NERC Environmental Risk to Infrastructure Innovation Programme (ERIIP)

Coastal Landfill and Shoreline Management: Implications for Coastal Adaptation Infrastructure

Case Study: **Pennington**

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Cover photograph, courtesy of Anne Stringfellow, University of Southampton. View of Pennington seawall (2018).

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Abbreviations

aOD	above Ordnance Datum
AONB	Area of outstanding natural beauty
ATL	Advance the line
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
EA	Environment Agency
HCC	Hampshire County Council
HSLR	High sea level rise
HTL	Hold the (existing defence) line
H++	Extreme high (H++) sea level rise
LSLR	Low sea level rise
LS	Liquid-solid ratio
NAI	No active intervention
NFDC	New Forest District Council
MHWS	Mean high water springs
MR	Managed realignment
MSL	Mean sea level
MSLR	Medium sea level rise
ODN	Ordnance Datum Newlyn (defined as the MSL at Newlyn in Cornwall between 1915 and 1921)
SMP	Shoreline Management Plan
SAC	Special Areas of Conservation
SPA	Special Protected Areas
SSSI	Site of special scientific interest

1. Introduction

This case study contributes to a project "Coastal landfill and shoreline management: implications for coastal adaptation infrastructure" funded by the Natural Environment Research Council (NERC) as part of the Environmental Risks to Infrastructure Innovation Programme.

The project aimed to improve understanding of the long-term management of coastal landfills on dynamic coasts and assess different management approaches to the problems that such sites pose. In the UK, there are approximately 2000 (mostly historic) landfills in England and Wales which are located in coastal flood plains and/or erosion zones. Flooding of landfills could lead to flushing of contaminants from the waste, and erosion may potentially release the waste into the marine environment. This is likely to increase in future due to sea level rise. In some less developed parts of the coastline, shoreline management plans (SMPs) seek to allow natural physical processes such as erosion to progress. Where landfills are present however, the shoreline is usually defended to protect the environment and people from hazards that may be released if the landfill is flooded or subject to erosion.

Coastal landfills therefore need to be protected, but this may be at odds with SMPs which may recommend "managed realignment" or "no active intervention" in less developed areas where there is a move towards allowing coasts to be more dynamic. The presence of coastal landfills in such areas may dictate a "hold the line" plan to defend the landfill against flooding and erosion due to sea level rise. However, many of these landfills are the responsibility of local authorities who do not have a budget to address these problems.

The project estimated the long-term impact of coastal processes affected by sea level rise on three selected landfills and investigated different management options to prevent pollution, including removing the waste material or protecting the sites. The outputs from the three case studies have given the project partners a better understanding of the impacts these landfills have on shoreline management plan strategic options (hold the line, managed realignment, and no active intervention) under different climate change scenarios. The three landfills selected are located on the south coast of England: (1) Lyme Regis, Dorset, (University of Southampton, 2018a), (2) Wicor Cams near Fareham, Hampshire, (University of Southampton, 2018b) and (3) Pennington near Lymington, Hampshire.

2. Background

2.1 Study Site

The Pennington study site is located between Lymington town and the villages of Keyhaven and Milford-on-Sea on the Southeast coast of England, lying at the western end of the Solent region in the county of Hampshire. Figure 1 shows the geographic location of the study area and the historic and authorised landfills at the site. The study site lies behind a sea defence wall, which fronts onto an area of salt marsh bordering the Solent.

The shoreline in the area is renowned for its outstanding scenic beauty, ecological significance, and historical importance. Figure 2 shows the distributions of the surrounding land use (including the landfill sites) and coastal wetland habitats as well as the various nature conservation sites in the study region. The coastline is characterised by extensive low-lying land with mudflats and saltmarsh systems of historic and nature conservation importance, backed by a series of seawalls, soft cliffs, barrier beaches and a shingle spit. Most of the coastline has a rich diversity of nationally and internationally important flora and fauna. Hence, the area is part of the South Hampshire Coast

AONB, and also designated as a SSSI under the national Wildlife and Countryside Act 1981 (e.g., for its valuable grazing marshes), SPA for its birds under the EC Birds Directive (79/409/EEC), SAC for its habitats under the EC Habitat Directive (92/43/EEC) and is listed as a Ramsar (conservation of Wetlands) site. Adjacent, but with some overlapping onto these sites, are the areas of gravel excavations that have been filled with waste materials and a historic waste disposal landfill site near the shoreline. A large area behind the sea defence, including parts of the landfill sites, lies within the 1 in 200 year indicative coastal floodplain. The existing sea wall is the main engineered structure that manages potential flooding of these sites and also potential loss of material and pollution from the historic landfill sites. This highlights the need for understanding the environmental and shoreline management issues associated with conflicts between the various land uses and designations at the site in order to take into account the potential implications in appraisal of future management policies.

2.2 Shoreline management plans

A SMP[1] policy provides a description of the preferred management measures to protect a stretch of coastline from the threats of coastal flooding and risks of erosion in the short, medium, and long-term (Nicholls et al, 2013). It is a high-level, non-statutory policy document that provides guidance aiming to balance flood and erosion risks with natural processes and the potential implications of future climate change. The choice of a preferred policy option for a particular area (i.e., stretch of coastline) takes into account the natural and built environments, existing sea defences, as well as associated compatibility with adjacent coastal areas. There are four different SMP policy options that can be implemented for a particular stretch of coastline. These are listed below as defined by the Environment Agency[2]:

- Hold the (existing defence) line (HTL): "An aspiration to build or remain artificial defences so that the position of the shoreline remains. Sometimes the type or method of defence may change to achieve this result",

- Advance the line (ATL): "New defences are built on the seaward side",

- Managed realignment (MR): "Allowing the shoreline to move naturally, but managing the process to direct it in certain areas. This is usually done in low-lying areas, but may occasionally apply to cliffs", and

- No active intervention (NAI): "There is no planned investment in defending against flooding or erosion, whether or not an artificial defence has existed previously".

It is worth noting that while the SMP policy selection mainly depends, among other factors, on the potential risks in the short, medium and long-term, the delivery of a given SMP policy for a particular stretch of coastline depends of availability of sufficient funding.

Table 1 presents the proposed short, medium and long-term shoreline management plan (SMP) policies for the seven policy units at the study region (Figure 1). The table shows that the SMP policy for the coastal stretch fronting the landfills at Pennington is to hold the existing defence line (HTL) for all the three epochs. As such, release of material or pollutants would only occur if the defence

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1 SMPs divide the shoreline into a series of cells/sub-cells, policy development zones, management areas, and policy Units. In the SMP2 policy, there are a total of 22 cells and related SMPs for the shoreline of England and Wales (i.e., classified based on coastal type and natural processes such as beach and seabed sediment movements within and between them) (see Burgess et al., 2004; Nicholls et al., 2013). These larger sediment-based plans/divisions are then sub-divided into nearly 2000 policy units, which represent detailed classification of the stretch of coastline along England and Wales.

2 See: http://apps.environment-agency.gov.uk/wiyby/134834.aspx

either fails to perform as designed, design conditions are exceeded, or the defence is poorly maintained and breaches occur. The former landfill site has previously been noted as an obstacle to the adoption of either a NAI, or MR policy. Maintenance and upgrade of the defences must provide protection to the various land use behind the defence line, including the landfill sites. However, the SMP policy documents notes that despite the proposed policy, "…detailed assessments that address the socio-economic and environmental implications…" are required "to determine the management option for the former landfill site in the medium to long-term".

Table 1: Shoreline management plan (SMP2) policies for the various units in the study area.

Location	SMP Policy Units	Preferred SMP2 policies for the three epochs		
		Short-term (0–20 years)	Medium-term (20–50 years)	Long-term (50–100 years)
Western Solent (Pennington)	5C22	HTL	HTL	HTL
Western Solent (Lymington)	5C21	HTL	HTL	HTL
Hurst Spit	A.1	HTL	HTL	HTL
Milford Seafront	A.2	HTL	MR	MR
Rook Cliff	A.3	HTL	HTL	HTL
Cliff Road	A.4	MR	MR	MR
Note: HTL – Hold the (existing defence) line, and MR – Managed realignment. See Figure 1 for locations of the policy units.				

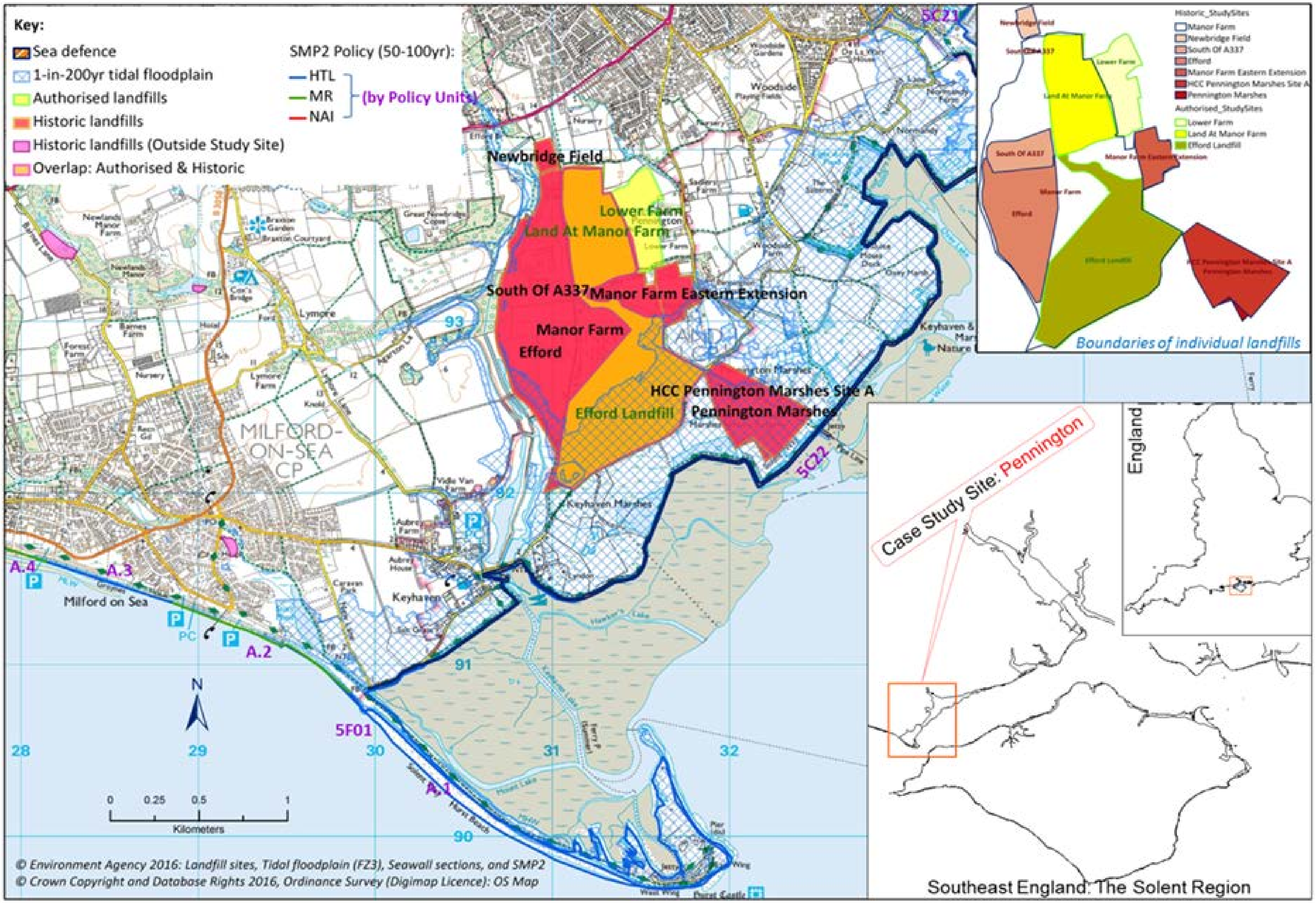


Figure 1: Geographic location of the study region and the historic and authorised landfill sites. Map scale: 1:25,000.

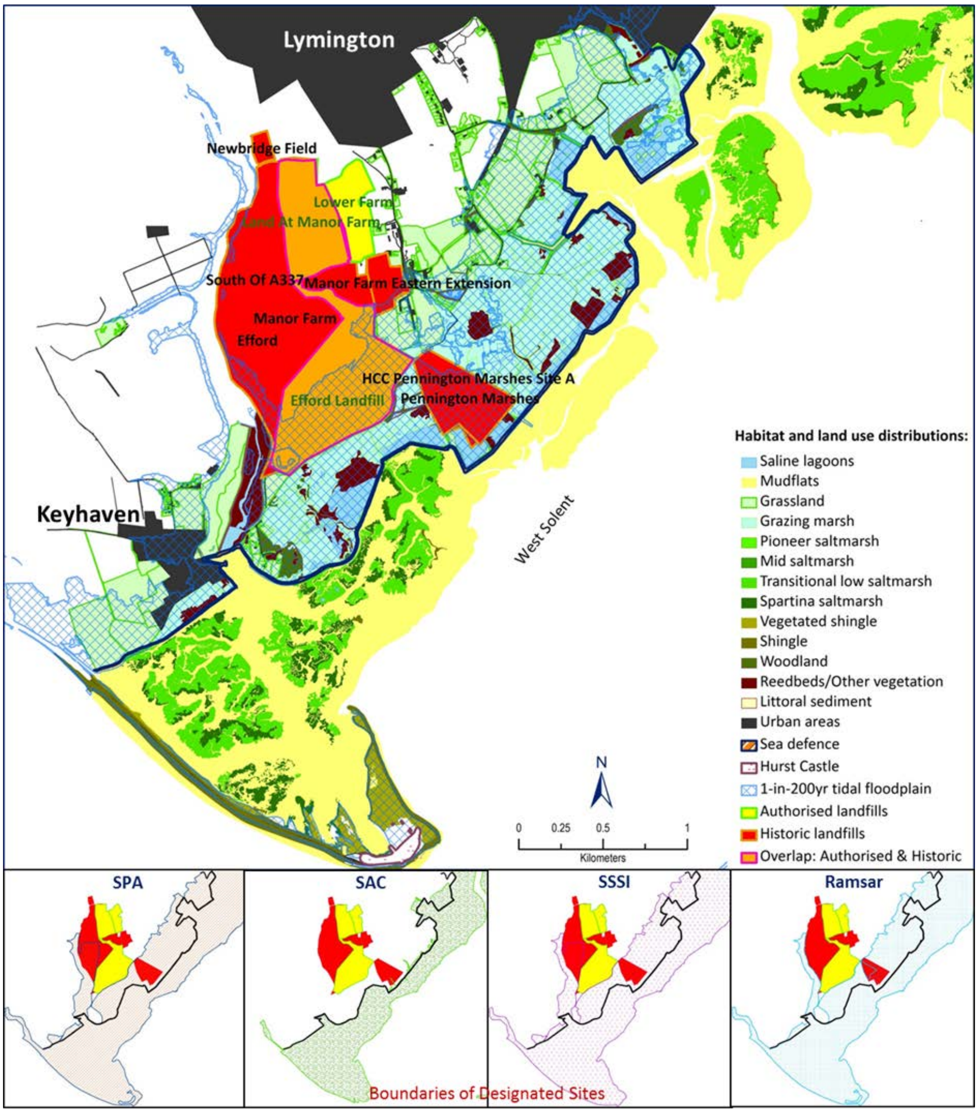


Figure 2: Map showing distributions of the various land use and coastal wetland habitats and the different nature conservation/designated sites at Pennington (Source: EA datasets). Map scale: 1:25,000.

3. Method

3.1 Literature and site survey

The Environment Agency's landfill database was consulted to investigate the history and ownership of the landfill sites at Pennington. Literature searches were carried out to find information relevant to the landfill sites and to shoreline management plans for this area. Site visits were carried out in August 2016, and July 2017, to understand the topography of the landfill sites, surrounding area and sea wall.

3.2 Coastal erosion survey

The analysis of potential coastal erosion and flooding used publicly available data as well as values and observations in published literature. Geographical models have been created using ArcGIS software. Descriptions of the data used, its use in these analyses, and relevant sources/citations are provided in Table 2.

The exposure of the landfill site to potential flooding under different still water level scenarios was assessed using a simple bath-tub flood analysis. In the bathtub method, areas which lie below the current and project still water levels will be flooded if they are hydraulically connected to the source of flooding. The topographic data (LiDAR DEM) was re-classified in ArcGIS to indicate the areas with an elevation below the still water levels predicted for each time-slice under low, medium, high and extreme high (H++) sea level rise. These were then assessed for hydraulic connectivity and edited accordingly to remove any areas which were incorrectly classified. In addition, landfill site cross-section profiles are extracted from the LiDAR DEM. Each cross-shore profile extends seaward of the seawall, while another long-shore profile intersects the Pennington Marshes landfill.

The site was not examined in terms of erosional rates due to the site's location on low-lying land; here the most significant cause of erosion would be caused by intermittent and tidally induced inundation.

Further analysis is focussed on assessing the performance of the seawall; this includes a simple overflow analysis using the seawall crest elevation and predicted still tide water levels and calculation of overtopping/overflow rates using Eurotop equations (2009, 2014).

Table 2: Data description and usage for the Pennington study site.

Data Description	Usage	Source/Citation
Environment Agency Historic Landfill data (last revised: 3/10/2015). Polygon data set that defines the location of, and provides specific attributes for, historic (closed) landfill sites.	Visualisation of the EA recognized area of landfill. Calculation of the area and volume of eroded waste (both historic and future).	Environment Agency, downloaded from data.gov.uk. Environment Agency (2015).
Digital Elevation Model (DEM) consisting of multiple LiDAR tiles with a 2m resolution mosaicked in to a single dataset. Collected in 2014.	Flood zone maps using the 'bath tub' or still water level method. Extraction of topographic profiles to compare to still water level scenarios.	Environment Agency, 2014.
Seawall Shapefile showing the location and length of the Lymington seawall.	Visualisation of the Lymington seawall	Channel Coastal Observatory (CCO 2008)
Predictions of anticipated recession at the site for the short, medium and long term.	Visualisation of the potential area of recession possible over the three epochs. Calculation of potential eroded area and volume of waste in the future over time.	Environment Agency (2014).
Sea level Rise Scenarios extracted from UKCIP09 projections for low, medium, high and extreme high (H++) sea level rise by the year 2050 and 2100 under low, medium and high sea level rise. Extreme Water levels	Examination of the impact of sea level rise on future erosive rates affecting the landfill site. Flood analysis	UKCIP09 relative projections (sea level rise and land subsidence) Lowe et al, (2009). Environment Agency.

4. Landfill assessment

4.1 Local setting

The Pennington study area was worked as gravel excavations for decades and has been progressively restored to an undulating landform, with much of the extraction workings comprising restoration with inert, industrial and domestic wastes. The underlying bedrock of Pennington is sedimentary, being part of the Headon and Osborne Beds, overlain by quaternary river terrace deposits of sand and gravel.

Current coastal defences at the Pennington study site consist of a ~1 km earth and grassed embankment (between the lee of Hurst Spit and Keyhaven), and the 8.1 km seawall (an embankment known as the Pennington seawall between Keyhaven and Lymington) (Figure 3). These are the first line of defence structures against flooding from the sea in the area of low-lying hinterland where the landfill sites lie. At MHW spring tides, over 500 ha of land are protected by the seawall (Wadey, 2015). The crest elevation of the defences varies along its length. This is due to the varying width of protective inter-tidal habitat (saltmarsh) which fronted the defences when it was originally designed (Figure 2). The defences were last upgraded following a large flood event in 1989 to provide a 1-in-50 year standard of protection.

Figure 3: Pennington sea wall embankment, looking east, with the wetland (Butts Lagoon) on the left and the Solent on the right (23 July, 2017).

4.2 Pennington landfill sites

The study site is a complex area, as it involves a number of both authorised (permitted) and historic landfill sites, with different landfills partly/wholly overlapping with one another, as shown in Figure 4. The landfill sites are: (i) Historic: a) Pennington Marshes/HCC Pennington Marshes Site A, b) Efford, c) South of A337, d) Manor Farm, e) Manor Farm Eastern Extension, and f) Newbridge Field; and (ii) Authorised: a) Efford Landfill Site, b) Manor Farm Landfill Site, Treatment and Transfer Facility, and c) Lower Farm Landfill. The records of these landfills (as reported in the Environment Agency's database[3] (What's in your backyard) are outlined in Table 3.

[3] The Environment Agency "What's in your backyard" map service is now closed. Further information about access to data regarding historic landfill sites is available from http://apps.environment-agency.gov.uk/wiyby/37829.aspx

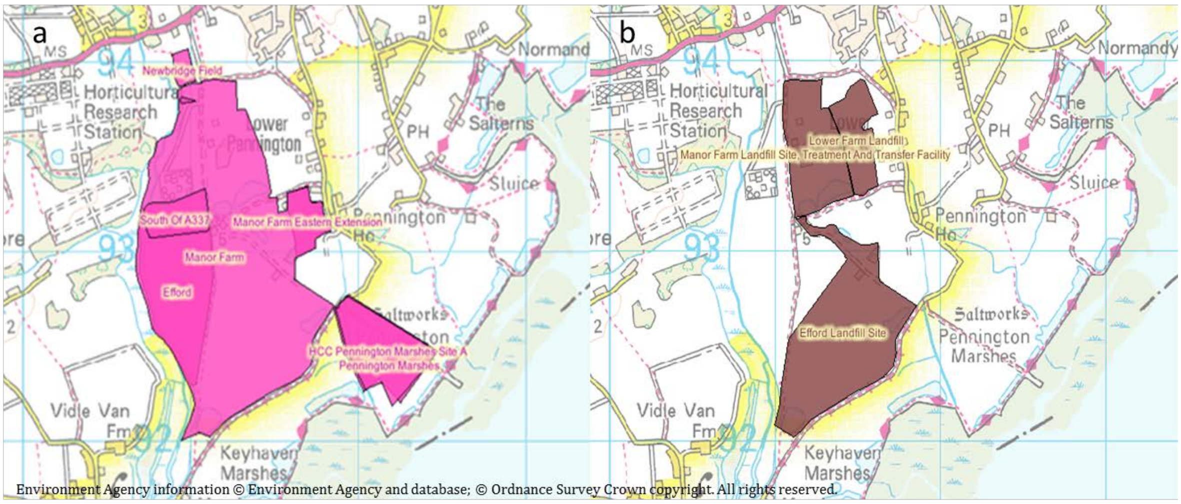


Figure 4: (a) Historic landfills, and (b) authorised landfills at the Pennington study site

Table 3 presents a summary of the landfilling history as well as key characteristics of the sites in terms of details of the licences and the types, age, and volume of waste material deposited within each site (as reported in the Environment Agency's database). The surface area and the ground elevations of the landfill sites were estimated using ArcGIS based on the size of the polygons as recorded in the EA's landfill database and LiDAR DTM (digital terrain model) data, respectively. As can be seen from Table 3, there was a lack of information about the historic landfill sites.

The total area covered by all sites is 169 ha, with some landfills overlapping each other. If an average waste thickness of 5 metres across the whole complex is assumed, this represents a total volume of waste on the sites of 8.5 million m^3. However, many parts of the overall site comprise excavations left by quarrying, and waste depths could be over 15 m in some areas. Therefore, the estimate of waste volume for the total landfill complex could be between 10 and 20 million m^3. With the closure of Efford landfill in 2007 landfilling of waste within the complex of Pennington landfills ceased. The now restored Efford landfill site (Figure 5) was a Hampshire County Council (HCC) landfill, although the landowner is H H and D E Drew Ltd (New Milton Sand and Ballast).

The landfill referred to as the HCC Pennington Marshes Site A, hereinafter referred to as the Pennington Marshes landfill, occupies a triangle of land to the south-east of the main landfill complex. The site is now owned and managed by HCC as part of the Lymington and Keyhaven Marshes Local Nature Reserve. Elevated ground above the surrounding marshes (Figure 6a) and an uneven surface topography (Figure 6b) indicates the presence of the landfill. There is a flooded wetland area known as Butts Lagoon to the south of the Pennington Marshes, immediately landward of the sea wall defence (Figure 7).

The geographically isolated nature of the Pennington Marshes landfill from the remaining landfill complex means that for the purpose of this study we have concentrated mainly on this site in terms of landfill and shoreline management options.

Figure 5: Efford landfill site, looking north (23 July, 2017).

Figure 6: Pennington Marshes landfill (a) from the northwest corner of the site (b) from the southeast corner of the site (23 July, 2017).

Table 3: Key summary of the history and characteristics of the landfill sites in the Pennington study area.

Historic Landfill Sites								
No.	**Landfill Sites**	**Site Operator / Licence Holder**	**License Issued / Surrendered**	**Waste Type**	**Landfilling Period**	**Gas / Leachate Control**	**Surface Area**	**Ground Elevation Ranges**
1	Efford	Borough of Lymington / Lymington Borough Council	01.04.1974 /unknown	Inert, industrial, commercial, household	01.01.1964 – date unknown	not known/|Yes	27.3 ha	-0.53 – 6.14m
2	HCC Pennington Marshes Site A (also referred to as Pennington Marshes in EA database)	No information/ Operated prior to requirement for site licence. Responsibility now with HCC	No information	Inert, industrial, commercial, household Commercial	31.12.1962 – 31.12.1969	No / no	18.0 ha 7.5 ha	-0.52 – 4.11m
3	Manor Farm	No info/ New Milton Sand and Ballast Company	29.03.1989 / no information	Inert, commercial, household	29.03.1989 – date unknown	Yes / no information	138.0 ha	-4.08 – 20.81m
4	Manor Farm Eastern Extension	New Milton Sand and Ballast / w Milton Sand and Ballast	18.01.1994 / 20.09.2002	Inert	No information	No information	5.7 ha	1.15 – 6.58m
5	Newbridge Field	? / New Milton Sand and Ballast	21.05.1999 / 08.04.2003	No information	No information	No information	1.9 ha	7.74 – 12.85m
6	South of A337	? / New Milton Sand and Ballast Company	02.04.1984 / No info 05.04.1983 / 08.01.1986	Inert Inert, industrial	No information 05.04.1983 – 08.01.1986	Yes / no information	7.1 ha 0.2 ha	2.53 – 10.10m 7.19 –

						? / ?		10.97m

Authorised Landfill Sites						
No.	Landfill Sites	Site Operator	Licence Type	Date Issued	Surface Area	Ground Elevation
1	Efford Landfill	Veolia E S Hampshire Ltd on behalf of HCC	A04 (Household, commercial & industrial waste landfill)	30/11/1982	46.5 ha	-4.08 – 7.98m
2	Lower Farm	H H and D E Drew Limited	L05 (Inert landfill)	14/09/2004	10.4 ha	3.00 – 10.71m
3	Land At Manor Farm	H H and D E Drew Limited	A05 (Landfill taking non-biodegradable wastes)	24/08/1998	21.1 ha	3.61 – 20.81m

Figure 7: Marshes south of Pennington Marshes Landfill, looking across Butts Lagoon to the Solent (23 July, 2017).

4.3 Pennington Marshes landfill site history and characteristics

Figure 8 shows the variations of the ground elevation of the landfill sites and the surrounding area, together with the height variations of the seawall. The map shows that the ground elevations of the landfill sites vary between -5.2m (light blue; a small lake in the southeast corner of the Efford landfill site) to 18.2m (light purple). These estimates are based on a 2008 topographical LiDAR data.

The Pennington Marshes landfill was filled between 1962 and 1969 by the Borough of Lymington with domestic and trade wastes collected by the Council with limited amounts of construction and demolition waste (builders skips). A 1999 report and site investigation by Marcus Hodges indicates that the waste is underlain by a thin alluvial clay across part of the site, but in other areas this is absent (presumed excavated) and the waste lies directly on underlying sand and gravel deposits. Anecdotal evidence reports that as a matter of course waste was burned prior to final landfilling. In 1974 HCC took over responsibility for the site and used it to operate a civic amenity site, before the site became part of the nature reserve.

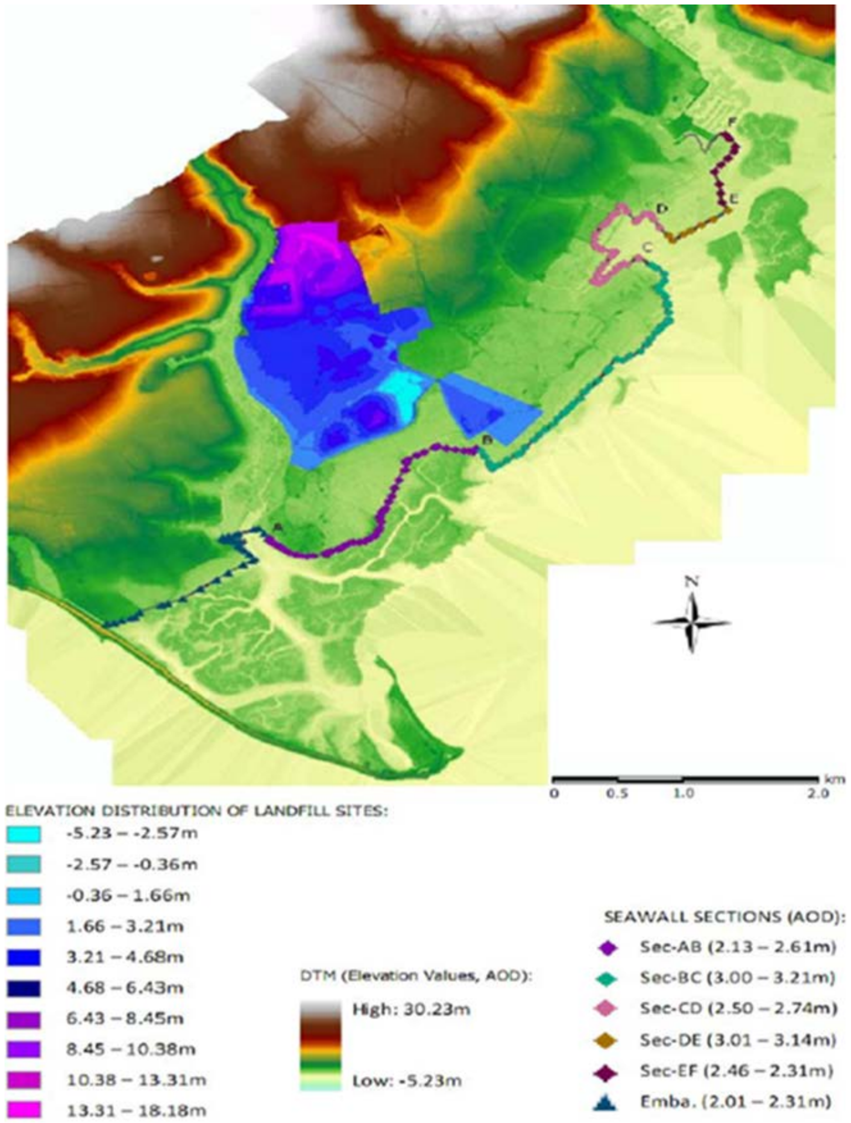
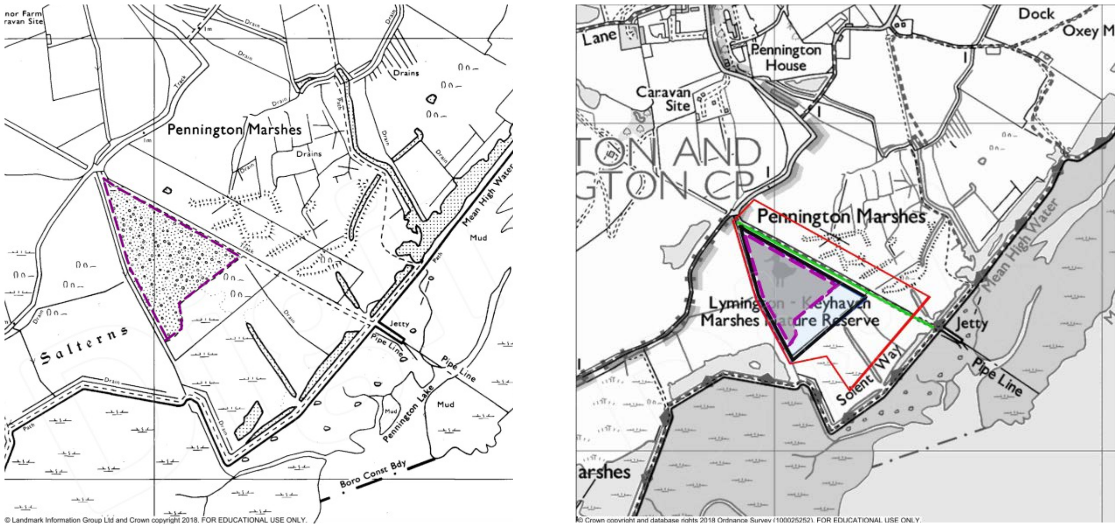


Figure 8: Map showing ground elevations of the landfill sites and surrounding area, plus the crest heights of the seawall (Kebede, 2009).

The area of Pennington Marshes landfill, as calculated from the EA database, is estimated to be 17.1 ha. However, the total area was not tipped. Figure 9a shows a map from 1973 in which the area identified as refuse tip (marked in purple) is significantly less than suggested in the EA database (Figure 9b; marked in red). The area shown in black in Figure 9b is at a higher elevation (~2.5 to 3 m aOD) than the surrounding areas (as shown in Figure 8). From this, we estimate that the area tipped at the Pennington Site amounts to approximately 7.5 ha.

Marcus Hodges (1999) calculated the volume of the landfill site as 160,000m^3 which includes 30,000 m^3 of inert cover materials comprising soils and subsoils. This relates to the smaller landfill area of 7.5 ha, and corresponds with an analysis of LiDAR data from 2008. The base elevations of the Pennington Marshes landfill vary considerably, but on average are thought to be about 0 m AOD.



Refuse tip
Elevated area
Area identified from EA database
Footpath

Figure 9: (a) 1973 map of Pennington site showing area identified as Pennington Marshes refuse tip (b) Pennington site showing potential landfill site areas. Maps sourced from DigiMap.

4.3.1 Waste, leachate and landfill gas analysis

The Marcus Hodges report (1999) on Pennington Marshes Landfill stated that the waste was between 1.9 and 3.7m depth and consisted of a mix of soil, plastic, wood, glass and rags. In some trial pits, a hydrocarbon odour was noticed and in others there was an odour of decomposing waste. Gas analysis did not find methane in any of the trial pits.

In the Marcus Hodges site investigation, leachate was found in the waste material at varying depths across the landfill site, but an average leachate depth of 0.5 m was estimated; this equates to an average leachate level of ~ 0.5 to 0.75 m aOD. The volume of leachate in the site at the time of investigation was estimated to be 5,000 m^3. Leachate analysis from trial pits and boreholes monitoring groundwater beneath the landfill showed very low concentrations of heavy metals, and low biochemical oxygen demand (BOD) (<20 mg/l), chemical oxygen demand (COD) (<125 mg/l) and ammonia (<100 mg/l).

It was found that ground water levels in the gravel aquifer below the waste were close to the original groundwater level in the winter and 0.5m lower in the summer. The natural flow of groundwater was from north to south, but quarrying in the area had reversed the flow and reduced groundwater levels. The investigation did not find ponding on the Pennington Marshes Landfill, suggesting that rainwater soaks into directly into the waste. No seepages of leachate were noted into the Lower Pennington Stream which borders the west side of the site. However, the concentration of BOD (16.2 mg/l) in Butts Lagoon adjacent to the landfill was greater than EQS recommended for protection of aquatic life (8 mg/l) at this site at the time. Analysis of groundwater samples from boreholes adjacent to the site showed higher COD concentrations potentially indicating that leachate was migrating from the site at that time.

Waste tipping at this site finished in the late 1960s, and, as the site was not capped, it is not surprising that contaminants had been flushed from the site resulting in low contaminant concentrations consistent with a weak leachate. The Liquid-Solid ratio (LS), which is the ratio of clean water that has passed through a unit dry mass of waste provides a useful estimate of how well flushed and stabilised waste is likely to be is. A LS value of 10 indicates very high degrees of flushing and clean-up, whereas values significantly less than 0.5 are typical of most modern "engineered landfills". An LS ratio of 13 was calculated for the site assuming an average waste depth of 2 m, a dry density of 0.8 t/m^3 and effective rainfall of 450mm/year acting over a 47 year duration (by 2017).

No site investigations were carried out at the site during the current study. It is likely that, in the ensuing 18 years since the Marcus Hodges study, leachate concentrations in the site will have declined further due to flushing of the waste with rainwater. The contaminants may have been transported to groundwater or to Butts Lagoon to the south of the site. The latter does not have a seawall overflow sluice (Bamber and Robbins, 2010), and therefore potentially contaminated brackish water is contained in the lagoon.

4.3.2 Landfill engineering: lining or capping

The Marcus Hodges report (1999) discussed results from trial excavations into the waste in the Pennington Marshes Landfill. The waste in Pennington Marshes Landfill was deposited directly onto the natural ground surface. No landfill liner was found. Inert materials comprising soils and subsoils were found to overly the waste. The inert material was loose clayey sand and gravels with some brick fragments.

5. Coastal flooding and erosion at Pennington

Many of the landfill sites in the study area are potentially at risk of coastal flooding due to both overtopping and breaching of the coastal defences (Wadey, 2015). The worst coastal flooding at Pennington was on 17th December 1989 (NRA 1990). Major breaches and overtopping of the Keyhaven-Lymington seawall occurred, causing extensive flooding of the urban areas of Keyhaven and Lymington, about 184 ha of reclaimed marshland (nature reserve) and 285 ha of agricultural land at Pennington (Oranjewoud, 1985). Flood water lay in the low-lying areas of the site for about 3 weeks during which there was significant environmental damage to the marsh habitat in the surrounding environment which caused long-term damage (NRA 1990). The storm surge was estimated at the time to have a return period of 1 in 100 years with a maximum water level of 2.10m ODN (NRA, 1990). Due to the prolonged high water stand, the resulting flooding was sudden with inundation depths rising rapidly to still water tide level. Although, there was no documented information about the actual impacts on the landfills and their environmental implications, it can be anticipated that due to the long-lasting ponding of the area and extent of flooding, it is likely that some water would have percolated into the less protected or unprotected landfills. Although there is no evidence that remobilization of waste material occurred, some landfill leachate may have been created which would have then drained when flood levels receded, potentially adding to the environment damage caused by the saline incursion into the surrounding coastal and marine habitats.

Other storm events were recorded with higher extreme sea-levels (e.g., ~2.05–2.17m ODN on the 10th March 2008 and ~2.26m ODN on the 14th February 2014). Although the impacts at Pennington are relatively small in the latter events, they are widely recognised as the highest extreme events in the region over the last 50 years (Ruocco et al., 2011; Wadey et al., 2015).

The 1989 flood event led to the upgrade of the seawall. Its crest was raised by up to 0.4–0.5m (the highest section being at the northeast end to accommodate wave run-up) to provide an approximately 1 in 50 year standard of protection. Figure 8 shows the land elevation and the height of the wall between Keyhaven and Lymington, with crest heights ranging from 2.13m in Sec-AB (at about 650m chainage distance from A) and 3.21m in Sec-BC (at about 300 m from point B).

5.1 Erosion and Implications of sea level rise

The coastal zone at Pennington is particularly susceptible to flooding and highly vulnerable to increase in water levels and erosion by wave action, and it has already been experiencing dramatic changes due to the rapid loss of the saltmarshes. Hurst Spit and the Isle of Wight provide a shield for the shoreline at the study region, with wave climate predominantly controlled by south-westerly winds and locally-generated waves (Wadey, 2015). The design of the Pennington seawall took into account the presence of a certain width of saltmarshes when it was rebuilt and assumed the continual presence of Hurst Spit. The Spit was nourished in 1996 after the 1989 storms, and a second nourishment is under design following the winter of 2013/14.

The saltmarshes and mudflats are an integral part of the coastal flood defence system, and they provide an effective and a primary natural method of flood coastal protection playing a major role in reducing the damaging effects of direct storm wave actions on the seawall. These habitats are also of nature conservation importance and contribute to the local economy, and are protected by national and European environmental legislations. However, there is a significant concern for the condition and long-term existence of these habitats (e.g. Gardiner et al., 2007). The major contributing factors for the rapid erosion of the saltmarshes are attributed, among others, to: (1) higher sea levels and effects of coastal protection (due to 'coastal squeeze'), (2) increased wave actions, (3) waterlogging of estuarine soils, (4) lack of sediment supply, (5) stronger tidal currents, and (6) natural vegetation dieback (e.g., Colenutt, 2002).

Sea level rise is occurring at Southampton and Portsmouth at rates of 1.19 (trend data range: 1935–2005) and 1.73 mm/yr (trend data range: 1962 to 2007), respectively (Haigh et al, 2009).. As a result, the seaward edges of the saltmarshes at the site are rapidly eroding. Losses of 0.3 to 6 m/yr at the seaward edges have been estimated (NFDC, 2004; Colenutt, 2012), and this is likely to continue to increase under rising sea levels. This could further increase the potential risk of overtopping and breaching of the seawall, section 6.1. The level of protection the existing defences can provide could therefore reduce over time and result in high risk of flooding of the protected hinterland behind the seawall, including the landfill sites and designated sites.

If sea defences are breached and/or abandoned then over time the Pennington Marshes landfill, especially, will erode resulting in waste material being washed into the sea. All 160,000 m^3 of waste would be eroded over time, although the rate that this would happen is very uncertain.

6. Coastal defence performance

6.1 Potential for overflow, overtopping and breaching

The performance of the current sea wall defence under sea level rise was analysed to examine potential overflow, overtopping and breaching. The seawall varies in elevation along its crest; it was divided into five sub-sections of similar average elevation (AB, BC, CD, DE, and EF) as shown on Figure 10, together with the area of embankment to the west of Avon Water (shown in red). The simple overflow analysis presented is based on the present and predicted 1-in-50 year (figure 12a, 12b) and 1-in-200 year (figure 13a, 13b) extreme high water levels. The figures show results of the analysis with and without set-up from waves, in relation to the crest elevations of the seawall along its length. Wave set-up is the increase in mean water level due to breaking waves. This analysis allows prediction of whether overflow could occur, and gives an indication of how significant it would be. However it must be noted that it considers maximum water levels and does not account for tidal variation, which, particularly in scenarios where the negative freeboard (Figure 11) is small, will have a significant impact on the volume of water able to flow over the seawall.

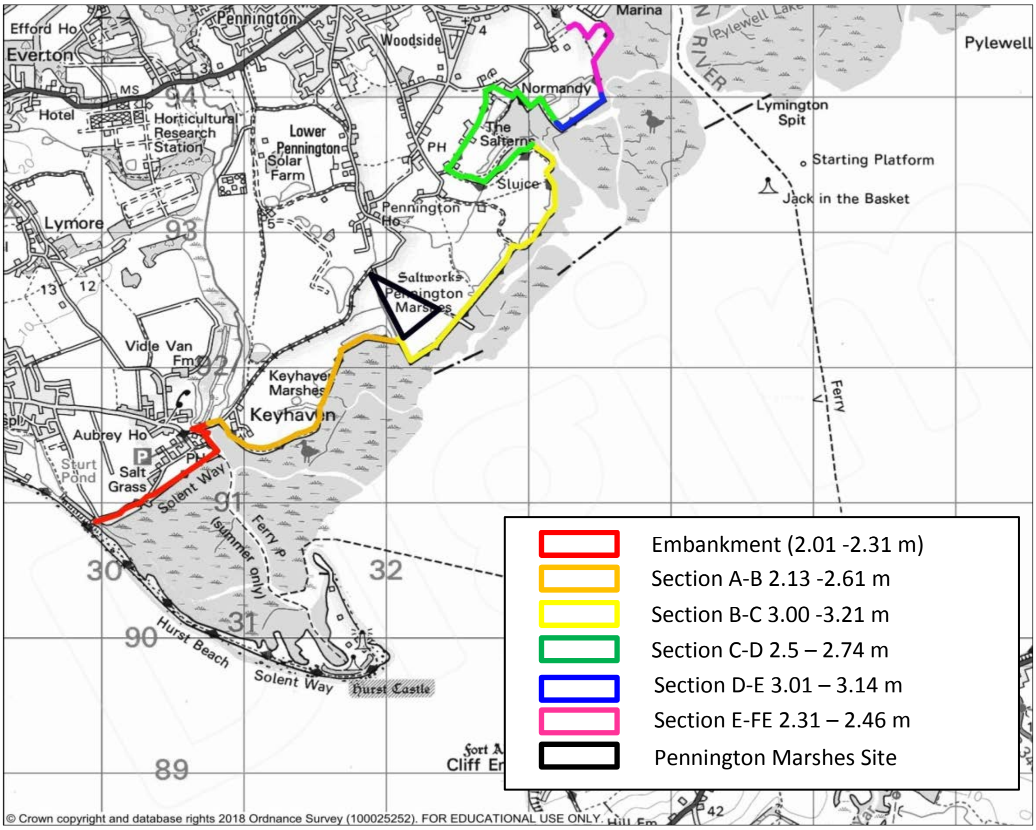


Figure 10: Map of Lymington Seawall highlighting the sub-sections of comparable elevation (m aOD) as defined by Kebede (2009).

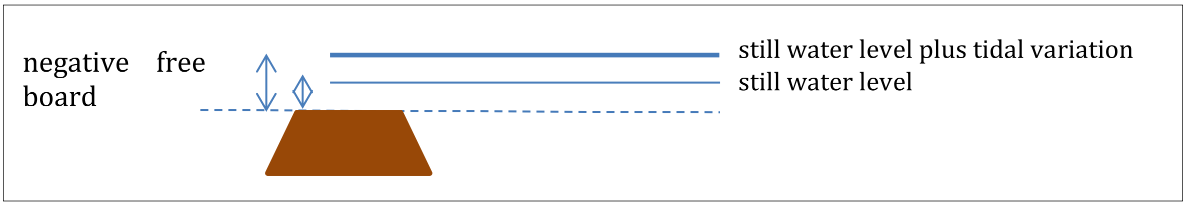


Figure 11: Freeboard depth, showing the impact of tidal variation.

The results of the analysis show that, under 1 in 50 year return period water levels (Figure 12), the sea wall protects the hinterland except for a short length of section A-B (at 300-500m seawall length) in the current day, 2050, and 2100 scenarios. This section of the sea wall protects five houses situated on the eastern side of the estuary at Keyhaven. The areas of inundation are described in section 6.2. Figure 18 shows that only limited flooding would occur in this area until 2050. By this time, with sea level rise, there is overtopping in other parts of section A-B, and by 2050 in the H++ sea level rise scenario, across the whole length of A-B, C-D and E-F (Figure 12).

Sections B-C and D-E are c.3m high. In the 1 in 50 year and the 1 in 200 year return period scenarios, the water level would overtop these sections by 2100 with HSLR and wave set up, and in H++ scenarios with or without wave set up (Figures 12 and 13).

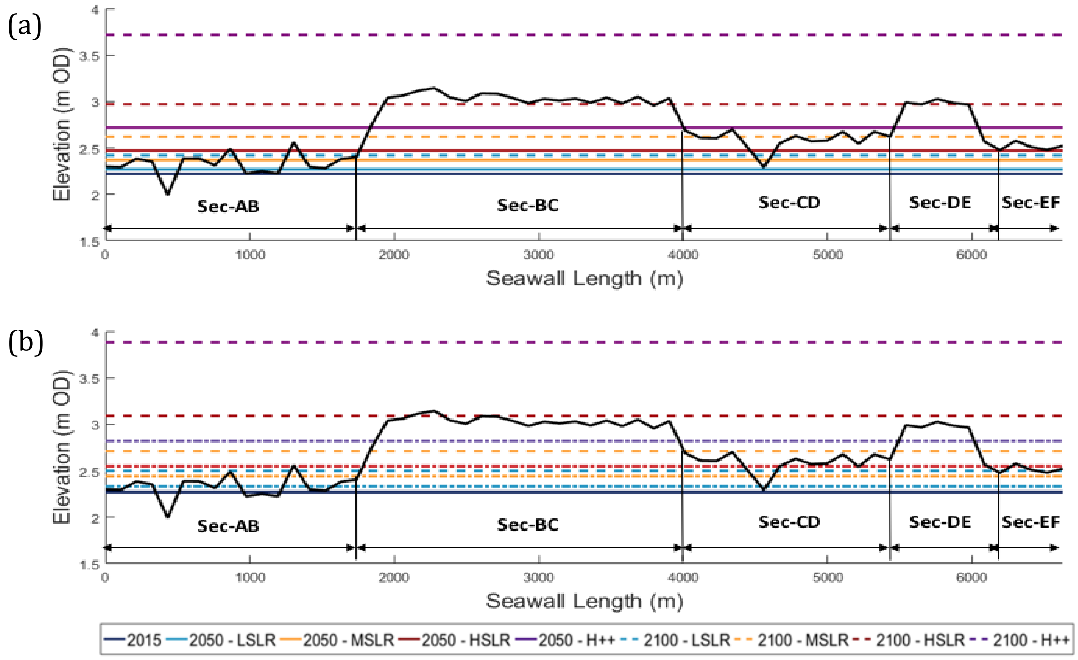


Figure 12: Pennington sea wall crest elevation along its length showing varying section heights. 1-in-50 year return period extreme water level in the current day (2015), plus future (2050, 2100) under projected low, medium, high and extreme high (H++) sea level rise without waves (a) and including set-up from current 1-in-5 year waves (b).

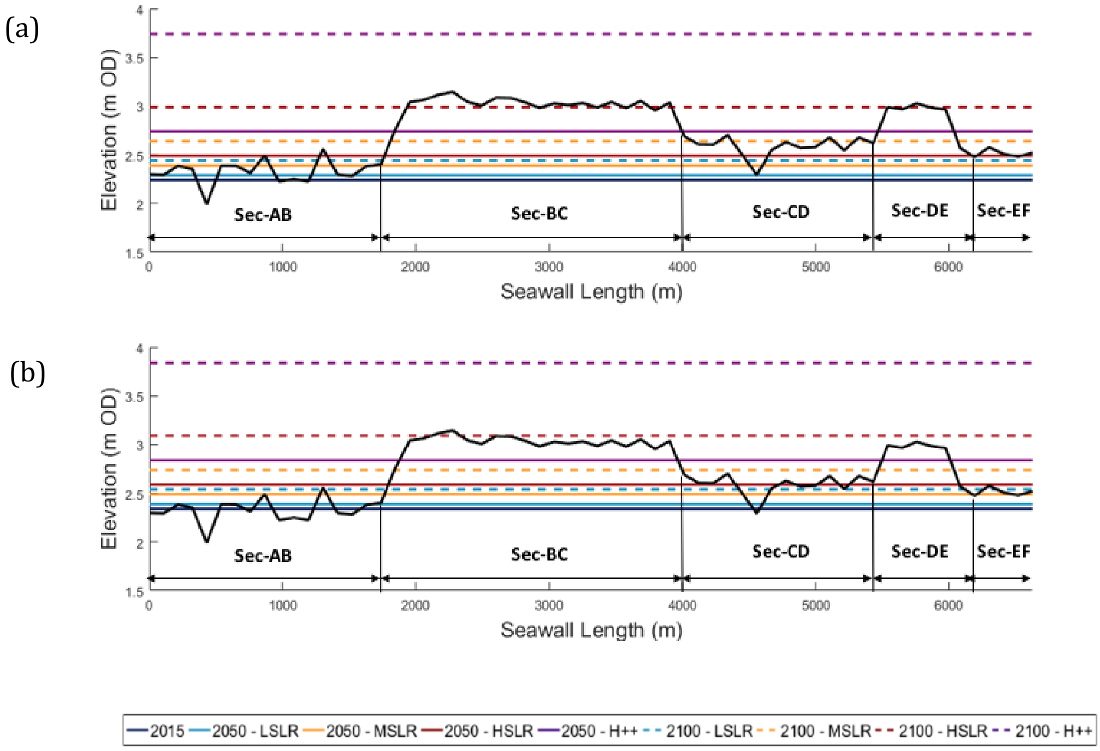


Figure 12: Pennington sea wall crest elevation along its length showing different section heights. 1-in-200 year return period extreme water level in the current day (2015) and future (2050, 2100) under projected low, medium, high and extreme high (H++) sea level rise without waves (a) and with set-up from current 1-in-5 year waves (b).

By choosing profiles which intersect the sea wall and landfill sites, we can further investigate exposure to tide flood levels.

Figure 14 shows profiles AB and CD intersect the Efford landfill site along its southern perimeter; profiles EF and GH intersect Pennington Marshes Landfill in the long-shore and cross-shore directions, respectively.

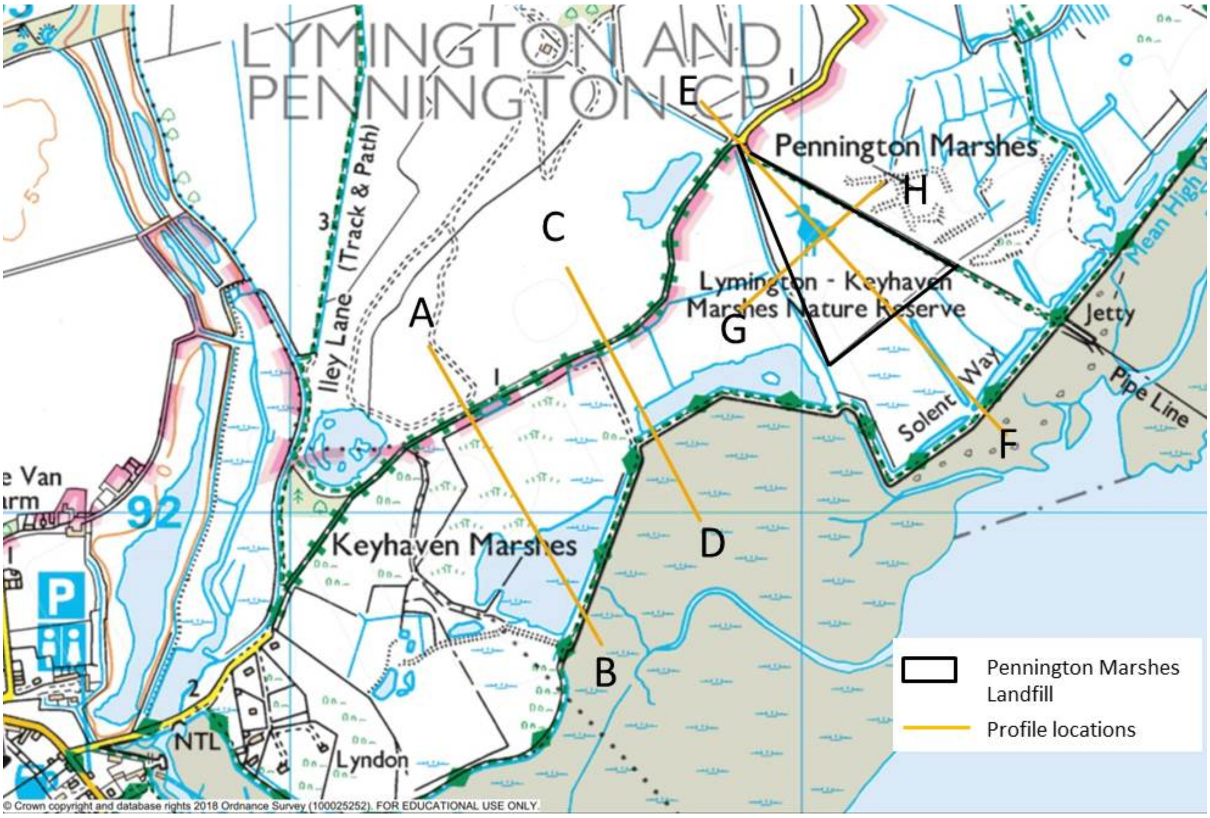


Figure 13: Location of topographic profiles extracted from the Lymington DEM.

Figure 15 shows cross sections of the topography at the profiles described above; the left hand set of figures show the results under current MHWS (2015, 0.98 m OD, blue) and in 2100 under low (1.18 m OD, yellow) and high (1.73 m OD, red) sea level rise, and the right hand set show results for a current 1-in-50 year water level event (2015, 2.12 m OD, blue) and in 2100 under low (2.32 m OD, yellow) and high (2.87 m OD, red) sea level rise. Under 2015 MHWS and low and high sea level rise 2100, the sea defence in these cross sections would be able to prevent flooding of the landfills. However, if breached, the toe of Efford landfill (Profiles AB and CD) along its southern perimeter would be exposed to adjacent water levels in all scenarios. Similarly, water would lie adjacent to Pennington Marshes landfill. These are dependent on the surrounding land elevation, which is lower to the south and west of the landfill site.

In the 1 in 50 year event, the sea wall prevents flooding in 2015, but by 2100 even under low sea level rise scenarios, water levels would overtop the defences. By 2100 under high sea level rise, the water level would be c. 3 m deep and parts of Pennington Marshes Landfill would be submerged (Figure 15; profiles E-F and G-H).

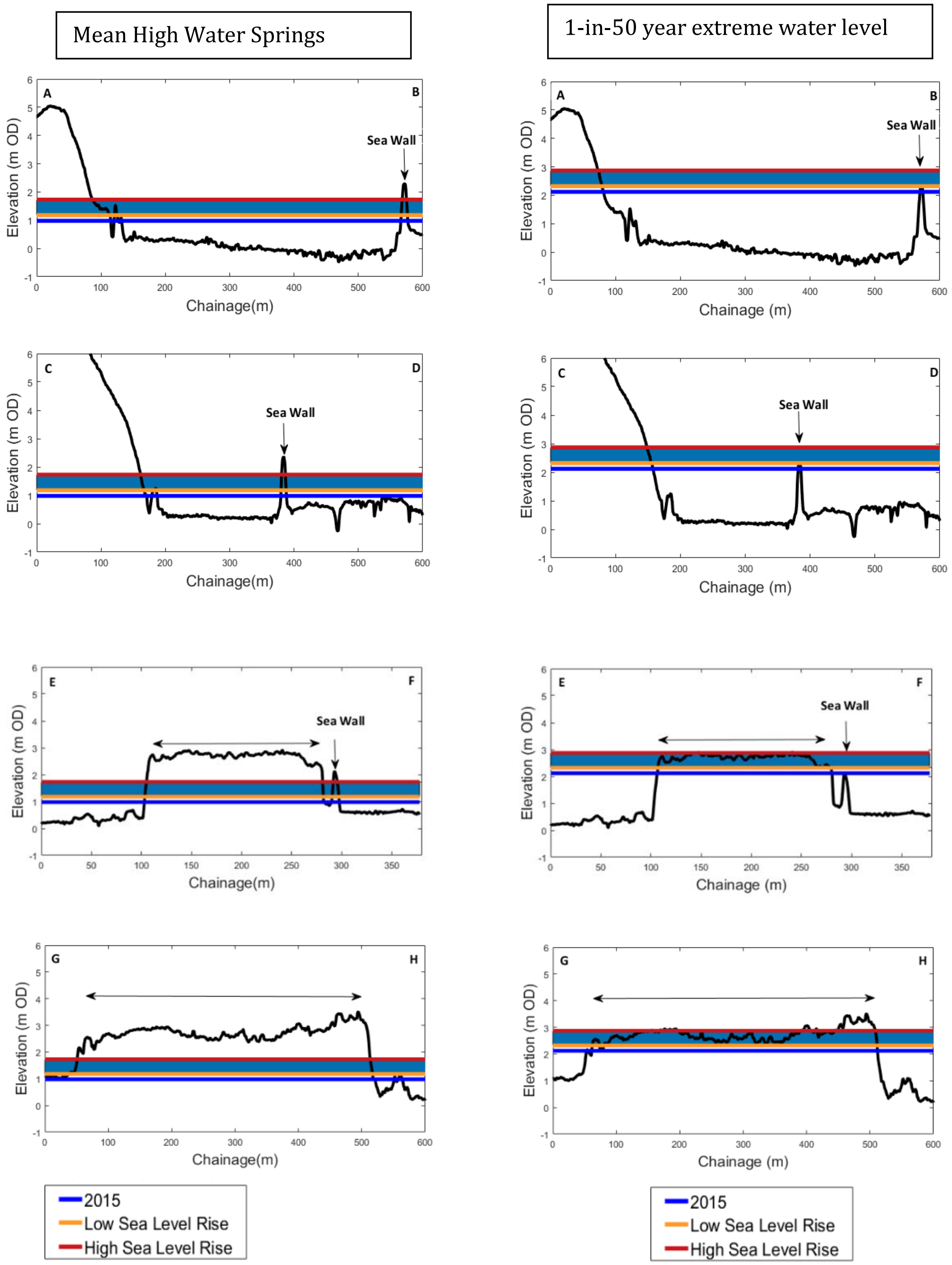


Figure 14: Cross-sections of topography at locations AB, CD, EF and GH (indicated on figure 12) showing water levels in 2015, and in 2100 with low and high sea level rise.

Kebede (2009) considered the impact of sea level rise on the integrity of the seawall around Pennington Marshes. The front face of the seawall is protected by concrete block-work, so breaching is more likely to be caused by erosion of the back face by excessive overflow or overtopping when wave action is high. Rapid erosion of the saltmarshes is already being observed, section 5.1. As a result it can be assumed that wave attack on the seawall will increase due to the loss of the protective saltmarsh (Moller et al., 2001). This may result in damage to the front face with slumping of the concrete block-work.

Kebede's analysis assessed the impact of peak sea levels during storms of different return periods, with and without the added influence of wave height. Table 4 shows the probability of structural failure of sections of the seawall under different scenarios in 2010, 2055 and 2100. The change in height of extreme water levels (with and without waves; mAOD) reflects the influence of sea level rise forecast for these dates. There is a high probability of failure of section AB.

The analysis predicted that by 2055 (under a projected sea level rise scenario equivalent to medium) a storm with a return period of 1 in 5 years would result in overtopping and breaching of the sea wall in this section, which lies immediately to the west of the Pennington Marshes landfill. The area and depth of flooding behind the wall depends on the extent of breaching, and where the breach occurs. The wall is currently at risk of potential breaching (even without taking into account waves) with a 1 in 50 year storm.

Table 4: Structural failure probabilities of the Pennington sea wall under different return periods and medium sea-level rise scenarios.

Time Slices	Extreme Water Levels (m aOD)		Structural Failure Probabilities (%)									
			AB		BC		CD		DE		EF	
	WoW	WW	WoW	WW	WoW	WW	WoW	WW	WoW	WW	WoW	WW
	Return Period: 1 in 1 year											
2010	1.90	3.20	0.0	86.25	0	0.14	0	3.85	0	0.185	0	13.13
2055	2.20	3.50	0.02	99.9	0	0.81	0	88.2	0	0.82	0	88.6
2115	3.00	4.30	1.20	100	0	100	0.41	100	0.15	100	0.64	100
	Return Period: 1 in 5 year											
2010	1.95	3.25	0	88.21	0	0.18	0	6.2	0	0.19	0	23.67
2055	2.25	3.55	0.03	99.95	0	1.45	0	89.4	0	1.45	0	93.45
2115	3.05	4.35	53.21	100	0.08	100	0.62	100	0.17	100	0.95	100
	Return Period: 1 in 10 year											
2010	2.00	3.30	0	89.37	0	0.28	0	28.7	0	0.29	0	25.01
2055	2.30	3.60	0.04	100	0	2.81	0	94.8	0	2.86	0	98.0
2115	3.10	4.40	69.05	100	0.09	100	1.06	100	1.75	100	1.77	100
	Return Period: 1 in 20 year											
2010	2.15	3.45	0.01	99.7	0	0.55	0	88.23	0	0.005	0	88.18
2055	2.45	3.75	0.13	100	0	75.7	0.08	99.8	0.02	75.61	0.08	99.99
2115	3.25	4.55	88.2	100	0.18	100	6.2	100	0.19	100	23.67	100
	Return Period: 1 in 50 year											
2010	2.25	3.55	99.95	99.95	0	1.45	0	89.36	0	1.45	0	93.45
2055	2.55	3.85	100	100	0	88.2	0.13	99.99	0.05	88.21	0.13	99.99
2115	3.35	4.65	100	100	0.38	100	77.25	100	0.39	100	86.68	100
	Return Period: 1 in 200 year											
2010	2.45	3.75	100	100	0	75.7	0.08	0.998	0.02	75.61	0.08	99.99
2055	2.75	4.05	100	100	0	97.42	0.15	100	0.07	97.6	0.15	100
2115	3.55	4.85	100	100	1.45	100	89.36	100	1.45	100	93.45	100
From: Kebede, A.S., 2009. WW = with waves (of 1 in 50 year); WoW= without waves.												

6.2 Potential areas of inundation

Using the bath-tub analysis method, the current day and future flood zones under extreme water levels with different return periods were assessed.

6.2.1 Inundation across the current tidal flood plain

The current defence line protects a significant area of low-lying coastal land from inundation over the tidal cycle. Figures 16 and 17 give an indication of the current (2015) tidal flood plain in the absence of sea defences under mean sea level (MSL) and mean high water springs (MHWS) respectively. The boundaries of the landfill sites are also marked. The figures indicate how exposure to tidal waters could change under the four proposed sea level rise scenarios by 2050 and 2100. Table 5 gives the water level values in metres aOD for each scenario.

If the sea wall was absent or breached, at MSL in 2015, modelling shows that some areas surrounding the Pennington Marshes landfill would have flooded (Figure 16). At MHWS, a significant area would transition to becoming intertidal at spring tides under 2015 tidal levels (Figure 17). By both 2050 and 2100, sea level rises under all scenarios (Table 5). The exposure of Pennington Marshes landfill does not increase significantly in area until 2100 under an H++ (+1.5 m aOD) scenario (indicated in red). Because of the elevation of the site, inundation is restricted predominantly to areas along the eastern boundary of the site and in the south-west corner. Adjacent to the site, along its perimeter, the low elevation land will be exposed to flooding at MHWS under all sea level rise scenarios.

Exposure to flooding over the tidal cycle also occurs at the Efford site, with the largest increase in inundated area occurring by 2100 under an H++ scenario. It should be noted that the lower elevation area in the south-eastern corner of this site is likely to have undergone significant changes in topography since the LiDAR used for this assessment was captured (2014). Aerial imagery captured in between 2001 to 2013 indicates significant restoration being undertaken, and a small lake is now present. Flooding is predicted to occur in the south west corner of the Efford site at MHWS in 2015 and at mean sea level by 2100. The EA database indicates the presence of both historic and authorised landfills in the area (Figure 4). However, there is a pond located in this corner of the site which may indicate that waste was not tipped here, at least on the authorised landfill. Flooding also occurs on the boundary of the Efford site with Avon Water at mean sea level by 2100 under the H++ scenario; at MHWS flooding is more extensive across the site. While flooding over the top of both sites is low, water levels adjacent to the sites under MHWS will lead to infiltration of the landfilled waste.

Table 5: Sea level rise projections for low, medium, high and extreme high (H++) scenarios at Pennington by 2050 and 2100.

Time Slice	Sea Level Rise Scenario	Sea Level Rise (m OD)	MHWS (m OD)
2015	N/A	N/A	0.98
2050	Low SLR	0.05	1.03
	Medium SLR	0.15	1.13
	High SLR	0.25	1.23
	H ++	0.5	1.48
2100	Low SLR	0.2	1.18
	Medium SLR	0.4	1.38
	High SLR	0.75	1.73
	H ++	1.5	2.48

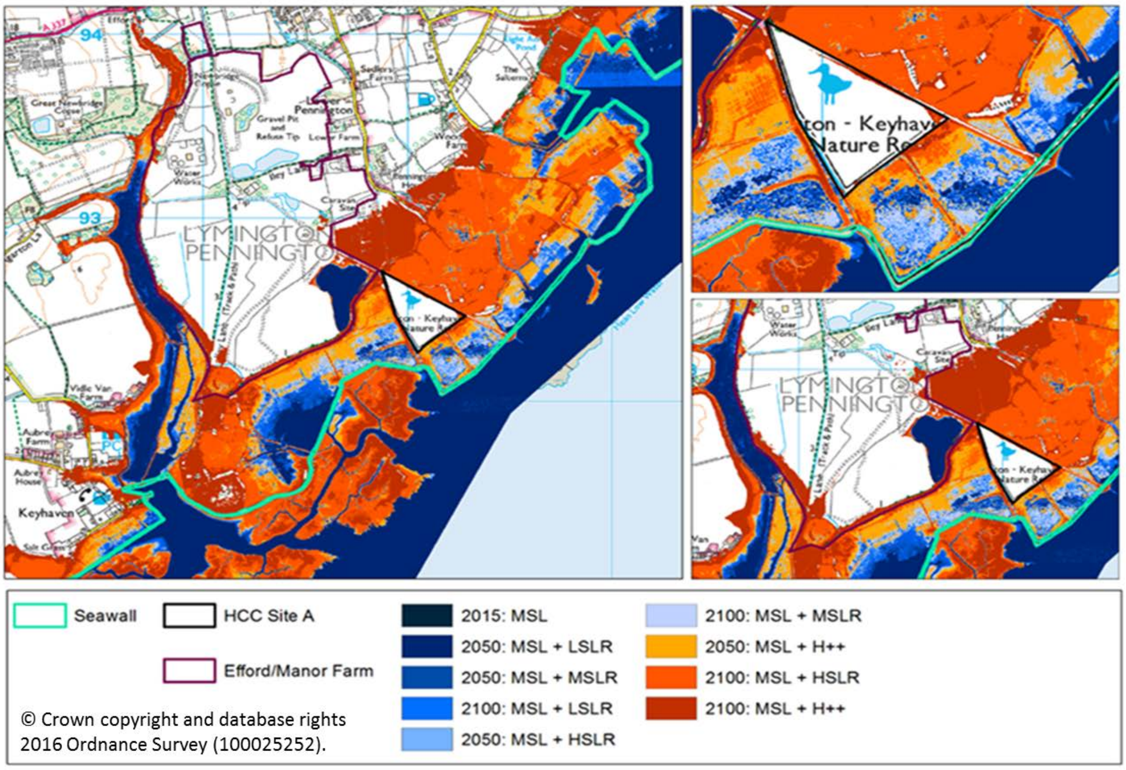


Figure 15: Indicative flood zone under mean sea level (MSL) in the current day (2015) and under different sea level rise scenarios (without waves).

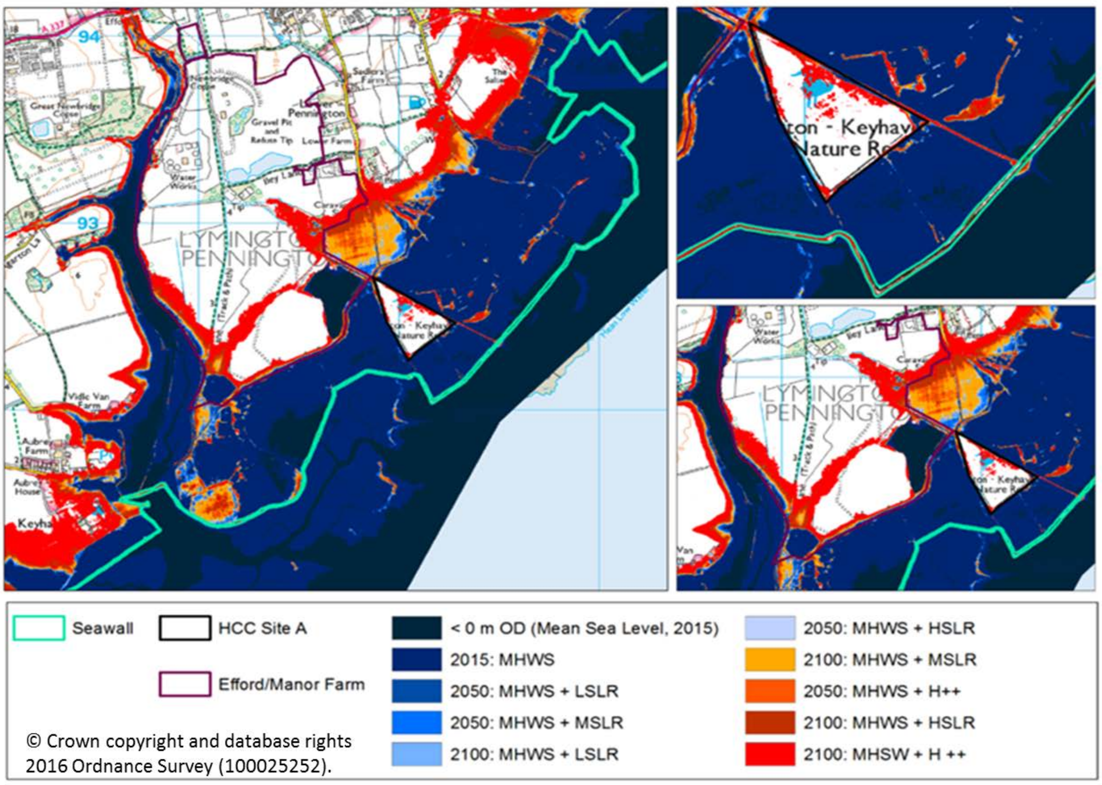


Figure 16: Indicative flood zone under mean high water springs (MHWS) in 2015 and under different sea level rise scenarios (without waves).

6.2.2 Extreme water level events

The exposure of the site to inundation in 2015, 2050 and 2100 under two extreme water level events of different return periods (1-in-50 and 1-in-200 year) was also investigated.

In the 1-in-50 return period event (Figure 18):

- MHWS is still the predominant cause of flooding
- The flood plain increases northwards across the Efford landfill site
- With rising sea levels, large areas of the Pennington Marshes landfill will be exposed to flooding although, actual over-site inundation does not start to become significant until around 2100 under HSLR or with an H++ scenario, due to the height of the landfill site.
- Rising sea levels will however increase the water level adjacent and through the landfill sites
- Water levels adjacent to both sites will range from 2 – 2.4 m at the southern extent in 2050, 0.7 – 1.1 m at the south-eastern perimeter in 2050, 2.1 – 3.4 m at the southern extent in 2100, 0.8 – 2.1 m at the south-eastern extent in 2100.

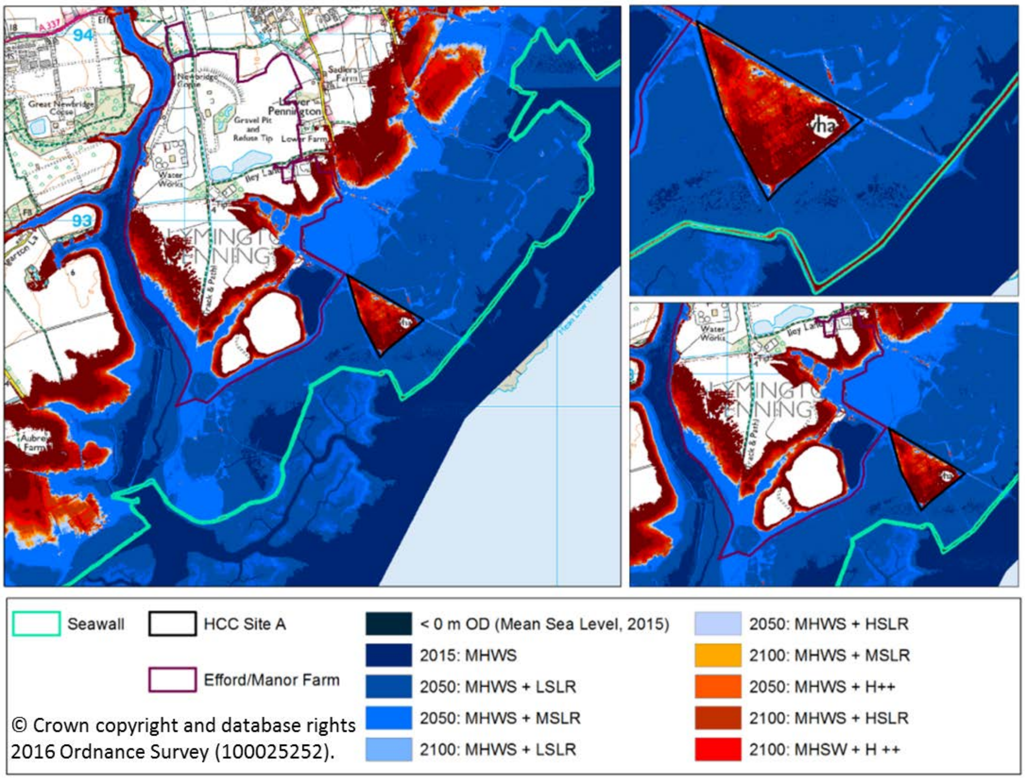


Figure 17: Indicative 1-in-50 year flood zones in the current day, 2050 and 2100 under projected low, medium, high and extreme high (H++) sea level rise.

In the 1-in-200 return period event (Figure 19):

- No significant difference in the 1-in-200 year event due to small height difference (0.12 m)
- Larger differences are seen on Pennington Marshes Landfill where tidal inundation increases and greater inundation occurs under a 2100 MSLR scenario.

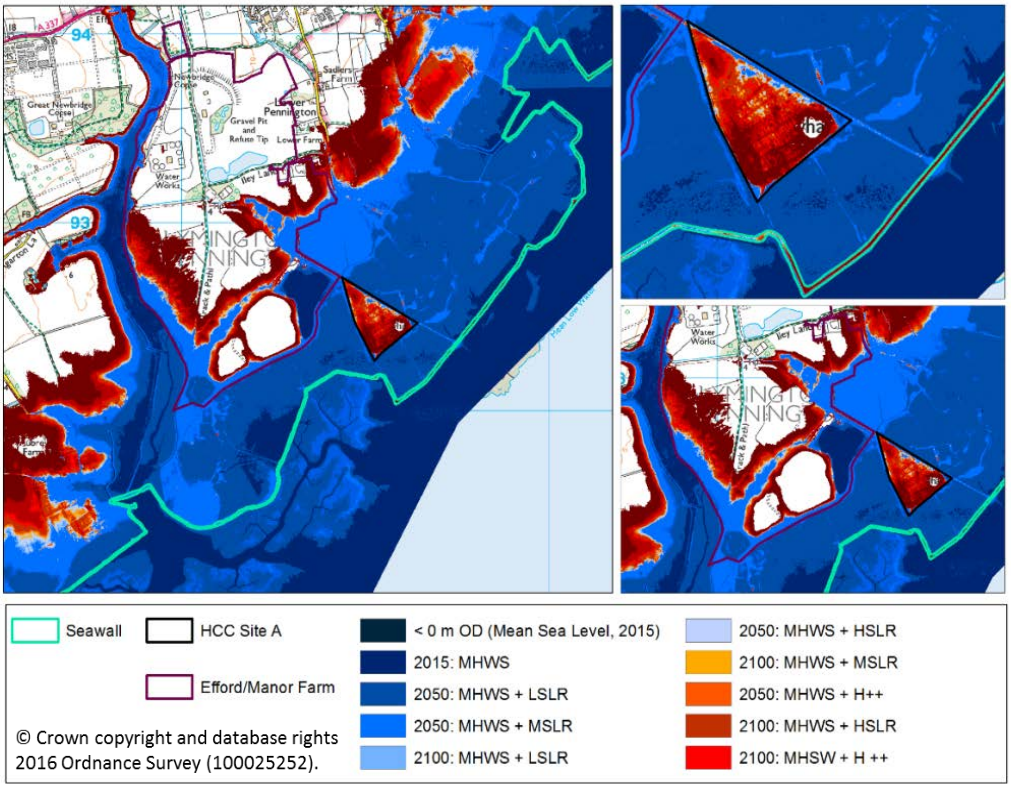


Figure 18: Indicative 1-in-200 year flood zones in the current day, 2050 and 2100 under projected low, medium, high and extreme high (H++) sea level rise.

6.2.3 Potential leachate generation in response to extreme water level events

Excess leachate volumes within Pennington Marshes Landfill in response to flooding were calculated based on flood levels above existing leachate levels in the site, which are assumed to be at 0.65 m aOD. Our calculations are based on a NAI policy (see section 7.2) where the sea wall will progressively be overtopped and eventually fully breached. If the wall is maintained and major breaches prevented, flooding of the landfills will not occur. Localised, and non-catastrophic (in terms of breaching) overtopping of the sea wall during storms will not affect the protected landfills.

As described in section 6.1, analysis predicted overtopping and breaching of the sea wall in the section to the west of the Pennington Marshes landfill. Once the sea wall is breached the flanks of the landfill will be flooded on a daily basis, and this will cause leachate levels in the landfill to fluctuate with the tide. As a worst case scenario, assuming full hydraulic connectivity and very permeable waste then leachate levels may track tide levels. Assuming that background leachate levels are at 0.75 m aOD, then a spring tide in 2050 under a medium sea level rise scenario could reach 1.13 m aOD (Table 5). Assuming a landfill surface area of 7.5 ha and a drainable porosity for the waste of 15%, then potentially 4,300 m^3 of leachate could be produced, which would have the potential to drain out onto the surrounding marsh land when the tide recedes. Full inundation of the landfill which could occur in 2100 during a 1 in 50 year storm under a high sea level rise scenario (Figure 18) could result in ~15,000 m^3 of leachate being created. Sampling and chemical analysis of leachate or groundwater was not undertaken for this case study. Nevertheless, it is likely that leachate concentrations would be low and have a low impact on the local environment.

7. Management options

The results from the flood analysis show that flooding is limited on the landfills under present day sea level conditions but there are greater risks of inundation in the future, especially under high sea level rise conditions. Therefore different options for the sea defences were considered.

7.1 Maintain the Hold the Line SMP

The original sea wall was designed to provide a 1-in-50 year standard of protection. In addition to this, the current defences were designed to be fronted in many locations by a substantial width of intertidal habitat. A study by Gardiner et al. (2007), however, predicted that by the 2080's, if the current defences were maintained, the mudflats will be the only intertidal habitat present in the Hurst-Lymington area under a medium high sea-level scenario due to erosion of the salt marsh. These factors are likely to necessitate significant and costly upgrades to the sea wall to maintain the required standard of protection. The crest elevation of the defences will need to be raised, accompanied by an associated increase in width and volume. Reinforcement may also need to be considered in light of increases in wave attack to prevent structural failure of the defences. An alternative scenario would be to increase the acceptable overtopping volume of the seawall. This would require works to reinforce the current defences instead of increasing their crest elevation.

Calculations were made using Eurotop (2009, 2014) to estimate the future increases in seawall elevation to provide the same level of protection it provides today. It is assumed that the design permissible overtopping (0.05 m) will not be altered in the future, the defence design in terms of crest width, and landward and seaward slope, were assumed to remain the same, and the total length of the wall from Lymington to Keyhaven was 8.1 km. Different sea level scenarios were examined. Minimum crest elevations were calculated by rearranging the Eurotop (2009, 2014) formula. From these heights, the base level was calculated using basic geometrical relationships and then used to estimate the volume increase required. Unit costs for sea wall structures were obtained from Environment Agency guidance. The results for the required crest elevation by the year 2100 under varying sea level rise scenarios along with the associated width increase and estimated cost are shown in Table 6, below. As might be expected, the greater the rise in sea level, the greater the cost associated with both increasing the sea wall height and maintaining it.

Table 6: Estimated height and width requirements, and indicative costs, for the Pennington sea wall under four sea level rise projections and a Hold the line SMP.

Sea Level Rise Scenario	Crest elevation increase (m)	Base Width increase (m)	Estimated Cost (£ million)	Estimated Maintenance Costs	
				Annual (£ million/m/yr.)	Over 50 year life span (£ million/m)
Low	0.5 – 2.47	0.2 – 3.8	28	0.28	14
Medium	0.2 – 1	1 – 4.7	40	0.40	20
High	0.5 – 1.3	2.8 – 6.3	65	0.65	32.5
H ++	1.3 – 2	6.4 – 10	128	1.28	64

Estimated capital costs are based on previous EA projects and use the average cost per cubic metre for embankments greater than 15,000 m^3. It must be noted that actual costs will be dependent on a number of different site specific factors. For example, other than physical size (length and volume) there are a number of other variables which can significantly affect the cost of works on embankments, these include but are not limited to, the transport distance for fill material, the type and source of fill material and site accessibility (i.e. haul length along the embankment). Adjacent designated habitats are likely to increase costs due to sensitive measures or limitations on when construction is able to take place. For example, if the site is identified as key for over-wintering birds then works may be limited to the summer months. These are all factors which highlight the complexity of this site as a case for a hold the line policy.

Under this scenario, no costs are required for the management of the landfill site itself as the risks from inundation are managed by the defences themselves. It must be noted that the estimated capital costs described in this section are also accompanied by maintenance costs, which can vary greatly.

7.2 No Active Intervention SMP

Under a 'No Active Intervention' (or 'do nothing') SMP, the crest level of the existing defences would not be raised and maintenance to the existing wall would not be undertaken. Inherent to this shoreline management policy, there are no capital or maintenance costs associated with the defences themselves. Under rising sea levels, the crest height would no longer offer protection under some of the scenarios described above and the wall would deteriorate over time. Rising sea levels, loss of fronting saltmarsh habitat and a subsequent increase in the height of potential waves able to reach the sea wall would also result in an increase in damaging overtopping and overflow events. Due to the variations in the elevation of the defence, the performance of the seawall will vary along its length under future extreme water level events. The section fronting Pennington Marshes landfill (Section BC) has the highest crest level, and from analysis, it will continue to perform well under a majority of scenarios. However, even for a low sea level rise scenario there are sections of the wall that are vulnerable to more frequent overtopping and overflow events followed by breaching (section 6.1).

The lack of any defined flood compartments, as can be seen in the flood exposure maps, would result in widespread inundation and affect the historic landfill site, Pennington Marshes landfill, and potentially the larger complex of sites including Efford. Section 6.2.3. describes the impact of seawater lying against the flanks of the Pennington Marshes landfill and estimates the potential volumes of leachate which could be formed due to seepage of water into the landfill. The leachate formed will be very dilute and is not likely to have a significant impact. However, the eventual loss of Pennington Marshes landfill due to erosion could lead to the release of any remaining solid waste to the local environment.

In addition, there are properties within the study area. The flood risk assessment showed that some houses are already at risk of flooding and by the year 2100 flooding would potentially affect 180 properties. Such flooding would also have a significant and adverse effect on the designated brackish and freshwater habitats and associated species behind the seawall. There would also be a loss to the important amenity footpath.

7.3 Managed realignment SMP

Managed realignment would allow the sea to access the currently defended areas of the coastline. This would create a larger inter-tidal area, similar to the end result if a 'do nothing' policy was adopted, however, managed realignment would occur in a controlled manner. It is an option best considered when expenditure on the current coastal defences cannot be justified, and/or where the erection of such defences would have an unacceptable environmental impact. The current seawall could either be deliberately removed (or breached) or left to degrade over time while a second line of defence is constructed. While much of Pennington is low-lying, the land does slope upwards naturally. This slope can be utilised to reduce the height of required defences.

Figure 20 shows an option for realignment of the sea wall and addition of a new wall around the Pennington Marshes landfill. The original wall (dark blue line in Figure 20; section A-B in Figure 10) is upgraded to provide protection under different sea level rise scenarios. The new wall (green line) then follows the southern and eastern boundary of the landfill back to the minor road. Sections of the current wall (B to F in Figure 10) would be left undefended, and may eventually breach to create a much larger intertidal area.

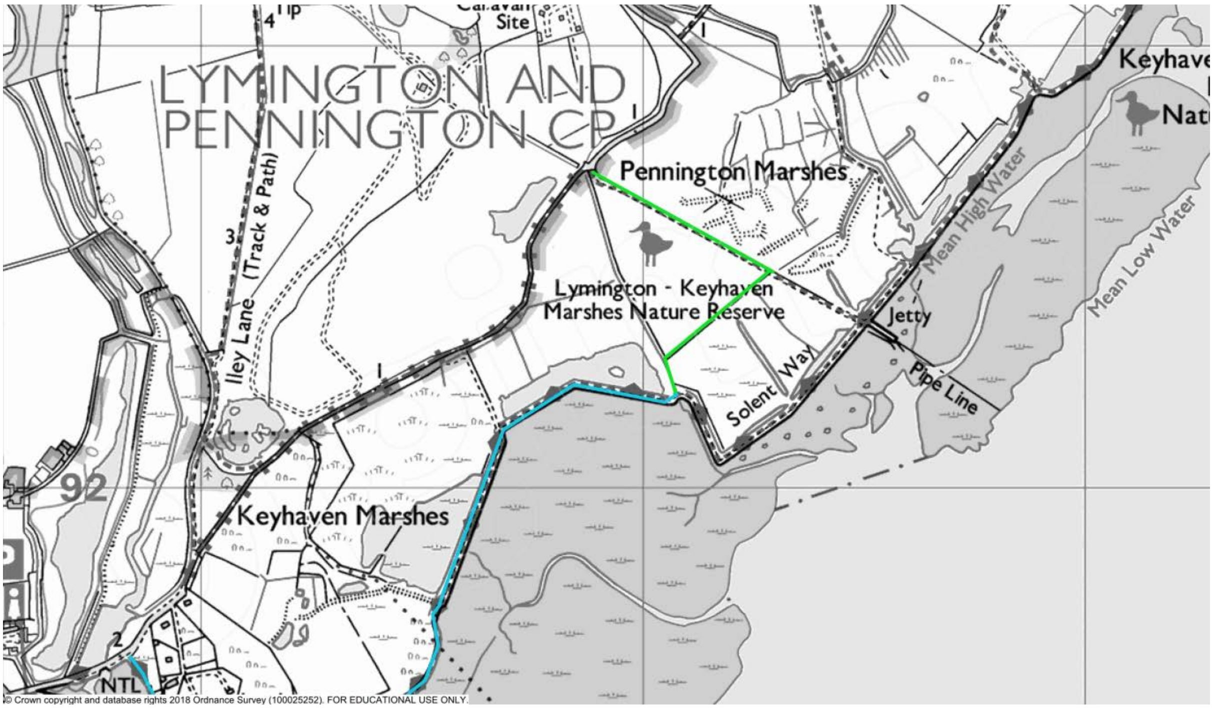


Figure 19: Realignment of the sea wall. The green line shows the option for new sea wall defences around Pennington Marshes landfill site. The blue line shows the existing sea wall which will be upgraded to provide protection under different sea level rise scenarios. Map sourced from Digimap.

In this scenario, only 0.9 km of new defence wall would be built around the landfill and 1.9 km of the existing sea wall upgraded (from Keyhaven to the start of the new wall). Maintenance of this part of the sea wall would enable protection of Efford landfill and the small number of houses to the east of the estuary at Keyhaven.

Table 7 shows a comparison of the costs for this MR SMP with the HTL SMP described in section 7.1. The costs for the MR SMP are £31M under a low sea level rise scenario and £42 M under high sea level rise, therefore lower than the HTL strategy under low sea level rise. The cost of the MR SMP assumes that a full height defence wall will be built around the Pennington Marshes landfill. However, it may be possible to reduce the costs of this wall significantly by building the defences against the landfill boundary. A low permeability plastic liner combined with an underlying layer of low permeability clay could be used to form a barrier to reduce saline intrusion into the waste and the barrier then covered with rock armour to prevent erosion. A similar approach was used during managed realignment at Greatham (Latham et al., 2014).

As previously discussed, the inter-tidal habitats in the region, particularly the saltmarsh, has been considered a key aspect of the defence system. Gardiner et al (2007) identified that in the inter-tidal habitat covers an area of 644 ha, made up of 210 ha of saltmarsh. Modelling conducted by

Gardiner et al. (2007) indicated that if managed realignment was undertaken, the predominant habitat will remain mudflats. This is because the elevation of new intertidal areas will be too low to replace lost saltmarsh. Additionally, designated coastal grazing marsh and saline lagoons, which should be maintained to comply with the Habitats Directive, will be lost. Relocation is an option as these are largely artificially managed habitats but opportunities are restricted within the case study site due to competition from urban and industrial land use. In the MR plan, some properties to the northeast of Pennington Marshes landfill site will be at greater risk of flooding in the case of any breach of the existing wall.

Table 7: Comparison of estimated costs for existing hold the line management and a realigned sea defence

SMP	**Sea Level Rise Scenario**	**Section of HTL defences**		**Section of New Defence wall**		**Total capital cost (£M)**	**Maintenance Costs**		**Total cost over 50 years (£ M)**
		Length (km)	Capital Cost (£ M)	Length (km)	Capital Cost (£ M)		Annual (£ M/yr)	Over 50 year life span (£ M)	
HLT	Low	6	28	n/a		28	0.28	14	42
	High		65			65	0.65	32.5	97.5
MR	Low	1.9	11.1	0.9	11.6	22.7	0.17	8.5	31
	High		14.8		15.7	30.5	0.23	11.3	42

7.4 Removal of the landfill

Removal of Pennington landfill would have potential long-term benefits to SMP in the region. However, there would be many regulatory challenges that would need to be addressed. Planning permission would be required which would include a consideration of the impact of lorry and other environmental nuisances on the local community. The Environment Agency would also need to issue a permit to cover the operation. An estimate of the cost of removing the waste from Pennington Marshes landfill was made. It was assumed that the waste will be transported to an unspecified landfill site 50 miles from Pennington. The disposal of the waste to landfill is currently liable to landfill tax charges, and waste characterisation would need to be made to determine whether the waste is subject to the full tax charges (£84.40/tonne – rate applicable at time of costing) or at the lower rate for inactive waste (£2.65/tonne). The total cost for removal of the Pennington Marshes landfill would be approximately £21M if all removed materials attracted the top rate of landfill tax (Figure 21). In this scenario, landfill tax would amount to 75% of the total costs. If it is assumed that only 30% of the removed and re-landfilled material attracted the higher rate of landfill tax, the total remediation cost is halved to around £10M (Figure 21). There are many uncertainties with the cost analysis, not least because the values chosen against the various categories are mostly estimates and are not based on a detailed analysis of costs. However, the analysis does give an indication of the magnitude of potential costs.

Excavation and in-situ treatment of the landfilled waste with recovery of some of the material for use on site or in shoreline defences may be possible, but a comprehensive waste characterisation would be needed to determine the feasibility and cost of this approach. An end of waste protocol would also probably be required to cover the nature of recovered materials.

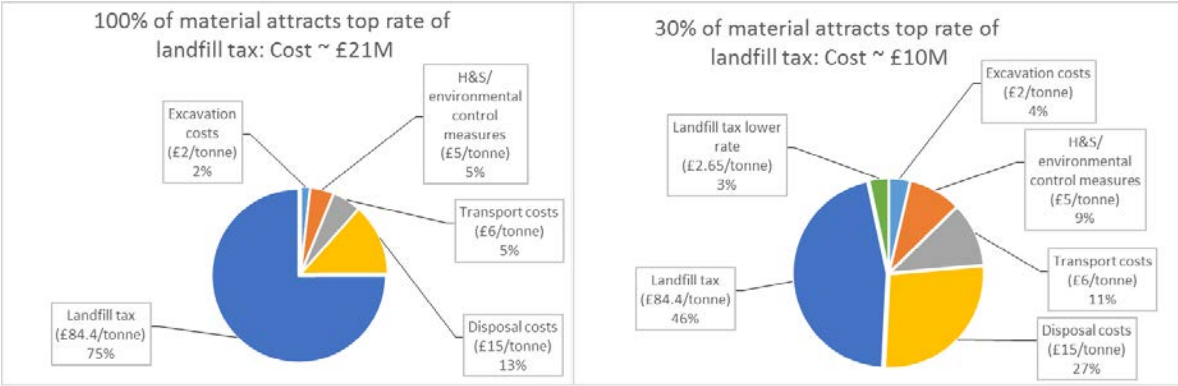


Figure 20: Possible magnitude of costs to remove Pennington Marshes landfill to an alternative landfill assumed to be within 50 miles driving distance.

8. Comments and Recommendations

Analysis of the potential for overflow and breaching of the current defences shows that a short length of the wall (section A-B) is at risk of flooding under a 1 in 50 year period in current, 2050 and 2100 scenarios. The risk of overtopping increases in this and other sections of the sea wall with increasing sea level rise and under extreme water level events. Extensive flooding behind the sea wall would occur in the event of a breach, although Pennington Marshes landfill is not likely to be subject to inundation in the short term. In the long term, with sea level rise and with extreme water level events, water levels could overtop the landfill. In this case, significant amounts of leachate would be formed. Even in low level flooding, water lying against the boundaries of the landfill could seep into the waste, resulting in loss of leachate to the surrounding area. A number of alternative shoreline management options were considered for the site:

- monitoring of the state of the defences continues to understand the likelihood of coastal flooding and erosion
- shoreline management proposals are re-evaluated, recognizing that some managed realignment is possible with the existing landfills in place. Removal of the Pennington Marshes landfill increases the options
- the alternative is to hold the line and increase defences or allow the landfill to erode and leachate and solid waste to escape into the environment. The rates of release are highly uncertain.

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