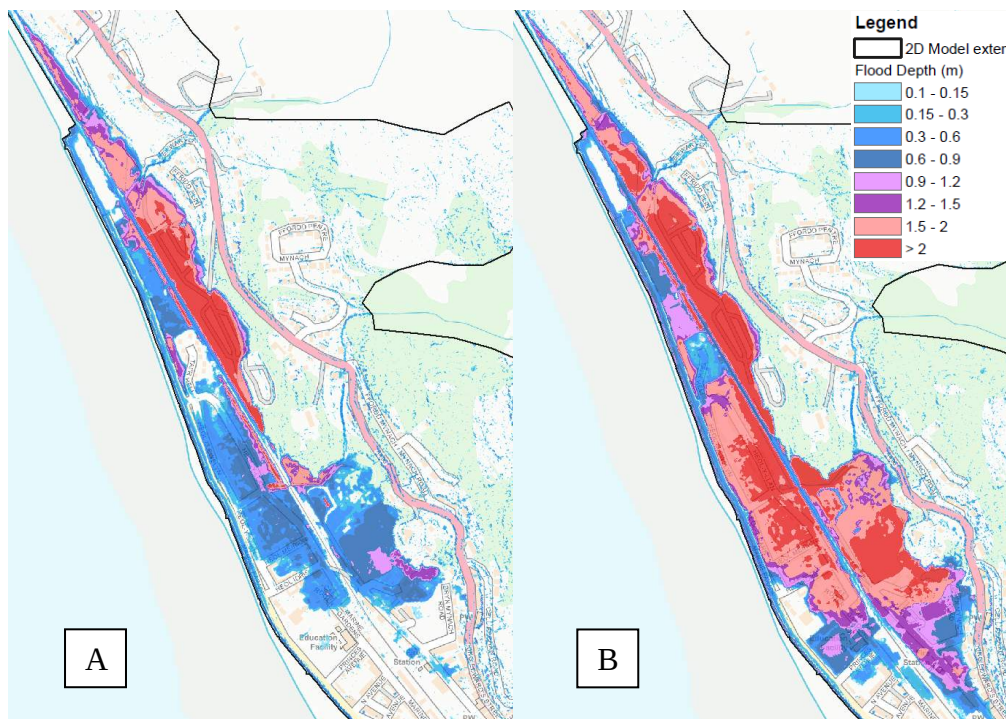


Figure 21 1 in 100yr modelled flood depths for A) Present day coastal 1yr, rainfall 100yr and B) 2119 coastal 1yr, rainfall 100yr.

10 Do Something Residual Risk model

As discussed in Section 4.2, it was proposed to model the residual flood risk based on the assumption that an ideal case would prevent inundation from wave overtopping or tidal still water levels for a range of standards of protection from the 1 in 50yr to 1 in 200yr events along the Northern Promenade frontage adjacent to overtopping profiles 1, 10 and 7. This assessment was undertaken to define the residual risk and support the economic assessment of the Do-Something options.

In order to understand what residual flood risk exists for various return periods, inundation modelling was undertaken using a Do Something model and running surface water only simulations only for the events in Table 15. Only present day and 2069 epochs were modelled for the do something residual risk scenarios; for 2119 it was assumed that the baseline modelling applies due to the absence of available overtopping data. This may slightly underplay the benefits of a Do Something option but given that it is in the far future, the effect of discounting will reduce this effect. The Do Something residual risk fluvial, and rainfall inputs for each return period were derived as described in Sections 7.7.4. Allowances for climate change were applied as described in Section 6.1.1.

The approach to the Do Something modelling has been to run the baseline model with zero coastal flooding inputs in order to assess the residual surface water risk. Checks of the baseline model results for the highest return period events in each epoch revealed that there is no significant flooding originating from coastal overtopping from the frontage south of the North Promenade study area (see Figures Figure 21). This confirms that the approach, although simple, is appropriate for the extent and sources of flooding and for the level of study of the OBC. It is recommended however that once the preferred option is decided, the impact of the option should be analysed through further detailed modelling to inform detailed design.

Table 15: Surface water return period and epochs to be assessed.

Do Something Residual Risk Options									
Standard of Protection		Combined RP	2019		2069		2119		
Option #	Epoch	AEP	Event	Coastal RP	Rainfall RP	Coastal RP	Rainfall RP	Coastal RP	Rainfall RP
1	2019	200	1	0	0	0	0	Assume Baseline modelling applies in absence of overtopping data	
			10	0	0	0	0		
			50	0	0	50	1		
			100	0	1	100	2		
			200	200	2	100	2		
			1000	1000	8	100	2		
2	2019	100	1	0	0	0	0	Assume Baseline modelling applies in absence of overtopping data	
			10	0	0	0	0		
			50	0	0	50	1		
			100	100	1	100	2		
			200	200	2	100	2		
			1000	1000	8	100	2		
3	2019	50	1	0	0	0	0	Assume Baseline modelling applies in absence of overtopping data	
			10	0	0	10	0		
			50	50	0	50	1		
			100	100	1	100	2		
			200	200	2	100	2		
			1000	1000	8	100	2		
4	2069	200	1	0	0	0	0	Assume Baseline modelling applies in absence of overtopping data	
			10	0	0	0	0		
			50	0	0	0	1		
			100	0	1	0	2		
			200	0	2	100	2		
			1000	0	8	100	2		
5	2069	100	1	0	0	0	0	Assume Baseline modelling applies in absence of overtopping data	
			10	0	0	0	0		
			50	0	0	0	1		
			100	0	1	100	2		
			200	0	2				
			1000	1000	8				

Do Something Residual Risk Options									
Standard of Protection		Combined RP	2019		2069		2119		
Option #	Epoch	AEP	Event	Coastal RP	Rainfall RP	Coastal RP	Rainfall RP	Coastal RP	Rainfall RP
6	2069	50	1	0	0	0	1	Assume Baseline modelling applies in absence of overtopping data	
			10	0	0	0	10		
			50	0	0	50	1		
			100	0	1	100	2		
			200	0	2				
			1000	1000	8				

KEY

	Residual risk models		Baseline models
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The baseline boundary condition database in the Do Something option model was updated so that zero wave overtopping would be applied.

Surface water management measures such as the surface water pumping station and outfalls were modelled as operational as per baseline conditions.

11 Do Something Residual Risk outputs

Hydraulic modelling outputs of flood depth, water level, velocity and hazard have been produced to assess the residual risk associated with a Do Something option that would protect from coastal inundation along the North Promenade frontage. The flood depths have been mapped accordingly in Appendix C.

The residual risk considers the surface water flood risk element of the combined coastal dominant flood events that remains once a theoretical coastal protection scheme is assumed to achieve a certain standard of protection. **Error! Reference source not found.** summarises the scenarios modelled which are detailed in full in section 4.2.

Residual risk model results show that while coastal inundation is minimised, areas of flood risk remain for all modelled return periods in both the present day and future 2069 epoch. This is mostly concentrated in three areas; the highway and properties immediately north of Viaduct Gardens, the area of land north of Maesteg and Park Road and the land adjacent to the Cambrian Railway from the northern extent of the model to Heol-Y-Plas including the Caravan Park (see Figure 22).

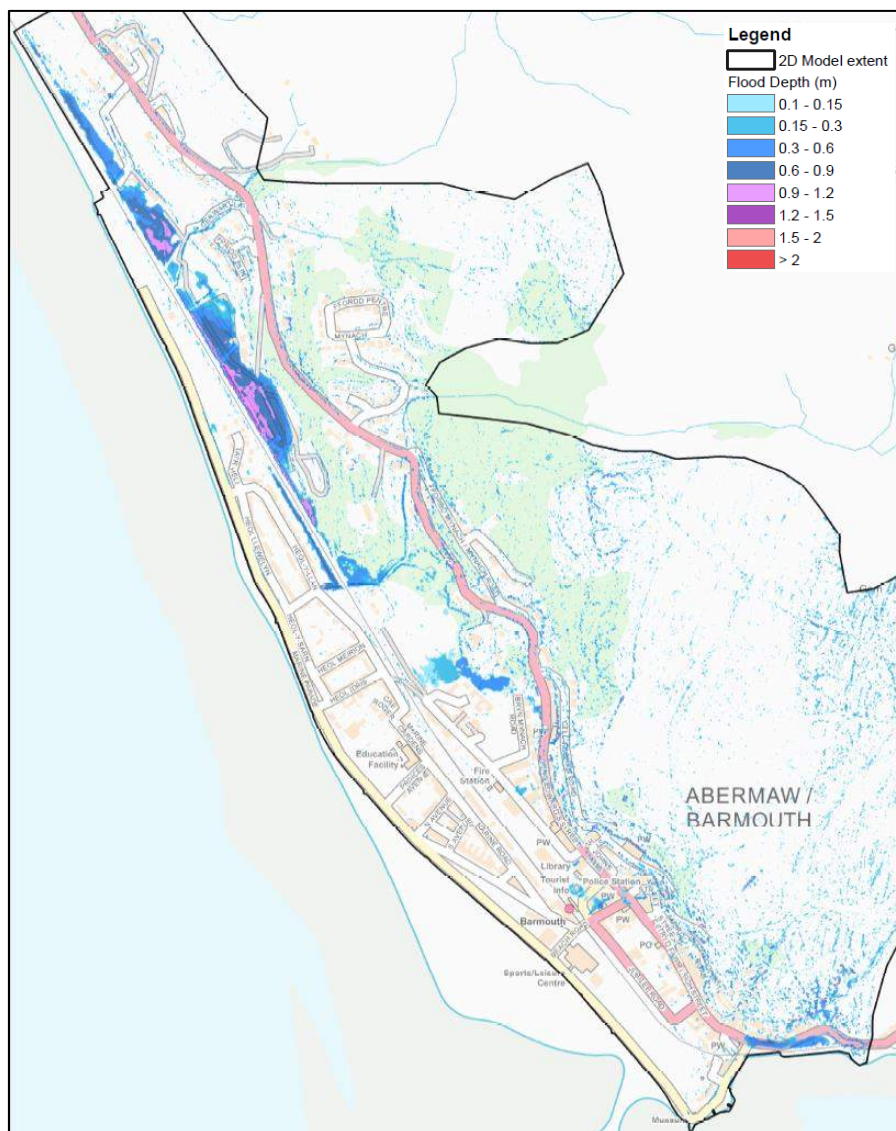


Figure 22 Present day residual risk flood depths for 1 in 200yr combined event (Coastal 0yr, Rainfall 2yr).

12 Assumptions and limitations

The TUFLOW inundation model has been based on a range of data and considers flood risk from multiple sources. There are therefore assumptions and limitations to the modelling.

Assumptions - topography

- The nature of the small, mountainous catchments of the two watercourses and the impact on the estimation of direct rainfall means that there are some uncertainties associated with the hydrological assessment. However, the method and approach used are suitable given the availability of data and in accordance with guidance as set out in the Hydrological Summary in Appendix D.

- As discussed in Section 7.3 there was a lack of appropriately high-resolution LiDAR for the upland areas of the study extent. This was resolved by adjusting direct rainfall application at the top of catchment Intermediate B.
- It is assumed that the LiDAR, topographic and culvert survey data were sufficiently accurate to inform the model, with the exception that survey data for the tertiary wave wall did not cover the entire length of the study area. This is because in places this wall comprises an informal structure as part of private property. The wall was not well represented in the LiDAR and therefore elevation for the sections excluded from the survey were estimated from aerial imagery and mapping.
- It should be noted that 9 of the 21 culverts modelled were estimated from LiDAR and aerial imagery due to their being situated on private land (such as Network Rail) which was unable to be accessed by YGC during the culvert survey. Following the survey, it was identified that several locations the surveyed elevation was up to 1m lower than that shown in the LiDAR. This was found to be in heavily vegetated areas and therefore it was assumed that the survey values were more accurate in this instance. However, in some locations the surveyed upstream elevations were lower than those downstream; these were amended using the slope indicated by LiDAR so that the culverts maintained positive flow directions.

The uncertainty associated with these culverts could impact the modelled results as the capacity and extent of vegetation screening the culverts, particularly those underneath the railway, could have a significant influence on the transfer of flood water to and from land either side of the railway embankment. However, sensitivity testing has shown model results are not sensitive to the operation of the surface water pumping station.

Assumptions - geometry and state of the wave walls

- Section 4.1 refers to the assumptions regarding the poor condition and residual life of the sea wall and revetment. Assumptions were also made regarding the location of possible breaches of the secondary and tertiary walls using information from sources such as the NRW 2014 report¹⁶. Breaches in the primary wall were tested as part of the sensitivity testing and were found to substantially increase the present-day flooding for the scenario tested.
- Breaches in the secondary and tertiary waves walls were set up to be in place at the start of the model rather than using a water level trigger. It was felt that this was justifiable due to the nature of the two walls which are low masonry not designed for the purpose of flood defence. It is assumed that the walls will fail near the start of a flood event when the effect of water pressure and debris is likely to cause the walls to fail in places as set out in Section 4.1.

Assumptions - wave overtopping

- Limitations to the NNT method used for calculating wave overtopping resulted in a reduction in the number of possible model simulations as discussed in Section 7.7.2 and 5. This meant that there was limited data

¹⁶ NRW Investigation Report: North Wales Flooding Jan 2014, Barmouth.

regarding flooding in future epochs to provide a comparison against the present-day baseline scenario.

- It is assumed that there was no significant secondary wave action within floodwaters landward of the frontage and primary defences. Any overtopping of secondary and tertiary wave walls due to the floodwaters is automatically calculated in the TUFLOW model rather than using separate wave overtopping calculations. Photos and videos of previous storm events such as those in the NRW 2014 report¹⁷ indicate that although there is often extensive overtopping of the set-back walls at certain locations, a substantial proportion of the wave power is dissipated by the primary wall.
- For further uncertainties associated with the wave overtopping, see the 2019 ABPmer wave modelling report¹.

Assumptions - other flood risk management infrastructure.

- It is assumed that flood risk management measures such as flood gates and the surface water pumping station were operational for all storm events. Sensitivity testing as discussed in Section 8.1 explored the impact of whether this infrastructure was operational or not and identified minimal change in flood depths for the conditions tested.

Assumptions - approach to modelling

- The sensitivity testing of model resolution as discussed in Section 8.1, showed that a 3m resolution model provided a sufficient representation of flow paths with no material impact on flood risk predictions.
- Given the coastal focus of the OBC, it was deemed appropriate to adopt the worst-case modelling results, which in this case were the coastally dominated events, for the economic appraisal and that the assessment of benefits between coastal and surface water effects would not be proportionate at this time. Surface water results were evaluated to assess residual risk.

13 Recommendations

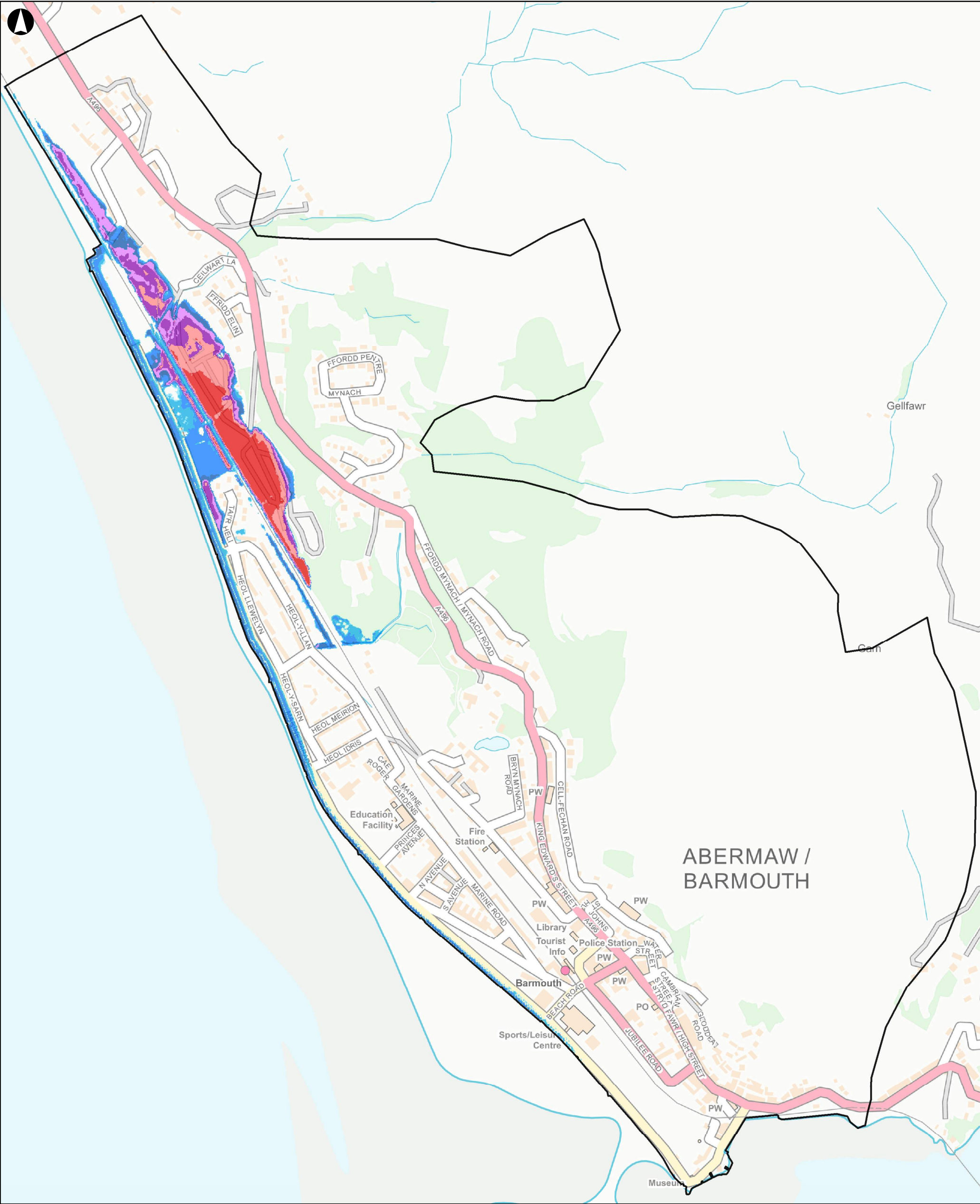
A proportionate approach to the Inundation Modelling has been undertaken to support the development of the Barmouth North Promenade Outlined Business Case. It is recommended that:

- Further modelling is undertaken prior to detailed design to assess the performance of, and further develop, the preferred Do-Something options.
- Additional surveys and investigations are undertaken with regards to the surface water drainage (including pumped system) and culvert network to confirm the drainage/culvert arrangement and performance.
- Post-review of future storm and overtopping events are undertaken (i.e. reviewing wrack marks and extents of flooding) to validate the model outputs further.

¹⁷ NRW Investigation Report: North Wales Flooding Jan 2014, Barmouth.

Appendix A

Baseline Flood Depth Maps



Legend

2D Model extent

Flood Depth (m)

- 0.1 - 0.15
- 0.15 - 0.3
- 0.3 - 0.6
- 0.6 - 0.9
- 0.9 - 1.2
- 1.2 - 1.5
- 1.5 - 2
- > 2

P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

63 St Thomas Street
Bristol BS1 6JZ
+44 117 976 5432
www.arup.com

Client
YGC

Job Title
Barmouth North Promenade OBC

Metres

0 100 200 400

**Baseline Flood Depths 2019
Combined 1 in 1yr event
(Coastal 1yr, Rainfall 0yr)**

Scale at A3

1:7,100

Job No 264326-00	Drawing Status Preliminary
Drawing No 001	Issue P0



Flood Depth (m)

 0.15 - 0.3

0.6 - 0.9

1.2 - 1.5

1.5 - 2

 1.0 $\leq$ λ
 ≥ 2

12. Project work\Barmouth20

Issue	Date	By	Chkd	Appd
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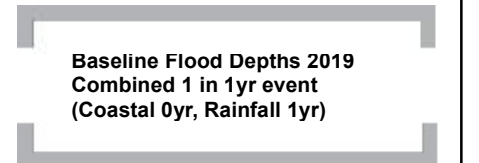
63 St Thomas Street
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+44 117 976 5432
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Job Title

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Scale at A3

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Job No

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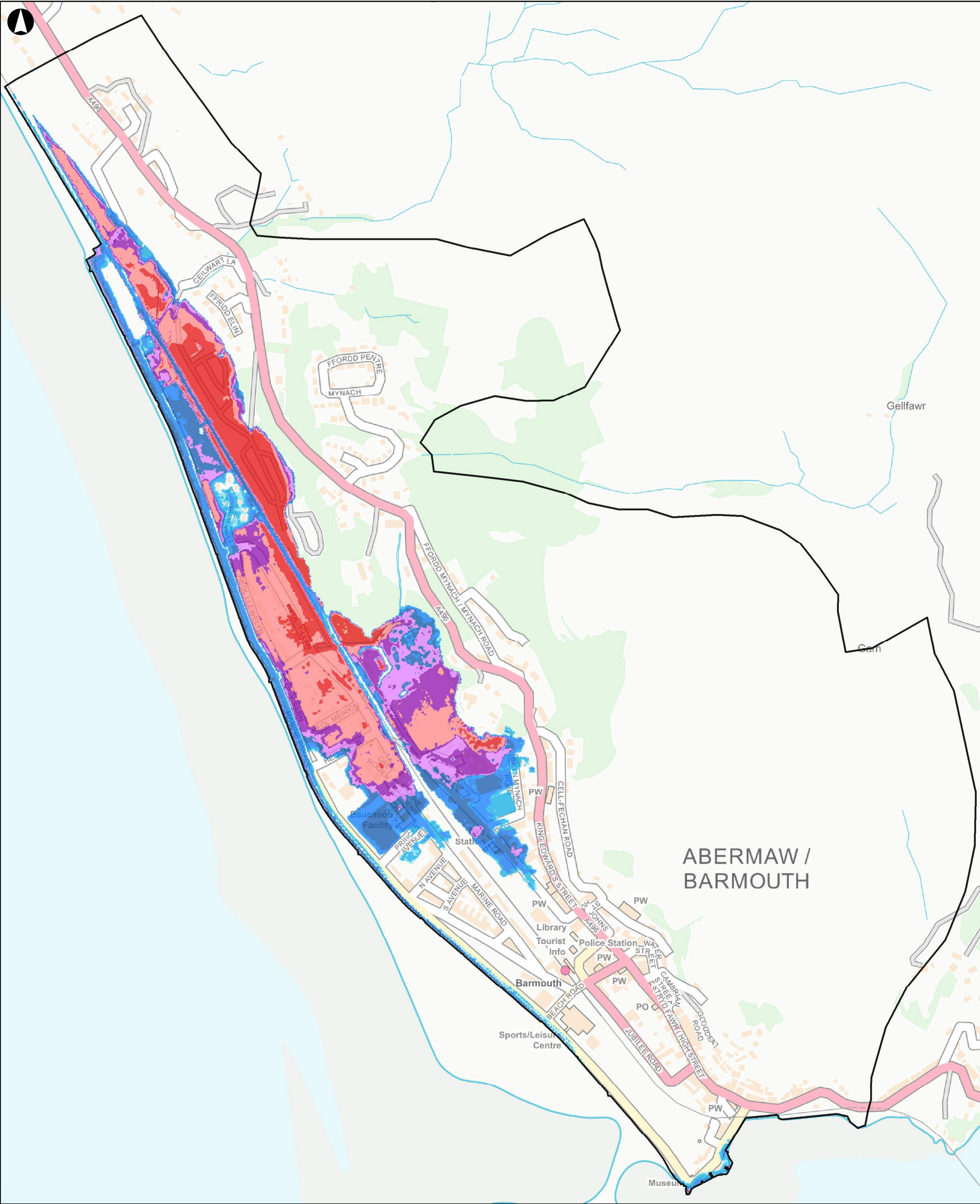
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Legend

2D Model extent

Flood Depth (m)

- 0.1 - 0.15
- 0.15 - 0.3
- 0.3 - 0.6
- 0.6 - 0.9
- 0.9 - 1.2
- 1.2 - 1.5
- 1.5 - 2
- > 2

P0	2019-03-15	TB	DvdL	RC
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Metres

0 100 200 400

**Baseline Flood Depths 2019
Combined 1 in 10yr event
(Coastal 10yr, Rainfall 0yr)**

Scale at A3

1:7,100

Job No 264326-00	Drawing Status Preliminary
Drawing No 003	Issue P0



Flood Depth (m)

0.1 - 0.15

 0.15 - 0.3

0.3 - 0.6

0.6 - 0.9

0.9 - 1.2

1.2 - 1.5

1.5 - 2

 $1.5 \leq z$
 ≥ 2

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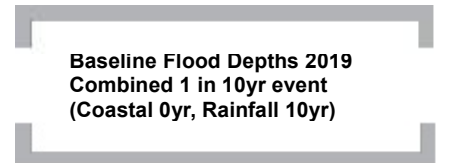
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Client

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Job Title

Barmouth North Promenade OBC



Scale at A3

1:7,100

Job No

264326-00

Drawing Status

Preliminary

Drawing No

004

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Flood Depth (m)

0.15 - 0.3

0.6 - 0.9

 1.2 - 1.5

$$\square > 2$$

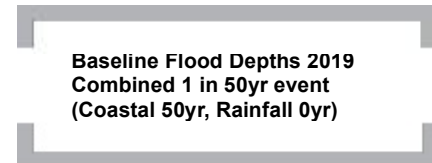
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P0



Flood Depth (m)

0.1 - 0.15
0.15 - 0.3

	0.3 - 0.6
	0.6 - 0.9

0.9 - 1.2
1.2 - 1.5

1.5 - 2

$$\boxed{} > 2$$

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Issue	Date	By	Chkd	Appd

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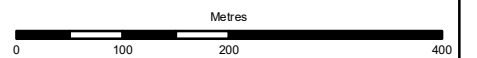
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Job Title

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**Baseline Flood Depths 2019
Combined 1 in 50yr event
(Coastal 0yr, Rainfall 50yr)**

Scale at A3

1:7,100

Job No

264326-00

Drawing Status

Preliminary

Drawing No

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Flood Depth (m)

 0.15 - 0.3

0.6 - 0.9

1.2 - 1.5

1.5 - 2

 1.0 $\leq$ 2
 ≥ 2

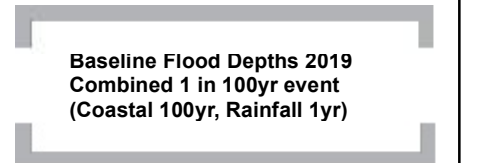
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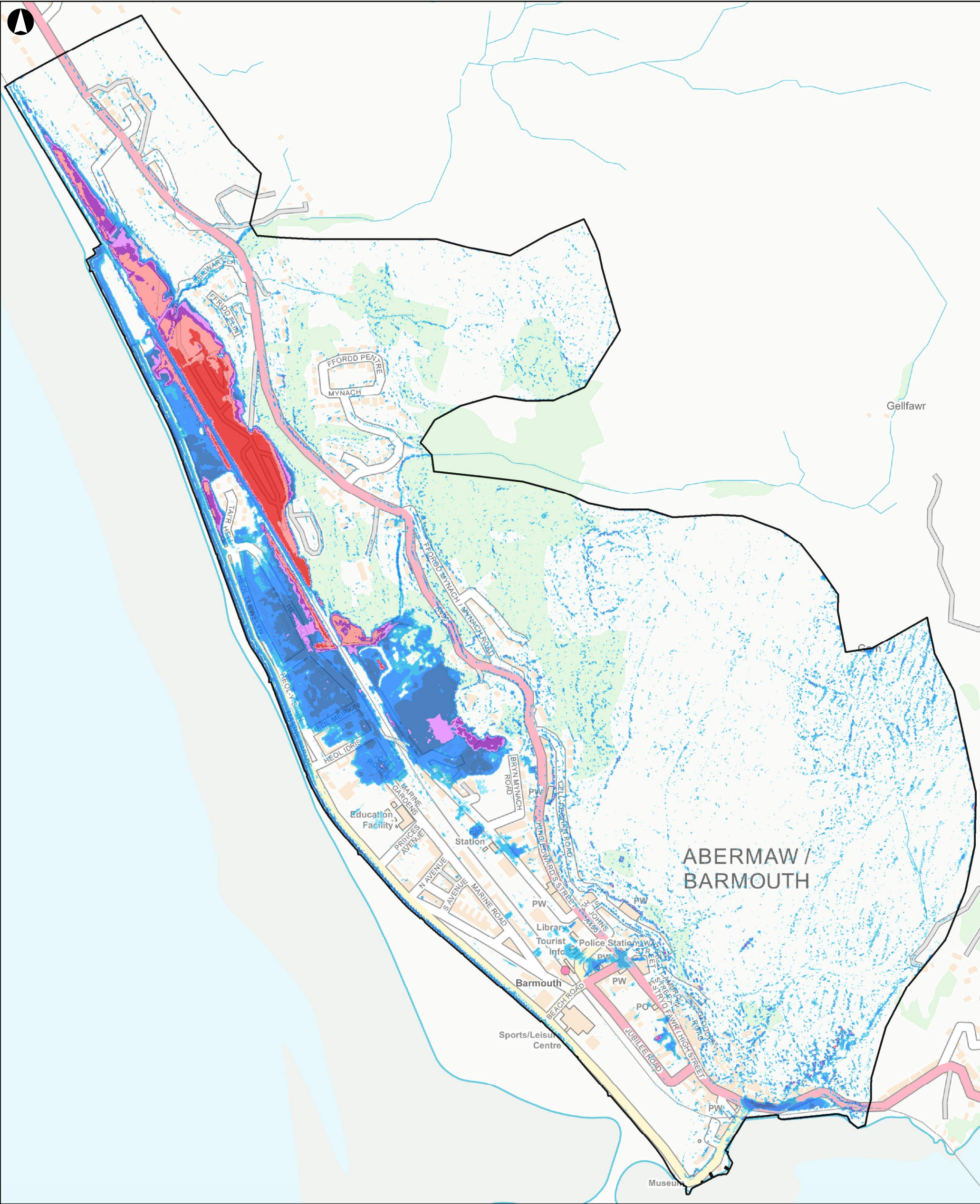
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Legend

2D Model extent

Flood Depth (m)

- 0.1 - 0.15
- 0.15 - 0.3
- 0.3 - 0.6
- 0.6 - 0.9
- 0.9 - 1.2
- 1.2 - 1.5
- 1.5 - 2
- > 2

P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

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Job Title
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Metres

0 100 200 400

Baseline Flood Depths 2019 Combined 1 in 100yr event (Coastal 1yr, Rainfall 100yr)

Scale at A3

1:7,100

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Drawing No 008	Issue P0



Flood Depth (m)

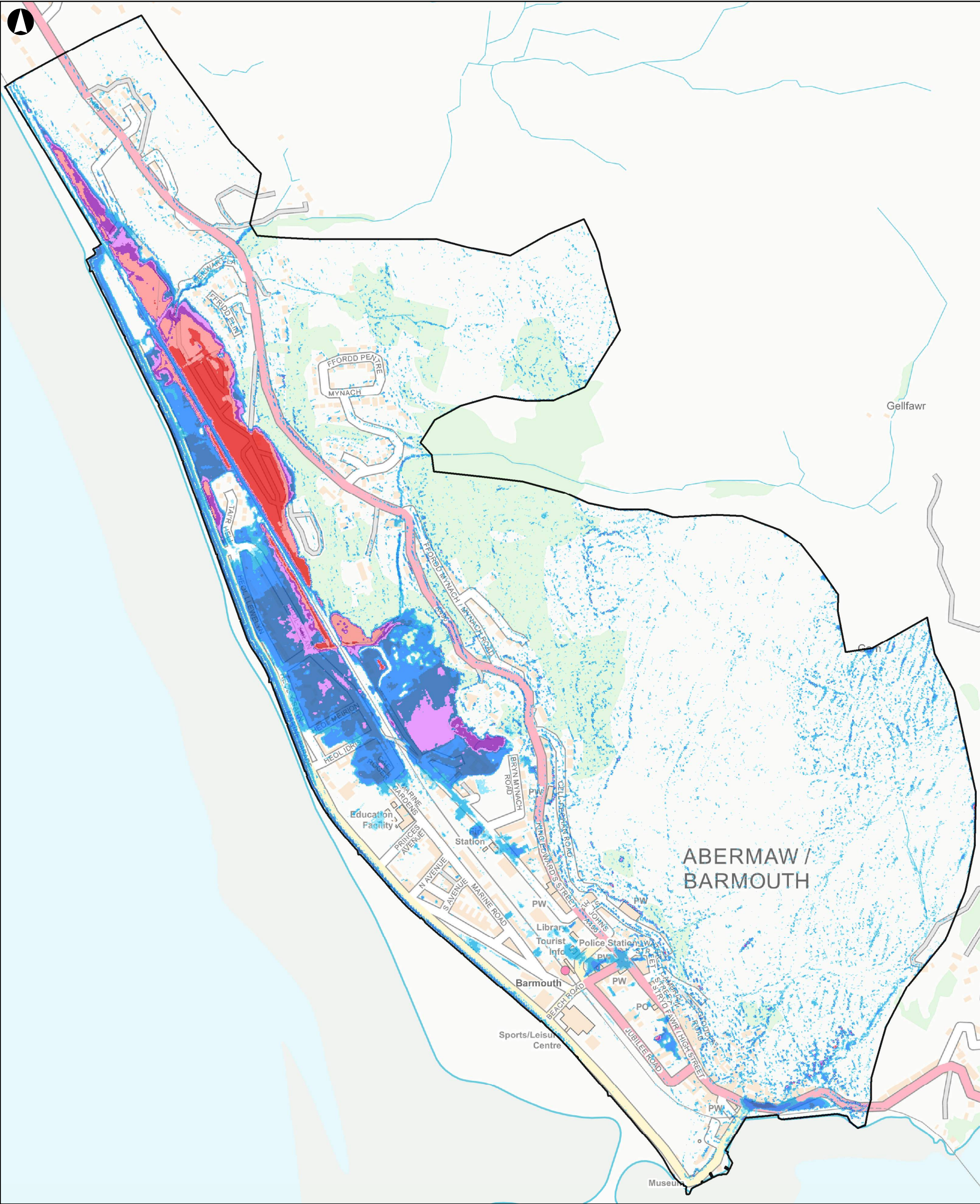
Issue	Date	By	Chkd	Appd
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Barmouth North Promenade OBC



Preliminary

90



Legend

2D Model extent

Flood Depth (m)

- 0.1 - 0.15
- 0.15 - 0.3
- 0.3 - 0.6
- 0.6 - 0.9
- 0.9 - 1.2
- 1.2 - 1.5
- 1.5 - 2
- > 2

P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

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63 St Thomas Street
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Client
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Job Title
Barmouth North Promenade OBC

Metres

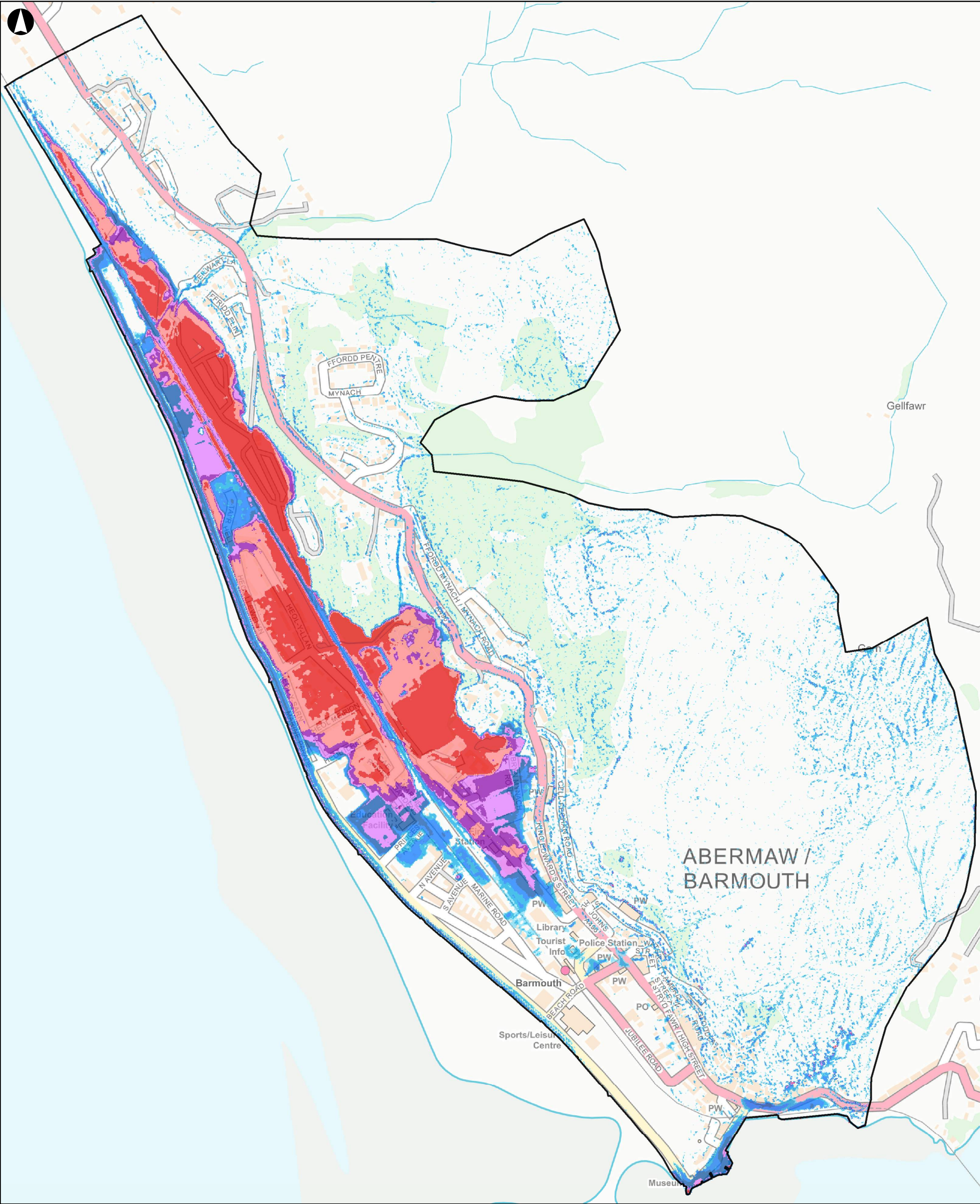
0 100 200 400

Baseline Flood Depths 2019 Combined 1 in 200yr event (Coastal 1yr, Rainfall 200yr)

Scale at A3

1:7,100

Job No 264326-00	Drawing Status Preliminary
Drawing No 010	Issue P0



Legend

2D Model extent

Flood Depth (m)

0.1 - 0.15

0.15 - 0.3

0.3 - 0.6

0.6 - 0.9

0.9 - 1.2

1.2 - 1.5

1.5 - 2

> 2

P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

63 St Thomas Street
Bristol BS1 6JZ
+44 117 976 5432
www.arup.com

Client
YGC

Job Title
Barmouth North Promenade OBC

Metres

0100200400

**Baseline Flood Depths 2019
Combined 1 in 1000yr event
(Coastal 1000yr, Rainfall 8yr)**

Scale at A3

1:7,100

Job No
264326-00

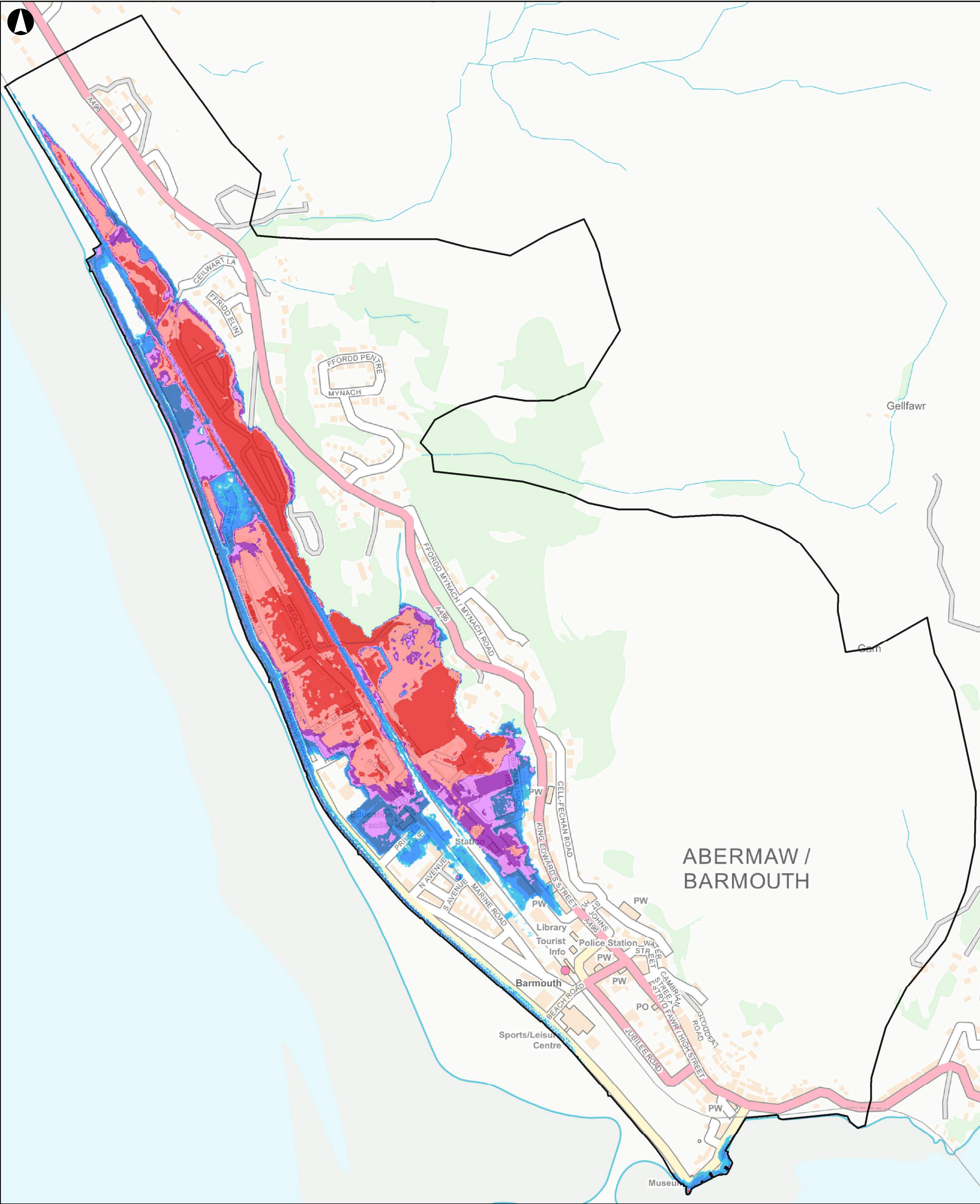
Drawing No
011

Drawing Status
Preliminary

Issue
P0

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© Arup



Legend

2D Model extent

Flood Depth (m)

- 0.1 - 0.15
- 0.15 - 0.3
- 0.3 - 0.6
- 0.6 - 0.9
- 0.9 - 1.2
- 1.2 - 1.5
- 1.5 - 2
- > 2

P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

63 St Thomas Street
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Client
YGC

Job Title
Barmouth North Promenade OBC

Metres

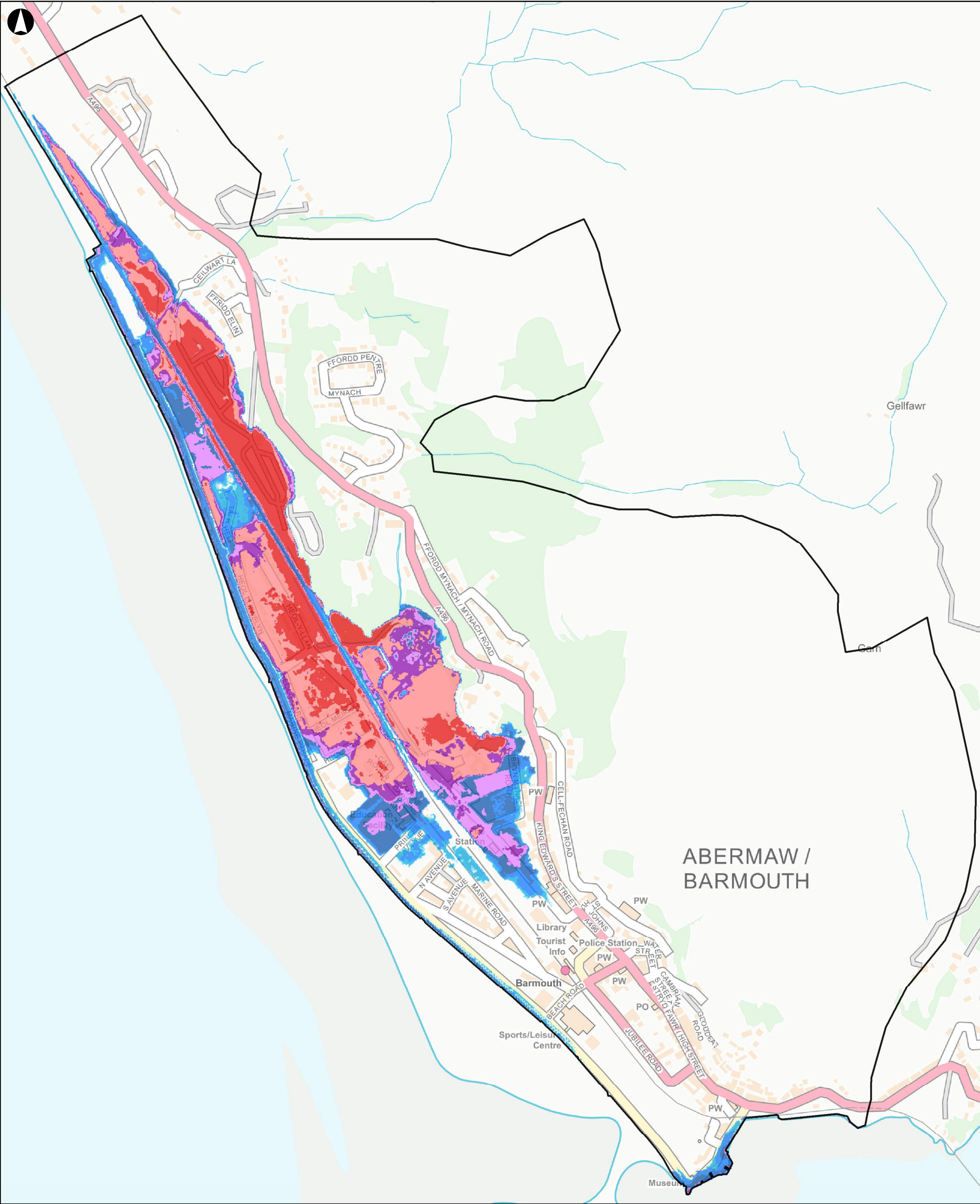
0 100 200 400

**Baseline Flood Depths 2069
Combined 1 in 1yr event
(Coastal 1yr, Rainfall 0yr)**

Scale at A3

1:7,100

Job No 264326-00	Drawing Status Preliminary
Drawing No 012	Issue P0



Legend

2D Model extent

Flood Depth (m)

- 0.1 - 0.15
- 0.15 - 0.3
- 0.3 - 0.6
- 0.6 - 0.9
- 0.9 - 1.2
- 1.2 - 1.5
- 1.5 - 2
- > 2

P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

63 St Thomas Street
Bristol BS1 6JZ
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Client
YGC

Job Title
Barmouth North Promenade OBC

Metres

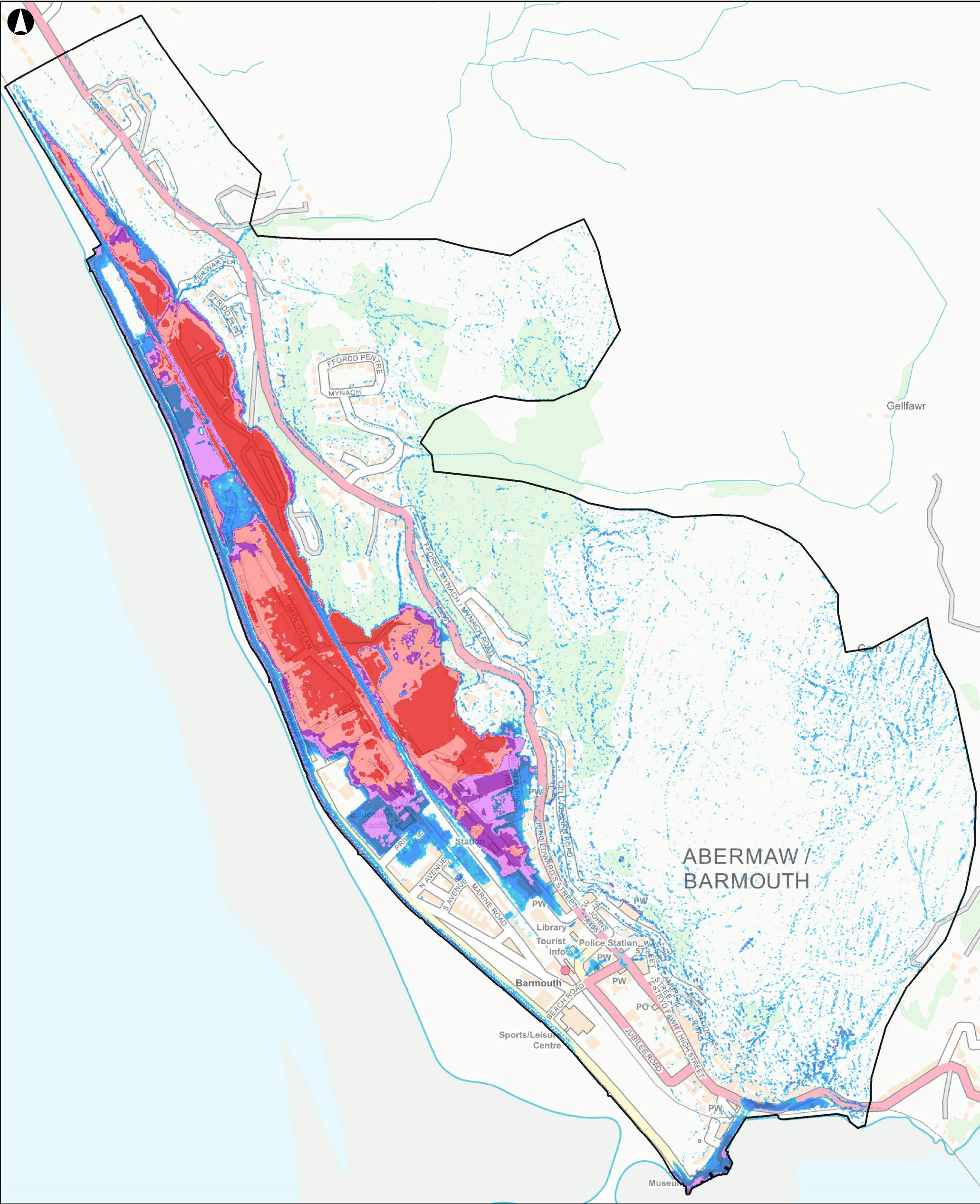
0 100 200 400

**Baseline Flood Depths 2069
Combined 1 in 10yr event
(Coastal 10yr, Rainfall 0yr)**

Scale at A3

1:7,100

Job No 264326-00	Drawing Status Preliminary
Drawing No 013	Issue P0



Legend

2D Model extent

Flood Depth (m)

- 0.1 - 0.15
- 0.15 - 0.3
- 0.3 - 0.6
- 0.6 - 0.9
- 0.9 - 1.2
- 1.2 - 1.5
- 1.5 - 2
- > 2

P0	2019-03-15	TB	DvdL	RC
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Issue	Date	By	Chkd	Appd
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ARUP

63 St Thomas Street
Bristol BS1 6JZ
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www.arup.com

Client
YGC

Job Title
Barmouth North Promenade OBC

Metres

0 100 200 400

**Baseline Flood Depths 2069
Combined 1 in 50yr event
(Coastal 50yr, Rainfall 1yr)**

Scale at A3

1:7,100

Job No 264326-00	Drawing Status Preliminary
----------------------------	--------------------------------------

Drawing No 014	Issue P0
--------------------------	--------------------



Flood Depth (m)

0.1 - 0.15

 0.15 - 0.3

0.3 - 0.6

0.6 - 0.9

 0.9 - 1.2

1.2 - 1.5

1.5 - 2

$$\square > 2$$

12. Project work\Barmouth2019\BarmouthJ

P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

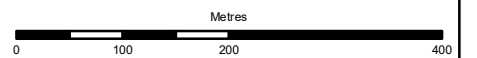
63 St Thomas Street
Bristol BS1 6JZ
+44 117 976 5432
www.arup.com

Client

YGC

Job Title

Barmouth North Promenade OBC



**Baseline Flood Depths 2069
Combined 1 in 100yr event
(Coastal 100yr, Rainfall 2yr)**

Scale at A3

1:7,100

Job No

264326-00

Drawing Status

Preliminary

Drawing No

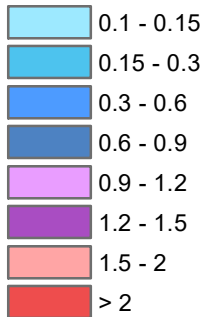
015

—
sue

0



Flood Depth (m)



P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

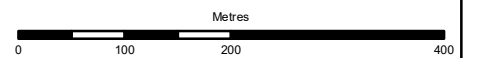
63 St Thomas Street
Bristol BS1 6JZ
+44 117 976 5432
www.arup.com

Client

YGC

Job Title

Barmouth North Promenade OBC



**Baseline Flood Depths 2069
Combined 1 in 100yr event
(Coastal 1yr, Rainfall 100yr)**

Scale at A3

1:7,100

Job No

264326-00

Drawing Status

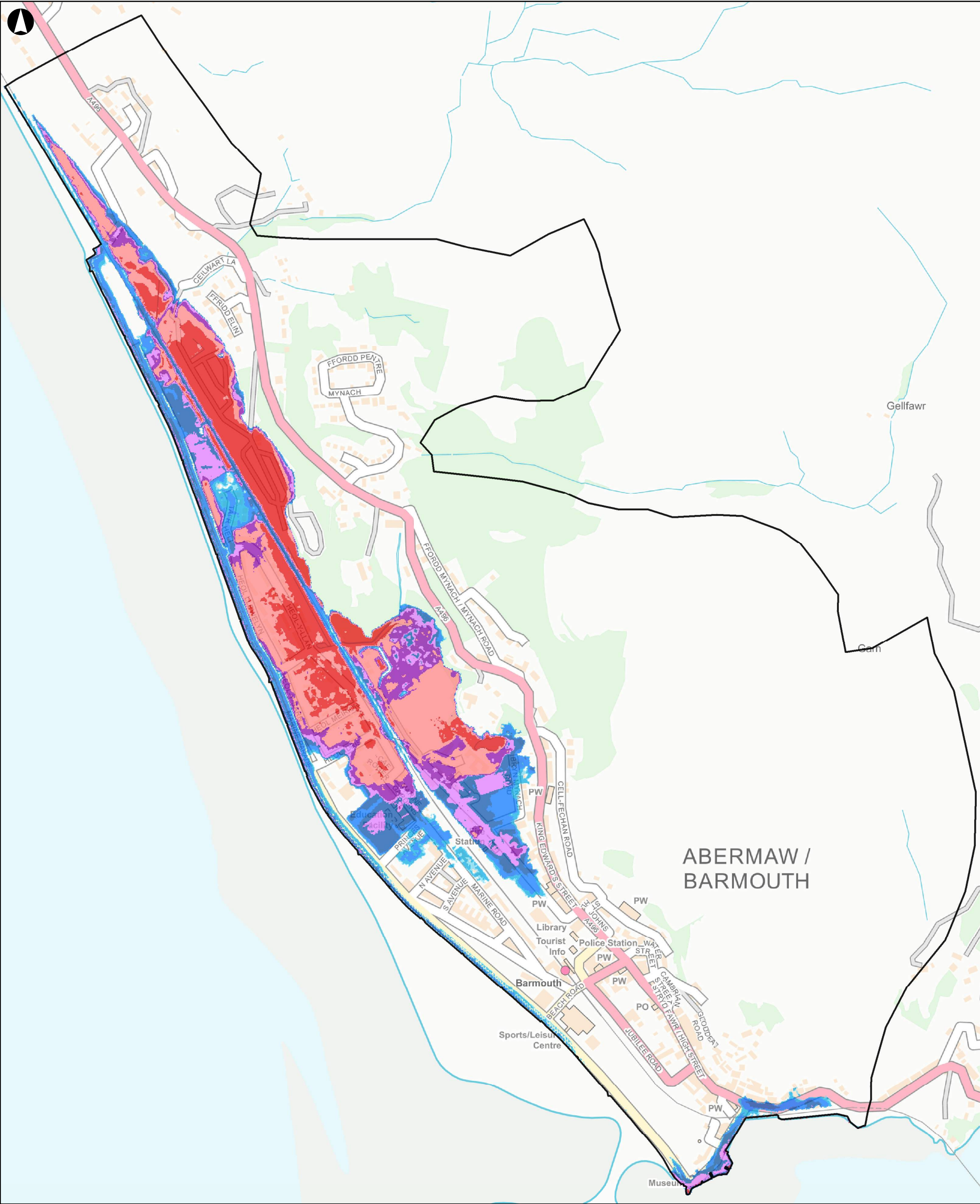
Preliminary

Drawing No

016

Issue

0



Legend

2D Model extent

Flood Depth (m)

- 0.1 - 0.15
- 0.15 - 0.3
- 0.3 - 0.6
- 0.6 - 0.9
- 0.9 - 1.2
- 1.2 - 1.5
- 1.5 - 2
- > 2

P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

63 St Thomas Street
Bristol BS1 6JZ
+44 117 976 5432
www.arup.com

Client
YGC

Job Title
Barmouth North Promenade OBC

Metres

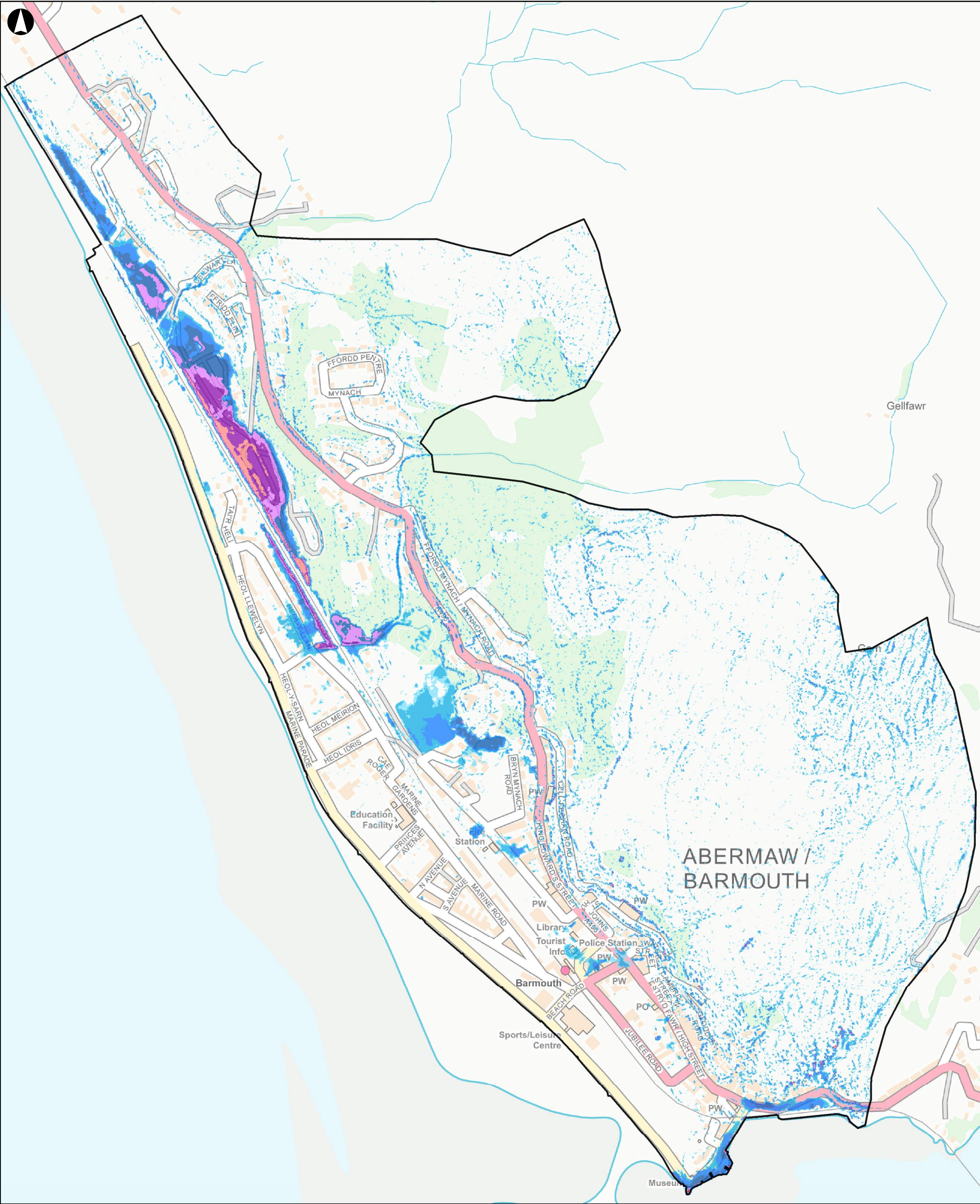
0 100 200 400

**Baseline Flood Depths 2119
Combined 1 in 1yr event
(Coastal 1yr, Rainfall 0yr)**

Scale at A3

1:7,100

Job No 264326-00	Drawing Status Preliminary
Drawing No 017	Issue P0



Legend

2D Model extent

Flood Depth (m)

- 0.1 - 0.15
- 0.15 - 0.3
- 0.3 - 0.6
- 0.6 - 0.9
- 0.9 - 1.2
- 1.2 - 1.5
- 1.5 - 2
- > 2

P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

63 St Thomas Street
Bristol BS1 6JZ
+44 117 976 5432
www.arup.com

Client
YGC

Job Title
Barmouth North Promenade OBC

Metres

0 100 200 400

**Baseline Flood Depths 2119
Combined 1 in 10yr event
(Coastal 0yr, Rainfall 10yr)**

Scale at A3

1:7,100

Job No 264326-00	Drawing Status Preliminary
Drawing No 018	Issue P0



Flood Depth (m)

 0.1 - 0.15

 0.15 - 0.3

0.3 - 0.6

 0.6 - 0.9

 0.9 - 1.2

1.2 - 1.5

1.5 - 2

$$\square > 2$$

12. Project work\Barmouth2019\BarmouthJ

P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

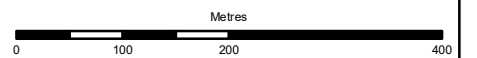
63 St Thomas Street
Bristol BS1 6JZ
+44 117 976 5432
www.arup.com

Client

YGC

Job Title

Barmouth North Promenade OBC



**Baseline Flood Depths 2119
Combined 1 in 50yr event
(Coastal 1yr, Rainfall 50yr)**

Scale at A3

1:7,100

Job No

264326-00

Drawing Status

Preliminary

Drawing No

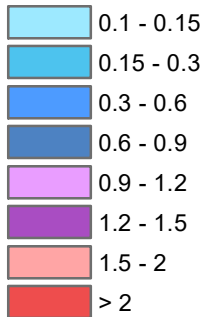
019

—
sue

0



Flood Depth (m)



P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

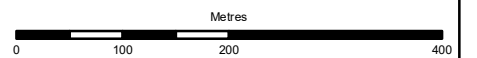
63 St Thomas Street
Bristol BS1 6JZ
+44 117 976 5432
www.arup.com

Client

YGC

Job Title

Barmouth North Promenade OBC



**Baseline Flood Depths 2119
Combined 1 in 100yr event
(Coastal 1yr, Rainfall 100yr)**

Scale at A3

1:7,100

Job No

264326-00

Drawing Status

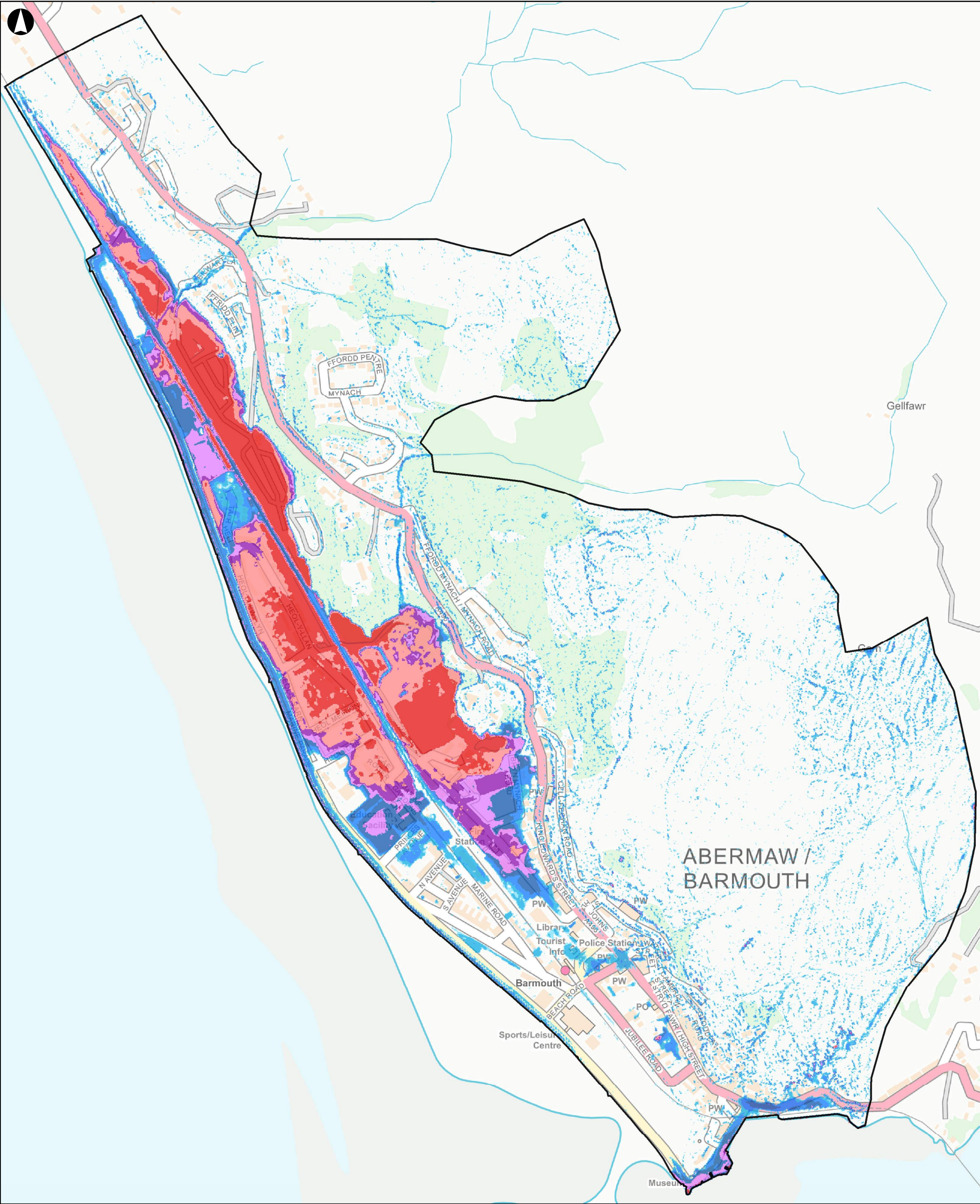
Preliminary

Drawing No

020

—
sue

0



Legend

2D Model extent

Flood Depth (m)

0.1 - 0.15
0.15 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 2
> 2

P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

63 St Thomas Street
Bristol BS1 6JZ
+44 117 976 5432
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Client
YGC

Job Title
Barmouth North Promenade OBC

Metres

0 100 200 400

**Baseline Flood Depths 2119
Combined 1 in 200yr event
(Coastal 1yr, Rainfall 200yr)**

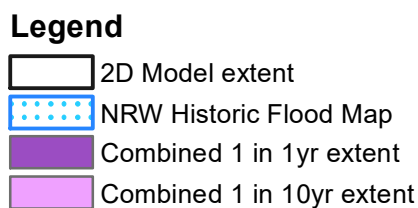
Scale at A3

1:7,100

Job No 264326-00	Drawing Status Preliminary
Drawing No 021	Issue P0

Appendix B

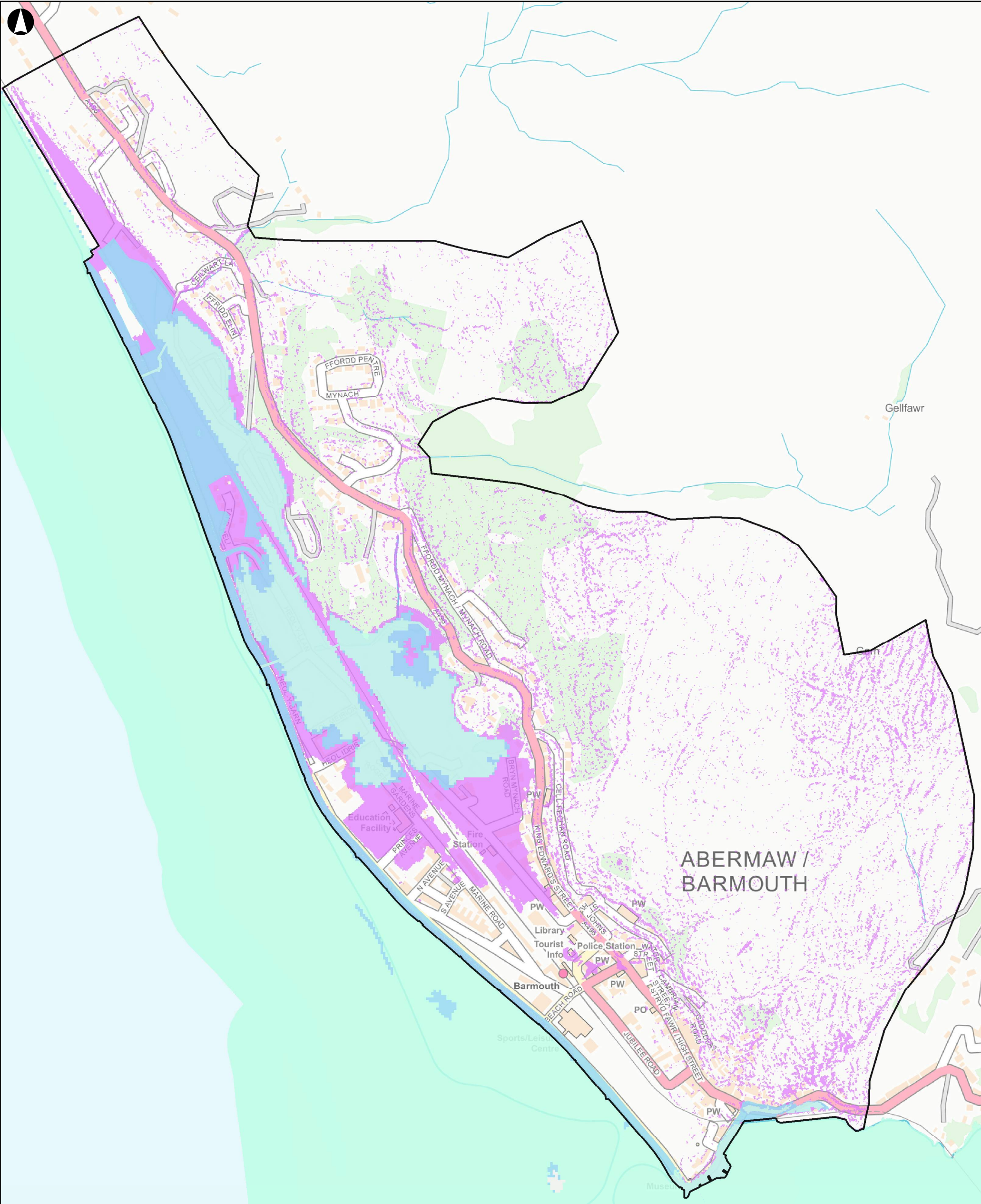
Baseline Validation and Sensitivity Maps



P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

Barmouth North Promenade OBC





Legend

- 2D Model extent
- NRW Flood Zone 3
- NRW Flood Zone 2
- Combined 1 in 200yr extent

P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

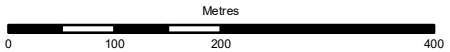
63 St Thomas Street
Bristol BS1 6JZ
+44 117 976 5432
www.arup.com

Client

YGC

Job Title

Barmouth North Promenade OBC



Validation Flood Extents 2019
Combined 1 in 200yr event
(Coastal 200yr, Rainfall 2yr)

Scale at A3

1:7,100

Job No

264326-00

Drawing Status

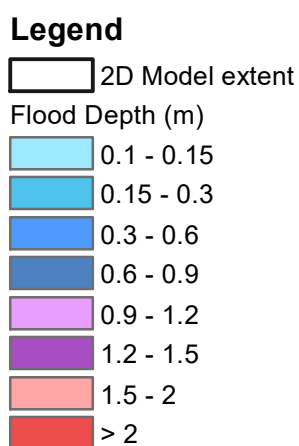
Preliminary

Drawing No

V02

Issue

P0



P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

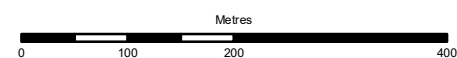
63 St Thomas Street
Bristol BS1 6JZ
+44 117 976 5432
www.arup.com

Client

YGC

Job Title

Barmouth North Promenade OBC



Sensitivity Test 00 2019
Combined 1 in 100yr event
(Coastal 10yr, Rainfall 8yr)

Scale at A3

1:7,100

Job No

264326-00

Drawing Status

Preliminary

Drawing No

\$00

Issue

P0



Flood Depth (m)

0.1 - 0.15

0.15 - 0.3

0.3 - 0.6

0.6 - 0.9

0.9 - 1.2

1.2 - 1.5

1.5 - 2

 $1.5 \leq z$
 $z \geq 2$

12. Project work\Barmouth201

Issue	Date	By	Chkd	Appd
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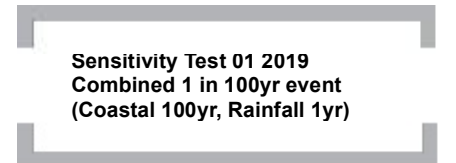
63 St Thomas Street
Bristol BS1 6JZ
+44 117 976 5432
www.arup.com

Client

YGC

Job Title

Barmouth North Promenade OBC



Scale at A3

1:7,100

Job No

264326-00

Drawing Status

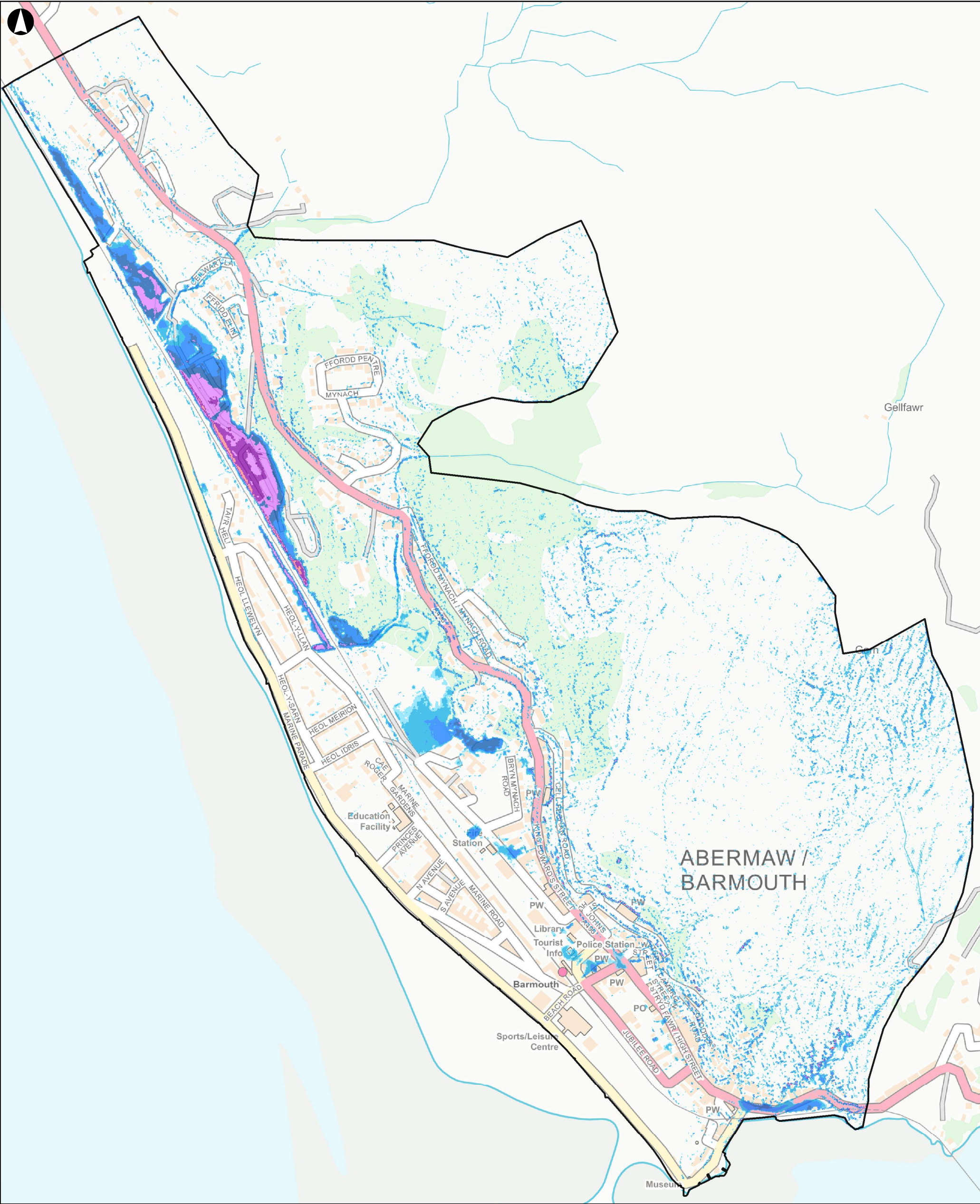
Preliminary

Drawing No

S01

—
sue

0



Legend

2D Model extent

Flood Depth (m)

- 0.1 - 0.15
- 0.15 - 0.3
- 0.3 - 0.6
- 0.6 - 0.9
- 0.9 - 1.2
- 1.2 - 1.5
- 1.5 - 2
- > 2

P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

63 St Thomas Street
Bristol BS1 6JZ
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www.arup.com

Client
YGC

Job Title
Barmouth North Promenade OBC

Metres

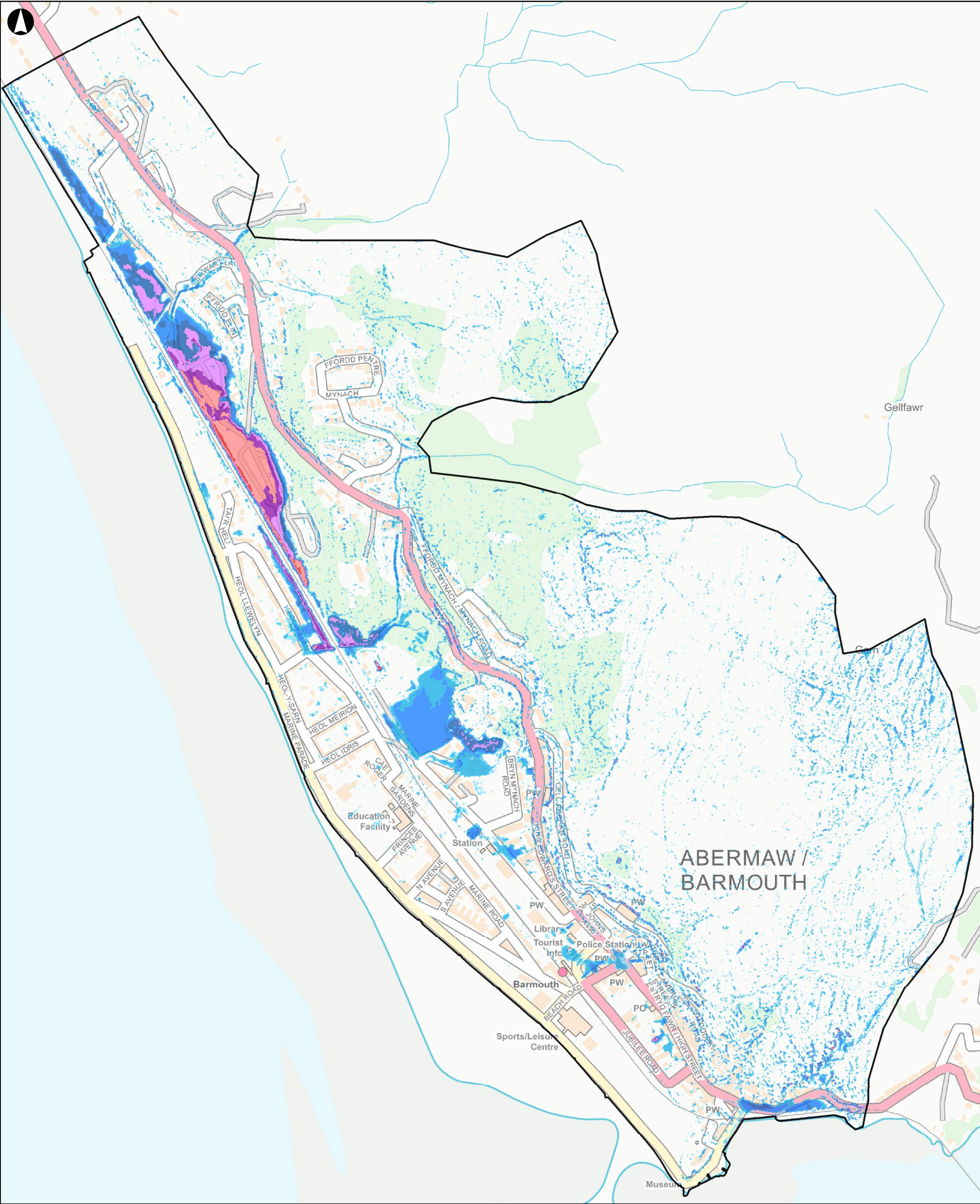
0 100 200 400

**Sensitivity Test 02 2019
Combined 1 in 10yr event
(Coastal 0yr, Rainfall 10yr)**

Scale at A3

1:7,100

Job No 264326-00	Drawing Status Preliminary
Drawing No S02a	Issue P0



Legend

2D Model extent

Flood Depth (m)

0.1 - 0.15

0.15 - 0.3

0.3 - 0.6

0.6 - 0.9

0.9 - 1.2

1.2 - 1.5

1.5 - 2

> 2

P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

63 St Thomas Street
Bristol BS1 6JZ
+44 117 976 5432
www.arup.com

Client
YGC

Job Title
Barmouth North Promenade OBC

0100200400

Metres

Sensitivity Test 02 2019

Combined 1 in 50yr event

(Coastal 0yr, Rainfall 50yr)

Scale at A3

1:7,100

Job No

264326-00

Drawing No

S02b

Drawing Status

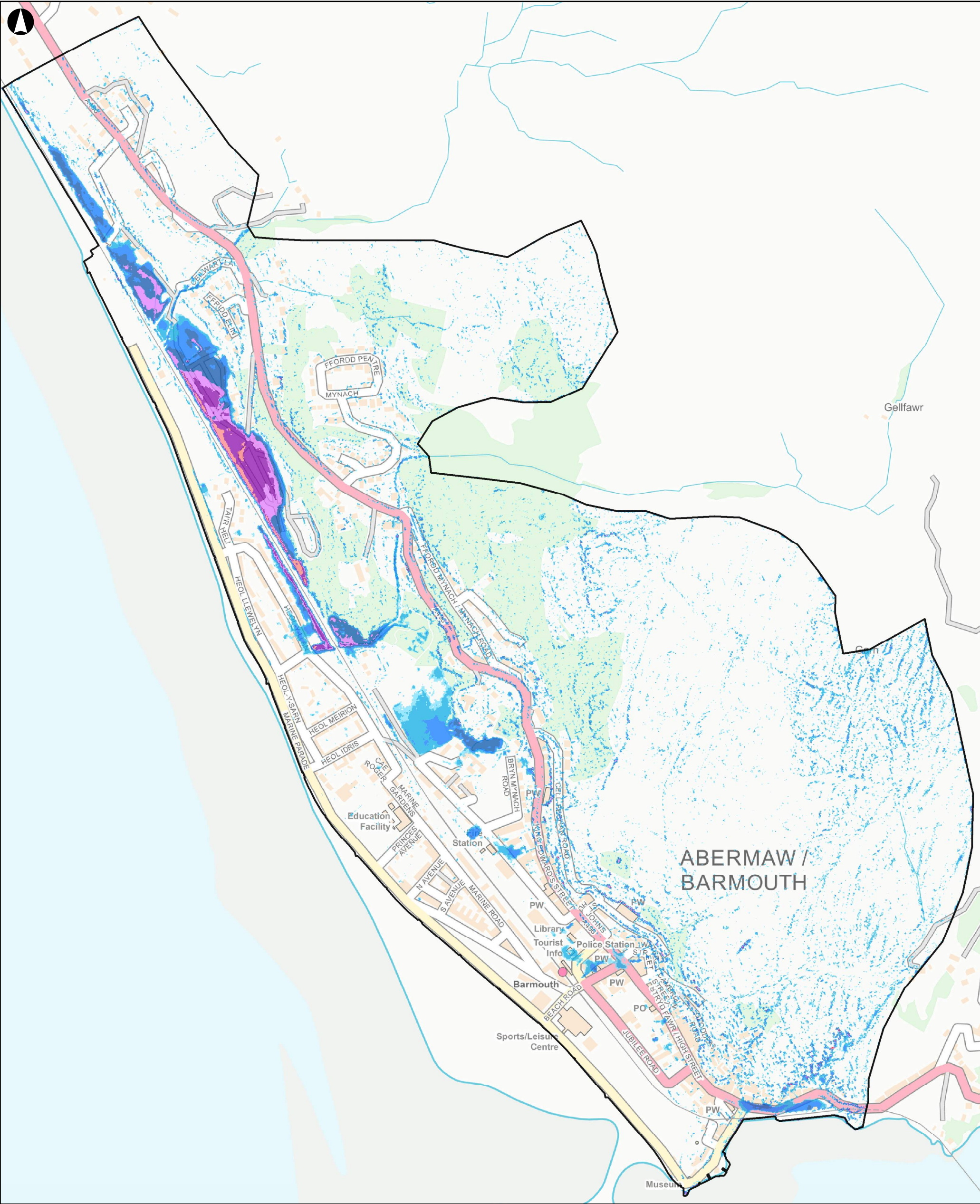
Preliminary

Issue

P0

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Legend

2D Model extent

Flood Depth (m)

0.1 - 0.15

0.15 - 0.3

0.3 - 0.6

0.6 - 0.9

0.9 - 1.2

1.2 - 1.5

1.5 - 2

> 2

P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

63 St Thomas Street
Bristol BS1 6JZ
+44 117 976 5432
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Client
YGC

Job Title
Barmouth North Promenade OBC

Metres
0 100 200 400

**Sensitivity Test 02 2069
Combined 1 in 10yr event
(Coastal 0yr, Rainfall 10yr)**

Scale at A3
1:7,100

Job No
264326-00

Drawing No
S02c

Drawing Status
Preliminary

Issue
P0

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Flood Depth (m)

0.1 - 0.15
0.15 - 0.3
0.3 - 0.6
0.6 - 0.9
0.9 - 1.2
1.2 - 1.5
1.5 - 2
> 2

P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

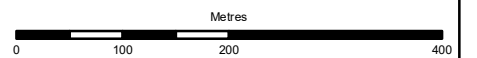
63 St Thomas Street
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Client

YGC

Job Title

Barmouth North Promenade OBC



Sensitivity Test 02 2069
Combined 1 in 50yr event
(Coastal 0yr, Rainfall 50yr)

Scale at A3

1:7,100

Job No

264326-00

Drawing Status

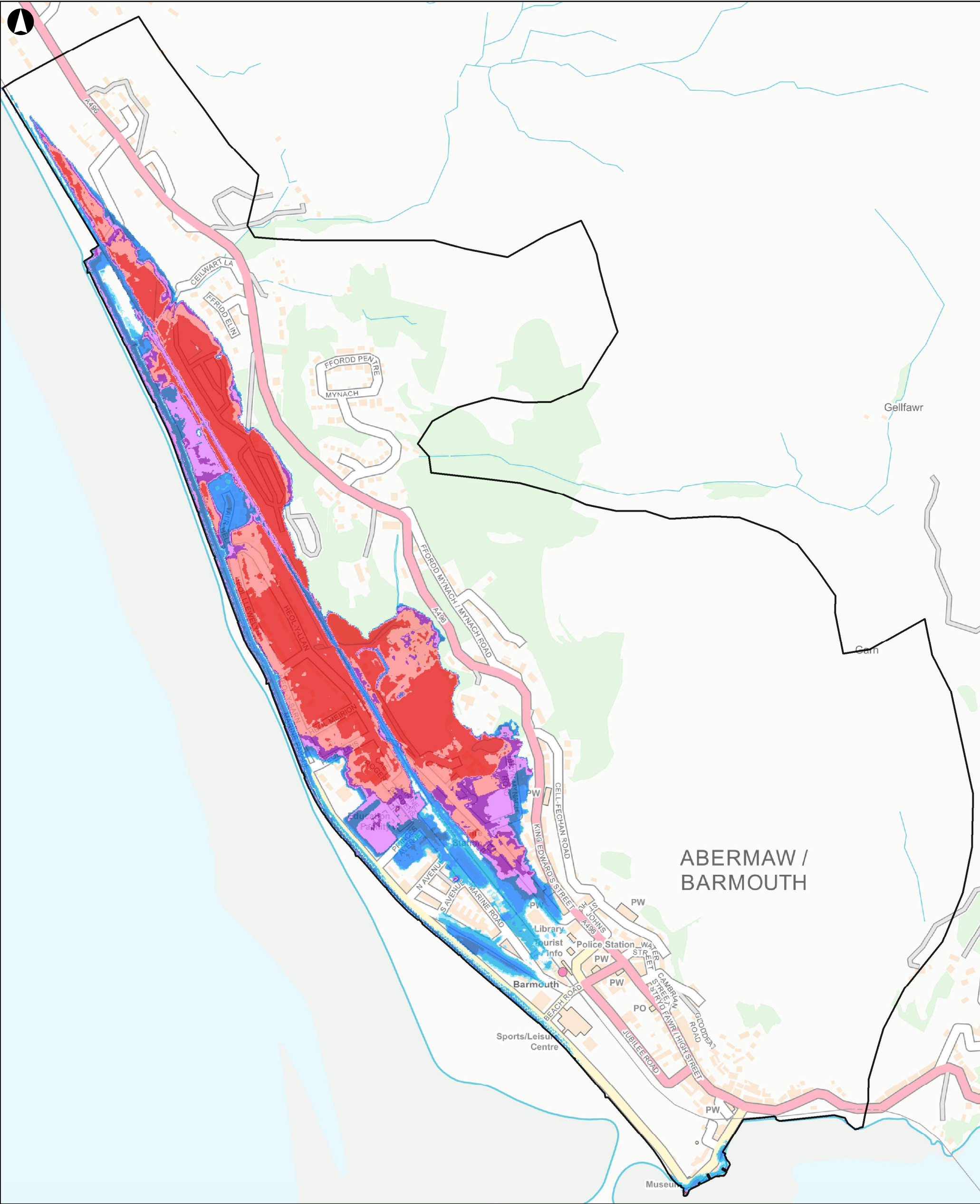
Preliminary

Drawing No

S02d

—
sue

0



Legend

2D Model extent

Flood Depth (m)

- 0.1 - 0.15
- 0.15 - 0.3
- 0.3 - 0.6
- 0.6 - 0.9
- 0.9 - 1.2
- 1.2 - 1.5
- 1.5 - 2
- > 2

P0	2019-03-15	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

63 St Thomas Street
Bristol BS1 6JZ
+44 117 976 5432
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Client
YGC

Job Title
Barmouth North Promenade OBC

Metres

0 100 200 400

**Sensitivity Test 03 2019
Combined 1 in 10yr event
(Coastal 10yr, Rainfall 0yr)**

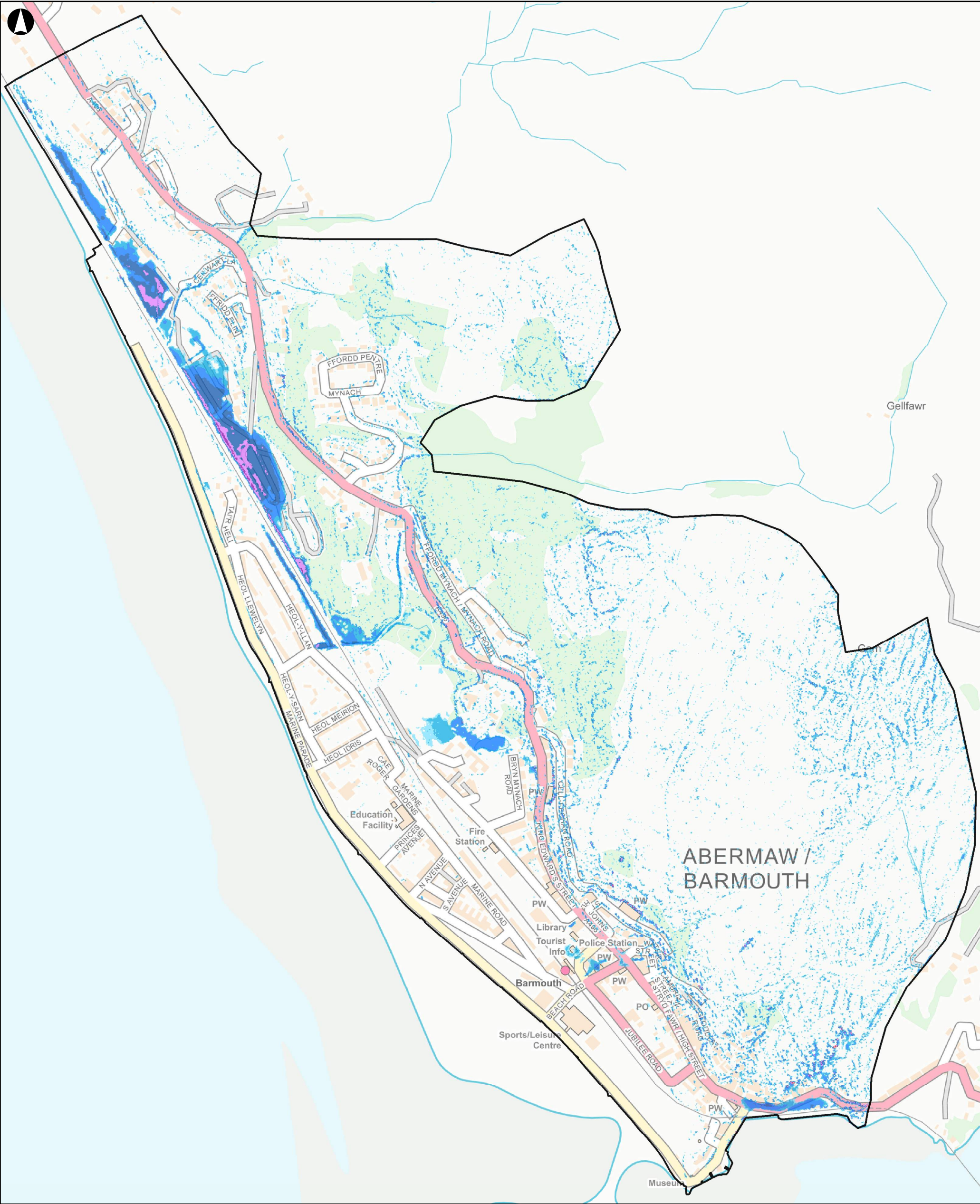
Scale at A3

1:7,100

Job No 264326-00	Drawing Status Preliminary
Drawing No S03	Issue P0

Appendix C

Do Something Flood Depth Maps



Legend

2D Model extent

Flood Depth (m)

- 0.1 - 0.15
- 0.15 - 0.3
- 0.3 - 0.6
- 0.6 - 0.9
- 0.9 - 1.2
- 1.2 - 1.5
- 1.5 - 2
- > 2

P0	2019-04-10	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

63 St Thomas Street
Bristol BS1 6JZ
+44 117 976 5432
www.arup.com

Client
YGC

Job Title
Barmouth North Promenade OBC

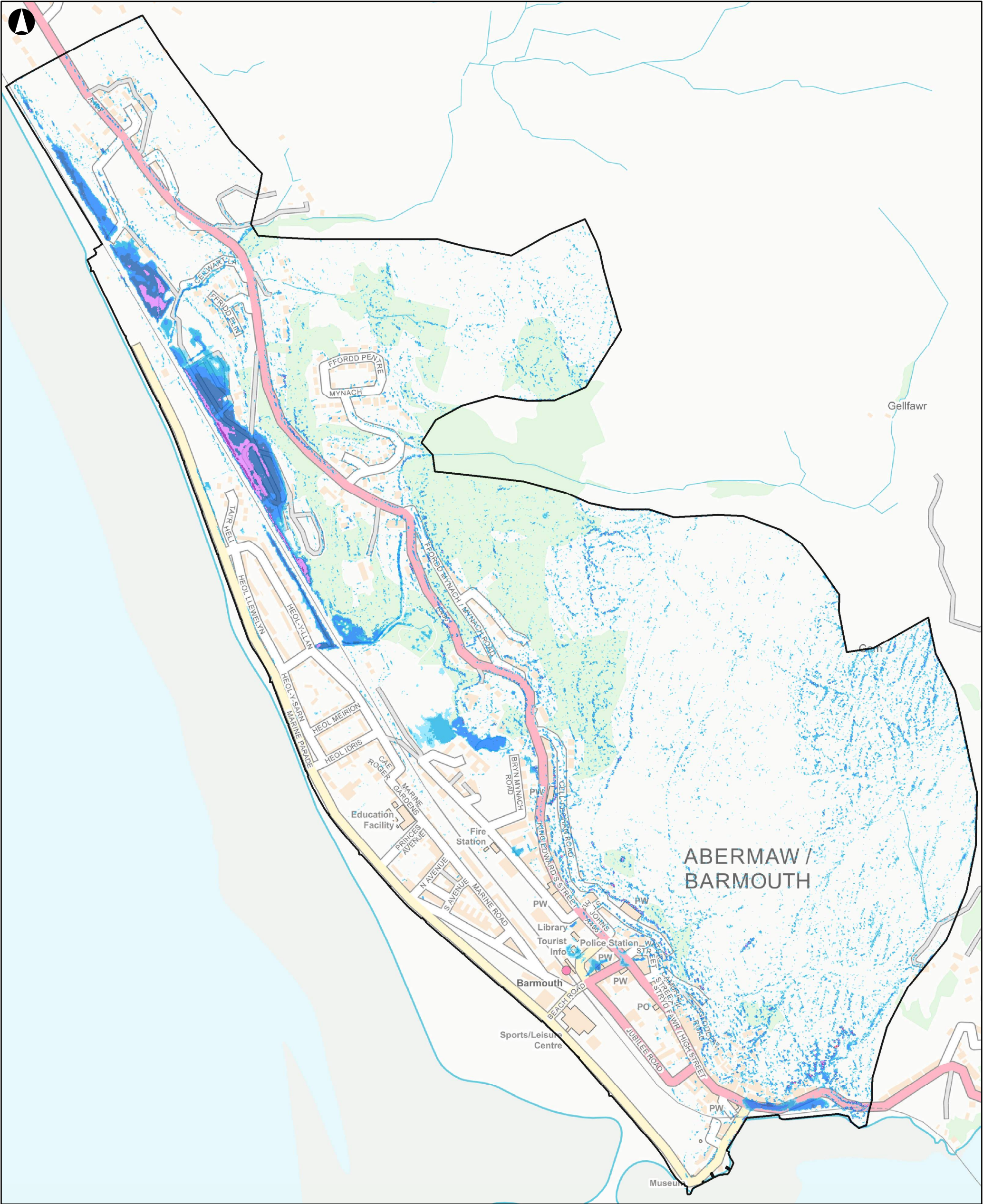
Metres

0 100 200 400

**Do Something Residual Risk
Flood Depths 2019
Combined 1 in 100yr event
(Coastal 0yr, Rainfall 1yr)**

Scale at A3
1:7,100

Job No 264326-00	Drawing Status Preliminary
Drawing No 022	Issue P0



Legend

2D Model extent

Flood Depth (m)

- 0.1 - 0.15
- 0.15 - 0.3
- 0.3 - 0.6
- 0.6 - 0.9
- 0.9 - 1.2
- 1.2 - 1.5
- 1.5 - 2
- > 2

P0	2019-04-10	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

63 St Thomas Street
Bristol BS1 6JZ
+44 117 976 5432
www.arup.com

Client
YGC

Job Title
Barmouth North Promenade OBC

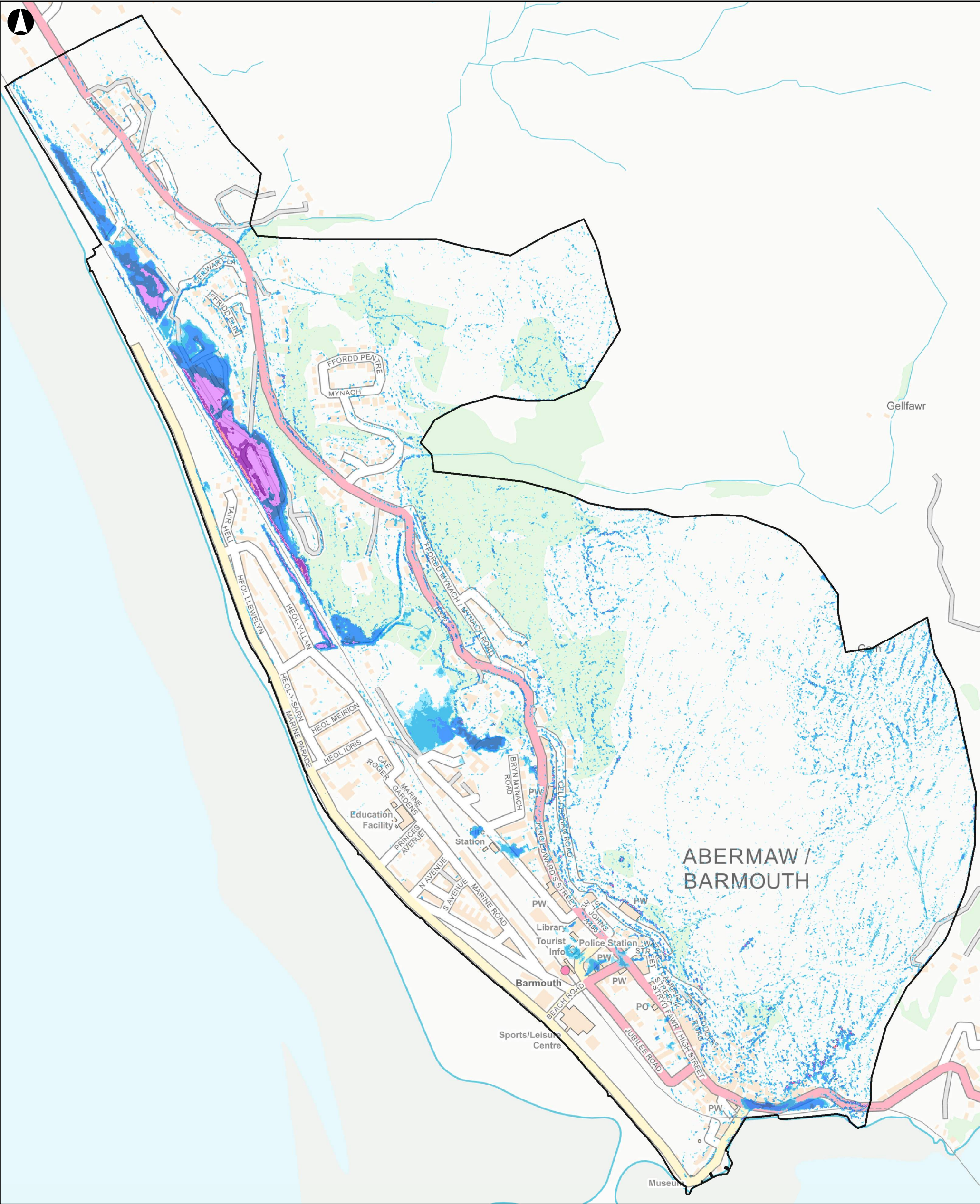
Metres

0 100 200 400

**Do Something Residual Risk
Flood Depths 2019
Combined 1 in 200yr event
(Coastal 0yr, Rainfall 2yr)**

Scale at A3
1:7,100

Job No 264326-00	Drawing Status Preliminary
Drawing No 023	Issue P0



Legend

2D Model extent

Flood Depth (m)

- 0.1 - 0.15
- 0.15 - 0.3
- 0.3 - 0.6
- 0.6 - 0.9
- 0.9 - 1.2
- 1.2 - 1.5
- 1.5 - 2
- > 2

P0	2019-04-10	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

63 St Thomas Street
Bristol BS1 6JZ
+44 117 976 5432
www.arup.com

Client
YGC

Job Title
Barmouth North Promenade OBC

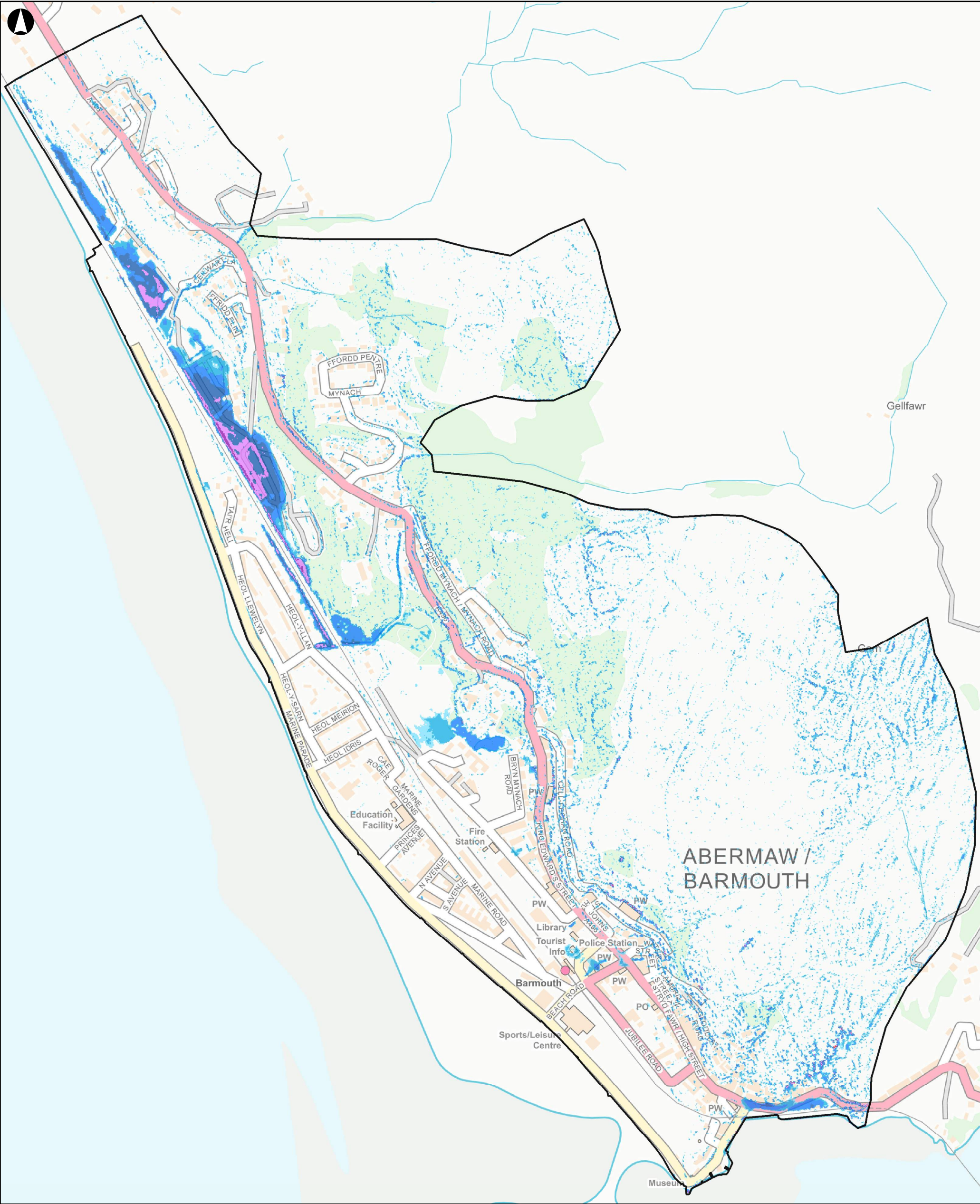
Metres

0 100 200 400

**Do Something Residual Risk
Flood Depths 2019
Combined 1 in 1000yr event
(Coastal 0yr, Rainfall 8yr)**

Scale at A3
1:7,100

Job No 264326-00	Drawing Status Preliminary
Drawing No 024	Issue P0



Legend

2D Model extent

Flood Depth (m)

0.1 - 0.15

0.15 - 0.3

0.3 - 0.6

0.6 - 0.9

0.9 - 1.2

1.2 - 1.5

1.5 - 2

> 2

P0	2019-04-10	TB	DvdL	RC
Issue	Date	By	Chkd	Appd

ARUP

63 St Thomas Street

Bristol BS1 6JZ

+44 117 976 5432

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Client

YGC

Job Title

Barmouth North Promenade OBC

0100200300400

Metres

Do Something Residual Risk

Flood Depths 2069

Combined 1 in 50yr event

(Coastal 0yr, Rainfall 1yr)

Scale at A3

1:7,100

Job No	Drawing Status
264326-00	Preliminary
Drawing No	Issue
025	P0

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Flood Depth (m)

0.1 - 0.15	0.1 - 0.15
0.15 - 0.3	0.15 - 0.3
0.3 - 0.6	0.3 - 0.6
0.6 - 0.9	0.6 - 0.9
0.9 - 1.2	0.9 - 1.2
1.2 - 1.5	1.2 - 1.5
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P0	2019-04-10	TB	DvdL	RC
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ARUP

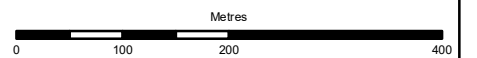
63 St Thomas Street
Bristol BS1 6JZ
+44 117 976 5432
www.arup.com

Client

YGC

Job Title

Barmouth North Promenade OBC



**Do Something Residual Risk
Flood Depths 2069
Combined 1 in 100yr event
(Coastal 0yr, Rainfall 2yr)**

Scale at A3

1:7,100

Job No

264326-00

Drawing Status

Preliminary

Drawing No

026

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Appendix D

Barmouth Hydrological Summary

Barmouth

Flood estimation calculation record

Revision	Author	Date	Issued for/Revision details
1	D. Allan	18/03/2019	First draft
2			

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Abbreviations and key acronyms

AEP	Annual Exceedance Probability
AREA	Catchment area (km ²)
BFIHOST	Base Flow Index derived using the HOST soil classification
BGS	British Geological Survey
DPLBAR	Parameter to categorise catchment size and configuration
DPSBAR	Mean Drainage Path Slope
FARL	FEH index of flood attenuation due to reservoirs and lakes
FEH	Flood Estimation Handbook
FPEXT	Floodplain extent
GIS	Geographical Information System
LiDAR	Light Detection and Ranging
mAOD	metres above ordnance datum
NGR	National Grid Reference
NRFA	National River Flow Archive
OS	Ordnance Survey
PROPWET	Proportion of time soils are wet
QMED	Median Annual Flood (with return period 2 years)
ReFH	Revitalised Flood Hydrograph method
SAAR	Standard Average Annual Rainfall (mm)
SPRHOST	Standard percentage runoff derived using the HOST soil classification
Tp(o)	Time to peak of the instantaneous unit hydrograph
UAF	Urban Adjustment Factor
UEF	Urban Expansion Factor
uFMfSW	updated Flood Map for Surface Water
URBEXT ₁₉₉₀	FEH index of fractional urban extent
URBEXT ₂₀₀₀	Revised index of urban extent, measured differently from URBEXT ₁₉₉₀
WINFAP-FEH	Windows Frequency Analysis Package – used for FEH statistical method

1 Method statement

1.1 Overview of requirements for flood estimates

- This document provides a summary record of the calculations and decisions made during the process of deriving design rainfall and peak flood flows; it is supplemented by a hydrological calculation spreadsheet and model files which contain a significant amount of additional information.

File:

[Barmouth - Hydrology - 08022019.xlsx](#)

Location:

[\\global\europa\Cardiff\Jobs\264000\264326-00\4 Internal Project Data\4-40 Calculations\Hydrology\](#)

- The return periods considered in this assessment are: 1 year (100% Annual Exceedance Probability (AEP)), 2 year (50% AEP), 4 year (25% AEP), 8 year (12.5% AEP), 10 year (10% AEP), 16 year (6.3% AEP), 20 year (5% AEP), 30 year (3.33% AEP), 50 year (2% AEP), 75 year (1.33 AEP%), 100 year (1% AEP), 200 year (0.5% AEP) and 1,000 year (0.1% AEP).
- The information given in this report will provide evidence on the catchment understanding, justification for the choice of methodology used in deriving peak flows / design rainfall and should enable the work to be reproduced in the future.

1.2 Initial choice of approach

Key Guidance:

- Environment Agency (2017). Making better use of local data in flood frequency estimation. Report – SC130009/R
- Wallingford HydroSolutions (WHS) (2016). The Revitalised Flood Hydrograph Model ReFH2.2: Technical Guidance
- Environment Agency (2015). Flood Estimation Guidelines. Technical Guidance 197_08. Version 5
- Environment Agency (2012). Estimating flood peaks and hydrographs for small catchments: Phase 1. Project: SC090031
- Kjeldsen, T. R. (2010). Modelling the impact of urbanization on flood frequency relationships in the UK. *Hydrology Research*, 41 (5), pp. 391-405.
- Environment Agency (2008). Improving the FEH statistical procedures for flood frequency estimation. Science Report - SC050050
- Bayliss, A.C., Black, K.B., Fava-Verde, A., and Kjeldsen, T.R. (2007). URBEXT2000 – A new FEH catchment descriptor: Calculation, dissemination and application. R&D Technical Report FD1919/TR. DEFRA/Environment Agency
- Kjeldsen, T.R., Stewart, E.J., Packman, J.C., Folwell, S.S. & Bayliss, A.C. (2005) Revitalisation of the FSR/FEH rainfall-runoff method. R&D Technical Report FD1913/TR. DEFRA/Environment Agency
- CEH (1999). The Flood Estimation Handbook. Vol. 1 – 5.

Approach:

The Environment Agency guidance (*Flood estimation guidelines – Operational Instruction 197_08*) recommends four possible methods for estimating catchment flows:

1. the Flood Estimation Handbook (FEH) Statistical method (WINFAP-FEH);
2. the Revitalised Flood Hydrograph (ReFH) method;
3. the Flood Studies Report (FSR) Rainfall-Runoff method (superseded by ReFH); or
4. the Modified Rational Method (MRM), Institute of Hydrology IH124 or Agricultural Development and Advisory Service (ADAS) for very small catchments or for greenfield runoff estimation.

Often a combination, or hybrid, approach adopting a number of the above methods is used.

Since the Environment Agency guidance was published (2015), the ReFH method has been updated to ReFH2. ReFH2 has superseded the IH124 and ADAS methods and is the recommended method within the CIRIA SuDS Manual (C753) for estimating greenfield runoff rates and volumes.

As ReFH2 allows for the generation of both peak flows and hydrographs, based on catchment descriptors and FEH2013 rainfall, this method is considered to be appropriate for this assessment. Due to the small nature of the study catchments, the FEH statistical method is not considered to be suitable, given that this assessment is based on developing a pooling group for hydrologically similar gauged catchments; which there are unlikely to be any within the Peak Flows database¹.

For this assessment:

The catchment boundaries and descriptors were identified and exported from the FEH Web Service² and peak flood flows, hydrographs and rainfall hyetographs were generated using ReFH2. Hydrology will be generated for the two main watercourses; subsequent hydrology will be derived for an intermediate catchment by proportioning the Hafotty flows by area. Direct rainfall modelling will also be undertaken making use of the design rainfall derived for the two main catchments.

Software:

- FEH Web Service²
- ReFH2 v.2.2.6029.28099

¹ <https://nrfa.ceh.ac.uk/peak-flow-dataset>

² <https://fehweb.ceh.ac.uk/>

2 Catchment Descriptors

2.1 Overview of catchment

Location

- Hydrology is required for two small catchments (Hafotty and Gellfawr) that drain an upland area to the north-east of the coastal town of Barmouth, Gwynedd, Wales. The catchments are within the Snowdonia National park.
- The channels are within incised gullies with steep sides.
- The topography shows the upper reaches of the catchment to be around 460 mAOD, draining all the way down, through Barmouth to the sea (0 mAOD).

Flow Record

- Neither of the catchments are gauged. A review of the NRFA³ did not identify any nearby, or hydrologically similarly, gauged catchments to help with the estimation of the hydrology.

Flood Risk

- The Natural Resources Wales fluvial and coastal flood maps⁴ show an extensive modelled flood extent across the town of Barmouth, although a level of coastal flood protection is offered. Neither of the small watercourses considered as part of this investigation have modelled flood plains associated with them.
- The Natural Resources Wales surface water flood maps⁴ show that flooding is contained within the steep incised channels along both watercourses, but then extensive surface water flooding is noted through much of Barmouth where the topography flattens out.
- There is no reservoir flood risk identified on the Natural Resources Wales Reservoir Flood Risk maps⁴.

Geology and Soils

- From the BGS⁵ maps the bedrock geology across the main area of interest is characterised by Rhinog Formation - sandstone and mudstone, and Hafotty Formation – mudstone and Barmouth Formation - sandstone and mudstone.
- The study area largely sits over a low productivity aquifer⁶.
- The BGS 1:50k maps⁵ show no evidence of any superficial deposits.
- Cranfield University soil database⁷, Soilscape, shows that the study area consists of naturally wet very acid sandy and loamy soils through the town of Barmouth with freely draining slightly acid loamy soils, freely draining acid loamy soils over rock and shallow very acid peaty soils over rock in the upper catchments.

Additional Information

- There are numerous quarries and manganese mines within the upper catchments. Details regarding mine drainage etc. are unknown.

³ <https://nrfa.ceh.ac.uk/data/search>

⁴ https://maps.cyfoethnaturiolcymru.gov.uk/Html5Viewer/Index.html?configBase=https://maps.cyfoethnaturiolcymru.gov.uk/Geocortex/Essentials/REST/sites/Flood_Risk/viewers/Flood_Risk/virtualdirectory/Resources/Config/Default&layerTheme=0

⁵ <http://mapapps.bgs.ac.uk/geologyofbritain/home.html>

⁶ <http://mapapps2.bgs.ac.uk/geoindex/home.html?layer=BGSHydroMap>

⁷ <http://www.landis.org.uk/soilscape/index.cfm>

2.2 Catchment Descriptors

Descriptor	Hafotty	Gellfawr
NGR	SH 60650 17250	SH 60950 16850
AREA (km ²)	0.8475 (1.214)	0.710 (0.679)
ALTBAR (m)	288	242
ASPBAR (degrees)	247	227
ASPVAR	0.75	0.58
BFIHOST	0.470	0.473
DPLBAR (km)*	1.29 (1.112)	1.06 (0.809)
DPSBAR (m/km)	235.9	240.6
FARL	1.000	1.000
FPEXT	0	0.0352
LDP (km)	2.13	1.98
PROPWET	0.66	0.66
SAAR (mm)	1,304	1,207
SAAR ₄₁₇₀ (mm)	1,386	1,321
SPRHOST (%)	38.11	39.33
URBEXT ₂₀₀₀	0.000	0.000
URBEXT ₂₀₁₈ **	0.000	0.000
Urban Classification (based on URBEXT ₂₀₀₀)	Essentially Rural	Essentially Rural
Note: values in brackets have been updated * DPLBAR - amended value after revision of AREA - (DPLBAR = AREA ^{0.548}); ** URBEXT ₂₀₁₈ calculated from URBEXT ₂₀₀₀ adjustment using Bayliss (2006)		

Urbanisation Classification

Essentially rural	0.000	≤ URBEXT ₂₀₀₀ <	0.030
Slightly Urbanised	0.030	≤ URBEXT ₂₀₀₀ <	0.060
Moderately Urbanised	0.060	≤ URBEXT ₂₀₀₀ <	0.150
Heavily Urbanised	0.150	≤ URBEXT ₂₀₀₀ <	0.300
Very Heavily Urbanised	0.300	≤ URBEXT ₂₀₀₀ <	0.600
Extremely Heavily Urbanised	0.600	≤ URBEXT ₂₀₀₀ ≤	1.000

2.3 Checking and adjusting catchment descriptors

Adjustments to catchment descriptors are shown in the above table (in brackets), the process for the adjustment is discussed below and is based on the methods outlined in the FEH Vol. 5.

- Catchment AREA - The FEH Web Service is limited to a minimum of 0.5km². Visual inspections using Ordnance Survey mapping and manual digitisation in GIS using LiDAR were made to confirm and amend the catchment boundary. The Natural Resources Wales surface water extents were also used to check catchment area based on modelled flow paths.
- DPLBAR, where necessary was adjusted using the revised catchment area and approach outlined in the FEH Vol. 5.
- BFIHOST & SPRHOST - Soils and geology were checked via the BGS website⁵, FEH Web Service² and Cranfield University soil information website⁷. The geology and soil types in the study area appear to support the values of SPRHOST and BFIHOST noted.
- FARL – the presence of waterbodies within the catchment was checked against the OS mapping and recalculated if required based on the approach outlined in the FEH Vol. 5.
- The URBEXT₂₀₀₀ values were updated to URBEXT₂₀₁₈ using the Urban Adjustment Factor (UEF) derived by Bayliss (2006) where no significant changes were made to the catchment area. For manually defined catchment areas the URBEXT values were calculated using OS background mapping and the Environment Agency Technical Report FD1919/TR.

2.4 Significant factors to consider

Factor	Comment	Potential Significance
Watercourse type	Ordinary Watercourse	Both catchments contain steep, mountain streams
Influence of reservoirs \ lakes	FARL	There are no ponds/lakes or reservoirs within the catchments.
Urbanised area	URBEXT ₂₀₀₀	Both catchments are considered to be essentially rural with only isolated buildings present
Land use	-	Mainly upland areas with rocky outcrops
Soils \ Geology	BFIHOST and SPRHOST	Given the soils types identified using the BGS datasets, the values of BFIHOST and SPRHOST seem reasonable
Other	-	There are numerous quarries and manganese mines within the catchments

3 Revitalised flood hydrograph method Version 2 (ReFH2)

3.1 Parameters for ReFH2 model

Method used to derive flows:	Catchment descriptors	Catchment or Plot ⁸ equations	Catchment
Country	England/Wales/NI	Rainfall Model	FEH2013
Urban or Rural	Rural	Storm area for ARF	Catchment area
Season of design event	Winter	Storm Duration (hrs)	02:54:00
* ReFH2 estimates the initial storm duration and design rainfall depths for each design event based on the FEH catchment descriptors. This recommended design storm duration is a function of the event time to peak parameter (Tp) and catchment average annual rainfall (SAAR). However, this duration may not always result in the highest peak flow. A sensitivity analysis was completed for the 100 year event to determine which duration gave the highest peak flow. This duration was then assumed to be representative of all other return periods.			

Catchment	Areal Reduction Factor (ARF)	Seasonal Correction Factor (SCF)	Time to peak - Tp (hours)	Maximum storage capacity - C _{max} (mm)	Baseflow lag - BL (hours)	Baseflow recharge - BR
Hafotty	0.972	0.783	1.00	328.541	24.323	1.485
Gellfawr	0.977	0.766	1.00	331.112	22.781	1.496

3.2 Flood estimates from the ReFH2 method

AEP	Return period	Peak Flow (m ³ /s)	
		Hafotty	Gellfawr
100%	1yr	0.832	0.433
50%	2yr	0.910	0.475
20%	5yr	1.203	0.634
10%	10yr	1.486	0.789
5%	20yr	1.890	1.012
3.33%	30yr	2.184	1.172
2%	50yr	2.592	1.388

⁸ See Table 2 (page 12) in the ReFH2 Technical Guidance Document. Issue 2.0.4.
http://files.hydrosolutions.co.uk/refh2/ReFH2_Technical_Report.pdf

Hydrological Estimation Record

AEP	Return period	Peak Flow (m ³ /s)	
		Hafotty	Gellfawr
1.33%	75yr	2.935	1.571
1%	100yr	3.189	1.707
0.5%	200yr	3.837	2.051
0.1%	1,000yr	5.532	2.953

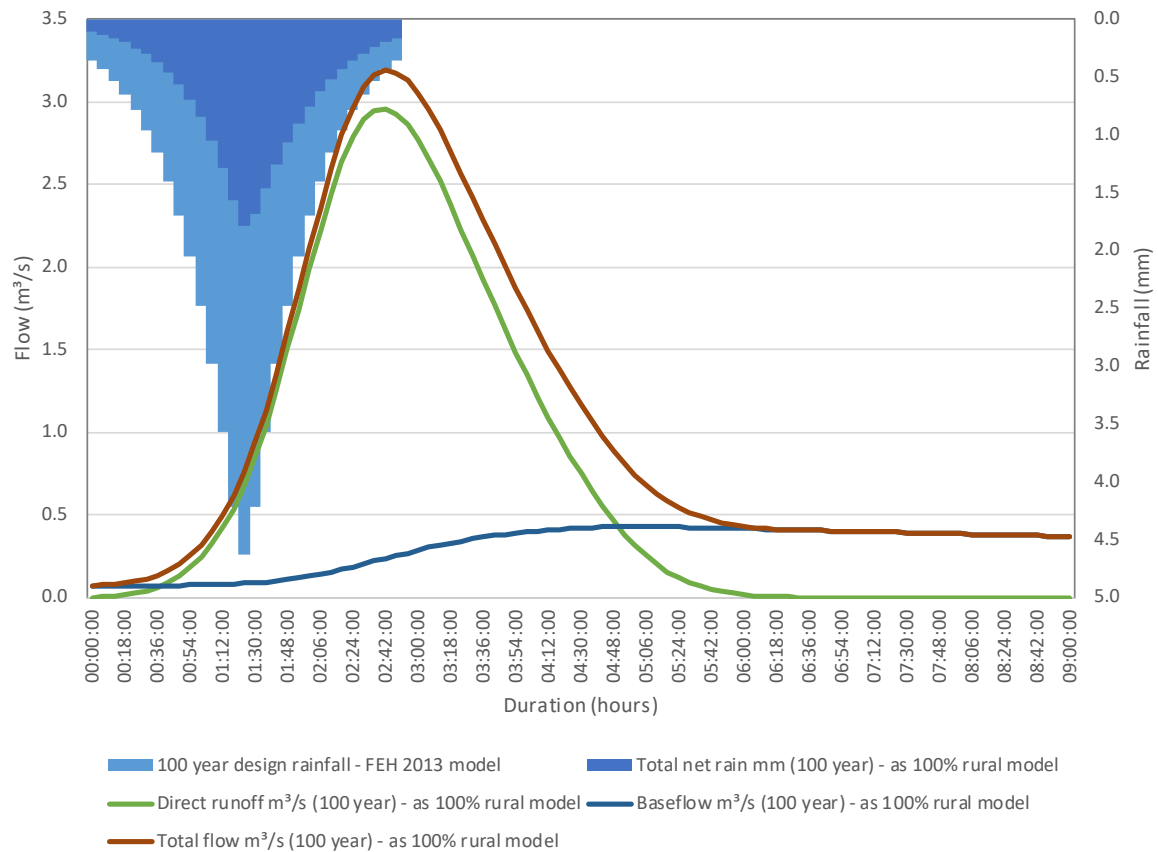


Figure 1: Example showing 100-yr Flood Hydrograph for the Hafotty catchment, calculated within ReFH2

Hydrological Estimation Record

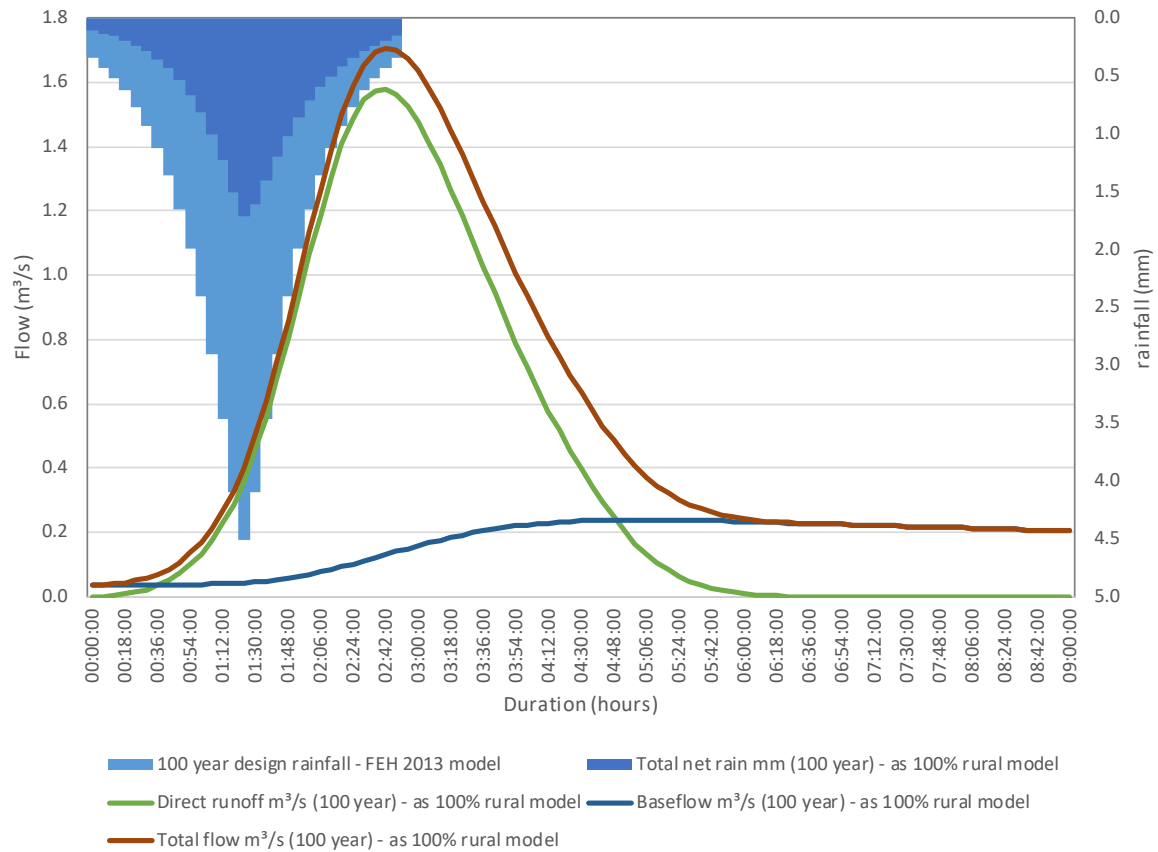


Figure 2: Example showing 100-yr Flood Hydrograph for the Gellfawr catchment, calculated within ReFH2

Additional storm durations were considered within ReFH2 for the 10-year and 200-year return periods to allow model sensitivity scenarios to be considered, presented below.

Duration (hrs)	Peak Flow (m^3/s)			
	Hafotty		Gellfawr	
	10-year	200-year	10-year	200-year
0.5	0.888	2.459	0.476	1.333
1.0	1.117	3.279	0.600	1.770
2.0	1.406	3.803	0.751	2.039
3.0	1.496	3.838	0.794	2.048
6.0	1.531	3.569	0.804	1.889
12.0	1.314	2.768	0.681	1.448
24.0	1.067	2.054	0.548	1.063

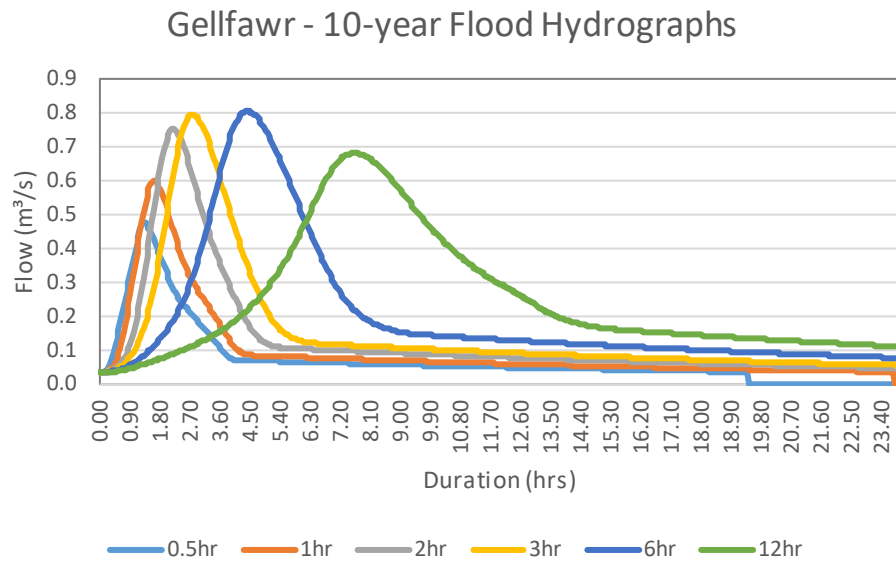


Figure 3: Comparison of 10-year flood hydrograph shapes for varying storm durations

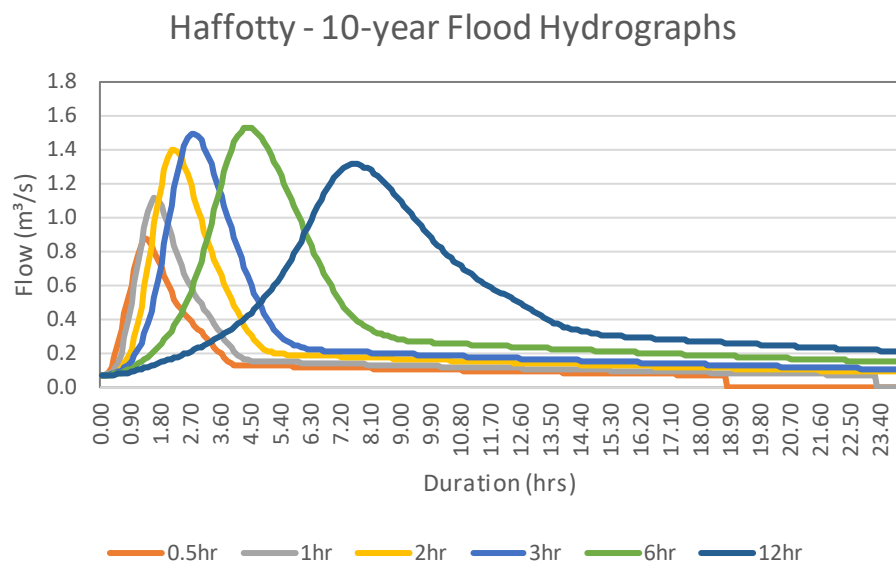


Figure 4: Comparison of 10-year flood hydrograph shapes for varying storm durations

The outcomes of the sensitivity runs required additional return periods to be considered for the 12-hour and 24-hour storm durations.

Return Period (years)	12-hour storm duration peak flow (m³/s)		24-hour storm duration peak flow (m³/s)	
	Hafotty	Gellfawr	Hafotty	Gellfawr
1	0.849	0.435	0.707	0.360
2	0.908	0.465	0.753	0.383
10	1.314	0.681	1.067	0.548
50	2.022	1.057	1.555	0.808

Return Period (years)	12-hour storm duration peak flow (m³/s)		24-hour storm duration peak flow (m³/s)	
	Hafotty	Gellfawr	Hafotty	Gellfawr
100	2.382	1.247	1.803	0.934
200	2.768	1.448	2.054	1.063
1,000	3.744	1.956	2.684	1.384

Additional return periods were considered to enable a Joint Probability Assessment to be considered; these included:

4-years;

8-years; and

16-years.

Further information on the Joint Probability Analysis (JPA) can be found in:

File:

[Scope and Notes.docx](#)

Location:

[\\global\europa\Cardiff\Jobs\264000\264326-00\4 Internal Project Data\4-40 Calculations\JPA_Rainfall_Surge\](#)

4 Statistical method

4.1 QMED

The QMED_{CDS} has been estimated based on the catchment characteristics for comparative purposes. Due to the rural nature of the catchment, no urban adjustment was applied.

$$QMED_{CDS\ Rural} = 8.3062 \times AREA^{0.8510} \times 0.1536^{(1000/SAAR)} \times FARL^{3.4451} \times 0.0460^{BFIHOST^2}$$

Catchment	QMED _{CDSrural} (m³/s)	Confidence Interval			
		68%		95%	
		Lower	Upper	Lower	Upper
Hafotty	1.180	0.82	1.69	0.58	2.42
Gellfawr	0.635	0.44	0.91	0.31	1.30

5 Discussion and summary of results

5.1 Comparison of results from different methods

The QMED values estimated from the two methods discussed above have been presented below. This comparison shows that the ReFH2 method produces lower values than the FEH statistical method.

Catchment	Ratio of ReFH2 peak flow to FEH Statistical peak flow	
	Return period 2 years	Return period 100 years
	ReFH2 / FEH	ReFH2 / FEH
Hafotty	$0.910 / 1.180 = 0.771$	-
Gellfawr	$0.475 / 0.635 = 0.748$	-

5.2 Final choice of method

The comparison between the ReFH2 and FEH Statistically derived values of QMED show that the ReFH2 approach estimates a lower value., however, ReFH2 was considered to be the most suitable methodology to use in the estimation of peak flows and hydrographs for both of the small, mountainous, ungauged catchments to the east of Barmouth.

The sensitivity analysis identified the 12-hour storm event as being the critical duration; hence all hydrology was derived based on this.

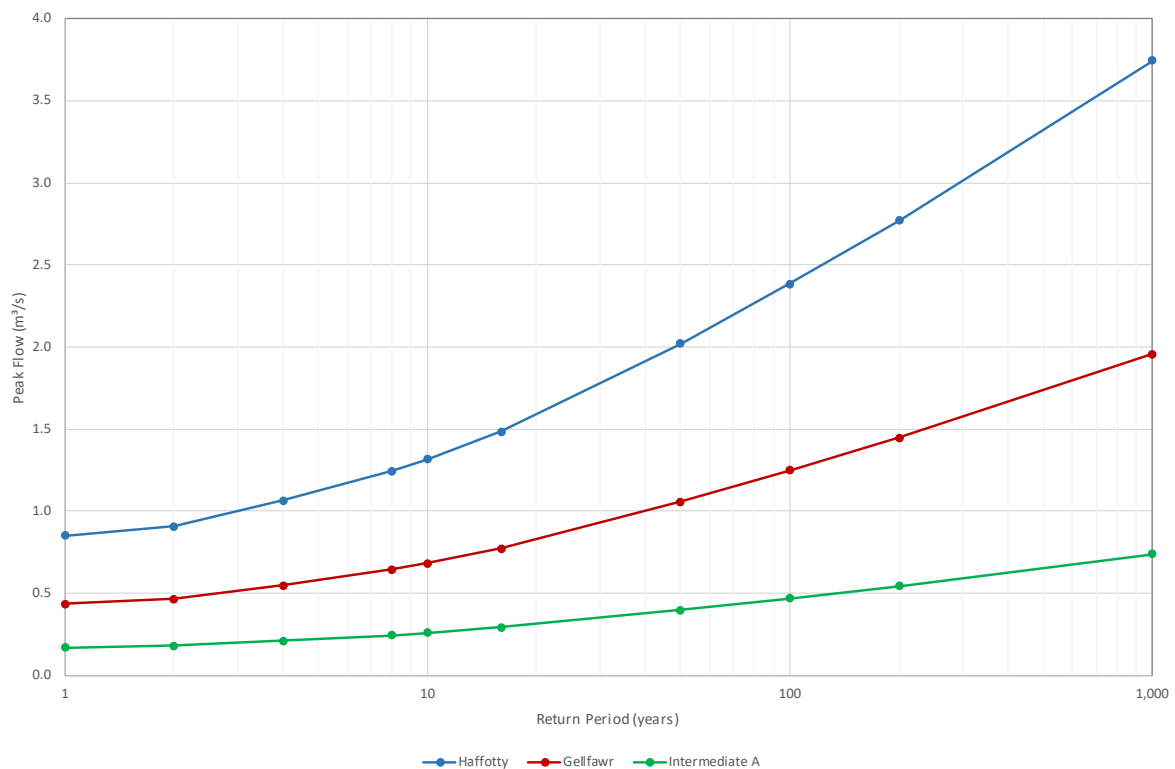


Figure 5: 12-hour peak flows under each return period for each catchment

5.3 Assumptions, limitations and uncertainty

- ReFH2 is considered to be a suitable method given the lack of gauged data and catchment size.
- No gauged data were available for either catchment, or in any neighbouring catchments, so the main assumption is that the methods used to derive peak flows and hydrograph shapes, based on catchment descriptors, are representative of the hydrological characteristics of the subject site.
- A site visit has not been completed to walk the catchment and understand processes/influences within it.
- It has been assumed that no significant land use changes within the catchment have occurred since the derivation of the FEH catchment descriptors.

- A detailed data gathering exercise has not been completed at this stage into historic flood events, or other available flood related reports, including SFRAs, or nearby site specific FRAs.
- Third parties have not been contacted regarding flood data, including Natural Resources Wales, Lead Local Flood Authorities (LLFA) or Internal Drainage Board (IDB).

5.4 Final Peak Flow Estimates

In addition to estimating the peak flows and hydrograph shapes for the two main catchments, the flows from a small intermediate catchment (A) were also required. The Intermediate (A) catchment flows were derived based on the Hafotty flows and proportioned based on differences between catchment areas. This is a satisfactory approach to estimating the peak flows for this small catchment.

A further two intermediate catchments, B and C, were included in the modelling and required rainfall rather than flows. The design rainfall from the two main catchments, Hafotty and Gellfawr, was used for each of these.

AEP	Return period	12-hour storm duration peak flow (m ³ /s)		
		Hafotty	Gellfawr	Intermediate A
100%	1yr	0.849	0.435	0.167
50%	2yr	0.908	0.465	0.179
25%	4yr	1.064	0.548	0.209
12.5%	8yr	1.244	0.643	0.245
10%	10yr	1.314	0.681	0.259
6.3%	16yr	1.483	0.774	0.292
2%	50yr	2.022	1.057	0.398
1%	100yr	2.382	1.247	0.469
0.5%	200yr	2.768	1.448	0.545
0.1%	1,000yr	3.744	1.956	0.737

Hydrological Estimation Record

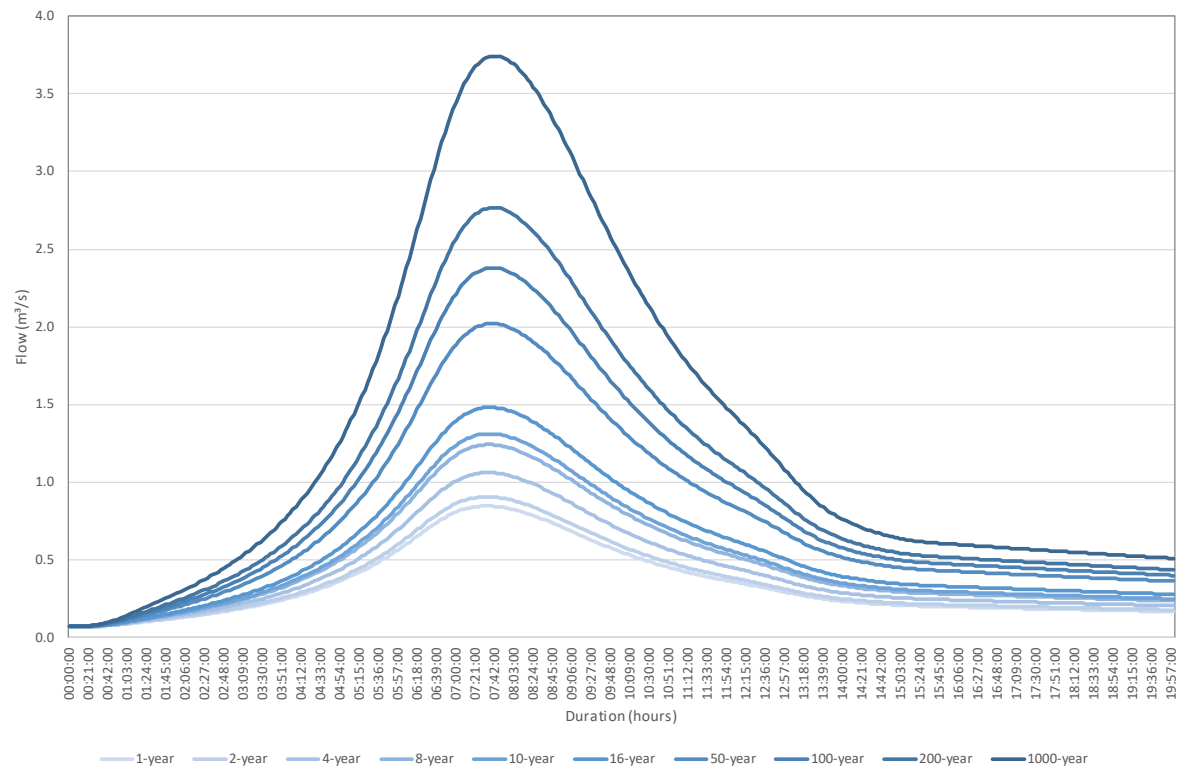


Figure 6: Hafotty peak flow hydrographs

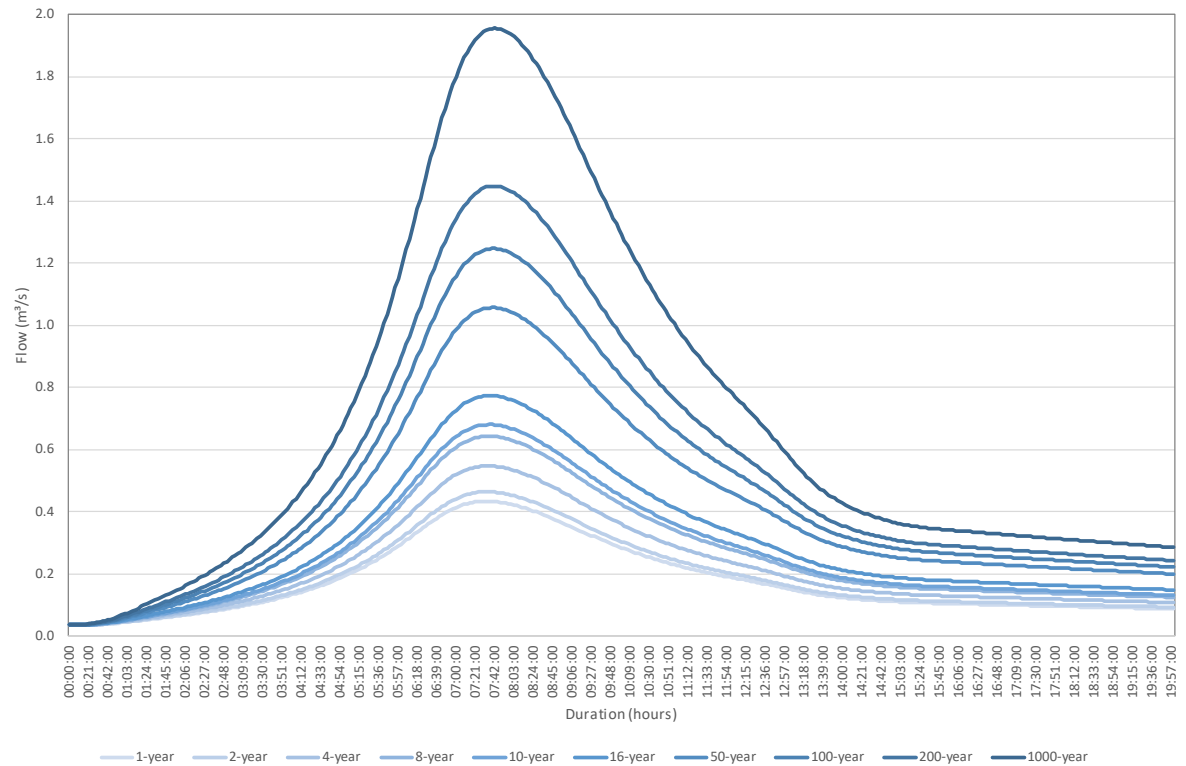


Figure 7: Gellfawr peak flow hydrographs

Hydrological Estimation Record

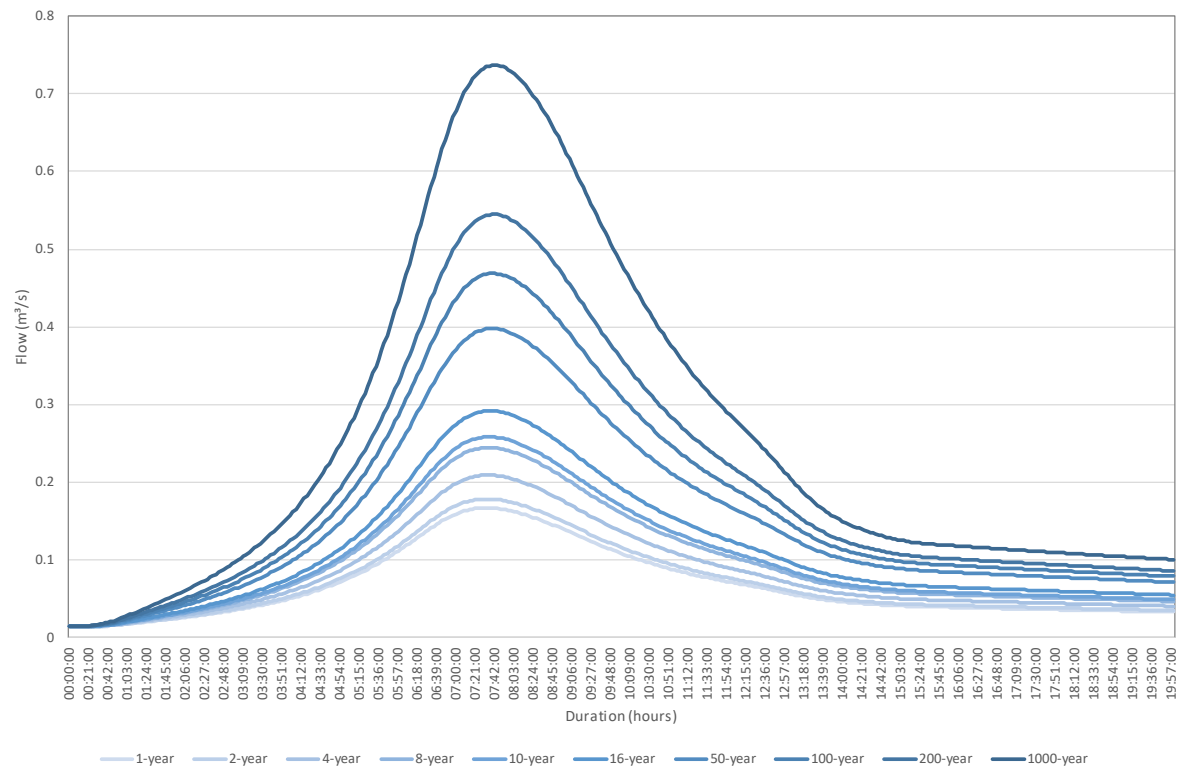


Figure 8: Intermediate A peak flow hydrographs

6 Annex - supporting information

6.1 Figures

Fig 6.1 - Location Plan

DRAFT