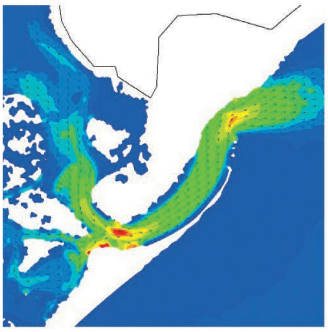
Arup

# Rhymney Polders

## Coastal Process Study to Support Design Development

September 2023

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# Document Information

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**ABPmer**
Quayside Suite, Medina Chambers, Town Quay, Southampton, Hampshire SO14 2AQ
T: +44 (0) 2380 711844 W: http://www.abpmer.co.uk/

# Executive Summary


ABPmer is providing coastal process and habitat creation support to Natural Resources Wales (NRW) in the development of a Polder scheme along the Rhymney Great Wharf frontage, Cardiff.

Having undertaken an initial review of the information to date, ABPmer and Arup has recommended that the project completes a coastal process assessment to develop an outline design. This design development study has completed a data gathering and literature review to document the baseline understanding of the coastal processes, and utilised a number of coastal process analysis tools, including numerical wave and hydrodynamic modelling, to identify a preferred Polder alignment. Arup and the wider team will use the outputs of the study to create the Outline Design necessary to support the licensing and construction of the scheme.

This design development study has:

- Produced a comprehensive conceptual understanding of the coastal processes operating along the Rhymney Great Wharf frontage using publicly available data and information along with utilising previous ABPmer studies:
- Reviewed information gathered by NRW on other Polder projects, principally in the Wadden Sea:
- From the above, drawn together the technical, environmental and habitat creation considerations for a Polder design:
- Completed topographic and geometric analysis of the frontage:
- Utilised an existing hydrodynamic model of the Severn Estuary, refined for the Rhymney Great wharf frontage, to provide an understanding of the likely flow regime within the Polders over a representative high tide:
- Refined an existing spectral wave model of the Severn Estuary to complete a number of tests of different Polder alignments in order to understand how the Polders operate under different wave and water level conditions: and
- Developed, tested and reviewed five different Polder alignments.

The study has shown that there is significant uncertainty associated with the viability of the Polders with respect to their survivability and potential to create established saltmarsh. If the project was to proceed, the Polder fields should be aligned such that the crest of the Polders are as close to Mean High Water Springs as possible to afford the greatest protection from sediment resuspension/erosion from waves. Five alignment options were developed and tested. Based upon the analysis, and recognising that there remains significant uncertainty in the likelihood of success, the following could be considered as a trial along the frontage:

- Installation of polders along alignment 3d to 3g; and
- Extension of Polder 4 and Polder 5 to 4 mODN.

The polders will require a high level of maintenance/intervention throughout the project period, and it is likely that the brushwood will be frequently damaged during storm events. The installation would need to be accompanied with a programme of maintenance for at least 25 years in order for saltmarsh to become established (and the benefits realised) along with an associated monitoring programme.

# Contents

## Appendix



## Tables



## Figures

# 1 Introduction

## 1.1 Background

ABPmer is providing coastal process and habitat creation support to the Arup/Natural Resources Wales (NRW) team in the development of a Polder scheme along the Rhymney Great Wharf frontage, Cardiff. The specification is required to implement the option set out in the Rhymney Great Wharf Saltmarsh Restoration / Enhancement Feasibility and Preferred Option Studies (March 21). This report recommended repair of old Polders and extension of the Polder fields as 'likely to be technically feasible, sustainable and have low impacts on the existing environment'. However, it also identified that:

- Analysis of available data indicated that the old Polders were able to trap substantial amounts of sediment. There was however considerable uncertainty about how much exactly they may have helped, or indeed how long the brushwood stayed, due to no monitoring or maintenance having been undertaken after the Polders were installed; and
- The conclusions ware based on a series of high-level assumptions. Residual uncertainties remained which needed to be recognised and addressed during any subsequent project stages in the development of a strategy for the Rhymney frontage.

Notwithstanding the noted uncertainties, the study concluded that the intertidal habitats at Rhymney Great Wharf would continue to rapidly decline without intervention, and that there were viable, if expensive, avenues for slowing this decline. The study recommended small scale trials to help reduce uncertainty. The feasibility report provided high level costings associated with the project, but it did not produce an outline design for the frontage.

To manage costs and programme associated with the consenting, NRW has identified that the most appropriate way forward is to proceed with the full implementation of the Polder project along the frontage. Arup and ABPmer have been commissioned to support NRW through the design development and consenting stage. The programme is for construction of the Polders to commence in July 2024.

Having undertaken an initial review of the information to date, ABPmer/Arup has recommended that the project first completes a coastal process assessment to further develop the design. Arup will use this to create the Outline Design necessary for the target cost setting and confirmation of the appropriate consenting route. This design development study utilises a number of coastal process analysis tools, including numerical wave and hydrodynamic modelling, to identify the following:

- Recommended positions for the Polders along the frontage in the context of the tidal geometry;
- The potential level of protection afforded to the mudflat by the Polders, how the Polders will aid accretion and protect the mudflat/saltmarsh over a normal tidal cycle;
- The current and residual level of exposure from wave action and the potential risk to saltmarsh creation; and
- The likelihood of success and risks associated with the project meeting the Business Justification Case outcomes.

This report documents the conclusions and recommendations for the Polder design. It is understood that NRW is intending the project to also include supporting 'trials' which will focus on the design details such as the design of the brushwood fencing, internal baffles and drainage channels and potential alterations to the height of the brushwood fencing. The project team will look to work with NRW to develop these design details as the project progresses, in parallel with the consenting programme.

# 2 Methodology

## 2.1 Introduction

This study supports the conceptual understanding of physical processes along the frontage and reviews the performance of various options for the development of an outline design for new Polders at Rhymney Great Wharf. The study has:

- Collated existing information on Polder projects in Germany and the Netherlands, including that provided by NRW;
- Collated existing information on the coastal processes operating in the Severn Estuary, focusing on the Rhymney Great Wharf frontage (known as a conceptual understanding);
- Identified the key considerations for the suitability and use of Polders along the frontage;
- Completed a number of high-level assessments and numerical model tests to review the current Polder alignment; and
- Identified and tested alternative Polder alignments/configurations to help identify a preferred option.

The simulations initially assessed the potential effects of reinstating the Polders along the existing alignment on currents and waves, in order to understand the potential effectiveness of the original project, if it had been maintained.

Based upon the simulations, along with the conceptual understanding of the coastal processes and analogues from other sites, the project team identified four Polder options for testing in the models.

The following sections outline the different analysis undertaken. The different tools and polder representations, have been defined to maximise the general understanding of their effects on coastal processes which allows the team to apply the knowledge gained in the development of the design as the project progresses. The analysis is not intended, therefore, to provide a true representation of the functioning of the original scheme.

## 2.2 Geometric analysis

An assessment of the geometry of the shoreline was undertaken using LiDAR datasets collected between May 2005 and November 2022 and available through DataMapWales. The following datasets were used:

- May 2005 - full coverage;
- January 2011 - partial coverage of the Polder field and eastern shoreline;
- February 2012 - partial coverage of the Polder field and eastern shoreline;
- February 2015 - full coverage; and
- November 2022 - full coverage.

The change in shoreline geometry between these five surveys was reviewed in both 2D (spatial) and 1D (cross sections), assessing the change in topography since the construction of the five polders at Rhymney Great Wharf. This analysis was aimed at reviewing the relationship between the location of the Polders in the tidal frame and bathymetric change (i.e., the historic success of these Polders in retaining sediments in the upper foreshore).

When considering the results of the analysis it is important to note that the Polders were not maintained since their installation and therefore the results should be considered indicative of the potential for sediment accumulation.

## 2.3 Hydrodynamic modelling

As part of this study, a 2D hydrodynamic (HD) model of Rhymney Great Wharf and the surrounding area was utilised to facilitate the assessment of hydrodynamic flows and support the review of hydrodynamic conditions in the vicinity of the Polder field.

To address this requirement, a detailed hydrodynamic model has been constructed by ABPmer using the Danish Hydraulic Institute (DHI) software package MIKE21 FM (Flexible Mesh). The modelling system was developed for complex applications within oceanographic, coastal and estuarine environments and allows accurate representation of water level variation and two-dimensional flow fields within an area of interest.

### 2.3.1 Model configuration

This section of the report provides a description of the hydrodynamic model, developed for this assessment. It details the validation process undertaken to demonstrate that the flow model produces a representative simulation of the existing processes and the impact of Polders on sedimentation conditions in the vicinity of the Polder fields.

The model has been used to assess the impact of the potential development of Polder options ton he retention of sediments in the lee of the Polders, and specifically on bed shear stresses.

#### Mesh design and bathymetry

This project has benefitted from ABPmer's existing HD model of the Severn Estuary and Bristol Channel region, which has previously been used for a number of projects, including the Coastal Impact Studies (CISs) for the Culver and Culver Extension aggregates dredging applications (ABPmer, 2013 and ABPmer, 2016a), as well as the CIS for the Area 531 (North Bristol Deep) application (ABPmer, 2019b).

The mesh has been designed using a FM to simulate conditions in two dimensions (2D), depth-averaged mode. This approach enables the necessary detail of the Severn Estuary, including the Polders at Rhymney, to be sufficiently resolved (5 m node spacing) within the model, while maintaining a coarser resolution away from the site of interest to maximise computational efficiency. The grid configuration of the HD model is shown in Figure 1 for the model domain, along with the Rhymney Great Wharf frontage as Figure 2.

The offshore boundary extents are designed to adequately capture the tidal approaches to the Severn Estuary. The extent of the model domain is defined by the following boundaries:

- Northern boundary: Across Caernarfon Bay from the Lleyn Peninsula (Wales) to Wicklow (RoI);
- Eastern inshore boundary: Upper Severn Estuary at Awre;
- Southern offshore boundary: Offshore, perpendicular to the southern Cornish coast; at Rame Head; and
- Western offshore boundary: Perpendicular to Baltimore on the southern Irish coast.

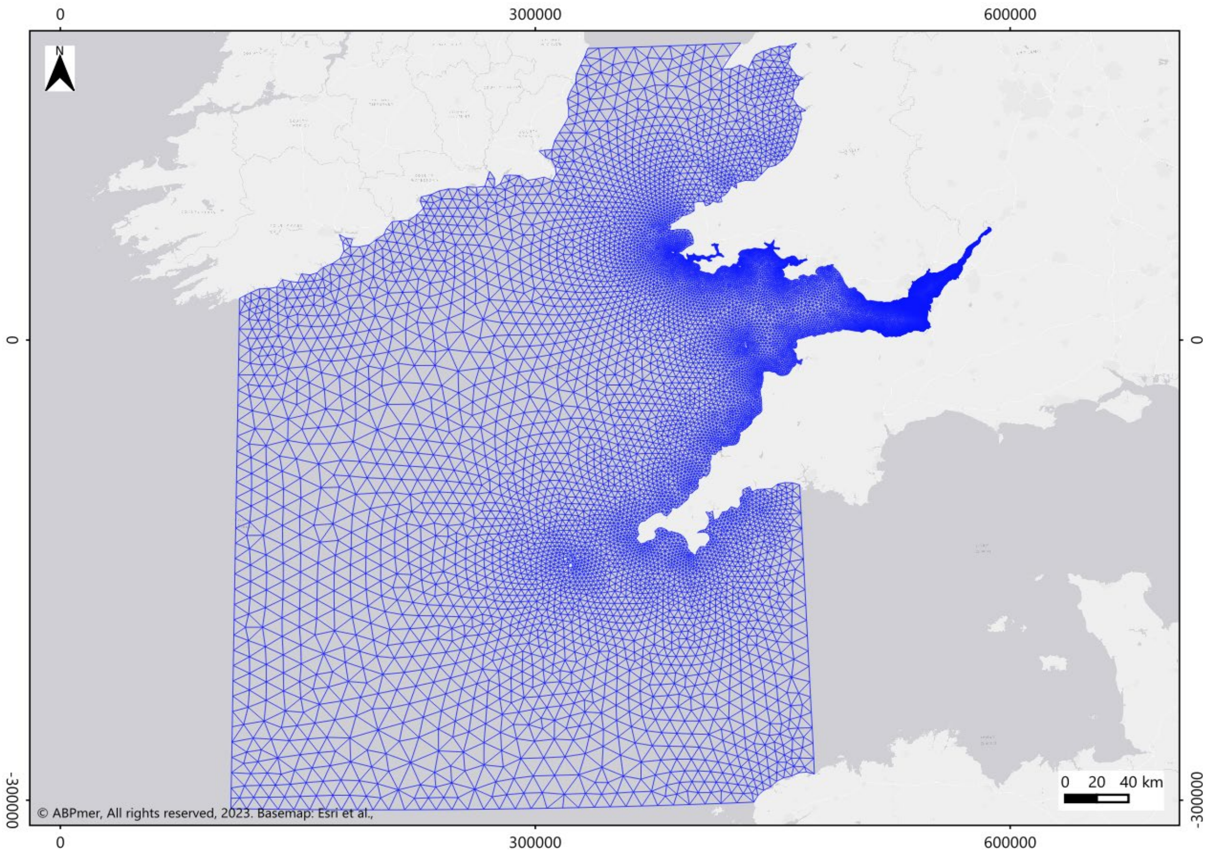



**Figure 1. Hydrodynamic model grid across the domain**

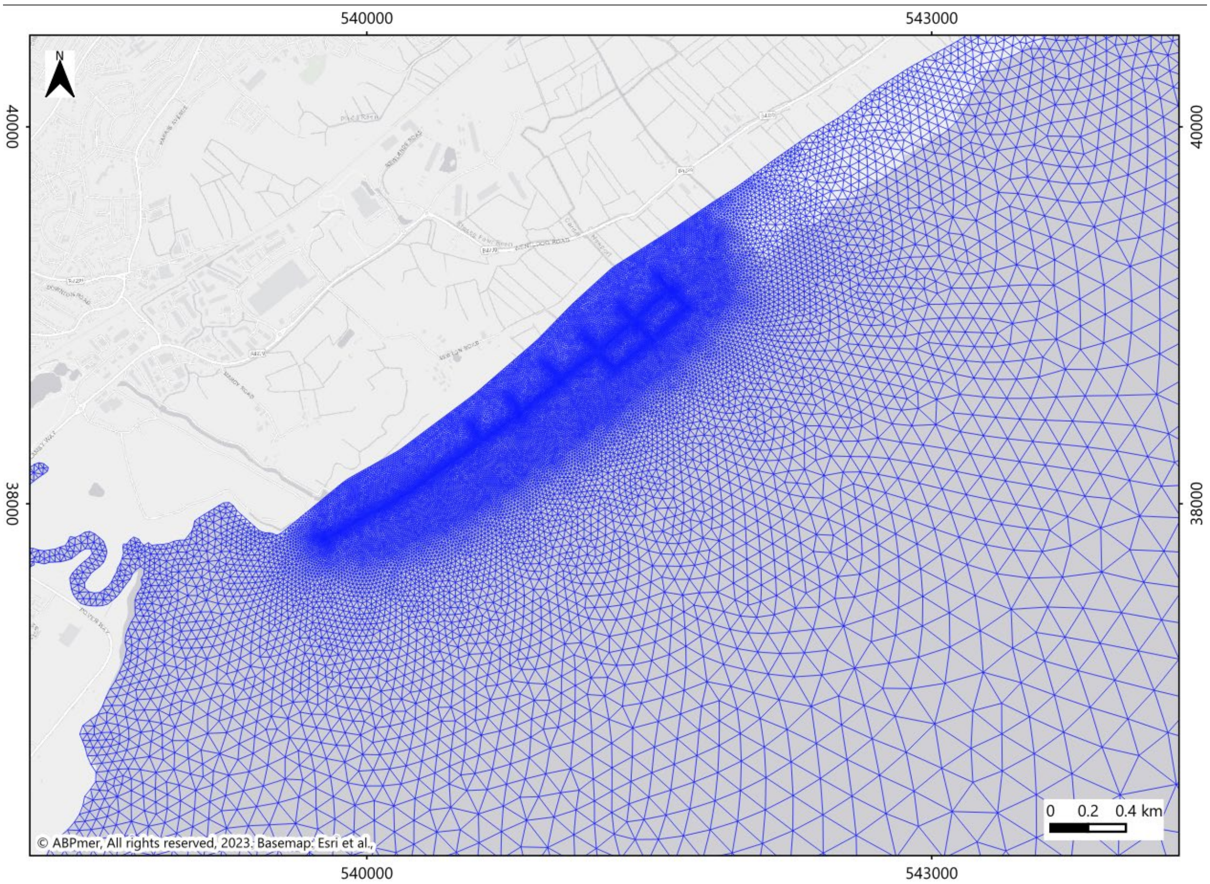



**Figure 2. Model grid representation at Rhymney Great Wharf**

Bathymetry data across the model domain is provided from the following sources:

- NRW 2022 terrestrial LiDAR DTM: Flown in November 2022 and extending down to -3 m Ordnance Datum Newlyn (ODN), this is available through DataMapWales (NRW 2022). This terrestrial DTM (Figure 12) has good representation of the intertidal foreshore and was used to represent the foreshore at Rhymney and the surrounding areas. Areas set back from the coastal frontage or defended from inundation were not included in the model.
- UK Hydrographic Office (UKHO) (Admiralty Surveys): Surveyed bathymetry data from around the UK coastline are available via the UKHO. Its database was searched for DTM datasets covering the mid and outer Severn Estuary from 2015 or later for inclusion in the model mesh. 56 bathymetric surveys were used. DTM data within the upper estuary was not readily available. To resolve this, two additional point depth surveys of the upper Severn Estuary from 2006 were also identified and interpolated to the model mesh.
- EMODnet 2020 DTM: This is an elevation model created by combining data from a wide range of European bathymetry repositories (including the UKHO). Datasets come from a selection of remote sensing techniques, including multibeam and single-beam echo soundings, satellite altimetry, and airborne lidar. This dataset was available at approximately 75 m resolution in the vicinity of Rhymney Great Wharf and was utilised where no other survey data are available.

Each bathymetry dataset was referenced to the same vertical datum, taken as Mean Sea Level (MSL). This datum was selected as it was the most relevant to model boundary conditions. Having concatenated the datasets, the bathymetry data were interpolated across both the hydrodynamic and wave model meshes.

### Representation of flooding and drying

Flooding and drying was included within the model setup, as this is an important consideration within the Severn Estuary due to the large tidal range and extensive intertidal areas. The settings used are defined in Table 1 below.

When the water depth is less than the wetting depth the model makes a further calculation. If the water depth is less than the drying depth, the element is removed from the calculation for that timestep within the model simulation.

The flooding depth is used to determine when an element is flooded (i.e., re-entered into the calculation). Consequently, any element within the model grid with a water depth less than 0.005 m at any point during the model simulation period will be considered as dry.

**Table 1. Flooding and drying depths**

| Parameter | Depth (m) |
|---|---|
| Drying depth | 0.005 |
| Flooding depth | 0.05 |
| Wetting depth | 0.1 |

### Bed roughness

Bed roughness in the model has a large influence on the way in which the water moves through a particular area, affecting both tidal range and phasing, as well as the speed and directions of tidal currents. It describes the friction from the seabed ‘felt’ by moving water and is therefore a key parameter in the model calibration process.

The existing bed roughness map for the Severn Estuary Model (which has been calibrated and validated for previous studies) has been used for this study. Manning's *M* was selected as the bed resistance type, and the map varies bed roughness based on the classification of bed substrate and depth.

### 2.3.2 Validation checks

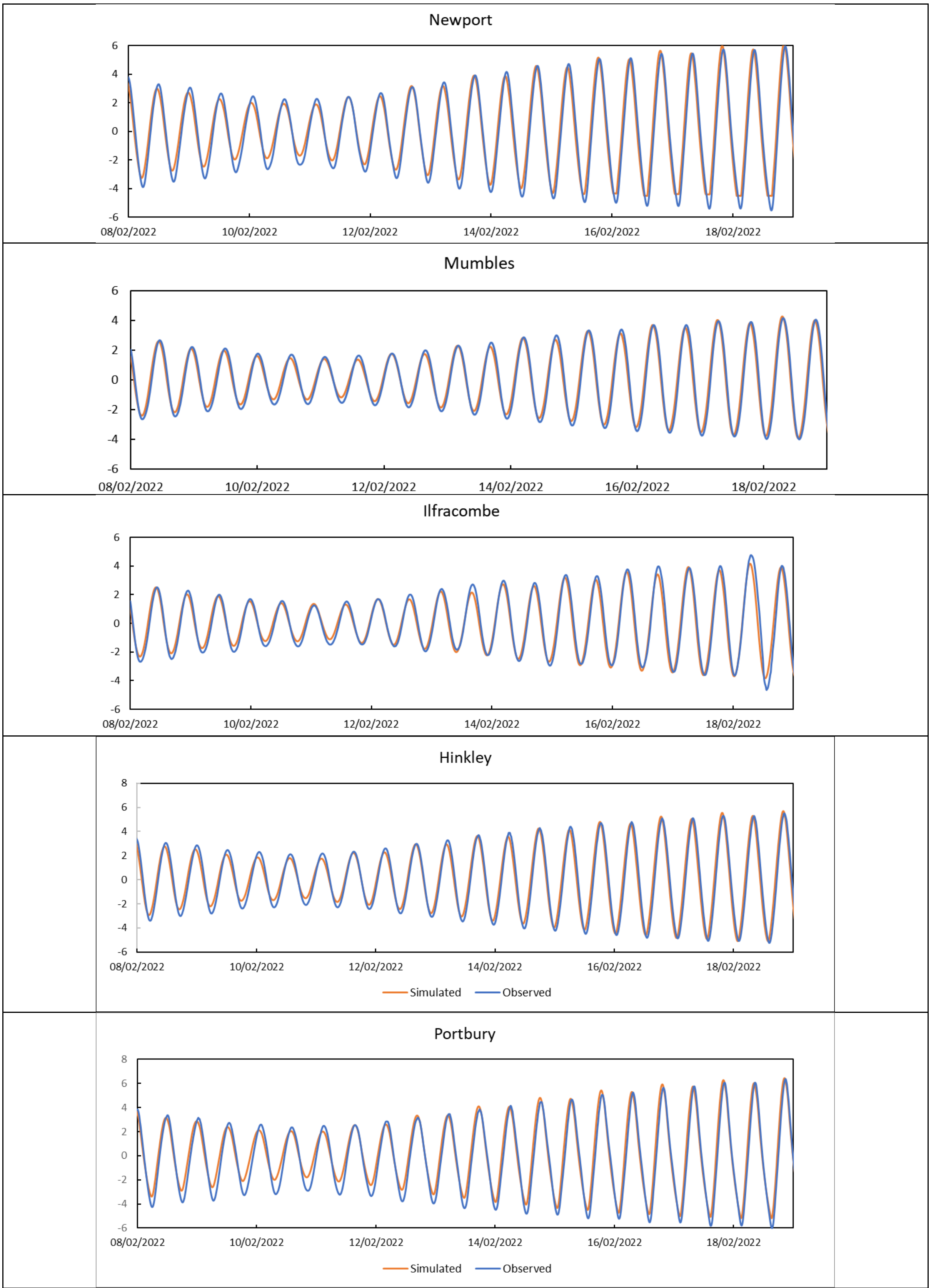
The HD model was validated against available National Tide and Sea Level Facility (NTLSF) tide gauge data available in the vicinity of Rhymney (Newport, Portbury, Mumbles, Hinkley and Ilfracombe). This comparison outlines that the model performs well, generating good agreement between the simulated and observed conditions, accurately predicting the timing and the magnitude of the observed tidal wave over a representative two-week simulation period. Details are outlined below in Figure 3..

The water level timeseries comparison between modelled and observed, presented in Figure 3 outline that the modelled conditions closely replicate the observed conditions at the validation locations, particularly at Newport, the closest location to Rhymney Great Wharf.

Based on this comparison, the model is considered to accurately replicate the timing (less than 15 minutes) and magnitude of high water (by -0.04-0.07 m) at the sites assessed. Based on this and the low root mean square error (RMSE) and mean absolute error (MAE) scores simulated (Table 2), particularly at Newport, the model performance is considered very good for its application in the assessment of the polders at Rhymney.

**Table 2. Model performance statistics at NTLSF gauges for simulation period**

| | Hinkley | Ilfracombe | Newport | Mumbles | Portbury |
|---|---|---|---|---|---|
| Mean Bias (m) | 0.09 | -0.03 | 0.20 | 0.08 | 0.39 |
| RMSE (m) | 0.41 | 0.33 | 0.35 | 0.23 | 0.57 |
| RMSE as % | 3.7% | 4.0% | 3.3% | 2.7% | 4.8% |
| MAE(m) | 0.36 | 0.26 | 0.28 | 0.20 | 0.48 |
| MAE as % | 2.87% | 3.12% | 3.12% | 2.12% | 4.03% |




Observed conditions are in Blue and simulated conditions are in Orange

**Figure 3. Simulated water level conditions at NTLSF water level gauges within the model domain.**

### 2.3.3 Representation of polders

To provide a conservative (overestimate) of the potential benefit the Polders could have on the hydrodynamic conditions, the Polder structures are represented in the model as impermeable weirs. In reality the structures will be permeable and thus have a smaller (lesser) influence on the flow regime.

The impermeable weirs have:

- 0.5 m width;
- 1 m height; and
- An open entrance (10-15 m wide) in the centre of the polder.

This representation within the model (Figure 4) provides consistency with general polder design and allows effective drainage (and fish passage) in and out of the Polder. It is assumed that all five polders had open entrances for drainage and fish passage although this is uncertain from the available drawings. The width of the open entrance is governed by the size of the model mesh elements in this location, with the channel represented across three cells.

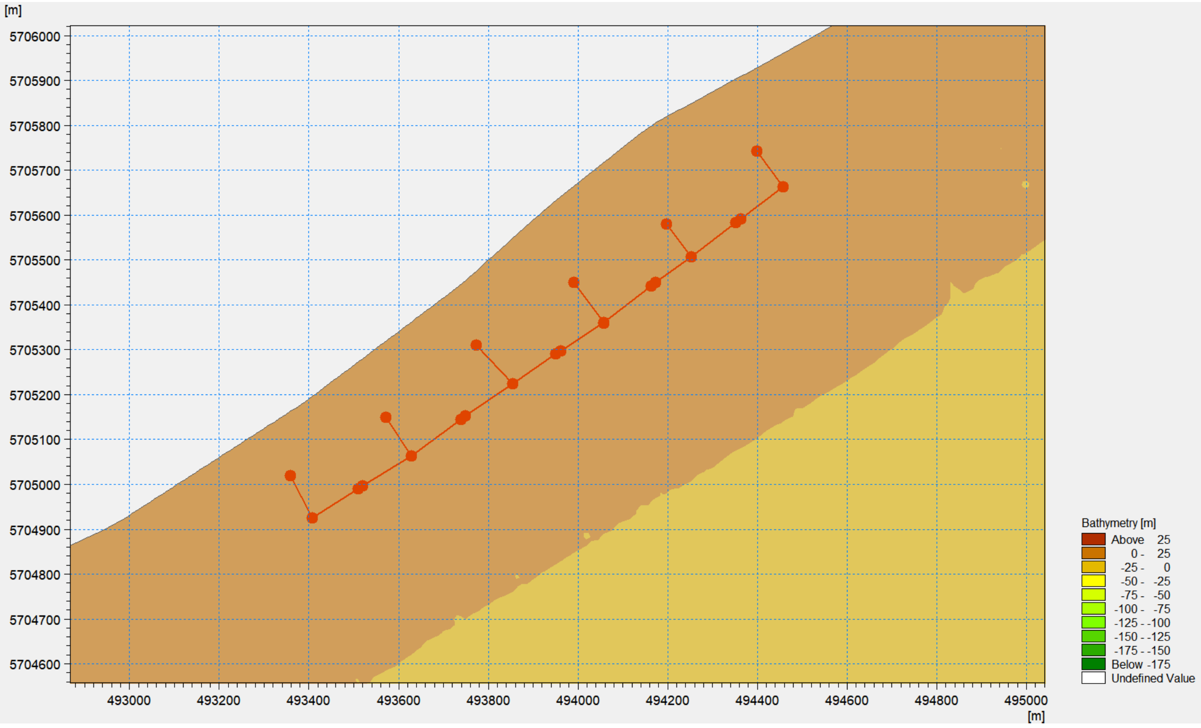



**Figure 4. Polder representation**

## 2.4 Wave transformation modelling

A Spectral Wave (SW) model of Rhymney and the Bristol Channel/Severn Estuary was developed to facilitate the assessment of wave conditions in the vicinity of the Polder field as a result of re-instating the existing Polder field.

To address this requirement, the HD model outlined in Section 2.3 was used as a basis to develop a detailed SW model, again using the DHI) software package MIKE21 FM.

### 2.4.1 Model configuration

This section of the report provides a description of the SW transformation model, developed for this assessment, producing a representative simulation of the existing processes and the impact of Polders on sedimentation conditions in the vicinity of the Polder fields.

The model has been used to assess the impact of the potential development of Polder options on the wave heights in their lee.

The model was run in non-stationary mode, assessing a fully developed sea as a result of discrete forcing conditions (outlined below) using uniform water levels and wind fields. No variation in bed roughness was applied.

#### Mesh design and bathymetry

A revised mesh with a more limited extent was developed based on the HD model mesh outlined in Section 2.3, retaining the detailed mesh resolution in the vicinity of the Polder fields. The model mesh can be seen in Figure 5 and extends from Linney head to St Ives and up the Bristol Channel and into the Severn Estuary.  The local mesh representation is the same as the HD model shown as Figure 2.

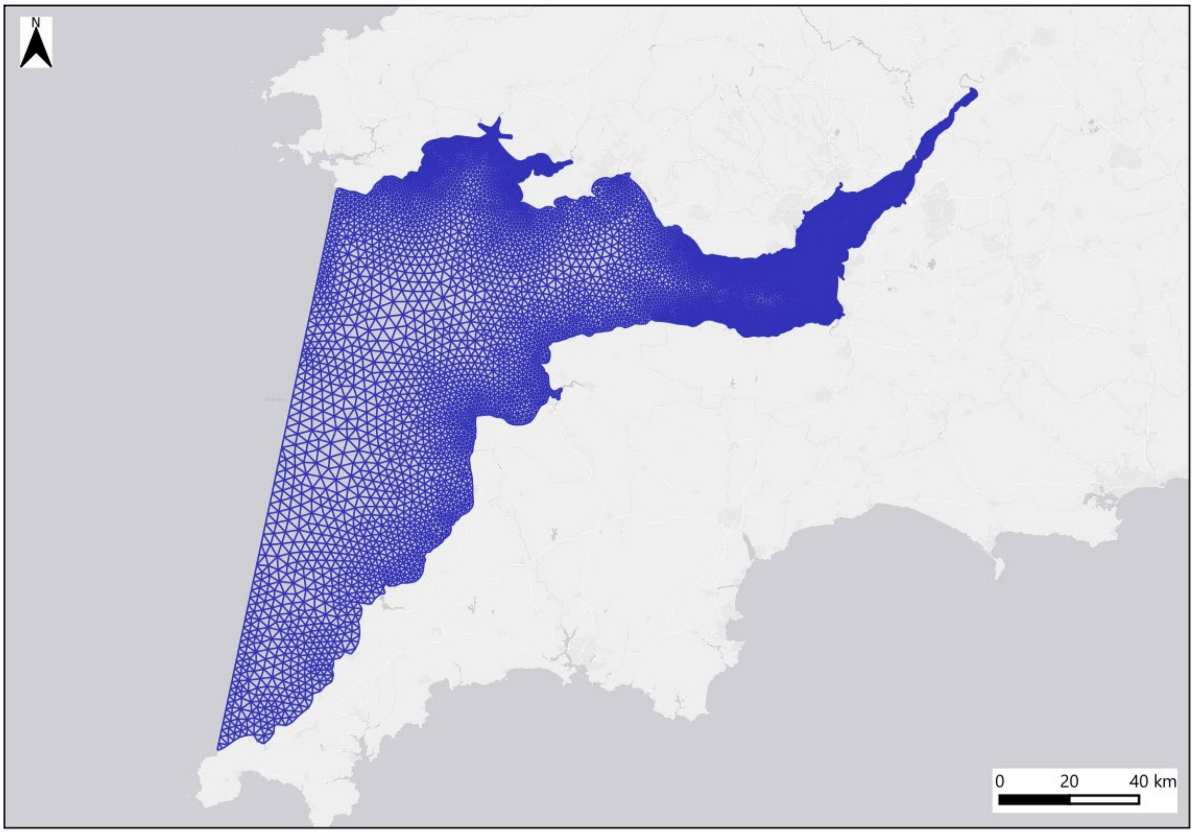



**Figure 5. Wave model domain**

#### Forcing conditions

Wave conditions were generated from ABPmer's SEASTATES 42-year hindcast model at the model boundary and within deep water, seaward of the Polder field as visible in Figure 6.  These datasets were reviewed for winds and waves respectively, with the following three south-westerly wave conditions extracted to review the effectiveness of Polders:

- 10 in 1 year (1,000% Annual exceedance probability(AEP))
- 5 in 1 year (500% AEP); and
- 1 in 1 year (100% AEP).

Nine water level conditions were used to review the impact of waves on the Polder conditions; these range from 3.00-7.00 mODN, between Mean High-Water Neaps (MHWN) and Mean High Water Springs (MHWS) +0.7 m. 36 individual wave and water level pairings were generated for application in the assessment.

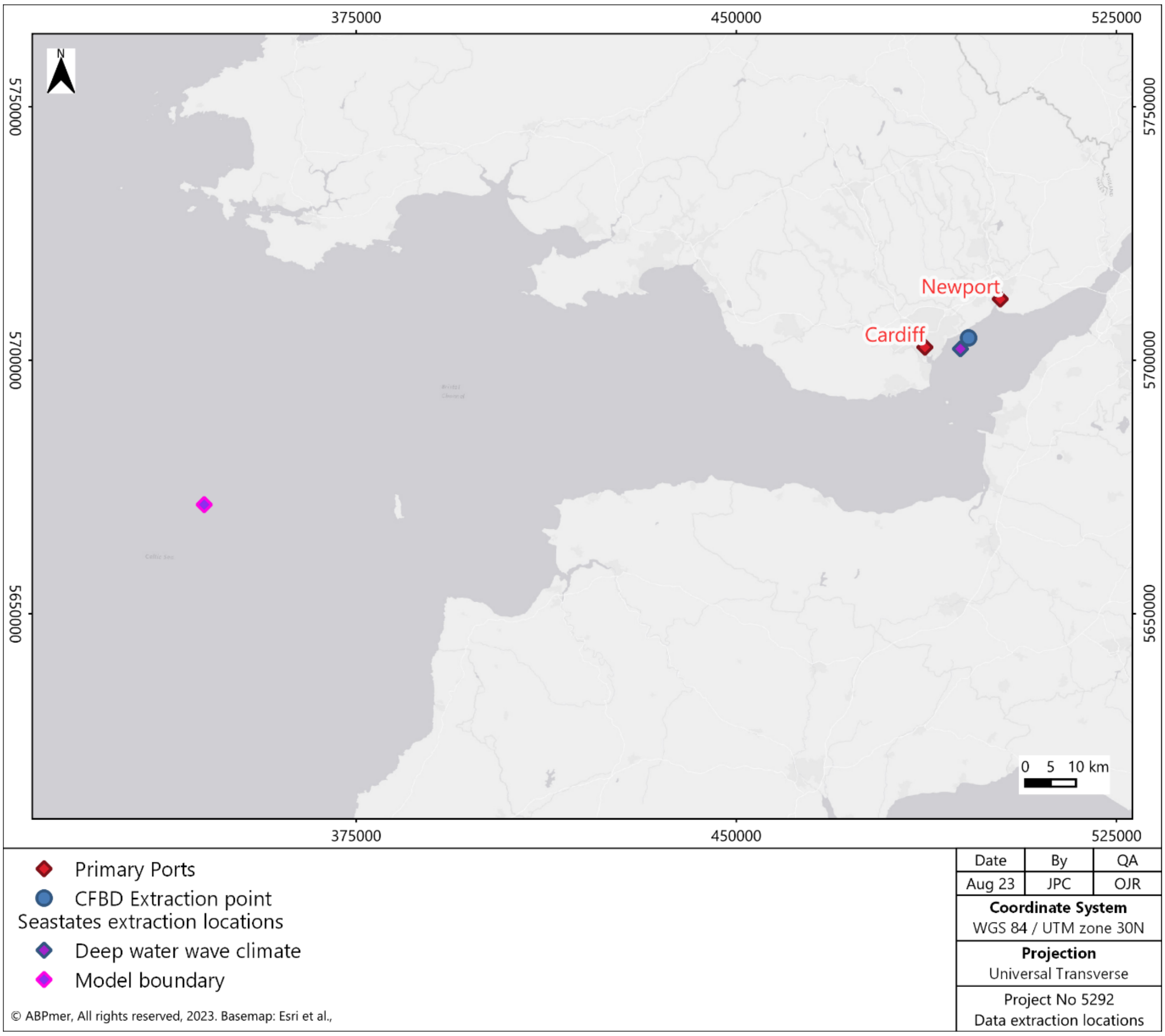



**Figure 6. Seastates extracted wave data**

Westerly wave conditions were identified as the dominant conditions at the site, with westerly and south-westerly waves propagating to the site at Rhymney. A location at the wave model boundary (Figure 6) was selected to generate representative morphological wave conditions from westerly wave directions that may impact the site.

Three indicative wave events were selected based on the simulated hindcast. A 5 in 1 and 1 in 1 year event was extracted using a generalized extreme value (GEV) analysis following a generalized Pareto distribution (GPD) extreme value analysis of wave heights originating from westerly directions. Generation of a 10 in 1 wave condition using the GEV assessment was not considered appropriate and a wave condition approximating the 90$^{th}$ percentile of westerly waves was selected and used for application. These conditions are listed in Table 3 and originated from 225° to allow maximum propagation to the Polders. Wave period (Tp) and windspeed were derived based on the linear relationship between these variables, and wave height (Hs) from the hindcast period.

**Table 3. South-westerly wave conditions**

| Condition | Hs (m) | Tp (sec) | Windspeed (km/hr) |
|---|---|---|---|
| 10 in 1 year | 4 | 9 | 15.5 |
| 5 in 1 year | 6.5 | 11.9 | 21.8 |
| 1 in 1 year | 9.1 | 14 | 28.4 |

### 2.4.2 Representation of the polders

Polders were represented within the model as vertical structures within the model mesh in a format and geometry consistent with the HD model, represented by the Gouda formula, incorporating an accurate representation of structure crest.

The modelling methodology assumes that the Polders will prevent the transmission of wave energy through the Polder structure. This is considered a conservative assumption as it is anticipated the Polders will allow a proportion of wave energy to pass through the structure (depending on the condition of brushwood fencing); however, a representation of this transmission was not possible within the model framework.

# 3 Baseline Coastal Process Understanding

## 3.1 Introduction

This section provides a comprehensive description of the coastal processes operating in the Severn Estuary, focusing on the Rhymney Great Wharf frontage (known as a conceptual understanding). The information has been drawn from a number of previous studies, both publicly available and previously completed by ABPmer, along with results from the numerical model tests.

The Severn Estuary is a funnel shaped estuary which extends in a south-westerly orientation from an upstream normal tidal limit (NTL[1]) at Llanthony Weir and Maisemore Bridge (near Gloucester) to a downstream limit ("estuary mouth") between the headlands at Lavernock Point (Welsh coast) and Brean Down (English coast), a line that also crosses Flat Holm. The area seaward of the estuary is commonly referred to as the Inner Bristol Channel, which includes Bridgwater Bay.

The Bristol Channel has an east-west orientation with a western limit which is open to the Atlantic. The change in orientation between the Bristol Channel and the Severn Estuary, around Flat Holm and Steep Holm, provides a degree of sheltering within the estuary, particularly to North Atlantic swell seas.

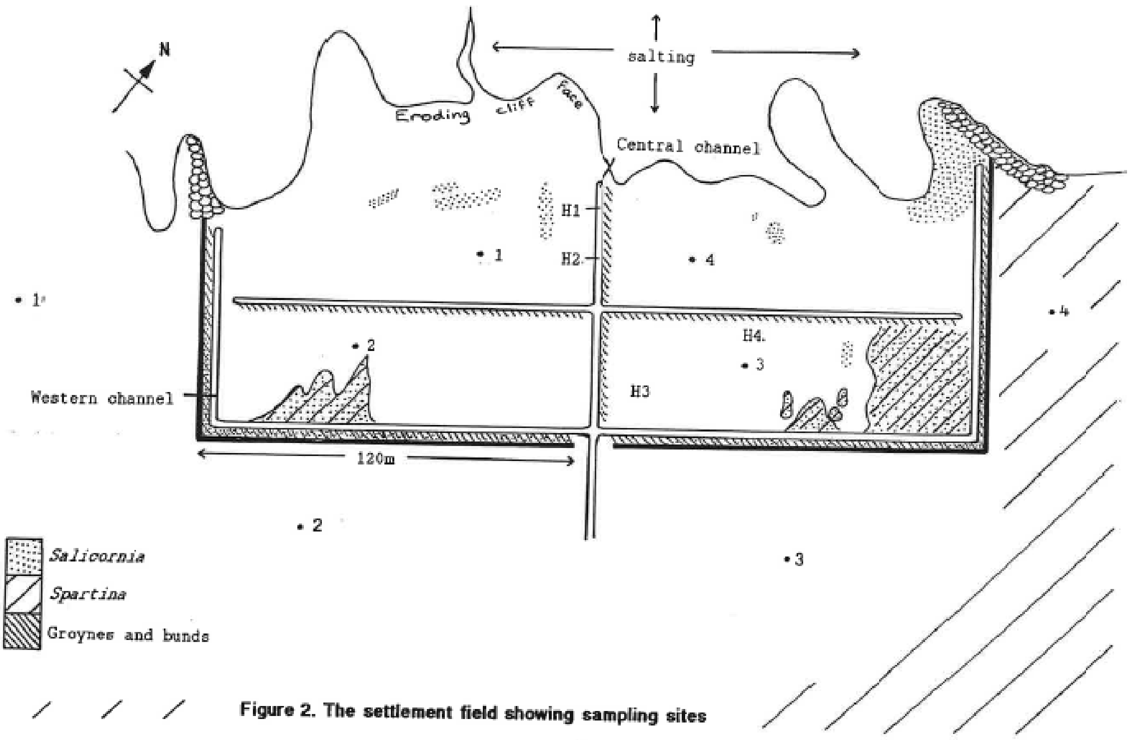
The Rhymney Great Wharf frontage is located on the Welsh coast between Cardiff and Newport.

## 3.2 Existing polders at Rhymney Great Wharf

The following is our understanding of the construction of the existing Polder field. This information has been summarised from the NRW (2023).

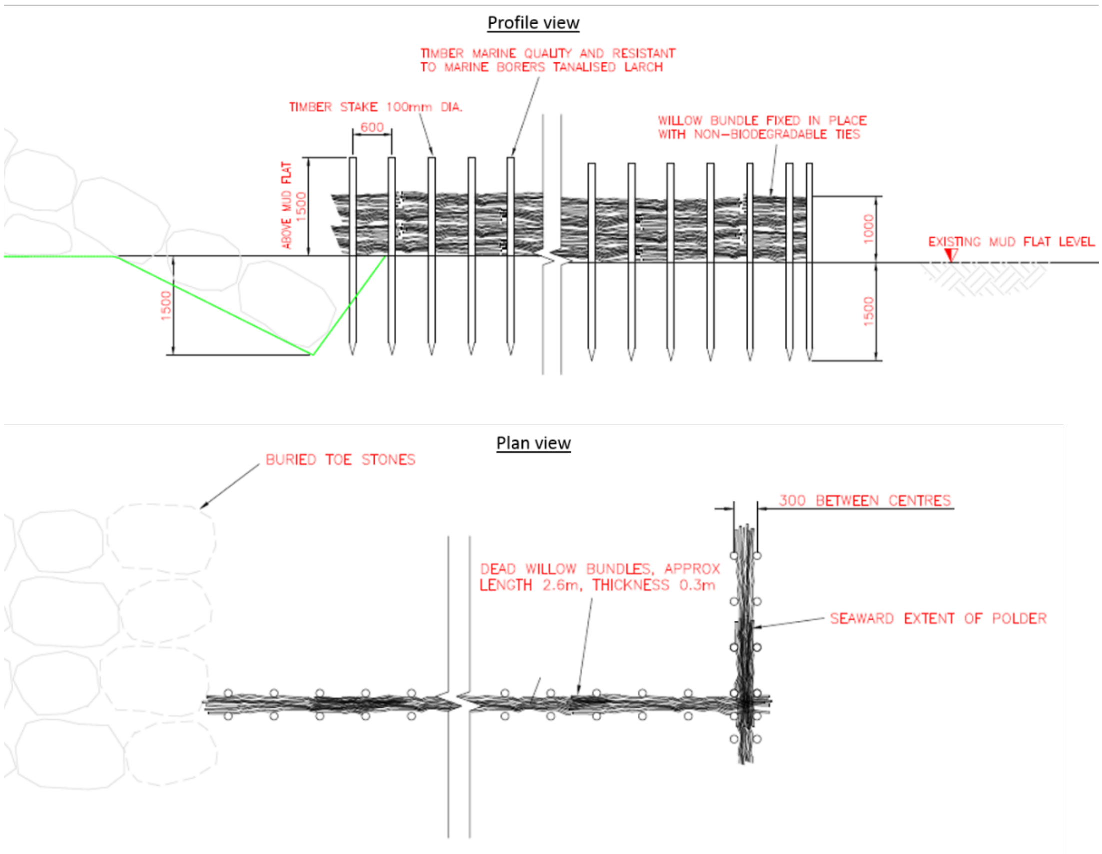
- **Polder 5,** the most easterly Polder, was constructed in August 1988, when the Welsh Water Authority constructed a sedimentation field using the Schleswig Holstein Poldering technique, in a pilot experiment to halt further erosion and to encourage recolonisation of the saltmarsh. The height of the posts has not been confirmed but those visible on site today remain ~90 cm tall from their base, with the rope used to fix the brushwood in place at ~10/15 cm from the top of the post and again roughly the same distance below the first fixing. The design is provided below as Figure 7. It is understood that maintenance works were undertaken in 2005 (along with the construction of Polders 1-4) but there are no associated details.
- **Polders 1 to 4** (west to east) were constructed in 2005 along with the installation of rock revetment along the upper frontage. The Polder design is shown in Figure 8. The fencing was extended >1 km across the frontage, constructing four more Polders immediately west of the original Polder 5. A review of the project was outlined in Case Study 57 to the 'Working with Natural Flood Management: Evidence Directory' (NRW, 2018) and insights are summarised below.

[1] On certain large tides Llanthony Weir may be overtopped and the tide propagates further upstream to Haw Bridge. This site is regarded as the furthest upstream point where estuarine sediments have been identified.




NRW, 2023

**Figure 7. Design of Polder 5 at Rhymney**




NRW, 2023

**Figure 8. Design of Polders 2-5 at Rhymney**

Polders 1-4 were constructed along with 7 km of rock armouring during the summers of 2004 and 2005, with the polders constructed during the second phase of work. Evidence from an earlier polder trial in this same area [Polder 5] showed that it would take many years for the foreshore and vegetation to become re-established. Accretion within the newly constructed polders indicated that the scheme has been successful (Atkins 2006) and Atkins concluded it could provide a long-term solution.

It is understood that maintenance to Polder 1 was completed in August/September 2009 (circa 4 years following construction), an Environment Agency document describes works to "install and secure faggots between folders on the westernmost section. Willow bundles installed to a height of 1 m. Length 900 m with a section of 4.8m on the seaward leg to be left without bundles to avoid fish trap (Figure 9).

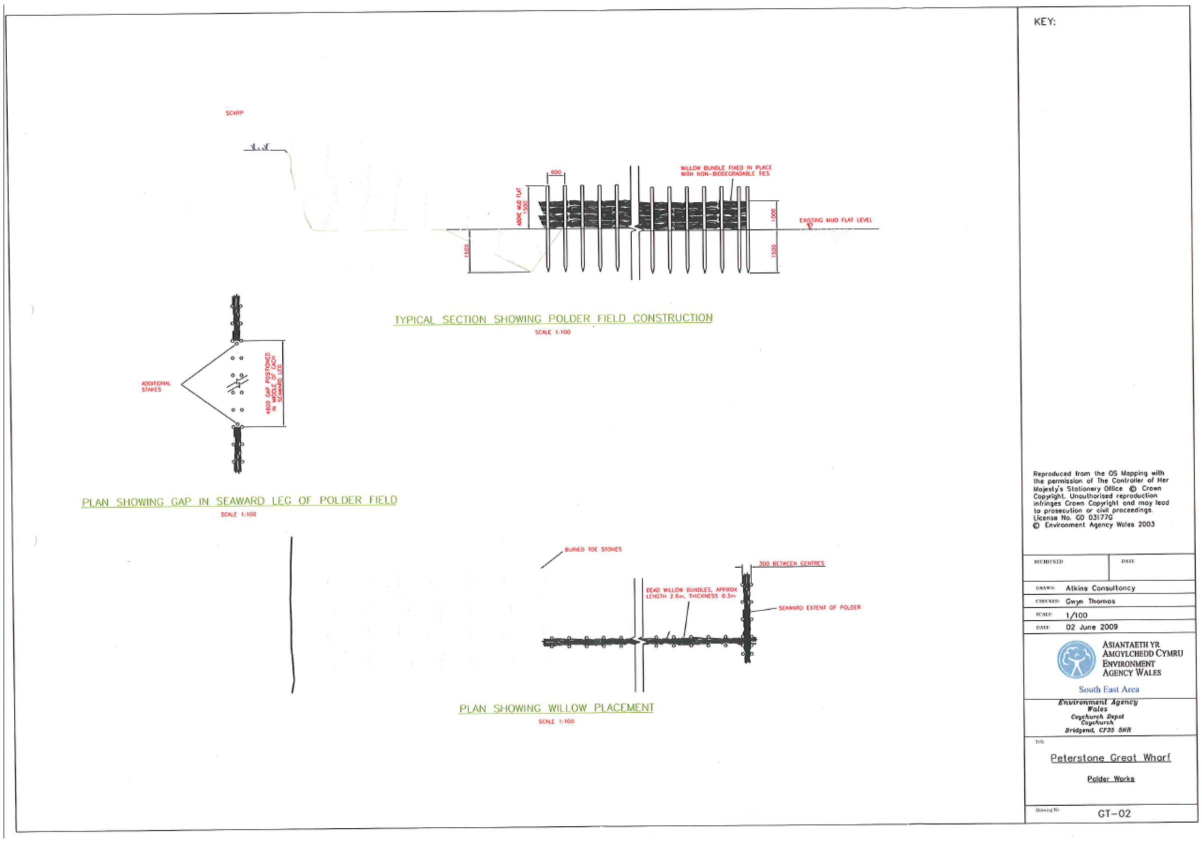



**Figure 9. Maintenance drawing; assumed to be Polder 1**

In 2006 Atkins completed a study into the feasibility of placing dredged material within the existing polders at Rhymney Great Wharf and to determine whether this might prove a viable long term flood defence option for the frontage (Atkins 2006).

The main conclusion is that the placement of dredged material within the polders is not appropriate at Rhymney Great Wharf. This conclusion is based on an appreciation that (Atkins 2006):

- The site is too hydrodynamically exposed to guarantee medium- to long-term success of dredged material placement;
- The polder areas are naturally accreting without any intervention and alternative eroding sites, such as Little Wharf further south of Rhymney, may be a more appropriate focus;
- There could be a significant environmental impact in placing aqueous or dewatered material on the foreshore: and

- Economically, the cost of dewatering dredged material far outweighs the current combined maintenance dredging and disposal costs.

The study made a number of recommendations for further study including trial monitoring. The report concluded that "As current visual monitoring within the polders suggests that natural accretion is taking place, it is strongly recommended that a dedicated monitoring programme is put in place as soon as possible to better understand how the current polder system is performing at Rhymney Great Wharf. The findings of this monitoring are necessary for any future decision to run test trials on the placement of dredged materials within polders. This would then be of benefit towards designing a trial pilot site, potentially at Little Wharf to test different placement techniques against a separate control site, which could be at, for example, Rhymney Great Wharf. This recommendation is the main option coming out of this study" (Atkins 2006).

A further review of the polders by NRW (2018) stated that the 2005 works (rock revetment and extension of the Polders) had effectively stopped or slowed the erosion of the wharf (i.e., upper marsh), thus maintaining the ecologically important land and preventing the undermining of the defences and maintaining their function. This function is protecting approx. 30 km² of agricultural land, business and numerous communities within the Wentlooge Levels'. Please noted that the report did not specify how much of the reduced erosion to the wharf had been due to the rock revetment, and how much due to the Polders).
The report further stated that the frontage was accreting and that:

> *'Due to the aforementioned accreting nature of the area, the favoured option was to attempt to encourage increased deposition of material through the use of rows of larch stakes infilled with willow faggots placed in twin rows parallel and perpendicular to the coast to create 'cells' (Polders 1-4)'.*

With regard to effectiveness of the Polders, NRW (2018) concluded that:

> *'Long term measures to re-establish the mudflats in front of the wharf has been less successful. No notable accretion has been seen albeit no real further loss'.*

It was noted that, in the years since completion, very little damage had been caused to the stone revetment, however, there had been a reasonable amount of damage caused to the wood stakes and brushwood of the Polders; the major issue being the loss of the brushwood / willow material from in-between the stakes. Whilst remedial work had been recommended, none was carried out, and this was considered to be the likely reasons for there having been *no real accumulation of mud has been seen on the mud flats*'.

NRW (2018) concluded that:

> *'The design of the Polders used was perhaps unsuitable for the location given the higher energy environment. A greater success may have been achieved if a higher number of parallel rows were used within each Polder field. A point to take away is that it is difficult to generalise parameters for the appropriate use of soft engineering/natural flood management methods, especially in higher energy coastal environments. Sites need to be assessed for suitability on an individual basis. There needs to be a greater understanding of the capabilities and limitations of the differing techniques.'*

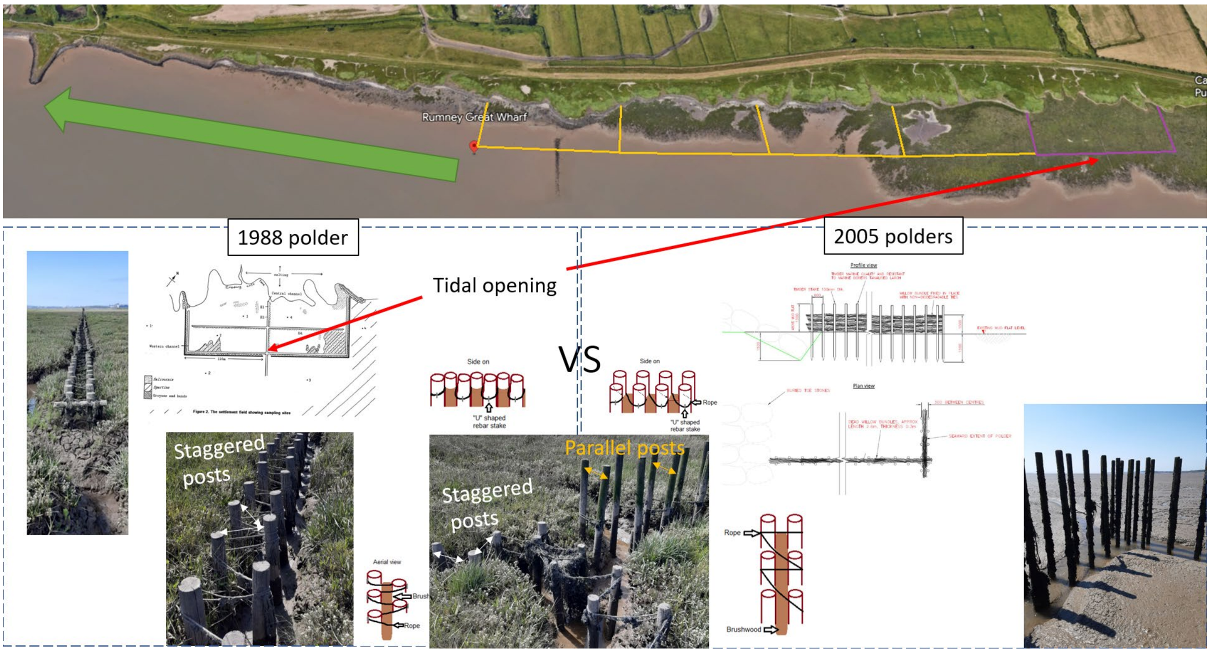
NRW (2018) also concluded that:

> *'The failure of the Polder fields to reinstate the mudflats may, in part, be a result of the lack of any annual maintenance work or ad hoc repairs following damage to the asset as specified by the designer. This emphasises the importance of establishing a well thought out maintenance regime for*

*these natural flood management techniques, the knowledge and skills within the workforce to carry out such works and also the need to 'set aside' extra revenue for these works during the project design and construction phases.'*

This design development study is looking to identify parameters which can be used to understand the risks and opportunities associated with the Rhymney polder project and identify a preferred alignment. However, as NRW (2018) highlight, the lack of maintenance is considered to be an important contributory factor in the lack of significant accumulations of mud found at the site. It is understood that, for this new project, there is a maintenance commitment only for the first five years of the project. This is considered a significant risk to the success of the project.

Various Polder design options are being considered by NRW (see Figure 10) with advice from others, NRW is planning to have tidal openings and staggered posts features in the final design for the new Polders. This study by ABPmer is focusing on the general alignment and height of the Polder fields.




NRW, 2023

**Figure 10. Differences in Polder design**

## 3.3 Geomorphological evolution

During the last ice age (the Devensian Glaciation, 73,000 to 10,000 years before present (BP)), ice sheets reached almost as far as the coast of Cardiff and Newport, sea levels were much lower and the Severn Estuary itself was much further to the west, with a river valley in its place. The Holocene commenced from around 12,000 BP with a rapid rise in sea level between 10,000-6,000 BP of *circa* 25 m resulting in the estuary transgressing into the river valley resulting in the estuary we see today.

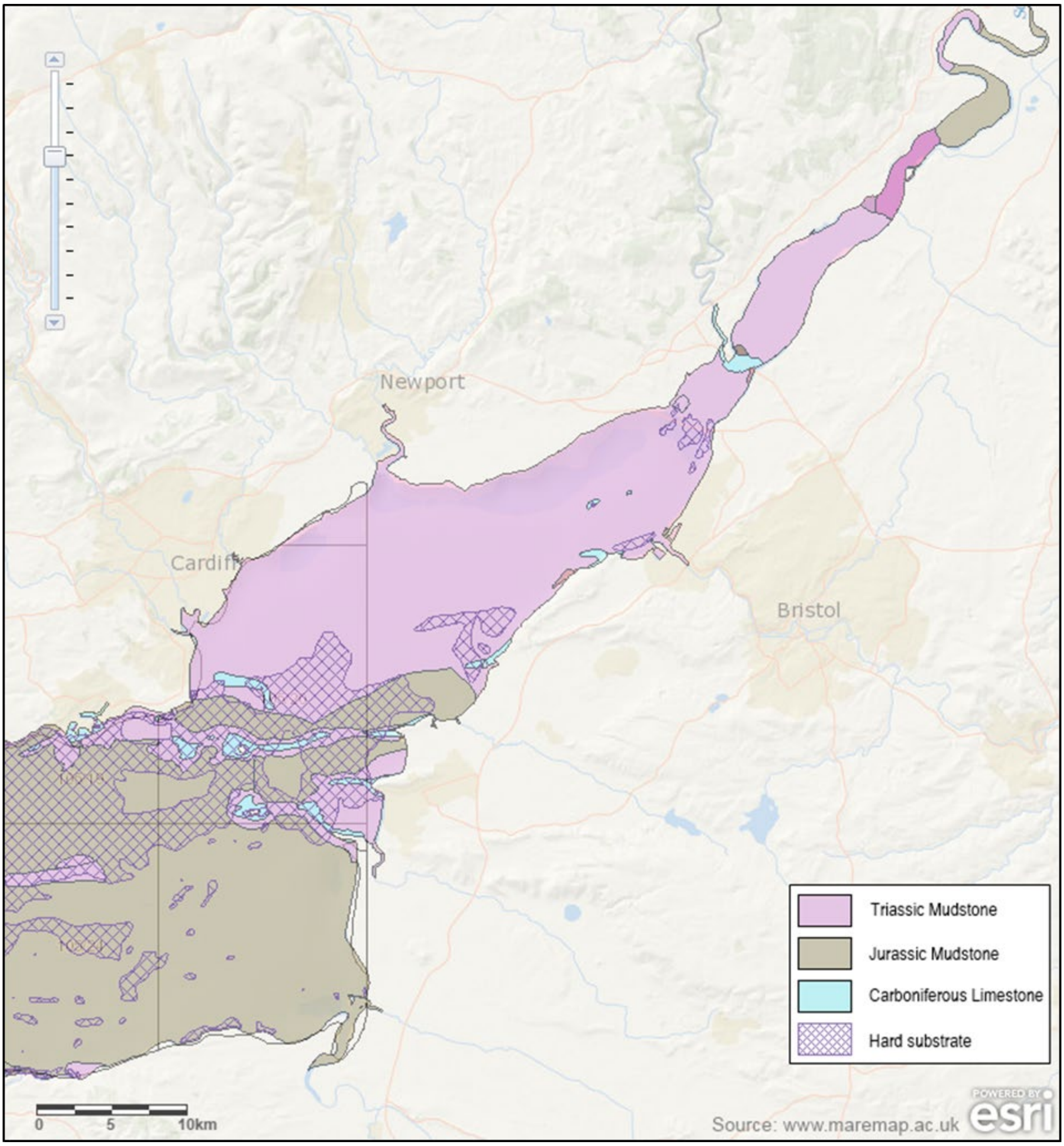
The general understanding is that the encroaching tide steadily worked the seabed and moved a sediment divide (a zone of seaward and landward bedload transport) into the estuary. This had the effect of pushing sandy marine sediments into the estuary to fill sections of paleochannels and form the extensive banks (e.g., Middle Ground) now found along the original river channel axis, but also releasing some material into the Celtic Sea from the seaward margin of the divide (also known as a bedload parting zone). The continual sweeping effect of the encroaching tide over this period has also resulted in a wide expanse of exposed bedrock. This area extends across the majority of the Inner Bristol Channel and into the Severn Estuary past Flat Holm and Steep Holm.

Coastal fine sediments laid down at this time extend along both the English and Welsh banks of the estuary as “The Wentlooge Formation” (Allen and Rae, 1987 cited in ABPmer, 2016a). River walls and earth embankments were initially raised during the Roman period and the reclaimed marshes drained, in part, for agriculture. This reclamation had the effect of narrowing the estuary and restricting the link with the natural sink for fine sediments. In many places land levels behind the embanked defences are now lower than mean high water spring tides (ABPmer, 2016a).

The local foreshore is now home to extensive mudflats and strips of saltmarsh of varying widths, which, along the Rhymney frontage, have been faced with rock armour in order to try and halt erosion. Furthermore, wooden fences filled with brushwood have been installed along parts of the frontage in order to better retain sediment (see below for more detail on these measures). The intertidal habitats are backed by substantial embankments which have crest heights which range between 8.8 m and 11 m ODN (ABPmer, 2019b).

## 3.4 Geology and sediments

The present-day shape of the estuary also reflects key geological exposures which are largely resistant to erosion and are likely to remain as constraints as the estuary responds to future pressures from sea level rise and local developments. These exposures exist along distinct parts of the coastline, as cliffs and rocky headlands, and also across parts of the estuary floor as bedrock. The bedrock type along the frontage is soft red Triassic mudstone as illustrated in Figure 11 below.




Derived from www.maremap.ac.uk and cited in ABPmer, 2016b

**Figure 11. Seabed geology**

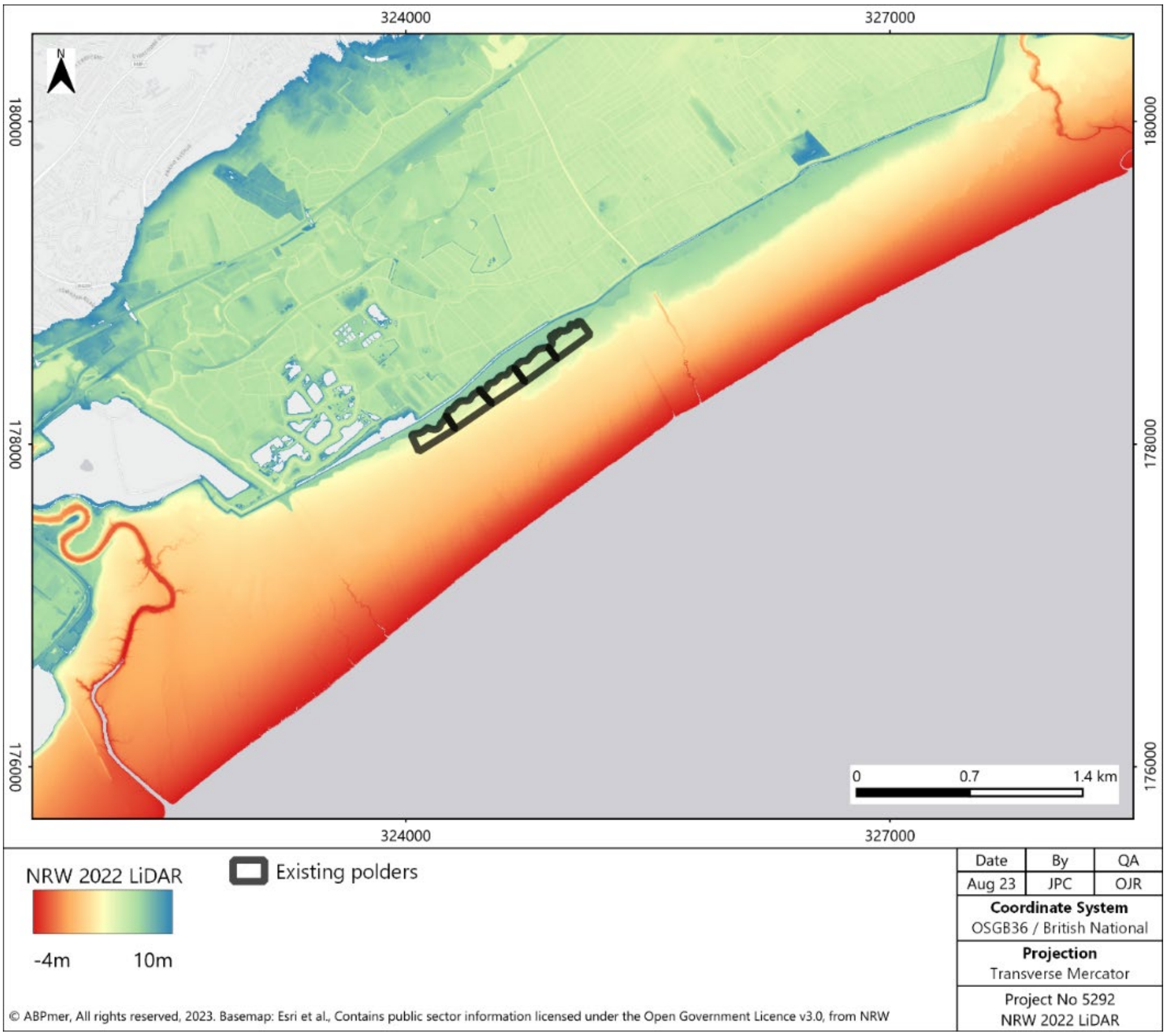
The mudflat at the adjacent Peterstone-Wentlooge frontage was examined in detail by O'Brien *et.al* (2000) which can be considered a direct analogue for the mudflats at Rhymney Great Wharf. The analysis showed that the mudflat consists of two Holocene sediment layers. The underlying layer is relict clay extending over the entire width of the intertidal. This is overlain by a thin veneer of modern sediment (between 0 and 30 cm) between the saltmarsh edge and mean sea level.

The sediment grain size is consistent for both the modern sediments and the underlying layer consisting of approximately 50% silt and 50% clay.

## 3.5 Topography and bathymetry

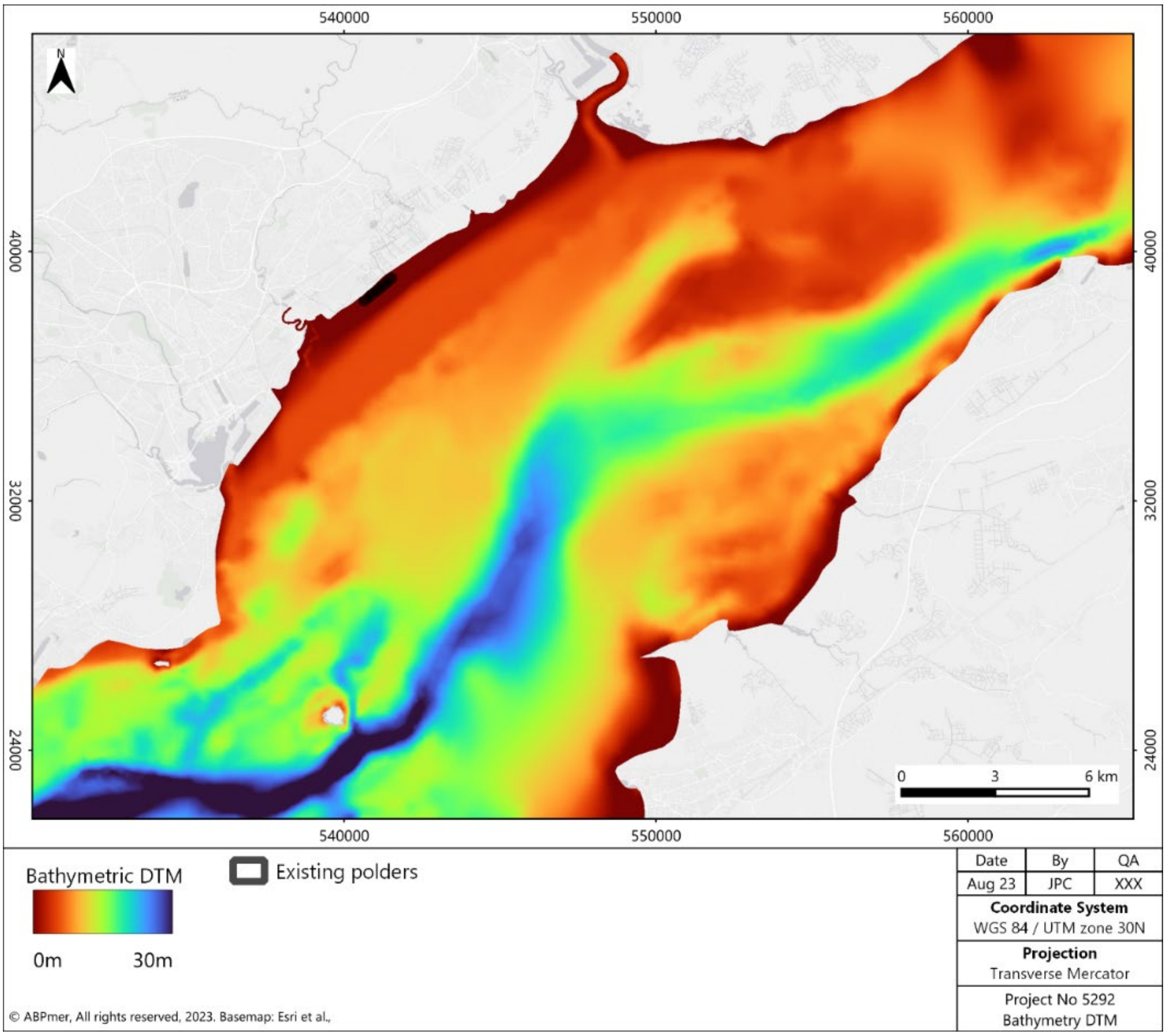
The shoreline at Rhymney can be categorised as a heavily managed intertidal saltmarsh fronting a significant earthen embankment (with a crest height of *circa* 10 mODN) acting as a primary flood defence and protecting low-lying hinterland to the west of Newport. The intertidal area in front of this embankment consists of a defended high saltmarsh plateau ('wharf') at *circa* 7 mODN, which is defended by a small riprap armour embankment. Seaward of these management strategies, the intertidal area is largely uncolonized mudflat, with patches of low to mid saltmarsh, gradually sloping southward into the subtidal Severn Estuary, where dominant tidal channels allow the propagation of tidal waves further east into the Severn.

The topography of the foreshore is presented as Figure 12 which also shows the larger drainage channels crossing the foreshore; the bathymetry is shown as Figure 13.




Source: NRW 2022 terrestrial LiDAR DTM downloaded from DataMapWales

**Figure 12. Site topography**




Source: Composite DTM generated from UKHO data and EMODnet DTM

**Figure 13. Site bathymetry**

## 3.6 Water levels

The Enhanced Estuaries Database (Manning, 2012) classifies the Severn Estuary as having an "Exceptionally Large" tidal range, this is otherwise known as a hyper-tidal range. This relative term refers to tidal ranges greater than 'macro-tidal', which conventionally covers the range 4 to 6 m on a mean spring tide. Nichols and Biggs (1985) considered how the propagation of the tidal wave varied along an estuary and with changes in tidal range. For funnel-shaped estuaries, the converging form of the estuary will squeeze the tide into a smaller cross-section leading to faster flows and increasing the height of the tidal wave, as well as potentially reflecting some of the wave. Frictional drag effects compete against this process, which will tend to increase for faster flows and as depths become shallower (ABPmer, 2016b).

The magnitude and frequency of the tide is inherently predictable, with diurnal (daily), lunar (monthly) and solar (equinox) type variations, as well as lower frequency variations such as lunar nodal cycles (18.6 years). It is noted that 2015 was the peak of the 18.6-year lunar nodal cycle, where there are predicted to be more large tides than at other times during this cycle.

The study completed by ABPmer in 2016 investigated the tidal asymmetry and concluded the following with respect to the flood and ebb tidal phase at Cardiff (ABPmer, 2016b):

- **Spring tide**: Flood tide is 0.5 hr longer than the ebb tide; and
- **Neap tide**: The neap tide exhibits a mixed pattern with a mixture of dominance between flood and ebb between 0.5 to 1.5 hr.

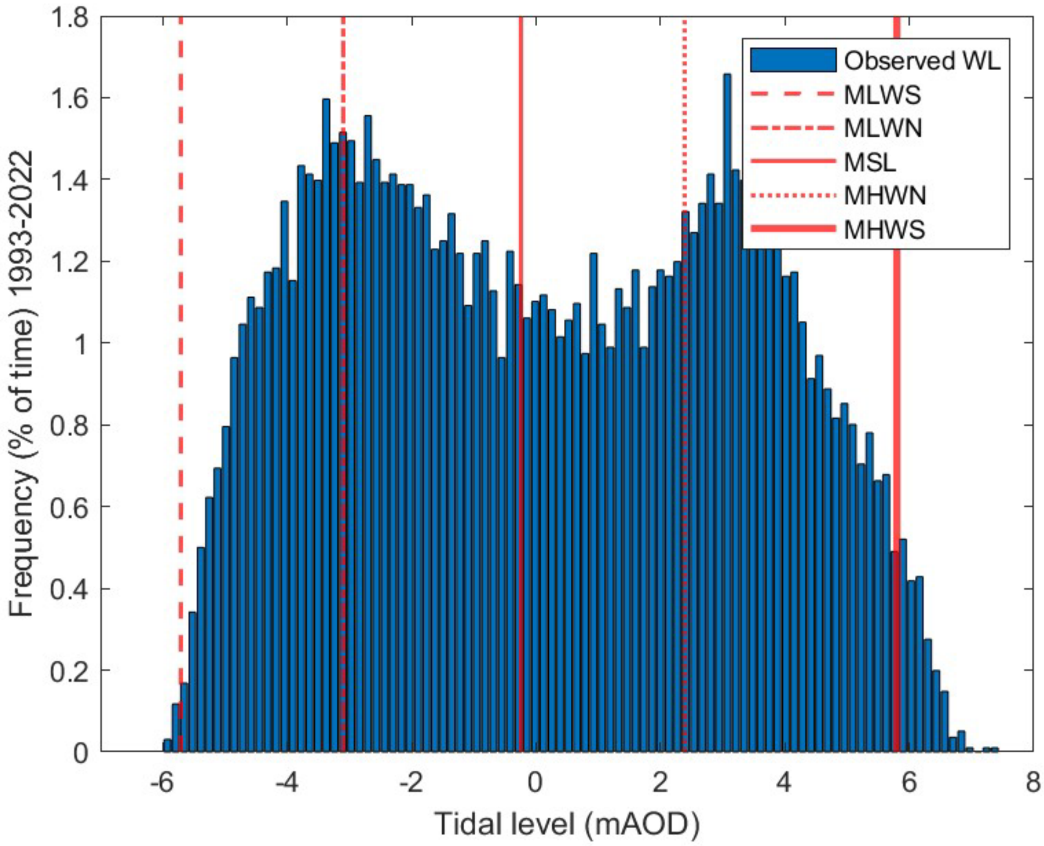
Tide levels have been obtained for the ports nearest to the study area (Cardiff and Newport) and interpolated for the Rhymney frontage. These are displayed in Table 4 below, which demonstrates that the mean spring tidal range at the frontage measures approximately 11.3 m, whereas during neap tides, it is 5.2 m.

**Table 4. Tide levels for the nearest ports and the study area frontage**

| Parameter | Astronomic Tidal Level for Nearest Port (UKHO) | | | | Interpolated Tide Levels Rhymney |
|---|---|---|---|---|---|
| | Cardiff | | Newport | | |
| | mCD | mODN | mCD | mODN | mODN* |
| Highest Astronomic Tide (HAT) | 13.5 | 7.17 | 13.6 | 7.79 | 7.48 |
| Mean High Water Spring (MHWS) | 12.3 | 5.97 | 12.3 | 6.49 | 6.23 |
| Mean High Water (MHW) | 10.7 | 4.37 | 10.6 | 4.79 | 4.58 |
| Mean High Water Neap (MHWN) | 9.1 | 2.77 | 8.9 | 3.09 | 2.93 |
| Mean Sea Level (MSL) | 6.58 | 0.25 | 6.26 | 0.45 | 0.35 |
| Mean Low Water Neap (MLWN) | 4 | -2.33 | 3.6 | -2.21 | -2.27 |
| Mean Low Water Spring (MLWS) | 1.2 | -5.13 | 0.8 | -5.01 | -5.07 |
| Lowest Astronomic Tide (LAT) | -0.1 | -6.43 | -0.4 | -6.21 | -6.32 |
| Astronomic Tidal Range (HAT-LAT) | 13.6 | | 14.1 | | 13.73 |
| Spring Range (MHWS-MLWS) | 11.1 | | 11.5 | | 11.2 |
| Neap Range (MHWN-MLWN) | 7.9 | | 5.3 | | 7.25 |
| * Based on linear interpolation between Cardiff and Newport tide levels, with the distance between the Cardiff and Newport stations set at 16.5 km (as crow flies) | | | | | |

Understanding the relationship between the height of the installed Polders with respect to MHWN, MHW and MHWS is a critical design element for the project as it controls the potential for sediment accumulation. This is described further in Section 3.10 and investigated in detail in Section 6. As illustrated in Table 4, the spring tidal range for the frontage is considerable at 11.5 m with a range of 5.3 m for neap tides.

A histogram of the number of times a year the tide level exceeds these levels is provided as Figure 14 below with MHWN is exceed approximately 30% of the time, MHW exceeded circa 9% and MHWS exceeded circa 2% of the time.




Source: NTLSF Newport 1993 to 2020

**Figure 14. Histogram of water levels**

### 3.6.1 Extreme water levels

Surge conditions can lead to both an increase in water levels (from low pressure) and a decrease in water levels (from high pressure) which may last as long as the passing pressure system and travel as fast. The surge effects will also interact with local winds and the tide which may help to amplify the surge effect.

Positive surges, associated with periods of low pressure, are of direct importance to flood risk concerns, especially when they combine with periods of higher spring tides. The main flood risk condition is when a low-pressure system travelling to the east passes north of the Bristol Channel with strong cyclonic winds that drive westerly winds behind an elevated water surface. When this type of surge event combines with a period of high spring tides the additional effect of the positive surge can lead to conditions of "extreme" water levels that are beyond any peak tidal elevation (ABPmer, 2016b).

ABPmer completed an analysis of the relationship between surge and extreme water levels in the Severn Estuary in 2016 using observed tidal levels has been carried out for data records at Newport. The data includes records dating from 1993 to 2014, and also included the surge component. The study concluded that (ABPmer, 2016b):

- The distribution of surge frequency indicates a tendency for the more frequent occurrence of larger positive surges than negative (a positive skew in the distribution).
- Of the 20 highest water levels all but one occurred as a result of a combination of a surge on top of a tide with a predicted high-water height larger than MHWS.

- Most extreme water level events at Newport tend to be caused by small to moderate surges occurring around high water of a relatively large tide.
- For a number of events, the time of the extreme water level occurs a few hours after the peak of the surge. This indicates that a level of interaction is occurring, between tidal and non-tidal components, which tends to result in the peak of the surge occurring on the rising tide.
- Previous research (ABPmer, 2004 cited in ABPmer 2016) has shown that the larger surge events tend to occur primarily as a result of large strong low-pressure systems and not local meteorological conditions and the 2016 analysis showed that the peak of the surge in the majority of the 10 largest events occurs around low water, again indicating that some sort of tide/surge interaction process appears to be occurring in the Severn.
- A general surge shape was identified; before the surge event there is generally a small negative surge, then over the next 15 hours the surge increases up to a maximum level. Over the following 15 hours the surge tends to then decrease, before again increasing in height slightly, 10 hours after the peak, and then decreasing down to zero. In total the events tend to last for about 30 hours.
- For the majority of the 20 largest surge events in the analysis record, the peak of the surge tends to occur within ±3 hours either side of low water. The secondary small peak in surge appears to then occur around the next low water. The surge profiles tend to reach a peak around the time of low water, before and after the extreme water levels are experienced, again suggesting interaction between the surge and tide.

Present day extreme water levels at Rhymney are provided below taken from the Environment Agency Coastal Flood Boundary Dataset (Environment Agency, 2018). The levels have been uplifted to 2023 by applying 0.04 m to the water levels utilising the UKCP18 RCP 8.5, 95$^{th}$ percentile estimates (Met Office, 2018).

**Table 5. Uplifted (2023) Coastal Flood Boundary Dataset extreme water levels for Rhymney, (RCP8.5, 95$^{th}$ percentile, CFBD chainage point 404).**

| Return Period (years) | Water Level (mODN) |
|---|---|
| 1 | 7.23 |
| 2 | 7.34 |
| 5 | 7.47 |
| 10 | 7.58 |
| 20 | 7.68 |
| 50 | 7.82 |
| 100 | 7.95 |
| 200 | 8.08 |
| 500 | 8.27 |
| 1000 | 8.43 |
| 10000 | 9.06 |

### 3.6.2 Climate change

Depending upon the time horizon for the project, climate change will affect conditions at the site through both sea level rise and storm surges and the elevation of the Polders within the tidal frame will change with sea level rise as the influence of the Polders reduce (assuming they are maintained) as water levels increase. Climate Change guidance has been produced by Welsh Government (Welsh Government, 2022) which has been used to derive the information below.

The guidance notes that [UKCP18] sea level rise allowances have been updated to reflect the higher central allowance (70th percentile) and upper end allowance (95th percentile) of Representative Concentration Pathway (RCP) 8.5, which reflects an increase in global mean surface temperature of around 4.3 ºC) by 2100 (Welsh Government, 2022). The sea level rise predictions for Rhymney from the UKCP18 predictions are provided as Table 6 below.

**Table 6. Sea Level Rise Predictions**

| Allowance (Percentile) | Mean Sea Level Rise (metres) by 2100 *(UKCP18 Baseline 1981-2000) | Mean Sea Level Rise (metres) by 2120 *(UKCP18 Baseline 1981-2000) |
|---|---|---|
| 70th | 0.85 | 1.11 |
| 95th | 1.11 | 1.47 |

Source: Welsh Government, 2022

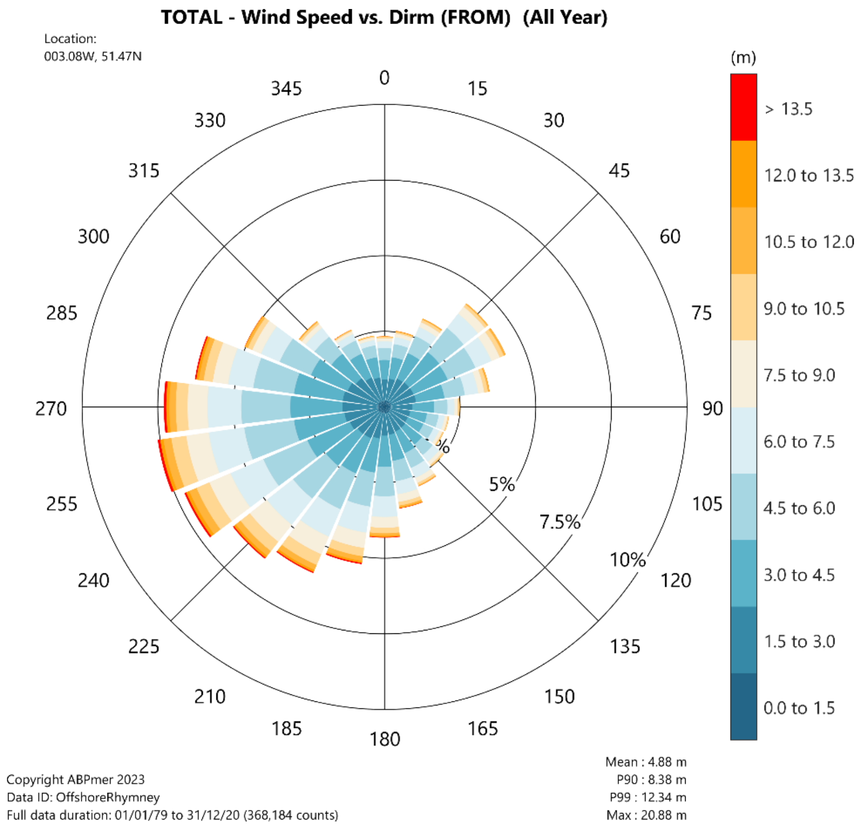
There is considerable uncertainty as to the potential effects of climate change on storm events around the UK. Welsh Government has advised on considering the following precautionary sensitivity ranges:

- Offshore windspeed allowances of +5% to 2055 and +10% between 2055-2120; and
- Extreme wave height allowances +5% to 2055 and +10% between 2055-2120

## 3.7 Wind regime

The wind influence on the Severn Estuary is primarily related to larger scale North Atlantic weather systems that develop over long westerly fetches leading to propagation of long period swell waves into the Bristol Channel, for a discrete set of westerly directions, as well as locally generated wind-waves from shorter estuary fetches. Wind interactions on the sea surface can also lead to periods of wind-setup (where wind blowing over the water surface for a consistent period can lead to a build-up of water against down-wind coastlines), enhanced surge effects and locally wind-driven surface flows.

The wind regime just offshore of the Rhymney Great Wharf frontage is shown in Figure 15 below, with the location of extraction visible in Figure 6 (deep water wave climate). This rose outlines that wind conditions frequently originate from westerly wind directions, specifically between 195 and 285°. The strongest wind speeds also originate from within this window with easterly windspeeds not exceeding 16.5 m/s throughout the 42-year hindcast period.




Source: ABPmer SEASTATES hindcast 1979 to 2022

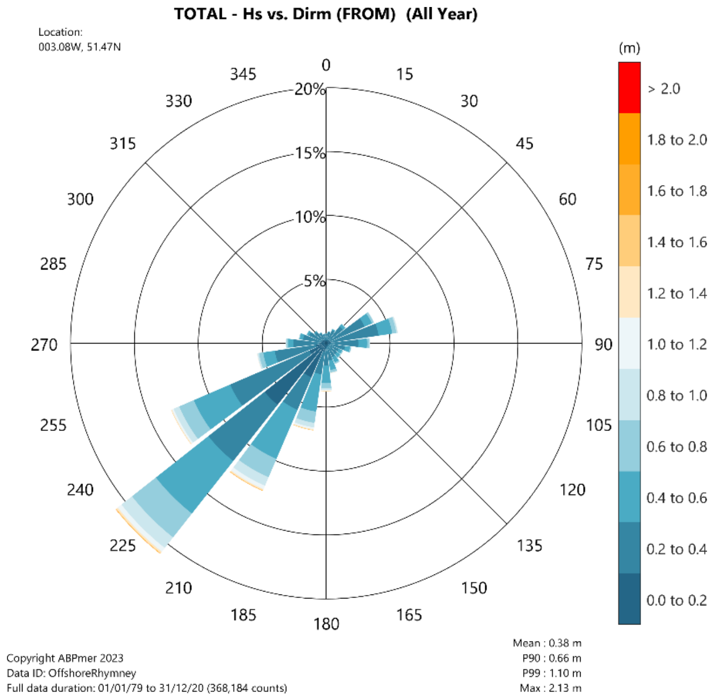
**Figure 15. Wind regime offshore of Rhymney Great Wharf frontage**

## 3.8 Wave regime

The wave regime is illustrated in Figure 16 below with the data extraction location identified in Figure 6. The change in orientation between the east-west aligned Bristol Channel and northeast-southwest Severn Estuary provides a degree of shelter to the estuary from large Atlantic swells from the west, with most long period swell waves which propagate into the estuary likely to be limited to reaching frontages in the outer estuary along the English coastline between Brean Down and Clevedon. The Rhymney Great Wharf frontage is, therefore, not exposed to the Atlantic swell being in the lee of Lavernock Point.

Wind wave is limited by much shorter fetches than swell waves. During periods of higher water levels, fetch lengths for the dominant westerly winds within the Severn estuary are around 20 to 25 km. It is also noted that during low water periods, when there are large drying areas across both intertidal and mid-estuary sand flats, the available fetch to many parts of the estuary is further reduced (by approximately 30%). The maximum wind generated wave fetch is *circa* 48 km (from a south-westerly direction) at high water.

As the alignment of the frontage is approximately south-west to north-east, it would not be affected by the predominant westerly winds, which would be from the land. The winds with greatest wave effects on the marshes are therefore likely to be from the south, albeit at lower frequency and, and the south-west, with the effects of diffraction around Penarth. Strong flood and ebb flows are also known to interact with wind waves leading to wave blocking (causing steepening) and tidal refraction in some locations and for some states of tide.

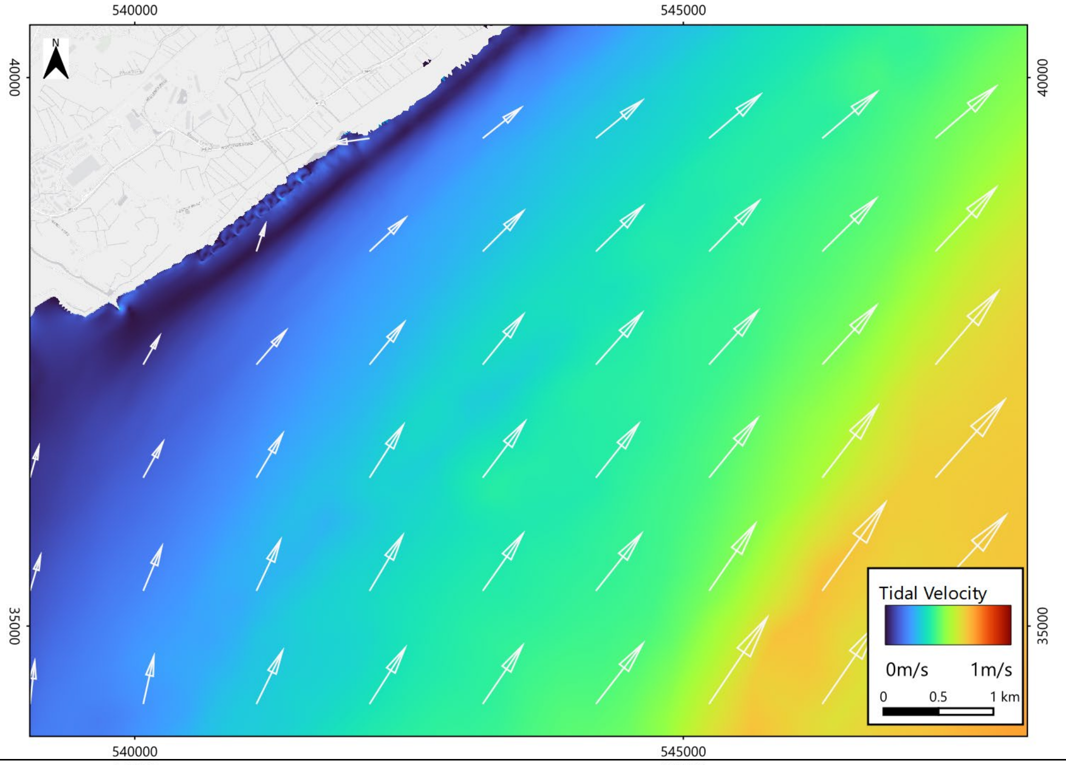
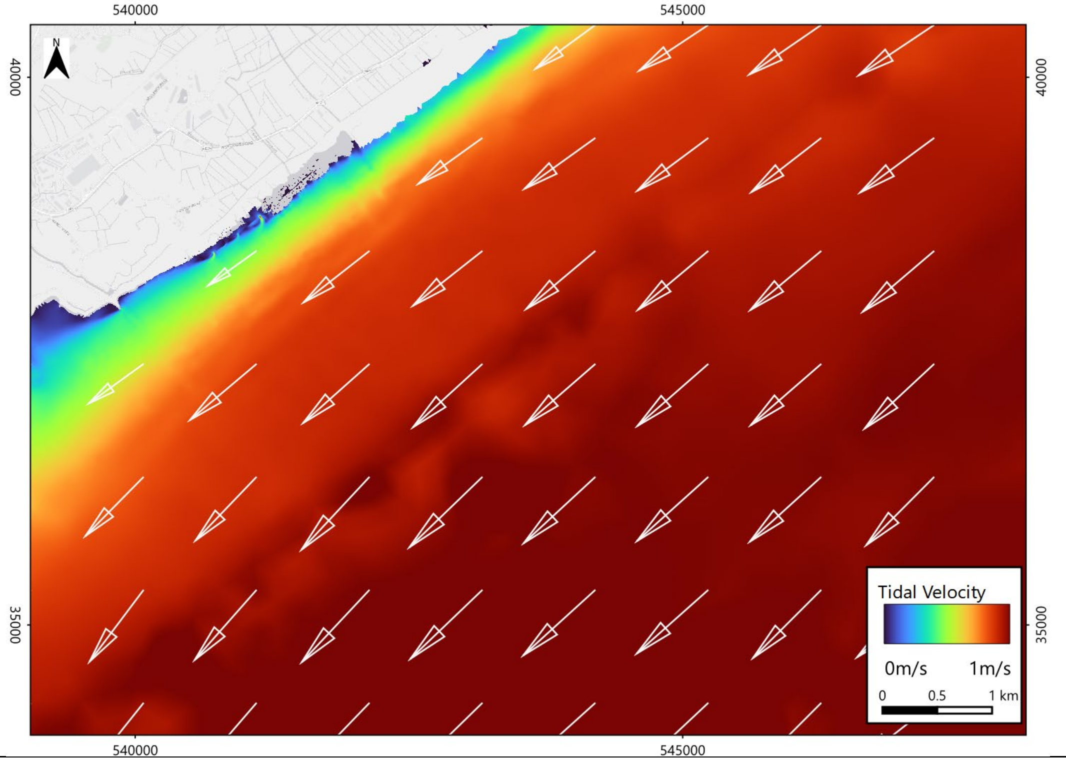


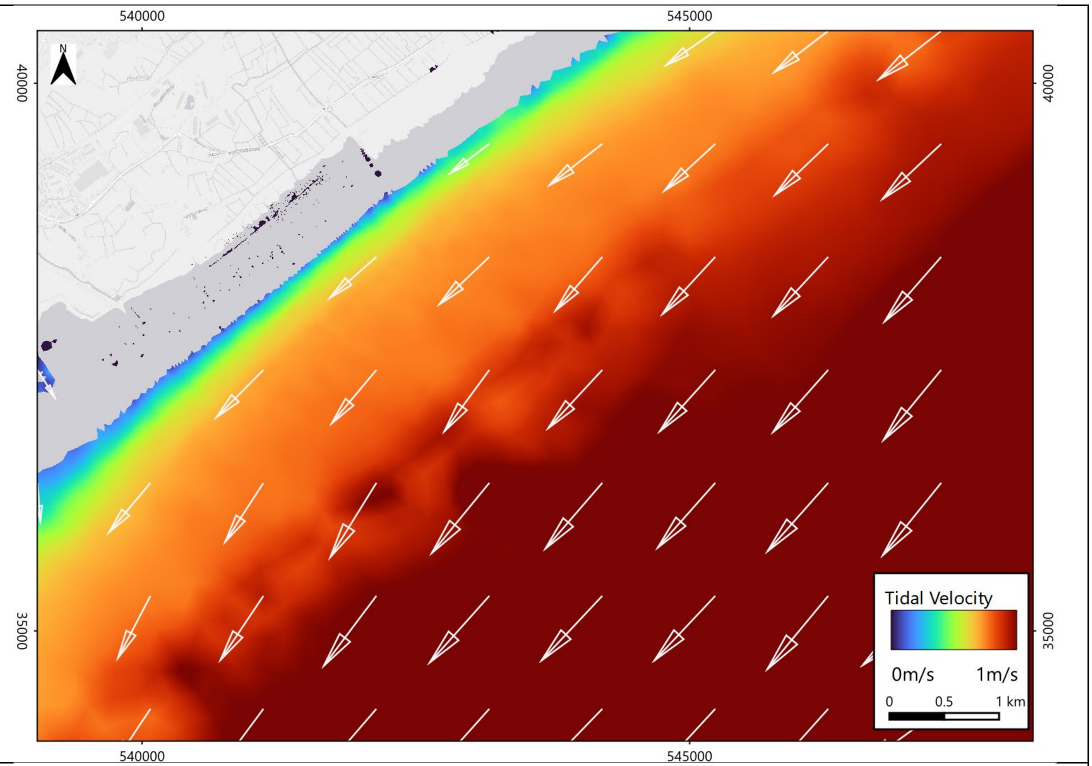
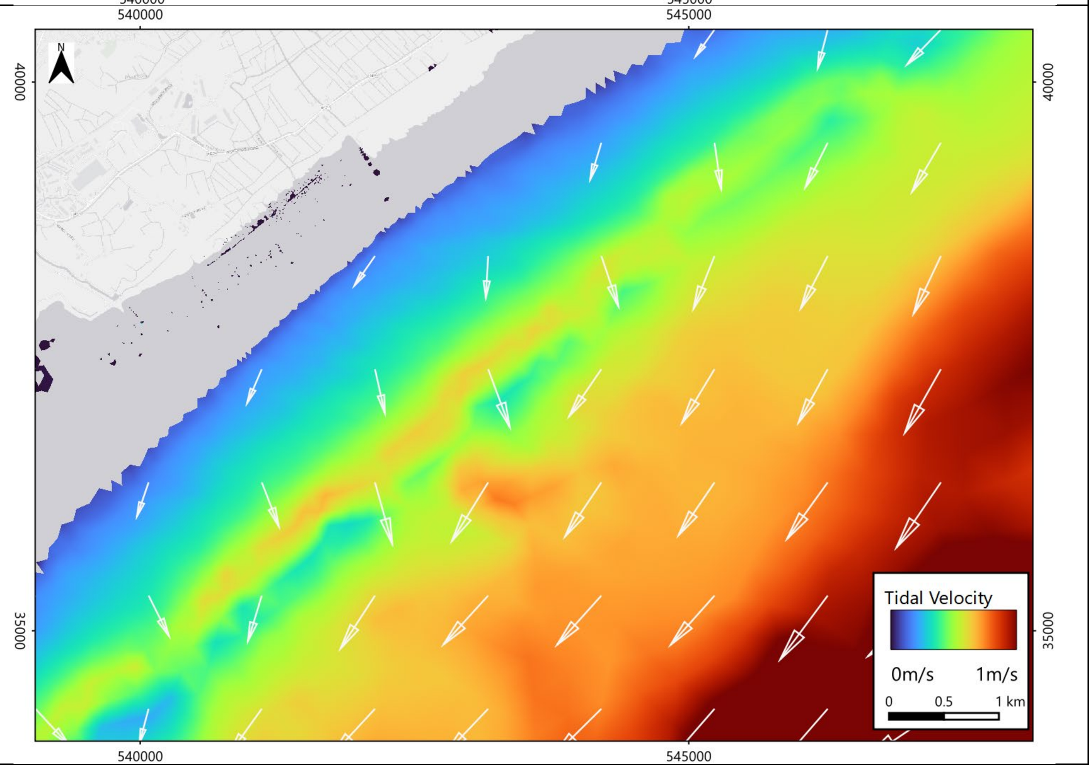

Source: ABPmer SEASTATES hindcast 1979 to 2020

**Figure 16. Offshore wave regime**

## 3.9 Flow regime

The flow regime is shown below as Figure 17 below which uses depth-averaged current speed data extracted from ABPmer's Severn Estuary tide model over a representative spring tide. This shows that flows are predominantly aligned along the frontage with both flood an ebb vectors shore parallel. Figure 17 also shows that flows along the nearshore of the Polders on the tidal ebb are elevated compared to flows on a flooding tide, with water velocities in the upper intertidal peaking at approximately 0.5 m/s on the tidal ebb.

| Tidal phase | Tidal current speeds in the vicinity of Rhymney marshes |
|---|---|
| HW |  |
| HW+2 |  |

| | |
|---|---|
| HW+4 |  |
| LW |  |

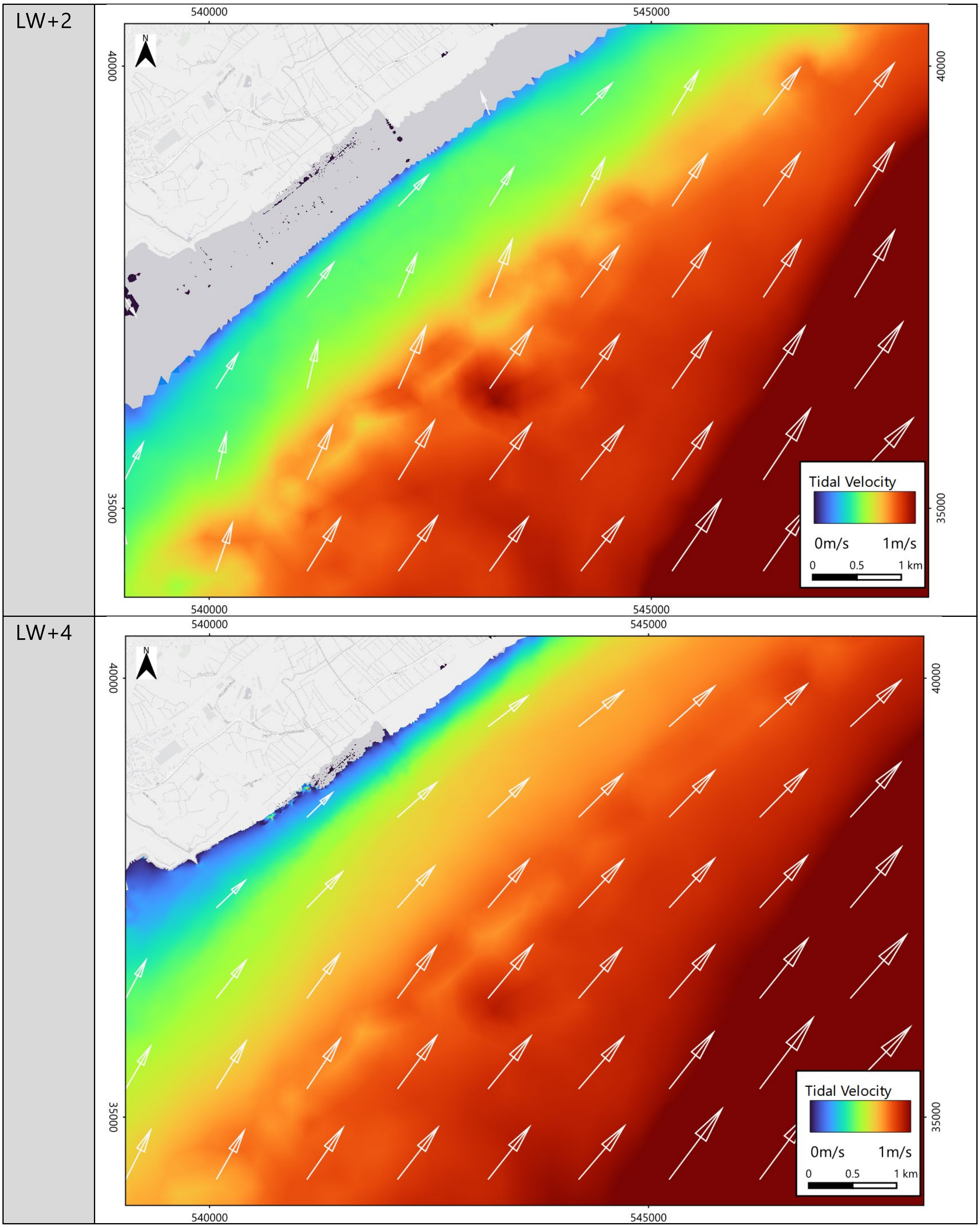


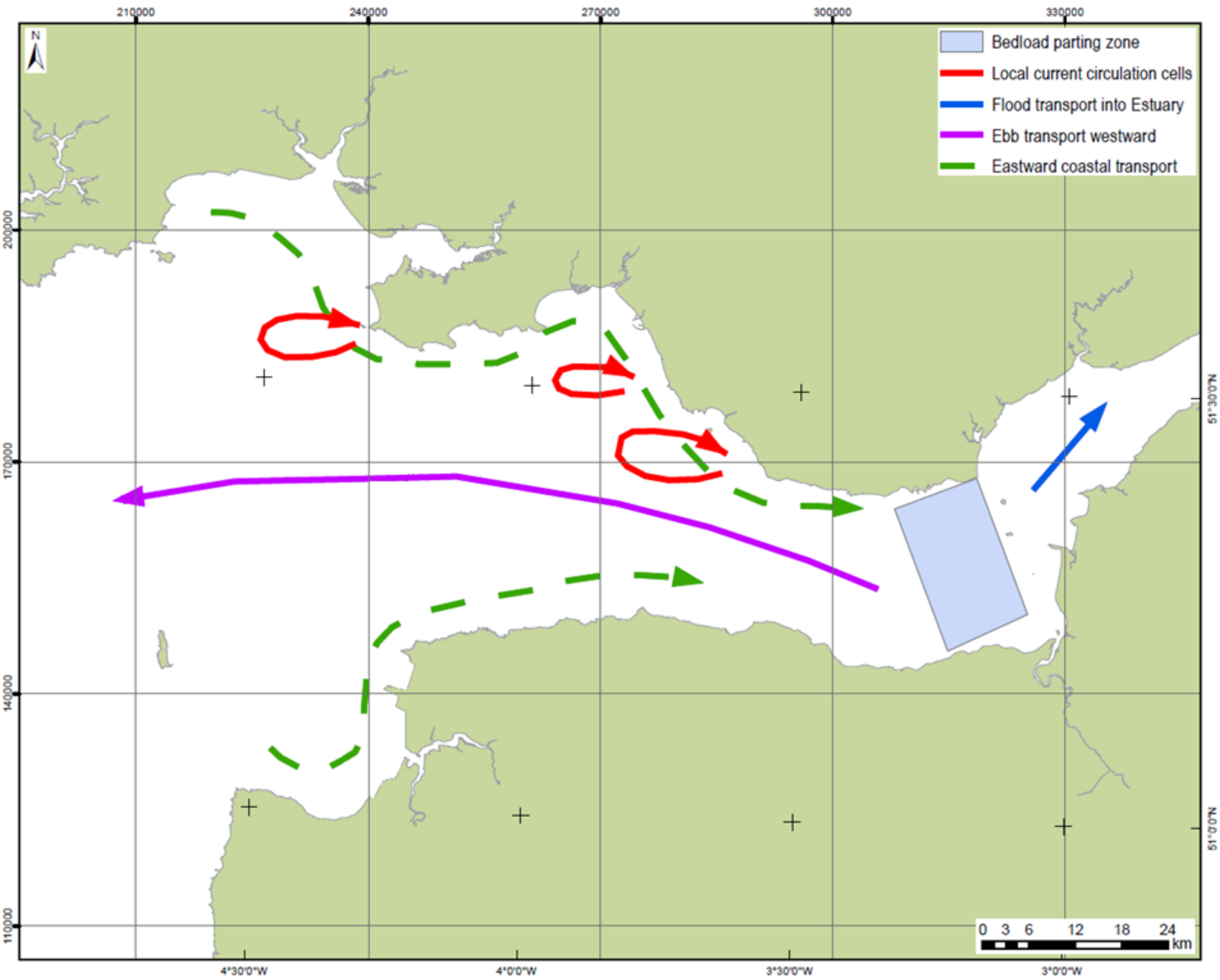

**Figure 17. Flow regime offshore of Rhymney Great Wharf**

# 3.10 Sediment transport regime

## 3.10.1 Sand transport

The conceptual sediment transport model for the transport of coarse sediment within the Bristol Channel is provided in Figure 18 below and illustrates a bedload parting zone just downstream of Flat Holm and Steep Holm, at the boundary between the Inner Bristol Channel and the Severn Estuary. To the east of the parting there is a net easterly transport pathway, driven by the dominant flood tide, into the Severn Estuary; to the west of the parting, through the Bristol Channel and beyond, the bedload transport direction is predominantly towards the west. In both cases the sediment transport is predominantly driven by the tidal asymmetry either side of the parting.

This process has swept the seabed clear of surficial sediment cover, leaving large expanses of exposed bedrock that characterise the bedload parting zone. The location of the bedload parting is seen to fit well with results from hydrodynamic modelling and is coincident with the area with the highest bed shear stress (Pingree and Griffiths, 1979); Mackie *et al*., 2006 (cited in ABPmer, 2016b)).




(Source: Developed by Posford Duvivier & ABP Research & Consultancy (2000) cited in ABPmer, 2016b))

**Figure 18. Conceptual bedload sediment transport pathways**

### 3.10.2 Mud transport

The main pathway for fine sediment transport is through tidal advection and flows are aligned with the main estuary channels with local circulations also developed around headlands and islands.

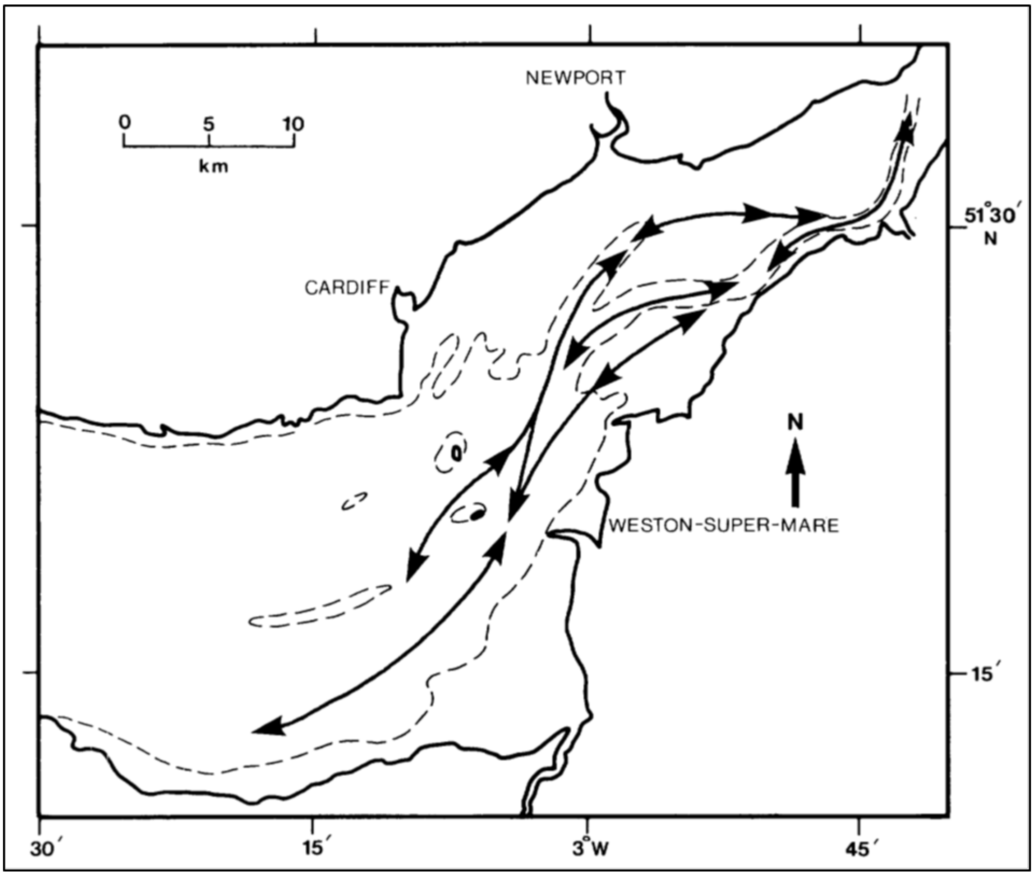
The ABPmer (2016) study concluded that the exchange of tidal volume with the high sediment load was an important mechanism for transporting fine sediment. It estimated that the tidal prism is around 11,000 million $m^3$ on typical spring tides, and around 6,600 million $m^3$ on typical neap tides (around 7,900 million $m^3$ along the study frontage). In addition, the volume of water which remains in the estuary at low water on spring tides was estimated to be 5,700 million $m^3$, which is around half of the spring tidal prism. This means that around half of the fine sediments resident in suspension at these times is discharged into the (Inner) Bristol Channel on the ebb before being advected back on the flood tide (assuming no periods of deposition). This exchange of tidal volumes with high sediment loads is considered to be an important mechanism for transporting (advecting) muddy sediments from the estuary into Bridgwater Bay (and back), noting that the bay may also act as a sink and store for large amounts of muds.

The sediment load within the Severn Estuary is estimated at 30 million tonnes on high spring tides, reducing to around 2 million tonnes on low neap tides. This suggests that under the lower energy neap conditions, material settles out of suspension, to the bed, before being resuspended as tidal range increases towards spring tides (ABPmer, 2016b).

Parker and Kirby (1981) offers a generalised circulation pattern for the mobile suspension (Figure 19) as cited in ABPmer 2016 and the volume of fine sediment being transported is illustrated through aerial photography (Figure 20) showing surface suspended sediment distribution across the Severn Estuary into the Bristol Channel from a satellite observation captured on 11 May 2009 (and coincident with a period of spring tides with a tidal range of around 10.8 m at Avonmouth).

Figure 20 provides an example of surface suspended sediment distribution across the Severn Estuary into the Bristol Channel from a satellite observation captured on 11 May 2009 (and coincident with a period of spring tides with a tidal range of around 10.8 m at Avonmouth). This example shows an extended 'plume' which reaches as far as Swansea Bay (Central Bristol Channel region) with higher concentrations within the Severn Estuary.

For mud transport, the conceptual model is further illustrated in Figure 21 below which shows an ebbing pathway from both the River Usk and the River Parrett by GeoSea and Collins (1988) (cited in ABPmer 2016) based on sediment trends analysis of seabed material. As a result within the Severn Estuary, intertidal mudflats typically occur within the middle reaches, approximately between the Rhymney and the Second Severn Crossing of the channel and reflect the mud transport lines denoted in Figure 21.

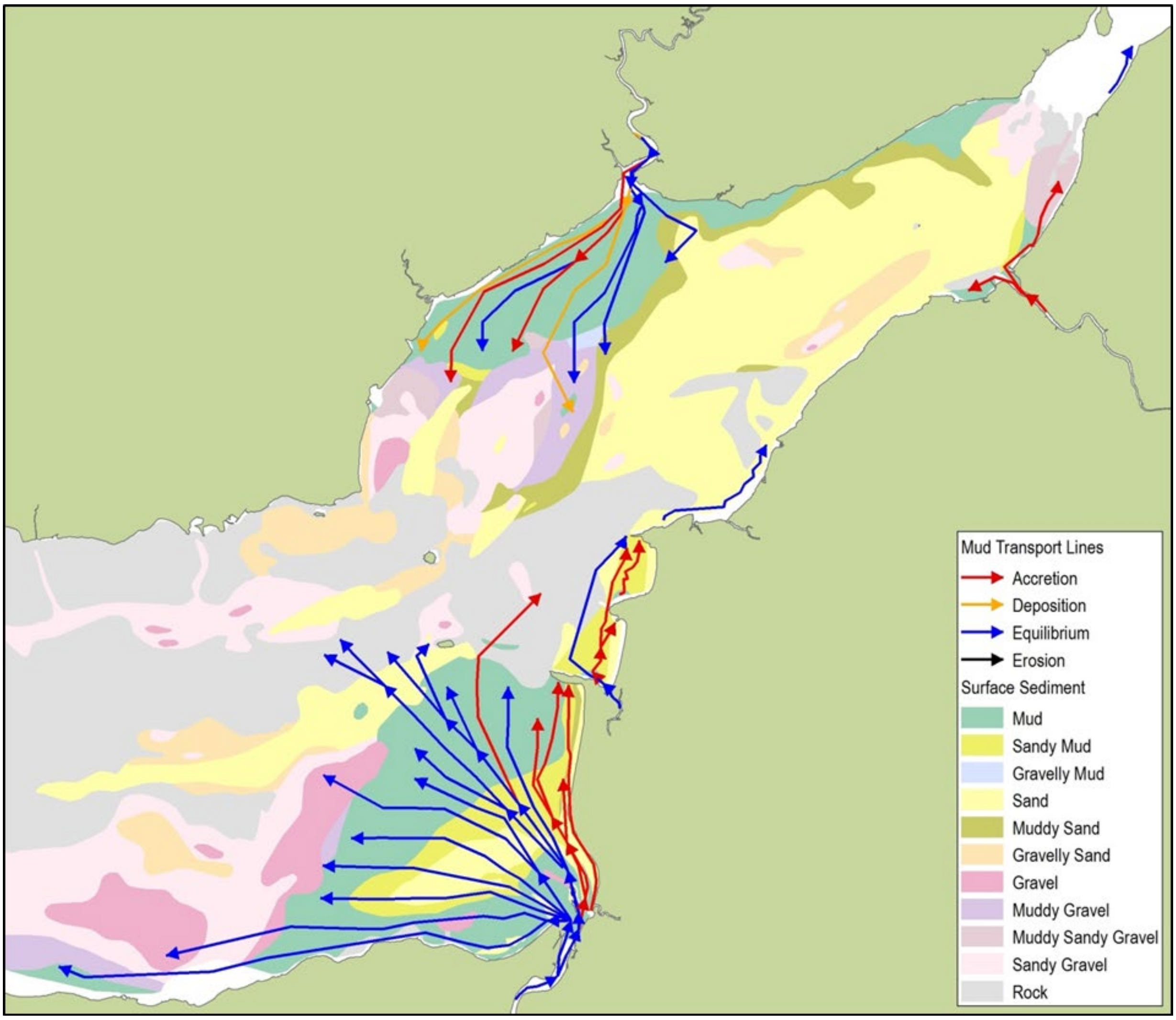



Source: Parker and Kirby, 1981

**Figure 19. Synoptic pathways for mobile suspensions in Severn Estuary (Parker and Kirby, 1981)**

Image from Chelys cited in ABPmer, 2016b

**Figure 20. Example of observed suspended sediment from satellite**



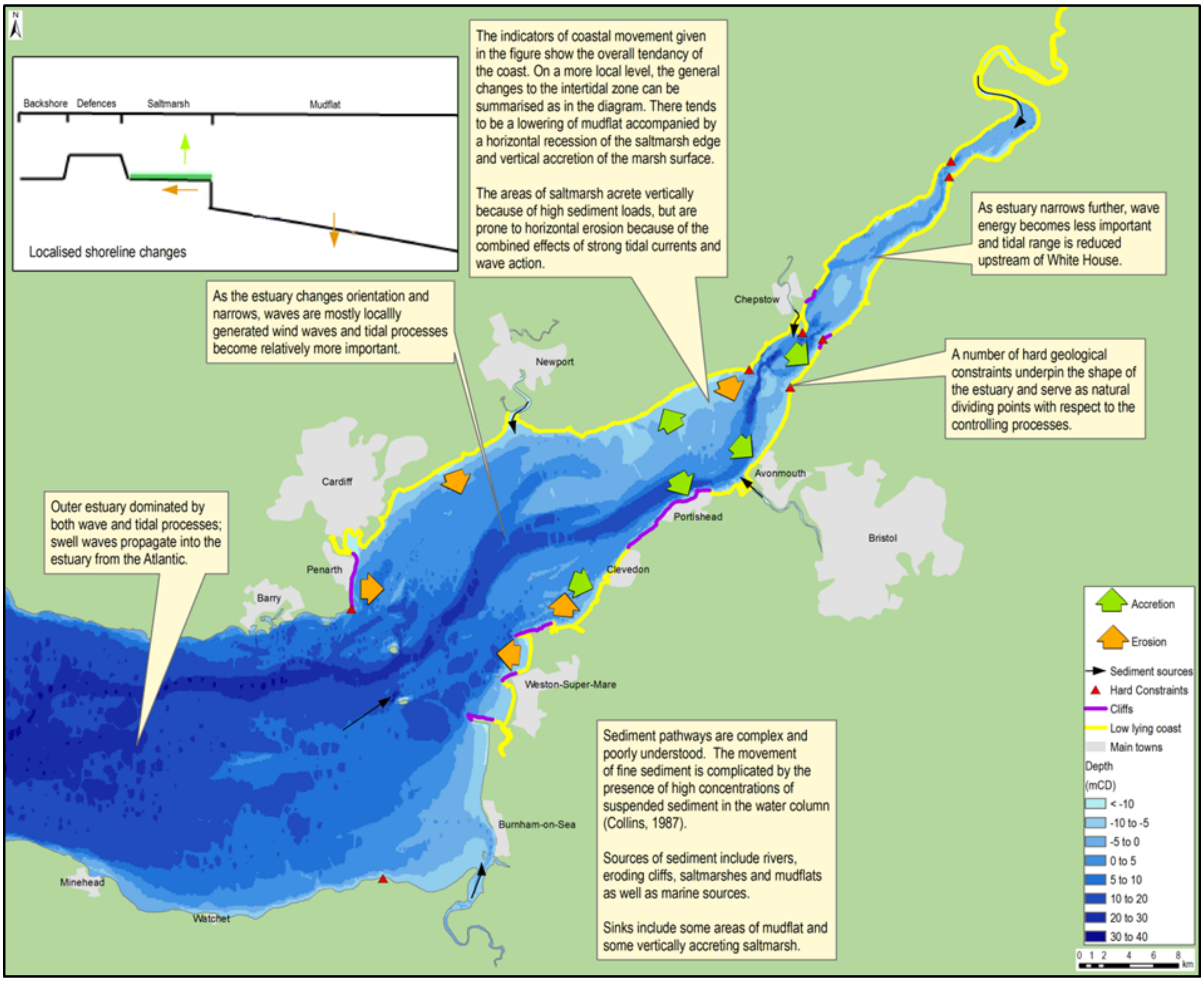

Source: After GeoSea and Collins, 1988,
Background image derived from BGS map of Quaternary sediment reproduced from ABPmer 2016)

**Figure 21. Mud transport lines, inferred by Sediment Trends Analysis.**

## 3.11 Erosion at the Rhymney Great Wharf frontage

The frontage, due to the number of pressures affecting the estuary, such as the presence of the tidal defences and sea level rise, is subject to erosion as illustrated in Figure 22 below taken from the Shoreline Management Plan (Severn Estuary Coastal Group, 2010).

A study by ABPmer (2016a) references evidence of erosion through the exposure of the Rhymney Valley Sewer Pipe (circa 4.5 to 5 km from Polder 5) having been revealed across the frontage, presumably by strong tidal currents, locally breaking waves and an over-consolidated Wentlooge Formation of bed material (Holocene deposits). The study noted that the sewer pipe was installed in 1920 but due to long-term local erosion the pipe is now fully exposed and rests on piles which stand some 3.3 m above the level of the mudflat (Kirby, 2010 referenced in ABPmer, 2016b). Google Earth shows further exposure and collapse of the sewer pipe.




Source: SMP2, Severn Estuary Coastal Group, 2010

**Figure 22. General indicators of intertidal trends**

## 3.11.1 Topographical change between 2005 and 2022

The more recent topographical change of the frontage has been investigated using 1 m LiDAR data of the foreshore between May 2005 and November 2022 available through DataMapWales. The following datasets were used:

- May 2005 - full coverage;
- January 2011 - partial coverage of the Polder field and eastern shoreline;
- February 2012 - partial coverage of the Polder field and eastern shoreline;
- February 2015 - full coverage; and
- November 2022 - full coverage.

The LiDAR datasets were reviewed against control points, where changes in elevation is unlikely, such as carriageways and carparks. The LiDAR datasets were found to fluctuate between ±0.05 m with errors as large as 0.12 m identified. Subsequently, change of ±0.10 m was considered to be within measurement error and not considered significant.

### 2005-2011

Polders 1-4 were constructed in 2005 and between 2005 and 2011, we see a general pattern of accretion from Polder 2 eastward.  This is most significant in Polders 4 and 5, where accretion over 0.5 m is observed. Seaward of this, there is erosion of the saltmarsh fronting Polders 4 and 5, with bed levels lowering as sediments are eroded.

This trend is replicated in Polders 3 and 2, with accretion of less than 0.5 m observed in the upper intertidal, and erosion observed directly behind the Polder fence at Polder 2.

Within Polder 1, erosion is noted (>0.25 m) over much of the Polder area, indicating that sediments have been lost from this area since Polder installation in 2005. This would indicate that the Polder was not functioning.

Further west, there was both erosion and accretion.


**Figure 23.** **Topographic change between 2005 and 2011**

### 2011-2012

Between February 2011 and February 2012, the area of assessment is limited to the upper foreshore of Polders 1-4, due to the coverage of the available data.


**Figure 24. Topographic change between 2011 and 2012**

### 2012-2015

Between 2012 and 2015 surveys, we see the reductions in elevations observed 2011-2012 reversed, with general accretion on the intertidal saltmarsh fronting the riprap armour, particularly in Polders 2-5.

However, the surrounding mudflat appears to be subject to ongoing erosion with a general reduction of 0.15 m observed, seaward of the established saltmarsh.

Polder 1 shows a continual pattern of erosion and whilst there appear to be small areas of accretion to the west, the general pattern is one of erosion of up to 0.25 m.


**Figure 25. Topographic change between 2012 and 2015**

### 2015-2022

Between 2015 and 2022, little change in elevation of the foreshore was observed, with migration of channels noted in the mid foreshore but no significant bed change. In the upper foreshore, while the figure shows intermittent erosion/accretion, this is within the range of data uncertainty and therefore considered to be no change.


**Figure 26. Topographic change between 2015 and 2022**

### Overall change 2005 – 2022

Between May 2005 and November 2022, the overall trend outside the Polders and within Polder 1 is one of erosion of up to 0.5 m vertically, and a general retreat of the saltmarsh edge (where present) although there is a thin band of sediment accumulation fronting the rip-rap outside the Polders. On the mid foreshore, a shore parallel feature of no change is noted which is a small bar feature visible in cross-sections discussed in Section 6.2.1 and presented in Appendix A.

The saltmarsh, particularly within Polders 4 and 5 has accreted significantly, with areas of up to 0.8 m observed. This would indicate that these Polders have been functioning. It is however important to note that the saltmarsh to the east of Polder 5 has also been accreting over this period, with accretion of up to 0.5 m seen; thus, it is difficult to conclude how much of the accretion in the Polders can be attributed to the presence of the fences, and how much would have occurred regardless. Figure 27 illustrates that there is ongoing erosion of the seaward edge of the saltmarsh along the whole frontage, with localised decreases of up to 1 m observed.

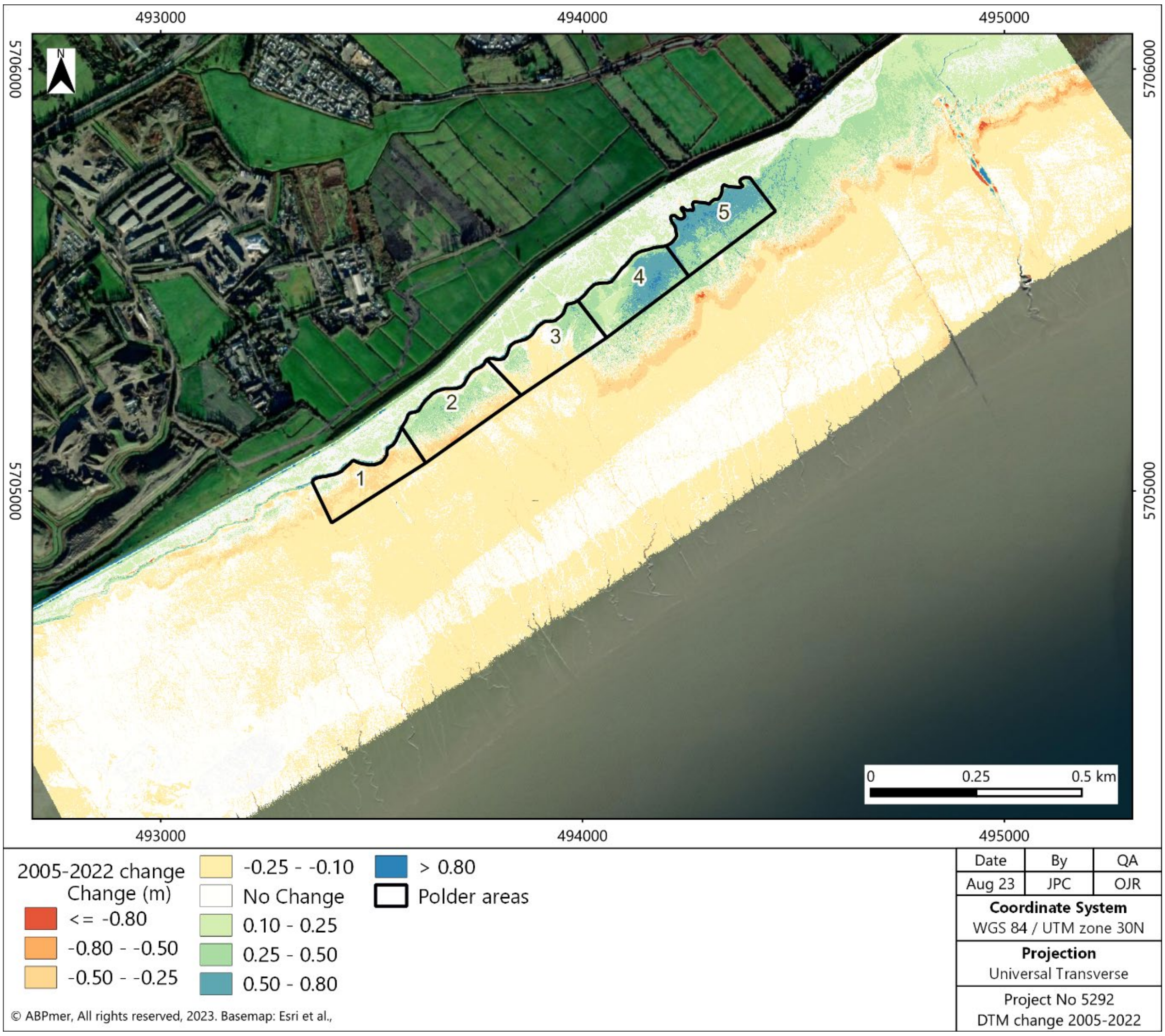



**Figure 27. Topography change between 2005 and 2022**

Within Polder 3, localised accretion is observed along the lateral (shore normal) boundaries of the Polder. However, the Polder area is dominated by bed level reduction, with erosion seen up to the riprap revetment in the centre of the Polder.

Within Polder 2, accretion is also observed towards the back of the Polder, with the most significant accretion observed between 2005 and 2011 (following its construction in 2005), although there is evidence of erosion just behind the seaward (shore parallel) alignment of the shore parallel fence.

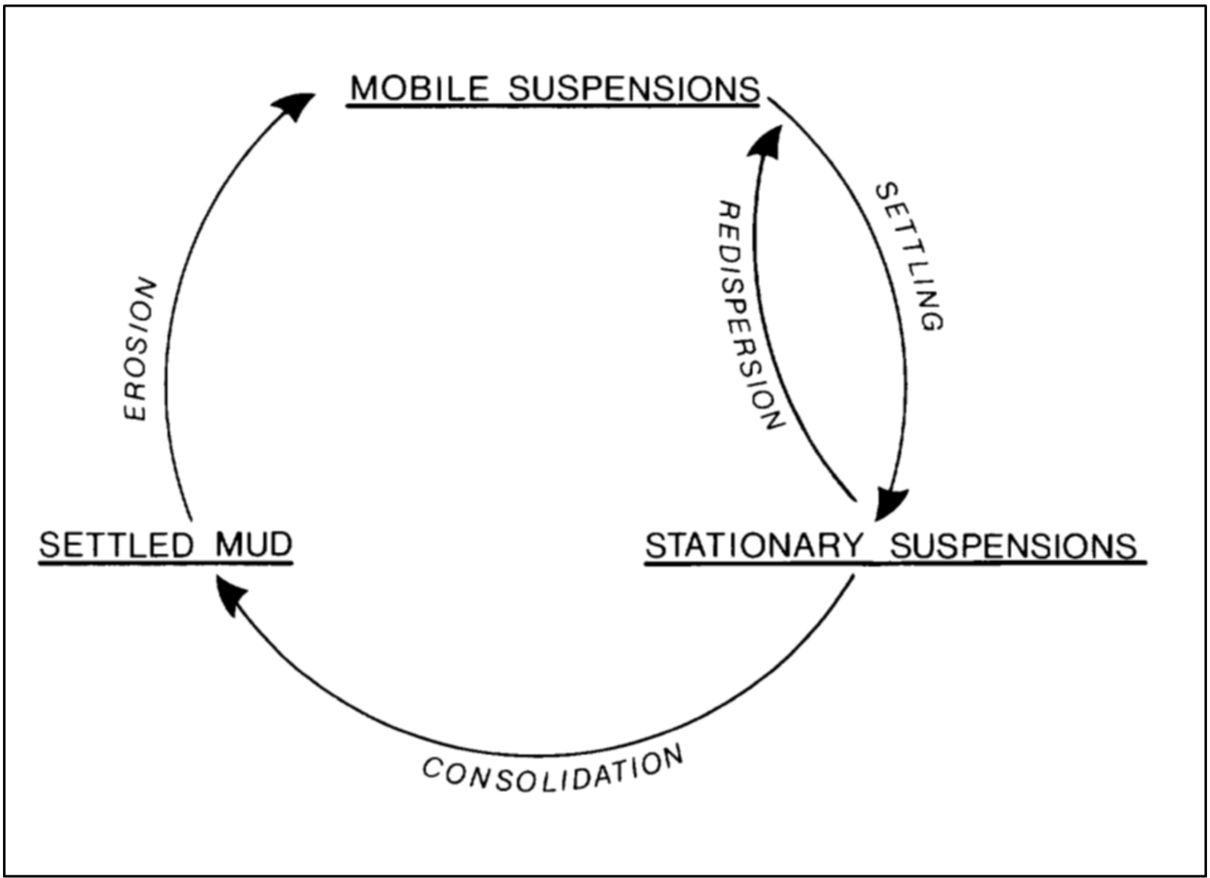
At Polder 1 and further west, while localised areas of accretion are observed, erosion dominates the foreshore with a general decrease of approximately 0.1 m throughout the profile, with areas decreasing by up to 0.3 m. There has been no trend of accretion visible at Polder 1 since its construction.

## 3.12 Potential for mudflat accretion at Rhymney Great Wharf

The Polders were intended to provide an environment which would be favourable to the settlement of the fine material out of the water column and onto the mudflat, thereby resulting in accretion and ultimately raising the bed level to a height suitable for colonisation by saltmarsh vegetation. The high levels of suspended sediment in the estuarine waters (as evidenced by Figure 20) suggest that there is substantial potential for accretion at Rhymney Great Wharf.

Material in suspension has the potential to settle to the bed under favourable conditions. The rate of settling for such material is dependent on a number of factors, including hydrodynamic conditions, material type, particle size, flocculation processes and suspended sediment concentrations (SSC).

The process is essentially a balance between competing forces acting on material in suspension. Gravitational forces will act to enable particles to drop down through the water column, and towards settlement on the bed; conversely, turbulent forces will act to encourage mixing, and maintain material in suspension, as illustrated in Figure 28. The relevant strengths of each of these forces will ultimately determine whether settling occurs and, if so, at what rate.




Source: Parker and Kirby, 1981 cited in ABPmer, 2016b

**Figure 28. Conceptual relationship in fine sediment behaviour in Severn Estuary**

Detailed analysis of sediment accumulation of the Wentlooge mudflats (immediately to the east of the study frontage) was undertaken by O'Brien *et al*. in 2000. This study examined the mudflats over a two-year period using a range of survey techniques. The study found that, as with the other evidence above, the mudflats are experiencing erosion, the rate of which increases offshore; this is also evidenced by the observed lowering of the lower intertidal, discussed in Section 6.2.1.

The O'Brien *et.al.* (2000) study can be considered as a direct analogue for the coastal processes operating at the Rhymney Great Wharf frontage, and provides important insights into the potential for the Polders to capture sediment. The study concluded that (O'Brien *et.al.*, 2000):

- Spring and neap tides showed markedly different SSC characteristics during each tidal inundation;
- Maximum SSC on a spring tide was on the peak flood and ebb, with between 3,000 and 4,000 mg/l observed; and
- Maximum SSC on a neap tide was during the first and last few minutes of tidal inundation, when the water depth was <1 m. This tended to be less than 1,000 mg/l.

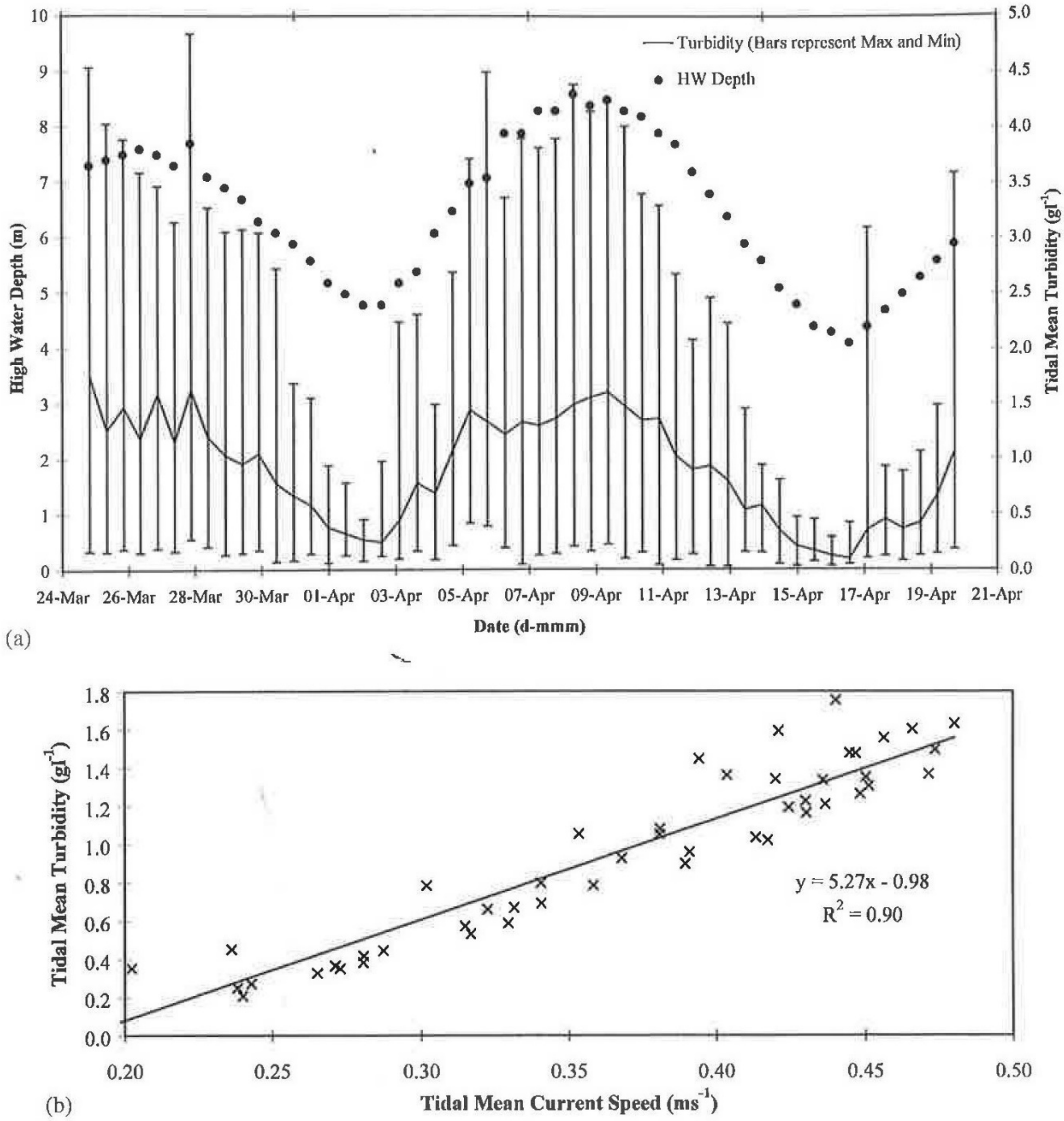
The relationship between mean turbidity and high water and mean turbidity and flow speed is illustrated in Figure 29 below, with O'Brien *et.al.* concluding that:

- Whereas the maximum and mean SSC is related to the position in the spring-neap cycle, the minimum (at HW slack) remains fairly constant;
- At mean HW slack, there is rapid deposition, with nearly all SSC deposited at all tidal conditions;
- The relationship between tidal mean SSC and tidal mean current speed is approximately linear; and
- Sediment accretion only occurs over the medium and long terms in areas where the maximum tidal current speeds are less than 0.9-1.0 $m/s^{-1}$.

The resulting pattern of sediment accumulation on the mudflats has been described in a conceptual model by O'Brien *et.al.* (2000) and is illustrated in Figure 30 below; this includes the ridge and runnel formations which will be relevant to any detailed design.

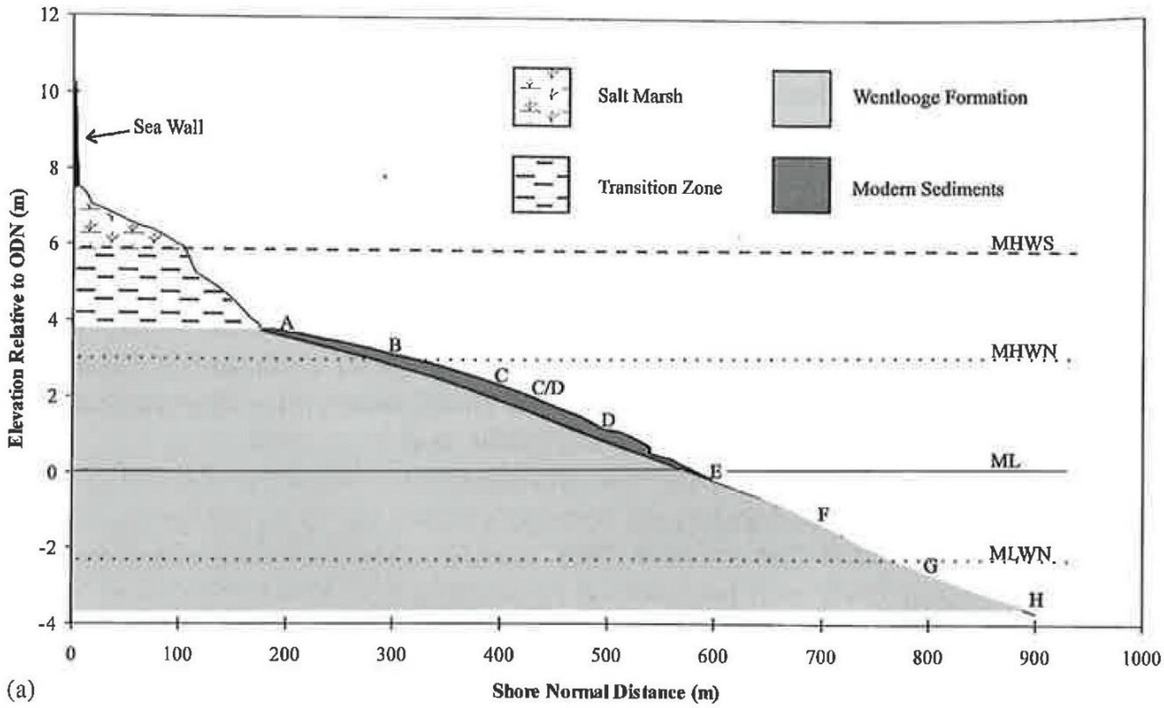
The conceptual model shows that the mudflats are subject to accretion during the summer periods, but then experience erosion during the winter months, in particular:

- Over the long term, measurements have demonstrated that the mudflats at Peterstone Wentlooge in the Severn Estuary is experiencing erosion, and the rate of this erosion generally increases with distance offshore;
- The modern [sediment] layer was completely removed during some winter periods and some erosion of the underlying Wentlooge Formation occurred;
- The deposition leads to the formation of fluid mud layers and wave agitation results in the resuspension of the sediment. Freeman (1994) cited in O'Brien *et.al.* (2000) speculated that deposition could be prevented by waves over 0.05 m based, upon a study in the southern shore of the Severn Estuary; and
- The surface topography varies in response to deposition events during high water periods and the occurrence of locally generated waves. The amplitude of the topography can change on a day-to-day basis (O'Brien *et.al.*, 2000).
- In general, there are consistent mechanisms to supply sediment to the intertidal, through tidal processes. When conditions are suitable, sediment is deposited, and overtime can start to consolidate. Whether deposited sediment remains *in situ*, is dependent on the interaction between episodic events (i.e., wave conditions) and how these coincide with the periodic tides (i.e., spring-neap cycle).




Source: O'Brien *et. al.* 2000

**Figure 29. Relationship between mean turbidity and water level (top) and mean turbidity and mean current speed (bottom)**




Source: O'Brien *et. al.* 2000

**Figure 30. Conceptual model of mudflat development and erosion at Wentlooge**

# 4 Other Polder Projects

This section highlights the lessons learned from project experience in the Wadden Sea. A brief summary of the environmental conditions of the area is also provided for consideration when comparing the projects with the conditions that would be experienced in the Severn Estuary.

## 4.1 Conditions in the Wadden Sea

McBride et. al. (2013) provides a comprehensive description of the conditions in the WaddenSea. This is reproduced below to provide a context to the history and success of saltmarsh creation through Poldering in the Wadden Sea.

The tidal range in the Wadden Sea varies between '1.*3 m in the in the southernmost part at Texel and increasing along the coast from west to east and reaching a maximum of 3.5 m in the German Bight at the outlet of the Elbe River. North of the Elbe River, the tidal range decreases gradually to about 1.5 m at the northernmost barrier island, Skallingen'*. About 65% of the Wadden Sea area emerges at low tide, exposing large areas of intertidal flats that are mainly composed of medium-grained sand and mud. Muddy tidal flats typically occur in the inner, sheltered parts of the tidal basins. In the northern part of the Wadden Sea, contemporary accretion rates of mud flats commonly are large, 10–20 mm $yr^{-1}$, exceeding sea-level rise considerably.

Most of the natural saltmarshes of the Wadden Sea were land claimed / diked during the last 500 years, and only minor areas of undiked saltmarsh remain. Today, undiked saltmarshes occur on the back-barrier side of the islands and along the mainland coast, in front of the dikes. The transition from the intertidal flats to the supratidal saltmarsh frequently is marked by an erosional cliff. The largest of the saltmarsh complexes is at the Skallingen peninsula in Denmark and covers some 10 $km^2$. During the past several decades, net deposition at Skallingen has been on the same order of magnitude as recent sea-level rise.

Little consensus exists among researchers as to the recent sediment budget for the Wadden Sea. Sediment accumulation rates for the Danish Wadden Sea area indicate that sedimentation probably can keep pace with sea-level rise, whereas research in some German areas points to a mud depletion because of a change in the normal energy gradient caused by dike construction. Most of the mainland coast is protected by dikes and sea walls.

Prevailing winds in the Wadden Sea region are westerly, especially during the autumn and winter periods, in connection with low-pressure systems moving across the North Sea. Typical average annual wind speed for the central part of the Wadden Sea is 8 m/s along the island coast, and about 6.5 m/s along the mainland coast. Westerly winds exceed 30 m/s almost every year, and cause wind setup inside the Wadden Sea of up to 5 m above mean sea level. Mean annual wave heights along the North Sea coast are about 0.5 m, and maximum wave heights are >5 m. Maximum tidal current velocity in the inlets is ~1.5 m/s, decreasing to about 1 m/s in major tidal channels inside the Wadden Sea. In small tidal creeks within the Wadden Sea, maximum current velocities rarely exceed 0.5 m/s. Typical maximum current velocity across tidal flats is 0.3 m/s.

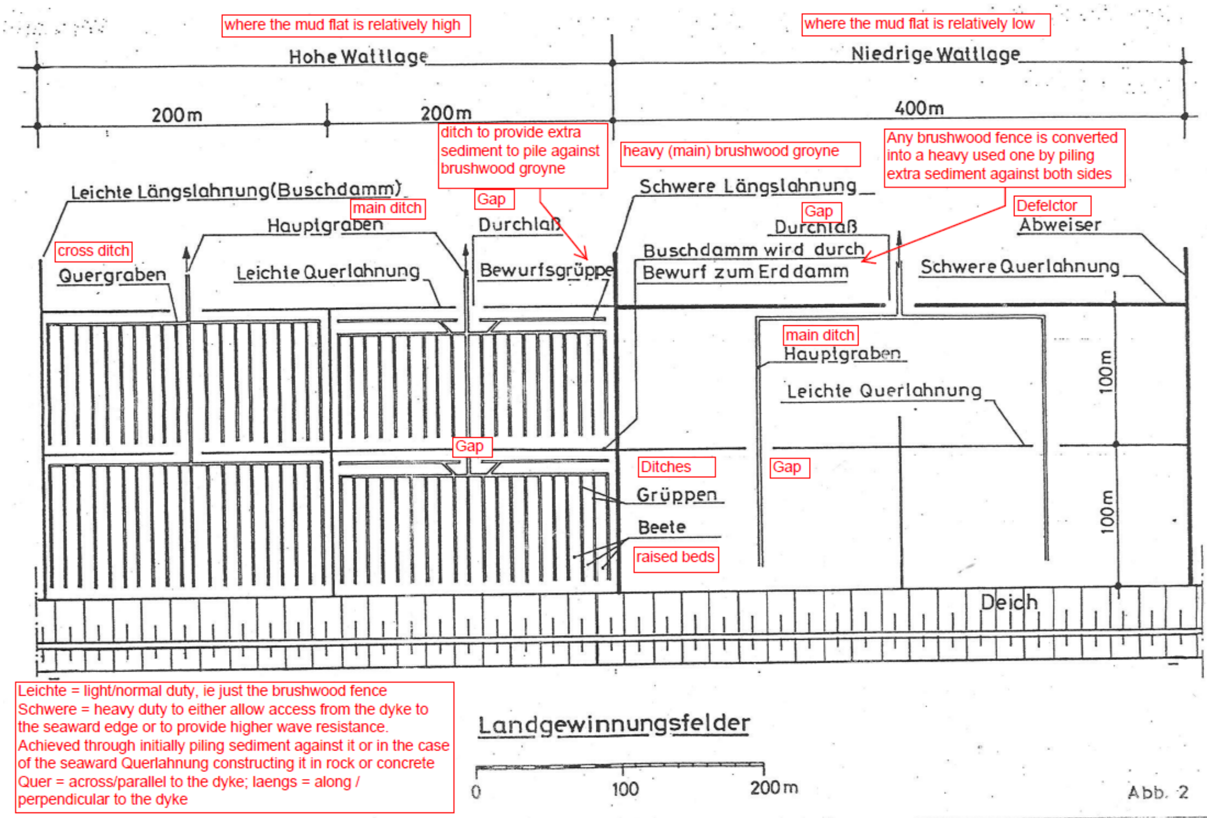
## 4.2 Other projects

The outputs of a fact-finding study to the Wadden Sea by the Environment Agency and Natural England in 2019 provides useful context to the designs. This is documented in Dornbusch (2019) and the findings are summarised below.

- '*The system was introduced as a process of land reclamation and only more recently being implemented as a solution for coastal defence and nature conservation*'.
- '*The brushwood barriers system is a combination of dominantly brushwood fences and ditches arranged shore perpendicular and shore parallel to speed up the accumulation of mud and silt in the intertidal*'. This is illustrated in Figure 30 below. It should be noted that the mudflat elevation at Rhymney is low in the tidal frame (lowering considerably from east to west).
- 'The orientation of the channel system can vary up to a 45° angle due changes in coastal alignment'.
- '*The brushwood fences or more substantial barriers at the seaward edge (Figure 31) reduce wave and current energy into the system to encourage sedimentation, reduce subsequent erosion and provide stabilisation of the sediment system'. The report notes that the Querlahnumg are 'breastwork structures that are parallel to the coastline made in the same way as a brushwood groyne; the most seaward has been built in Lower Saxony since the 1970s often from precast concrete segments or more recently as rubble mound; in Schleswig-Holstein gabion basket walls have also been used. They act as a wave breaker, encourage sedimentation landwards and direct flow paths towards the gap within the fields*'.
- The ditch system has the following four functions:
  - 'It efficiently allows for suspended sediment to be carried landwards to the areas intended for deposition.
  - Sedimentation within the channels and ditches is transferred through regular excavation onto the raised beds between (Figure 17), which accelerates the topographic build-up of the land and to bring them into the elevation zone where pioneer vegetation can start to grow. Vegetation will then stabilise the sediment further through root growth and also retain sediment
  - It efficiently drains the system which stabilises the sediment on the beds by allowing it to de-water and consolidate
  - It guides the flow of water'.

It is noted in the report that the drainage system is also considered important for maintaining the integrity of the dykes (sea walls) with a dich to the rear of the Polder field, as the areas behind the systems in the Wadden Sea require draining. The need to accommodate rear drainage at Rhymney to maintain the long-term integrity of the rock faced embankment, should be considered as part of the detailed design.

The drainage density within the brushwood barriers system is up to an order of magnitude higher than in natural marshes, leading to highly efficient transport of sediment laden water into the entire site and efficient drainage allowing the beds to dry out and compact leading to faster accumulation. The design is geared to the quickest way to reclaim land and bring it into agricultural use.




Source: Dornbusch, 2019

**Figure 31. Schematic plan view of a brushwood barrier system in Lower Saxony (Germany), with translations**

The conclusions of the study with respect to its application in the UK are '*the brushwood barriers system to reduce wave and current energy and providing some scope to physically retain higher sediment within to improve the Window of Opportunity associated with surface elevation, seed availability and lack of seedling disturbance during the initial growth phase. Depending on the existing levels, the creation of ditches and raised beds may be required initially to increase existing elevations to those suitable for pioneer vegetation, however, the direct impact and legacy these ditches have on the evolution of any drainage patterns needs to be considered seriously*'.

The report notes that land raising could be achieved through sediment import as has been done at Lymington (Lowe, 2013) and Brightlingsea in 2017 and 2018 (Exo Environmental, 2018, 2017) or if the SSC is sufficient through the use of biodegradable structures. An additional benefit of brushwood barriers in the English environment, where disturbance through leisure craft activity is most pronounced in the growing season of the pioneer vegetation, is the reduction in vessel wake energy and physical boat access to these areas. The physical exclusion of boats would also reduce any resuspension of mud through these vessels.'

The mudflat elevation at Rhymney is low in the tidal frame and land raising would be beneficial for the development of saltmarsh.  An assessment into the beneficial use of dredge materials to increase mudflat elevation at Rhymney was conducted by Atkins in 2006 (Atkins 2006) as discussed in Section 3.2.


Dornbusch (2018)

**Figure 32. Images of a concrete seaward toe of the Polder system at the outer Querlahnung**

NRW has also liaised with an employee of the Schleswig Holstein (Germany) flood risk and national park management agency, who provided the following design advice which is summarised below along with considerations with regard to the Rhymney frontage:

- Classic sedimentation field ('Lahnungsfeld') design is 200 m deep[2], 400 m wide with two deflectors as shown in Figure 33
    - The depth will need to be dependent upon the frontage bathymetry in relation to the tidal frame).
    - The mudflat elevation at Rhymney is low, drainage would not be beneficial.
- The Polders should not be more than 1 m above the mudflat.
- The Polder is usually not higher than 10 cm above MHW.
    - Due to the very high tidal range at Rhymney, this is likely to significantly limit the visibility of the structure in the tidal frame and hence the ability to trap sediment over the tidal cycle.

2 Note this will be dependant upon the bathymetry at Rhymney!

- The hydrodynamic pressure limits the brushwood height to around 90 cm tall.
- Recommended offset posts (as per the 1998 design) with a 40 cm spacing (60 cm used at Rhymney).
- Softwood spruce recommended for the brushwood as the resin is more resistant to saltwater.

The above insights support those summarised in the 2019 ABPmer report, which noted:

*Construction methods vary along the Dutch and German North Sea coasts and are often informed by local traditional experience. However, the fences tend to be constructed at 1 m height, and the top of the fences would be constructed to be at, or near, the MHW mark (e.g., von Lieberman et al., 1998; Blumenthal, 1966). The bottom of the fences is frequently protected by small wedges, with materials scraped from adjacent mudflats. Furthermore, the shore parallel fence line, where located in an exposed location, would tend to be reinforced using a variety of methods, including armouring with rocks or concrete, double fencing / installation of additional brushwood bundles, and the utilisation of filled geotextile tubes (e.g., Erchinger, 1970). Field dimensions vary from around 100 m by 200 m to 400 m by 400 m (e.g., von Lieberman et al., 1998; Blumenthal, 1966).*

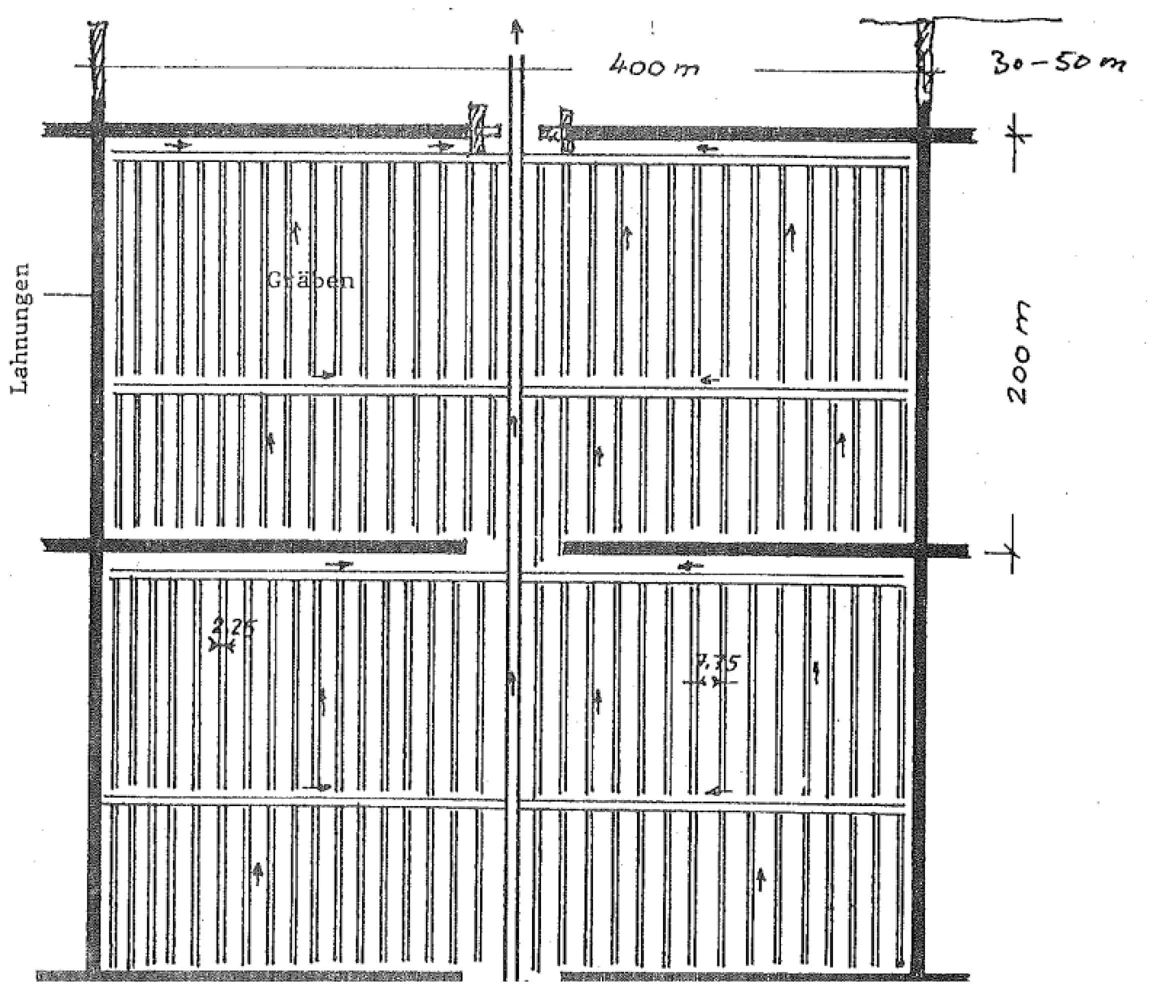
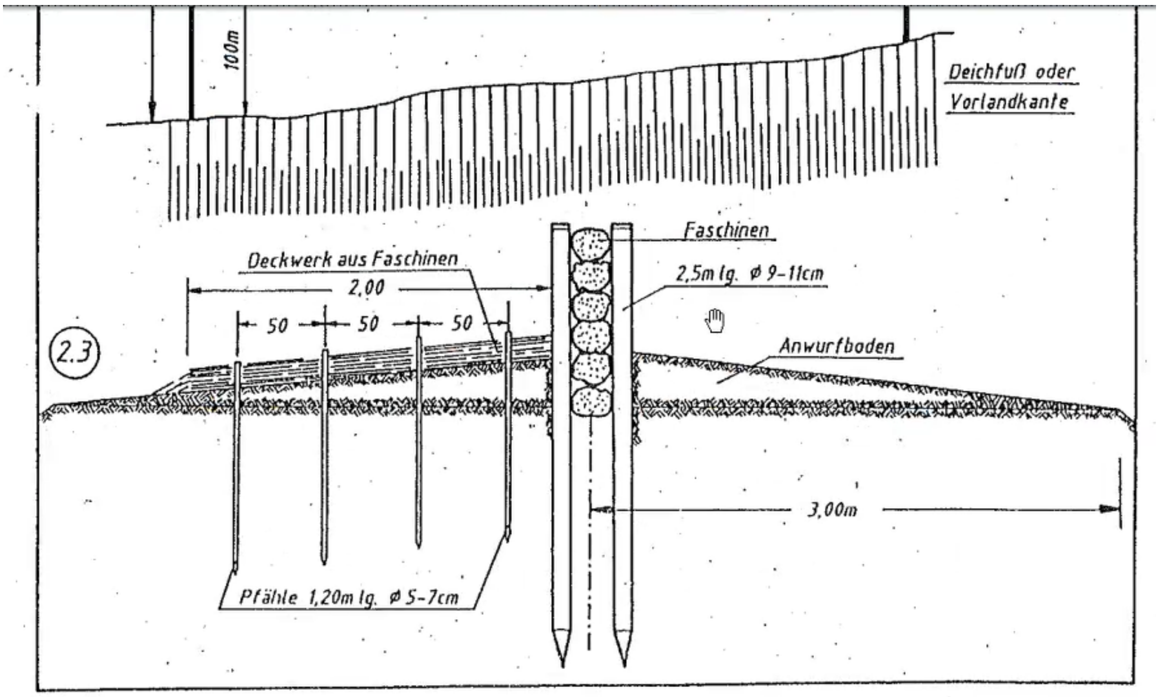



**Figure 33. Classic Lahnungsfeld design (provided by Fabian Luecht)**


Pprovided by Fabian Luecht

**Figure 34. Example of scour protection using brushwood**




Pprovided by Fabian Luecht

**Figure 35. Example of a mud ramp covering the lowest brushwood bundle for scour protection**

# 5 Design Considerations

The following provides a summary of the design considerations for the study.

## 5.1 Technical considerations

Funding is secured for five years of maintenance but for the purposes of the outline design it is assumed maintenance will be ongoing. The following should be considered (Salix, pers. com.):

- Chestnut posts/steaks have a life expectancy of 10-15 years;
- Hazel brushwood has a life expectancy of 3-4 years; willow brushwood *circa* 1-2 years; and

The project has reviewed a range of data and information to support the design development. Whilst there is information available on the design and management of Polder systems in Germany and the Netherlands (ABPmer, 2019a and Dornbusch, 2019), there is little information in the UK and the existing Polder system at Rhymney Great Wharf has not been maintained or monitored. The information gathered has identified the following design considerations:

- The Polder heights in the Wadden Sea are at a maximum of 90 cm, it is considered that higher Polders are subject to too much tidal energy;
- The brushwood fencing in the Wadden Sea reaches the full height of the Polders;
- The smaller the Polder fields, the greater the sedimentation;
- The maximum height the brushwood and Polder steaks can withstand is generally considered to be 1 m;
- Wave heights of greater than 1 m are likely to cause damage (Salix, pers. com.);
- The traditional field alignment proved more successful in numerical model tests in the Wadden Sea (Siemes *et. al.,* 2020).

## 5.2 Environmental considerations

The key conclusions from the conceptual understanding are:

- The frontage has been subject to erosion, particularly in the lower foreshore and erosion of the saltmarsh edge;
- The topography steepens significantly from east to west;
- There are suitable volumes of sediment in suspension to support deposition and siltation onto the mudflat, when hydrodynamic conditions allow;
- The substantial tidal range of *circa* 11 m is a significant limiting factor;
- The design needs to reduce flow velocities at high spring tides (which contains the greatest proportion of sediment in suspension);
- Sediment accretion is only found to occur over the medium and long terms in areas where the maximum tidal current speeds are less than 0.9/1.0 $m/s^{-1}$;
- Wave conditions are further significant limiting factor in the scheme's ability to retain sediment with wave agitation resulting in resuspension of the sediment with evidence of sediment accumulated during the summer months lost during winter periods. Freeman (1994) cited in O'Brien et.al. (2000) speculated that deposition could be prevented by waves over 0.05 m based upon a study in the southern shore of the Severn Estuary; and
- The Polders will need to protect the frontage from wave conditions during the winter months to maintain the sediment accumulated in the summer months.

## 5.3 Saltmarsh development considerations

When considering the design of a scheme for saltmarsh creation, using hypsometry is an important initial step in understanding the potential for establishing saltmarsh habitat. The Rhymney Great Wharf frontage consists of mudflat and saltmarsh and the following is the industry standard guide to the position of intertidal habitat in the tidal frame:

- Mudflat (MLWS to MHWN);
- Saltmarsh (MHWN to MHWS); and
- Grazing marsh (MHWS to HAT +1 m).

The above is considered to be a general guide and mapping of the existing saltmarsh and analysis of the LiDAR data has indicated that along the Rhymney Great Wharf frontage, saltmarsh is forming at approximately the MHW tidal level (± *circa* 1 m) rather than MHWN. As such, **MHW is taken to be the key tidal level when considering the development of saltmarsh along the frontage** (noting however that, with enhanced shelter, saltmarsh may well establish to lower elevations).

These tidal frames will be the focus for the topographic analysis in Section 6.2.1 below.

# 6 Analysis of Polder Alignments

## 6.1 Introduction

This section provides the results of the analysis undertaken to identify a preferred outline option for Polder alignment. The analysis uses the understanding gained from the literature review, conceptual understanding, geometric analysis and results of tests using the HD and wave numerical models.

The first step was to complete the analysis and tests for the original Polder alignment in order to provide an understanding of the potential success of the Polders should they have been maintained.

Following a review of the results from the existing Polders, a further four alignments have been developed for testing. The five options have then been subject to a high-level assessment to identify a preferred option to take forward.

When reviewing the results of analysis, it is important to consider the experience and design considerations which are summarised in Section 4.2 above.

## 6.2 Existing polder alignment

### 6.2.1 Geometric analysis

To review the success of the Polder field since 2005, 23 cross-sections were extracted from the LiDAR data along 2.8 km of shoreline as illustrated in Figure 36. A selection of cross sections are provided below along with supporting discussion. The remaining cross sections are provided as Appendix 1.

It should be noted that LiDAR datasets from 2011 and 2012 do not extend further east than Polder 5.

For the purposes of the analysis:

- The Polder crest is taken to be 1 m which is the design height of the top of brushwood fencing (section 3.2).
- The locations of the Polders have been identified from Google Earth
- The Polder locations have been added to the cross sections
- The level of the Polders is taken from the 2005 LiDAR.

The Polder levels are provided as Table 7 along with the relative distance between the Polder crest (taken to be 1 m high) and MHW. MHW having been identified as an important design consideration in Section 4.2 above (Waddensea polders are not normally 10 cm above MHW).

**Table 7. Polder elevation derived from 2005 LiDAR**

| Polder | Bed Level (mODN) | Indicative Polder Crest Height (mODN) | Difference from MHW (4.6 mODN) | Difference from MHWS (6.24 mODN) |
|---|---|---|---|---|
| 1 | 3.1-3.2 | 4.1 | -0.5 | -2.13 |
| 2 | 3.2-3.5 | 4.5 | -0.1 | -1.73 |
| 3 | 3.0-3.5 | 4.7 | 0.1 | -1.53 |

| | | | | |
|---|---|---|---|---|
| 4 | 4.7-4.8 | 5.8 | 1.2 | -0.43 |
| 5 | 4.5-4.8 | 5.8 | 1.2 | -0.43 |

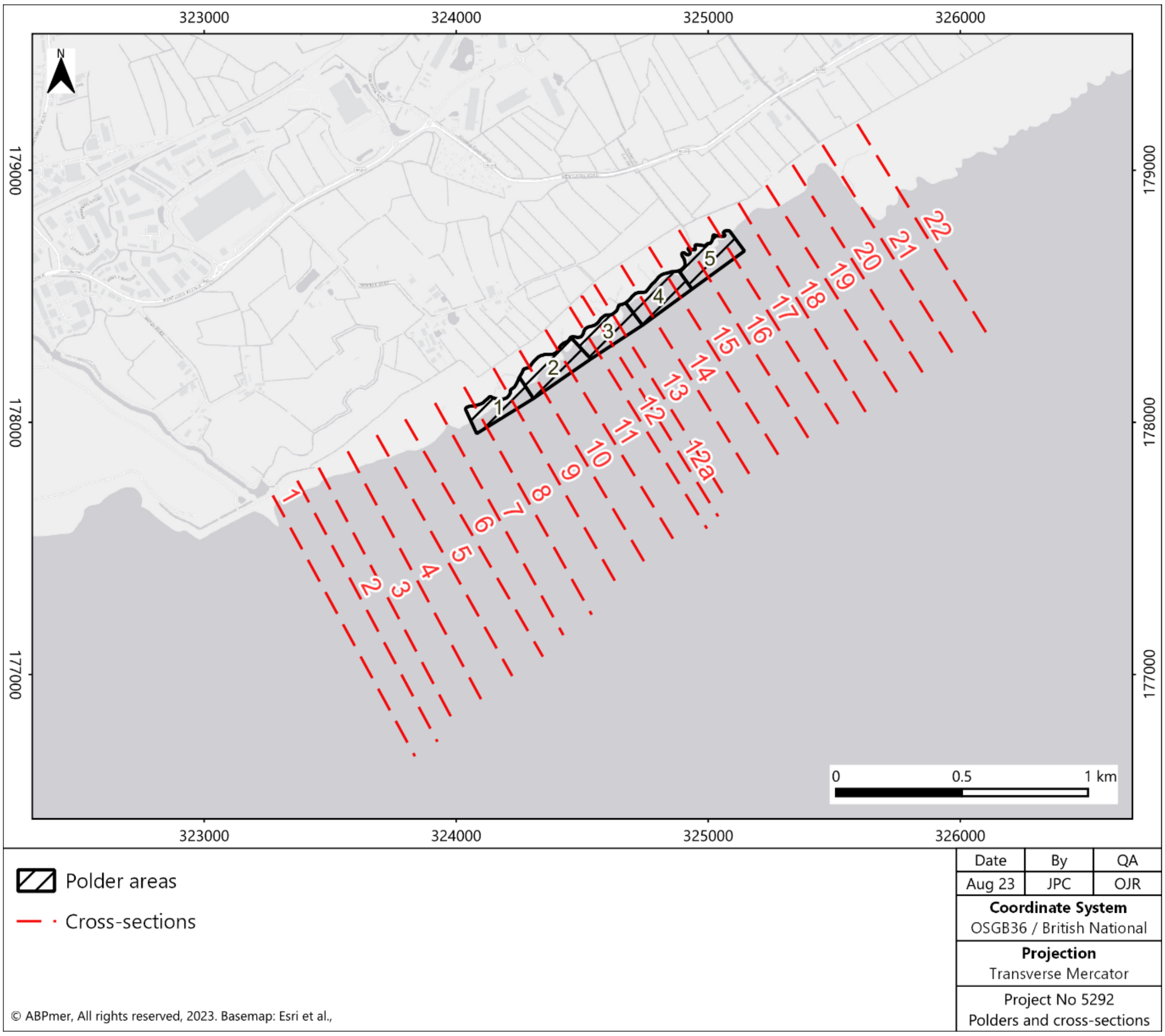



**Figure 36. Cross-section locations and Polder areas**

### Change across the study area

The cross-sections extend from the 2-4 m high earthen embankment behind the foreshore to 0 mODN. This earthen embankment (~10 mODN) is fronted by a flat topographic feature (formerly saltmarsh) of varying width and at *circa* 7 mODN, extending to a riprap rock armour embankment that extends to the intertidal. The area between the riprap armouring and the earthen embankment has remained relatively stable throughout the assessment period with accretion observed across this area. Seaward of the rip-rap, the cross sections vary with eastern cross sections displaying an established upper intertidal saltmarsh, with a gradual slope. Conversely the western cross-sections display a steep slope fronting the riprap armouring. Over the analysis period elevations from Polder 4 eastwards have increased in the upper foreshore by up to 0.8 m (in Polders 4 and 5) as well as to the east where no Polders are present.

As we move further west, we see decreases in the extent of established saltmarsh and a deepening bathymetry with MHWN at the toe of the riprap armouring at Polder 1 and further west. These areas are associated with progressive steepening of the mid foreshore over the majority of the shoreline, with 2022 levels the lowest seaward of the riprap toe along Profiles 1-5. Along with the steepening of the foreshore below MHWN, the study highlights the existing saltmarsh extent has eroded since 2005 with the most significant losses identified seaward of the boundaries of Polders 4 and 5.

### Polders 5 and 4

Cross-sections within Polders 5 and 4 outline accretion shoreward of the Polders, particularly at cross-sections 15 to 17 (Figure 37), with increases of up to 1 m observed since 2005. Cross-section 14 displays a reduced aggregation shoreward of the Polders between 2005 and 2011, since then the elevations have remained stable. **It is noted that Polder fences 4 and 5 are close to MHW with a brushwood crest level close to MHWS**.

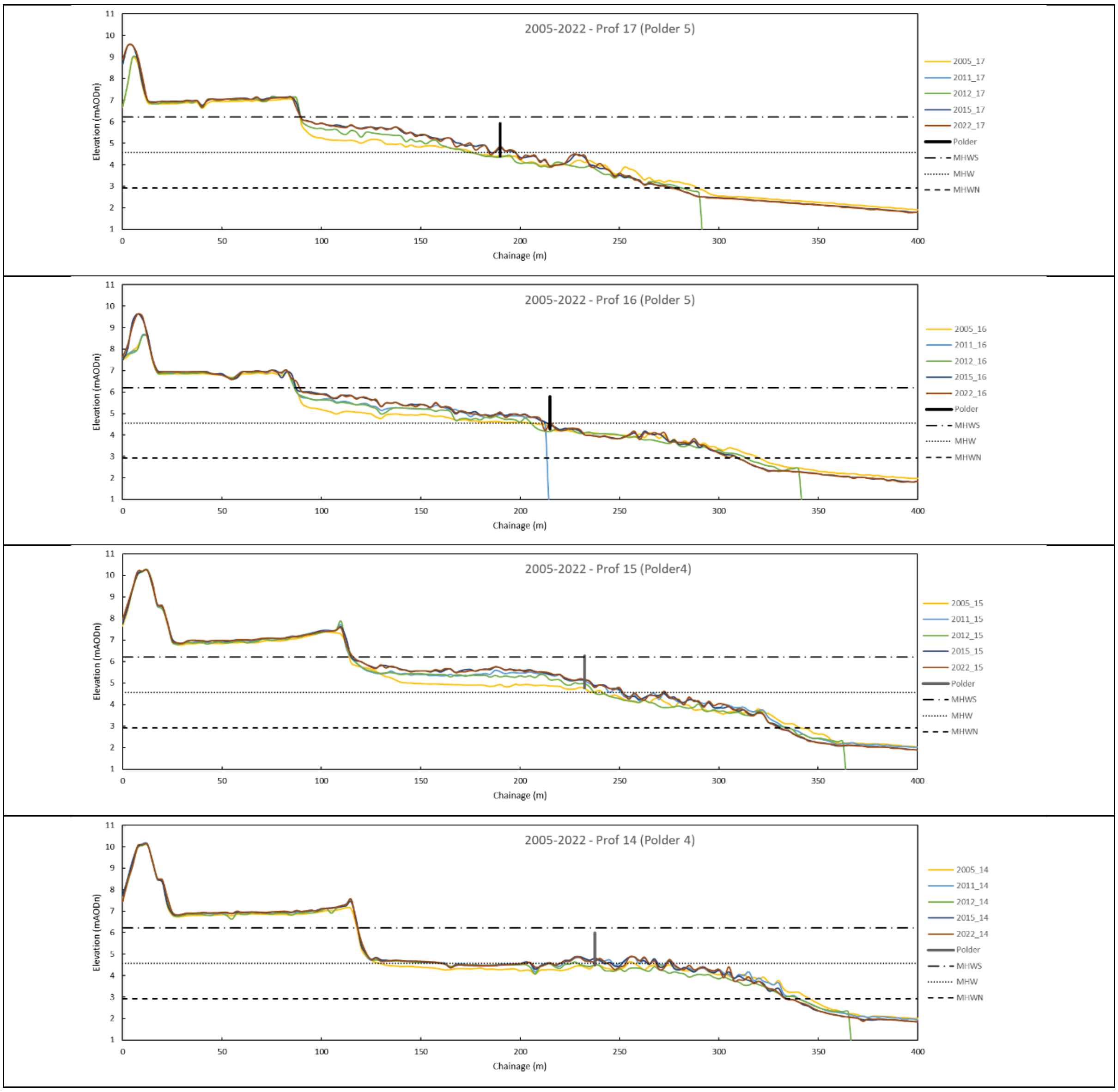



**Figure 37. Cross-sections 17-14 (Polders 5 and 4)**

The topographic analysis indicates that Polders 4 and 5 have been successful at encouraging the retention of sediments and saltmarsh growth since 2005, with ~30% more elevation gained within Polder 5 than areas directly east and beyond the shoreward boundary of Polder 4. Here, there is the establishment of a distinct saltmarsh vegetation both within and seaward of the Polders by approximately 80 m.

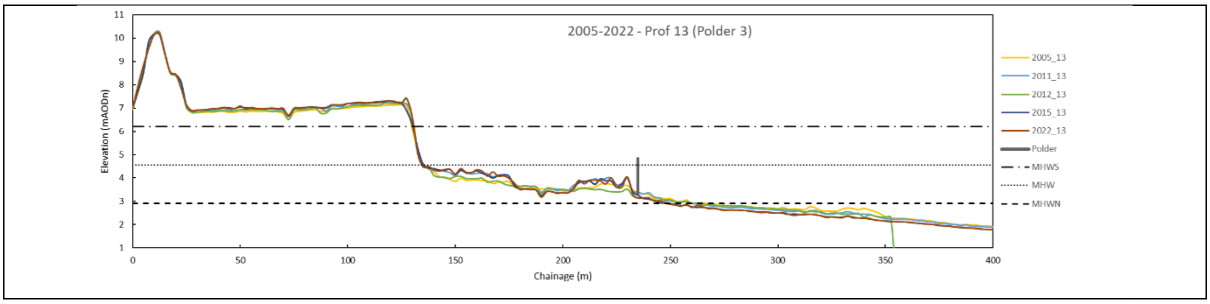
Despite the growth of the saltmarsh within these areas after the construction of Polder 5 and 4 in 1988 and 2005 (respectively), the seaward edge of the saltmarsh has eroded since 2005 (Profiles 14-17) indicating a loss of area since its peak extent (pre-2005) across the whole frontage.

### Polder 3

Polder 3 holds some saltmarsh habitat along the lateral edges of the Polder; however there has been only very limited expansion of the saltmarsh habitat since 2005. Within the Polder this area is lower in the tidal frame and also has some natural drainage channels facilitating runoff from Polder 4 (east of Polder 3) and runoff from the upper saltmarsh which is also causing riling at the toe of the riprap armour as shown in Figure 38 and Profile 13 in Figure 39 below.

At cross-section 13, within Polder 3 we see a varied trends in profile elevation since 2005. The profile timeseries outlines that elevations shoreward of the Polders have increased since 2005, with the most significant accretion between 2005 and 2011 (Figure 39). This accretion is concentrated close to the lateral Polders and the riprap embankment with a drainage present that prevents the establishment of saltmarsh in the centre of the Polder area (Profile 12a). Seaward of the Polders at this cross section we see a general reduction in elevation relative to the 2005 profile. **It is important to note that due to the topography, the brushwood crest height of the Polder is significantly lower at approximately MHW**.


**Figure 38. Rilling within Polder 3**



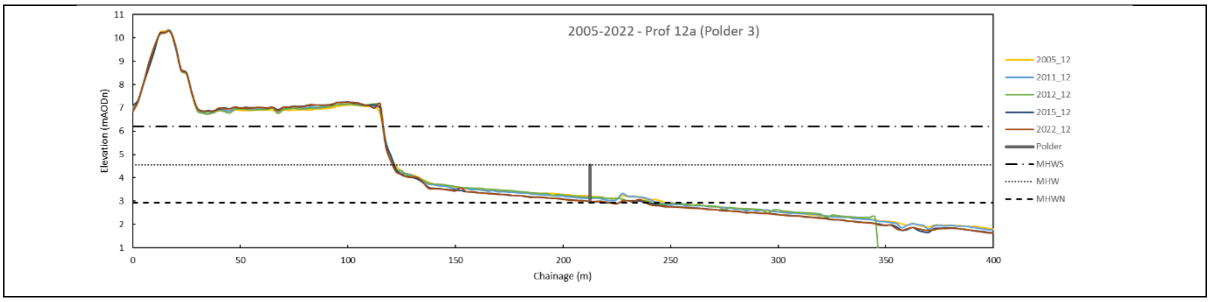



**Figure 39. Cross-section 13 and 12a (Polder 3)**

### Polder 2

Within Polder 2, an area of saltmarsh has also been present since pre 2005 at a low elevation (between MHWN and MSL) at limited extent fronting the riprap armour. The area of saltmarsh has increased in elevation between 2005 and 2011 (following construction) and between 2012 and 2015, remaining stable until 2022. Google Earth also shows a slight expansion in the area of saltmarsh.

The profiles are shown as Profiles 11 and 10 in Figure 40. These display net increases in elevation shoreward of the Polders since 2005, with the most significant increase between 2005 and 2011. Following this the profile elevation is varied but stable with reductions observed in 2012. At Profile 10, erosion (*circa* 0.3 m) is observed directly behind the Polder since 2005 while accretion is observed in the upper intertidal, similar to Profile 11. The Polder crest height in Polder 2 is again at the lower level of MHW.

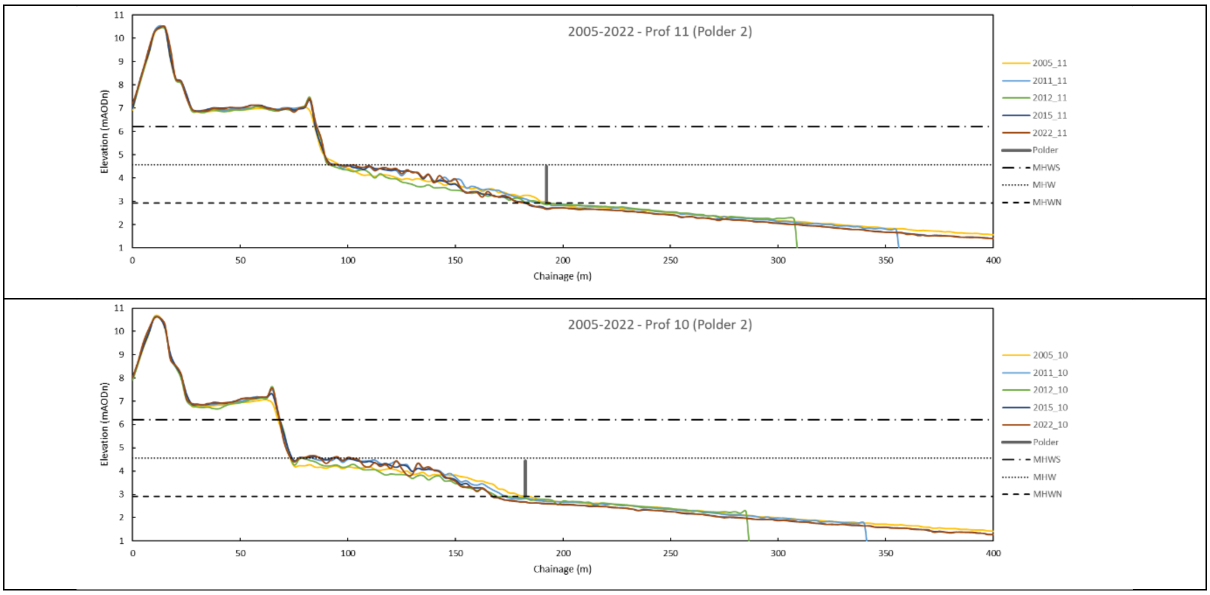



**Figure 40. Cross-sections 11 and 10 (Polder 2)**

## Polder 1 and to the west

At Polder 1 the mid and lower foreshore has lowered with MHWN now at the toe of the riprap armour and while localised areas of accretion were observed (refer to Section 3.11.1), there appears to be no evidence that the Polder has resulted in any notable retention of sediments when compared to the adjacent shoreline.

No accretion is evident in the profiles of Polder 1 with no discernible differentiation in slope identified in the four historic cross-sections at the two profiles (8 and 9). Here bed lowering of *circa* 0.3 m have been observed similar to the majority of Polders further east. The Polder crest height in Polder 1 is again at the lower level of MHW.

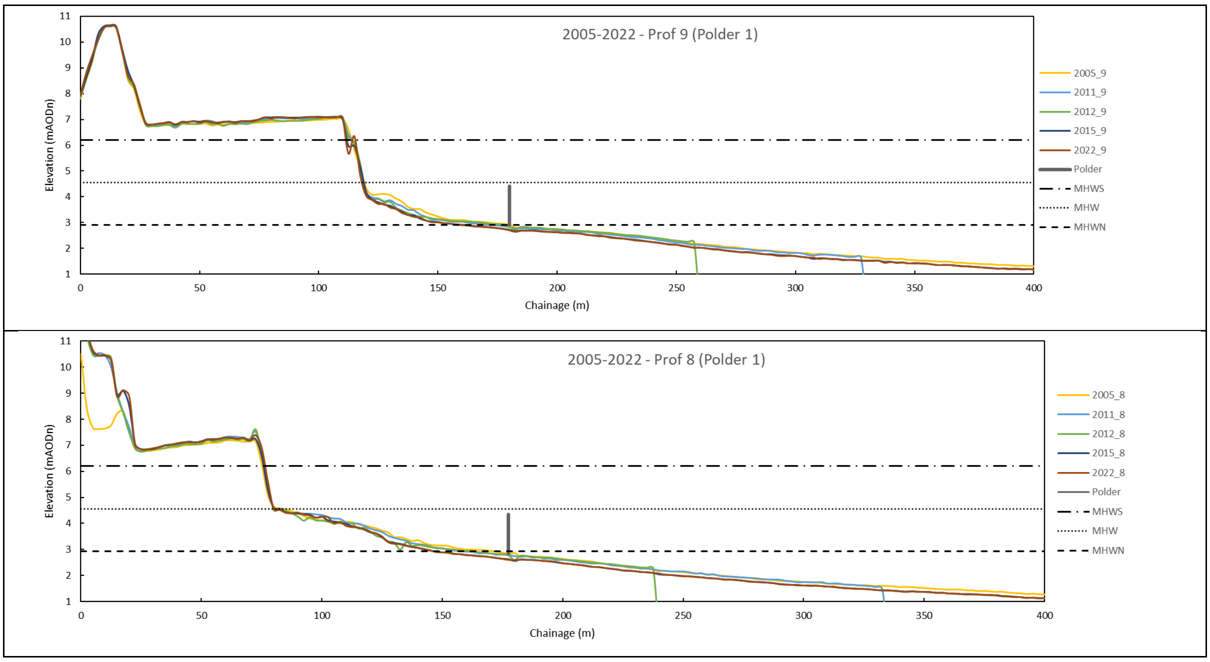



**Figure 41. Cross-sections 9 and 8 (Polder 1)**

Further west of the Polder fields we see a lowering in bed levels along many of the profiles. Reductions of up to 0.3 m since 2005 in the mid to lower foreshore are observed (Profiles 1-5 Appendix A). Along these cross sections, profiles recorded in 2012 tend to be at highest elevation while those recorded in 2022 tend to be at lowest elevation. Profiles 6 and 7 (adjacent to Polder 1) illustrate a brief accretive period between 2005 and 2011 above MHWN, followed by erosion until 2022.

## Summary

Based on the assessment presented above it is hypothesised that Polder viability at Rhymney Great Wharf is governed by the topography and the position of the Polders in the tidal frame.

The frontage to the east of the Polders shows a continued accretion of saltmarsh, Polders 4 and 5 (which have a crest elevation level of *circa* MHWS) show a level of accretion higher than elsewhere along the frontage. Moving west from Polder 3 the topography lowers significantly with Polders 1-3 has a lower crest elevation of around MHW with only a little saltmarsh development evident. The topography continues to lower to the west of Polder 1.

### 6.2.2 Hydrodynamic modelling

The effect of reinstating the current Polders on their current alignment has been tested over a representative spring high water (as the Polders are dry for the remaining phases of the tide) to understand how they would function in reducing flow speeds, thereby supporting the conditions for sediment deposition. As noted in section2.3 the study has represented the polders as impermeable structures in order to understand the maximum potential (opportunity) for flow reductions behind the polders; and hence the likelihood for them to function as required hydrodynamically. In reality the permeability in the brushwood would mean the flow speeds would not be reduced as significantly and this could be tested as part of future design iterations.

The flow regime, seaward of the Polders is highly energetic, with flooding flows oriented along a shore parallel, north easterly access, peaking at 0.7 m/s. On an ebbing tide, within the estuary, increased flow is directed west and as a result, while the flow orientation inverts, remaining shore parallel, spring speeds are slightly higher peaking at 0.8 m/s.

The reinstatement of Polders is simulated to understand the potential change the flow regime along the shoreline, with current speeds of 0.45 m/s simulated at the western end of Polder 1 on the ebb tide. Higher current speeds are also simulated in the entrances to the Polder fields but this is a result of the structures impermeable representation in the model, and would be lower and should not be considered a limiting factor at this time.

Following high water, the modelling shows how the Polder fields reduce the flows allowing the settling of sediment from suspension. Polder 1 is also having a beneficial (sheltering) effect to the west in lee of the Polder.

Since the establishment of Polder 5 in 1988 there has been growth of saltmarsh in the vicinity, extending to the current saltmarsh coverage at Polder 4 and 5. Although no simulations have been performed comparing velocities associated with 2005 bathymetry, it is likely that this aggregation and the colonisation of saltmarsh here has progressively reduced tidal ebbing current along the shoreline and facilitated lower velocities in the intertidal areas of Polders 1-3. This current speed reduction is not anticipated to have a significant impact on Polder success (discussed later).

The hydrodynamic modelling identifies that the most notable changes in velocities, i.e., the reduction in the flow speeds to encourage sedimentation, occurs when the Polder fields are not overtopped. This is because when the tide is passing through the entrance it will speed up as it is throttled through the entrance but then slows as it fills the polder; when the water level exceeds the height of the brushwood polders the influence of the structure on the flow regime reduces.

In Polders 4 and 5, the elevation of the existing saltmarsh prevents frequent inundation, although the Polders do significantly decrease velocities within the Polder areas over spring tide, allowing sediments to be deposited.

It should be noted that the maximum potential for sediment accretion will be over the spring tide as this is carries the most heavily laden sediment (section 3.12). The potential for the polder to deposit sediment will, therefore, be determined by its position in the tidal frame. Those polders with a brushwood crest lower in the tidal frame will have a reduced potential to accumulate sediment over the spring tides.

More detail is provided below.

### 1.5 hours before high water spring

At this stage of the tide water begins to inundate Polders 1-3. The restriction in flow introduced by the Polders causes localised increases in velocities at the entrances (to note these localised increased are considered to be an overprediction). Localised decreases in velocity are observed along the seaward extent of the Polder lines, as flow is obstructed by the structure.

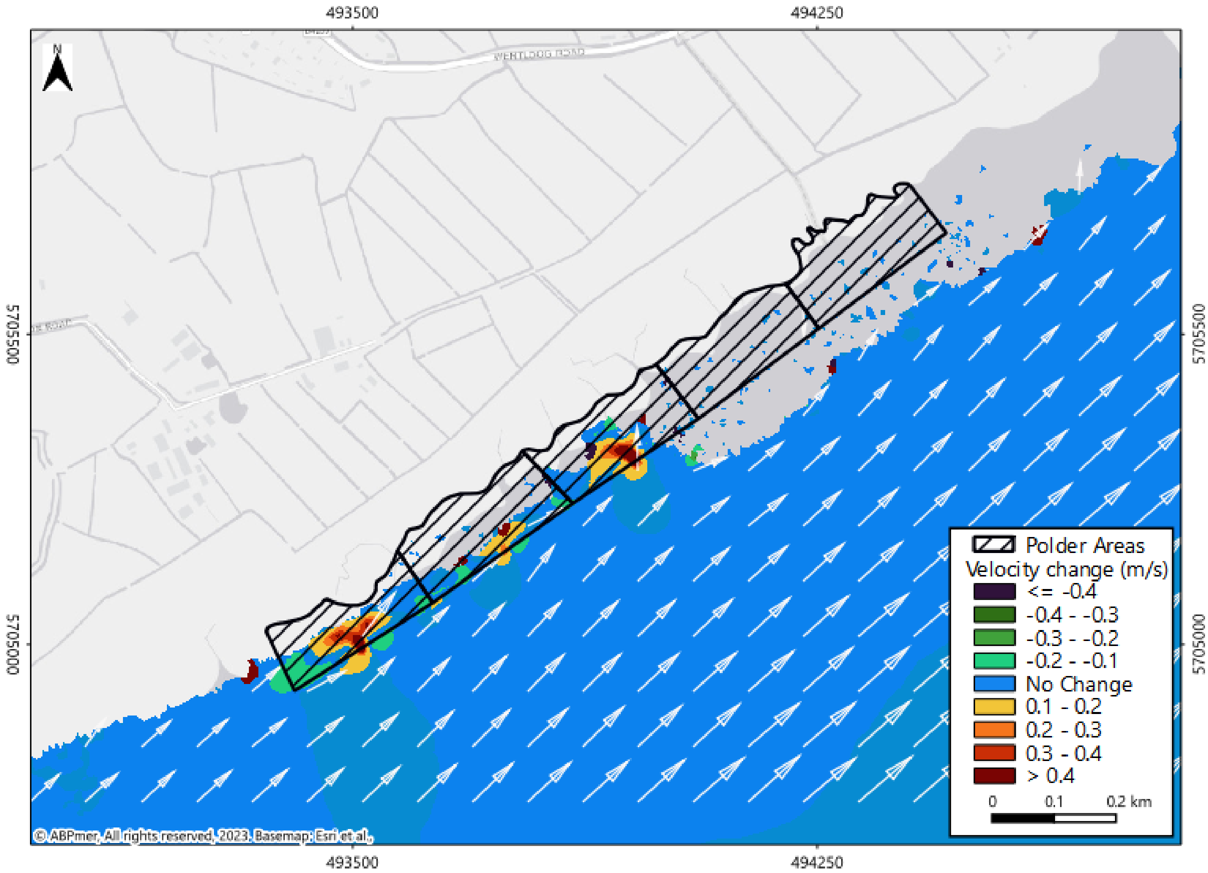



**Figure 42.** **Reinstatement of Polders; spring HW-1.5 hr**

### 0.5 hours before a spring high water

As the flood tide progresses, velocities in the centre of the Polder fields remain elevated (relative to the baseline) as water continues to flow through the entrance to the Polders. It is noted that this velocity change decreases from Polder 1 to Polder 3 as the Polders are overtopped and water is permitted to flow into the Polder. Polders 4 and 5 show significant increases in water velocities in the gap between as water begins to inundate these Polder areas.

Toward the southwest of Polder 4, localised increases in velocity is simulated as water flows southwest over the lower lateral (shore normal) Polder boundary of Polder 3. This is in part a result of the representation in the model. Consideration should be given to raising the Polder height of the lateral Polder line between 3 and 4 to avoid water 'spilling' over from Polder 4 to Polder 3.

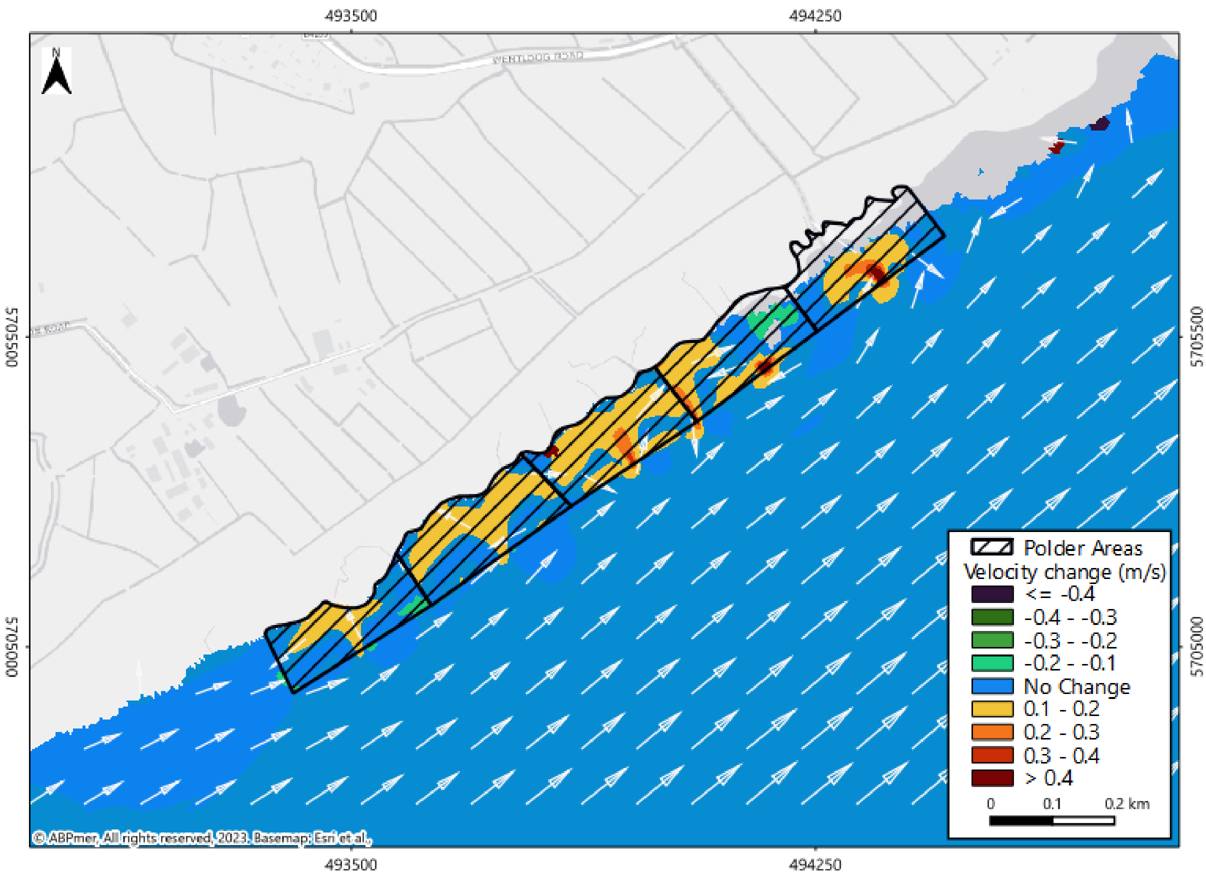



**Figure 43. Reinstatement of Polders; spring at HW-0.5 hr**

### High water

At this stage of the tide, the Polders are reducing the velocities throughout the Polder areas. At slack water the flow into and out of the Polders is greatly reduced with only Polder 5 simulating some localised increases through the entrance. A localised increase is also simulated to occur at the south edge of Polder 1 as flows diverted around the structure.

Within the Polders current speeds are simulated to decrease significantly by over 0.15 m/s as currents drop away.

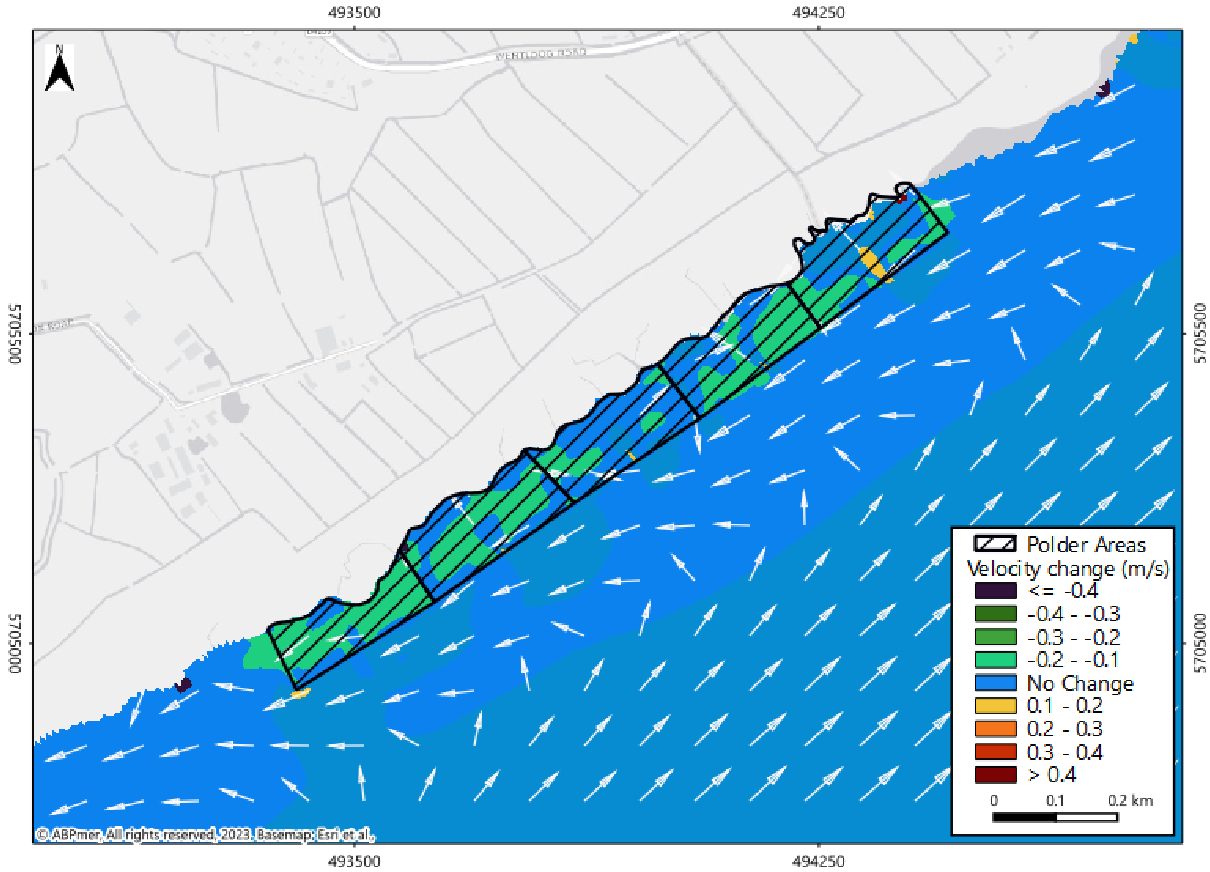



**Figure 44. Reinstatement of Polders; spring at HW**

### 0.5 hr after high water

As the ebb tide begins strengthening, current speeds decrease across the Polders as they reduce flow along this section of the shoreline. These simulated decreases in velocities are greater than at HW as the north-east to south-west flow is prevented from penetrating the Polder area. Reductions in current speed of up to 0.3 m/s are noted.

The impact on velocity has extended to approximately 350 m downdrift of Polder 1. The reduction in velocities also extends slightly seawards of Polders 1 and 2 at this phase of the tide.

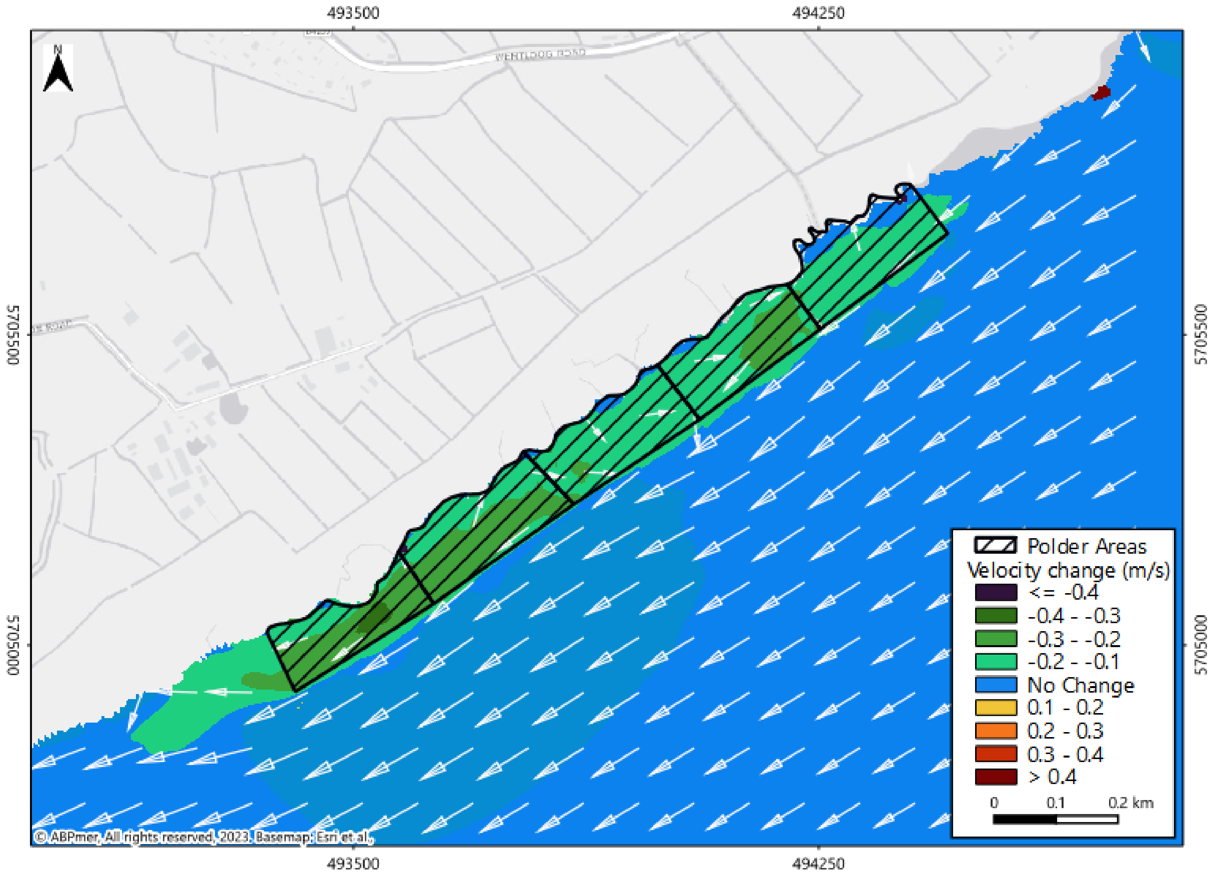



**Figure 45. Reinstatement of Polders; spring HW+0.5 hr**

### 1.5 hours after a spring high water

As water continues to ebb, the water depth in within the Polder fields reduces, as does the general velocities in the vicinity of the Polders. The last of the water can be seen draining from Polder 5 and much of Polder 4 has also drained with only the westerly (lower) section still draining. Subsequently the reduction in current speed is less than at earlier stages of the tide within Polders 4 and 5, with localised increases in flow simulated in the entrances as the Polders drain. This period aligns with significant drainage from Polder 3 as can be seen in Figure 46.

Lower in the tidal frame, Polders 1 and 2 are still performing with over 0.3 m/s reduction along the seaward Polder line. This decrease in velocity extends 450 m longshore allowing a notable reduction in velocities along the shoreline as the tide ebb.

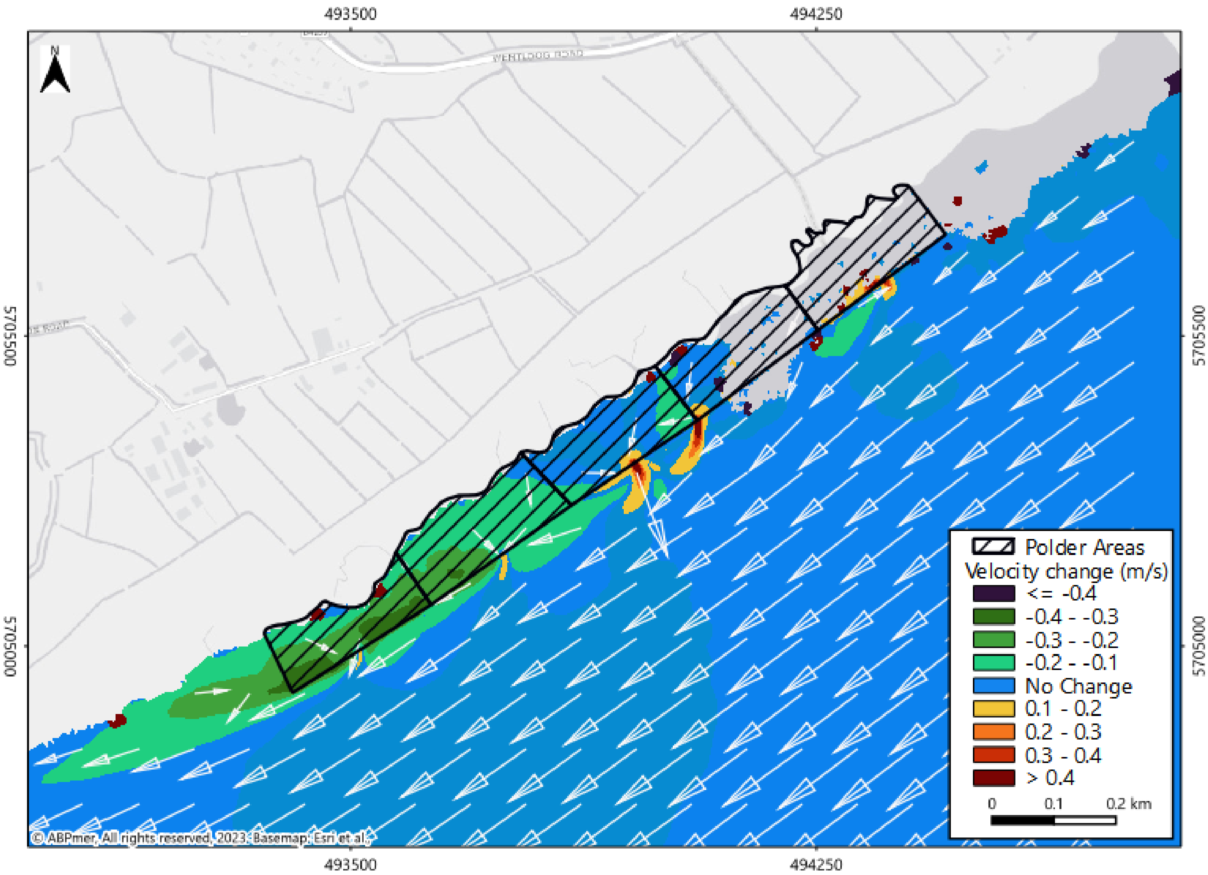



**Figure 46.** **Reinstatement of Polders; spring HW+1.5 hr**

### 2 hours after high water

At HW +2 hr Polders 5 and 4 are fully drained. Polder 3 is now rapidly draining, joining the south westerly ebb currents, Polders 1 and 2 are still functioning hydrodynamically. Polder 1 begins to drain with both of the remining Polders draining over the next 30 minutes.

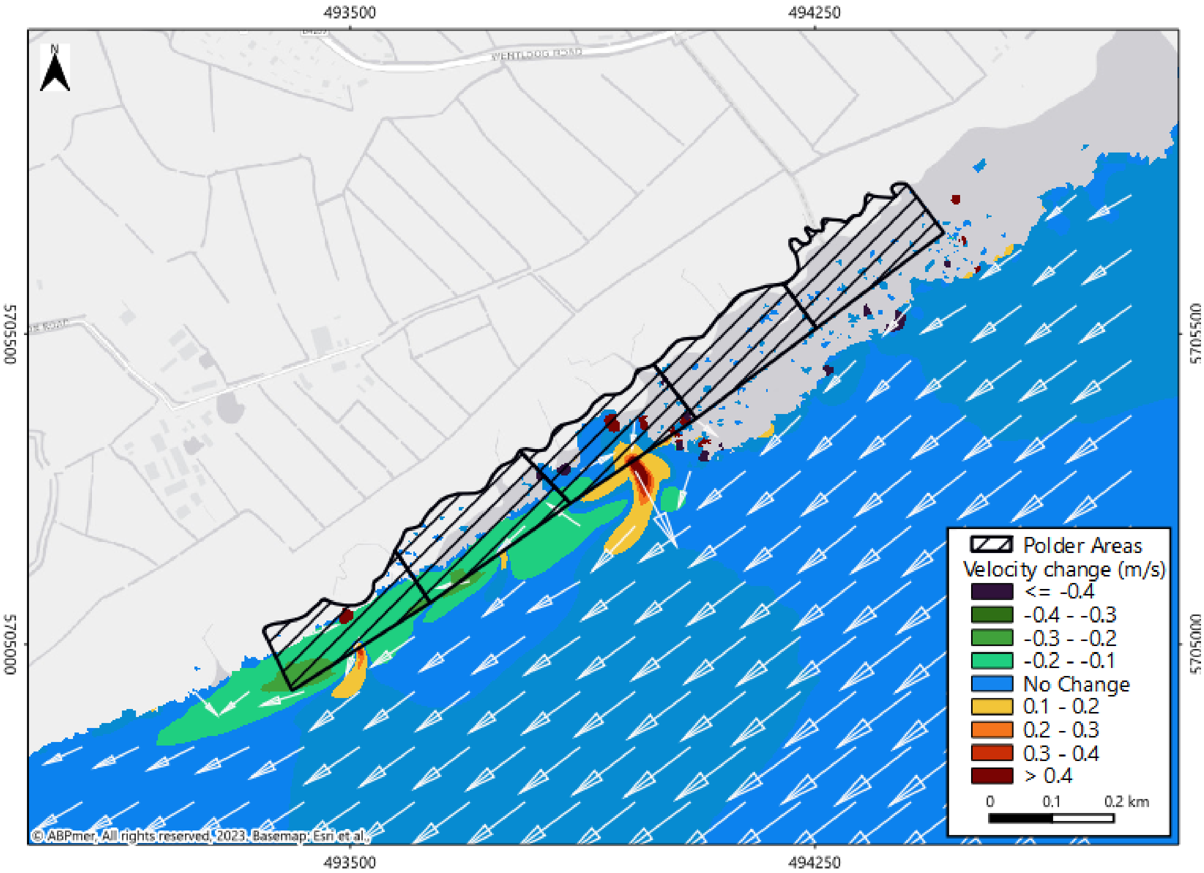



**Figure 47. Reinstatement of Polders; spring HW+2 hr**

### 6.2.3 Wave modelling

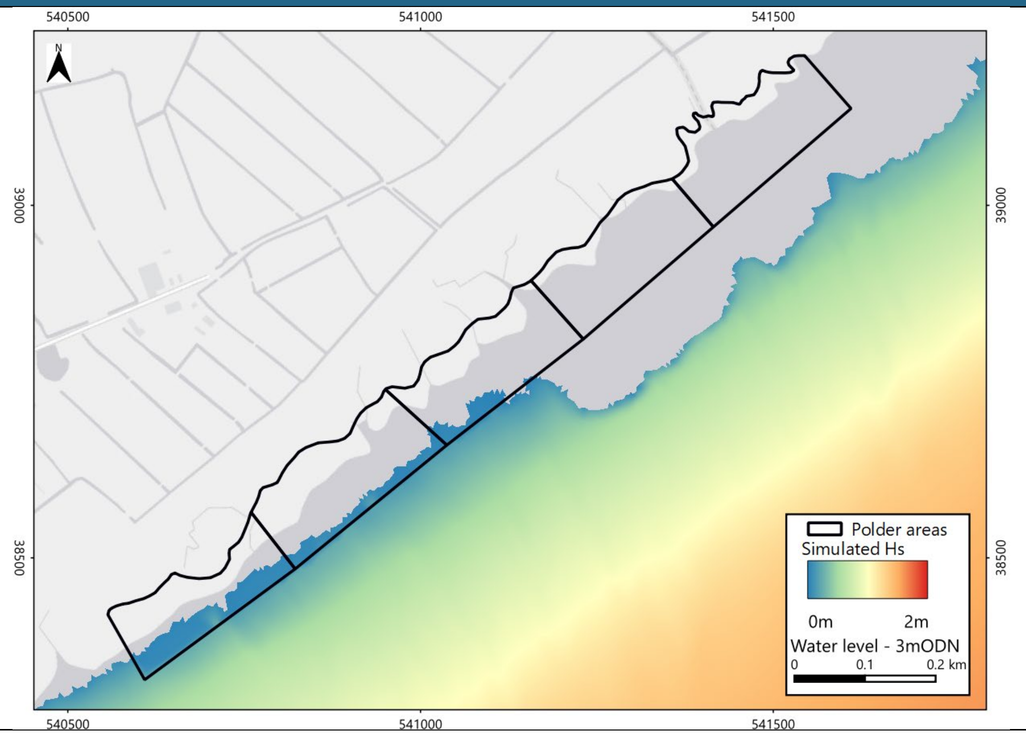
The wave transformation simulations have assessed the potential effect of reinstating the five Polders at Rhymney Great Wharf on wave heights within the Polder field using the three wave conditions described in Section 2.4.

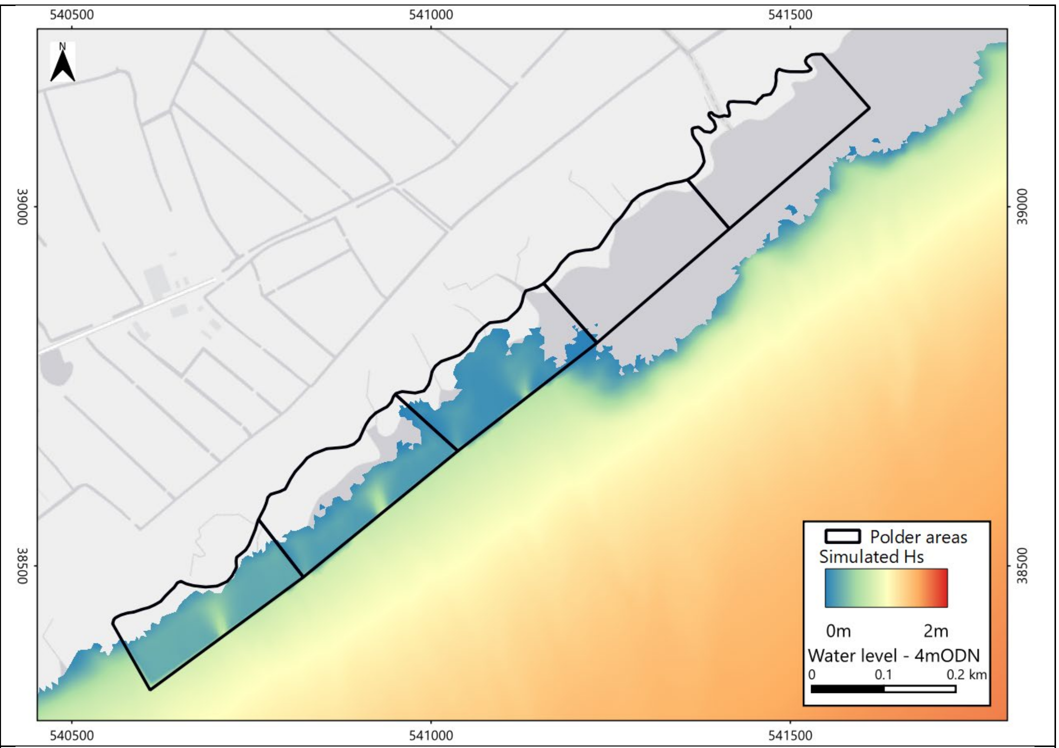
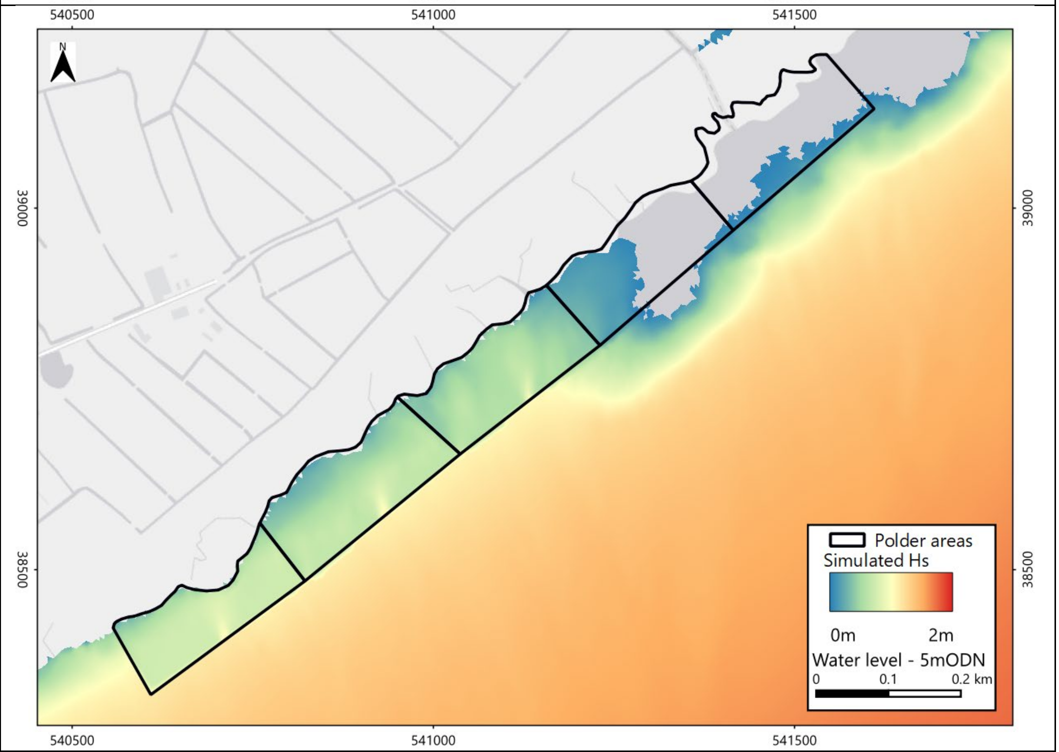
Table 8 and Table 9 provide the wave modelling results for Polders 2 and 5. Polder 2 is used as an analogue for Polders 1-3 and Polder 4 has similar characteristics to Polder 5. An illustration of the dissipation of the wave energy for various water levels is also shown as Figure 48 for the 10 in 1 year wave.

#### Effect of the polders on the dissipation of wave energy

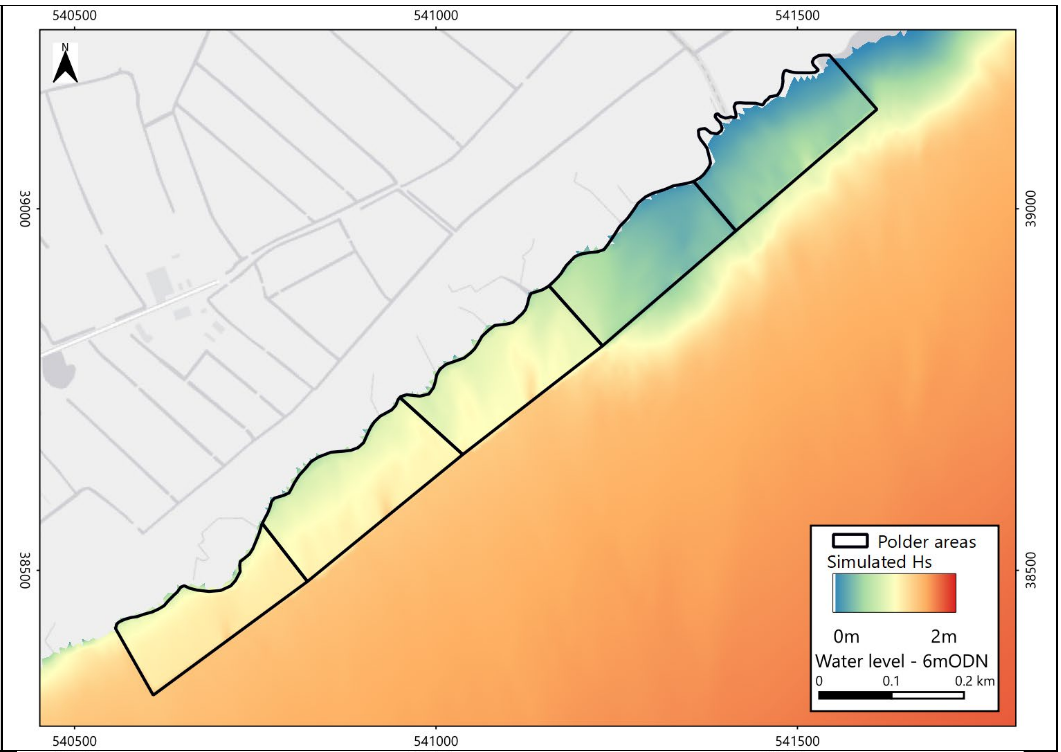
The assessment predicts that the Polders (when maintained) will reduce wave height within the Polder fields, these reductions are significant when water levels are up to *circa* 1.5 m above the crest of the Polder.

Polders 4 and 5 are positioned at a higher tidal elevation and the fronting saltmarsh is dissipating wave energy, preventing larger waves from impacting the Polder structure (see water levels 6.00 and 7.00 mODN in Figure 48.

| Water level (mODN) | Wave impact |
| --- | --- |
| 3.00 |   |

| | |
|---|---|
| 4.00 |  540500 541000 541500 39000 38500 Polder areas Simulated Hs 0m 2m Water level - 4mODN 0 0.1 0.2 km |
| 5.00 |  540500 541000 541500 39000 38500 Polder areas Simulated Hs 0m 2m Water level - 5mODN 0 0.1 0.2 km |

6.00




7.00

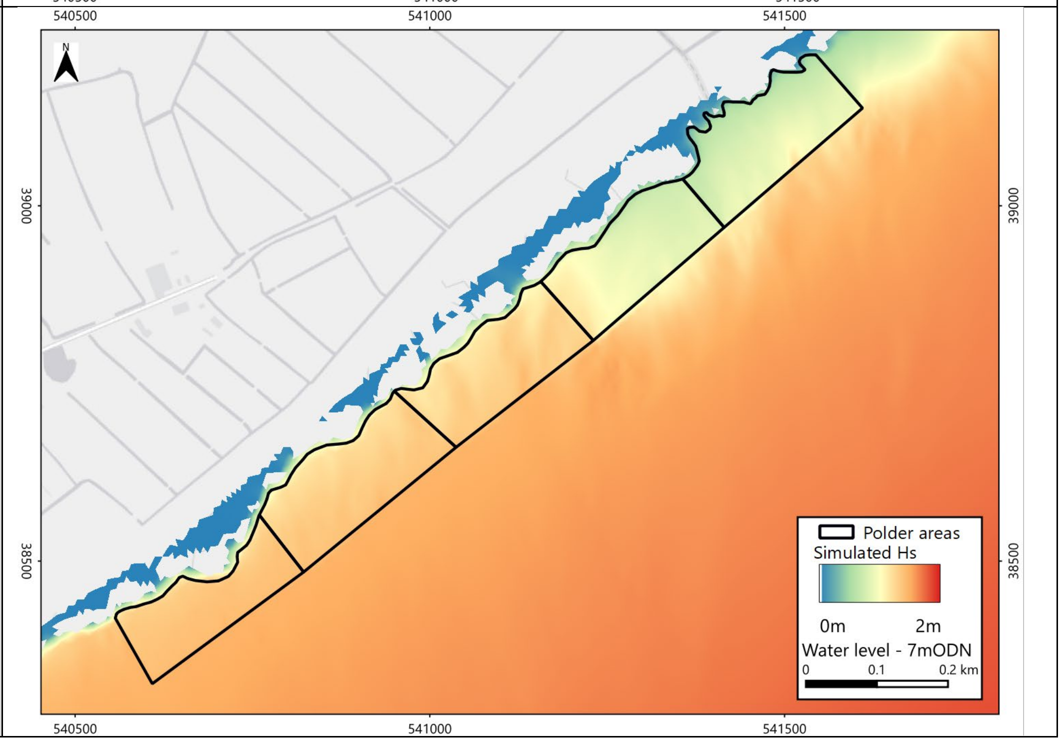



**Figure 48.** **Wave energy outside and inside the Polders at varying water levels (10 in 1 westerly wave condition)**

### Potential for erosion from waves

The conceptual understanding identified that the sediment accumulated during the summer months along the frontage is resuspended and eroded during the winter months. The study referenced in O'Brien *et al* 2000 identified a wave height of 0.05 m was potentially sufficient to mobilise sediment on the mudflats in the Severn Estuary. For the purposes of uncertainty, this study has used a threshold of 0.1 m as an indicator of sediment erosion (Section 5.2.).

Table 8 shows when the wave height within the Polders exceeds the 0.1 m threshold for the 10 in 1 wave condition (in red) and hence when erosion would be expected to occur.

The simulated reductions in wave height as a result of Polder installation are unlikely to fully mitigate resuspension associated with wave activity. However, it is considered likely that the area protected by Polders 1-3 will be more frequently affected by wave conditions which can result in resuspension, and hence re-erosion of the sediment accumulated during periods of more benign conditions.

**Table 8. Potential for sediment removal from wave activity**

| Water Level (mODN) | Polder 2 | | Polder 5 | |
|---|---|---|---|---|
| | 10 in 1 year Hs (m) | | 10 in 1 year Hs (m) | |
| | In front of polder | Behind polder | In front of polder | Behind polder |
| 3 | 0.19 | 0.12 | - | - |
| 3.5 | 0.46 | 0.28 | - | - |
| 4 | 0.7 | 0.39 | - | - |
| 4.5 | 0.91 | 0.55 | - | - |
| 5 | 1.1 | 0.74 | 0.28 | 0.05 |
| 5.5 | 1.24 | 0.92 | 0.6 | 0.36 |
| 6 | 1.35 | 1.09 | 0.87 | 0.65 |
| 6.5 | 1.41 | 1.23 | 1.1 | 0.9 |
| 7 | 1.47 | 1.36 | 1.28 | 1.12 |

### The risk of damage to the polders

It is recognised that the Polders will require regular maintenance due to the relatively exposed position of the study area in the Severn Estuary. Estimations of *circa* five years for replacement of the brushwood and potential damage occurring with wave conditions of greater than 1 m are given.

The study has therefore reviewed the occurrence of wave conditions greater than 1 m associated with the more extreme wave conditions as Table 9. It is concluded that Polders 1 -3 are exposed to greater wave conditions more frequently due to exposure at lower stages of the tide.

Most importantly, it is considered that waves greater than 1 m are likely to result in damage. Table 9 shows that Polder 2 could be experiencing wave heights of circa twice this around five time per year. The likelihood of damage to the structures should therefore be a key consideration when determining the survivability and viability of the project.

Table 9. Risk of damage to the polders from wave activity

| Water Level (mODN) | Polder 2 | | Polder 5 | |
|---|---|---|---|---|
| | 5 in 1 year Hs (m) In front of polder | 1 in 1 year Hs (m) In front of polder | 5 in 1 year Hs (m) In front of polder | 1 in 1 year Hs (m) In front of polder |
| 3 | 0.21 | 0.21 | - | - |
| 3.5 | 0.49 | 0.51 | - | - |
| 4 | 0.76 | 0.78 | - | - |
| 4.5 | 1.01 | 1.04 | - | - |
| 5 | 1.25 | 1.3 | 0.31 | 0.33 |
| 5.5 | 1.47 | 1.54 | 0.67 | 0.71 |
| 6 | 1.69 | 1.78 | 0.99 | 1.05 |
| 6.5 | 1.89 | 2.01 | 1.28 | 1.36 |
| 7 | 2.09 | 2.24 | 1.54 | 1.65 |

### 6.2.4 Summary of existing polder performance

The geometric analysis and models tests presented above indicate that the success of Polders (if maintained) in retaining sediments in the upper foreshore is still likely to be mixed, dependent upon the level of wave exposure whilst others (polder 4 and 5) have effectively encouraged saltmarsh growth. This section summarises the processes likely affecting the success of each Polder in retaining sufficient sediment for saltmarsh development.

#### Polder 1 - Little evidence of sediment accumulation

- No significant bed increase has been observed since installation in 2005 even with maintenance works in 2009 extending the life of the structure.
- The Polder is exposed to potentially damaging waves when water levels reach 4.5 mODN (~MHW).
- Most exposed Polder to incoming wave conditions and more frequently waves of greater than 1.0 m which have the potential for damage.
- Polder is located low in the tidal frame, with the base of the polder approximately ~MHWN and the crest of the brushwood lower than MHW, this is resulting in exposure to potentially scouring waves for a greater proportion of the tide, potentially re-eroding the sediments being deposited.
- Frequent damage from storm events likely.

#### Polder 2 - Some evidence of limited sediment accumulation

- Increases in bed level was observed between 2005 and 2011, corresponding to the approximate design life of the structure. Following this the bed level remains static.
- The Polder is exposed to potentially damaging waves when water levels reach ~ 4.5 mODN (MHW).
- Polder is located relatively low in the tidal frame, with the base of the polder approximately ~MHWN and the crest of the brushwood lower than MHW, this is again resulting in exposure to potentially scouring waves for a greater proportion of the tide, eroding sediments deposited.
- Frequent damage from storm events likely.

#### Polder 3 - Evidence of sediment accumulation limited by drainage channels

- Increases in bed level was observed between 2005 and 2011, corresponding to the approximate design life of the structure. Following this, the bed level remains steady.

- Polder 3 is exposed to potentially damaging waves with water levels + 4.5 m.
- The Polder is likely to have benefitted from the reduction in flow and wave attenuation from the seaward saltmarsh in front of Polders 4 and 5 allowing increased sedimentation in the lee of the Polder structures.
- Polder is again located relatively low in the tidal frame with its base ~MHWN and crest below MHW, resulting in exposure to potentially scouring waves for a greater proportion of the tide.
- Two drainage channels from the area on top of the riprap armour and from the saltmarsh at Polders 4 and 5 drain into the area behind Polder 3, along with a lower topography in the centre of the Polder potentially increasing erosion and negatively impacting the formation of saltmarsh.
- Frequent damage from storm events likely.

#### Polder 4 - Evidence of sediment accumulation and saltmarsh development

- Increases in bed level was observed between 2005 and 2022 compared to saltmarsh locations East and seaward of the Polders.
- Polder is located higher in the tidal frame with the base positioned at ~MHW reducing the exposure to potentially scouring waves allowing saltmarsh to become established.

#### Polder 5 - Evidence of sediment accumulation and saltmarsh development

- Increases in bed level was observed between 2005 and 2022 compared to saltmarsh locations East and seaward of the Polders.
- Polder is located higher in the tidal frame with the base positioned ~MHW reducing the exposure to potentially scouring waves allowing saltmarsh to become established.

# 7 Design Options

## 7.1 Introduction

Polders have historically been constructed for land reclamation, predominantly in the Netherlands and around the Wadden Sea, with their use in coastal defence and nature conservation being developed more recently. As described in Section 4.2, these are generally brushwood fences and ditches arranged shore perpendicular and shore parallel to speed up the accumulation of mud and silt in the intertidal, often protected with a concrete or rock toe.

The team developed five alignment options drawing upon the conceptual understanding and resulting design considerations outlined in Section 5 and the results of the topographical, hydrodynamic and wave modelling tests of the current polder alignment as set out in Section 6. The options have taken account of the following key parameters identified in the study:

1. There needs to be sufficient sediment in the system.
2. Long term sediment accretion requires a maximum tidal current speeds less than 0.9/1.0 m/s$^{-1.}$ Exceedance of current speed over the indicative spring tide.
3. The effectiveness of the polders is dependent upon their location in the tidal frame, crest height of the polders along the frontage should be near MHWS (6.24 mODN), conversely those constructed with a base topography of below MHW (4.59 mODN) are unlikely to function sufficiently at the higher states of tide [due to the 11m tidal range in this location].

4. Wave heights within the Polders of > 0.1 m could result in resuspension/erosion of material: An indicator of frequency of exceedance has been taken to be water level at which waves greater than 0.1 m occur with the 10 in 1-year westerly wave within the Polder.
5. Wave heights outside the Polders greater than 1.0 m could result in damage to the structure: The water level at which waves greater than 1 m occur with the 10 in 1-year westerly wave outside the structure has taken to be an indicator of frequency.

Gullies were noted by NRW and Salix on a site visit (NRW email 20/07/23) with discussion on the options for either filling with stone or having open sections. We would advise against having additional open sections within the polders as they will reduce the beneficial effects of the polders in reducing flow velocities. Filling the existing gullies with stone would divert the drainage channels (as described in Section 4) but would likely need to follow the full length of the shore parallel fencing to be successful.

## 7.2 Design Options

Initial option layouts included extension of the Polders east and west. NRW has requested that the options are amended to remove the eastern extensions as they were not considered to meet the project objectives and unlikely to be cost beneficial.

For all the original and revised options, the Polder (brushwood) height is taken to be 1.0 m, the revised options are presented as Figure 49 and summarised below:

1. **Reinstatement of existing Polders** along current alignment. Investigated and analysed in Section 6.2 above.
2. **Reinstatement of the existing Polders and extension west** along the existing alignment to the end of the study area.
3. **Partial reinstatement and extension west at higher elevation**. Reinstatement of Polders in their current position at Polder 4 and Polder 5. Polders 1,2 and 3 are brought landward to be higher in the tidal frame, 30 to 60 m seaward of the riprap armour, and western extension (initially presented in ABPmer 2019a)
4. **Partial reinstatement aligned to the 4 m contour**. Alignment defined by the present day 4 m contour, Polders 4 and 5 are extended approximately 60 m seaward. Polders 3 and 2 are brought landward. Polder 1 is not reinstated and there are no new Polders to the west.
5. **Partial reinstatement to 4.5 m contour**. Alignment defined by the present day 4.5 m contour, Polders 4 and 5 are extended approximately 30 m seaward. Polders 3 and 2 are brought landward. Polder 1 is not reinstated and there are no new Polders to the west.


**Figure 49. Polder alignment options two to five**

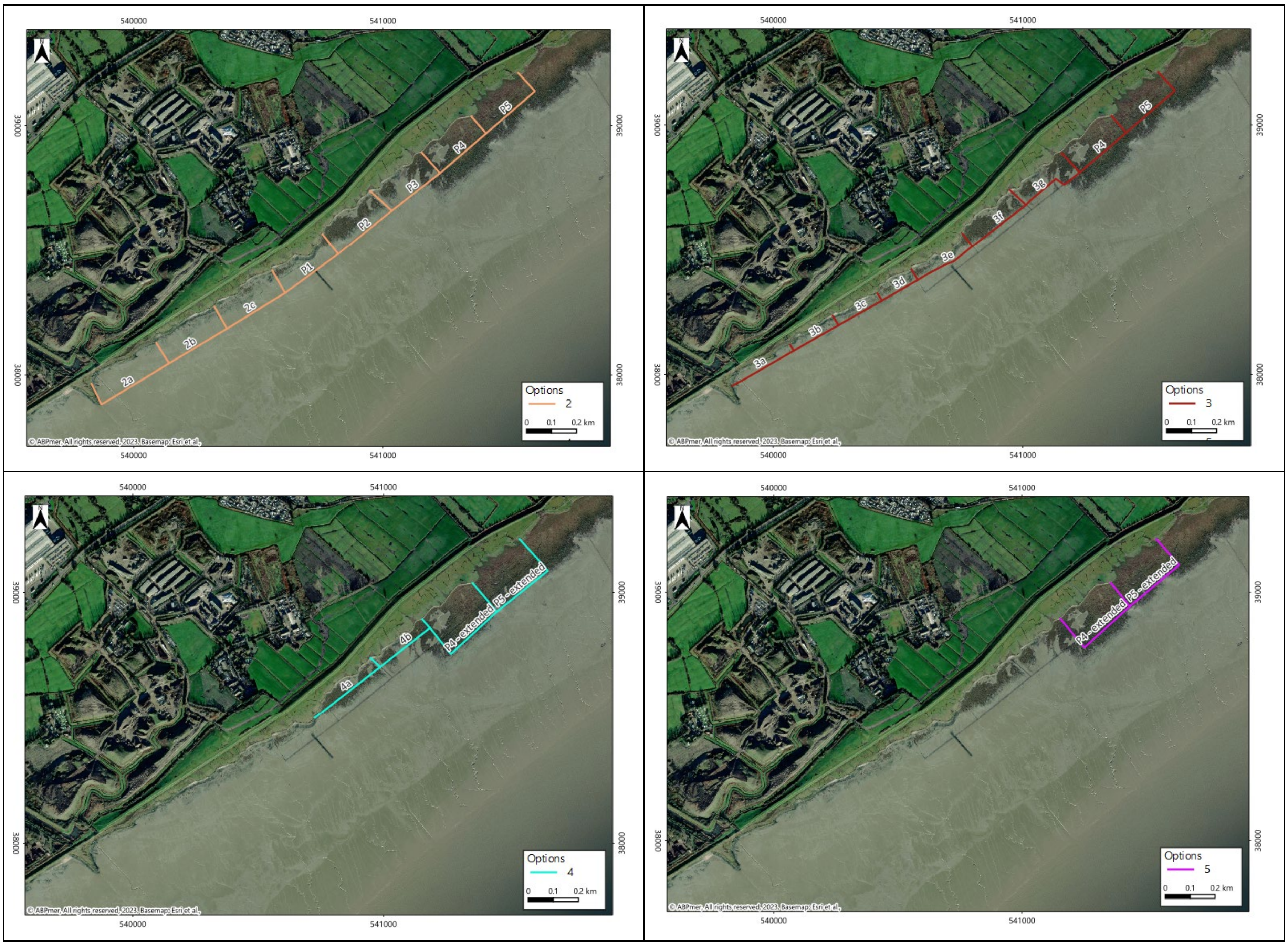



**Figure 50. Individual alignment options two to five**

## 7.3 Wave analysis of new alignments

The study has identified that there is a risk of sediment resuspension along the frontage when wave heights reach an indicative 0.1 m and a risk of damage to the brushwood when wave heights exceed 1.0 m. To understand the potential for resuspension and damage Options 2-5 have been tested in the wave model using the 10 in 1 year wave condition.

The results of the wave model tests for each of the polders in each of the Options are presented in Appendix B and are discussed below.

It is very important to highlight that the wave model tests show that for all the Options, all the polders are subject to potentially damaging waves under the relatively frequent 10 in 1 year wave condition and hence there is significant risk to the survivability of the structures.

**Option 2 reinstatement and extension west:** The extension of the existing Polder line west interacts with the steeper foreshore at this location and, subsequently the Polders are located lower in the tidal frame (Polder crests of between 3.5 and 3.7 mODN. Subsequently the simulated wave conditions within the Polder areas are similar to those simulated in the adjacent Polder 1. Results of the wave model tests are provided as Table 12. The simulated wave conditions outline that wave conditions exceed 1 m in front of the Polders and 0.10 m in their lee as soon as the Polder is inundated, *circa* MHWN (below the level at which saltmarsh develops along the frontage). This will cause frequent resuspension/erosion of sediments as well as greater exposure to damaging wave conditions.

**Option 3 reinstatement and extension west at a higher elevation:** As the shoreline slopes progressively steeper as we move westward from the NEW Polder 3, this option was proposed by ABPmer in 2019a utilising the elevation of MHWN along this frontage. The crest height of the Polder ranges from 3.6 mODN in the west to 4.8 mODN in within the existing Polder footprint (Polders 5-7 in Figure 50). It should be noted that this alignment reduces the area of potential area for habitat creation within the existing Polders 1, 2 and 3. Table 13 illustrates that while the western-most Polders, are closer to the shoreline than Option 2 and while the wave conditions in their lee are less than the Polders presented in Option 2, they are still in excess of the simulated conditions within the existing Polder 1 (which has not been successful to date albeit without the benefit of maintenance since 2009).

The simulated wave conditions outline that wave conditions exceed 1 m in front of the Polders from *circa* 5 mODN (*circa* 0.5 m above MHW). Whilst wave heights are slightly lower at this alignment when compared with Option 2, meaning that the polders would be exposed to the large wave heights for a greater period in the tidal frame. Within the Polders resuspension/scour through wave action could occur as soon as the water level reaches the crest of the Polders.

**Option 4 extension to bed level of 4 mODN:** The reduction in wave conditions in a revised Polder 2 and 3 outlined in Option 3 were revised further inshore for Option 4, with a crest elevation 0.3 m higher (4.8 mODN) than Option 3. This shoreward placement was found to further reduce wave conditions within the polder fields, increasing the likelihood of success of these Polders. Additionally, this option reviewed the extension of the existing Polders 4 and 5 seaward, to the edge of saltmarsh currently undergoing erosion. This corresponds to an approximate bed level of 4 m and a Polder crest of 5 mODN. Table 14 outlines the wave model results for Option 4. The simulated wave conditions outline that wave conditions exceed 1.00 m in front of the Polders less frequently than Options 1,2 and 3, with waves in excess of 1.00 m experienced only at higher water levels (between 5.5 and 6.5 m) and wave heights > 0.10 m in the polders at the higher water levels 4.5-5.0 m, with the exception of Polder 4.

**Option 5 seaward extension of polders 4 and 5 to 4.5 mODN:** Option 4 was further refined to elevate the Polder crest by migrating the Polder line inshore to an elevation of *circa* 4.5 mODN. This location higher in the tidal frame is associated with a smaller advance on the current Polder line in the existing Polders 4 and 5 and a reduction in Polder area when compared to Option 4. Shoreline elevations to within the existing Polders 2 and 3, did not permit installation of Polders. Table 15 outlines that the elevation of the Polders in this option (relevant to Option 4) further reduces wave conditions, with wave heights in excess of 1.00 m occurring in front of the Polders at water levels above 6.5 m. Additionally, the critical resuspension threshold is not exceeded for water levels below 5.0 m for all Polders (sparing Polder 2). This infrequent exceedance of critical resuspension thresholds and the relatively low wave conditions fronting the Polders is likely to result in less damage and scour of the polders.

## 7.4 Theoretical accretion levels

The potential for accretion within the Polders is set out in Table 10 below for the present day and for 5, 10 and 20 years in the future. These theoretical estimates have been calculated using an accretion value of 0.05 m per annum. The table calculates the area within each Polder that has accreted to the tide level of MHW, the level at which saltmarsh is predicted to establish along the frontage (Section 5.3). This indicative value has been derived from reviewing the topographic change within Polders 4 and 5 (Appendix A); this identified circa 0.5 m accretion between 2005 and 2015 (the frontage does not show accretion after 2015).

It should be noted that these are based entirely upon an estimated level of accretion and do not take account of the specific dynamics of each of the Polders or outline alignments. It also does not take into account:

- The functionality of the Polders
- The additional period of time the saltmarsh would take to establish and mature
- Sea level rise

Discussion on the risk/likelihood of the Polders functioning (and thus the establishment of saltmarsh habitat) is provided further below.

**Table 10. Area of potential saltmarsh creation**

| Option | Polder | Area (ha) | Area currently above MHW (ha) | Area currently above MHW (ha) in 5 yrs | Area currently above MHW (ha) in 10 yrs | Area currently above MHW (ha) in 20 yrs |
|---|---|---|---|---|---|---|
| 1 | Polder 1 | 2.2 | 0.0 | 0.1 | 0.4 | 0.8 |
| | Polder 2 | 3.0 | 0.2 | 0.8 | 1.4 | 2.0 |
| | Polder 3 | 2.7 | 0.1 | 0.5 | 0.9 | 1.6 |
| | Polder 4 | 2.7 | 2.2 | 2.5 | 2.6 | 2.7 |
| | Polder 5 | 2.9 | 2.8 | 2.9 | 2.9 | 2.9 |
| 2 | 2a | 3.3 | 0.0 | 0.1 | 0.1 | 0.2 |
| | 2b | 3.0 | 0.0 | 0.1 | 0.1 | 0.3 |
| | 2c | 2.9 | 0.1 | 0.2 | 0.5 | 1.1 |
| | Polder 1 | 2.2 | 0.0 | 0.1 | 0.4 | 0.8 |
| | Polder 2 | 3.0 | 0.2 | 0.8 | 1.4 | 2.0 |
| | Polder 3 | 2.7 | 0.1 | 0.5 | 0.9 | 1.6 |
| | Polder 4 | 2.7 | 2.2 | 2.5 | 2.6 | 2.7 |
| | Polder 5 | 2.9 | 2.8 | 2.9 | 2.9 | 2.9 |
| 3 | 3a | 0.9 | 0.0 | 0.1 | 0.1 | 0.1 |
| | 3b | 0.8 | 0.0 | 0.0 | 0.1 | 0.2 |
| | 3c | 0.8 | 0.0 | 0.1 | 0.1 | 0.4 |
| | 3d | 0.8 | 0.0 | 0.2 | 0.4 | 0.7 |
| | 3e | 1.1 | 0.0 | 0.1 | 0.4 | 0.8 |
| | 3f | 2.1 | 0.2 | 0.8 | 1.4 | 2.0 |
| | 3g | 2.1 | 0.2 | 0.5 | 0.9 | 1.6 |
| | Polder 4 | 2.7 | 2.2 | 2.5 | 2.6 | 2.7 |
| | Polder 5 | 2.9 | 2.8 | 2.9 | 2.9 | 2.9 |
| 4 | 4a | 1.3 | 0.2 | 0.8 | 1.2 | 1.3 |
| | 4b | 1.1 | 0.1 | 0.4 | 0.6 | 0.9 |
| | P4 (extended) | 4.2 | 2.9 | 3.6 | 4.0 | 4.2 |
| | P5 (extended) | 4.5 | 3.1 | 3.5 | 3.9 | 4.4 |
| 5 | P4 (extended) | 3.5 | 2.8 | 3.3 | 3.5 | 3.5 |
| | P5 (extended) | 3.8 | 3.1 | 3.5 | 3.7 | 3.8 |

# 7.5 Comparison of options

This section provides a comparison of the five alignment options.

## 7.5.1 Functionality of the polders

The conceptual understanding and review of the hydrodynamic model indicates that there is both sufficient sediment and an appropriate flow regime for the accumulation of sediment on the frontage. It can, therefore, be anticipated that all five options are suitable from a hydrodynamic and sediment availability perspective.

However, the likelihood of success is shown to be limited by the hyper-tidal range in the Severn Estuary and the foreshore topography which means that the polders are submerged during the higher states of the tide and limiting the period during which they are acting as sediment traps. The conceptual understanding has also identified that the frontage is very susceptible to resuspension of material from wave agitation and the position of the polders relatively low in the tidal frame also means that the structures are not affording the protection from wave action at these higher states of the tide.

The choice of the preferred alignment is therefore dependent upon the level of risk deemed acceptable with respect to structural damage and the likelihood of accretion for saltmarsh establishment. Using the assessment criteria in section 7.1, Table 11 provides a summary of the potential suitability of the different options reviewed for criteria 3-5 (waves and position in the tidal frame).

In summary, the study concludes that:

- All the structures are at risk of damage from a relatively frequent 10 in 1 year wave condition.
- The frontage topography is a key factor in understanding the patterns of sediment accretion and erosion. The area to the east of the existing Polders has a flatter, shallower elevation with a wide expanse of unprotected saltmarsh (albeit there is erosion of the front toe of the marsh). Moving across the frontage from east to west the topography lowers and steepens and there is an associated reduction in the area of saltmarsh fronting the rip-rap.
- For all options there is suitable sediment availability in the system.
- For all options maximum tidal current speeds are generally sufficiently for the long-term accretion of sediment.
- The proximity of the crest of the Polder to MHWS is a key indicator of success. This is due to both the level of protection it affords during the tidal cycle from wave activity and that high spring tides carry the greatest proportion of sediment in suspension.
- Resuspension of material due to wave activity will be the critical limiting factor.
- The extension of the Polder field west (option 2) is unlikely to be successful due to the lower bathymetry. This results in the Polders being too low in the tidal frame and little protection from wave action.
- For all options the Polder fields are susceptible to resuspension of sediment due to wave action (represented by the 10 in 1 westerly return period). However, greater protection is afforded further east. The most westerly Polders do not provide any protection from wave activity during higher states of the tide with potential for sediment resuspension from approximately 3.0 m (approximately MHWN) for the indicator wave condition. Even the easterly Polders are susceptible to wave resuspension/erosion from *circa* 4.5 m (approximately MHW); approximately 3 m lower than HAT at 7.5 mODN.
- It is also generally accepted that the Polders require maintenance on an approximate five-year basis and that further interventions may be required to repair storm damage. The maintenance

commitment is likely to be higher for Polders lower in the tidal frame with the structures subject to the hydrodynamic and wave forces for a longer duration of the tidal cycle.

When considering the functionality of the Polders, the study recommends the Polder fields are aligned such that the crest of the Polders is as close to MHWS as possible to afford the greatest protection from sediment resuspension/erosion from waves. When considering the existing polders (noting their limited maintenance), it could be considered that having a crest height of > 2m below MHWS and subsequent submergence of >10% of the tidal cycle could also be considered an indicator for risk of failure as illustrated in Table 11.

Option 4 and Option 5 are associated with a higher potential for accretion in the longer term, but it is recognised that these do not necessarily meet the overall objectives of the project. This is discussed further below.

It is noted that the installation of baffles within the Polder fields may be an option to attenuate wave scour. It is recommended that this is investigated in more detail as the design develops.

The brushwood is expected to need replacing every 4- 5 years as well as additional maintenance following storm events. Without the maintenance the polders will fail and the establishment of further saltmarsh would be very unlikely (as with the existing polders); without maintenance it is anticipated that the foreshore would continue as present in the short term, currently stable with no evidence of notable accretion or erosion since 2015. In the long term the foreshore is likely to be more erosional with the foreshore unlikely to accrete in line with sea level rise.

**Table 11 Option assessment matrix**

| Review Criteria | | Area (ha) | Difference Between brushwood crest and MHWS (m) | Percentage of time the polder crest is exceeded by the tide | Water level at which there is a risk of damage to the structure (>1 m wave) (mODN) | Water level at which there is a risk of sediment resuspension (0.1 m wave) (mODN) |
|---|---|---|---|---|---|---|
| Option 1 | P1 | 2.21 | -2.3 | 13% | 5.5 | 3 |
| | P2 | 3.01 | -2.2 | 12% | 6 | 3 |
| | P3 | 2.70 | -1.9 | 10% | 5.5 | 4 |
| | P4 | 2.67 | -0.7 | 3% | 7 | 6 |
| | P5 | 2.89 | -0.8 | 3% | 6.5 | 5.5 |
| Option 2 | 2a | 3.33 | -2.9 | 19% | 4.5 | 3.5 |
| | 2b | 3.00 | -2.9 | 19% | 4.5 | 3.5 |
| | 2c | 2.94 | -2.5 | 15% | 4.5 | 4 |
| | P1 | 2.21 | -2.3 | 13% | 5.5 | 3 |
| | P2 | 3.01 | -2.2 | 12% | 6 | 3 |
| | P3 | 2.70 | -1.9 | 10% | 5.5 | 4 |
| | P4 | 2.67 | -0.7 | 3% | 7 | 6 |
| | P5 | 2.89 | -0.8 | 3% | 6.5 | 5.5 |
| Option 3 | 3a | 0.87 | -2.6 | 16% | 5 | 4 |
| | 3b | 0.83 | -2.4 | 14% | 5 | 4 |
| | 3c | 0.78 | -2.1 | 11% | 5 | 4 |
| | 3d | 0.84 | -1.7 | 8% | 5 | 4.5 |
| | 3e | 1.11 | -1.7 | 8% | 5 | 4.5 |
| | 3f | 2.09 | -1.7 | 8% | 5 | 4.5 |
| | 3g | 2.12 | -1.7 | 8% | 5.5 | 4.5 |
| | P4 | 2.67 | -0.7 | 3% | 7 | 6 |
| | P5 | 2.89 | -0.8 | 3% | 6.5 | 5.5 |
| Option 4 | 4a | 1.27 | -1.7 | 8% | 6 | 4.4 |
| | 4b | 1.08 | -1.7 | 8% | 6.5 | 4.5 |
| | P4 (extended) | 4.20 | -1.7 | 8% | 5.5 | 5 |
| | P5 (extended) | 4.54 | -1.7 | 8% | 5 | 4 |
| Option 5 | P4 (extended) | 3.53 | -2.9 | 19% | 7 | 5.5 |
| | P5 (extended) | 3.77 | -2.9 | 19% | 7 | 5 |

### 7.5.2 Option comparison with business case outcomes

This section provides discussion and comparison of the five options (including Option 1, reinstatement along the existing alignment). The comparison takes account of the design criteria along with consideration of the following outcomes listed in the Outline Business Case (NRW 2018):

1. Protect the frontage of RGW from existing erosive pressures upon mudflat and saltmarsh habitats.
2. Promote sediment deposition in the first instance, to reduce or ideally reverse the erosive trends currently being experienced.
3. Create conditions that will support both mudflat and saltmarsh features to varying extents over time.
4. Support the flood risk management of the area

Outcomes 1 and 4 refer to the opportunities arising from the creation of saltmarsh habitat for flood and coastal erosion risk management whilst outcomes 2 and 3 relate to ecological enhancement and creation. The following section discusses the pros and cons of the different options with respect to these two themes.

**Flood and coastal erosion risk management**
When considering the benefits for flood risk management of the area, the establishment of saltmarsh can reduce wave energy and have the following benefits:

- Reduce the wave energy reaching the structure, potentially lowering maintenance requirements; and
- Reduce the wave height at the crest of the defence, potentially reducing the risk of overtopping.

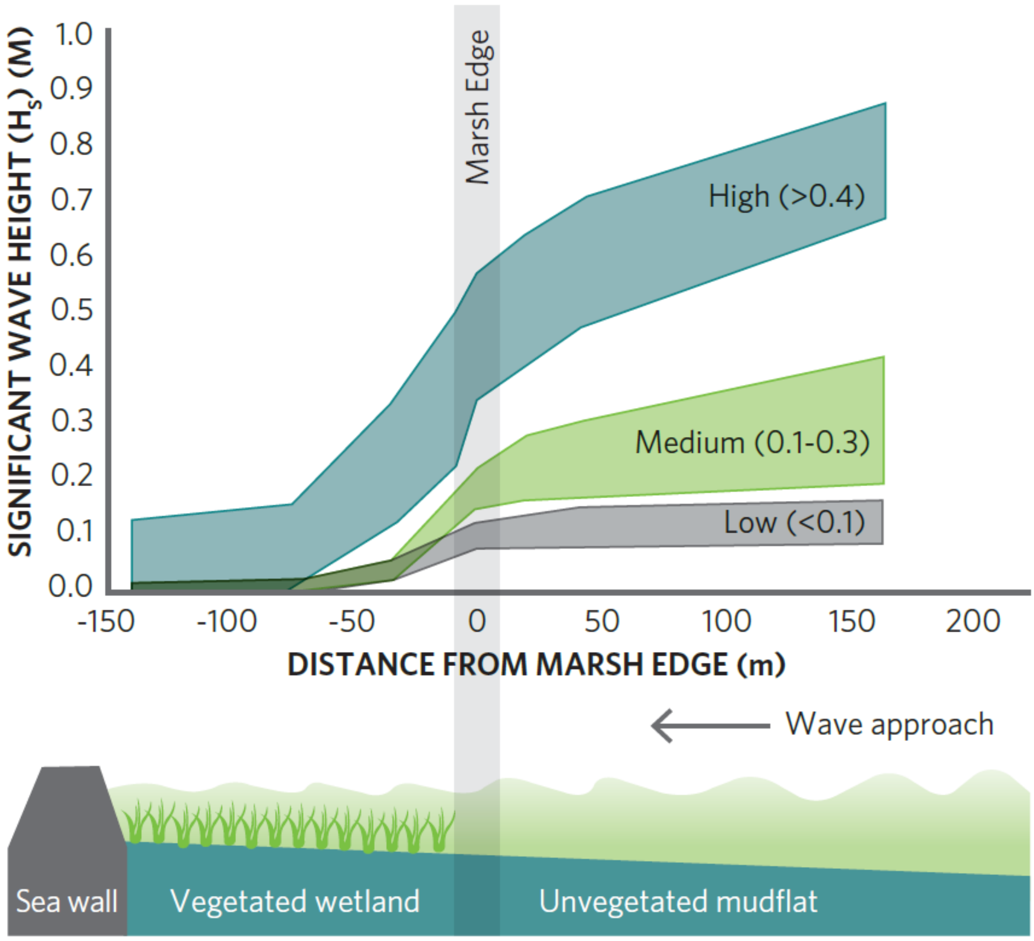
Whilst quantifying the potential flood risk benefits are outside the scope of this assessment, the team have considered the potential for the project to reduce wave attenuation and Figure 51 below shows how an established saltmarsh can significantly reduce wave heights at the defence.

The flood and coastal erosion benefits could be considered from Polder 3 westward and would be a factor of both the health of the established saltmarsh (its ability to absorb wave energy) and the distance over which the wave would travel (Figure 51). For the benefits of wave attenuation to be realised the saltmarsh will need to be well established as already exists at Polders 4 and 5.

As shown in Table 10, with fully functioning polders and a rate of accretion of 5cm per year, the level would still be insufficient for saltmarsh to establish in much of the polders, even in 20 years' time, due to the steepening topography found along the frontage (noting this does not take into account sea level rise).

It should again be noted that the structures themselves will be subject to potentially damaging waves under the relatively frequent 10 in 1 year wave condition and hence there is significant risk to the survivability of the structures from the time of installation.

The likely success of the project in meeting flood and coastal erosion risk outcomes, is therefore dependent upon the establishment of mature saltmarsh for an extended distance in front of the existing defence. This will require regular maintenance of the structures at least until the saltmarsh is fully mature in order to protect the frontage regular scour events over the winter periods as well as reactive maintenance following damaging storm events.




*Note: the blue vertical band in the centre of the figure marks the transition to permanent vegetation on the marsh to its left; without the permanently vegetated marsh, wave heights would continue to reduce only at the rate with which waves reduce to the right of this transition.*

Source: Saltmarsh Restoration Handbook, 2021

**Figure 51. Wave height reduction over a saltmarsh on the Essex coast, UK for waves of high, medium and low height (approximate height given in metres in brackets) approaching the shore in different water depths (variation with the wave height bands).**

**Ecological enhancement and creation**

The business case outcomes for habitat enhancement do not allow comparison between alignments or to understand what success would look like. All alignments could be argued to meet the outcomes even if the polders fail as outlined below.

*To protect the frontage of RGW from existing erosive pressures upon mudflat and saltmarsh habitats.*

Installing Polders along the length of the frontage will reduce the erosive pressures on the frontage. However, they will not necessarily protect all the frontage because the different alignments will protect the frontage to a lesser or greater extent, as described in Section 7.5.1 above.

*Promote sediment deposition in the first instance, to reduce or ideally reverse the erosive trends currently being experienced.*
All the alignments will promote sediment deposition. However, in order to reduce or reverse the erosive trend the Polders need to protect the frontage from wave scour. This requires the Polders to be positioned higher in the tidal frame to reduce the potential frequency of scour inducing waves.

*Create conditions that will support both mudflat and saltmarsh features to varying extents over time.*
The Polders will create conditions that support mudflat and saltmarsh conditions. Depending upon the mosaic of habitats, and over what timescale, different Polder alignments could be preferred. For example, if the Polders are intended to maintain the mudflat in the short, medium and longer term, then the western polders (if maintained) could be considered suitable.

However, if the project is seeking the establishment of saltmarsh (which may then contribute to the flood and coastal erosion risk management outcomes), then the Polder success is more reliant on alignments higher in the tidal frame.

### 7.5.3 Summary

The Polders are at risk of structural damage under all the alignment options for a relatively frequent 10 in 1 year wave condition and the survivability of the structures is an important consideration when determining the viability of the scheme.

The choice of the preferred alignment will be dependent upon the level of risk deemed acceptable with respect to structural damage, maintenance commitment, and the likelihood of accretion for saltmarsh establishment.

When comparing the different alignments, Options 4 (seaward extension of Polder 4 and 5 and bringing Polder 3 landward) and 5 (seaward extension of Polder 4 and 5) offer the higher levels of confidence in their success in creating saltmarsh. However it is recognised that these options do not provide the area of habitat creation anticipated by the project.

Option 1 (reinstatement of existing polders) and 2 (reinstatement and extension west along existing alignment) are considered highly unlikely to be successful even with a long-term programme of maintenance. This is due to their position lower in the tidal frame leaving much of the upper frontage exposed to wave scour. Extending the polders west along the current alignment is considered the least likely option to be successful.

Option 3 has brought the alignment closer to the shore and could be considered more likely to be successful. Whilst accretion rates in polders 3a and 3b are still insufficient to reach MHW, the level at which saltmarsh will establish, Polders 3d to 3g could accrete to the required levels in 20 years' time. It must again be noted that this assumes the polders are maintained, fully functioning and there are no significant scour or storm events which could re-erode the foreshore.

Based upon the analysis, and recognising that there remains significant uncertainty in the likelihood of success, the following could be considered, in combination, as a trial for habitat creation along the frontage:

- Installation of polders along alignment 3d to 3g

- Extension of Polder 4 and Polder 5 to 4 mODN.

This would need to be accompanied with a programme of maintenance for at least 25 years in order for saltmarsh to become established (and the benefits realised) along with an associated monitoring programme.

# 8 References

ABPmer, 2013. Culver Sand: Dredging Impact Assessment. ABPmer Report No. R.2034.

ABPmer, 2016a. Area 526 Culver extension: Coastal Impact Study. ABPmer Report No. R.2701.

ABPmer, 2016b. Tidal Lagoon Cardiff - Conceptual Process Model. ABPmer Report No. R.2617 (unpublished confidential draft).

ABPmer, 2019a. Rumney Great Wharf Saltmarsh Restoration / Enhancement Feasibility and Preferred Option Studies. Produced by ABPmer for NRW. NRW Evidence Report No: 528, 96p, NRW, Cardiff.

ABPmer, 2019b. Area 531: North Bristol Deep Extension, Coastal Impact Study, ABPmer Report No. R.3059.

Atkins, 2006. Feasibility Study: Incorporating dredged material within Polders at Rhymney Great Wharf. Atkins, Epsom.

Blumenthal, K.P., 1966. Some Aspects of Land Reclamation in the Netherlands. 19p. From: Proceedings of the Tenth International Conference on Coastal Engineering. September, 1966. Tokyo, Japan.

Dornbusch, U., 2019. Fact-finding tour: Saltmarsh (Vorland1) management in Germany. oint report by Environment Agency and Natural England, 19-11-2018. Worthing: Environment Agency.

Environment Agency, 2009. Works Information for the maintenance of the westernmost Polder at Rhymney Great Wharf. Environment Agency.

Environment Agency, 2018. Coastal flood boundary conditions for the UK: update 2018 Technical summary report: SC060064/TR6 [Available online 15/03/2023: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/827778/Coastal_flood_boundary_conditions_for_the_UK_2018_update_-_technical_report.pdf ]

Erchinger, H.F., 1970. Land reclamation and groin-building in the tidal flats. Coastal Engineering Proceedings, 1(12), 66.

Exo Environmental, 2017. Brightlingsea Dredging & Restoration - Year 1 Summary Report. Brightlingsea Harbour Commissioners, Norwich.

Exo Environmental, 2018. Brightlingsea Dredging & Restoration - Year 2 Summary Report. Brightlingsea Harbour Commissioners, Norwich.

Hudson, R., Kenworthy, J. and Best, M. (eds) (2021). Saltmarsh Restoration Handbook: UK and Ireland. Environment Agency, Bristol, UK.

Lowe, S., 2013. Lymington Harbour Habitat Replenishment Scheme – Phase II - Summary of Works. The Crown Estate.

Manning A.J., 2012. TR167 – Enhanced UK Estuaries database: explanatory notes and metadata. HR Wallingford Report DDY0427-RT002-R02-00. December 2012

McBride R.A., Anderson J.B., Buynevich I.V., Cleary, W. Fenster, M.S. FitzGerald D.M., Harris M.S., Hein, C.J. Klein, A.H.F. Liu, B. de Menezes, J.T. Pejrup, M. Riggs, S.R. Short, A.D. Stone, G.W. Wallace, D.J. Wang.,

2013. Morphodynamics of Barrier Systems: A Synthesis Treatise on Geomorphology, Volume 10, 2013, Pages 166-244 (Elsiver).

Met Office, 2018. UK Climate Projections (UKCP18): Marine climate change projections Available at: https://www.metoffice.gov.uk/research/approach/collaboration/ukcp [last accessed June 2023]

Natural Resources Wales (NRW), 2018. Case study 57. Rhymney Great Wharf. Prepared for 'Working with Natural Flood Management: Evidence Directory' project. Cardiff: NRW.

Natural Resources Wales (NRW), 2023.Presentation on Rhymney Great Wharf. 8 May 2023

Nichols M.M. and Biggs R.B., 1985. Estuaries, in Coastal Sedimentary Environments, Davis R.A. (ed). Springer-Verlag, New York. pp 77 – 186.

O'Brien, D.J, Whitehouse R J S and Cramp A, 2000. The cyclic development of a macrotidal mudflat on varying timescales. Continental Shelf Research, 20, 1596-1600.

Parker, W.R. and Kirby, R., 1982. Sources of Transport Patterns of Sediment in the Inner Bristol Channel and Severn Estuary. Severn Barrage Proceedings of Symposium held at the Institution of Civil Engineers, London.

Posford Duvivier and ABP Research and Consultancy, 2000. Bristol Channel Marine Aggregates: Resources and Constraints Research Project. Final Report, Vols 1 and 2, Aug 2000.

SEASTATES - ABP Marine Environmental Research Ltd: http://www.seastates.net/

Severn Estuary Coastal Group, 2010 - Severn Estuary Coastal Group (2010). Severn Estuary Shoreline Management Plan Review (SMP2).

Siemes, R.W.A., Borsje, B.W., Daggenvoorde, R.J., and Hulscher, S.J.M.H, 2020. Artificial Structures Steer Morphological Development of Salt Marshes: A Model Study. Journal of Marine Science and Engineering 2020, 8, 326, 22p.

von Lieberman, N., Matheja, A., and Schwarze, H., 1998. Optimised design of land reclamation fields for sustainable foreland development. Hannover: University of Hannover. 11p.

Welsh Government, 2022. Adapting to Climate Change: Guidance for Flood and Coastal Erosion Risk Management Authorities in Wales. WG46400, Digital ISBN 978-1-80535-019-4. Crown Copyright

# 9 Abbreviations

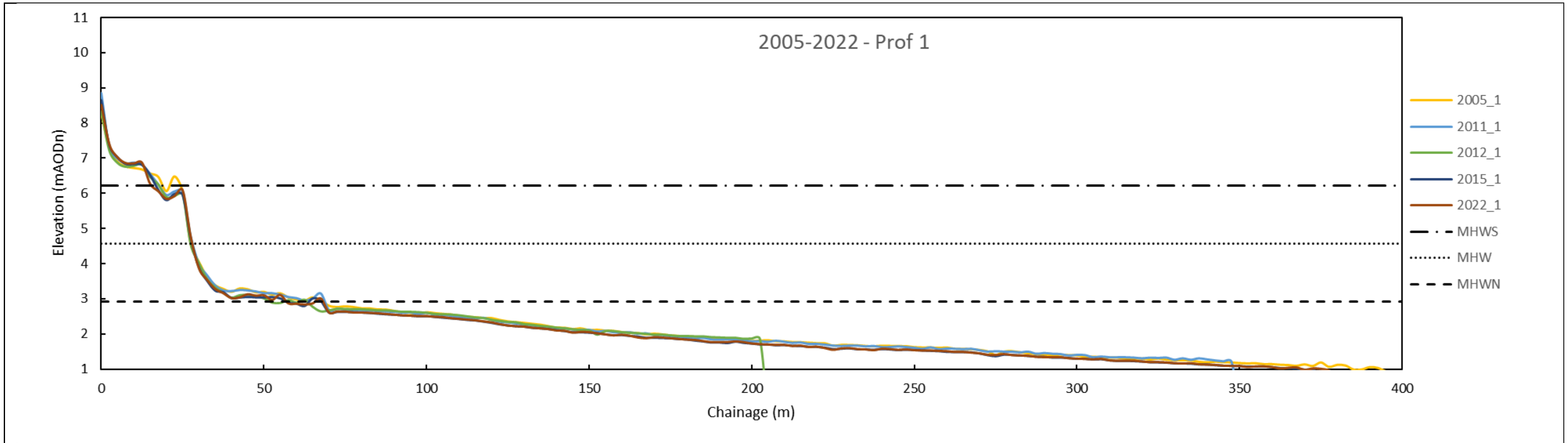
| | |
|---|---|
| 1D | One-Dimension(al) |
| 2D | Two-Dimension(al) |
| AEP | Annual Exceedance Probability |
| BGS | British Geological Survey |
| BP | Before Present |
| CD | Chart Datum |
| CFBD | Coastal Flood Boundary Dataset |
| CIS | Coastal Impact Studies |
| DataMapWales | Data and Maps from the Welsh Public Sector (Welsh Government |
| DHI | Danish Hydraulic Institute |
| DTM | Digital Terrain Model |
| EMODnet | European Marine Observation and Data Network |
| FM | Flexible Mesh |
| GEV | Generalized Extreme Value |
| GPD | Generalized Pareto Distribution |
| ha | Hectare |
| HAT | Highest Astronomical Tide |
| HD | Hydrodynamic |
| Hs | Wave Height |
| LAT | Lowest Astronomical Tide |
| LiDAR | Light Detection and Ranging |
| LW | Low Water |
| MAE | Mean Absolute Error |
| MHW | Mean High Water |
| MHWN | Mean High Water Neaps |
| MHWS | Mean High Water Springs |
| MLWN | Mean Low Water Neaps |
| MLWS | Mean Low Water Springs |
| MSL | Mean Sea Level |
| NRW | Natural Resources Wales |
| NTL | Normal Tidal Limit |
| NTLSF | National Tide and Sea Level Facility |
| ODN | Ordnance Datum Newlyn |
| RCP | Representative Concentration Pathways |
| RMSE | Root Mean Square Error |
| RoI | Republic of Ireland |
| SMP2 | Shoreline Management Plan 2 |
| SSC | Suspended Sediment Concentrations |
| SW | Spectral Wave |
| Tp | Wave Period |
| UK | United Kingdom |
| UKCP | UK Climate Predictions |
| UKHO | United Kingdom Hydrographic Office |
| WL | Water Level |
| WoO | Window of Opportunity |

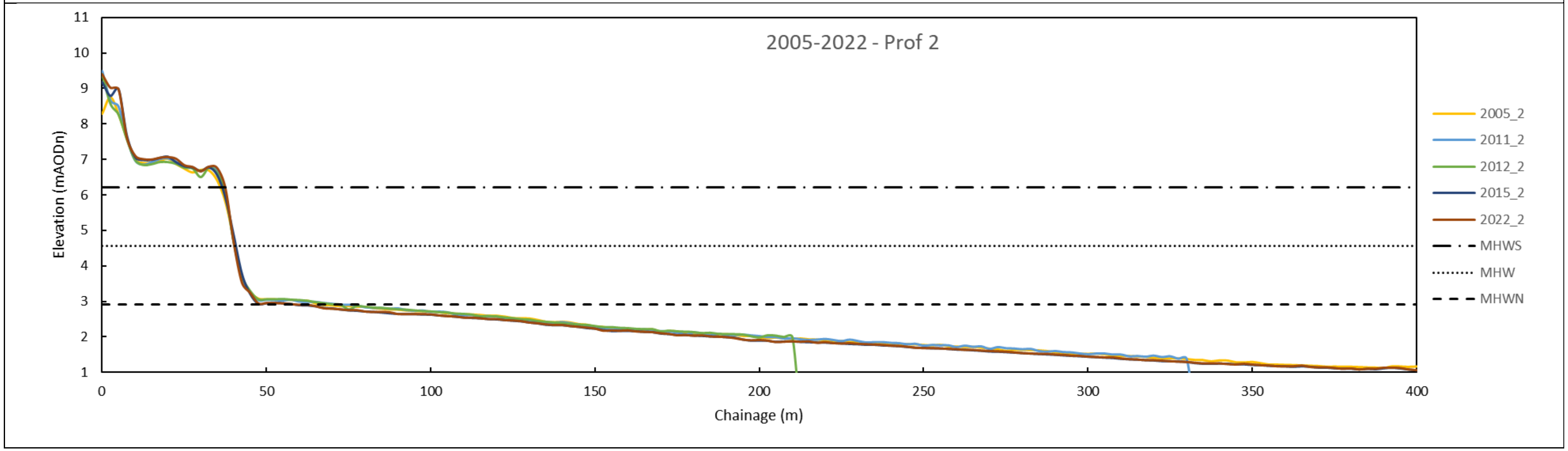
Cardinal points/directions are used unless otherwise stated.
SI units are used unless otherwise stated.

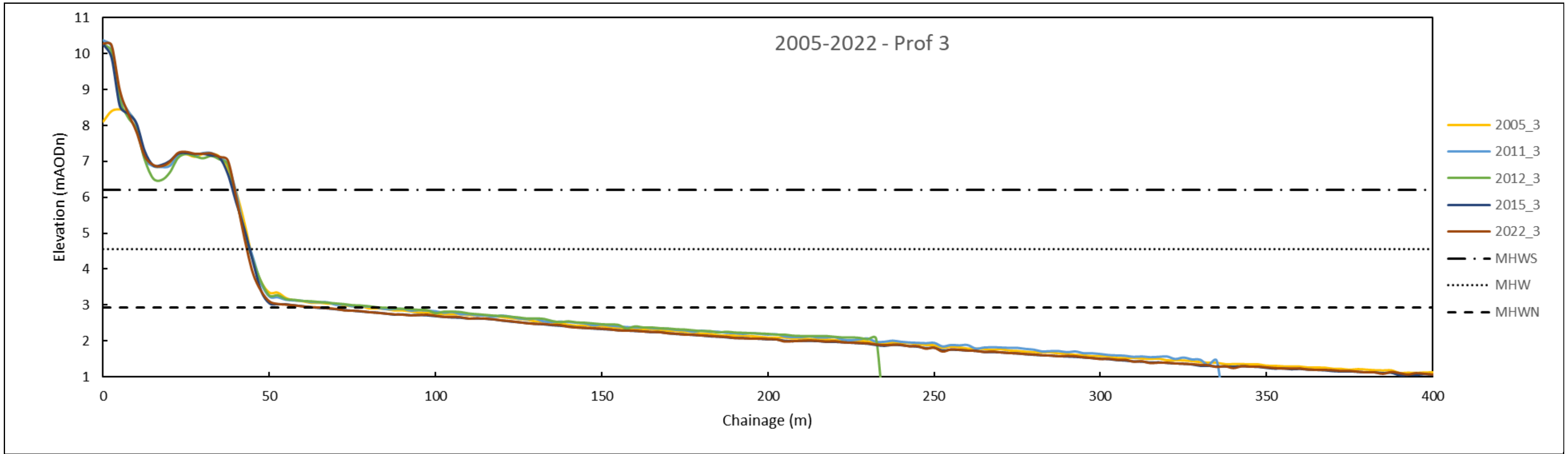
# Appendix

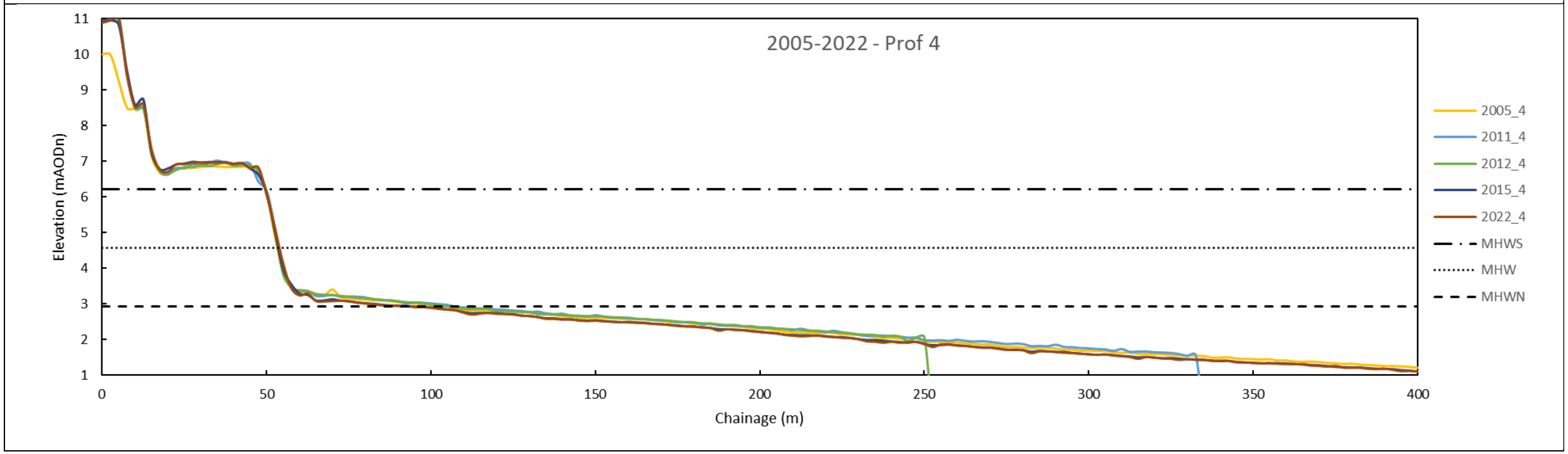
Innovative Thinking - Sustainable Solutions

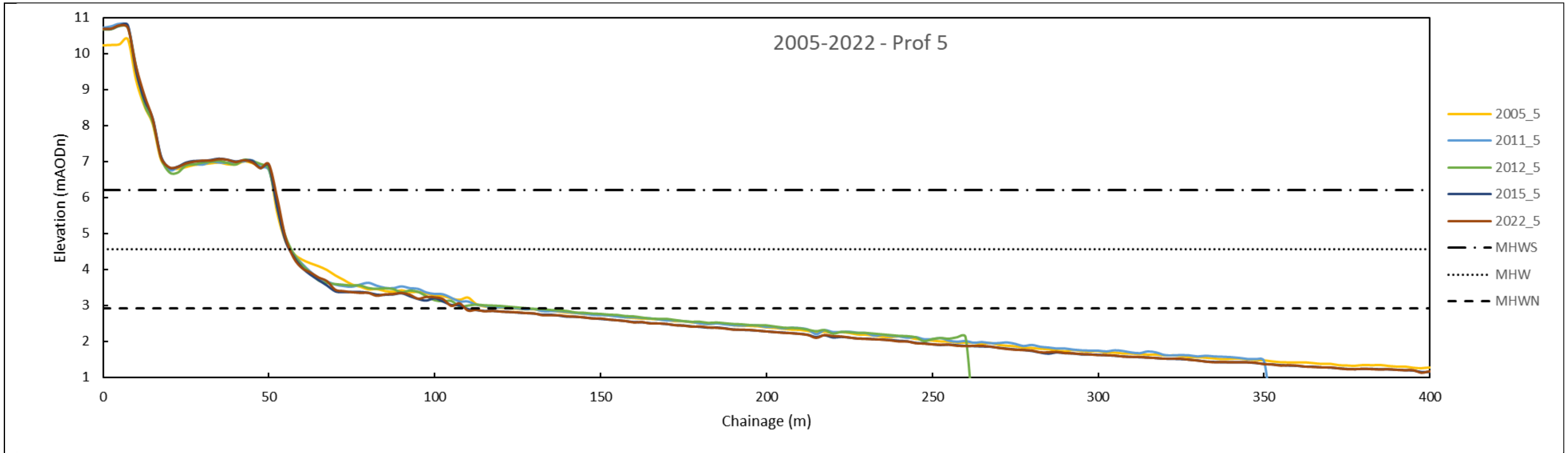
# A Shoreline Profiles

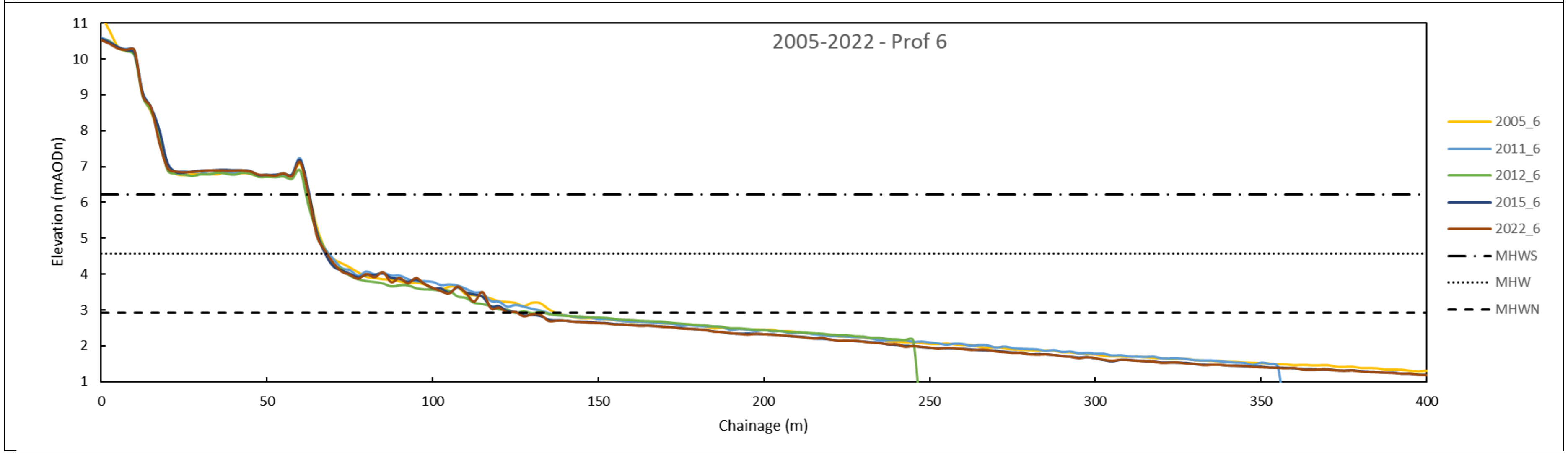


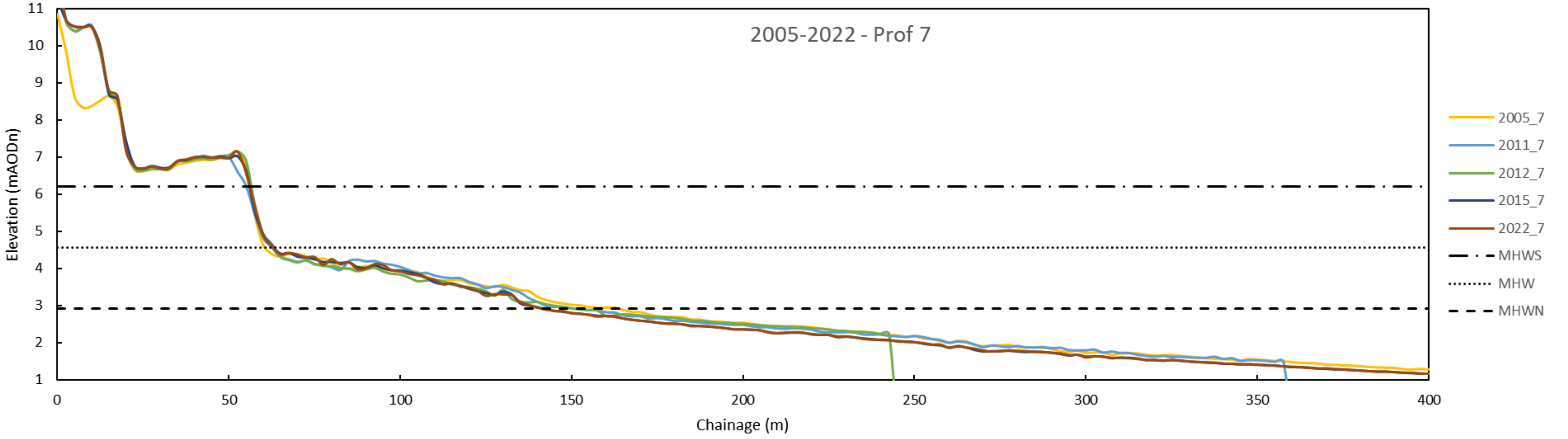



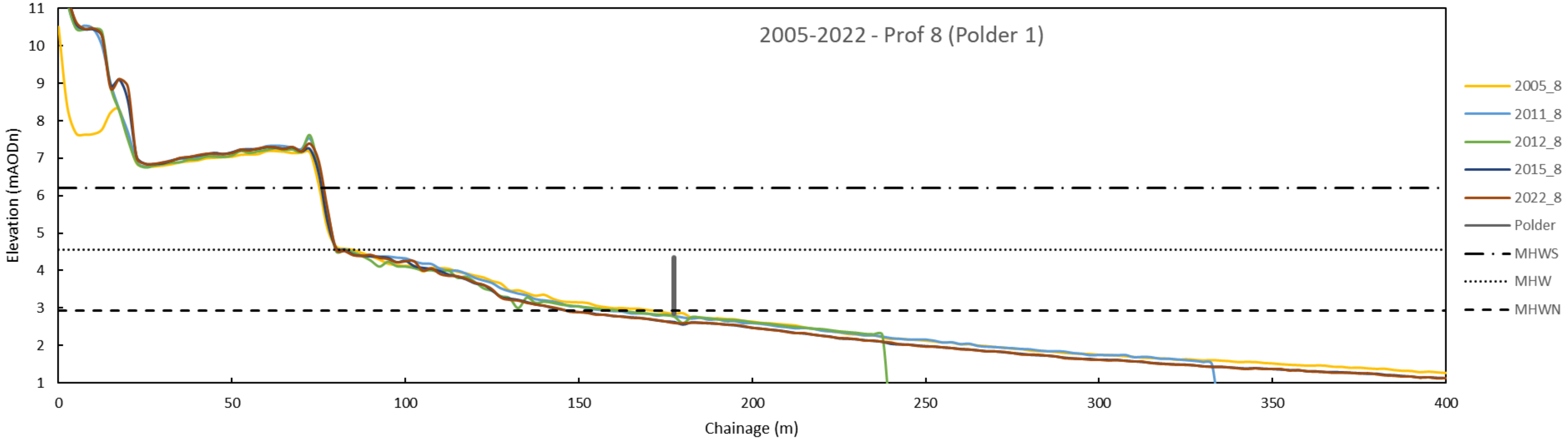

2005-2022 - Prof 3
Elevation (mAODn)
Chainage (m)
2005_3
2011_3
2012_3
2015_3
2022_3
MHWS
MHW
MHWN

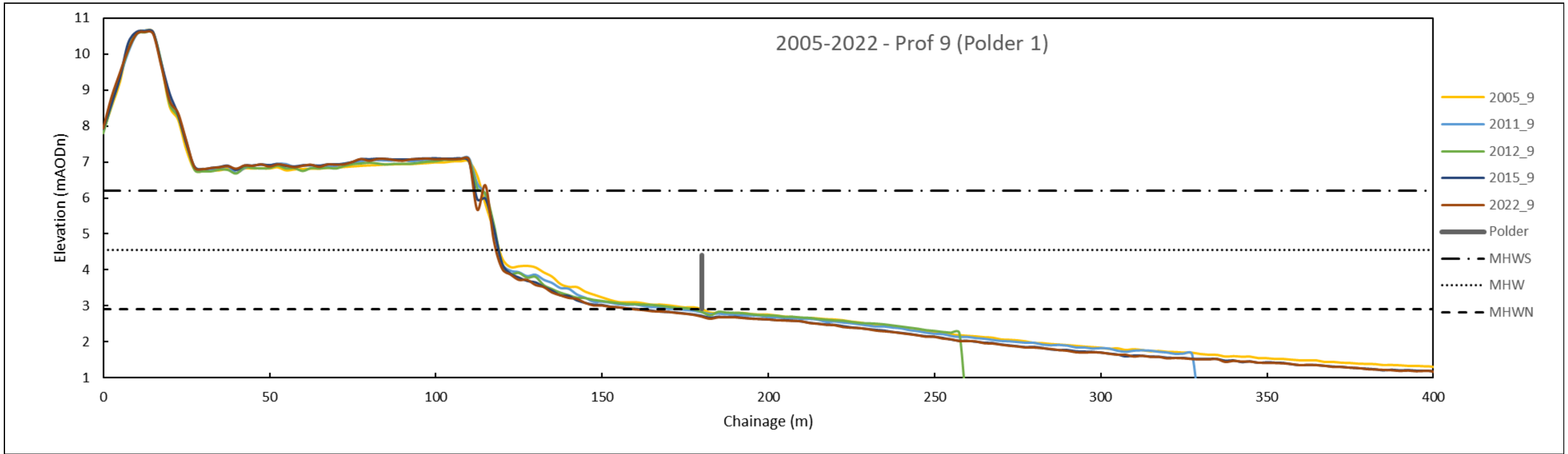

2005-2022 - Prof 4
Elevation (mAODn)
Chainage (m)
2005_4
2011_4
2012_4
2015_4
2022_4
MHWS
MHW
MHWN

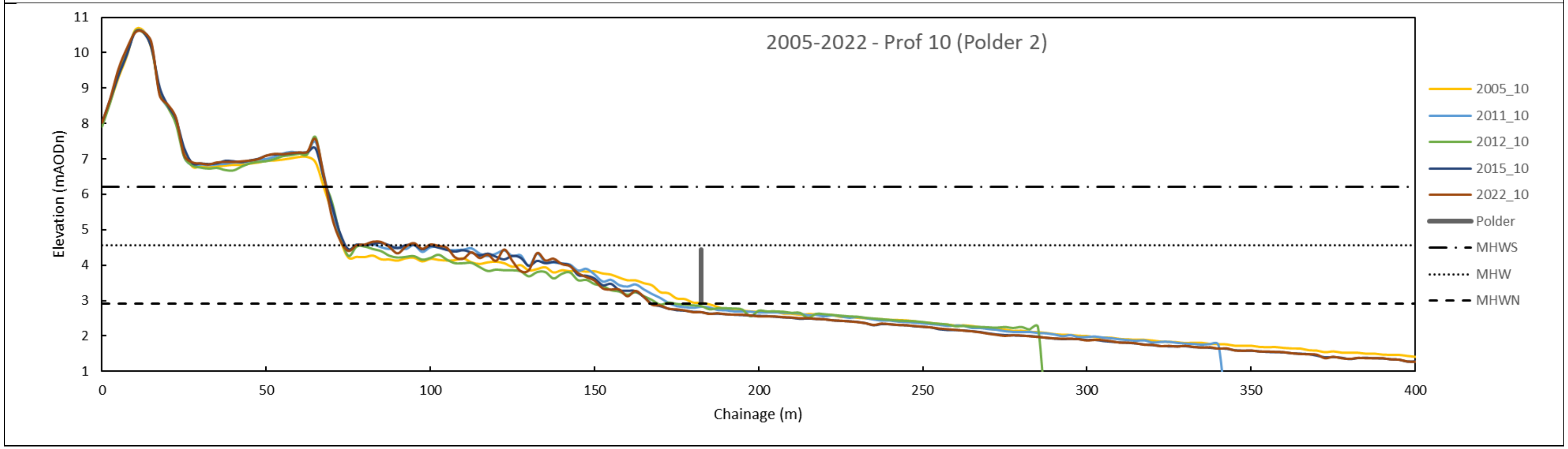

2005-2022 - Prof 5
Elevation (mAODn)
Chainage (m)
11
10
9
8
7
6
5
4
3
2
1
0
50
100
150
200
250
300
350
400
2005_5
2011_5
2012_5
2015_5
2022_5
MHWS
MHW
MHWN

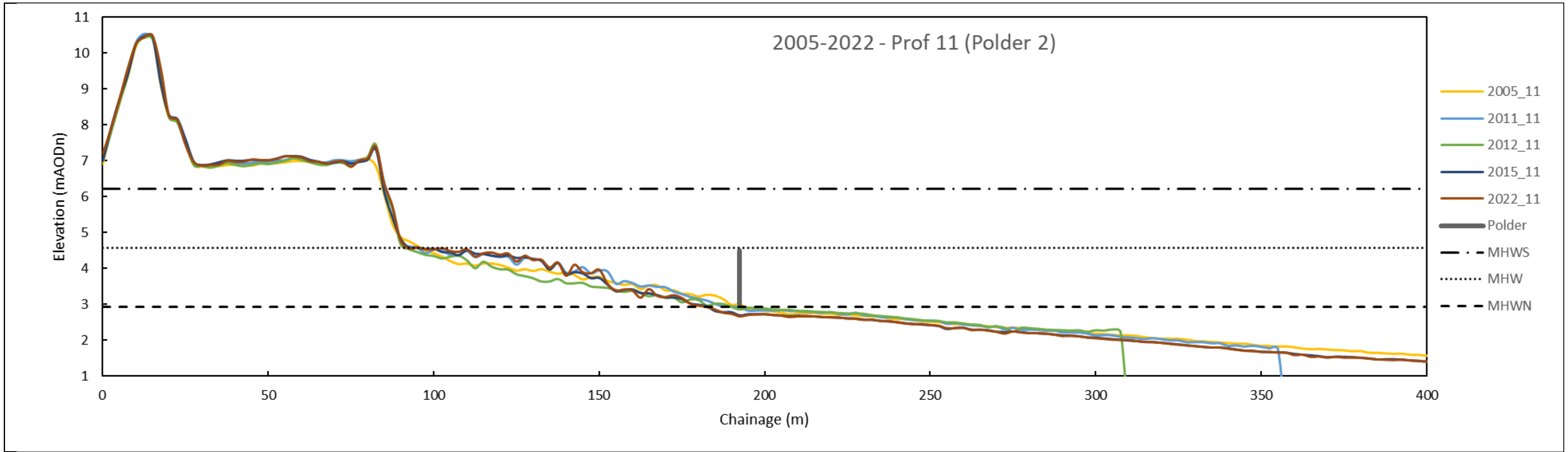

2005-2022 - Prof 6
Elevation (mAODn)
Chainage (m)
11
10
9
8
7
6
5
4
3
2
1
0
50
100
150
200
250
300
350
400
2005_6
2011_6
2012_6
2015_6
2022_6
MHWS
MHW
MHWN

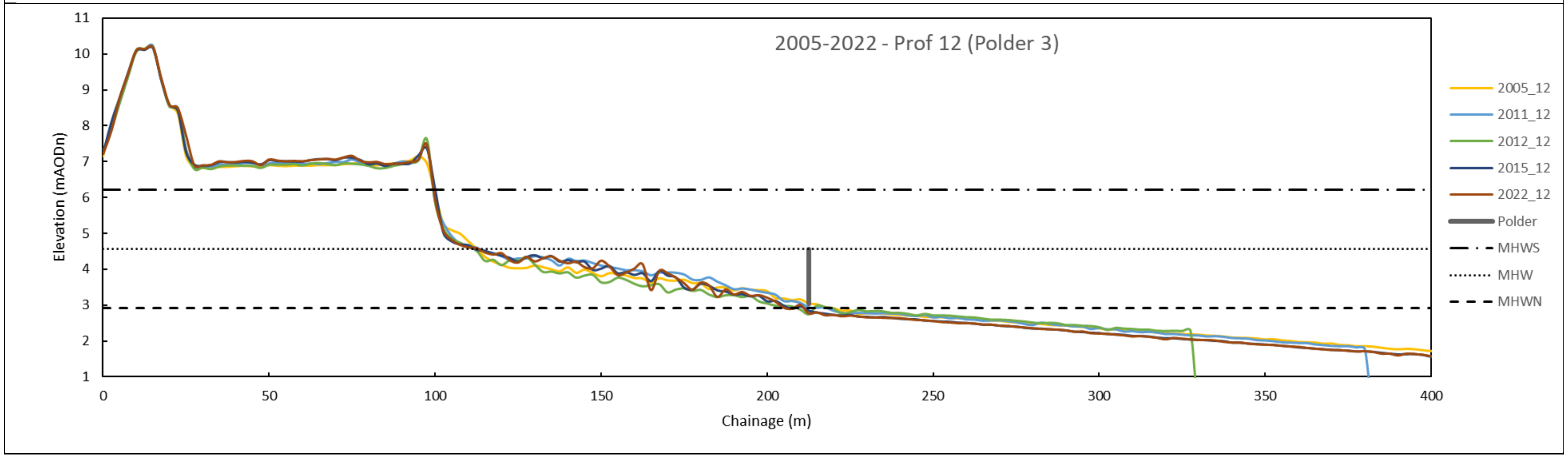

2005-2022 - Prof 7
Elevation (mAODn)
Chainage (m)
0
50
100
150
200
250
300
350
400
1
2
3
4
5
6
7
8
9
10
11
2005_7
2011_7
2012_7
2015_7
2022_7
MHWS
MHW
MHWN

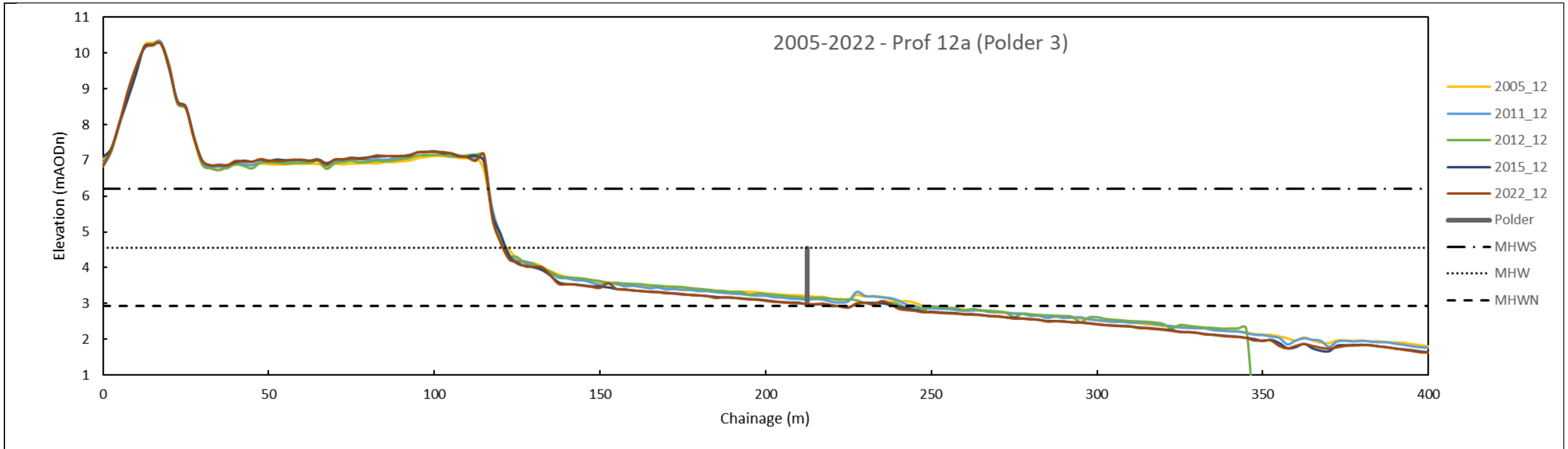

2005-2022 - Prof 8 (Polder 1)
Elevation (mAODn)
Chainage (m)
0
50
100
150
200
250
300
350
400
1
2
3
4
5
6
7
8
9
10
11
2005_8
2011_8
2012_8
2015_8
2022_8
Polder
MHWS
MHW
MHWN


2005-2022 - Prof 9 (Polder 1)
Elevation (mAODn)
Chainage (m)
2005_9
2011_9
2012_9
2015_9
2022_9
Polder
MHWS
MHW
MHWN

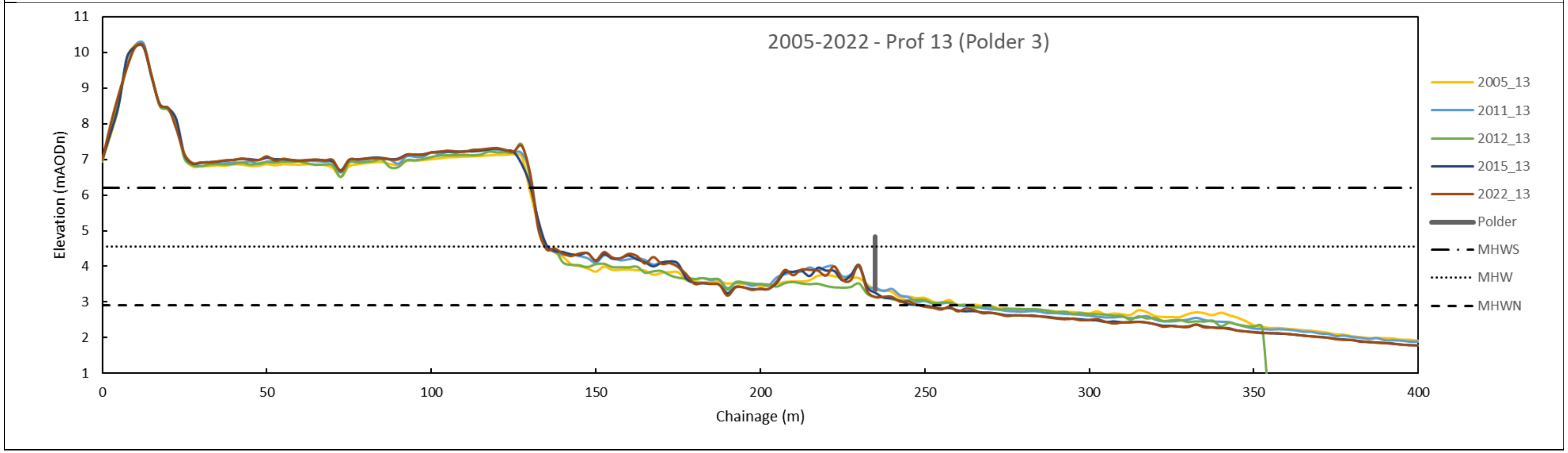

2005-2022 - Prof 10 (Polder 2)
Elevation (mAODn)
Chainage (m)
2005_10
2011_10
2012_10
2015_10
2022_10
Polder
MHWS
MHW
MHWN


2005-2022 - Prof 11 (Polder 2)
Elevation (mAODn)
Chainage (m)
2005_11
2011_11
2012_11
2015_11
2022_11
Polder
MHWS
MHW
MHWN

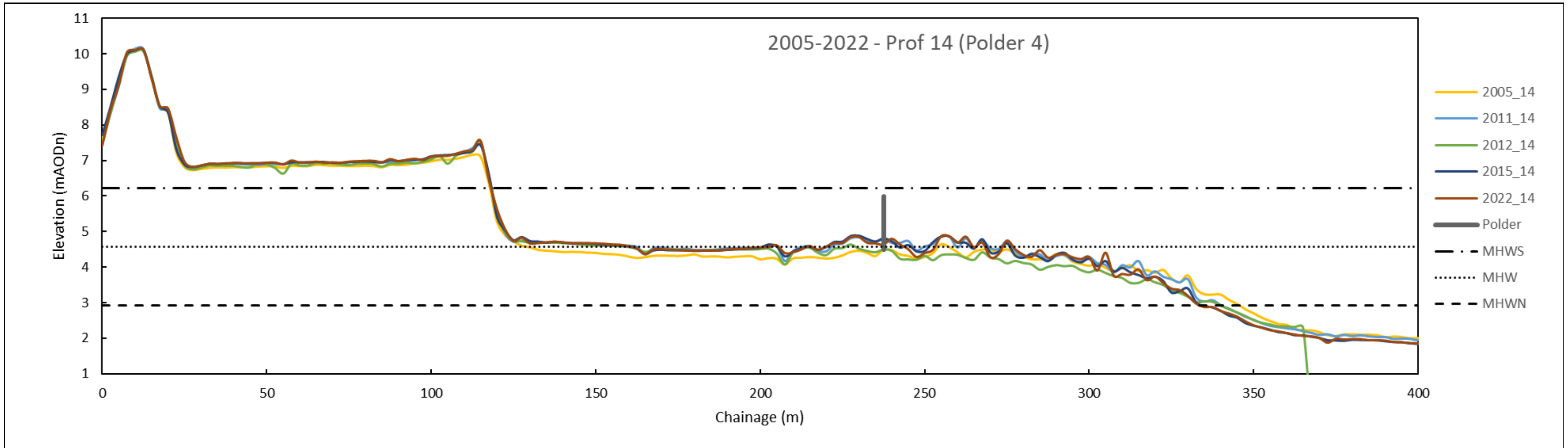

2005-2022 - Prof 12 (Polder 3)
Elevation (mAODn)
Chainage (m)
2005_12
2011_12
2012_12
2015_12
2022_12
Polder
MHWS
MHW
MHWN

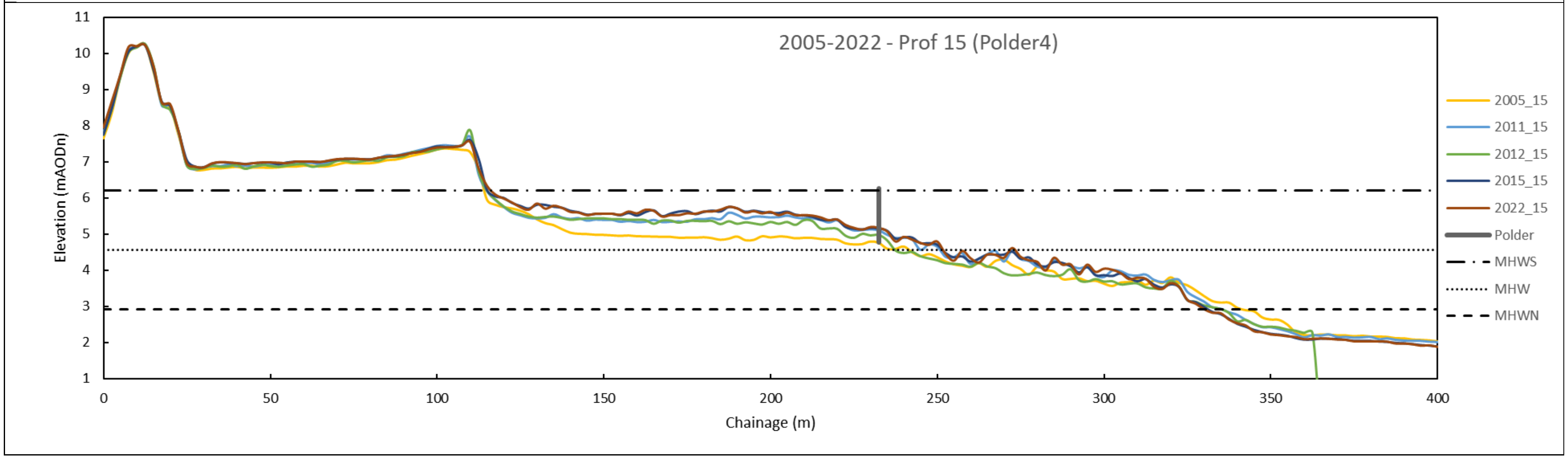


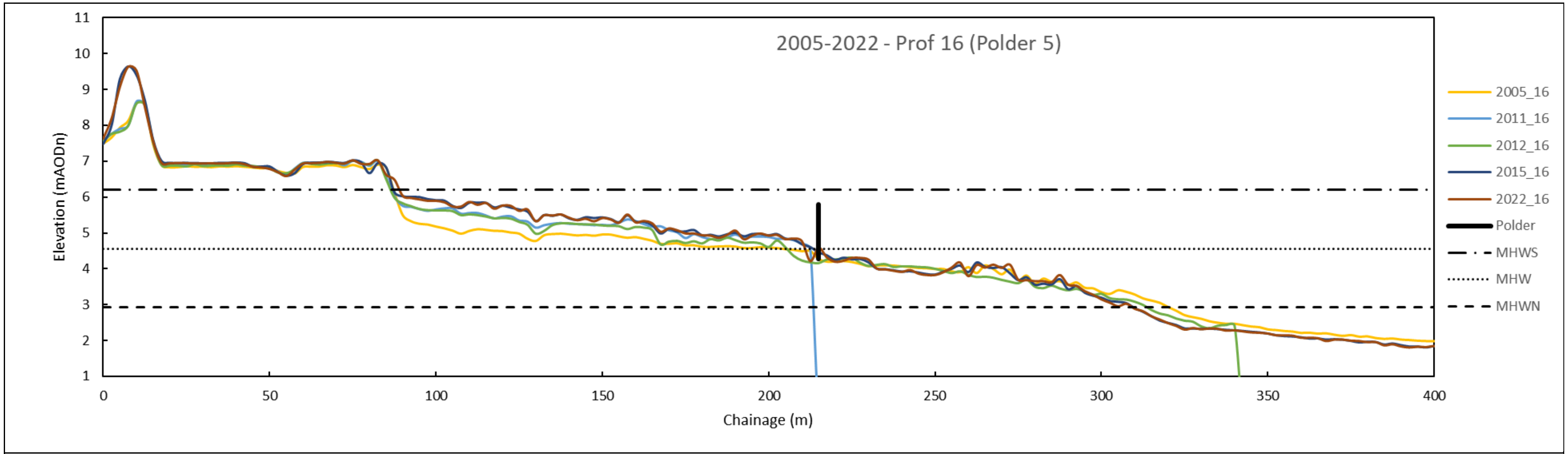
2005-2022 - Prof 12a (Polder 3)
Elevation (mAODn)
Chainage (m)
2005_12
2011_12
2012_12
2015_12
2022_12
Polder
MHWS
MHW
MHWN

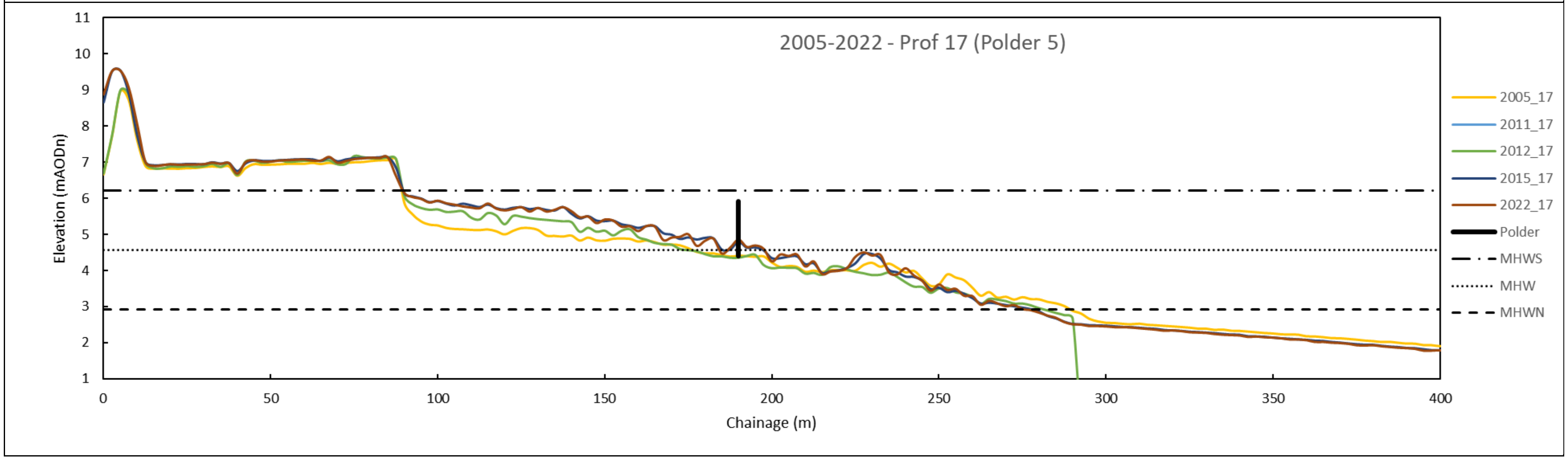



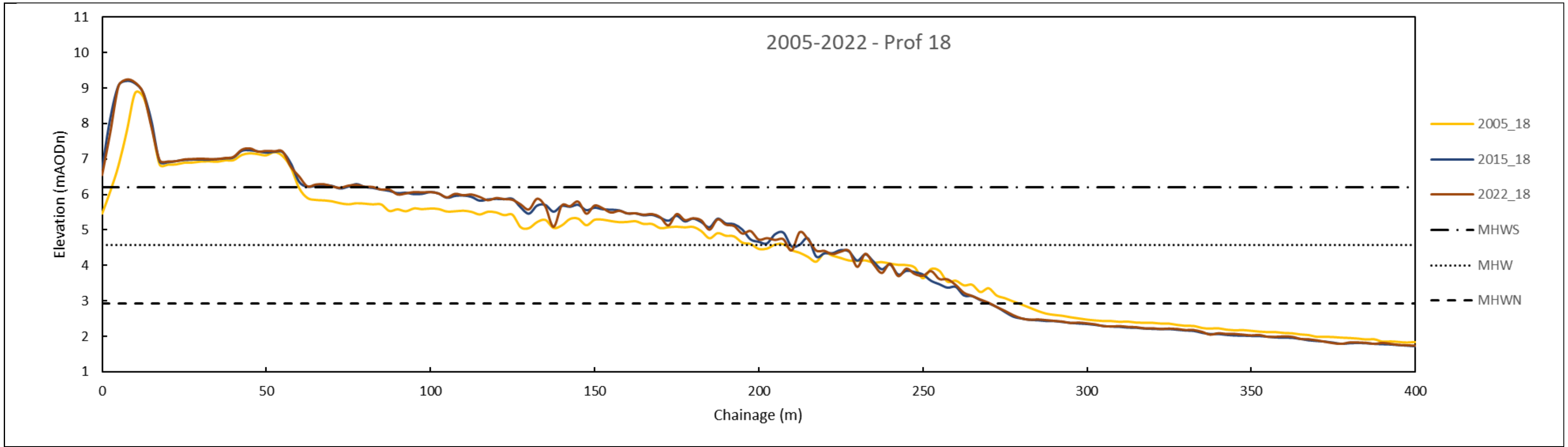
2005-2022 - Prof 13 (Polder 3)
Elevation (mAODn)
Chainage (m)
2005_13
2011_13
2012_13
2015_13
2022_13
Polder
MHWS
MHW
MHWN

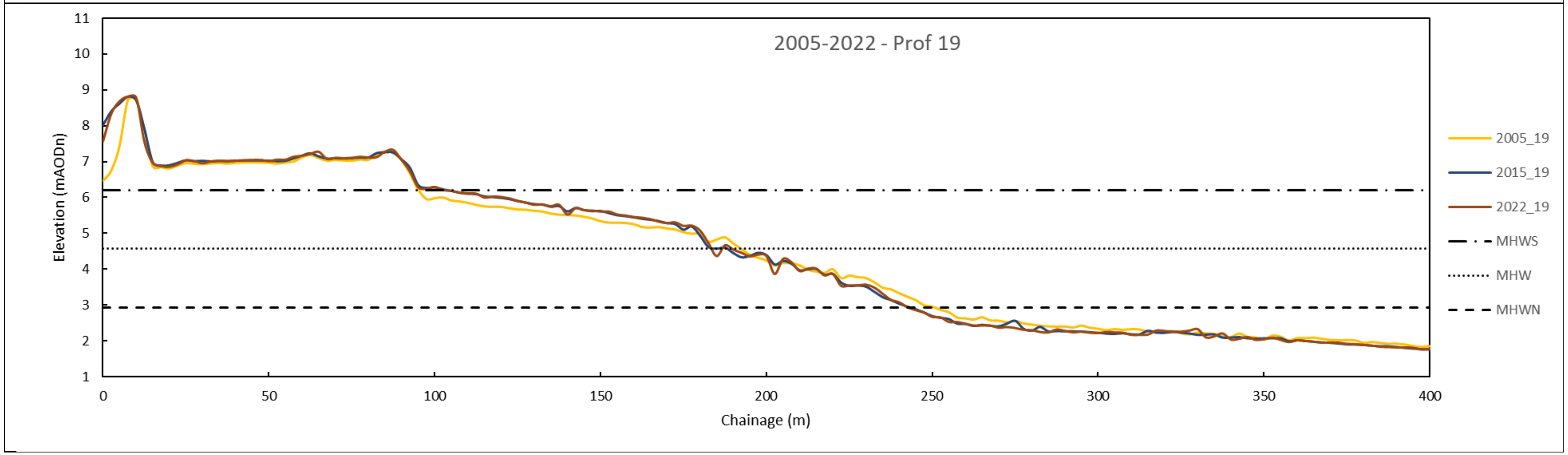

2005-2022 - Prof 14 (Polder 4)
Elevation (mAODn)
Chainage (m)
2005_14
2011_14
2012_14
2015_14
2022_14
Polder
MHWS
MHW
MHWN

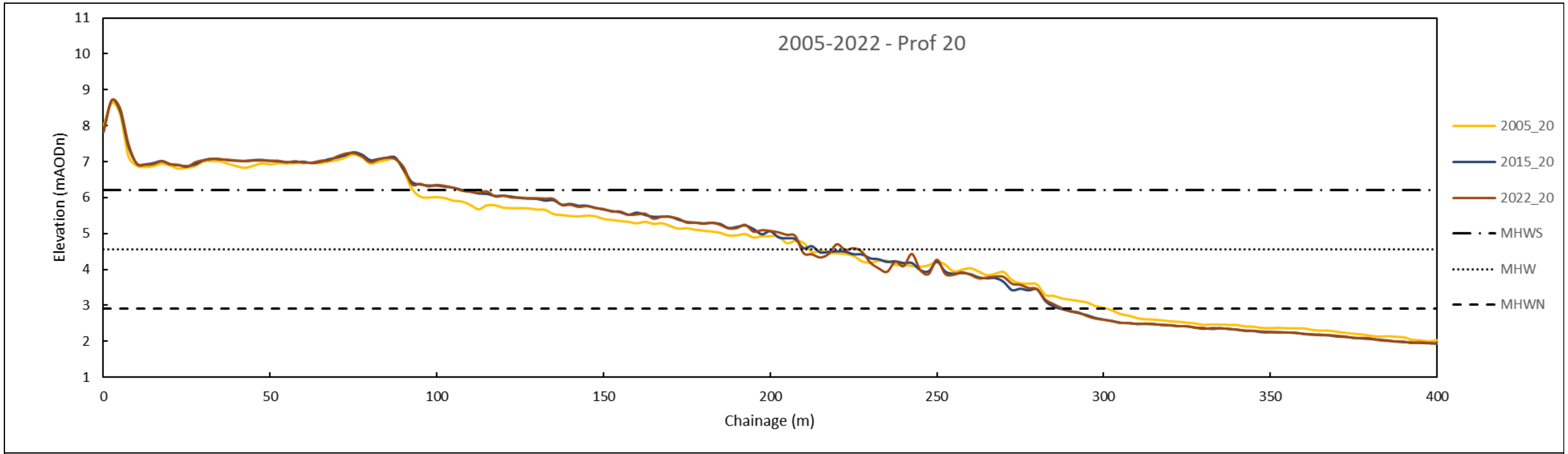

2005-2022 - Prof 15 (Polder4)
Elevation (mAODn)
Chainage (m)
2005_15
2011_15
2012_15
2015_15
2022_15
Polder
MHWS
MHW
MHWN

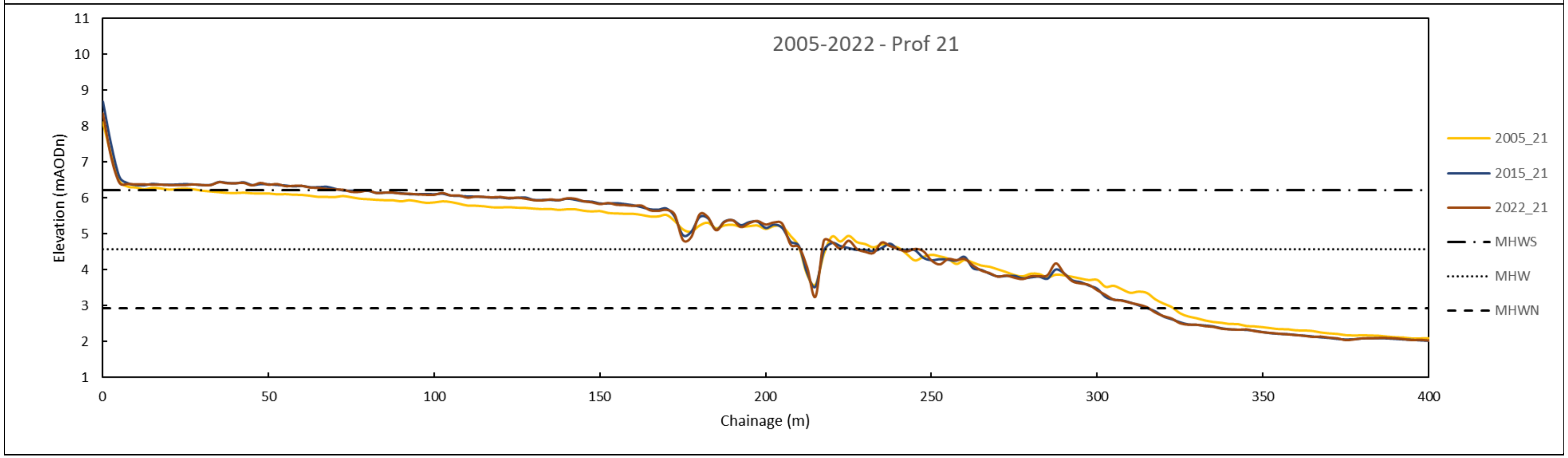

2005-2022 - Prof 16 (Polder 5)
Elevation (mAODn)
Chainage (m)
2005_16
2011_16
2012_16
2015_16
2022_16
Polder
MHWS
MHW
MHWN

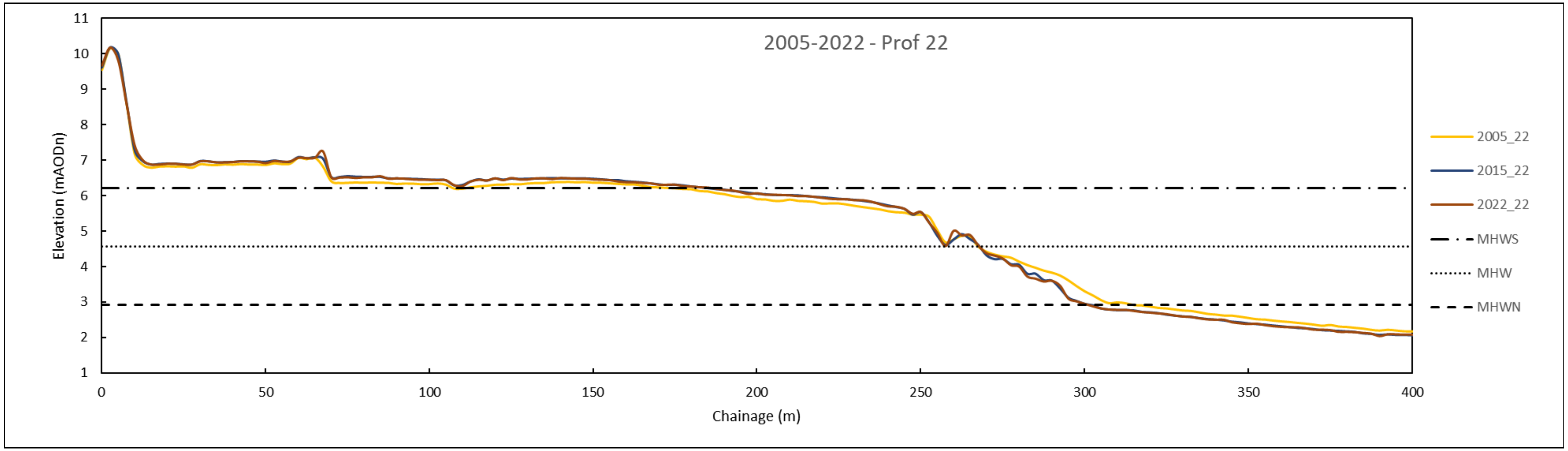

2005-2022 - Prof 17 (Polder 5)
Elevation (mAODn)
Chainage (m)
2005_17
2011_17
2012_17
2015_17
2022_17
Polder
MHWS
MHW
MHWN


2005-2022 - Prof 18
Elevation (mAODn)
Chainage (m)
11
10
9
8
7
6
5
4
3
2
1
0
50
100
150
200
250
300
350
400
2005_18
2015_18
2022_18
MHWS
MHW
MHWN


2005-2022 - Prof 19
Elevation (mAODn)
Chainage (m)
11
10
9
8
7
6
5
4
3
2
1
0
50
100
150
200
250
300
350
400
2005_19
2015_19
2022_19
MHWS
MHW
MHWN


2005-2022 - Prof 20
Elevation (mAODn)
Chainage (m)
2005_20
2015_20
2022_20
MHWS
MHW
MHWN


2005-2022 - Prof 21
Elevation (mAODn)
Chainage (m)
2005_21
2015_21
2022_21
MHWS
MHW
MHWN


2005-2022 - Prof 22
Elevation (mAODn)
Chainage (m)
11
10
9
8
7
6
5
4
3
2
1
0
50
100
150
200
250
300
350
400
2005_22
2015_22
2022_22
MHWS
MHW
MHWN

# B Wave model tests: Options 2-5

**Table 12. Polder impact on wave conditions with for the 10 in 1 year wave condition Option 2**

| WL (mODN) | 2a | | 2b | | 2c | | P1 | | P2 | | P3 | | P4 | | P5 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | In front of Polder | Behind Polder | In front of Polder | Behind Polder | In front of Polder | Behind Polder | Infront of polder | Behind polder | Infront of polder | Behind polder | Infront of polder | Behind polder | Infront of polder | Behind polder | Infront of polder | Behind polder |
| 3 | - | - | - | - | - | - | 0.28 | 0.17 | 0.19 | 0.12 | 0.04 | - | - | - | - | - |
| 3.5 | 0.68 | 0.23 | 0.6 | 0.2 | 0.61 | 0.08 | 0.55 | 0.33 | 0.46 | 0.28 | 0.34 | 0.07 | - | - | - | - |
| 4 | 0.88 | 0.49 | 0.83 | 0.45 | 0.83 | 0.32 | 0.78 | 0.47 | 0.70 | 0.39 | 0.60 | 0.37 | - | - | - | - |
| 4.5 | 1.06 | 0.72 | 1.02 | 0.7 | 1.02 | 0.57 | 0.98 | 0.64 | 0.91 | 0.55 | 0.84 | 0.62 | - | - | - | - |
| 5 | 1.2 | 0.94 | 1.18 | 0.92 | 1.18 | 0.8 | 1.15 | 0.83 | 1.10 | 0.74 | 1.04 | 0.85 | - | - | 0.28 | 0.05 |
| 5.5 | 1.3 | 1.11 | 1.3 | 1.11 | 1.3 | 1.01 | 1.28 | 1.00 | 1.24 | 0.92 | 1.21 | 1.06 | 0.14 | 0.08 | 0.60 | 0.36 |
| 6 | 1.36 | 1.25 | 1.38 | 1.26 | 1.38 | 1.19 | 1.36 | 1.16 | 1.35 | 1.09 | 1.33 | 1.22 | 0.49 | 0.36 | 0.87 | 0.65 |
| 6.5 | 1.41 | 1.36 | 1.43 | 1.37 | 1.43 | 1.33 | 1.42 | 1.29 | 1.41 | 1.23 | 1.41 | 1.34 | 0.79 | 0.62 | 1.10 | 0.90 |
| 7 | 1.45 | 1.42 | 1.47 | 1.44 | 1.48 | 1.43 | 1.47 | 1.40 | 1.47 | 1.36 | 1.47 | 1.43 | 1.04 | 0.87 | 1.28 | 1.12 |

**Table 13. Polder impact on wave conditions with for the 10 in 1 year wave condition Option 3**

| WL (ODN) | 3a | | 3b | | 3c | | 3d | | 3e | | 3f | | 3g | | P4 | | P5 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | In front of Polder | Behind Polder | In front of Polder | Behind Polder | In front of Polder | Behind Polder | In front of Polder | Behind Polder | In front of Polder | Behind Polder | In front of Polder | Behind Polder | In front of Polder | Behind Polder | In front of polder | Behind polder | In front of polder | Behind polder |
| 3 | 0.18 | 0.03 | 0.11 | 0.01 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 3.5 | 0.44 | 0.06 | 0.38 | 0.05 | 0.31 | 0.03 | 0.18 | 0.01 | 0.32 | 0.01 | 0.32 | 0.01 | 0.23 | 0.05 | - | - | - | - |
| 4 | 0.67 | 0.32 | 0.62 | 0.22 | 0.58 | 0.1 | 0.52 | 0.06 | 0.59 | 0.06 | 0.59 | 0.04 | 0.49 | 0.02 | - | - | - | - |
| 4.5 | 0.89 | 0.57 | 0.84 | 0.47 | 0.82 | 0.36 | 0.79 | 0.21 | 0.83 | 0.24 | 0.82 | 0.18 | 0.73 | 0.19 | - | - | - | - |
| 5 | 1.06 | 0.8 | 1.04 | 0.72 | 1.02 | 0.62 | 1.01 | 0.47 | 1.03 | 0.49 | 1.01 | 0.43 | 0.94 | 0.43 | - | - | 0.28 | 0.05 |
| 5.5 | 1.2 | 0.99 | 1.2 | 0.94 | 1.19 | 0.85 | 1.19 | 0.71 | 1.19 | 0.72 | 1.17 | 0.67 | 1.12 | 0.67 | 0.14 | 0.08 | 0.60 | 0.36 |
| 6 | 1.28 | 1.15 | 1.3 | 1.13 | 1.31 | 1.06 | 1.32 | 0.93 | 1.3 | 0.93 | 1.28 | 0.89 | 1.25 | 0.89 | 0.49 | 0.36 | 0.87 | 0.65 |
| 6.5 | 1.33 | 1.27 | 1.37 | 1.28 | 1.38 | 1.23 | 1.4 | 1.11 | 1.37 | 1.11 | 1.36 | 1.08 | 1.34 | 1.07 | 0.79 | 0.62 | 1.10 | 0.90 |
| 7 | 1.38 | 1.35 | 1.42 | 1.38 | 1.44 | 1.36 | 1.45 | 1.27 | 1.43 | 1.26 | 1.41 | 1.24 | 1.4 | 1.23 | 1.04 | 0.87 | 1.28 | 1.12 |

Table 14. Polder impact on wave conditions with for the 10 in 1 year wave condition Option 4

| WL (ODN) | 4a | | 4b | | Extended P4 | | Extended P5 | |
|---|---|---|---|---|---|---|---|---|
| | In front of Polder | Behind Polder | In front of Polder | Behind Polder | In front of Polder | Behind Polder | In front of Polder | Behind Polder |
| 3.0 | - | - | - | - | - | - | - | - |
| 3.5 | - | - | 0.06 | 0.03 | - | - | 0.35 | - |
| 4.0 | - | - | 0.11 | 0.09 | 0.19 | - | 0.63 | 0.11 |
| 4.5 | 0.39 | 0.18 | 0.30 | 0.28 | 0.62 | - | 0.86 | 0.45 |
| 5.0 | 0.65 | 0.47 | 0.53 | 0.50 | 0.89 | 0.25 | 1.04 | 0.70 |
| 5.5 | 0.85 | 0.71 | 0.75 | 0.71 | 1.09 | 0.59 | 1.18 | 0.91 |
| 6.0 | 1.02 | 0.93 | 0.94 | 0.90 | 1.22 | 0.87 | 1.28 | 1.08 |
| 6.5 | 1.17 | 1.11 | 1.11 | 1.06 | 1.32 | 1.10 | 1.35 | 1.21 |
| 7.0 | 1.29 | 1.27 | 1.25 | 1.20 | 1.40 | 1.29 | 1.41 | 1.31 |

Table 15. Polder impact on wave conditions with for the 10 in 1 year wave condition Option 5

| WL (ODN) | Extended P4 | | Extended P5 | |
|---|---|---|---|---|
| | Infront of Polder | Behind Polder | Infront of Polder | Behind Polder |
| 3.0 | - | - | - | - |
| 3.5 | - | - | - | - |
| 4.0 | - | - | 0.04 | - |
| 4.5 | - | - | 0.15 | - |
| 5.0 | 0.22 | - | 0.36 | 0.30 |
| 5.5 | 0.49 | 0.30 | 0.57 | 0.57 |
| 6.0 | 0.75 | 0.59 | 0.78 | 0.80 |
| 6.5 | 0.97 | 0.84 | 0.97 | 1.00 |
| 7.0 | 1.17 | 1.06 | 1.14 | 1.18 |

# Contact Us

ABPmer

Quayside Suite,
Medina Chambers
Town Quay, Southampton
SO14 2AQ

T +44 (0) 23 8071 1840
F +44 (0) 23 8071 1841
E enquiries@abpmer.co.uk

**www.abpmer.co.uk**