Protection of Fairbourne village from flooding

Report presented to Arthog Community Council

Graham Hall, PhD, FGS

December 2021

CONTENTS

Summary	3
1. Introduction	4
2. Sea level and wave height forecasting	5
3. Current flood protection scheme	7
4. Proposed flood protection scheme	9
Geology	10
Sea defences	11
Railway embankment	15
Estuary embankment	17
Proposed flood embankment	18
Internal drainage	20
Retention pond	25
Sea water interception	27
5. Hydrological modelling	30
Flooding from the sea	30
Flooding from the estuary	33
Flooding from hillslope runoff	35
Coastal lowland	38
Internal drainage of the Fairbourne area	40
6. The outer flood protection area	44
Arthog Bog	45
Estuary outfall	47
7. Summary of works for the proposed scheme	48
Construction sequence	48
Monitoring and maintenance	52
8. Conclusions and recommendations	53
9. Discussion	55
References	61

SUMMARY

Fairbourne is a coastal community at the mouth of the Mawddach estuary in Cardigan Bay. The village is built on land reclaimed during Victorian times from salt marsh and reed beds behind a large shingle spit.

As a consequence of climate change, Fairbourne is considered to be at a progressively increasing risk of flooding. A decision was taken by Gwynedd County Council that continued coastal protection for Fairbourne is not feasible. The village will be abandoned and demolished at some time in the next 50 years, with all residents resettled elsewhere.

In this paper, the current coastal protection scheme for Fairbourne is assessed, and an alternative scheme proposed. This would incorporate the existing sea wall, estuary flood embankment and railway embankment, and would require the construction of approximately 700m of new flood embankment across agricultural land. Integral to the proposed flood protection scheme is the restoration and extension of a network of drainage ditches in and around Fairbourne village and the creation of a temporary water storage pond. Floodwater would be discharged from the ditch system into the estuary by gravity flow.

Modelling was carried out to determine boundary conditions for the Fairbourne flood protection area during a worst case storm scenario based on the predicted sea level for 2065. The sea wall was found to be above the level of the highest predicted spring tide and storm surge, but might be overtopped by occasional extreme storm waves. The maximum quantity of water likely to wash over the sea wall during a storm event was estimated. The tidal and storm surge level in the estuary stabilised below the top of the estuary flood embankment. Stream runoff from the hillside above Fairbourne carried by the Afon Henddol remained within channel capacity without overbank flooding.

Modelling then simulated hydrological conditions within the Fairbourne flood protection area. Rainfall was applied for the duration of an extended storm event of two days. Rates of flow were calculated for the internal routing of flood water along drainage ditches, making use of the temporary storage pond as necessary. Output to the estuary was dependent on the tide, but it was found that this could be achieved by gravity flow alone without the need for pumping.

It is concluded that the proposed scheme would operate effectively in protecting Fairbourne from flooding in a worst case storm scenario based on a predicted sea level for 2065. Modelling suggests that no increase in the heights of the existing sea wall and estuary flood embankment would be necessary up to this date, but a modest increase in height of 1m may then be needed.

Investigations were carried out to check that the proposed flood protection scheme for Fairbourne village would not have a detrimental effect on the wider flood protection area between Fairbourne and Arthog. It was found that the ecologically important area of the Arthog Bog SSSI would not be affected, whilst an opportunity exists for improving the drainage of agricultural land between Fairbourne and Morfa Mawddach through the upgrading of an existing tidal gate.

A suggested schedule of works is provided for implementation of the flood protection scheme, along with a schedule for monitoring and maintenance in the period up to the year 2065 and beyond.

1. INTRODUCTION

Fairbourne is an active coastal community at the mouth of the Mawddach estuary in Cardigan Bay. The village is built on land reclaimed during Victorian times from salt marsh and reed beds behind the large shingle spit of Ro Wen. The village is made up from Victorian terraces and villas, along with more recent houses and bungalows, and a mobile home park. Amenities include the beach and sand dunes, narrow gauge railway with a ferry connection to Barmouth, and a golf course. Shops and food businesses cater for local residents and visitors. The village has a railway station on the Cambrian Coast line between Machynlleth and Pwllheli.

Planning decision

The West of Wales Shoreline Management Plan (Haskoning, 2012) was commissioned by a consortium of County Councils and Environmental Agencies responsible for flood protection along the West Wales coast. The report was produced in response to concerns about climate change and increases in sea level. A map was presented which indicates that the entire village of Fairbourne would be flooded by normal spring tides within the next 100 years.

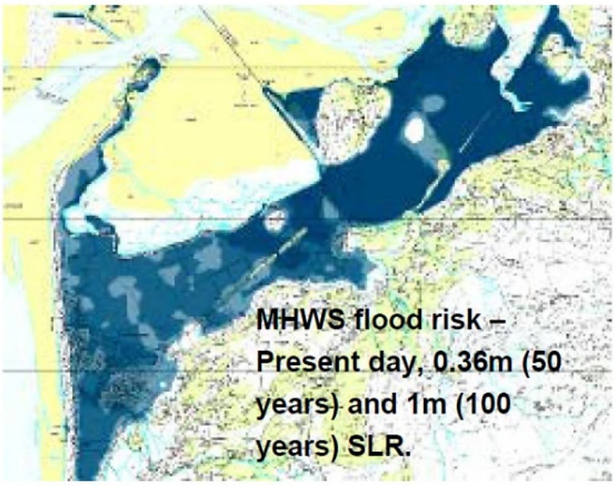


Figure 1

Map included in the shoreline management plan, showing the predicted area of flooding at high water during spring tides under calm sea conditions. This flooding is assumed by the model to develop at some time in the coming century.

In a separate study, Robins (2011) predicted that Fairbourne could be totally submerged at the present day in the event of flooding during a high spring tide accompanied by an additional 2 m storm surge.

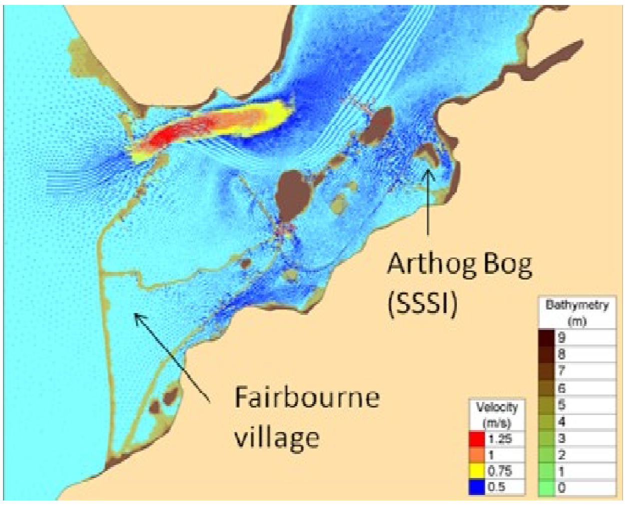


Figure 2

Map indicating the possible area of flooding at the present day if a 2m storm surge corresponded with high water during a spring tide. Computer modelling by Robins (2011).

As a consequence of these studies, Gwynedd County Council has made a decision that continued coastal protection for Fairbourne is not feasible. The village will be abandoned and demolished at some time in the next 50 years, with all residents resettled elsewhere:

> "Fairbourne is a community at risk from various sources – coastal storms, rising sea levels, a river that carries mountain run off and a high groundwater table," says Gwynedd Council senior project manager, flood and coastal erosion risk management, Lisa Goodier. "The village can be defended sustainably for the next 40 years but from 2045 it will have to be decommissioned and from 2055 it will not be possible to defend." (New Civil Engineer, 2018).

The purpose of this paper is to critically examine the scientific case for abandoning the village of Fairbourne, and to evaluate a revised flood protection scheme.

Flood modelling

Although said to be based on sophisticated computer modelling, the forecasts illustrated in figures 1 and 2 appear to do little more than select a contour line on the map and assume that every point below this height would be flooded. The validity of the models may be questioned on two counts:

- The tidal and storm wave heights which were input to the models may not be accurate.
- The models assume that no active flood defences are in place to prevent storm inflow or remove flood water.

A key argument for the abandonment of Fairbourne appears to be that the village will at some time in the future lie below high tide level. It might be pointed out that much of the Netherlands, and almost all of the city of Rotterdam, already lie below sea level. Systems have been developed to protect the Netherlands from flooding.

2. SEA LEVEL AND WAVE HEIGHT FORECASTING

The Intergovernmental Panel on Climate Change (2014) provided a summary for policymakers:

		2046–2065		2081–2100	
	Scenario	**Mean**	***Likely* range[c]**	**Mean**	***Likely* range[c]**
Global Mean Surface Temperature Change (°C)[a]	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8
	Scenario	**Mean**	***Likely* range[d]**	**Mean**	***Likely* range[d]**
Global Mean Sea Level Rise (m)[b]	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

Figure 3: Different modelling predictions for increases in global mean temperature and sea level.

The upper limit for predicted sea level rise by 2065 is given as 0.38m, with a lower figure likely. Beyond this date, predictions become highly unreliable as much depends on political decisions by countries around the World, along with developments in technologies to reduce carbon emissions or even remove carbon from the atmosphere.

Phillips et al. (2017) have compiled mean sea level data recorded at Barmouth railway bridge over the period 1990 – 2016. Data points are shown in fig.4, along with predictions for future mean sea level based on the UK Climate Change model and a separate model by the Department for Agriculture and Rural Affairs. Predictions for the year 2065 range from 0.2m to 0.5m:

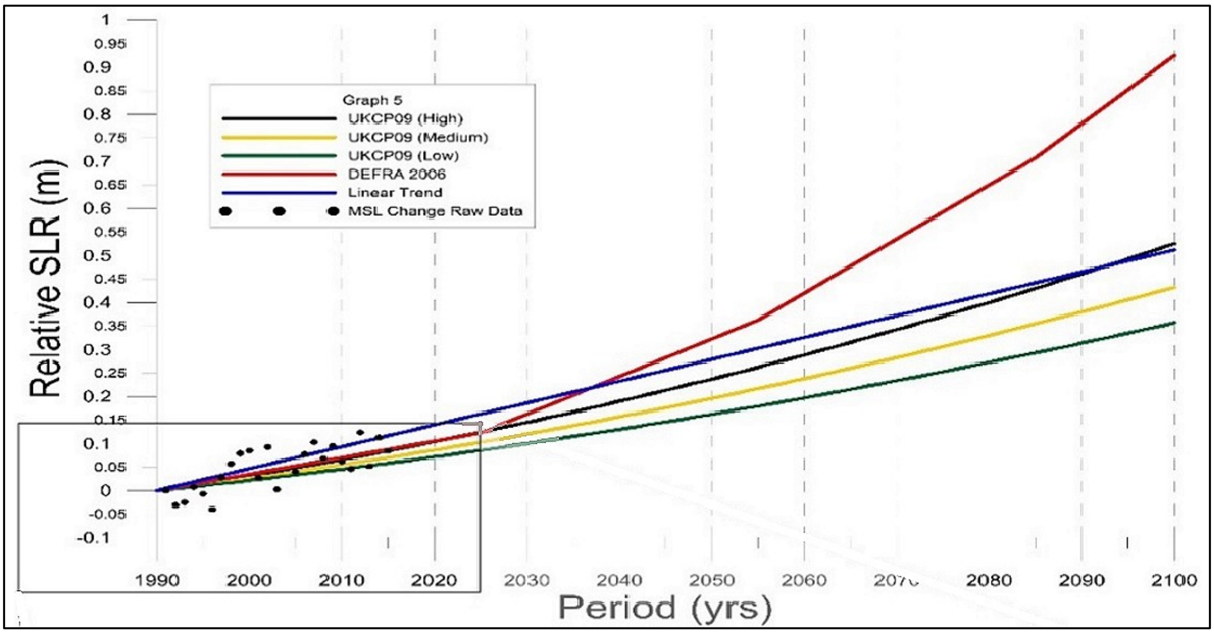


Figure 4: Predictions of mean sea level based on data recorded at Barmouth (Phillips et al. 2017)

Modelling carried out for the present study will assume a rise of 0.5m compared to present day sea level, which is consistent with predictions for at least the year 2065 and probably beyond.

Storm wave height

During a severe storm, the sea surface will reach a height significantly above the astronomically predicted calm water tidal height. This is due to a combination of:

- a sea surge due to reduced atmospheric pressure,
- wind generated waves on the sea surface.

Observations of waves in Cardigan Bay were carried out by Thompson, Karunarathna, & Reeve (2017). It was found that waves reached a maximum height of 7m above specified tidal height under extreme storm conditions (fig.5).

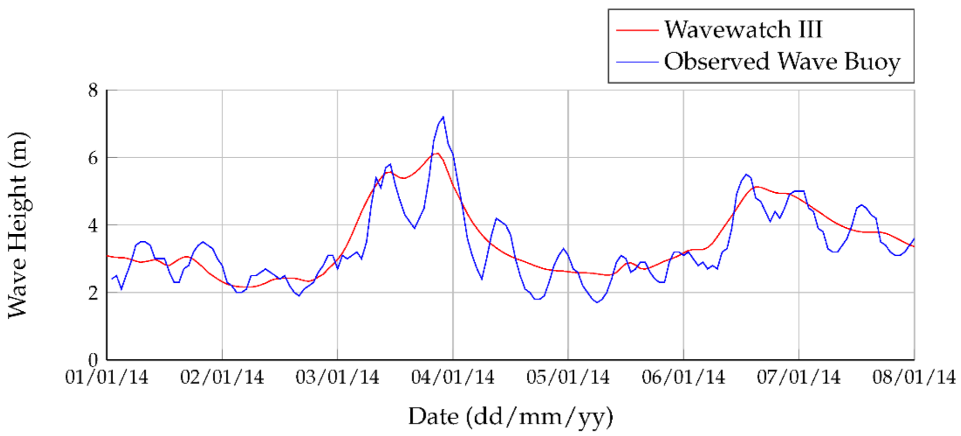


Figure 5

Wave heights in Cardigan Bay at an offshore recording point (blue) during storm conditions. A computer model (red) is shown for comparison. (Thompson et al. 2017)

Phillips et al. (2017) compiled observations and made predictions of maximum extreme wave heights for Fairbourne on an assumption that storms will increase in severity in the future due to climate change. Results are shown in Fig.6.

	Description	Trend	Projected			
			2025	2055	2085	2100
Wave Analysis	Maximum Extreme Wave Height (m)	Increase	4.980	5.797	6.615	7.023

Figure 6: Predictions of extreme wave heights above specified tidal height at Fairbourne (Phillips et al. 2017)

For the purpose of the current study, a storm wave height of 6m above the calm water tidal height will be assumed, made up from a pressure surge of 2.5m and a wind generated wave height of 3.5m.

3. CURRENT FLOOD PROTECTION SCHEME

Flood defences have been reinforced in recent years by Natural Resources Wales. The current defences consist of a series of embankments linking existing landscape features, to produce an enclosure around the Fairbourne and Arthog area. The boundary is marked in fig.7 below.

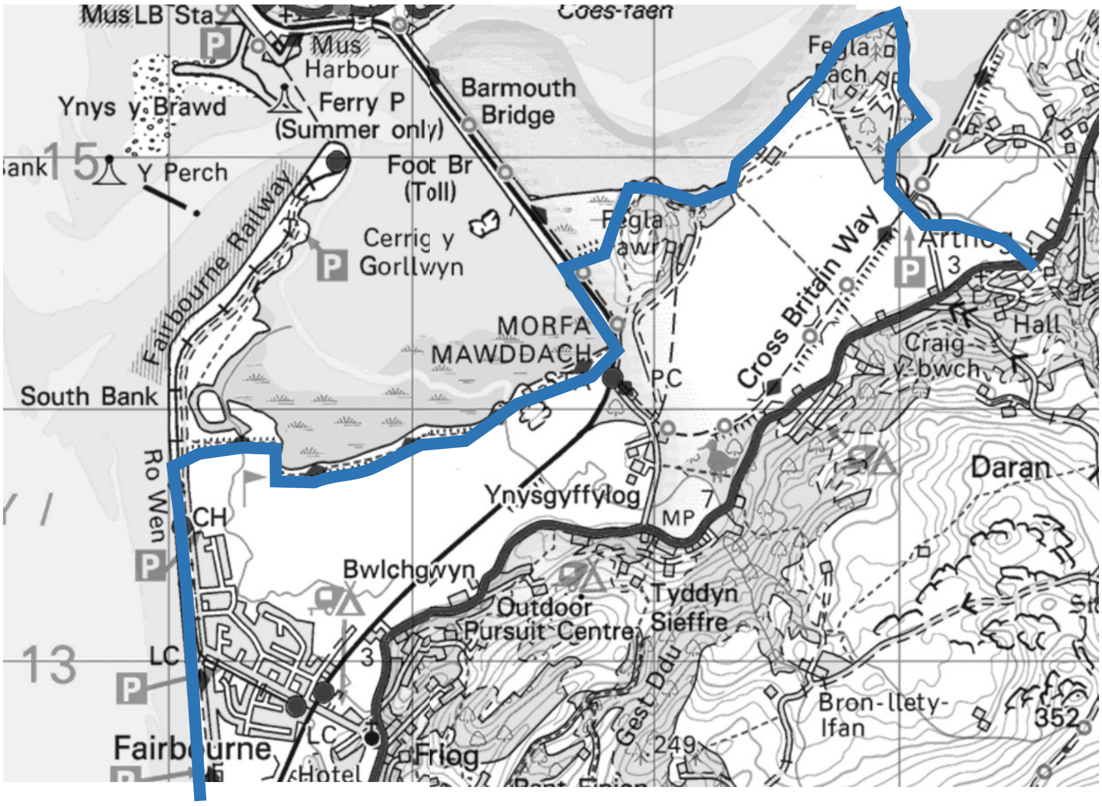


Figure 7: Flood defence boundary for the Fairbourne and Arthog area.

The current defences are unlikely to adequately protect the village of Fairbourne in the future.

The enclosed area extends for a long distance eastwards to the mouth of the Afon Arthog. Within this enclosure are several significant streams draining from the hills between Friog and Arthog. These streams (fig.8) must cross the flood protection area and discharge into the estuary through tidal gates.

Figure 8

Meandering stream crossing the flood protection area at Arthog. This carries rainfall runoff from the hillside above the Bryngwyn Quarry.

Any major storm event threatening Fairbourne is likely to combine a series of meteorological effects: low atmospheric pressure causing a storm surge, strong onshore winds producing large waves, high water levels in the estuary due to floods on the rivers Mawddach and Wnion at the estuary head, and high flows from the hills above the flood protection area. Flooding in Fairbourne is as likely to result from estuary or river flooding, as from sea flooding.

Figure 9

Flooding at Arthog following a rain storm. River discharge from the hillside has exceeded the carrying capacity of the stream channel, causing overbank flooding.

4. PROPOSED FLOOD PROTECTION SCHEME

An alternative flood protection scheme is proposed for the village of Fairbourne, as summarised in fig.10 below. A new and more restricted flood defence boundary would be created.

A: The western boundary would follow the existing sea wall from Friog cliff to the end of the golf course.

B: The south eastern boundary would follow the railway embankment from Friog cliff to Fairbourne railway station, then continue for approximately 200m beyond.

C: The northern boundary would follow the existing flood embankment around the edge of the golf course, to a point where a track slopes down onto agricultural land.

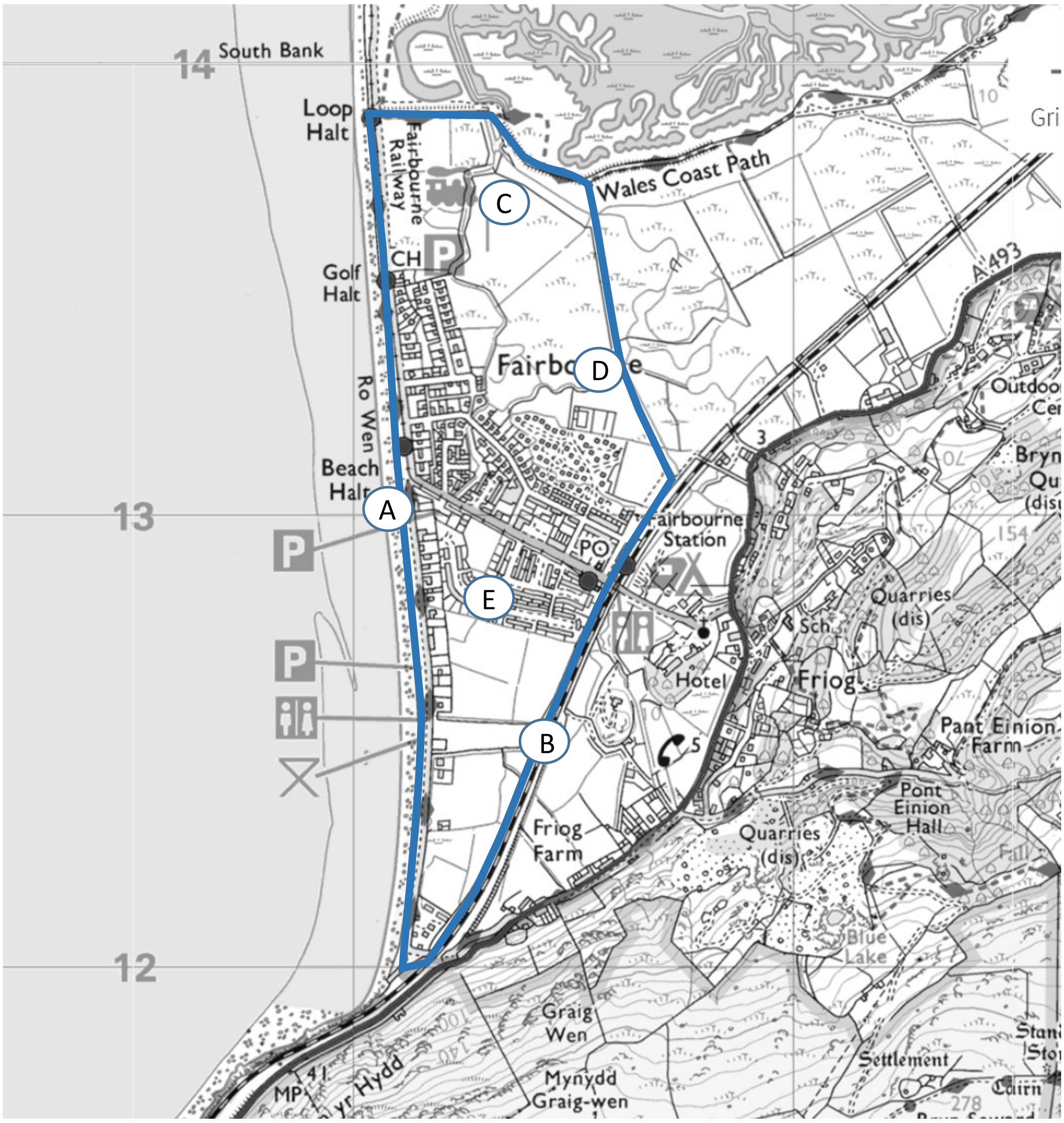


Figure 10: Proposed flood protection scheme for the village of Fairbourne

D: A new flood embankment would be created to link sections B and C. This would cross the agricultural land, following for part of its course an existing low flood embankment constructed as part of a flood protection scheme in 2016.

E: A system of ditches in and around the village would provide drainage within the flood protection boundary. Some flood water would be directed to a holding area, where it could then be discharged at low tide or pumped into the estuary.

Geology

The proposed Fairbourne flood protection area is underlain by superficial deposits which have accumulated in the 6,000 years since the end of the Ice Age (fig.11):

Pebble storm beach deposits make up the shingle spit of Ro Wen, behind which Fairbourne village is situated. The shingle has accumulated naturally to a height of approximately 5m above the sand beach, which marks the normal level of high tide under calm sea conditions.

Tidal flat deposits underlie Fairbourne village, agricultural land to the north and some agricultural land to the south. These are mixed deposits of sand and clay which generally provide good drainage.

Peat underlies the most southerly fields near Friog. Drainage through peat is generally poor, causing the ground to remain saturated for a longer period after wet weather.

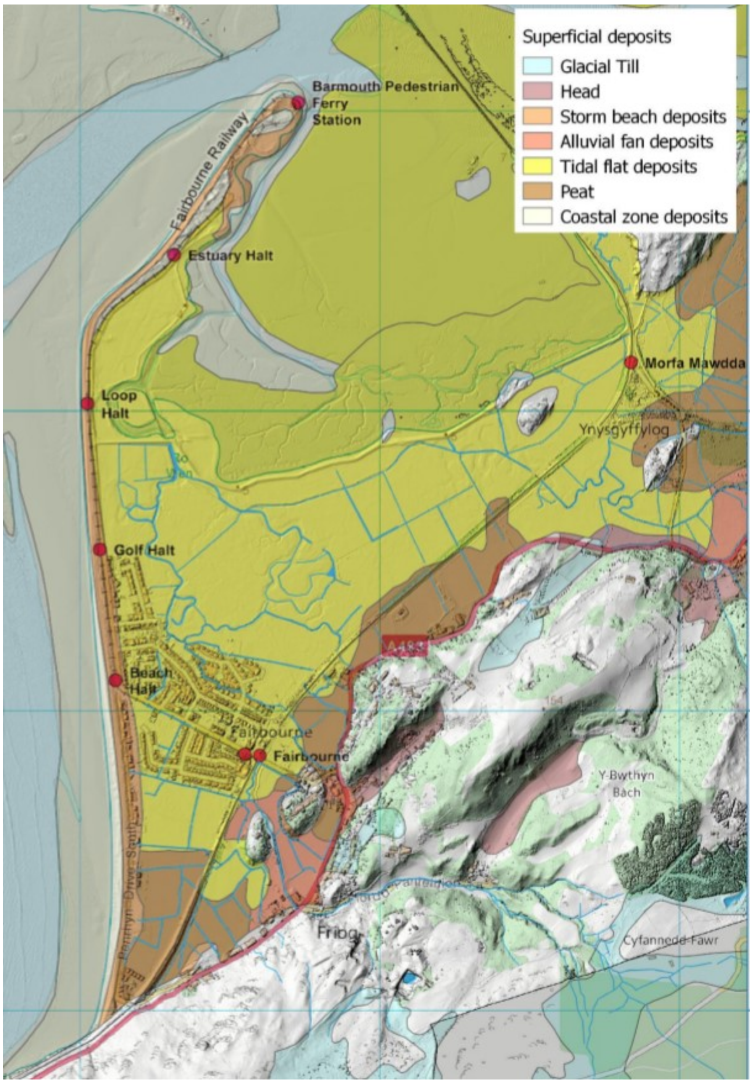


Figure 11

Geological map showing superficial deposits around Fairbourne.

(after Buss, 2018)

Sea defences

Surveying was carried out at the northern end of the golf course to determine the relative heights of the existing flood defences. The work was undertaken at a high spring tide with calm sea conditions, when the tidal height was quoted as being 5.1m above Chart Datum. Heights are shown in fig.12. (Note that Chart Datum for Barmouth lies at 2.4m below Ordnance Datum)

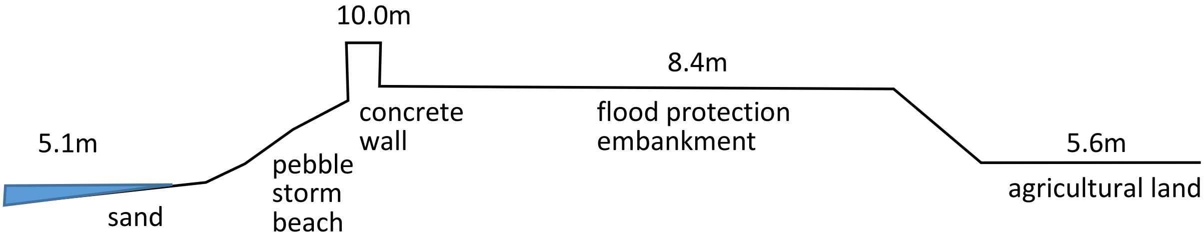


Figure 12: Heights of land components above Chart Datum

At the current time, the area of agricultural land, as well as the village of Fairbourne, lies at approximately the level of high spring tides. It is unlikely that this situation will change significantly before 2065.

The situation caused by storm waves is of greater concern. However, if the concrete sea wall is maintained in good condition at a height of approximately 10m C.D. for the full distance to Friog cliff, then no direct overtopping by waves is expected for a storm pressure surge of 2.5m height.

Flooding has occurred in recent years during storm conditions in the area south of Fairbourne village (fig.13), although the village itself has not been flooded.

Figure 13

Localised flooding to the south of Fairbourne village during storm conditions.

It is understood that deterioration in the sea defences at the Friog corner allowed water to seep through the embankment. A major strengthening of the embankment has recently been carried out by Gwynedd County Council and Natural Resources Wales, including the emplacement of sheet steel piles to prevent water inflow, and the addition of large boulders to dissipate wave energy (fig.14). This work should be very effective in preventing the future infiltration of storm water.

Figure 14

Friog cliff, showing large rocks recently added to the sea defences.

During storm conditions, breaking waves may carry water over the current sea wall. The volume of sea water entering the Fairbourne flood enclosure could be reduced by increasing the height of the wall by perhaps 1m. The broad flat top of the sea wall embankment (fig.15) should make this feasible.

Figure 15

Recently reconstructed sea wall embankment at Friog.

It is of concern that a very limited pebble storm beach is present at Friog corner. A comparison of air photographs indicates that marine erosion is taking place (fig.16).

2009 2021

Figure 16: Comparison of the extent of storm beach deposits at Friog corner (Google Earth).

The problem of shingle spit erosion appears to be confined to Friog. Observations by Phillips et al. (2017) indicate that the spit further north is maintaining a stable or slightly increasing volume of storm beach shingle (fig.17).

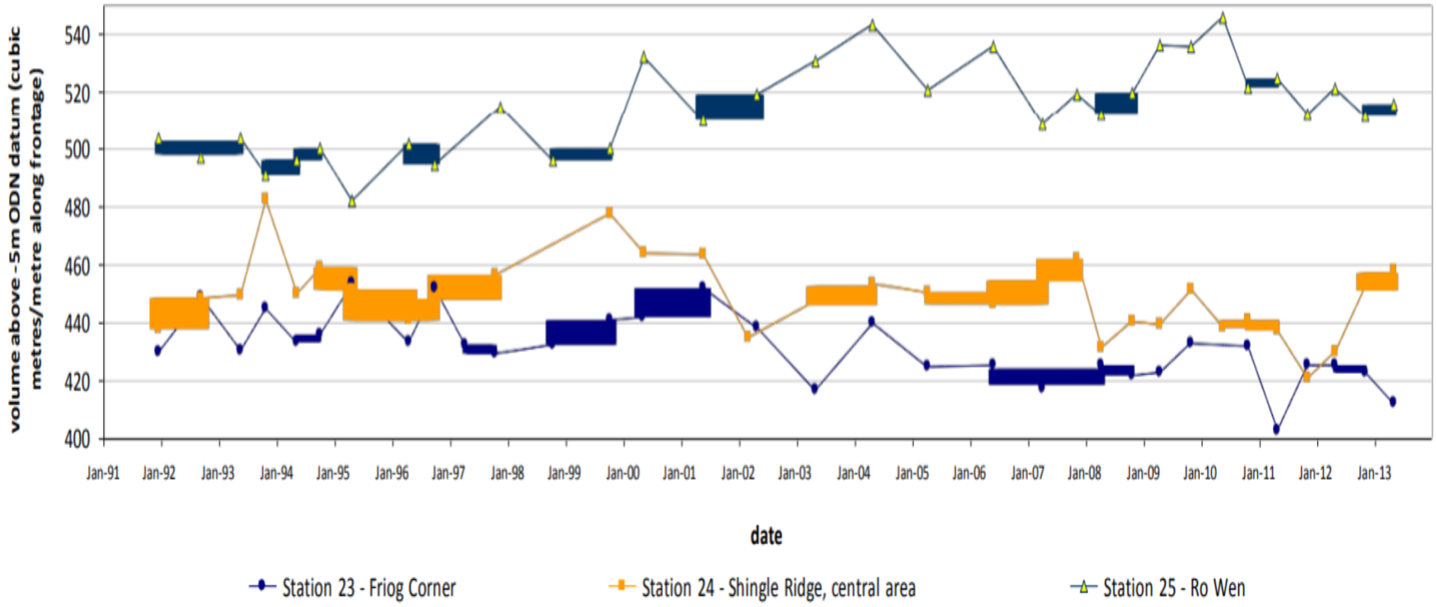


Figure 17: Volume of storm beach shingle over the period 1991-2013 (Phillips et al., 2017). The storm beach is seen to be losing shingle at Friog corner (blue), stable at Fairbourne village (yellow) and slightly gaining shingle at the northern end of the spit (green).

Replenishing the beach deposits at Friog corner would dissipate the power of storm waves, and reduce the amount of wave overtopping of the sea wall.

The beach might be replenished directly by adding sediment. It is found that angular rock material from a land quarry is more stable than rounded pebbles from a beach source, and less likely to be removed by wave action. Measurements have shown that the shingle storm beach material at Friog is generally of larger diameter than pebbles found further north along the spit (fig.18):

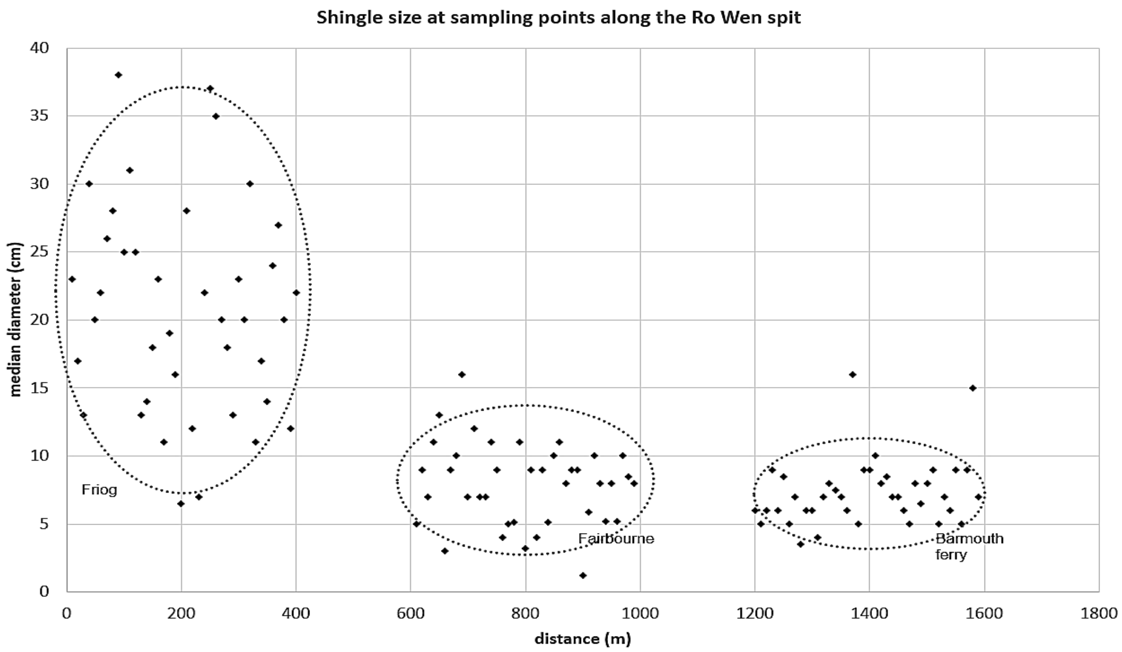


Figure 18: Sizes of random samples of storm beach pebbles. (Fieldwork by students of Coleg Meirion Dywyfor, Dolgellau)

It appears that the long shore water velocity vector is greater at Friog corner, perhaps due to the abrupt change in direction of the coastline. This results in smaller shingle being carried northwards by longshore drift, whilst larger material is left in situ. It is therefore recommended that rock material with a mean diameter of 15cm or greater is used in beach replenishment at Friog, to prevent its rapid loss.

An alternate strategy would be to trap sediment which is being carried naturally along the coast in a northerly direction by longshore drift. This material is likely to be a mixture of sand and coarser pebbles derived from the soft cliffs of glacial deposits between Tywyn and Llwyngwril. Trapping of sediment could be achieved by the installation of a series wooden groynes across the beach, perpendicular to the shore, between Friog and Fairbourne village.

Trapping of sediment can also be carried out by constructing an off-shore reef parallel to the sea wall, with sediment then accumulating along the beach in the sheltered water that this creates.   The reef might be constructed from rocks, concrete blocks or other obstacles placed on the sea bed.

Figure 19

Diagram illustrating the emplacement of concrete cylinders to create an artificial reef.

In addition to dissipating wave energy and preventing wave overtopping of the sea wall, a reef has benefits in providing sheltered habitats for fish and other marine life. A reef structure is currently being constructed nearby at Borth as part of the coastal protection scheme:

> "The most significant element of the new defences, when they are completed, will be the broad shingle beach. The multi-purpose reef is a relatively new concept for use in coastal defence, and being located 400m offshore, it will be unobtrusive, only being visible when the tide is out. Waves will break over the reef, reducing energy to protect the beach from erosion, and encouraging the development of a wider beach inshore. " (Johnson, 2021)

Effective computer modelling software is now available to evaluate the likely outcomes of the different coastal interventions possible.

Railway embankment

The south eastern boundary of the proposed flood defence area would be formed by the existing railway embankment. The line gradually descends after passing around the Friog cliffs (fig.19). Some measures might be necessary to ensure that drainage water from the hillside above Friog does not flow down the road under the railway bridge during storms. This might involve building up the road surface below the bridge.

Figure 20

Railway bridge at Friog.

On the landward side of the railway embankment, the Afon Henddol crosses fields after descending from the hillside above Friog. It is then directed alongside the railway embankment for some distance in a newly constructed flood alleviation channel.

Figure 21

Afon Henddol flood alleviation channel. The structure in the left foreground is the entrance to a culvert beneath the main road at Fairbourne level crossing. This inlet is fitted with a screen to catch flood debris and prevent blockage of the culvert.

Linked to the flood channel is a drainage ditch which has passed through a culvert under the railway (fig.22). This carries an outflow of water from fields to the south of Fairbourne village. In the proposed flood protection scheme, this culvert would be blocked to prevent any risk of inflow of flood water from the Afon Henddol. Internal drainage from fields to the south of Fairbourne would be redirected along a drainage ditch system through the village to reach a tidal gate at the estuary.

Figure 22

Culvert carrying a drainage ditch under the railway, 100m to the south west of Fairbourne level crossing.

The railway has descended by the time Fairbourne station is reached, but the level of the line remains at about 2m above the general level of Fairbourne village (fig.23).

Figure 23

Approach to the level crossing at Fairbourne station. The road rises by about 2m to cross the railway.

Since the railway embankment would be protecting the village only from hillslope runoff, the low embankment of 2m appears adequate. In the event of floods affecting the railway line at some future date, it is likely that the problem would be addressed by Network Rail and the level of the track bed would be raised.

Estuary embankment

The northern boundary of the flood protection area is formed by the existing flood embankment (fig.24). This structure has been enlarged and strengthened in recent years by Natural Resources Wales, and provides good protection from high water levels in the estuary.

The embankment would not be subject to extreme wave heights, as in the case of the sea defences, because waves would be dissipated gently through the large lower basin of the Mawddach estuary. However, it would not be a major engineering problem to raise the level of the embankment by perhaps 1m if this should become necessary at some time in the future.

Figure 24

Flood embankment constructed around the edge of the golf course and adjacent agricultural land.

At the point where the embankment reaches the sea wall, the narrow gauge railway crosses the flood boundary at a slightly lower elevation than the top of the embankment (fig.25). A control structure has been built, which allows a flood gate to be positioned across the track when necessary to prevent inflow of water from the estuary.

Figure 25

Control structure with a flood gate which can be closed across the Fairbourne railway.

Proposed flood embankment

The proposed scheme would require the construction of a new flood embankment to the east of Fairbourne village, to connect the line of the railway with the existing embankment alongside the estuary.

The new embankment would begin at a point where a culvert carries a stream under the railway, approximately 200m to the east of Fairbourne station. This marks the start of a stone built causeway constructed during flood alleviation works in 2016.

Figure 26

Railway embankment east of Fairbourne station, with the causeway in the foreground.

The causeway structure continues northwards towards the estuary (fig.27), before turning west towards the village of Fairbourne. The causeway is well constructed from substantial rocks, and would form a firm base for a new flood embankment.

Figure 27

Causeway forming part of the 2016 flood alleviation scheme.

The proposed flood embankment would continue northwards across agricultural land, following the line of a vehicle access track created during the 2016 flood protection work (fig.28). This track was used to transport clay for the estuary embankment construction. An access ramp has been built at the point where this track reaches the embankment.

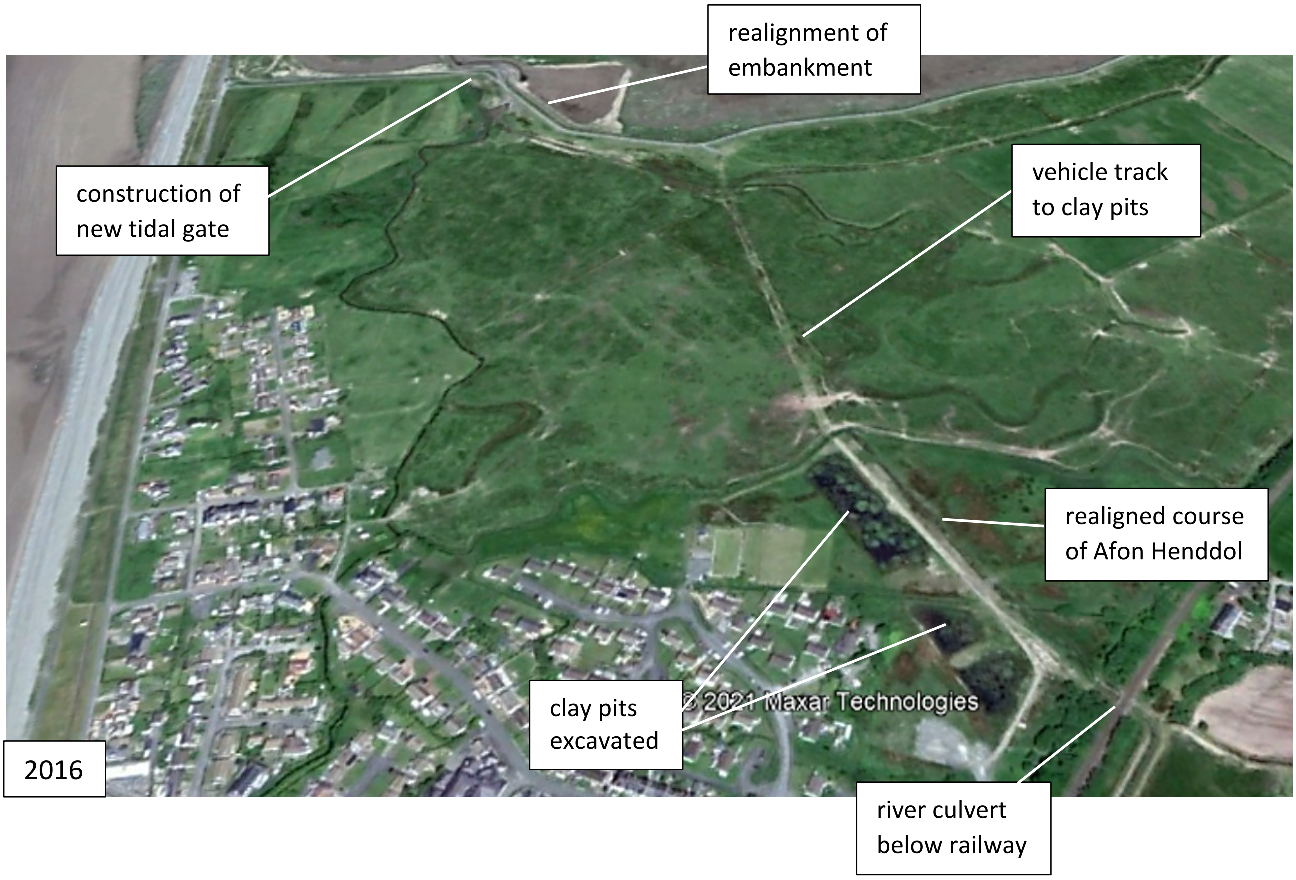


Figure 28
(above) Area of agricultural land north of Fairbourne village in 2009 before construction began.
(below) The same area in 2016 after construction of the flood alleviation scheme. An area of farmland has been excavated to provide clay for the embankment works. This has now created a series of water filled pools.
Air photographs: Google Earth

The proposed flood embankment lies along the approximate line marked in fig.29, connecting to the existing embankment alongside the estuary. Reliable engineering designs are available for the construction of small flood embankments which minimise seepage through or below the structure. It is appreciated that the embankment would inhibit agricultural activities, but access ramps could be constructed on either side to allow movement of livestock and machinery.

Figure 29: Proposed embankment. 1- along the rock causeway, 2 - continuing across agricultural land

Internal drainage

Despite the presence of boundary walls and embankments, it is inevitable that some drainage water will enter the Fairbourne flood protection area, for example: from direct rainfall or wave overtopping of the sea wall. This will be discharged into the estuary through the existing tidal gate located near the golf course.

A map of the drainage ditch network in the southern section of Fairbourne is shown in fig. 31. The series of culverts beneath the railway labelled A – D would be blocked to maintain the integrity of the Fairbourne flood protection area, with all drainage directed northwards.

A mobile home park is situated at the southern point of the Fairbourne flood protection area (fig.30). A new drain connection is proposed, which will link the mobile home park with the Fairbourne village drainage ditch network, as shown in fig.31.

Figure 30

Mobile home park at the southern tip of the Fairbourne flood protection area.

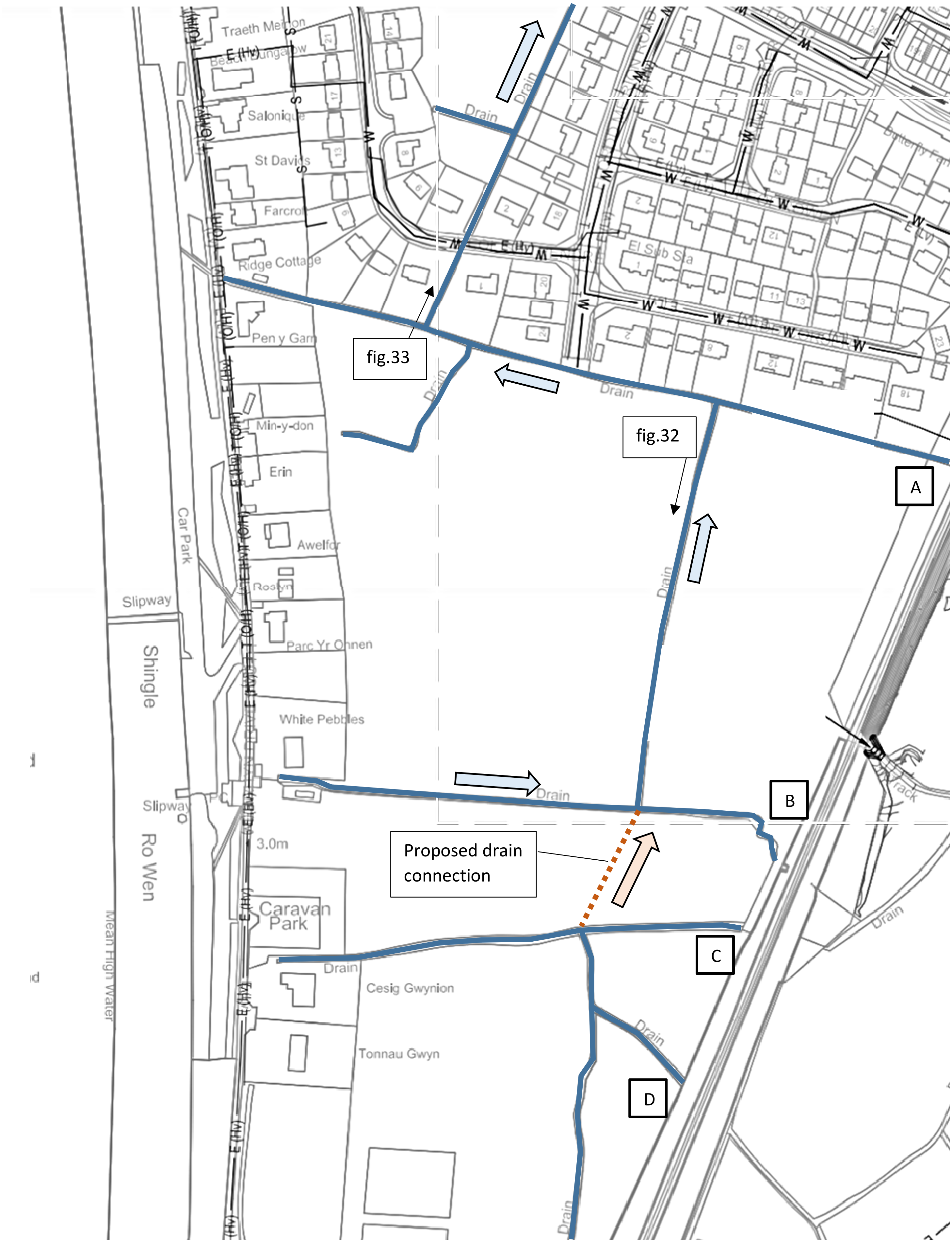


Figure 31: Drainage network in the southern section of the Fairbourne flood protection area. Map after Black and Veatch (2012)

The main drainage ditch runs northwards across fields to reach Fairbourne village (fig.32). The ditch route continues alongside houses in Ffordd Meirion (fig.33) to reach Beach Road.

Figure 32

Main drainage ditch crossing farmland to the south of Fairbourne village.

Figure 33

The drainage ditch route alongside Ffordd Meirion.

Figure 34

Drainage ditch continuing alongside the narrow gauge railway track on Beach Road.

A map of the drainage ditch network in the southern section of Fairbourne is shown in fig. 35.

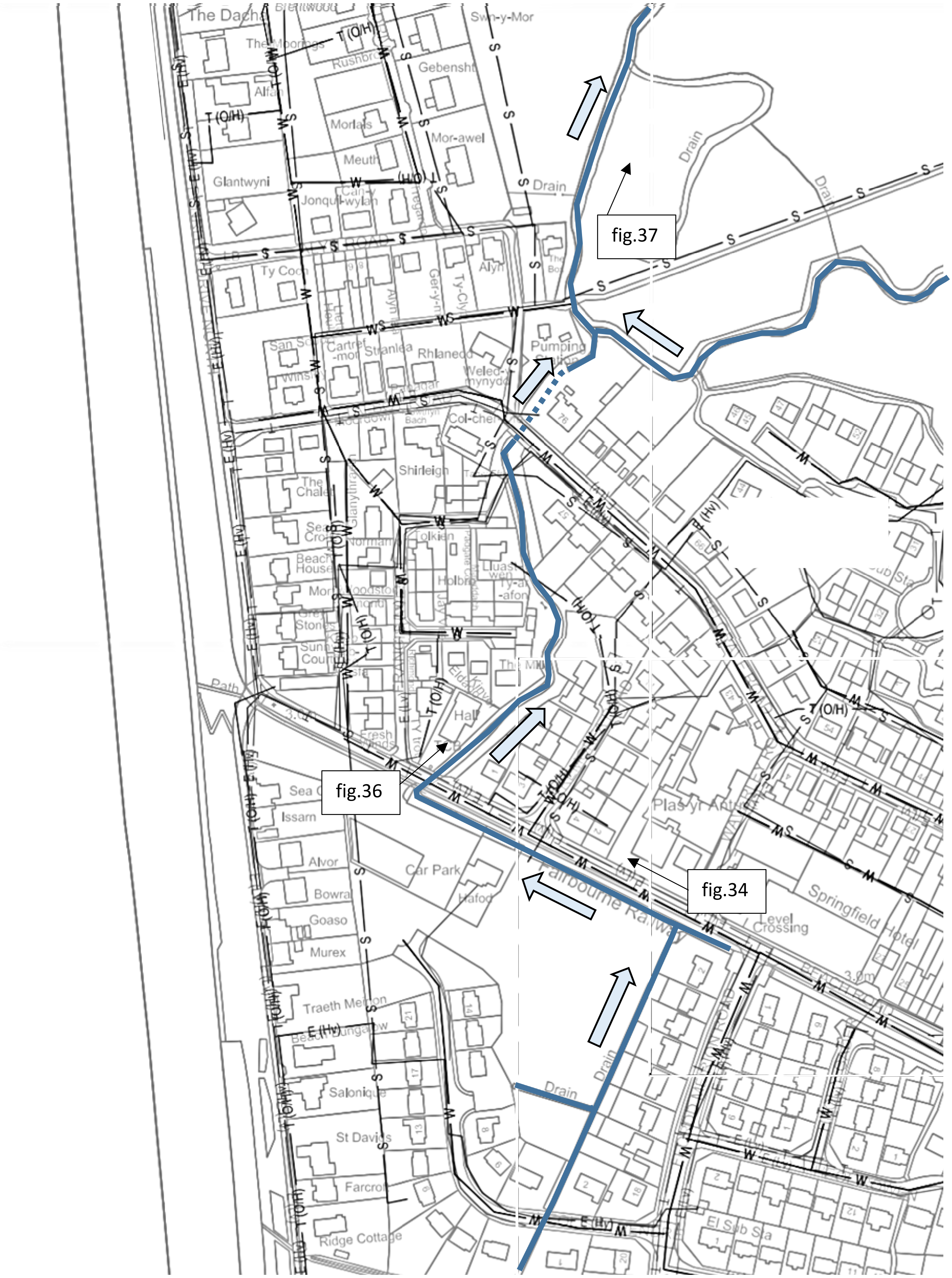


Figure 35: Drainage network in the northern section of the Fairbourne flood protection area. Map after Black and Veatch (2012)

From Beach Road, the drainage ditch route continues northwards through the village, passing Fairbourne village hall (fig.36). The drainage water flows into a culvert at Belgrave Road, to emerge onto agricultural land at the north of the village (37).

The drainage ditch route from Fairbourne village has a confluence with the Afon Henddol, which was re-routed around the village by the 2016 flood alleviation scheme. From the confluence, the river continues northwards to reach a tidal gate where it discharges into the Mawddach estuary (fig.38).

Figure 36

Drainage ditch routed northwards alongside Fairbourne village hall.

Figure 37

The drainage ditch reaches agricultural land north of Fairbourne village.

In the proposed scheme, the Afon Henddol would be routed outside the Fairbourne flood protection area to reach the estuary at an alternative tidal gate further to the east. The current Afon Henddol tidal gate would be retained, but would only discharge water from the Fairbourne village drainage ditch network.

Retention pond

The current Afon Henddol tidal gate is shown in fig.38. This has a pair of hinged doors which open at low tide to allow outflow from the drainage channel, then close with a rising tide to prevent inflow of water from the estuary.

Figure 38: Tidal gate alongside Fairbourne golf club at the mouth of the drainage ditch network. (left) Inlet from the stream channel (right) outlet to the estuary.

In the proposed scheme, the main channel of the Afon Henddol would be redirected to another tidal gate further east, so the outflow volume at this point would be greatly reduced.

It would be possible to route all drainage water directly from the Fairbourne drainage ditch network to this tidal gate. However, discharge into the estuary is generally only possible for a few hours before and after low tide. During a major storm event, water may penetrate the boundaries of the flood protection area or fall within the area as heavy rainfall. This could cause the drainage ditch system to fill to capacity and overbank flooding occur, endangering properties. To avoid this risk, it is proposed that a retention pond be created which would temporarily store water during a storm event and discharge it safely to the estuary at the next low tide.

Although most of Fairbourne is in use for housing or agriculture, a significant area of wetland was created when excavating clay for the 2016 flood alleviation scheme construction work. A series of open pools now exist, bordered by reed beds (fig.32). This would form a suitable location for developing a flood water retention pond. A map of the area is shown in fig.33.

Figure 32

Area of wetland created by excavation of clay, and now vegetated with reed beds .

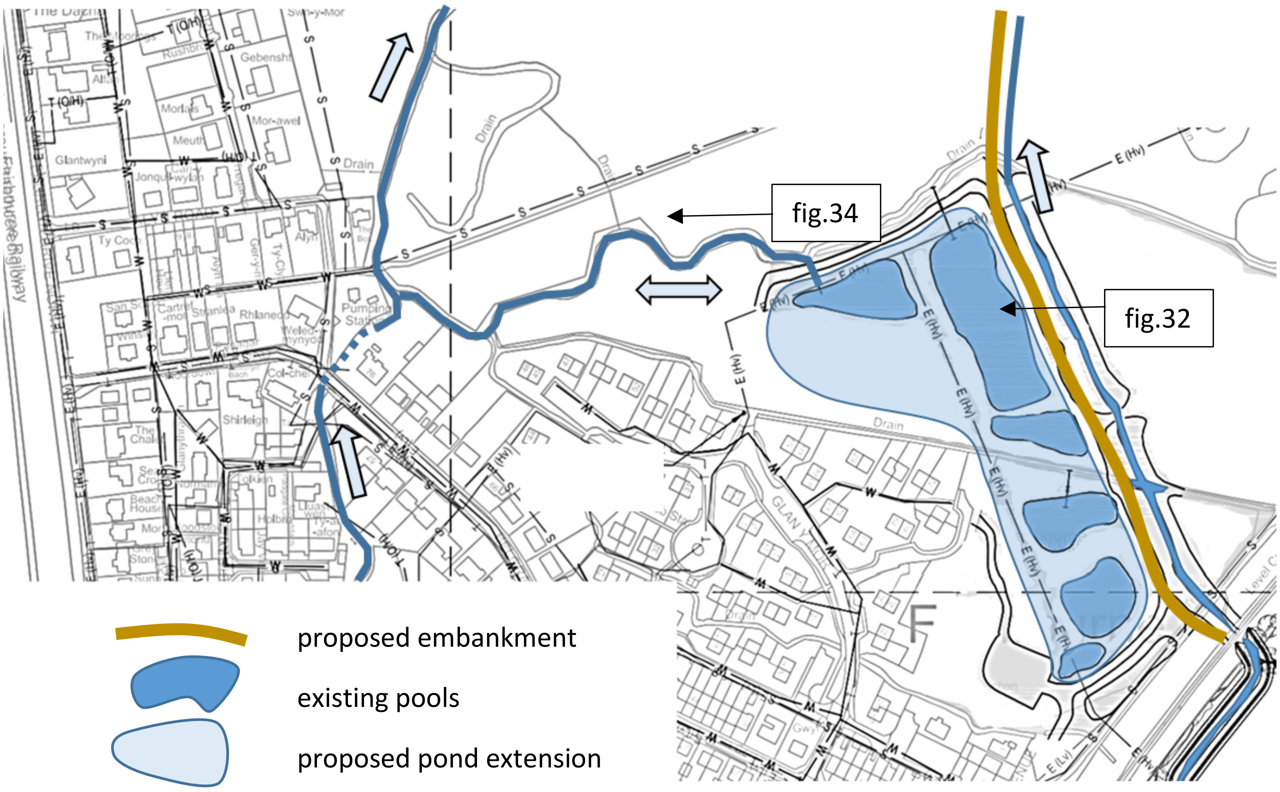


Figure 33: Area of wetland reed beds proposed as a flood water retention pond.

The retention pond would be created by further excavation of clay, which in turn could be used in the construction of the new flood embankment. The pond would be linked by a culvert to the existing river channel which meanders westwards to its confluence with the Fairbourne drainage ditch outlet. The section of former river channel between the retention pond culvert and the new flood embankment would be filled with earth and the land surface restored.

During a storm event at a high tide, when drainage water accumulates in the ditch network and cannot discharge through the tidal gate, water will flow instead to the retention pond. This will avoid the risk of overbank flooding. At the next low tide, water will flow out from the retention pond and re-join the outlet channel to the tidal gate.

Figure 34

Current course of the Afon Henddol passing the northern edge of the wetland and flowing towards the confluence with the Fairbourne drainage ditch network.

Sea water interception

Fairbourne village may be occasionally at risk from storm waves overtopping the storm beach, and possibly from slight seepage of sea water through the sea wall during periods of high sea level.

A buried sewer runs along Penrhyn Drive to the north and south of the Beach Road junction, in front of the rows of properties which face the sea embankment. Surface water can drain into roadside grids (fig.35), and is then transported through the sewerage system to a treatment works on the outskirts of the village.

Figure 35: (left) Utilities map indicating the location of a buried sewer along Penrhyn Drive (after Black and Veatch, 2012). (right) Roadside drainage grids in front of properties in Penrhyn Drive.

Figure 36 shows the Fairbourne coastline at the height of Storm Clara on 9 February 2020. This storm caused extensive flooding across North Wales, for example in the villages of Llanrwst and Beddgelert. However, no flooding occurred in Fairbourne, with the repairs to the sea wall at Friog proving effective.

Figure 36: The Fairbourne coastline during Storm Clara, February 2020.

At the present time, there seems to be no flood risk to properties from water carried over the sea embankment. If this situation should change due to increasing sea level or storm intensity, a solution would be to construct a surface water French drain along the base of the sea wall embankment (fig.37) in front of properties in Penrhyn Drive.

Figure 37

Proposed line of a French drain to collect water from occasional overtopping waves.

The drain may consist of a gravel filled trench containing a perforated plastic drainage pipe into which water may flow (fig.38). Space for this drain exists between the narrow gauge railway track and the road (fig.39).

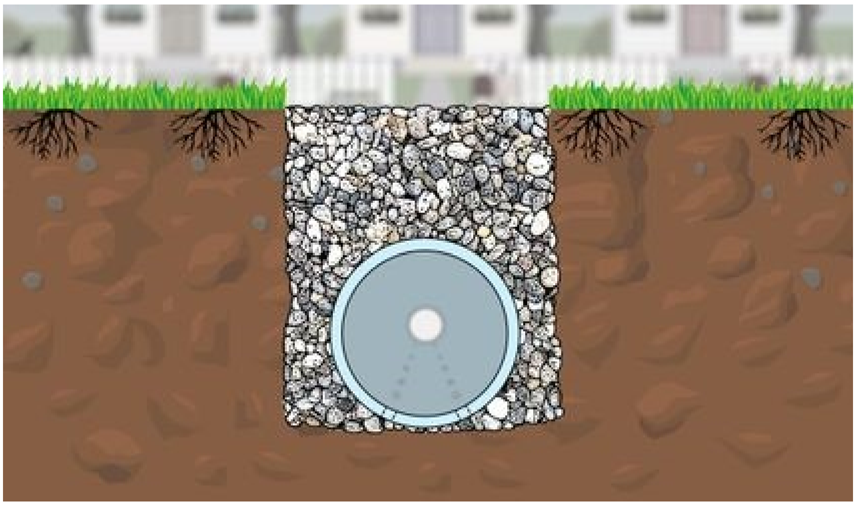


Figure 38

Construction of a French drain, with a slotted plastic drainage pipe buried in a gravel filled trench.

Figure 39

Possible site for a French drain along the grass verge between the narrow gauge railway and the road, Penrhyn Drive.

The drain may be linked to the Fairbourne village drainage ditch network by means of a culvert underneath Penrhyn Drive and alongside Beach Road (fig.40).

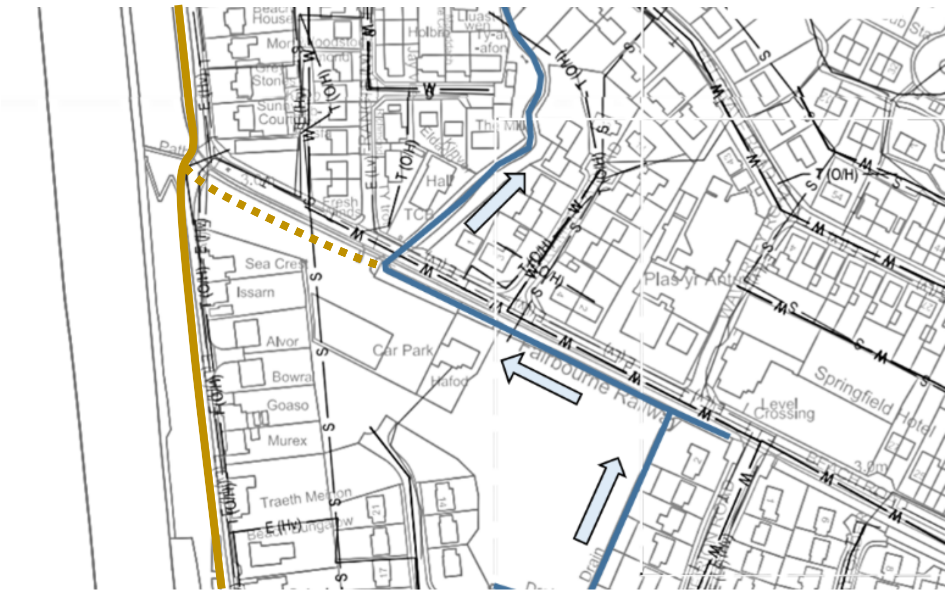


Figure 40

Connection of the sea embankment drain (brown) by culvert to the drainage ditch network, Beach Road.

5. HYDROLOGICAL MODELLING

Computer modelling was carried out to evaluate the effectiveness of the proposed flood defence scheme for Fairbourne village. Conditions along each boundary were applied to represent a worst case storm scenario for sea level as predicted for the year 2065.

The modelling considered the possibilities of water entering the Fairbourne flood protection area from a number of sources:

- Wave overtopping of the sea wall, and water seepage through the sea wall.
- Estuary overtopping of the flood embankment, and water seepage through the embankment.
- Hillslope runoff overtopping the railway and flood embankments, and seepage of hillslope runoff through the embankments.
- Direct addition of rainfall over the flood protection area.

Modelling simulated the movement of water through the flood protection area, temporary storage, and then its discharge into the estuary by gravity flow or pumping.

Flooding from the sea

Surveying has shown that the sea wall between Friog cliff and Fairbourne golf club provides a clear height difference of 1.5 m above the level of the maximum spring tide and storm surge predicted for the year 2065. However, major winter storms have occurred in Cardigan Bay in recent years, with significant damage occurring at Aberystwyth promenade due to breaking waves.

Figure 41

Aberystwyth storm of January 2014

The wave amplitude experienced in Cardigan Bay is the result of a number of factors: the approach direction of the waves, which determines the maximum distance of travel across open sea; the wind speed and duration of the storm; and the local configuration of the sea bed and coastline. Very large waves approaching Fairbourne during a storm might typically have a frequency of 10 sec. and an amplitude of 6m.

Water circulates in cells beneath sea waves (fig.42).

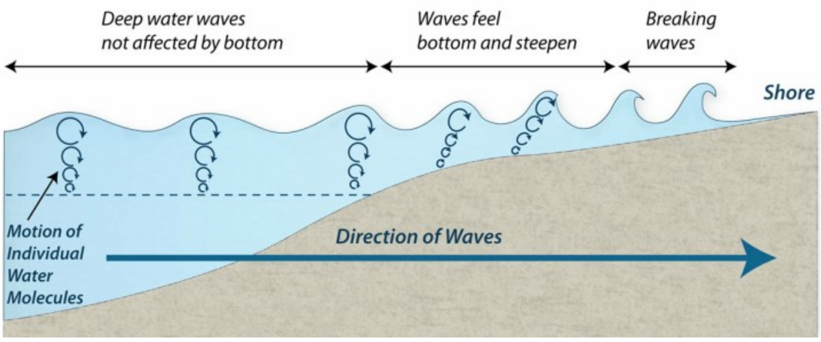


Figure 42

Diagram showing changes to water motion below sea waves as they approach a shoreline.

As the zone of rotating water encounters a beach, the wave crest maintains its forward velocity whilst the water cells below are slowed by drag at the sediment surface. This causes the wave to overturn or 'break'.

Where a wave encounters a gently sloping beach, the rotational motion is gradually dissipated and the wave spills (fig.43a). The water has sufficient forwards momentum to continue up the beach, carrying beach sediment which is deposited on the upper slope. However, where a wave encounters a steeply sloping beach, there is no opportunity to dissipate the rotational water motion. The wave plunges (fig.43b) and water continues to rotate. This creates an erosional backwash which carries beach material back towards the sea.

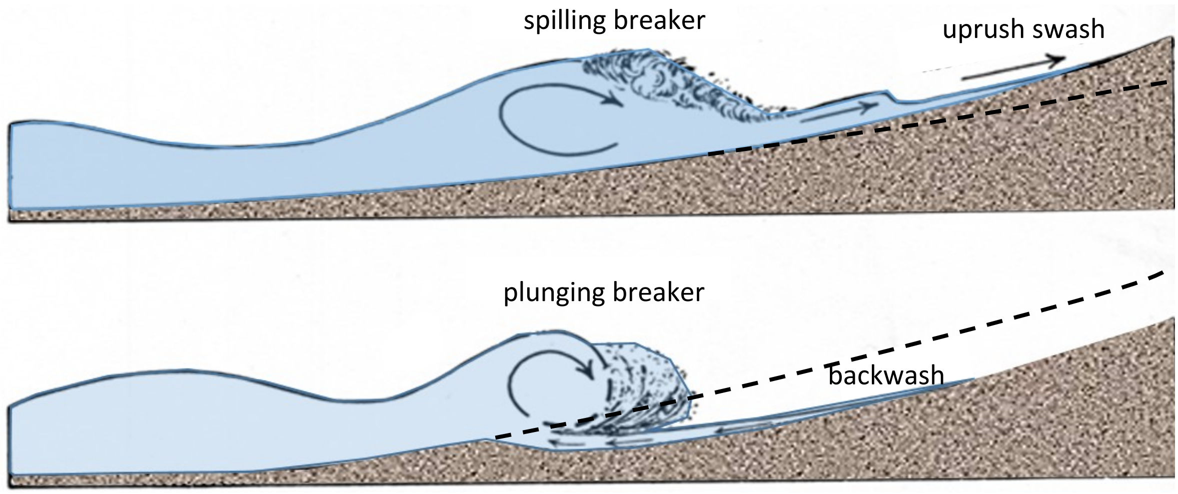


Figure 43a: (above) Constructive spilling breaker. **b**: (below) Erosional plunging breaker.

This mechanism can explain erosion at the narrow, steeply sloping beach at Friog, whilst deposition is occurring on the Ro Wen spit further to the north where the beach is wider and slopes more gently.

The pebble storm beach at Friog rises at an angle of approximately 35° from the sandy foreshore. Wave energy is dissipated effectively, with only the occasional wave crest overtopping the sea wall. The sea wall would only be at risk of overtopping for about an hour either side of high tide.

Figure 44: Maximum predicted storm wave height in relation to the shingle storm beach near Friog.

From models of breaking waves at a gently sloping sea wall, it is estimated that $1m^3$ of water might cross 1m of the sea wall as an extreme wave breaks. Such a large breaking wave might occur once in ten waves, representing an occurrence once every 100 sec. This is equivalent to an average flow rate of 10 litres/sec/m over the affected length of sea wall.

Taking into account all factors, a maximum estimate for the total volume of sea water which might cross the sea wall and enter the flood protection area at Fairbourne in an extreme storm is 8 $000m^3$.

Further north along spit, beach rises more gently, as seen in the middle distance in fig.45.

Figure 45

Ro Wen shingle storm beach, looking northwards towards Fairbourne village.

Spilling breakers occur along this section of the shoreline, with the storm beach stable or a small amount of shingle being added during storms. Modelling by Phillips et al. (2017) indicates that after a wave has spilled, the water elevation reduces to the normal tidal height plus any additional storm surge due to low atmospheric pressure. This is the water height which would be observed at the shingle storm beach. The authors tested their modelling by photography during actual storms, and found the model to be accurate (fig.46).

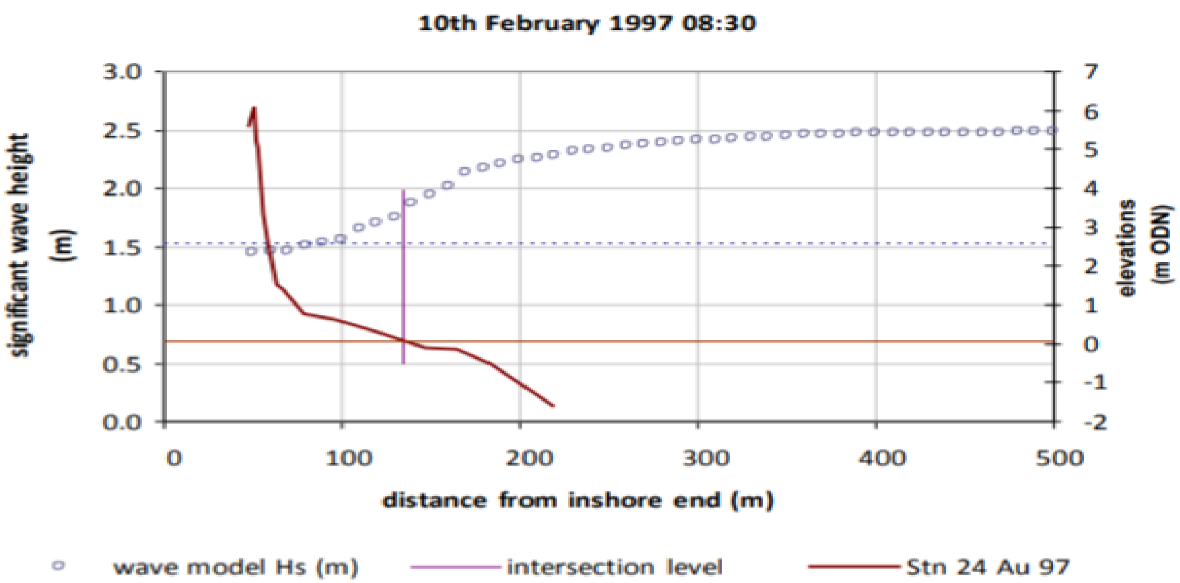


Figure 46: Model for change in water depth on approach to the Ro Wen shingle spit (after Phillips et al., 2017)

It is concluded that protection by the pebble storm beach becomes more effective northwards along the Ro Wen spit. No significant wave overtopping is expected at Fairbourne village during storms up to and beyond the year 2065, allowing for predicted increases in sea level and storm surge heights.

Flooding from the estuary

Water heights along the banks of estuaries may be influenced by the tidal height, waves, or river inflow. Chen et al. (2018) have made a study of wave heights in the Delaware estuary in the USA, which is hydrologically similar to the Mawddach estuary. They found that sea waves are propagated mainly along the deeper water channel and quickly dissipate in shallow water along the margins of the estuary, particularly where salt marsh vegetation is present. It is safe to assume that the water height alongside the Fairbourne estuary embankment will not be increased by wave action by more than a couple of centimetres.

Figure 47

Saltmarsh between the estuary flood embankment and the mouth of the Mawddach estuary.

The possibility of river flooding at the head of the estuary affecting the water level at the Fairbourne embankment must be considered. The largest flood event ever recorded on the rivers Mawddach and Wnion was in July 2001, causing extensive damage to river bridges in the Coed y Brenin area. Hydrographs (fig.48) indicate a maximum flow rate of $400m^3$/sec. on the Afon Mawddach and $320m^3$/sec. on the Afon Wnion.

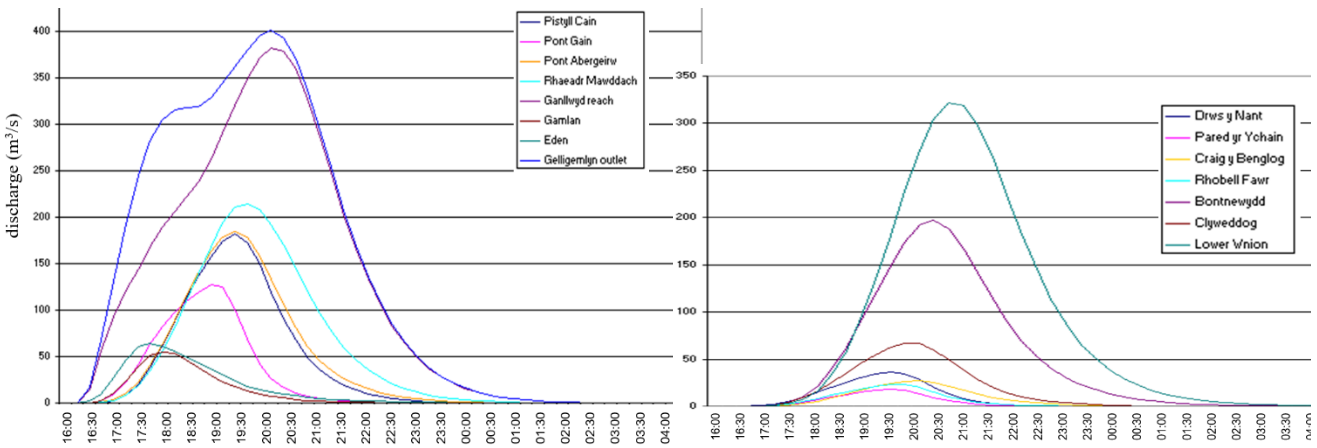


Figure 48: Hydrographs for points on the rivers Mawddach (left) and Wnion (right) during the extreme flood event of 3 July 2001.

The July 2001 flash flood event was caused by exceptional summer convective thunderstorms over the mountains, and was not accompanied by a tidal surge and high sea waves as would occur in a winter gale. Maximum flood discharges recorded on the rivers Mawddach and Wnion in response to winter frontal storms have been significantly lower.

A typical month's tidal data for Barmouth is shown in fig.49. Variation occurs between spring and neap tides, with the maximum tidal height around 5.5m.

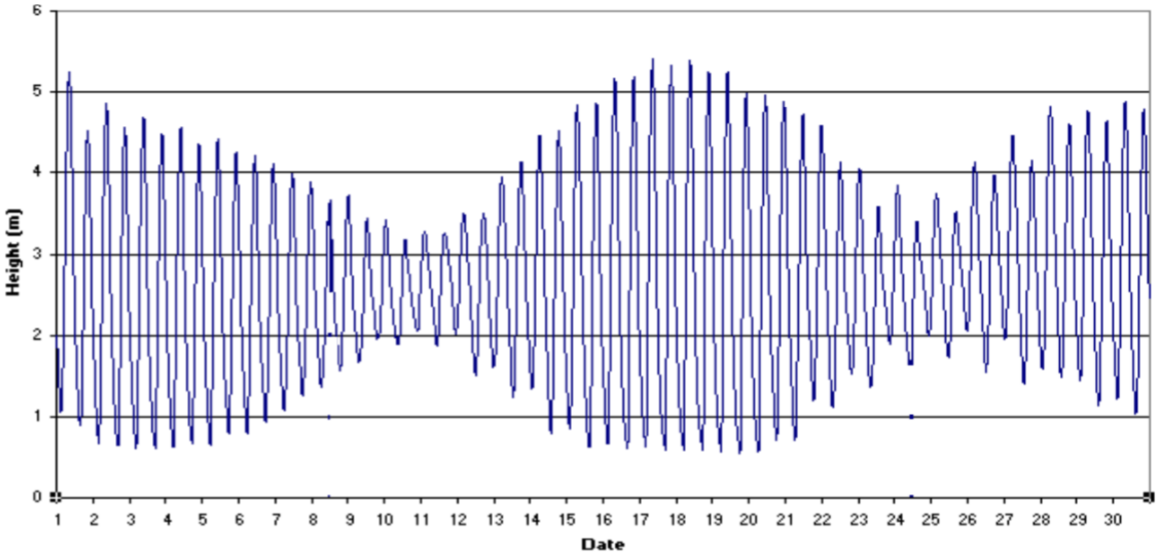


Figure 49: A typical month's tidal data recorded by the tidal gauge at Barmouth railway bridge. Chart Datum for Barmouth lies at 2.4m below Ordnance Datum.

Flood modelling for the Mawddach estuary was carried out using River2D software (Steffler & Blackburn, 2002). The program has effective functions for simulating the wetting and drying of saltmarshes during tidal cycles, allowing different values of resistance to water flow to be applied to areas of sand and salt marsh vegetation.

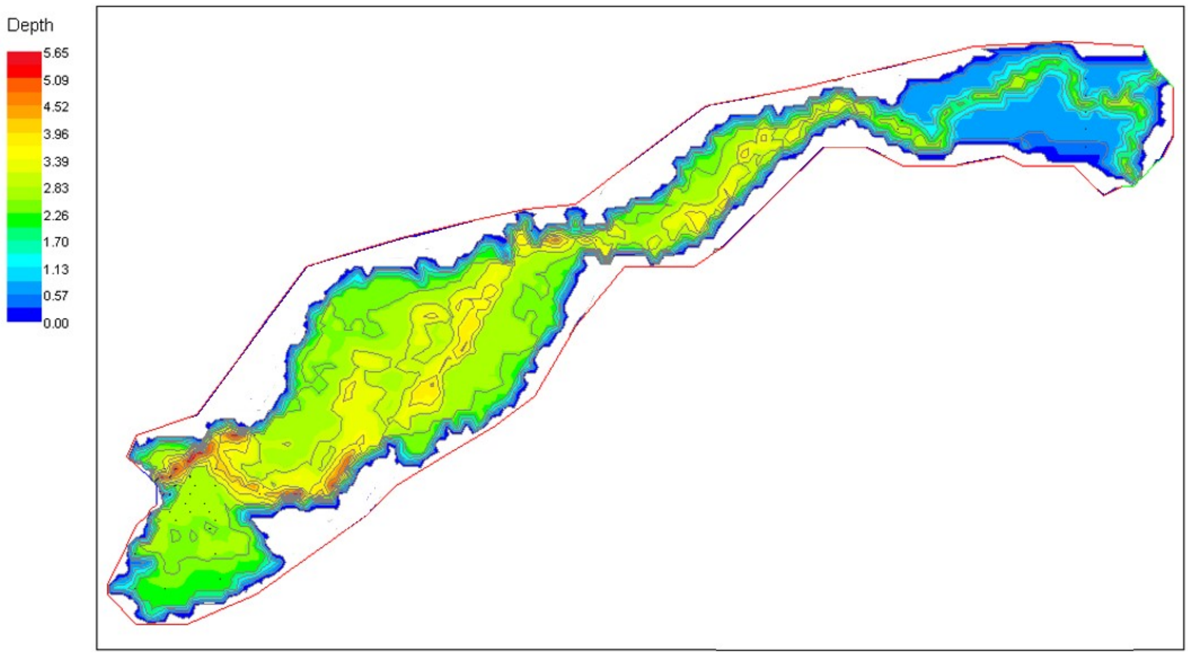


Figure 50: Model for the Mawddach estuary at maximum tidal and storm surge height, along with flood inflows from the rivers Mawddach and Wnion.

To model an extreme worst case future storm scenario, a tidal surge of 2.5m at the estuary mouth was added to a spring high tide of 5.5m. Such a storm would also be likely to cause flooding on the rivers Mawddach and Wnion which discharge into the head of the estuary. Flows of 300m^3/sec. and 250m^3/sec. were applied for the rivers Mawddach and Wnion.

The model predicted extensive shallow flooding of low lying fields between Dolgellau and Penmaenpool in the upper basin of the estuary. However, the river inflow dissipated through the large middle and lower basins and no measurable increase in water depth above the tidal and storm surge height was observed around Fairbourne as a result of the river flood.

Water inflow on the rising tide reached a maximum of 8 000 m^3/sec., with a maximum flow velocity through the estuary mouth of 5m/sec.

The maximum water level stabilised against the Fairbourne flood embankment approximately five minutes after the peak water level at the estuary mouth, at a level of 0.4m below the top of the flood embankment, and 2.4m above the level of the adjacent agricultural land. The water remained at this level against the embankment for only a short period before receding with the falling tide.

Flooding from hillslope runoff

The mountainous hinterland above Fairbourne has mainly thin podsolic soils overlying low permeability mudstones, slates and igneous rocks. This results in quick saturation and fast runoff during rain storms.

Figure 51

Mountain land above Arthog.

Modelling was carried out to determine the effects of an extended period of heavy storm rainfall over the mountains above Fairbourne. This made use of hillslope hydrology software developed previously to investigate flooding in the Mawddach catchment (Hall & Cratchley, 2015).

The model divides the land surface into 50m squares. The soil and subsoil depth and water conductivity within each square are then estimated, based on the underlying geology and superficial deposits, slope angle, and type of land use. The selected thicknesses of the soil and subsoil are each subdivided into layers (fig.52).

A storm event extending over several days is simulated as a series of 15 minute time intervals. During each time interval, rainfall is added to the grid square. Water moves between layers of the soil and subsoil according to the conductivity and degree of saturation. Water may be transmitted down the slope to adjacent grid squares in response to the hydraulic head, and may be lost to the underlying bedrock according to its permeability. Where the uppermost soil layer becomes saturated, the excess water is released at the surface as overland flow, and may enter a stream channel.

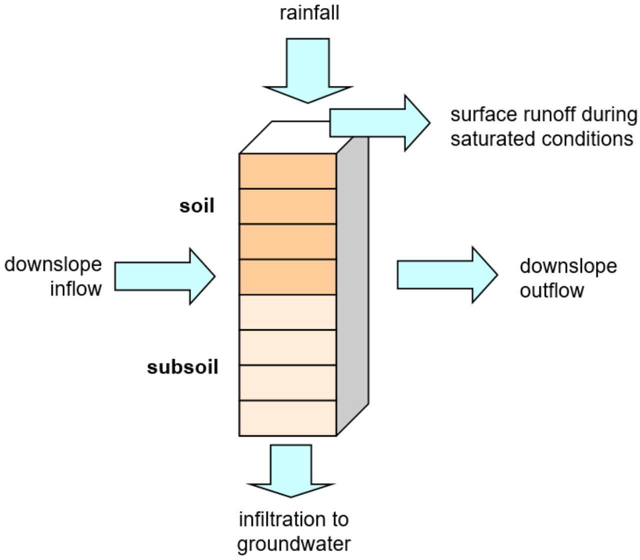


Figure 52

Mathematical structure of the hillslope hydrological model.

Water flow in open streams and channels is modelled using hydraulic equations based on the gradient, roughness and wetted perimeter of the channel. The model takes into account work done during the 2016 Fairbourne flood alleviation scheme. This included raising the heights of sections of the river banks of the Afon Henddol where it crosses fields after descending from the hills to the south of Fairbourne (fig.53).

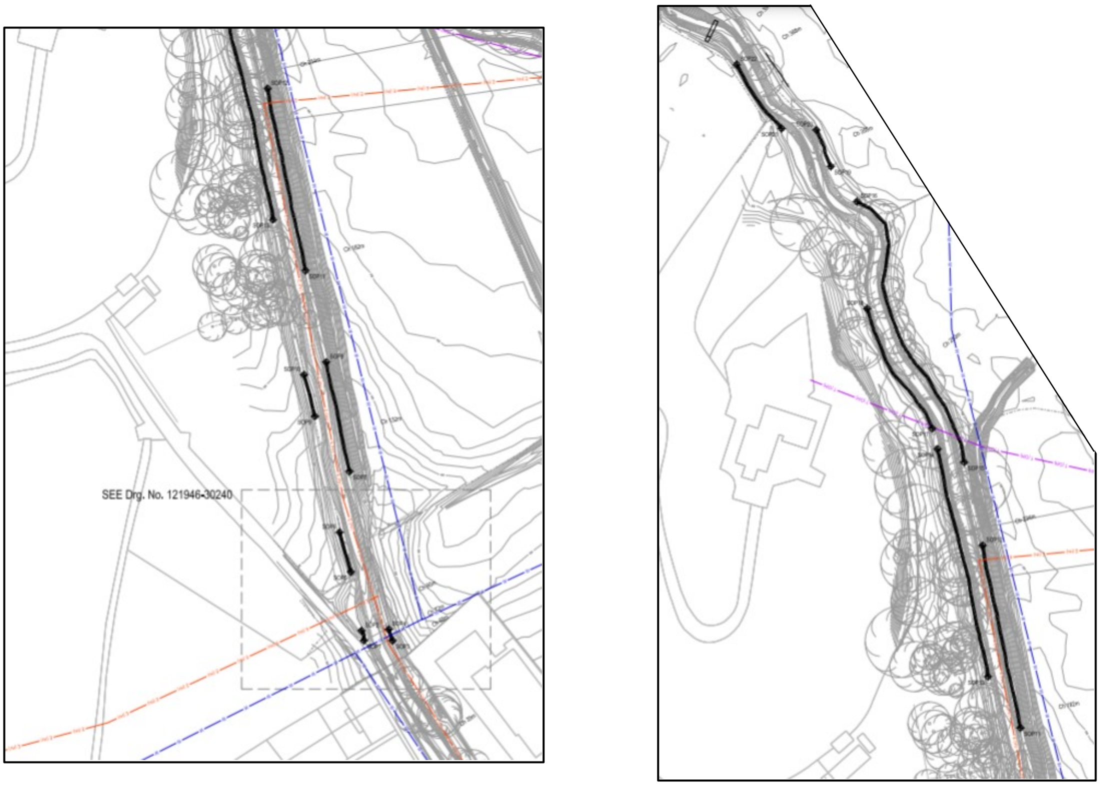


Figure 53: Drawings indicating sections of the river banks of the Afon Henddol which have been raised to prevent overbank flooding (Black and Veatch, 2012).

The model was run using data for an exceptional storm event which extended over three days in February 2004. Hourly rainfall recordings were available for the duration of the storm (fig.53).

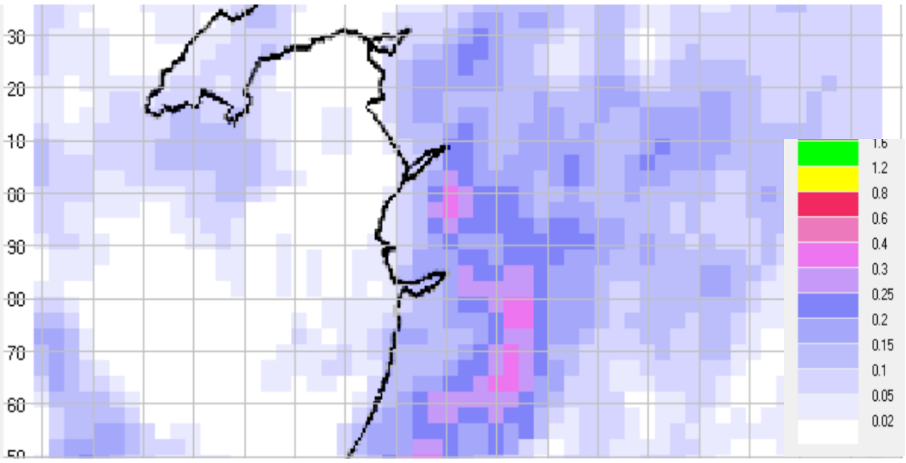


Figure 54

Rainfall pattern over the Meirionnydd coastal region during one hour of the severe storm event in February 2004.

This storm resulted in severe flooding on the Afon Wnion in Dolgellau (fig. 55).

Figure 55: Flooding on the Afon Wnion in Dolgellau in February 2004, following several days of continuous heavy frontal rainfall.

The objective of the hillslope runoff modelling was to estimate the volume of water reaching the southern boundary of the proposed Fairbourne flood protection area at the railway embankment. Results are shown in fig.56 below.

It was found that the runoff caused a rise in the water table to within 5cm of the ground surface in the fields south of the railway. Stream flow, however, remained within the channels and no overbank flooding occurred. This is a reasonable result, since the catchment area of the stream draining from the hillside above Fairbourne is relatively small. It was concluded that the existing railway embankment provides adequate protection for the village of Fairbourne against storm water runoff from the surrounding hills.

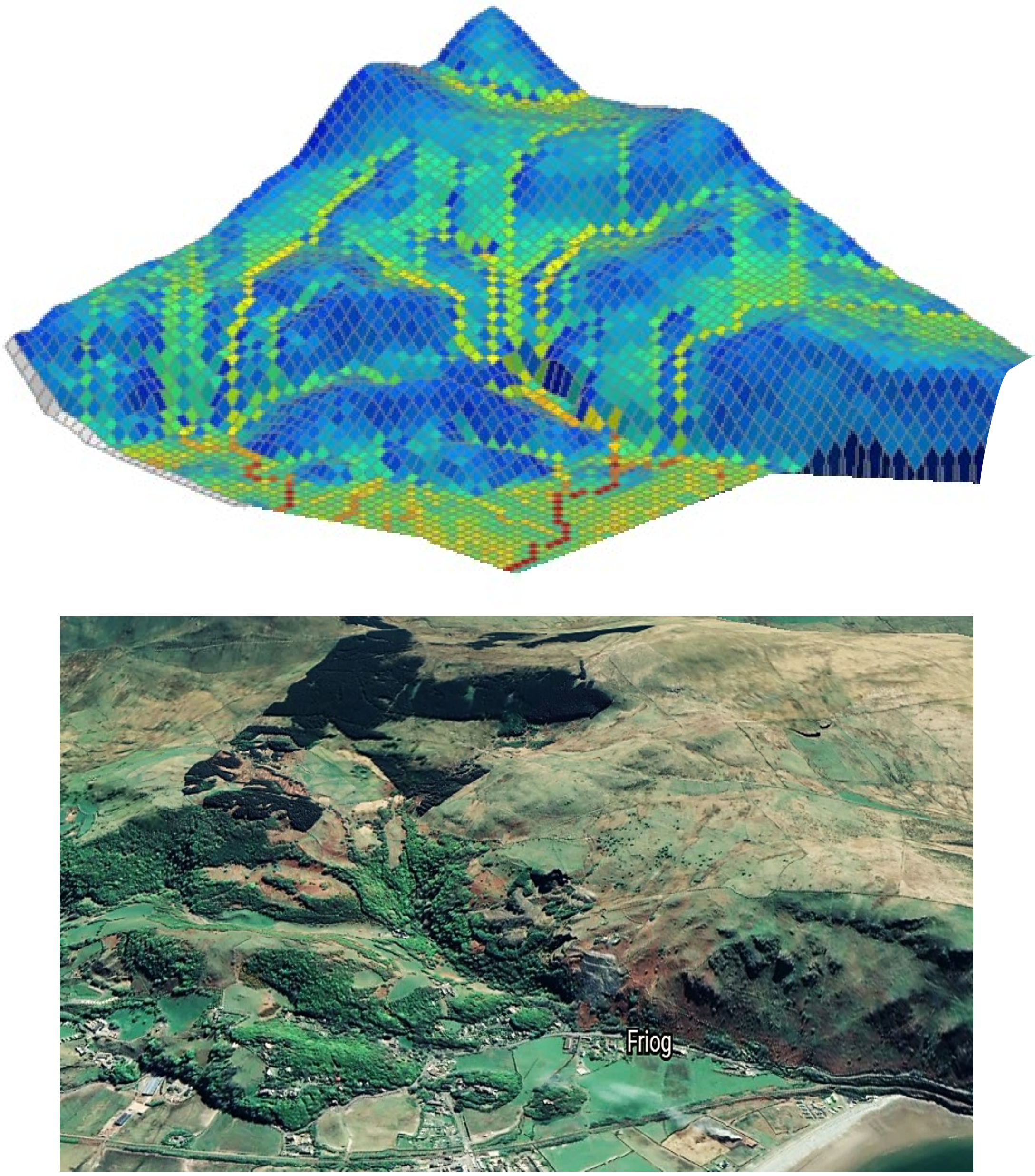
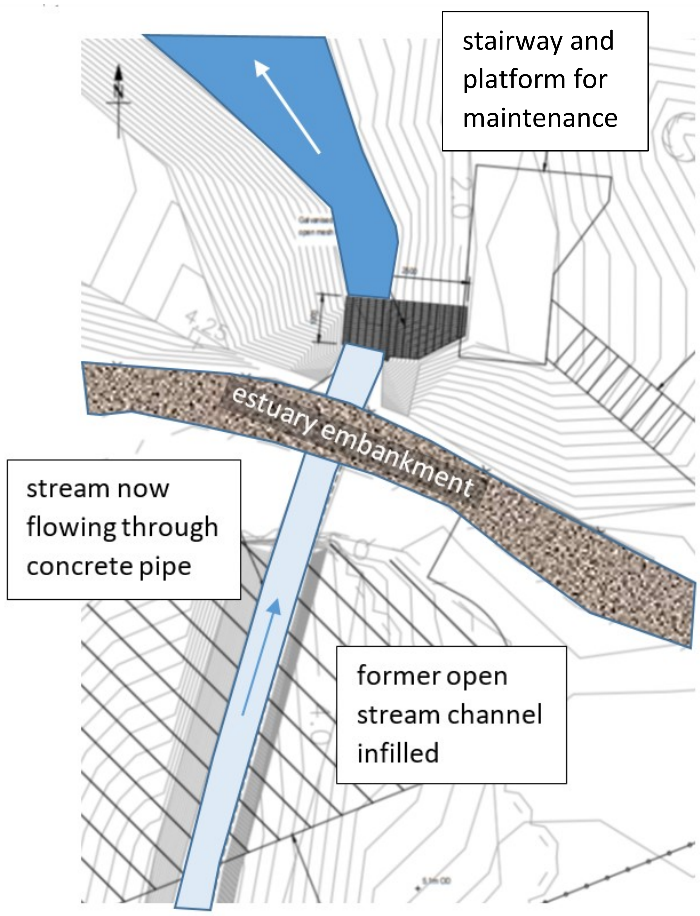


Figure 56: (above) Flood model for the hillslopes above Fairbourne after simulation of two days of continuous heavy rainfall. Yellow and green colours indicate a water table close to the surface, whilst red indicates open runoff in a stream channel or flooding of the ground surface. (below) Air photograph of the area covered by the computer model.

Coastal lowland

The proposed construction of a flood protection embankment to the east of Fairbourne village would require the re-routing of the Afon Henddol which descends from the hillside, then skirts around the north of the village to enter the estuary through a tidal gate alongside the golf course (fig.38). This tidal gate would continue in use for the discharge of water only from within the Fairbourne flood protection area.

The Afon Henddol would now flow across fields to the east of the new flood embankment, and would discharge into the estuary through another tidal gate at the mouth of the Afon Morfa stream. There is currently a tidal gate at this point, of a simple self-acting design with a flap valve that opens with the water flow at low tide. The gate is closed by the pressure of a rising tide (fig.57).



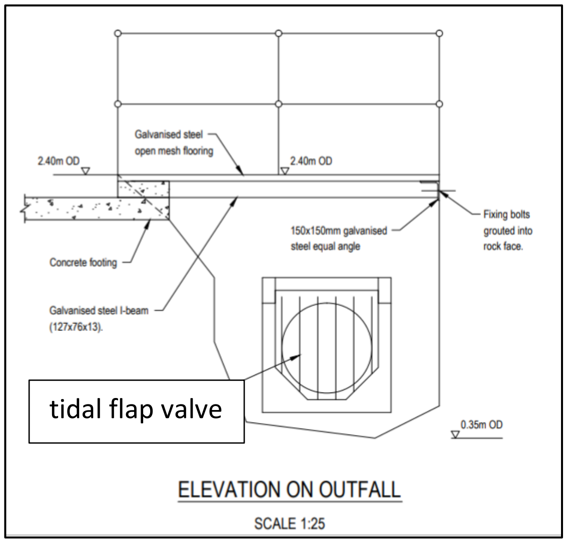


Figure 57

Design drawings for the Afon Morfa tidal gate (after Black and Veatch, 2012).

Figure 58: Location of the Afon Morfa tidal gate (air photograph: Google Earth).

The coastal lowland between the proposed new Fairbourne flood embankment and the Afon Arthog is crossed by a number of streams draining the hills to the south. It is necessary to provide culverts under the current railway embankment and the embankment of the disused Dolgellau branch in order to discharge water into the estuary through tidal gates. This low lying area of fields is adequately protected from estuary flooding by the existing series of flood embankments around the former islands of Fegla Fawr and Fegla Fach, then along the banks of the Afon Arthog. However, the land is liable to overbank flooding from the streams and drainage ditches during storm events (fig.59).

Figure 59
Minor flooding of agricultural land at Arthog following a severe storm in December 2018.

For the purpose of the modelling, it will be assumed that the fields of the coastal lowland are fully saturated as a result of several days of prolonged rainfall, with 5cm of surface water present. This represents an extreme worst case scenario, as surface flooding of this extent occurs rarely, if ever.

Internal drainage of the Fairbourne area

Modelling was carried out to evaluate the proposed flood protection scheme. Soil hydrological properties used in the model were based on a soil profile close to the line of the proposed new flood embankment, as recorded by Owen (2010).

Figure 60
Soil sampling pit excavated close to the line of the proposed new flood embankment (Owen, 2010).

The soil profile is described as: "Mid orangey grey silty sand with some clay content, depth of 0.25m. Orangey grey silty clayey sand, soft texture with a depth of 1.25m. The lower layer was an orangey grey silty clay, although less clay and more sandy as the trench progressed downwards."

This is typical of sediments laid down at the margins of an estuary, where alternating conditions of sand and salt marsh mud deposition may occur over a period of time. For the purpose of the current modelling, an estimated hydraulic conductivity value is 10^{-8} m/sec and a porosity above the water table of 0.5 is assumed.

A model was run for the Fairbourne flood protection area, assuming an extended storm event of two days duration and using the worst case boundary conditions obtained from the previous modelling, as summarised in fig.61. The model allows for overtopping of the sea wall by waves as a result of a 0.5m increase in sea level compared to the present day, combined with a storm surge of 2.5m at a high spring tide.

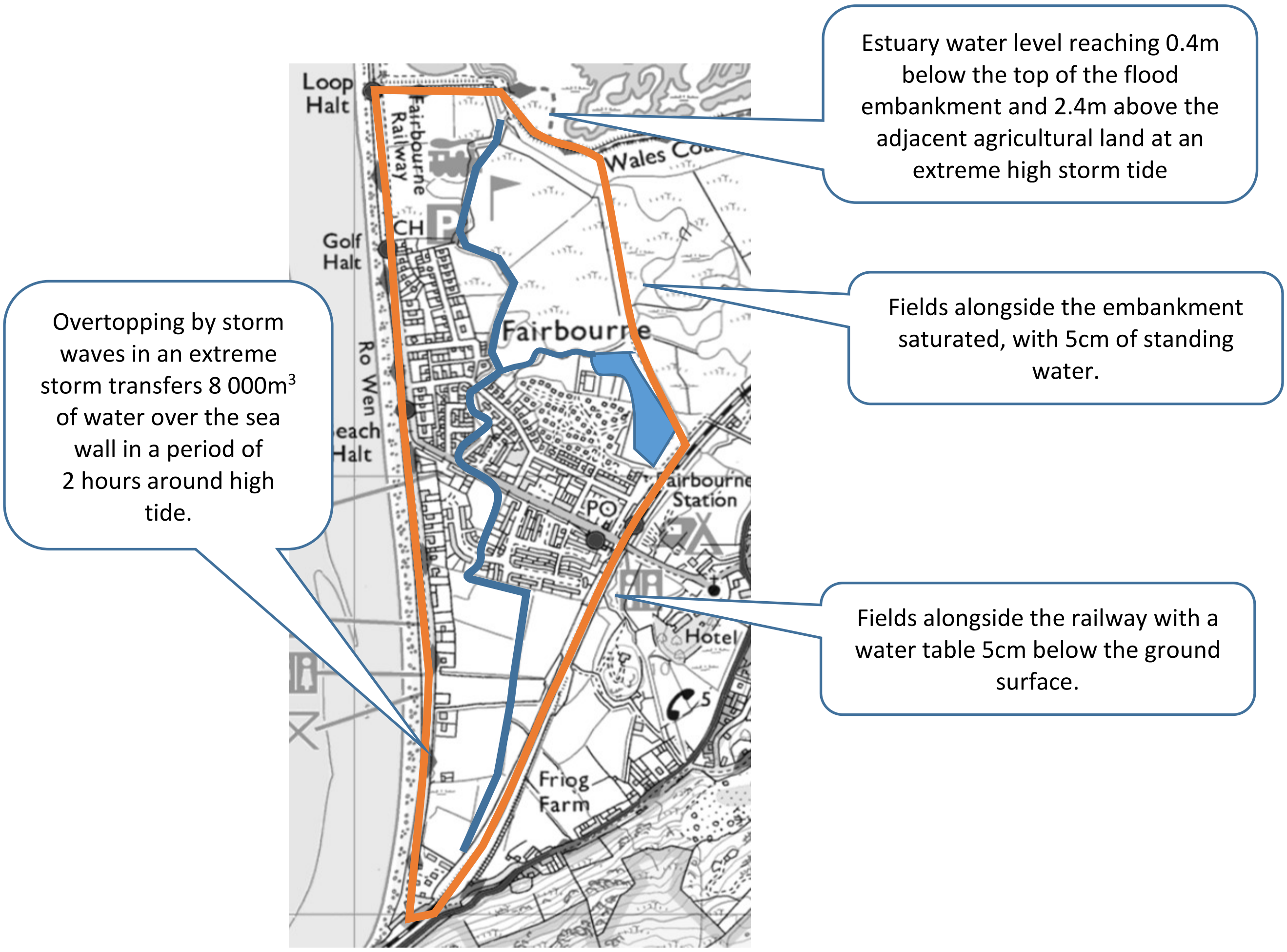


Figure 61: Boundary conditions assumed for a worst case flood event, using the sea level prediction for the year 2065

A cascading store model was used, as shown in fig.62. Calculations were updated for time intervals of 15 minutes. Rainfall was added for the whole Fairbourne area, along with water from overtopping waves in only the section of sea wall south of Beach Road. Discharge of water from the soil into drainage ditches was found using the specified soil hydraulic conductivity.

Flow of drainage water through the drainage ditch network was computed, along with outflow through the tidal gate when possible. Water was directed to the storage pond when estuary outflow was prevented. On a falling tide, the storage pond could release water back into the drainage network. Calculations of seepage through or under the embankments and sea wall were made, dependent on difference in hydraulic head across the structures.

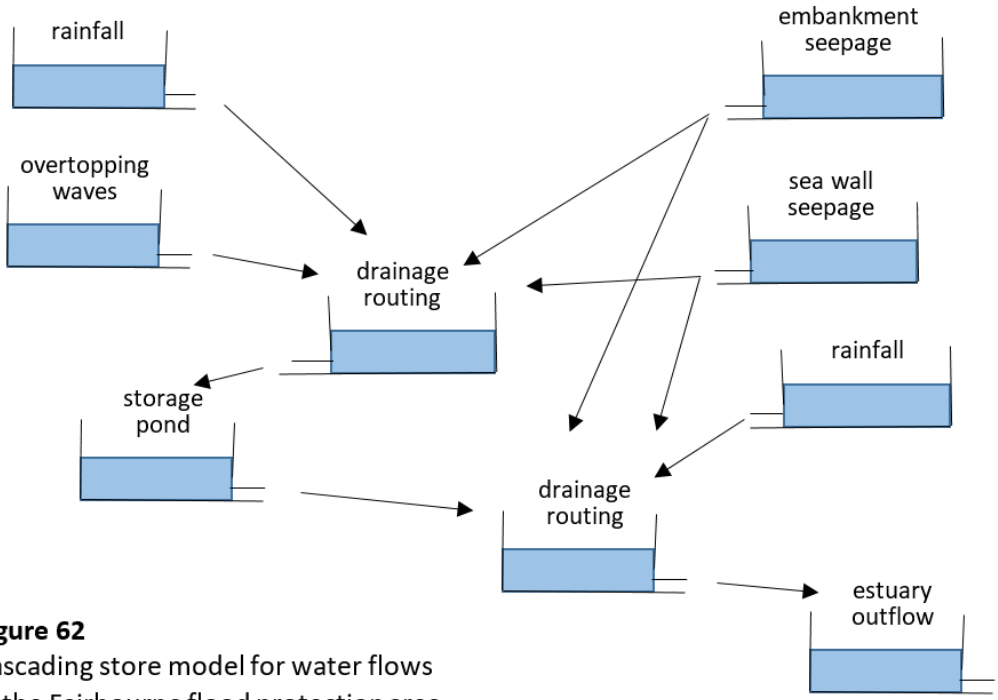


Figure 62
Cascading store model for water flows in the Fairbourne flood protection area.

Results of the modelling are shown in fig.63 below:

- Maximum spring tides were simulated, with the addition of a storm surge to one high tide.
- A long period of storm rainfall represents the slow passage of a frontal system.
- It was found that seepage through and below the sea wall and flood embankments was very limited, due to the low hydraulic conductivity of the clay soil and the low difference in hydraulic head across the structures.
- Rainfall was the principal input of water to the system. Wave overtopping of the sea wall was briefly of significance at extreme high tide. Water was effectively transferred to drainage channels without any significant surface water flooding.
- Routing of water from the area south of the village was periodically to the storage pond east of Fairbourne railway station. This pond provided an adequate buffer for temporary storage during the couple of hours on either side of high tide when direct outflow to the estuary was inhibited.
- Output to the estuary was dependent on the tide, but appeared to be achieved by gravity flow without pumping. Maximum flow at low tide reached approximately $2m^3$/sec. The double outflow peaks observed around low tide represent different travel times for water flow from the village drainage ditch network and discharge from the storage pond.

It is concluded that the flood protection boundary would provide adequate defence against inflow of sea, estuary and surface water to Fairbourne village during a predicted worst case storm scenario for the year 2065. Internal water flows can be adequately handled by the drainage ditch network and retention pond, without surface water flooding.

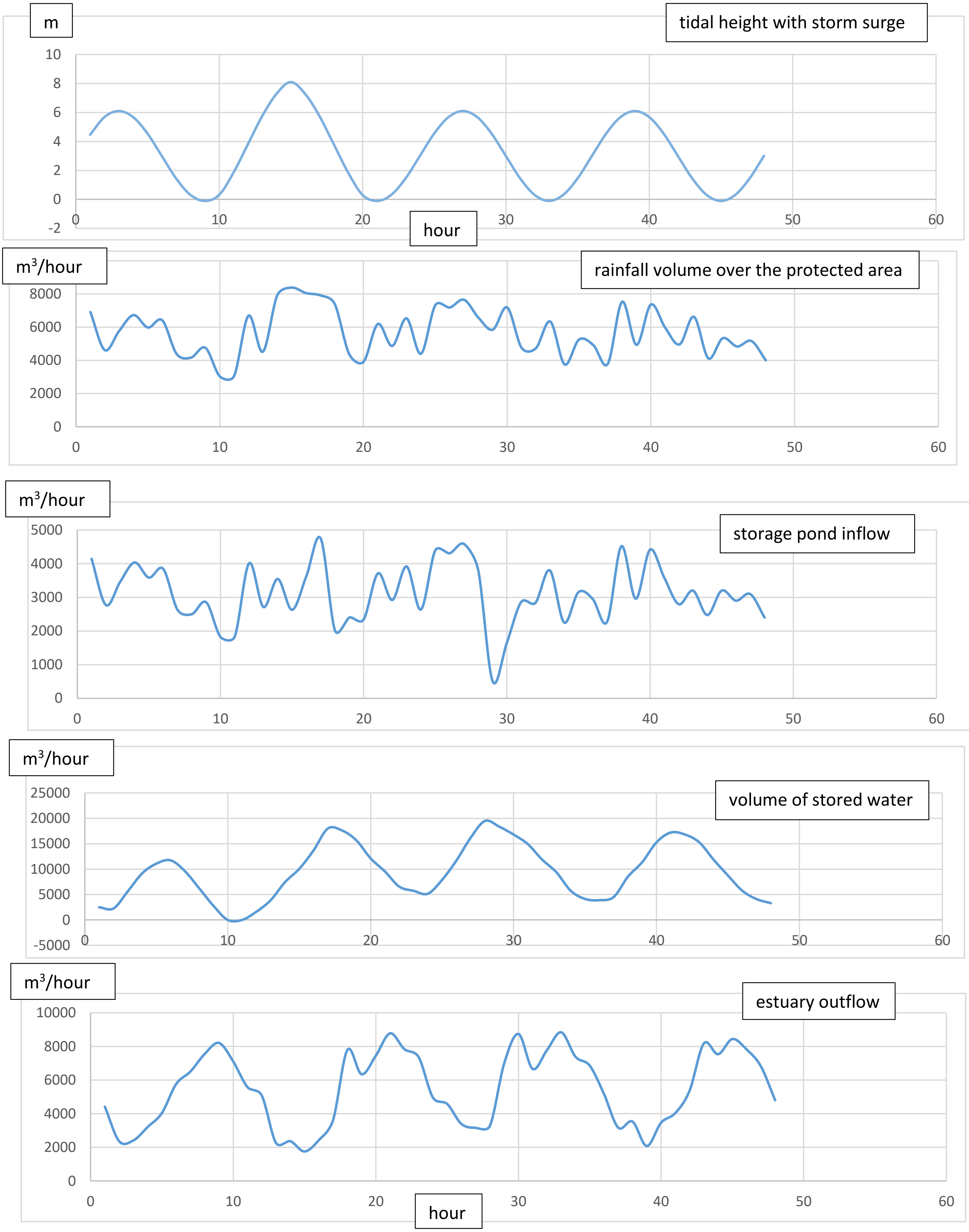


Figure 63: Results of modelling a worst case storm event for Fairbourne for the year 2065.

6. THE OUTER FLOOD PROTECTION AREA

The flood protection scheme for Fairbourne village would be implemented by enclosing a section of the existing outer Fairbourne–Arthog flood protection area. It is important to verify that the new scheme would not have a detrimental effect on the hydrology of this outer area.

The central section of the Fairbourne–Arthog flood protection area is illustrated in fig.64.

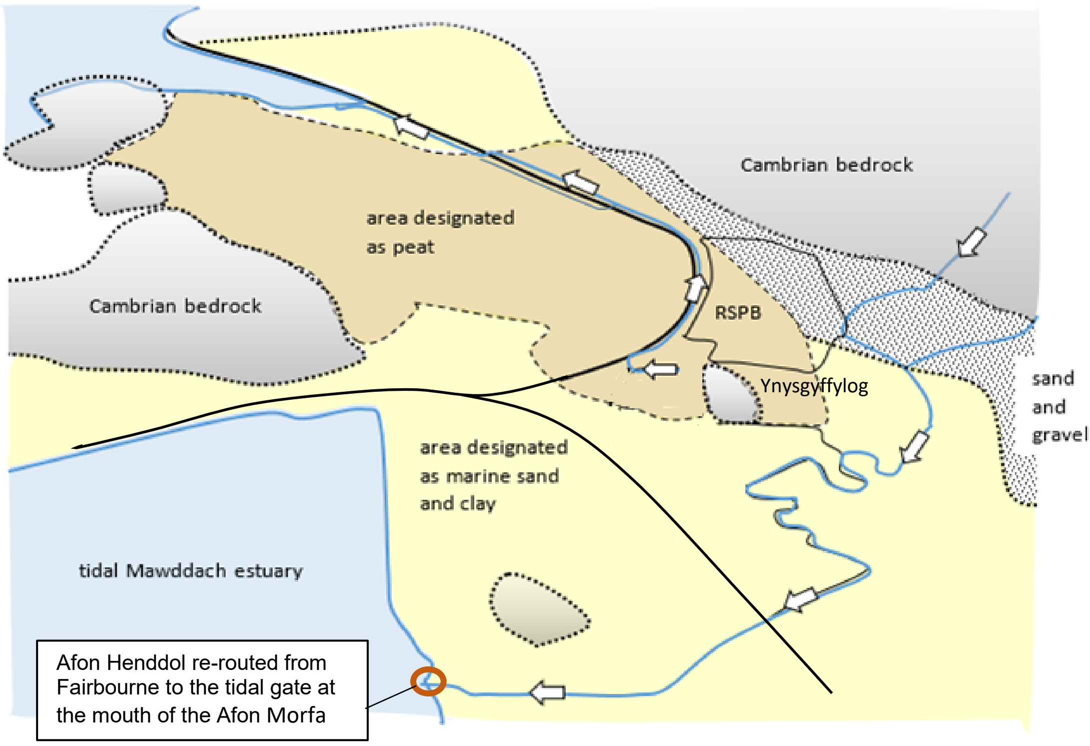


Figure 64: Central area of the Fairbourne-Arthog flood protection area.

The former rocky island of Ynysgyffylog marks an approximate watershed between eastward and westward flowing streams and drainage ditches:

- To the east of Ynysgyffylog, streams follow the embankment of the disused railway to enter the Afon Arthog through a tidal gate.
- To the west, streams currently flow to the Afon Morfa tidal gate at the location indicated in fig.64.

Arthog Bog

Within this central area is the ecologically important site of Arthog Bog, located roughly between the former rocky islands of Fegla Fawr, Fegla Fach and Ynysgyffylog.

Figure 65

Reed beds at Arthog Bog.

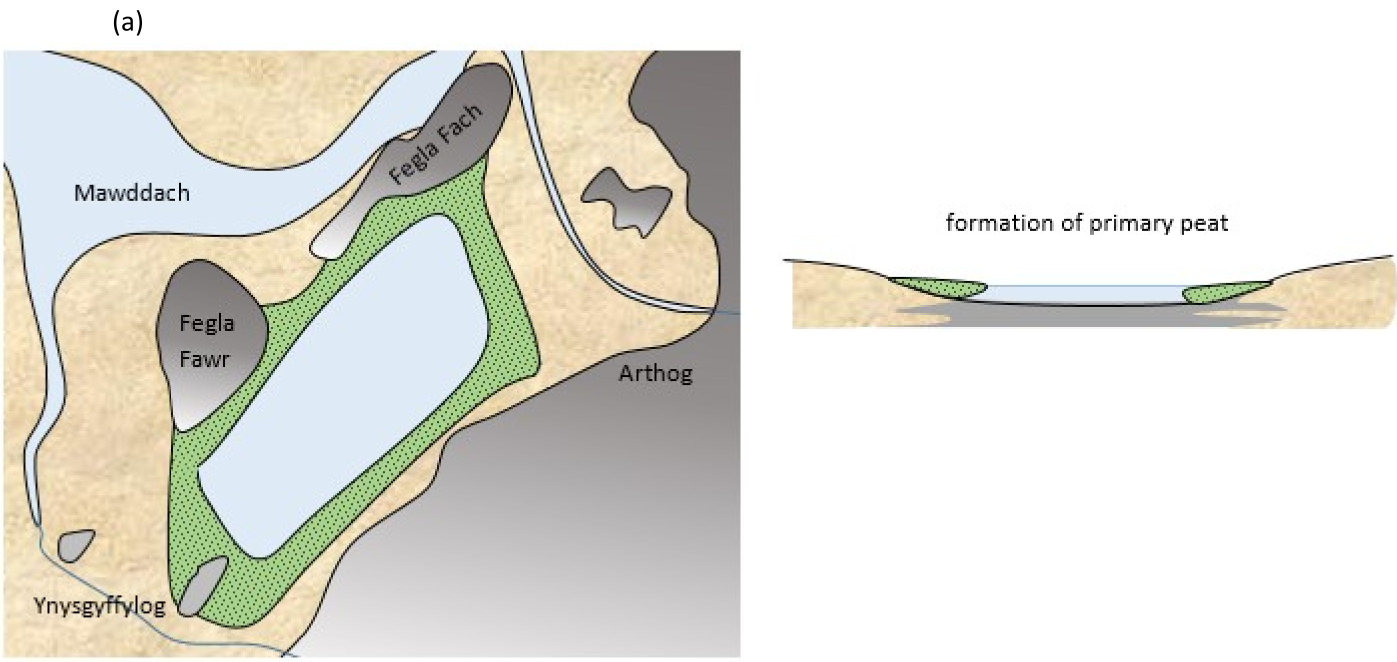
The bog has an unusual drainage pattern. To understand this, we may examine a tentative model for the formation of the bog, as illustrated in fig.66:

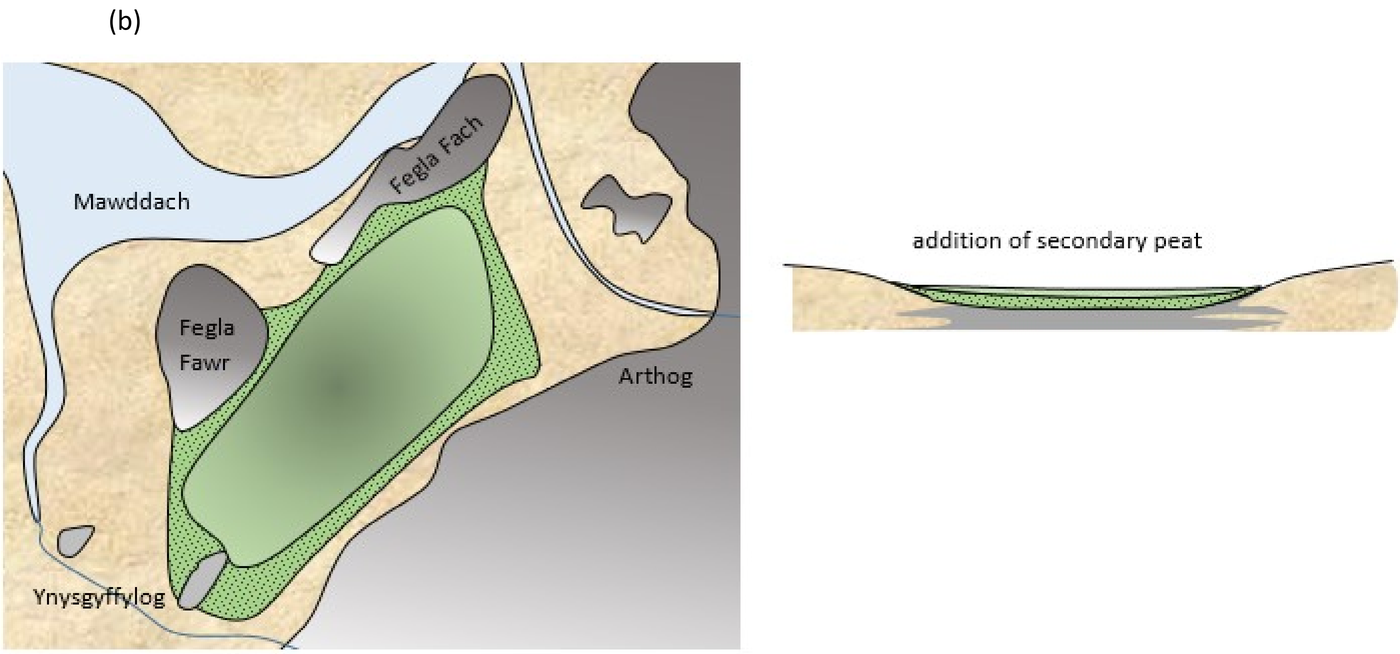
(a) Around 6,000 years before the present, sand carried into the Mawddach estuary by tidal flows was deposited in the bays to the west and east of the islands of Fegla Fawr and Fegla Fach. A lagoon was created, with growth of trees and aquatic plants began around its margins. Over a period of thousands of years, vegetation extended into the lagoon and a thick layer of primary peat accumulated.

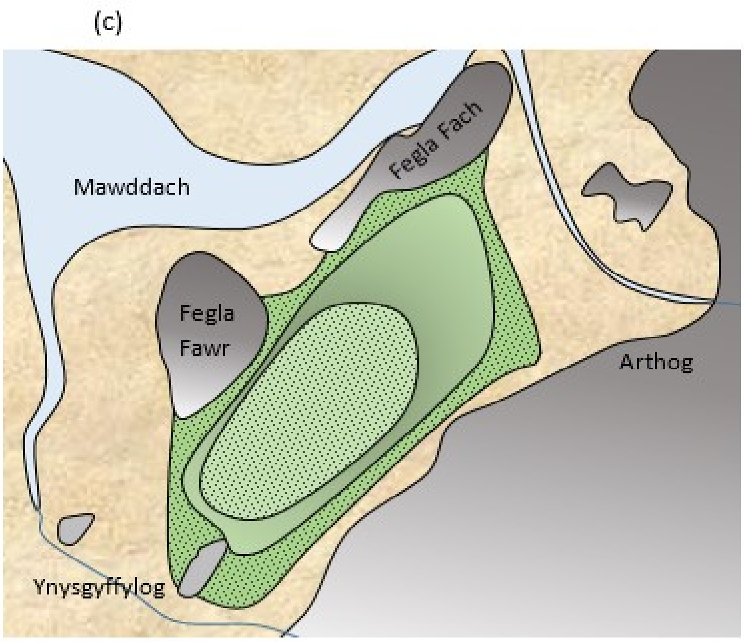
(b) As vegetation growth continued, plants became rooted in the primary peat deposits and no longer had any access to minerals in the underlying clay sediments. This led to an increase in acidity of the growth medium. Combined with the waterlogged conditions, grasses, sedges and rushes now dominated and a layer of secondary peat accumulated.

(c) With time, peat growth and accumulation within the central area of the bog caused its surface to rise above the level of the basin margins. This prevented external flows of surface and ground water reaching the central area, leading to further acidification. Mosses and Phragmites australis reed beds could now dominate, creating tertiary peat. The very low permeability of the dense peat maintains wet conditions within the central area of the bog.

Stages (a) to (c) outlined above occurred in response to increasing acidification of the growth medium for the peat. At the present day, the raised nature of the central bog produces an outwards radial drainage pattern. Water flows are low, due to the low hydraulic conductivity of the peat.







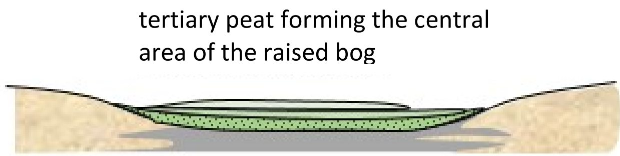


Figure 66: Development of Arthog Bog.

The central core of the bog is effectively isolated from the surrounding drainage system and would be unaffected by changes to the course of streams to the west of Ynysgyffylog.

The natural development of Arthog bog has been disturbed in various ways by human activity over several centuries. The construction of the embankment of the Dolgellau to Morfa Mawddach railway has separated the southern and western marginal areas from the central core of the bog and facilitated their drainage and improvement for agriculture.

Streams issuing from the central area of the bog and its former extensions beyond the railway embankment generally flow eastwards to the tidal gate at the Afon Arthog. An exception is streams which flow northwards towards the gap between Fegla Fawr and Fegla Fach, then discharge into the estuary through a tidal gate at this point.

Estuary outfall

It is proposed that the Afon Henddol, diverted around the new Fairbourne flood defence embankment, will reach the Afon Morfa tidal gate by a new channel cut across the agricultural land.

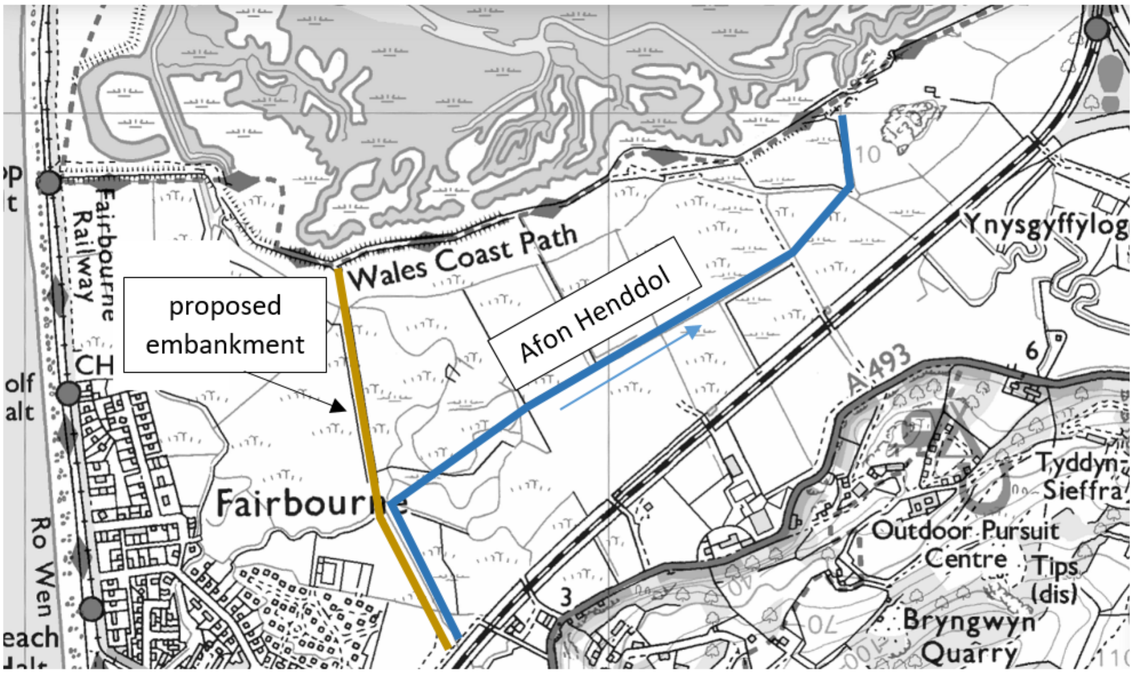


Figure 67: Proposed diversion of the Afon Henddol

Consideration of the relative heights of the farmland and the expected tidal range for the year 2065 suggest that a drainage potential of at least 2m exists at the tidal gate (fig.68).

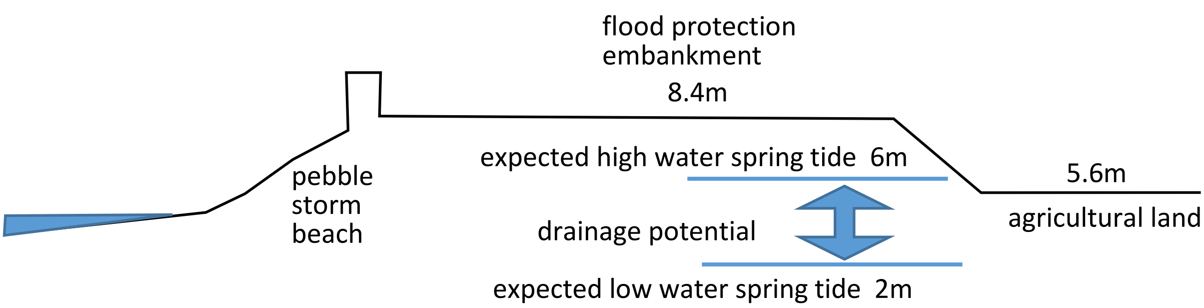


Figure 68: Heights of land components above Chart Datum

The current depth of drainage channels (e.g. fig.69) could be increased and drainage water would continue to flow towards the tidal gate at low tide. The deepening of channels would have the benefits of reducing the water table to make the land less susceptible to flooding, and would provide an increased temporary water storage capacity during storm events.

Figure 69: Drainage channel in agricultural land south of the estuary flood embankment. Photograph: K. Owen

We may conclude that the proposed flood protection scheme for Fairbourne village would not have a detrimental effect on the wider flood protection area between Fairbourne and Arthog. The ecologically important area of the Arthog Bog SSSI would be unaffected, whilst an opportunity exists for improving the drainage of agricultural land between Fairbourne and Morfa Mawddach through linking drainage to the Afon Morfa tidal gate.

7. SUMMARY OF WORKS FOR THE PROPOSED SCHEME

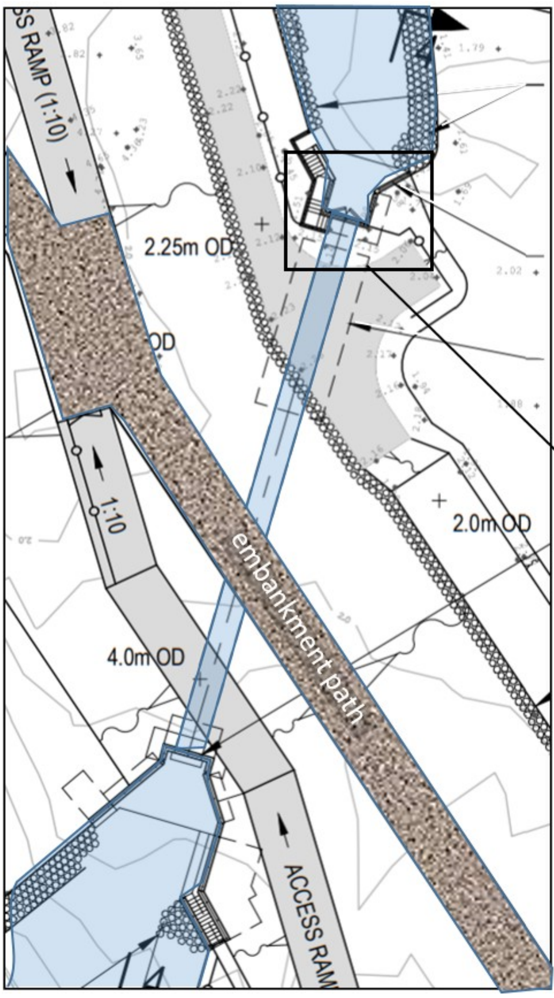
Construction sequence

1	Upgrading of the Afon Morfa tidal gate to handle larger water volumes delivered by the Afon Henddol.
2	Diversion of the Afon Henddol by construction of a new drainage channel across agricultural land to connect with the Afon Morfa tidal gate.
3	Construction of a new flood protection embankment connecting the railway embankment east of Fairbourne station to the estuary embankment east of Fairbourne golf course.
4	Clearing and deepening the area of wetland reed beds to the east of Fairbourne station to provide a flood water retention pond. The outlet from the pond will be connected to the existing drainage channel leading to the tidal gate alongside the golf course.
5	Closure of culverts through the railway embankment south west of Fairbourne station. Connection of the southern drainage ditches at Friog to the Fairbourne drainage ditch network.

Notes

1. Upgrading of the Afon Morfa tidal gate to handle larger water volumes delivered by the Afon Henddol.

The tidal gate of the Afon Morfa (fig.57) has an inlet pipe of oval cross section with principal diameters of 1000mm and 550mm, and a simple flap valve, whilst the current tidal gate of the Afon Henddol (fig.70) has a much larger inlet pipe of 2000mm diameter and a double door outlet valve (Black and Veatch, 2012). It will be necessary to upgrade the Afon Morfa tidal gate to handle the larger flow volume from the relocated Afon Henddol.



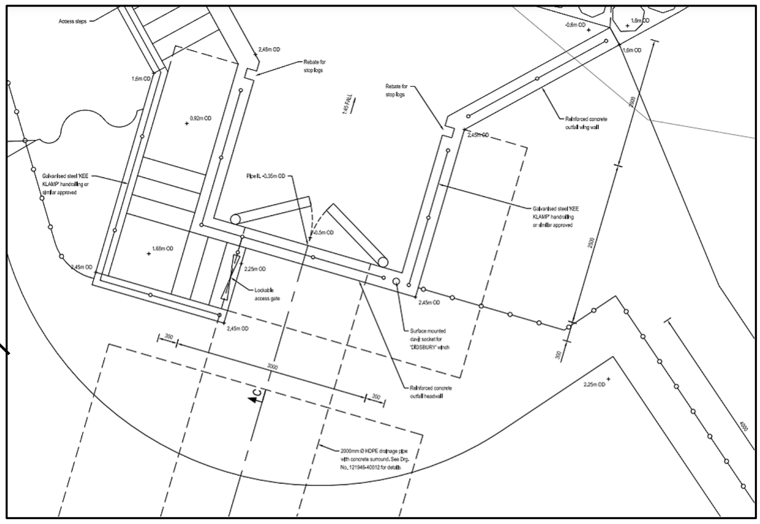


Figure 70

Design of the current tidal gate of the Afon Henddol alongside Fairbourne golf course.

It may be possible to modify the existing Afon Morfa tidal gate by upgrading the inlet pipe, or it may be preferable to construct an additional tidal gate to the higher specification at a nearby location along the estuary embankment.

The inlet area for the tidal gate should provide a deep channel as a collection area for drainage water before discharge into the estuary in the period around low tide. This should be similar to the layout of the current Afon Henddol tidal gate (fig.71).

Figure 71: Construction of the Afon Henddol tidal gate, showing the water collection channel.

2. Diversion of the Afon Henddol by construction of a new drainage channel across agricultural land to connect with the Afon Morfa tidal gate.

The excavated channel should be similar in design to the new channel created for the river alongside the railway embankment at Fairbourne station (fig.72)

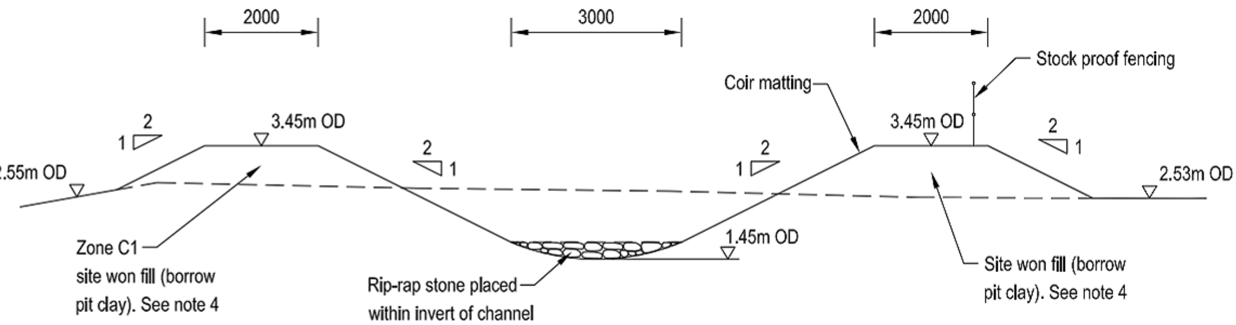


Figure 72: Design diagram for the Afon Henddol channel south of Fairbourne (Black and Veatch, 2012).

3. Construction of a new flood protection embankment connecting the railway embankment east of Fairbourne station to the estuary embankment east of Fairbourne golf course.

This new structure will have an approximate length of 700m and height of 2.5m. This would be similar in design to the estuary embankment (fig.73), but might be 2000mm in width at the crest rather than 4000mm.

The estuary embankment was constructed from clay on the seaward side and estuary sand and clay soil on the landward side. Similar materials would be available for use in the new embankment: clay from excavations for the retention pond, and sand and clay soil from the diversion of the Afon Henddol river channel.

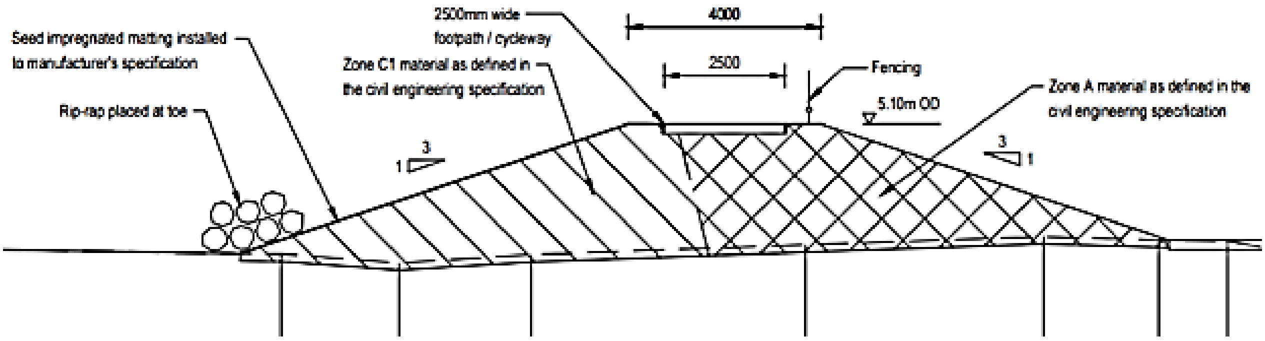


Figure 73: Design diagram for the estuary embankment (Black and Veatch, 2012).

4. Clearing and deepening the area of wetland reed beds to the east of Fairbourne station to provide a flood water retention pond. The outlet from the pond will be connected to the existing drainage channel leading to the tidal gate alongside the golf course.

The available area for clay excavation is indicated in pale blue in fig.74. The pond should have a depth of at least 3m. It should be connected to the existing outlet river channel by a concrete pipe of 1000mm diameter.

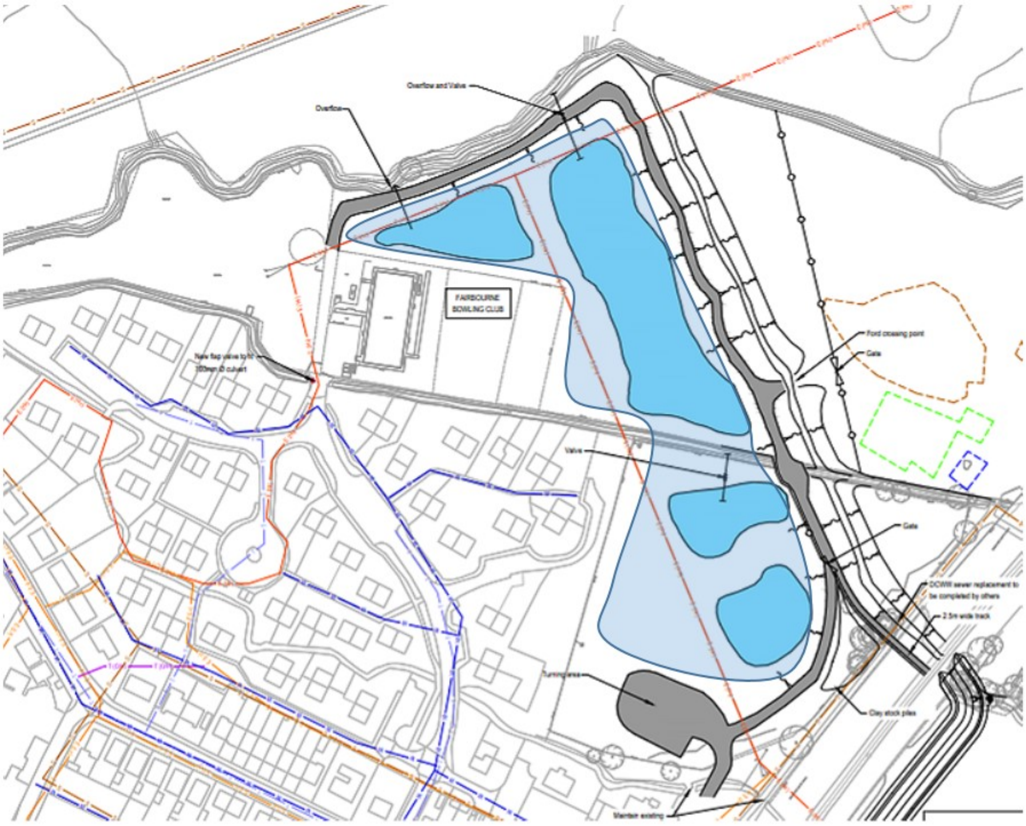


Figure 74: Available area for excavation of clay and creation of a flood water retention pond (after Black and Veatch, 2012).

Monitoring and maintenance in the period up to the year 2065 and beyond

Activity	Expected outcome	Possible intervention needed
Inspection of the sea wall between Friog and Fairbourne golf course at regular intervals and after major storm events.	The sea wall and embankment are currently in good condition and of adequate height, so no intervention should be necessary.	In the event of storm damage to the sea wall, localised rebuilding of the damaged area would be undertaken. This would follow the pattern of recent repairs at Friog. Sheet metal piles would be inserted to prevent sea water infiltration, the concrete sea wall would be reconstructed, and protected by rock armour.
Monitoring of wave overtopping during storms.	Predictions of rises in sea level and storm surge height suggest that it will be necessary to raise the height of sections of the sea wall and embankment by 1m at some time around the year 2050. Natural protection from the pebble storm beach increases northwards along the Ro Wen spit, so it may only be necessary to raise the height of the sea defences in the southern section between Friog and Beach Road, Fairbourne.	In the event of erosion of the embankment by water from overtopping waves, localised reconstruction on the landward side of the embankment may be necessary. Consideration should be given to localised raising of the sea wall height at any point where wave overtopping becomes a problem.
Monitoring of beach erosion.	Marine erosion appears to be taking place at Friog corner where the shingle spit connects to the cliffs. However, there is no current threat to the sea defences.	If marine erosion continues, wave overtopping may become a serious problem and the sea wall structure may be damaged. Before this happens, some intervention is recommended. Possible strategies to restore the beach are: direct addition of rock material, construction of groynes, or a protective offshore reef.
Inspection of the estuary flood embankment at regular intervals and after major storm events.	The embankment is currently in good condition and of adequate height, so no intervention should be necessary. Predictions of a rise in sea level and storm surge height suggest that it will be necessary to raise the height of embankment by 1m at some time around the year 2050.	In the unlikely event of overtopping or near-overtopping of the embankment at a high spring tide during an extreme storm event, the height of the embankment should be raised as a matter of urgency.
Inspection of the railway embankment at regular intervals and after major storm events.	The railway infrastructure is maintained by Network Rail. The embankment is in good condition and of adequate height, so no intervention should be necessary for flood control.	In the unlikely event of hillslope runoff endangering the railway under more extreme future storm conditions, it is expected that remedial action would be undertaken by Network Rail to raise the level of the embankment by the addition of ballast.

Inspection of the newly constructed flood embankment at regular intervals and after major storm events.	It is expected that the new embankment will be of substantial construction and adequate height, so no intervention is expected.	Repairs would be carried out in the unlikely event of erosion of the embankment faces by surface water or water seepage through the structure.
Monitoring of the operation of estuary tidal gates.	It is expected that self-operating tidal flaps will be effective in preventing the inflow of estuary water at high tide, whilst allowing outflow at low tide. River and estuary sediment may accumulate around the tidal gate structures. This sediment should be cleared when necessary, to ensure unobstructed operation of the gates.	Leakage of estuary water through the tidal gate could possibly occur, creating a risk of flooding within the Fairbourne protection area. Should this occur, the tidal flap could be replaced by an electrically operated gate valve which would close automatically in response to tidal rise, and only open when safe to do so at low tide.
Monitoring of the internal drainage network.	Periodic clearance of vegetation and sediment will be necessary for the drainage ditches, culverts and the flood water retention pond. It is expected that outflow to the estuary will occur by gravity flow through the channel network.	If surface water flooding is observed in any area of the village, the drainage system should be enlarged or deepened to prevent a recurrence. If it is found that outflow to the estuary cannot be achieved by gravity flow alone under future more extreme storm conditions, then pumping should be introduced. Options exist to generate the necessary electrical energy locally by renewable wind or tidal power.

8. CONCLUSIONS AND RECOMMENDATIONS

It would be technically feasible to protect the village from further flooding until the year 2065 and well beyond. The cost should be reasonable, as most of the required infrastructure is already in place and in a good state of repair.

Flood modelling for the period up to the year 2065 should allow for a sea level rise of 0.5m compared to the present day, and a possible storm surge height of 2.5m to allow for increased storm intensity due to climate change.

The flood models for Fairbourne published by Royal Haskoning (2012) and Robbins (2011) are considered to now be invalid. The models take no account of the flood alleviation scheme carried out by Natural Resources Wales in 2016 which has very significantly reduced the flood risk from the Mawddach Estuary and from the Afon Henddol.

The village of Fairbourne remains at some risk of flooding from rivers and streams which descend from the hills and cross the coastal lowland to reach the estuary. A new flood protection boundary is proposed for Fairbourne which would exclude the Afon Henddol and other streams, eliminating the risk from river flooding. The proposed flood protection boundary would be made up from the existing sea defences and estuary embankment, the railway embankment, and a new section of embankment which would be constructed across agricultural land between the railway and the estuary.

The majority of the proposed flood protection area in and around Fairbourne village is underlain by estuary deposits of mixed sand and clay. This material drains reasonably well after a rain storm, so surface water flooding is not a problem. Modelling by Buss (2018) predicts that the extent of surface water flooding is unlikely to increase in the period up to and beyond 2065. A small area in the south of the proposed flood protection area at Friog is underlain by peat. This material has poor drainage properties and is likely to become waterlogged after heavy rain. The area is currently occupied by a mobile home park. If an opportunity exists to relocate the mobile homes to a field further north underlain by estuary sand and clay, it is recommended that this is done.

The ground elevation of Fairbourne village and the surrounding agricultural land is approximately at the level of the maximum spring tide. This is not of immediate concern, since the storm beach and sea wall extend for 4.5m above this level, and the estuary embankment extends for 2.8m above this level. These structures currently provide adequate protection for the village against sea and estuary flooding.

The Ro Wen shingle spit in front of Fairbourne village is currently stable. Observations and modelling by Phillips et al.(2017) predict no significant changes to the storm beach profiles up to and beyond the year 2065.

To the south of Fairbourne village at Friog corner, coastal erosion has actively eroded the storm beach. This led to the failure of the sea wall and inflow of sea water. The sea wall has now been repaired and substantially strengthened by Natural Resources Wales, and is providing effective protection from flooding. However, there is a continuing problem of coastal erosion at this location. It is recommended that actions be taken to reduce or prevent erosion by the regular addition of rock material in front of the sea wall, or by the construction of beach groynes or an offshore reef to encourage natural deposition of beach sediment.

Overtopping of the sea wall by storm waves is not a significant problem, and is seen only to the south of Fairbourne village. Further north, the storm beach is better developed and provides effective natural protection against storm waves. Modelling indicates that this situation is unlikely to change in the period up to and beyond 2065. In the unlikely event that climate change leads to storm wave overtopping in front of Fairbourne village, it would not be a major engineering task to locally raise the height of the sea wall by a modest amount such as 1m.

The estuary embankment to the north of Fairbourne village has recently been reconstructed by Natural Resources Wales, and provides good protection from estuary flooding. Modelling indicates that the embankment height will be adequate up to the year 2065, but sea level rise may then require the height to be raised by 1m to ensure that no overtopping will occur.

The south eastern boundary of the proposed Fairbourne flood protection area would be formed by the embankment of the railway. Although descending to only 2m above the elevation of Fairbourne village, modelling indicates that this would be adequate to prevent any inflow of water from the surrounding fields. The Afon Henddol runs alongside the railway embankment for part of its course in a large channel constructed during the 2016 flood alleviation work, and at other points the river banks have been raised and strengthened. The river is not expected to present any flood risk to Fairbourne village.

Between Friog and Fairbourne, four small culverts carry streams underneath the railway embankment. In the proposed scheme, these culverts should be blocked to prevent any risk of flood water inflow to Fairbourne village during a storm.

Work would be carried out to construct a new embankment to the east of Fairbourne village, linking the railway with the estuary embankment. For part of its course, this would run alongside a series of flooded pits, dug during the 2016 flood alleviation scheme to provide clay for the construction works. The new embankment would have a similar height and profile to the estuary embankment.

The Afon Henddol would be re-routed across agricultural land to the east of Fairbourne to reach the existing tidal gate of the Afon Morfa. This gate allows discharge of river water at low tide, but closes to prevent inflow of estuary water when the tide rises. It will be necessary to increase the capacity of the tidal gate to allow for the higher volume of flow of the Afon Henddol. This might be done by reconstructing the existing estuary outfall, or by building an additional floodgate through the estuary embankment nearby.

The Fairbourne flood protection area will generally be isolated from surrounding bodies of water, but water may enter due to direct rainfall or occasional overtopping by sea waves during a storm. This water will be conducted through the existing network of drainage ditches in and around the village, to reach the tidal gate alongside the golf course where it will discharge at low tide into the estuary. The tidal gate will have more than adequate capacity up to 2065 and beyond, since it was designed to handle much larger flow volumes from the Afon Henddol.

It is proposed that the area of clay pits alongside the new embankment will be developed as a water retention pond. This would act as a buffer for temporary storage of flood water during periods of high tide when discharge into the estuary is not possible. The retention pond would be connected directly to the existing drainage ditch network.

Modelling indicates that the current network of drainage ditches, linked to the water retention pond, would allow the effective discharge of water into the estuary through the flood gate under the worst case storm conditions predicted for 2065. No surface water flooding is expected within the village or surrounding fields.

Excavation of the water retention pond will provide clay, whilst excavation of the new channel for the Afon Henddol to the tidal gate will provide sand and clay estuary deposits. These materials should be suitable for use in the construction of the new flood embankment.

9. DISCUSSION

Modelling indicates that the proposed flood protection scheme will work effectively up to and beyond the year 2065. However, it is recommended that regular monitoring of all aspects of the hydrological system is carried out, so that any necessary remedial action can be carried out quickly.

Calculations indicate that water from a worst case storm event could be discharged into the estuary by gravity flow alone. However, the option exists to increase the rate of water transfer by pumping if this should prove necessary.

If pumping is necessary, it would be an advantage if this could be carried out by means of electricity generated locally from renewable sources. An on-shore wind turbine would be a relatively cheap and reliable option, although there may be a reluctance to allow a wind turbine in the Snowdonia National Park due to intrusion on the landscape. An off-shore wind turbine may be an acceptable alternative; the sea bed is fairly shallow offshore from Fairbourne and Barmouth so construction should not be a problem. An opportunity also exists to site an electric generator on the sea bed around the mouth of the Mawddach estuary. Computer modelling has shown that water flows reach high velocities at the period of maximum inflow on a rising tide (Hall, 2008).

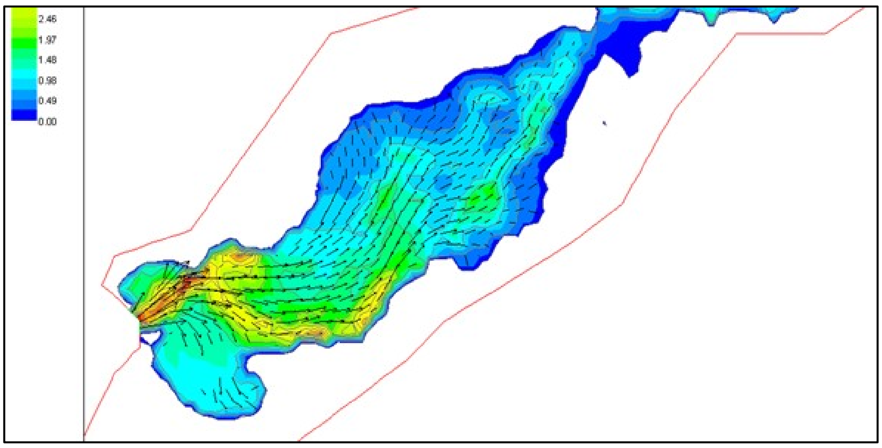


Figure 75

Water flow vectors for the Mawddach estuary between Barmouth and Penmaenpool: maximum inflow on a rising tide.

A number of designs of generator are available or being developed (fig.76) which could be secured to the sea bed at a depth where they would not present a hazard to boats using the estuary.

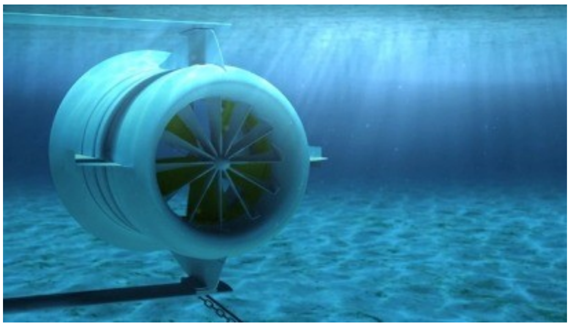


Figure 76(a)

Fixed underwater turbine for electricity generation.

Figure 76(b)

Underwater turbine tethered to the sea bed by cable and free to move in the water current.

After undertaking the current study, it has become apparent that the decision to decommission the village of Fairbourne has been based on misleading information from previous flood modelling:

There have been a number of cases of serious flooding or damage in Wales from coastal storms in recent years, for example: in Tywyn near Abergele (fig.77) and in Aberystwyth. Repairs to the coastal railway line were necessary north of Barmouth due to severe storm damage. However, during this period there has been only minor flooding of land around Fairbourne and this can be attributed to seepage through the damaged sea wall which has now been repaired. Fairbourne occupies a relatively sheltered position below the headland of Friog, and has a high degree of natural protection from the large shingle storm beach of Ro Wen.

Figure 77

Flooding at Tywyn near Abergele.

It should be noted that a major coastal protection scheme is being implemented nearby at the village of Borth, which occupies a similar site on reclaimed land behind a shingle spit at an estuary mouth (fig.78). There is no plan for Borth to be decommissioned.

Figure 78: Borth

A brochure entitled 'Fairbourne: A Framework for the Future' was published in 2019 by the Fairbourne Moving Forward Partnership. It is of concern that this document contains a number of misleading statements as a justification for abandoning Fairbourne.

> "Fairbourne is built on very low lying land, even when compared to other coastal communities. The land level within the village is generally between 2 and 2.5m above sea level; this compares to 3.5 to 4.5m above sea level for the most vulnerable part of Barmouth while Aberystwyth's promenade is generally higher than 6m above sea level."

This statement seems to demonstrate a basic misunderstanding of wave action at sea walls:

The overtopping of sea walls by storm waves has been modelled by Pu & Shao (2012). The volume of sea water projected over the sea wall is dependent on tidal and wave height, and the nature of the sea wall. The modelling predicts a wave run-up and smooth overtopping where the wall slope is gentle, but conversion to a vertical plume of spray where a vertical wall is encountered.

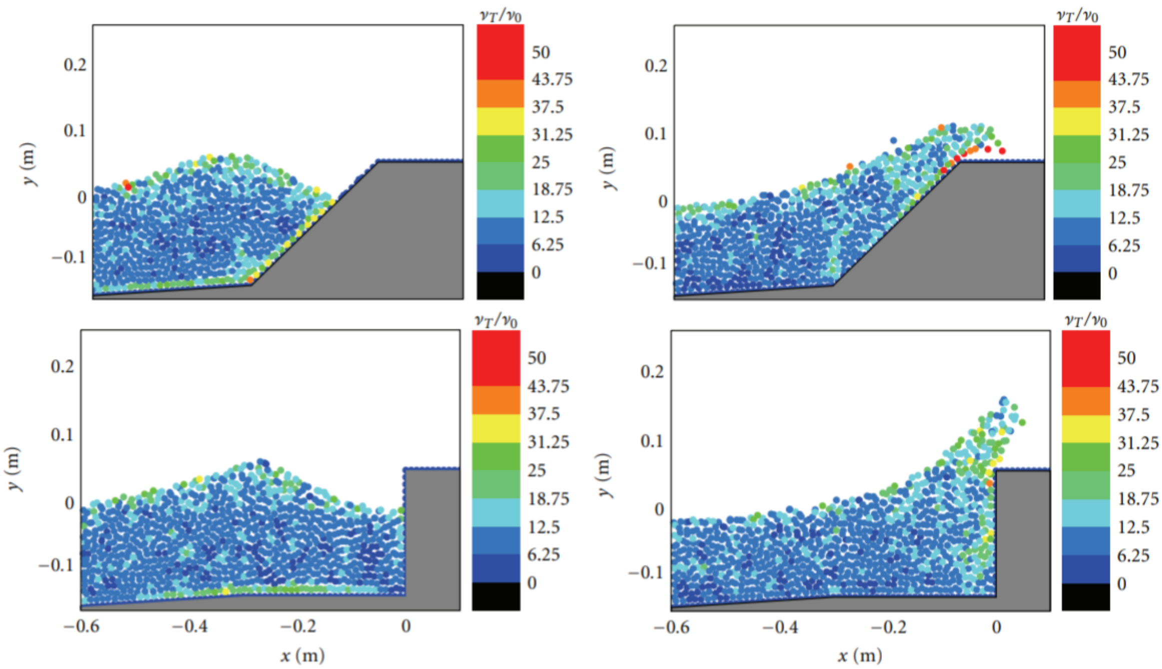


Figure 79: Models for the overtopping of sea walls by storm waves.

Simple overtopping of the sea wall occurs around Barmouth harbour and in surrounding streets under very high tide and storm surge conditions (fig.80).

Figure 80

Flooding around Barmouth harbour and neighbouring streets.

At Aberystwyth, the direct impact of storm waves on the vertical sea wall creates vertical columns of water. The sea wall and promenade can be damaged by mechanical impact of waves.

Figure 81

Storm waves hitting the sea wall, Aberystwyth.

However, the situation at Fairbourne is quite different. Where waves impact on a permeable structure, water enters the structure rather than travelling up and over it.

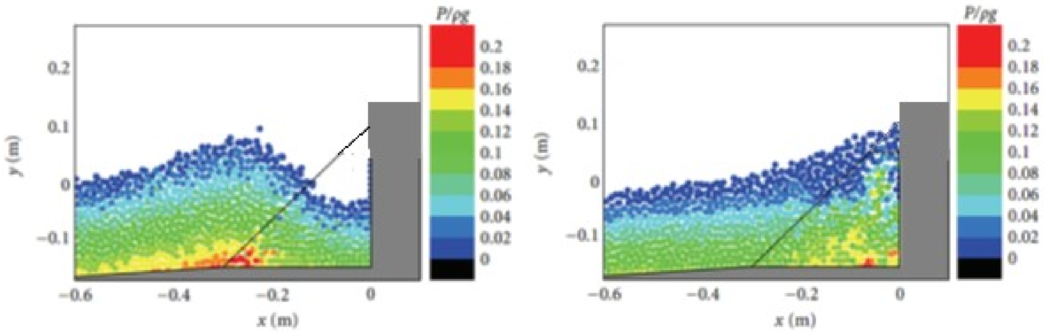


Figure 82: Model for the impact of storm waves on a permeable structure.

The storm beach at Fairbourne is of this type. Breaking waves are largely absorbed into the shingle, and there is little likelihood of waves travelling over the top of the shingle bank.

Figure 83

Shingle storm beach, Fairbourne.

The brochure 'Fairbourne: A Framework for the Future' contains the diagram reproduced in fig.84. This purports to show the flood risk to properties in Fairbourne village, and seems to imply that a catastrophic failure of the sea defences is possible and would cause flooding of homes up to roof level.

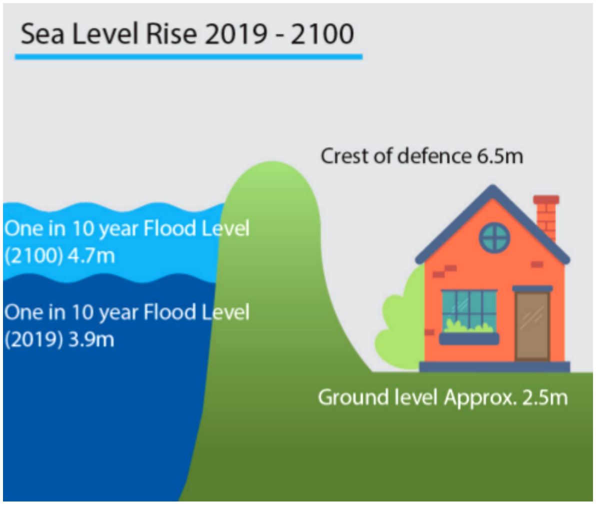


Figure 84

Flood risk diagram from the publication: 'Fairbourne: A Framework for the Future'.

The brochure goes on to make the statement:

> Risk to life from flooding
> There is a significant and increasing risk that a coastal or estuary defence breach could cause a sudden surge of floodwater with little or no warning. The fact that Fairbourne is home to a high proportion of retired and older residents living in bungalows significantly increases this risk, as does the fact that the village is a popular tourism hotspot with most holiday-makers unlikely to be aware of the flood risk and evacuation procedures.

The diagram and statement are misleading, as a coastal or estuary defence breach is extremely unlikely. Contrary to the diagram above, the true cross section of the storm beach and sea wall in front of Fairbourne village is as shown in fig.85 below. High water levels at spring tides, with added storm surge as predicted for the year 2065, are shown.

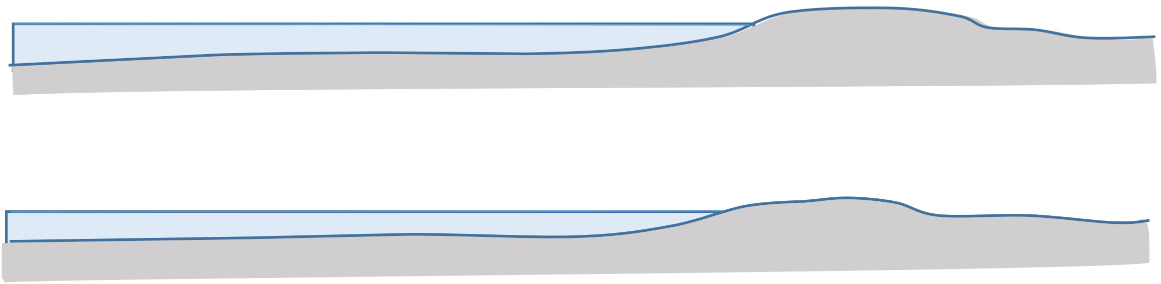


Figure 85: True scale cross sections of the Ro Wen spit at Fairbourne.

Figure 86: View along the Ro Wen spit, Fairbourne showing the considerable width of the storm beach and landward embankment.

The estuary embankment (see fig.73) is a very substantial gravity dam structure. Modelling has shown that there is little chance of sea waves or estuary water overflowing or damaging these structures, and any slight risk that develops could be mitigated by raising the embankment levels by the small amount of 1m.

REFERENCES

Black and Veatch (2012) Fairbourne FRMS As-built drawings. Environment Agency Wales.

Buss, S. (2018) Fairbourne: modelling future risk of groundwater flooding. Stephen Buss Environmental Consulting Ltd, Shrewsbury.

Chen, J. L., Ralston, D. K., Geyer, W. R., Sommerfield, C. K., & Chant, R. J. (2018). Wave generation, dissipation, and disequilibrium in an embayment with complex bathymetry. *Journal of Geophysical Research: Oceans*, *123*(11), 7856-7876.

Fairbourne Moving Forward Partnership (2019) Fairbourne: A Framework for the Future. Gwynedd County Council.

Hall, G. (2008). An Integrated Meteorological / Hydrological Model of the Mawddach Catchment, North Wales. PhD Thesis, Bangor University.

Hall G. and Cratchley R., (2015). Flood forecasting for the Mawddach catchment, North Wales. Proc. 3rd IMA International Conference on Flood Risk, Swansea.

Haskoning (2012). West of Wales Shoreline Management Plan 2-Cardigan Bay and Ynys Enlli to the Great Orme Coastal Groups. *Haskoning UK, Peterborough*.

Haskoning (2018). Technical Group Overview Report: the Technical Summary of Impacts of Changing Risk at Fairbourne. *Haskoning UK, Peterborough*.

Johnson A. (2021) Borth coastal protection scheme. Royal HaskoningDHV.

New Civil Engineer (2018) Facing Down the Floods. www.newcivilengineer.com

Owen, K. (2010) Fairbourne flood alleviation scheme: ground investigation programme report no. 877. Environment Agency.

Phillips, M., Thomas, T., Morgan, A. (2017) Flood and Coastal Erosion Risk Management: Fairbourne Going Forward coastal processes, beach profiles and aerial photographs assessment of change. University of Wales Trinity Saint Davids.

Pu, J. H., & Shao, S. (2012). Smoothed particle hydrodynamics simulation of wave overtopping characteristics for different coastal structures. *The Scientific World Journal*, *2012*.

Robins P.E. (2011) Application of TELEMAC-2D and SISYPHE to complex estuarine regions to inform future management decisions. Researchgate.

Steffler, P., & Blackburn, J. (2002). Two-dimensional depth averaged model of river hydrodynamics and fish habitat. *River2D user's manual, University of Alberta, Canada*.

Thompson, D. A., Karunarathna, H., & Reeve, D. E. (2017). Modelling extreme wave overtopping at Aberystwyth Promenade. *Water*, *9*(9), 663.