Investigating the impact of landfill sites at the coast on Marine Protected Area features in Wales

Report No: 673

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Report series: NRW Evidence Report

Report number: 673

Publication date: March 2023

Contractor: ABPmer

Contract Manager: Harriet Robinson

Title: **Investigating the impact of landfill sites at the coast on Marine Protected Area features in Wales**

Author(s): **Robbins**, K., **Bernard**, B. **Brooks**, A., **Frost**, N.

Technical Editors: Carmichael J., Lewis, G., Robinson H.,

Quality assurance: Tier 2 .

Peer Reviewer(s): Nicola Rimington, Karen Robinson, Tyrone Ward, Rowland Shard, Neil Smith, Maggie Hatton-Ellis, Sarah Poulton, Stefan Le Roy, Nicholas Roberts, Joanna Ibrahim, Kate Cameron, Tom Stringell, Matty Murphy, Ida Nielsen, Lara Moggridge, Heather Lewis, Julie Creer, Jenny Carmichael, Gareth Lewis and Harriet Robinson.

Approved By: J. Sharp

Restrictions: None

Distribution List (core)

NRW Library, Bangor	2
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Recommended citation for this volume:

Robbins, K; Bernard, B; Brooks, A; Frost, N. 2023. Investigating the impact of landfill sites at the coast on Marine Protected Area features in Wales. NRW Evidence Report. Report No: 673, 84pp, Natural Resources Wales, Cardiff.

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Cynhaliwyd y prosiect hwn mewn dau gam allweddol. Yn gyntaf, pennwyd y risg o wastraff yn cael ei ryddhau o safleoedd tirlenwi ar arfordir Cymru drwy nodweddu pob safle tirlenwi yn seiliedig ar ffactorau gan gynnwys lefel bosibl llifogydd ac erydu yn yr ardal, a phresenoldeb a chyflwr amddiffynfeydd arfordirol (gan ddefnyddio Systemau Gwybodaeth Ddaearyddol). Yn ail, aseswyd pa mor agored i niwed yw nodweddion cynefin Ardaloedd Morol Gwarchodedig i'r mathau o wastraff ym mhob safle tirlenwi ar sail y dystiolaeth orau sydd ar gael a chrebwyll arbenigol. Penderfynwyd ar hyn drwy asesu'r pwysau posibl sy'n debygol o godi o'r gwahanol fathau o wastraff tirlenwi, y pellter y gallai'r pwysau gael effaith arno, a sensitifrwydd posibl nodweddion cynefinoedd Ardaloedd Morol Gwarchodedig i'r pwysau. Yna cyfunwyd y ddau gam hyn i bennu sgôr gyffredinol ar gyfer y bygythiad y mae'r safle tirlenwi yn ei achosi i nodweddion cynefin Ardaloedd Morol Gwarchodedig. Ailadroddwyd yr asesiadau hyn ar gyfer pob cyfnod i ymchwilio i'r newid yn y bygythiad o safleoedd tirlenwi i nodweddion Ardaloedd Morol Gwarchodedig dros amser.

Yn seiliedig ar lifogydd ac erydu arfordirol heddiw, dangosodd yr asesiad fod gan 265 o safleoedd tirlenwi y potensial i ryddhau gwastraff i'r amgylchedd morol. Cynyddodd hyn i 306 a 332 o safleoedd tirlenwi yn y tymor canolig a'r tymor hir, yn y drefn honno. Cynyddodd cyfran y safleoedd tirlenwi a oedd yn peri bygythiad canolig neu uchel i Ardaloedd Morol Gwarchodedig dros amser. Yn ogystal, roedd y safleoedd tirlenwi a oedd â risg uwch o ollwng gwastraff yn tueddu i fod mewn ardaloedd lle ceir perygl uchel o lifogydd, yn ddiamddiffyn ac roedd ganddynt ffin dirlenwi fawr, agored i effaith tonnau.

Roedd y crynodiad uchaf o safleoedd tirlenwi o amgylch aber Afon Dyfrdwy, Cilfach Tywyn, Abertawe, Caerdydd a Chasnewydd. Roedd Ardal Weithredol Gogledd-orllewin Cymru ac Ardal Weithredol De-orllewin Cymru (gan gynnwys Cilfach Tywyn) yn cynnwys y cyfrannau uchaf o safleoedd tirlenwi a oedd yn peri bygythiad cyffredinol uchel i nodweddion cynefinoedd Ardaloedd Morol Gwarchodedig. Ystyriwyd bod ardaloedd â chrynodiadau uchel o safleoedd tirlenwi a/neu ardaloedd â safleoedd tirlenwi a oedd yn peri bygythiad cyffredinol uchel i nodweddion Ardaloedd Morol Gwarchodedig yn flaenoriaeth ar gyfer ymchwiliadau rhanbarthol neu safle-benodol pellach. Y nodweddion cynefin yr ystyriwyd eu bod yn wynebu'r perygl mwyaf o ollwng gwastraff o safleoedd tirlenwi oedd aberoedd a riffau, gyda riffau biogenig dan ddylanwad tywod, ogofâu a gwastadeddau llaid a gwastadeddau tywod hefyd mewn perygl uwch o gymharu â'r nodweddion Ardaloedd Morol Gwarchodedig eraill a aseswyd.

Yna trafodwyd mesurau rheoli sydd â'r potensial i leihau'r risg o wastraff yn cael ei ryddhau i'r amgylchedd morol lle y gallai effeithio ar Ardaloedd Morol Gwarchodedig. Roedd mesurau o'r fath yn cynnwys cael gwared ar wastraff tirlenwi, diogelu'r arfordir, trin halogiad, ac archwilio ac arolygu.

Mae’r adroddiad hwn yn darparu dull lefel uchel o benderfynu pa safleoedd tirlenwi ar yr arfordir sydd â’r potensial o beri'r bygythiad mwyaf i nodweddion Ardaloedd Morol Gwarchodedig yng Nghymru. O ystyried dull lefel uchel yr asesiad hwn, y nod oedd hysbysu lle y dylid cynnal ymchwiliadau manylach ar safleoedd tirlenwi penodol neu ranbarthau o bryder posibl. O ystyried lefel yr hyder sy'n gysylltiedig â rhai o allbynnau'r prosiect, nid yw'n bosibl defnyddio'r wybodaeth hon i gael gwybodaeth gywir sy'n benodol i safle. Yn lle hynny, argymhellir bod astudiaethau yn y dyfodol yn defnyddio data lleoliad-benodol i fireinio canlyniadau'r asesiad hwn. Er enghraifft, bydd data am yr hydrodynameg leol, amodau amgylcheddol lleol, y mesurau rheoli presennol sydd ar waith, union gynnwys a lefelau halogiad sydd yn y safle tirlenwi ac a ryddhawyd ohono, a sensitifrwydd cynefinoedd/rhywogaethau penodol i bwysau tirlenwi penodol, yn helpu i ddeall yn well yr effeithiau safle-benodol lleol sy'n deillio o safleoedd tirlenwi. Am restr lawn o dybiaethau a chyfyngiadau'r asesiad, gweler Adran 4.

Ni chafodd rhywogaethau symudol a warchodir o dan Ardaloedd Morol Gwarchodedig Cymru eu cynnwys yn yr asesiad hwn oherwydd diffyg gwybodaeth am effeithiau anuniongyrchol ac uniongyrchol gwastraff tirlenwi ar rywogaethau. Felly ymgymerwyd ag adolygiad llenyddiaeth byr (yn Atodiad10.3) i amlygu effeithiau posibl ystod o wastraff tirlenwi ar adar, mamaliaid a physgod.

Executive summary

Many landfill sites in Wales are located at the coast and sit within or adjacent to Marine Protected Areas (MPAs). It has been identified that these sites therefore present a potential threat to the condition of marine features that make up the Welsh MPA network. The aim of this high-level assessment was to determine the coastal landfill sites which pose the greatest threat to Welsh MPA features in the present day (2005-2025) and in two future scenarios corresponding to a medium-term (2025-2055) and long-term (2055-2105) epoch.

This project was conducted in two key steps. Firstly, the risk of waste being released from landfill sites on the Welsh coast was determined by characterising each landfill site-based on factors including the potential level of flooding and erosion in the area, and presence and condition of coastal defences (using Geographic Information Systems (GIS)). Secondly, the vulnerability of MPA habitat features to the waste types within each landfill site was assessed based on the best available evidence and expert judgement. This was determined by assessing the potential pressures likely to arise from the different landfill waste types, the distance the pressures could have an impact, and the potential sensitivity of MPA habitat features to the pressures. These two stages were then combined to determine an overall score for the threat the landfill site poses to MPA habitat features. These assessments were repeated for each epoch to investigate the change in the threat of landfill sites to MPA features over time.

The assessment showed that, based on flooding and coastal erosion in the present day, 265 landfill sites have the potential to release waste into the marine environment. This increased to 306 and 332 landfill sites in the medium and long-term epochs, respectively. The proportion of landfill sites which posed a medium or high threat to MPAs increased over time. In addition, the landfill sites which had a higher risk of releasing waste tended to be in high flood risk areas, were undefended and had a large, exposed landfill boundary to wave impact.

The highest concentration of landfill sites occurred around the Dee Estuary, Burry Inlet, Swansea, Cardiff and Newport. The North West Operational Area and the South West Wales Operational Area (including the Burry Inlet) contained the highest proportions of landfill sites which posed a high overall threat to MPA habitat features. Areas of high concentrations of landfill sites and/or areas with landfills which posed a high overall threat to MPA features were considered a priority for further regional or site-specific investigations. The habitat features deemed most at risk to the release of waste from landfill sites were Estuaries and Reefs, with Sand Influenced Biogenic Reefs (SSSIs), Caves and Mudflats and Sandflats also being at a higher risk compared to the other MPA features assessed.

Management measures which have the potential to reduce the risk of waste being released into the marine environment where it could impact MPAs were then discussed. Such measures included the removal of landfill waste, coastal protection, treating contamination, and inspection and surveillance.

This report provides a high-level approach for determining which landfill sites at the coast have potential to pose the greatest threat to MPA features in Wales. Given the high-level approach to this assessment, the aim was to inform where more detailed investigations should be undertaken on specific landfills or regions of potential concern. Given the level of confidence related to some of the project outputs it is not possible to use this information to ascertain accurate site-specific information. Instead, it is recommended that future studies use location specific data to refine the results of this assessment. For example, data about the local hydrodynamics, local environmental conditions, current management measures in place, exact contents and contamination levels contained within and released from the landfill, and specific habitat/species sensitivity to specific landfill pressures, will aid a better understanding of the local site-specific impacts arising from landfills. For a full list of the assumptions and limitations of the assessment, see Section 4.

Mobile species protected under Welsh MPAs were not included in this assessment due to a lack of information on the indirect and direct impacts of landfill waste on species. A short literature review was therefore undertaken (in Appendix 10.3) to highlight the potential effects of a range of landfill waste on birds, mammals and fish.

1 Introduction

1.1 Background

There are over 1,500 individual landfill sites recorded in Wales, classed as operational, closed or historic. Many of these are located at the coast and sit within or adjacent to Marine Protected Areas (MPAs). Through NRW’s MPA Condition Improvement Programme, and review of protected site actions, it was identified that landfill sites at the coast (particularly around the Dee Estuary) are a potential pressure affecting the condition of marine features that make up the Welsh MPA network.

Flooding and erosion of coastal landfill sites could lead to physical (marine litter) and chemical (leachate) contamination, and air pollution entering the environment, potentially affecting the condition of MPA features. The release of landfill waste could be further exacerbated by the effects of climate change, such as sea-level rise and increase in extreme weather events, which will lead to increased likelihood of inundation of landfill sites with sea water or landfill site failure with increased rates of erosion. In addition, changes in Shoreline Management Plan (SMP) policies over different epochs have the potential to affect the exposure of landfill sites to flooding and coastal erosion.

Landfill sites, particularly historic landfills which pre-date modern environmental regulations, can contain a wide range of material that can be harmful to marine habitats and species, such as asbestos, plastics, inorganic and organic contaminants. Managing the pressures posed by waste released from landfill sites is therefore a significant challenge. It is important to prioritise the management of landfill sites which pose the most risk of releasing waste or pollutants, particularly in areas where MPA features could be most sensitive.

The aim of this project was to determine which of the known coastal landfill sites pose the greatest threat to Welsh MPA features in the present day (2005-2025) and in two future scenarios corresponding to a medium-term (2025-2055) and long-term (2055-2105) epoch. Due to a lack of evidence to support a detailed assessment, mobile species features were assessed in a separate literature review (in Appendix 10.3). In addition, there is limited information on how landfill sites may alter air quality and how this may interact with MPA features, therefore this was not included in the assessment. The key objectives for this high-level assessment for MPA marine habitat features were:

- Assess the risk of waste being released from coastal landfill sites in Wales under present day, medium and long-term epochs;
- Assess the vulnerability of MPA habitat features to waste if released from coastal landfill sites under present day, medium and long-term epochs;
- Produce a list of prioritised landfill sites which pose the greatest threat to Welsh MPA features; and
- Review potential management measures that have been used to reduce the potential release of waste from landfill sites or the impact of waste of habitats and species.

2 Methodology

To assess the potential impact of the coastal landfill sites on MPA features under different epochs, six project phases were identified.

- Phase 1: Characterise the landfill sites – assess waste type and risk of waste being released into the marine environment;
- Phase 2: Define the zones of impact should waste be released;
- Phase 3: Identify MPAs which occur within defined zones of impact. Identify and determining the sensitivity of MPA habitat features (within identified MPAs) to the pressure arising from released waste;
- Phase 4: Vulnerability scoring habitat features to released waste;
- Phase 5: Prioritise landfill sites with potential greatest impact on MPA habitat features;
- Phase 6: Assess potential impact under different epochs; and
- Phase 7: Identify potential management measures to reduce impact of coastal landfills on MPA habitat features.

The approach for addressing each of the phases is detailed below. A flow diagram depicting how each of the phases link together is shown in Figure 1.

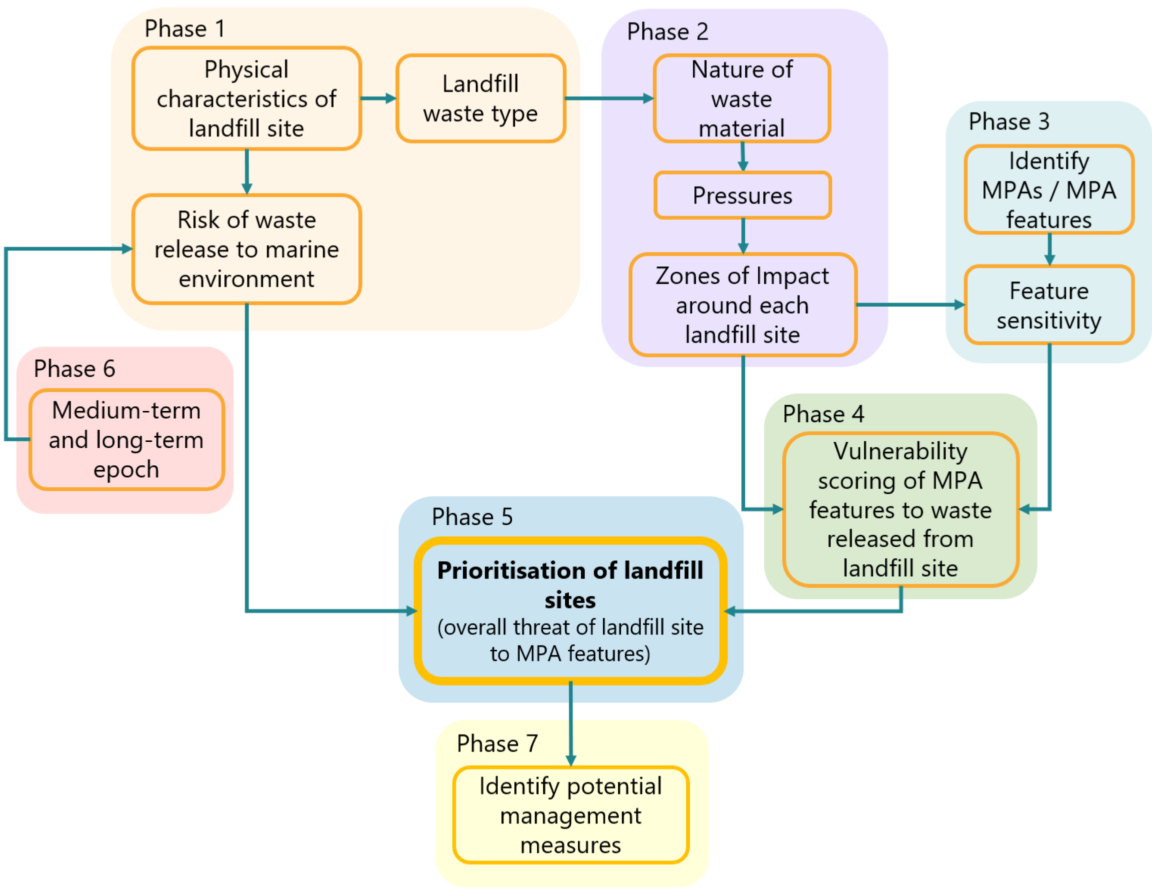


Figure 1. Flow diagram of the project phases 1-7

2.1 Phase 1: Characterise the landfill sites

2.1.1 Determining coastal landfill sites

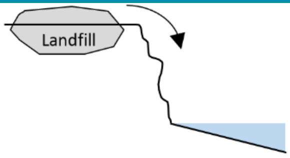
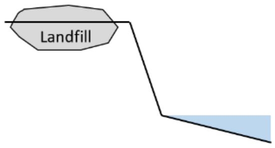
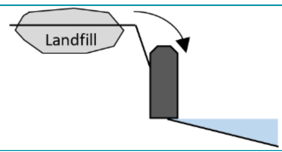
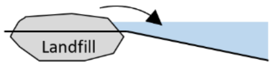
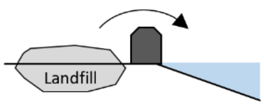
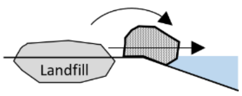
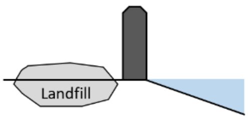
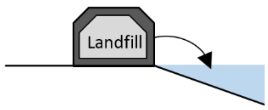
Both authorised and historical landfill sites have been considered in this assessment. Authorised landfill sites are those which currently hold a licence. Historical landfill sites are those which have been licensed previously but have since been removed from the list of Authorised landfill sites after the waste licence has either expired, been revoked, or surrendered.

Data in the form of Geographic Information System (GIS) shapefiles on the Authorised landfill sites in Wales was provided by NRW and data on the historical sites was taken from DataMapWales (https://datamap.gov.wales/). The majority of landfill sites were provided as polygons. Some landfill sites were represented as a single point, therefore for these sites, a buffer was created around the point from which to undertake the assessment based on the average area of coastal landfill polygons in Wales.

Landfills that have the potential to impact MPA features are assumed to be those in close proximity to the coast with waste or pollutants potentially being released under a range of coastal erosion and/or coastal flooding scenarios (Table 1).

To identify the landfill sites with the potential to release waste into the marine environment (termed for the purposes of this report as ‘coastal landfill sites’), the landfill shapefiles were firstly clipped to Wales to exclude any which are wholly in England. As a second filter, landfill sites which lie outside the furthest landward extent of present-day coastal floodwater (using the Flood Risk Assessment Wales (FRAW)) and/or coastal erosion risk area (using the 50th percentile from the National Coastal Erosion Risk Mapping (NCERM) dataset) were removed, as this was considered the maximum realistic distance from the coastline that waste could be released into the marine environment.

Table 1. Potential scenarios of landfill material being released to the sea (redrawn and adapted from Nicholls et al. (2021))

Process of waste release	Protected or unprotected coast	Release of waste from landfill	Description
Erosion (e.g. landfills on cliffs)	Unprotected		Soft rock cliffs - waste released due to direct erosion of the cliff or a landslide
Erosion (e.g. landfills on cliffs)	Unprotected		Hard rock cliffs - waste release unlikely/minimised due slow erosion processes
Erosion (e.g. landfills on cliffs)	Protected		Defended cliffs – waste released if defence or slope failure occurs
Flooding (e.g. landfills on flood plains)	Unprotected		No defence – waste release with flooding, storm surges or sea level rise
Flooding (e.g. landfills on flood plains)	Protected		Hard defence – waste release if defence fails, during storm surges, or sea level rise
Flooding (e.g. landfills on flood plains)	Protected		Soft defence – waste release if defence fails, during storm surges, or sea level rise
Flooding (e.g. landfills on flood plains)	Protected		Highly defended – waste release unlikely/minimised, likely in densely populated areas
Flooding (e.g. landfills on flood plains)	Protected		Defence built from waste – waste release if defence fails

2.1.2 Categorising waste type

The exact contents and contaminants of historical landfill sites in Wales are unknown (Irfan et al., 2019). However, high-level categories for waste type are available. These categories differ between authorised and historic landfill sites.

The data available on the type of waste within the sites include:

- Historic:
    - Inert;
    - Household;
    - Industrial;
    - Commercial;
    - Special (hazardous); and
    - Liquid sludge.
- Authorised:
    - A1: Co-Disposal Landfill Site;
    - A2: Other Landfill Site taking Special Waste;
    - A4: Household, Commercial & Industrial Waste Landfill;
    - A5: Landfill taking Non-Biodegradable Wastes;
    - A6: Landfill taking other wastes;
    - A7: Industrial Waste Landfill (Factory cartilage);
    - 5.2 A(1) a): Waste Landfilling; >10 T/D with capacity >25,000 T excluding inert waste;
    - 5.2 A(1) b): Waste Landfilling; Any other Landfill to which the 2002 regulations apply;
    - L04: Non Hazardous Landfill; and
    - L05: Inert Landfill.

The majority of the landfill sites contain a mixture of these waste types. The categories for the type of waste in Authorised landfill sites were aligned with the categories used in the historical landfill dataset resulting in 4 categories of landfill waste:

- Inert:
    - L05: Inert Landfill.
    - A5: Landfill taking Non-Biodegradable Wastes;
- Household, Industrial and Commercial (HIC):
    - A1: Co-Disposal Landfill Site;
    - A3: Household, Commercial & Industrial Waste Landfill;
    - A6: Landfill taking other wastes;
    - A7: Industrial Waste Landfill (Factory cartilage);
    - 5.2 A(1) a): Waste Landfilling; >10 T/D with capacity >25,000 T excluding inert waste;
    - 5.2 A(1) b): Waste Landfilling; Any other Landfill to which the 2002 regulations apply;
    - L04: Non Hazardous Landfill
- Special (hazardous):
    - A1: Co-Disposal Landfill Site;
    - A2: Other Landfill Site taking Special Waste; and
- Liquid sludge.

2.1.3 Risk of waste release into the marine environment

To understand the level of risk posed by waste (physical and chemical) released by coastal landfills sites in Wales it is necessary to understand the potential for the landfill to release waste, based on the position of the landfill in the context of the surrounding environment (Table 1). For example, the potential risk of waste being released from a landfill site may increase due to coastal flooding extents, and / or due to the coastline eroding. Both these parameters may increase in extent landward over time due to the effects of climate change, meaning that the risk of potential release of waste from landfills into the marine environment may also change overtime.

In this study, the main parameters identified as important for assessing the potential risk of waste from a landfill site being released into the marine environment are:

- Flooding, and tidal range (Laner et al. 2009; McLaughlin and Cooper 2010; Neuhold and Nachtnebel 2011; Neuhold 2013; Rosendahl Appelquist 2013);
- Coastal geomorphological type;
- The presence of vegetated intertidal areas (for example, the presence of vegetated saltmarshes can significantly attenuate the impact of waves) (McLaughlin and Cooper 2010; Rosendahl Appelquist 2013; Denner et al. 2015);
- The presence or absence of flood defences;
- Flood defence condition and type; and
- The distance from the landfill to mean high water (Alaska Department of Environmental Conservation 2015).

The engineering characteristics of the landfill sites have not been included in this assessment due to insufficient data, however, it is important to note that any engineering has the potential to affect the release of waste from a landfill site.

Following a similar approach to that set out by Brand & Spencer (2018), a high-level risk screening assessment methodology, that enables the level of risk of waste being released into the marine environment to be assigned to each landfill site, was used. This incorporated the main parameters set out above. Each parameter was assigned relative 'risk of waste being released' scores to allow both quantitative and qualitative data to be used in the same assessment. The analysis was undertaken in a semi-automated manner using a GIS. The parameters and associated approach to scoring the level of risk of waste being released is summarised in Table 2 with the rationale for using the parameters set out in Appendix 10.1 (Table 7).

The overall risk of waste being released from each landfill site was then determined as the sum of scores from the assessment in Table 2. The higher the score the higher the risk that waste could be released from the landfill into the marine environment.

The scores were then categorised into levels of high, medium or low risk of waste being released which was then used in the prioritisation exercise in Phase 5.

Table 2. Risk scoring matrix showing the associated scores for each parameter considered to assess the level of risk of waste being released into the marine environment from a landfill site under present day conditions. Scores of 5 were assigned to the highest potential risk that waste could be released, and 1 the lowest risk. This scoring was applied to all landfill sites identified (adapted from Brand & Spencer, 2018). * depicts the datasets which were adjusted in Phase 6 in line with different epochs.

Parameter	Measure	Risk score - 1	Risk score - 2	Risk score - 3	Risk score - 4	Risk score - 5	Source data
Tidal classification	Tidal range	Macrotidal (>4 m)	-	Mesotidal (2-4 m)	-	Microtidal (<2 m)	ABPmer (2008)
Flooding	Risk of flooding the sea	Low risk of flooding	-	Medium risk of flooding	-	High risk of flooding	FRAW – Flood Risk Assessment Wales (present/short term epoch)*
Landfill position	Landfill boundary to mean high water (m)	>40 m	30-40 m	20-30 m	10-20 m	0-10 m	Nearest distance to mean high water line
Exposed boundary	Length of landfill boundary facing foreshore (m)	≤500	>500 to 1000	1000 to 2000	2000 to 3000	>3000	Manual measurement of landfill seaward boundary
Geology	BGS erosion susceptibility index	Low	Low-moderate	Moderate	Moderate-High	High	British Geological Survey (2022)
Defence condition	Flood defence condition grade	Very good	Good	Fair	Poor	Very poor / unchecked / no information available	Areas Benefitting from Flood defences datalayer (NRW 2019a)
Defence type	Flood defence condition grade	Hard (bridge abutment; demountable; flood gate; promenade; quay, wall)	Mixed (embankment; high ground; cliff)	Soft (beach barrier; beach; dune)	Partly undefended (derived from GIS)	Undefended (derived from GIS)	Areas Benefitting from Flood defences datalayer (NRW 2019a)

Parameter	Measure	Risk score - 1	Risk score - 2	Risk score - 3	Risk score - 4	Risk score - 5	Source data
Buffer zone	Width of salt marsh (m)	>50	20-50	10-20	0-10	No salt marsh	Manual measurement of saltmarsh width
Shoreline Management Plan	SMP2 policy	Hold the line	-	Managed realignment	-	No active intervention	SMP2 datalayer (NRW 2019b)*

2.2 Phase 2: Define the zones of impact should waste be released

In order to assess the potential threat of landfill sites to MPA features, potential vulnerability (based on exposure and sensitivity) of MPA habitat features to the waste released from landfill sites was determined. Exposure was estimated by determining the zone of impact from each landfill. The zone of impact around each landfill site was based on the distance waste released from a landfill site could extend and exert pressure on the marine environment.

2.2.1 Zone of impact and level of intensity

The zone of impact was based on the nature of the waste material, which plays an important role in how waste is transported from a landfill site, and the distance the waste may travel in the marine environment. Hence the area where pressure could be exerted. Four categories for the nature of waste that could be release from the landfill were identified as:

- Heavy solid waste (e.g. rubble);
- Buoyant solid waste (e.g. plastic);
- Suspended / particulate matter (e.g. sediment); and
- Leachate (e.g. dissolved contaminants).

For each of the four categories, expert judgement was used to determine the zones of impact. An assumption was made that the concentration of waste, and therefore level of intensity of the impact, would be higher closer to the landfill site. The zones of impact for each category of waste material were split into three groups to determine the intensity within these zones (namely high, medium and low intensity). It is important to note that it is extremely challenging to accurately determine potential zones of impact based on simplistic relationships such as those used here. Whilst appropriate for this high-level study, it must be recognised that the assumptions below are crude and waste dispersal would ultimately depend on upon local meteorological, oceanographic and sediment transport processes.

The zone of impact for heavy solid waste was split into three groups assuming that the concentration of the waste (and associated level of pressure) will be highest closer to the landfill site. Heavy solid waste is expected to travel the shortest distance from landfill sites as it requires a higher level of energy to move material. Thus, the zone of impact for heavy solid waste was split into three intensity groups of 0 – 0.5 km (high intensity), 0.5 – 2 km (medium intensity) and 2 – 5 km (low intensity) (see Figure 2). For the purposes of this study, heavy solid waste was not expected to have an effect on the MPAs features at over 5 km from the landfill site. It should be emphasized that the determination of these zones is somewhat subjective and smaller particles of waste could, over time, travel further than 5 km from the point of release due to littoral processes. However, at this distance, the concentration of waste can be reasonably expected to be low.

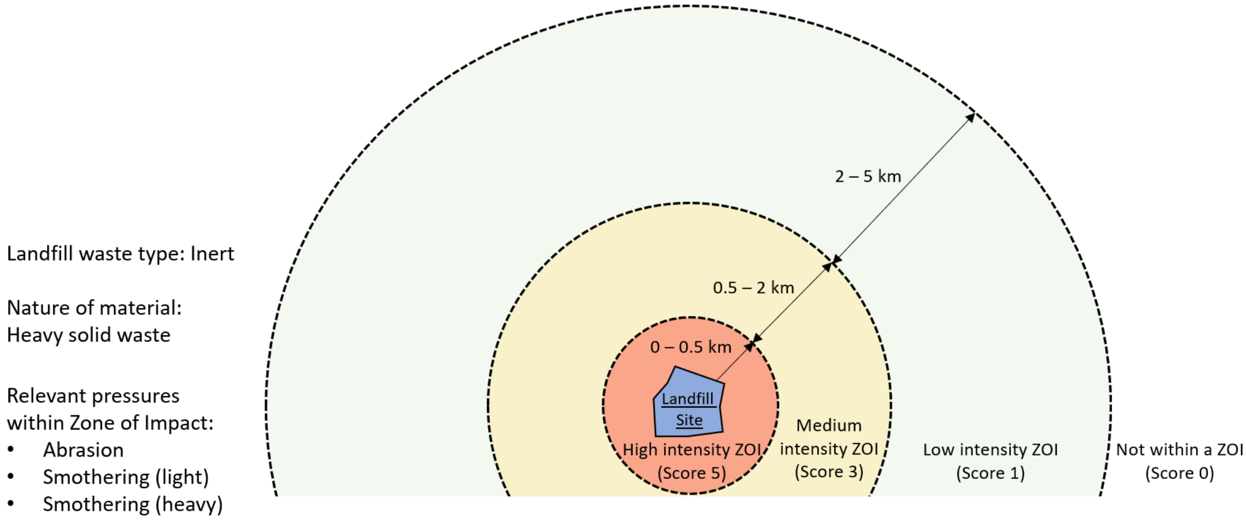


Figure 2. A diagram to show an inert landfill releasing heavy solid waste. The Zone of Impact shows the distance and intensity of associated pressures on the marine environment.

Buoyant solid waste includes waste that is less dense than water and therefore floating on or near the water's surface. It has the potential to disperse much further than heavy solid waste due to meteorological forcing. The zone of impact for buoyant solid waste was conservatively split into three groups of 0 – 5 km (high intensity), 5 – 20 km (medium intensity) and 20+ km (low intensity). It is acknowledged that buoyant waste such as plastic could disperse far beyond 20 km in response to prevailing winds, hence for the purposes of this study, it is assumed that MPA features have a (theoretical) risk of being affected by buoyant waste from any landfill site.

The zone of impact for both suspended/particulate and leachate waste were based on how far the material could be transported over a single spring tide, using the tidal excursion distance over the course of one tidal cycle (calculations of tidal excursion based on sinusoidal change are summarised in Figure 3). Current speed information was obtained for each landfill location from the UK Renewables Atlas (ABPmer et al. 2008), thereby taking into account, at a high level, the hydrodynamics of the local area for each landfill. It was assumed that beyond this distance waste material would be at a concentration too low to exert significant pressure on MPAs habitat features. The tidal excursion distance for each landfill site was split into three equal groups to represent the zones of high/medium/low intensity. For example, for a site associated with a spring tidal excursion distance of 12 km, high intensity would equate to 0–4 km from the landfill; medium intensity corresponding to a distance of 4–8 km away and low intensity, a distance of 8-12 km.

Each landfill waste type (Inert, Household, Commercial and Industrial (HIC), Special Hazardous, Liquid Sludge) was then assigned nature of waste categories and associated zones of impact (Heavy Solid Waste, Buoyant Solid Waste, Suspended / Particulate, Leachate) which were deemed relevant to the waste types (Appendix Section 10.2, Table 8).

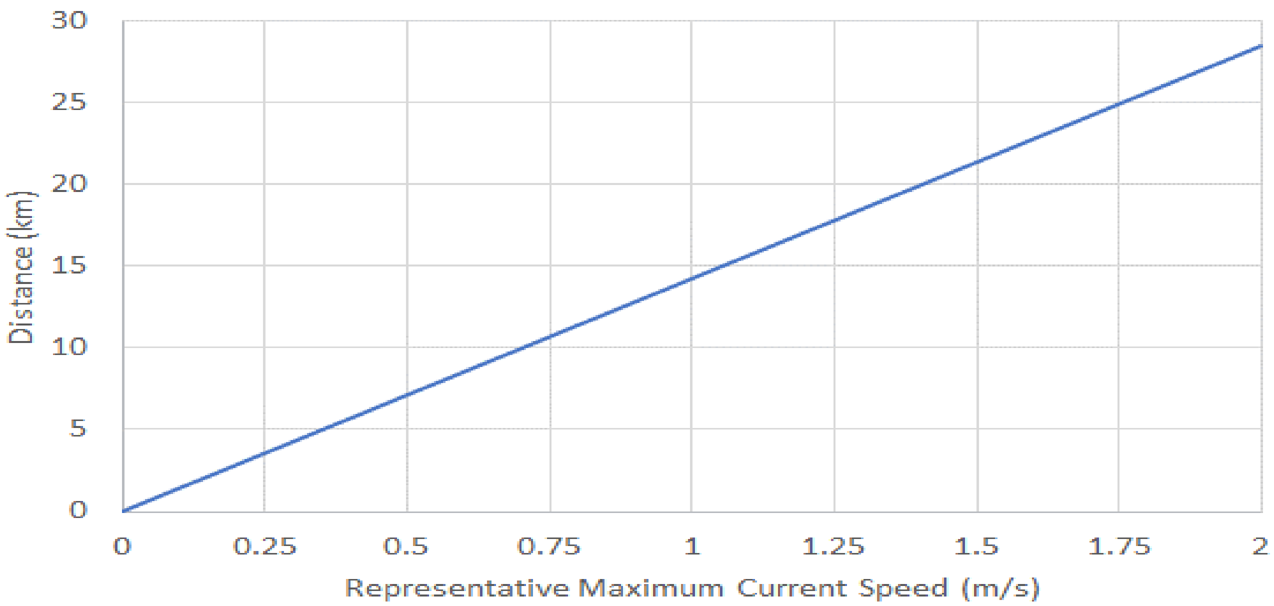


Figure 3. Summary of the relationship between current speed and excursion distance

The zones of impact were used as a radius to place buffers around each relevant landfill based on the waste type. For example, if a landfill site has HIC waste, then a buffer for each material type will apply, i.e., heavy solid waste, buoyant solid waste, suspended/ particulate matter and leachate (based on Appendix 10.2, Table 8). The buffer distances of the zones of impact are summarised in Appendix 10.2, Table 9.

2.2.2 Pressures arising from landfill waste release

In order to assess the potential impacts of release of landfill waste on MPA features, a list of the potential marine pressures which may arise from the release of waste from landfill sites was adapted from the pressures recognised in the OSPAR Joint Assessment Monitoring Programme 2014-2023 (OSPAR, 2014). The pressure types included in this study were:

- Abrasion;
- Changes in suspended solids (water clarity);
- Collision BELOW water with static or moving objects not naturally found in the marine environment (e.g., boats, machinery, and structures);
- Deoxygenation;
- Litter;
- Nutrient enrichment;
- Organic enrichment;
- Smothering and siltation rate changes (Light);
- Smothering and siltation rate changes (Heavy); and
- Chemical contamination (combined OSPAR pressures relating to hydrocarbon PAH, radionuclides, synthetic compounds, transitional elements and priority substances listed in Annex II of Directive 2008/105/EC.)

Chemical contaminants were grouped into one category for the purposes of this assessment due to two main factors. Firstly, there could be a large number of regulated, emerging and unknown hazardous chemicals which could form part of the waste being released from a landfill site. Secondly, there is relatively limited information on the numerous pressures these chemicals may have on marine habitats. This is due in part to the lack of information on the physical properties of these chemicals, how they might react in the marine environment, and how this impacts the ecology / biology of marine habitats. As the types and concentrations of chemical waste in each landfill site are unknown, it was assumed that a risk exists if any of the types of chemicals listed under the chemical contaminants pressure had the potential to be released from a landfill site and therefore come into contact with a marine habitat feature.

These pressure types were linked to the appropriate landfill waste types and nature of waste materials for which they are likely to arise from. For example, a landfill with inert waste and heavy solid material has the potential to exert pressures such as abrasion and smothering. However, a landfill with HIC waste and heavy solid material will exert these pressures and also chemical contamination. This means that for a given landfill waste type and nature of waste material, the zone of impact distances and associated high/medium/low intensity areas around the landfill site were applicable to a range of pressures (see on Appendix 10.2, Table 8).

2.3 Phase 3: Identify MPAs which occur within defined zones of impact. Identify and determining the sensitivity of MPA habitat features (within identified MPAs) to the pressure arising from released waste

As well as the zone of impact, sensitivity of MPA features was assessed in order to determine the vulnerability of MPA features to the release of waste from landfill sites. It is important to note that sensitivity was only based on direct impacts due to the uncertainty around the indirect impacts the waste from landfill sites will have on features.

In order to determine the MPA features relevant to the assessment, the MPAs, which include Special Areas of Conservation (SACs), Special Areas of Protection (SPAs), Ramsar, Sites of Special Scientific Interest (SSSI) and Marine Conservation Zones (MCZs), which intersected with the zones of impact were screened in. For example, Figure 4 depicts the MPAs screened in for an inert landfill releasing heavy solid waste and the zone of impact shows the distance and intensity of abrasion. The features within the screened in MPA sites were then assessed for sensitivity to the pressures outlined in Section 2.2.2. The screening in of MPAs was repeated for all pressure types associated with all the waste types being released from a landfill site.

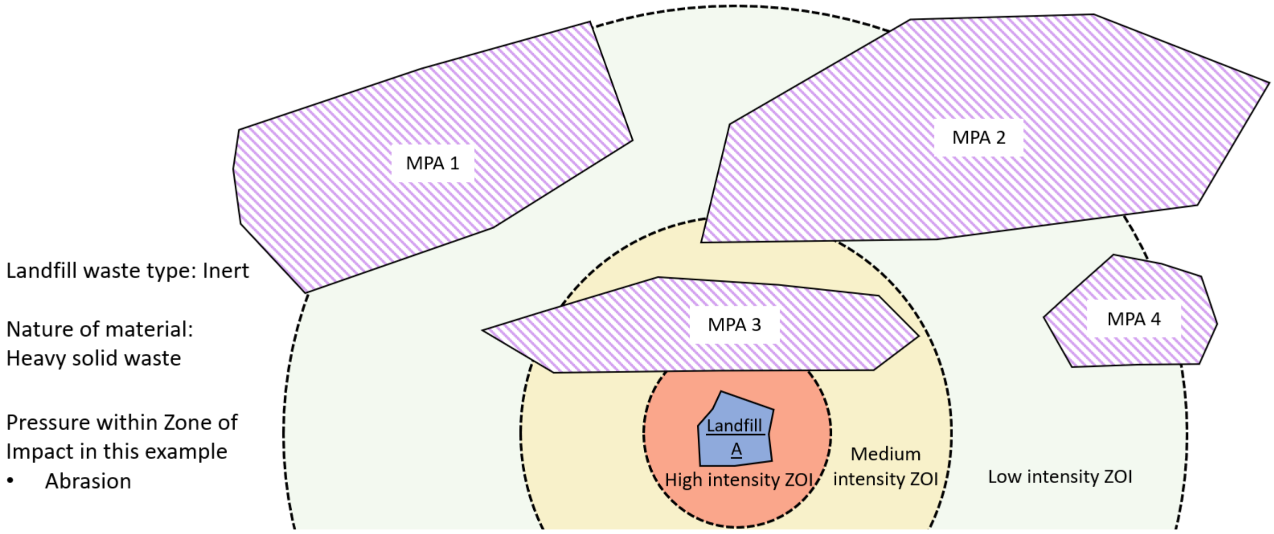


Figure 4. A diagram to illustrate the screening in of Marine Protected Areas (MPAs) based on the overlap of the MPA boundaries with the Zones of Impact (ZOI) for a landfill.

2.3.1MPA habitat features sensitivity

As mentioned above, the MPA habitat features which occur within the designated sites that intersect with the zone of impact, were assessed for their sensitivity to the pressures posed by the nature of the waste released from landfills sites. The habitat features assessed were Annex I marine habitats designated within SACs and habitat features of interest within SSSIs in Wales. The SAC habitat features for which sensitivity was assessed include:

- Annual vegetation of drift lines;
- Atlantic salt meadows *Glauco-Puccinellietalia maritimae;*
- Coastal lagoons;
- Dunes;
    - Embryonic shifting sand dunes;
    - Fixed dunes with herbaceous vegetation ('grey dunes')/ humid dune slacks/ dunes with *Salix repens* argentea (*Salicion arenariae*);
    - Shifting dunes along the shoreline with *Ammophila arenaria* ('white dunes');
- Estuaries;
- Large shallow inlets and bays;
- Mudflats and sandflats not covered by seawater at low tide;
- Perennial vegetation of stony banks;
- Reefs;
- *Salicornia* and other annuals colonising mud and sand;
- Sandbanks which are slightly covered by seawater all the time;
- Submerged or partially submerged sea caves; and
- Shore dock (Annex II).

Dunes, although not wholly a marine feature, were included in the sensitivity assessment due to their position on the coast.

Many marine SSSIs and their features in Wales overlap with marine SACs and have similar feature types. To avoid double counting, the sensitivity of SSSIs and their habitat features were only assessed where the site did not overlap with a SAC. A total of 29 SSSIs and their habitat features did not overlap and were therefore included in this sensitivity assessment. The SSSI features of interest at these sites, which were included in the assessment were:

- Caves and overhangs;
- Chalk and very soft rock;
- Dunes;
    - Embryonic shifting sand dunes;
    - Fixed dunes with herbaceous vegetation ('grey dunes')/ humid dune slacks/ dunes with *Salix repens* argentea (*Salicion arenariae*);
    - Shifting dunes along the shoreline with *Ammophila arenaria* ('white dunes');
- Eelgrass;
- Exposed rock;
- Moderately exposed rock;
- Moderately exposed sand;
- Muddy gravel;
- Rockpools;
- Sand influenced biogenic reefs;
- Saltmarsh;
- Sheltered mud;
- Soft piddock bored substrata;
- Surge gullies;
- Tide-swept algae; and
- Under-boulders.

The sensitivity of the SAC habitat features (Section 2.3.1) to the pressures arising from landfill waste release (Section 2.2.2) were derived first. Where possible, sensitivity was derived using the Marine Life Information Network's (MarLIN) Marine Evidence based Sensitivity Assessment (MarESA). MarESA (Tyler-Walters et al., 2018) assessed the sensitivity of biotopes to each pressure based on the best available scientific literature encompassing a range of human activities and the biology and ecology of the biotopes. MarESA was used for this assessment as it provides the most relevant information on habitat sensitivity to pressures where specific data relating to the impacts of landfill waste are lacking. Further detailed investigations and site-level analysis would be required to understand the impacts of landfill sites on MPA features.

The biotopes assessed for sensitivity were those which form a component of the habitat features in Wales. The highest sensitivity of the component biotopes for each habitat feature was used as the overall sensitivity of the feature. Where the sensitivity of a habitat to a pressure was not assessed by MarESA, expert judgement and relevant literature was used to determine the level of sensitivity. It was assumed that where a pressure arising from waste released from a landfill comes into contact with a habitat feature, there is a level of sensitivity that the habitat will have to that pressure type. These sensitivities were categorised as High, Medium or Low.

The sensitivity of SSSI habitat features (Section 2.3.1) to the pressures was determined in two different ways. Firstly, the majority of SSSI features were similar to an equivalent SAC feature, therefore, where appropriate, features were matched up and the same sensitivity score used for consistency. Secondly, some SSSI features which were deemed biologically / ecologically different to a SAC feature, or relatively specific compared to the SAC features (sand influenced biogenic reefs, eelgrass, under-boulders, chalk and very soft rock, and soft piddock bored substrata): here, the highest MarESA sensitivity of the biotopes matching these descriptions was used. These sensitivities were categorised as High, Medium or Low.

The sensitivity of each SAC and SSSI habitat feature to each pressure is shown in Table 3 and Table 4. The confidence in these scores were all low, whether MarESA, literature or expert judgement were applied due to the lack of direct evidence between the type of landfill waste being released and the pressures and the level of exposure they exert on marine habitat features.

2.3.2 MPA Mobile Species Features

Mobile species features were initially considered as part of the sensitivity assessment. However, they were removed from the main sensitivity assessment scoring for two main reasons. Firstly, due to the lack of information regarding the sensitivity of mobile species to the pressures and threats posed by waste released from landfill sites, Secondly, the difficulty in determining the distribution of mobile features, and thus, where they may come into contact with the pressures arising from landfill waste. Hence SACs mobile species, Special Protection Areas (SPAs), Ramsar features, and SSSI (where mobile species are a feature of interest) were not included in the feature sensitivity assessments. Instead, a literature review has been undertaken to investigate current knowledge on the potential sensitivity of the mobile features to landfill waste (see Appendix 10.3).

Table 3. The sensitivity of Special Area of Conservation (SAC) marine habitat features to the potential pressures arising from the release of waste from individual landfill sites. * Depicts features where MarESA sensitivity scores of component biotopes was used (Tyler-Walters et al., 2018). ^ Depicts features where literature and/or expert judgement were used to assess sensitivity.

SAC feature	**Abrasion / disturbance of the substrate on the surface of the seabed**	**Changes in suspended solids (water clarity)**	**Smothering and siltation rate changes (Heavy)**	**Smothering and siltation rate changes (Light)**	**De-oxygenation**	**Nutrient enrichment**	**Organic enrichment**	**Chemical contamination**
Atlantic salt meadows *Glauco-Puccinellietalia maritimae*^	Medium (Tyler-Walters et al., 2001)	Low	Medium (Tyler-Walters et al., 2001)	Low (Tyler-Walters et al., 2001)	Low	Medium (Tyler-Walters et al., 2001; Turner et al., 2009; Deegan et al., 2012)	Medium	High
Annual vegetation of drift lines^	Medium (English Nature, 2001; European Commission, 2019a)	Not relevant	High (English Nature, 2001)	Medium (English Nature, 2001)	Not relevant	Medium	Medium	High
Coastal lagoons*	High	Medium	High	Medium	Low	Not sensitive	Medium	High
Estuaries*	High	High	High	High	High	Medium	High	High
Large shallow inlets and bays*	High	High	High	High	High	Medium	High	High
Mudflats and sandflats not covered by seawater at low tide*	High	High	High	High	Medium	Medium	Medium	High

SAC feature	Abrasion / disturbance of the substrate on the surface of the seabed	Changes in suspended solids (water clarity)	Smothering and siltation rate changes (Heavy)	Smothering and siltation rate changes (Light)	De-oxygenation	Nutrient enrichment	Organic enrichment	Chemical contamination
Perennial vegetation of stony banks^	Medium (Murdock et al., 2014); European Commission, 2019b)	Not relevant	High (Murdock et al., 2014)	Medium (Murdock et al., 2014)	Not relevant	Medium	Medium	High
Reefs*	High	Medium	High	High	High	Not sensitive	Medium	High
Salicornia and other annuals colonising mud and sand^	Medium (Tyler-Walters et al., 2001)	Low	Medium (Tyler-Walters et al., 2001)	Low (Tyler-Walters et al., 2001)	Low	Low (Tyler-Walters et al., 2001; Turner et al., 2009; Deegan et al., 2012)	Low	High
Sandbanks which are slightly covered by seawater all the time*	Medium	Low	Medium	Low	Medium	Not sensitive	Medium	High
Shore dock^	Low (NRW, 2018; European Commission, 2019c)	Not relevant	Low	Low	Not relevant	Medium	Medium	High

SAC feature	Abrasion / disturbance of the substrate on the surface of the seabed	Changes in suspended solids (water clarity)	Smothering and siltation rate changes (Heavy)	Smothering and siltation rate changes (Light)	De-oxygenation	Nutrient enrichment	Organic enrichment	Chemical contamination
Submerged or partially submerged sea caves*	High	Low	Medium	Low	High	Not sensitive	Not sensitive	High
Embryonic shifting sand dunes^	Medium (European Commission, 2019d)	Not relevant	High	Medium	Not relevant	Medium (UK Centre for Ecology and Hydrology, *undated*; Rhind et al., 2013)	Medium	High
Fixed dunes with herbaceous vegetation ('grey dunes')/ humid dune slacks/ dunes with *Salix repens* argentea (*Salicion arenariae*)^	Low (European Commission, 2019e)	Not relevant	Medium	Low	Not relevant	Medium (UK Centre for Ecology and Hydrology, *undated*; Rhind et al., 2013)	Medium	High
Shifting dunes along the shoreline with *Ammophila arenaria* ('white dunes')^	Low	Not relevant	Medium	Low	Not relevant	Medium[11,] (UK Centre for Ecology and Hydrology, *undated*; Rhind et al., 2013)	Medium	High

Table 4. The sensitivity of Site of Special Scientific Interest (SSSI) marine habitat features to the potential pressures arising from the release of waste from landfill sites. * Depicts features where MarESA (2018) sensitivity scores of component biotopes was used (Tyler-Walters et al, 2018). ^ Depicts features where literature and/or expert judgement were used to assess sensitivity

SSSI feature	Sensitivity source	Abrasion / disturbance of the substrate on the surface of the seabed	Changes in suspended solids (water clarity)	Smothering and siltation rate changes (Heavy)	Smothering and siltation rate changes (Light)	De-oxygenation	Nutrient enrichment	Organic enrichment	Chemical contamination
Chalk and very soft rock*	MarESA assessment	Medium	Low	Medium	Medium	Medium	Not sensitive	Not sensitive	High
Eelgrass*	MarESA assessment	Medium	High	High	Medium	Not sensitive	Medium	Medium	High
Sand influenced biogenic reefs*	MarESA assessment	Medium	Not sensitive	Medium	Not sensitive	Low	Not sensitive	Not sensitive	High
Soft piddock bored substrata*	MarESA assessment	Medium	Low	Medium	Medium	Not sensitive	Not sensitive	Not sensitive	High
Under-boulders*	MarESA assessment	Medium	Low	Medium	Low	Not sensitive	Not sensitive	Not sensitive	High
Caves and overhangs*	SAC sensitivity - Reef	High	Medium	High	High	High	Not sensitive	Medium	High
Exposed rock*	SAC sensitivity - Reef	High	Medium	High	High	High	Not sensitive	Medium	High

SSSI feature	Sensitivity source	Abrasion / disturbance of the substrate on the surface of the seabed	Changes in suspended solids (water clarity)	Smothering and siltation rate changes (Heavy)	Smothering and siltation rate changes (Light)	De-oxygenation	Nutrient enrichment	Organic enrichment	Chemical contamination
Moderately exposed rock*	SAC sensitivity - Reef	High	Medium	High	High	High	Not sensitive	Medium	High
Moderately exposed sand*	SAC sensitivity- Mudflats and sandflats not covered by seawater at low tide	High	High	High	High	Medium	Medium	Medium	High
Muddy gravel*	SAC sensitivity- Mudflats and sandflats not covered by seawater at low tide	High	High	High	High	Medium	Medium	Medium	High
Rockpools*	SAC sensitivity - Reef	High	Medium	High	High	High	Not sensitive	Medium	High
Saltmarsh^	SAC sensitivity- Atlantic salt meadows Glauco-Puccinellietalia maritimae	Medium	Low	Medium	Low	Low	Medium	Medium	High

SSSI feature	Sensitivity source	Abrasion / disturbance of the substrate on the surface of the seabed	Changes in suspended solids (water clarity)	Smothering and siltation rate changes (Heavy)	Smothering and siltation rate changes (Light)	De-oxygenation	Nutrient enrichment	Organic enrichment	Chemical contamination
Sheltered mud*	SAC sensitivity- Mudflats and sandflats not covered by seawater at low tide	Medium	Low	Medium	Low	Low	Medium	Medium	High
Surge gullies*	SAC sensitivity - Reef	High	Medium	High	High	High	Not sensitive	Medium	High
Tide-swept algae*	SAC sensitivity - Reef	High	Medium	High	High	High	Not sensitive	Medium	High
Embryonic shifting sand dunes^	SAC sensitivity - Embryonic shifting sand dunes	Medium	Not relevant	High	Medium	Not relevant	Medium	Medium	High

SSSI feature	Sensitivity source	Abrasion / disturbance of the substrate on the surface of the seabed	Changes in suspended solids (water clarity)	Smothering and siltation rate changes (Heavy)	Smothering and siltation rate changes (Light)	De-oxygenation	Nutrient enrichment	Organic enrichment	Chemical contamination
Fixed dunes with herbaceous vegetation ('grey dunes')/ humid dune slacks/ dunes with *Salix repens* argentea (*Salicion arenariae*)^	SAC sensitivity - Fixed dunes/ humid dune slacks/ dunes with *Salix repens* argentea	Low	Not relevant	Medium	Low	Not relevant	Medium	Medium	High
Shifting dunes along the shoreline with Ammophila arenaria ('white dunes')^	SAC sensitivity – Shifting dunes	Low	Not relevant	Medium	Low	Not relevant	Medium	Medium	High

2.4 Phase 4: Vulnerability scoring habitat features to released waste

For each MPA screened in, vulnerability of its habitat features to the landfill sites was determined. Vulnerability was based on a combination of feature sensitivity and exposure to the pressures (relating to the zone of impact) posed by waste released from the landfills. This part of the assessment firstly looks at the exposure of MPA features to the pressures posed by the released waste by overlapping MPA features with the identified zone of impacts. This exposure was then combined with feature sensitivity to determine an overall score for the vulnerability of marine features to the landfill site if waste were released.

2.4.1 Scoring landfills based on MPA habitat feature vulnerability to the nature of waste being released

The assessment of the vulnerability of MPA habitat features related to where these features intersected with a landfill's zones of impact. Where a feature intersected with a high intensity zone of impact, a score of 5 was given. For medium and low intensities, a score of 3 and 1 were given, respectively. If a feature intersected multiple intensities a worst-case scenario was assumed so that the highest ZOI score was applied. This was repeated for each landfill, based on the landfill's waste type, nature of waste material and pressures within the zones of impact.

In addition, the sensitivity of the feature to the related pressure within the zone of impact was also used within the scoring. For example, where a feature was considered to be highly sensitive to a pressure this was given a score of 5. Where the feature was considered of medium or low sensitivity to the pressure, this was given a score of 3 and 1, respectively. The overlap with intensity within the zone of impact was then applied. Therefore, if a highly sensitive feature (scoring 5) intersected with a high intensity area of that zone (scoring 5) this would result in a score of 25. The scores for the features, based on each landfill's zone of impact type and intensity, were then added together to understand the vulnerability of the features to each pressure arising from the nature of the waste released. Again, this was repeated for each landfill, based on the landfill's waste type, nature of waste material and pressures with the zones of impact. An overall score for each landfill site was then calculated based on the sum of the scores for overall score of sensitivity of the features within in each zone of impact. An example of the scoring is shown in Figure 5 and Table 5.

The overall scores for the landfill sites were then categorised into levels of high, medium or low MPA feature vulnerability to the landfill sites which was then used in the prioritisation exercise in Phase 5.

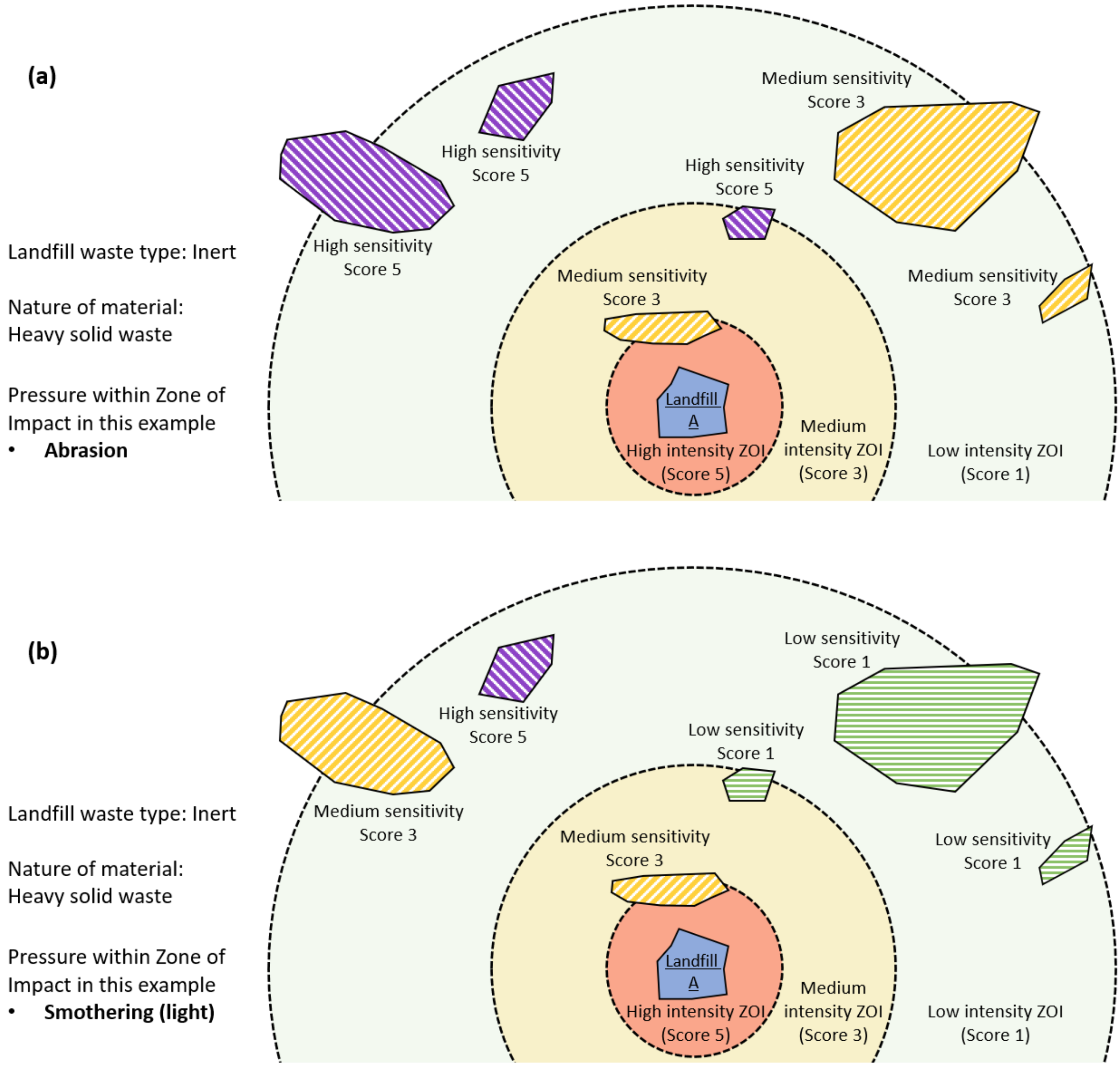


Figure 5. A diagram to illustrate the process for scoring the vulnerability of Marine Protected Areas (MPAs) habitat features to the pressures associated with a waste type being released from a landfill site. a) An inert landfill releasing heavy solid waste. The Zone of Impact (ZOI) shows the distance and intensity of abrasion. The location and sensitivity of MPA habitat features is overlayed to determine the overall vulnerability of the MPA features to this pressure from the landfill site. Example b) An inert landfill releasing heavy solid waste. The zone of impact shows the distance and intensity of smothering (light). The location and sensitivity of MPA habitat features to this pressure is overlaid to determine the overall vulnerability of the MPA features to this pressure from the landfill site. This is repeated for all pressure types associated with all waste types being released from this landfill site. The sum of these scores gives the overall vulnerability of the features to the landfill site.

The scoring for this example is shown in Table 5.

Table 5. Process for scoring for landfill site A in Figure 5 assuming an inert waste type, a nature of material as heavy solid waste and the associated pressures of abrasion and smothering (light) on MPA features. ZOI = zone of impact.

Landfill Name	Pressure	ZOI Score High = 5 Medium = 3 Low = 1	Number of High Sensitivity Features that intersect with the ZOI	High Sensitivity Features Score (Total No. x 5)	Number of Medium Sensitivity Features that intersect with the ZOI	Medium Sensitivity Features Score (Total No. x 3)	Number of Low sensitivity features that intersect with the ZOI	Low Sensitivity Features Score (Total No. x 1)	Overall score for sensitivity of features within each ZOI (ZOI x Each Sensitivity Score)
A	Abrasion	**5 (High)**	NA	NA	1	**3**	NA	NA	**15** (5 x 3)
A	Abrasion	**3 (Medium)**	1	**5**	NA	NA	NA	NA	**15** (3 x 5)
A	Abrasion	**1 (Low)**	2	**10**	2	**6**	NA	NA	**16** (1 x 10) + (1 x 6)
A	Smothering (light)	**5 (High)**	NA	NA	1	**3**	NA	NA	**15** (5 x 3)
A	Smothering (light)	**3 (Medium)**	NA	NA	NA	NA	1	**1**	**3** (3 x 1)
A	Smothering (light)	**1 (Low)**	1	**5**	1	**3**	2	**2**	**10** (1 x 5) + (1 x 3) + (1 x 2)
-	-	-	-	-	-	-	-	-	**Overall landfill score: 74**

2.5 Phase 5: Prioritise landfill sites with potential greatest impact on MPA habitat features

In order to determine which landfill sites pose the greatest threat MPA marine habitat features, a final scoring matrix was applied (Figure 6). This was used to combine scores from the risk of waste being released from the landfill sites (i.e. Phase 1 of the method) and the vulnerability of the features within the zones of impact, should the waste be released (i.e. Phase 4). This resulted in a level of overall threat each landfill site poses to MPA habitat features in Wales.

Risk of waste release from a landfill	Vulnerability of MPA features to the waste released from a landfill: High	Medium	Low
High	High	High	Medium
Medium	High	Medium	Low
Low	Medium	Low	Low

Figure 6. Matrix for determining the overall threat to MPA marine habitat features for each landfill site.

2.6 Phase 6: Assess potential impact under different epochs

The likelihood of Authorised and Historic coastal landfill sites flooding, or eroding is increasing due to climate change. Climate change predictions for the coastal zone include increases in sea level and in the magnitude and frequency of coastal storm surge events. As a result of these, the risk of coastal flooding could increase by a factor of ten by the 2080s and with it, coastal erosion (IPCC, 2013). Accordingly, over time it is increasingly likely that coastal landfills will be inundated by saline waters, thereby increasing leachate production. Solid waste is often fully contained and isolated from the marine environment by lining and capping materials and often protected by flood defences (Brand & Spencer 2018). However, landfills and their defences are increasingly at risk of breaching, because inundation will increase the probability of failure through erosion or excessive seepage (Bujis et al. 2007).

In order to account for the increased risk to landfills presented by climate change, the assessment undertaken in Phases 1-5 was repeated for a medium-term (2025-2055) and long-term (2055-2105) epoch, taking into consideration:

- The potential future position of the coast during each epoch due to erosion, based on mapping set out in the National Coastal Erosion Risk Mapping (NCERM) (with the SMP2 policy in place);
- Future flooding extents. These were based on two datasets: for the medium-term epoch, the NRW Tidal CC50_1000 dataset was used which covers flooding extent and takes into consideration sea level rise for 2070. For the long-term epoch, NRW (2022) Flood Map for Planning Flood Zone 2 & 3 extents were used which take into consideration sea level rise to 2120; and
- The SMP2 policy. This was based on the change in the SMP policy under each epoch from the SMP2 datalayer (NRW 2019b).

2.6.1 Emission scenarios

NRW's data, used to predict coastal flood risk in the present (FRAW), medium term (NRW Tidal CC50_1000 dataset) and long term (Flood Map for Planning), is based on a combination of UKCP09 and the latest projections from the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (IPCC, 2014). This provided a single uplift value for all of Wales (rather than regional variations) for each Climate Change scenario. In this case, for future flooding scenarios NRW used the Climate Change Central estimate. This data used to predict coastal flooding pre-dates the publication of UKCP18 (Met Office Hadley Centre, 2018) when Representative Concentration Pathways (RCP) replaced the emission scenarios used for UKCP09 (Hadley Centre for Climate Prediction and Research, 2017).

The NCERM dataset used to predict the coastal erosion in the present, medium and long term predates the UKCIP18 projections. For soft cliff frontages, the NCERM default approach provided the facility to incorporate Sea Level Rise (SLR) as an increase in the baseline (historic) recession rate taken from the Futurecoast data set (DEFRA 2002; Environment Agency 2018). This additional rate was based on a modified version of the Bruun Rule (as presented in the Soft Cliffs Manual, Defra/EA 2002), to take some account of sediment budgets. NCERM considered complex cliffs separately and, while incorporating the assessment of historic and future erosion rate, the analysis included a more event triggered cliff failure assessment, generating (episodic) recession potential lines. For complex cliffs, other climate change factors (e.g., rainfall) were highlighted but not explicitly factored in. No SLR factor was included for non-cliff frontages.

2.7 Phase 7: Identify potential management measures to reduce impact of coastal landfills on MPA habitat features

A literature review of potential management measures was undertaken. This included, where available, the costs (time, resources and money) required for implementing the management measure.

3 Results and discussion

3.1 Landfill characteristics

In total, there are 1632 individual authorised and historic landfill sites across the whole of Wales. Based on flooding and coastal erosion in the present day, 265 of these sites are at the coast and have the potential to release waste directly into the marine environment. This increased to 306 and 332 landfill sites in the medium (based on 2070 predictions) and long-term (based on 2120 predictions) epochs, respectively. This was due to the increase in landward extend of coastal erosion and coastal flooding in the future epochs.

The most common waste type contained within the landfill sites was HIC (approximately 80-90% of landfill sites contained this waste type across the three epochs), followed by Inert waste (55-65%), Special (hazardous) (20%) and liquid sludge (1-2%). The most common pressures which impacted MPA habitat features were abrasion and chemical contamination. Abrasion accounted for approximately 40% of the pressures being exerted, and chemical contamination accounted for 30%. This likely reflects the high number of landfill sites which contain HIC and/or Inert waste for which chemical contamination and abrasion are common pressures likely to arise.

High concentrations of coastal landfill sites in Wales tended to exist predominately around urbanised or industrialised areas, notably around the Dee Estuary in north Wales, and Burry Inlet, Swansea, Cardiff and Newport on the south coast (see Section 3.2.2). In addition, the landfill sites in the Dee Estuary, Burry Inlet Cardiff and Newport are all within estuarine environments which are typically areas with higher concentrations of MPAs and as a result MPA features. Coastal landfill sites were generally sparse on the west coast of Wales between the north coast of Milford Haven and the Llŷn Peninsula. This area contains approximately only 10-11% of the number of the coastal landfill sites considered in this assessment.

The transportation of waste within in an estuarine environment is different to the open coast. In estuaries, there is a bi-directional freshwater-seawater flow which can lead to the accumulation of material in these systems (Pinheiro et al., 2021). This is compared to the open coast where there is a more uni-directional flow of material. Hence waste released from a coastal landfill site in estuaries has the potential to be contained in estuaries for longer periods of time and potentially at higher concentrations than on the open coast where it would be distributed further. Due to the combination of a high concentration of coastal landfill sites around estuaries (e.g. around the Dee Estuary, Burry Inlet, and Cardiff and Newport in the Severn Estuary), and the potential accumulation of waste in estuarine environments, these areas should be the focus of future investigation.

3.1.1Risk of waste release scores

There was a wide range of risk of waste release scores, ranging from 14-36 in the present day and 18-37 in the medium-term and long-term epochs. The landfill sites which scored the highest tended to be in high flood risk areas, were undefended and had a large, exposed boundary to wave impact. These sites were also often in areas with typically high susceptibility to erosion with a low distance to Mean High Water Springs (MHWS). Landfill sites which scored the lowest tended to be defended with defences in fair or good condition, and a small, exposed boundary.

Overall, most landfill sites occurred within Shoreline Management Plan (SMP) policy units with a Hold the Line (HTL) policy (Figure 7). This is reflected by the high number of landfill sites which tended to occur in densely populated areas (Section 3.1). However, it is important to note that whilst the SMP policy is HTL, more than 30% of the landfills within this SMP policy were regarded as undefended (i.e. the defence was not regarded as protecting the landfill site from flooding or erosion). Whilst a landfill site may be located within a HTL policy unit, there is no guarantee that they will be protected or that funding will be available (Beavan et al., 2020). This is particularly the case as funding for defences often prioritises the protection of human life or development (Wadey et al., 2019; Nicholls et al., 2021).

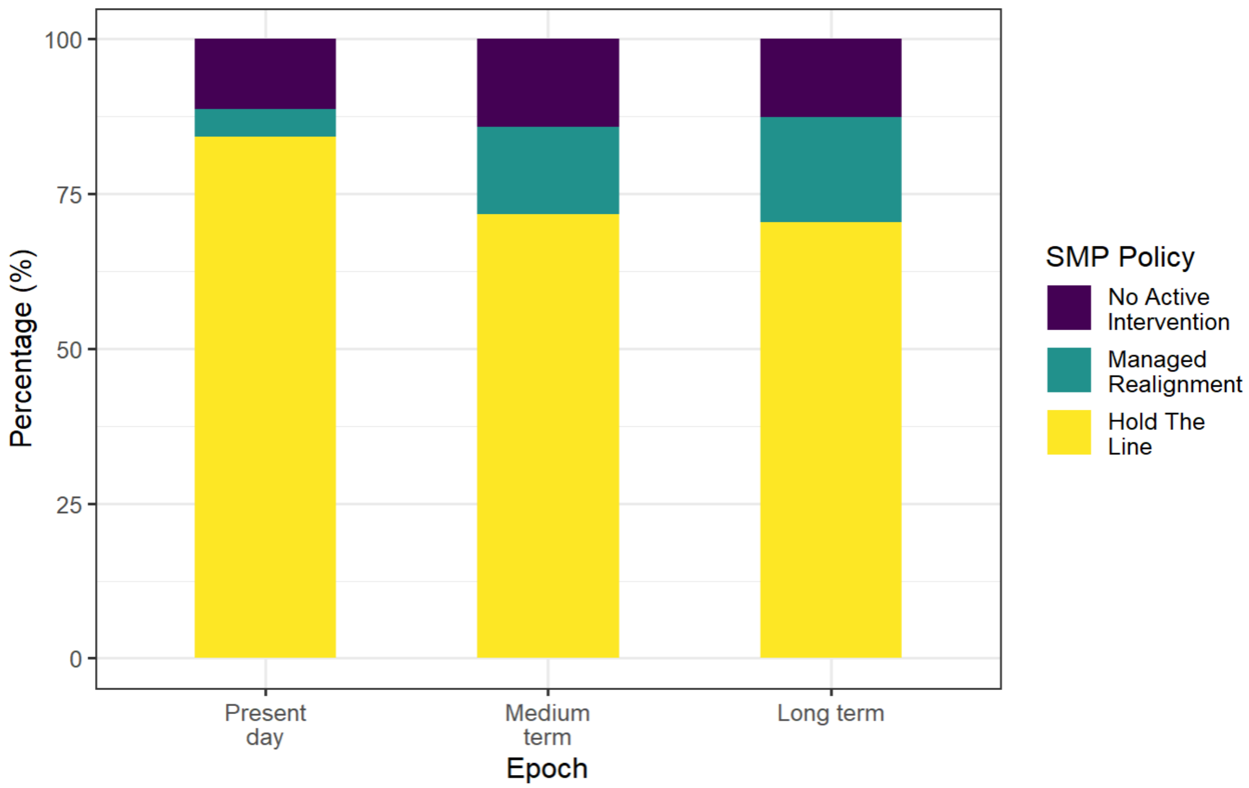


Figure 7. The percentage of landfill sites in each epoch within each Shoreline Management Plan (SMP) policy type

The proportion of landfill sites within the HTL policy decreased in the medium and long-term epochs with a shift away from HTL policy and towards managed realignment. Nicholls et al. (2021) stated that the presence of landfill sites could constrain decisions on how best to manage the coastline, particularly with sea level rise. Therefore, where No Active Intervention or Managed Realignment policies could be appropriate from a coastal processes perspective, it may not be appropriate where landfills sites are at high risk to coastal erosion or flooding (Wadey et al., 2019).

In the present assessment, coastal landfills fronted by saltmarsh habitat were given a lower risk score as saltmarshes can significantly dissipate wave energy and reduce the risk of defences being overtopped or breached (Möller and Spencer 2002; Committee on Climate Change 2013). However, the presence of saltmarsh did not correlate with a lower overall risk of waste release or the overall threat to MPA features (due to the coastal landfill sites often scoring poorly on flood defences and being in areas at high to flooding and erosion). In order to assess the level of protection saltmarsh provides to coastal landfill flooding, it would be useful to investigate in more detail the coastal physical processes in these areas. Whilst existing saltmarshes may lead to some protection of coastal landfills, it is worth noting that saltmarshes are often MPA features and their condition could be impacted if waste is released from nearby landfill sites. Therefore, landfills at these locations should not necessarily be a lower priority for management.

3.2 Threat of landfill sites to MPA habitat features

3.2.1MPA screening

All 139 MPAs around Wales were screened into the assessment. This was primarily due to both the coastal nature of the majority of the MPAs and the distances/extents of the zones of impact. For example, the zone of impact assumed for buoyant solid waste was more than 20 km due to the large distances waste such as marine plastic can disperse from points of introduction. However, it should be acknowledged that the impact from buoyant waste at over 20 km will likely be minimised due to the low concentrations of the waste at these distances.

Although all MPAs were screened in, an assessment of the vulnerability of mobile species features was not possible (see Section 2.3.2). It is important to highlight that the species features within these MPAs have the potential to be impacted either directly or indirectly by waste if released from Welsh landfill sites. However, more detailed investigations are needed into species sensitivities to landfill waste, how they may come into contact with the waste or how the waste may directly and indirectly impact them.

3.2.2Overall threat to MPA habitat features

Overall, the proportion of coastal landfill sites which posed a medium or high threat to MPA habitat features increased after the present-day epoch. For example, the proportion of coastal landfills sites which pose a medium threat to MPA features increased by 10% between the present day and medium-term epochs (Table 6).

Table 6. The number and proportion of coastal landfill sites which have the potential to release waste into the marine environment which present a high, medium or low threat to MPA habitat features in Wales. The total number of coastal landfill sites which have the potential to release waste into the marine environment are provided (n).

Overall threat to MPA habitat features	Number (proportion) of coastal landfills in present day epoch (n = 265)	Number (proportion) of coastal landfills in medium-term epoch (n = 306)	Number (percentage) of coastal landfills in long-term epoch (n = 332)
High	53 (20.0%)	71 (23.2%)	76 (22.9%)
Medium	95 (35.8%)	140 (45.8%)	154 (46.4%)
Low	117 (51.7%)	95 (31.0%)	102 (30.7%)

To identify potential key areas of landfill sites which may require further investigation, the overall threat of landfill sites to MPA habitat features was summarised for each Welsh Operational Area (Figure 8, Figure 9).

Across all epochs, South Wales Central Operational Area contained the highest total number of coastal landfill sites at risk of releasing waste to the marine environment compared to the other Operation Areas in Wales. Whilst there is a high number of landfill sites in South Wales Central, it contained sites which were of medium to low threat to MPAs (Figure 9). This is similar to South East Wales Operation Area where the majority of landfill sites presented a medium to low overall threat to MPA features.

The majority of landfill sites in South Wales Central and South East Wales were concentrated around Cardiff, Rumney and Newport (Figure 10 and Figure 11). Around Cardiff and Rumney there were over 70 coastal landfill sites, and over 40 around Newport. These coastal landfill sites were generally well protected with embankments and walls in ‘good’ and ‘fair’ condition, potentially due to the areas being densely populated. In addition, the vulnerability of MPA habitat features to waste being released from these coastal landfill sites was generally medium. Whilst these coastal landfill sites may not present the highest threat to MPA features, there is a high concentration of coastal landfill sites in this area, and therefore there is the potential for multiple landfill sites to release waste at one time with flooding or erosion.

South West Wales Operational Area contained the largest number of coastal landfill sites with a high overall threat to SAC and SSSI habitat features across each epoch (Figure 9). The majority of landfill sites in South West Wales, including those which pose a high overall threat to MPAs, occurred around the Burry Inlet (Figure 12) and Briton Ferry in the River Neath. The landfill sites in these areas were predominately undefended, in areas with a high susceptibility to erosion and surrounded by a high concentration of MPA features.

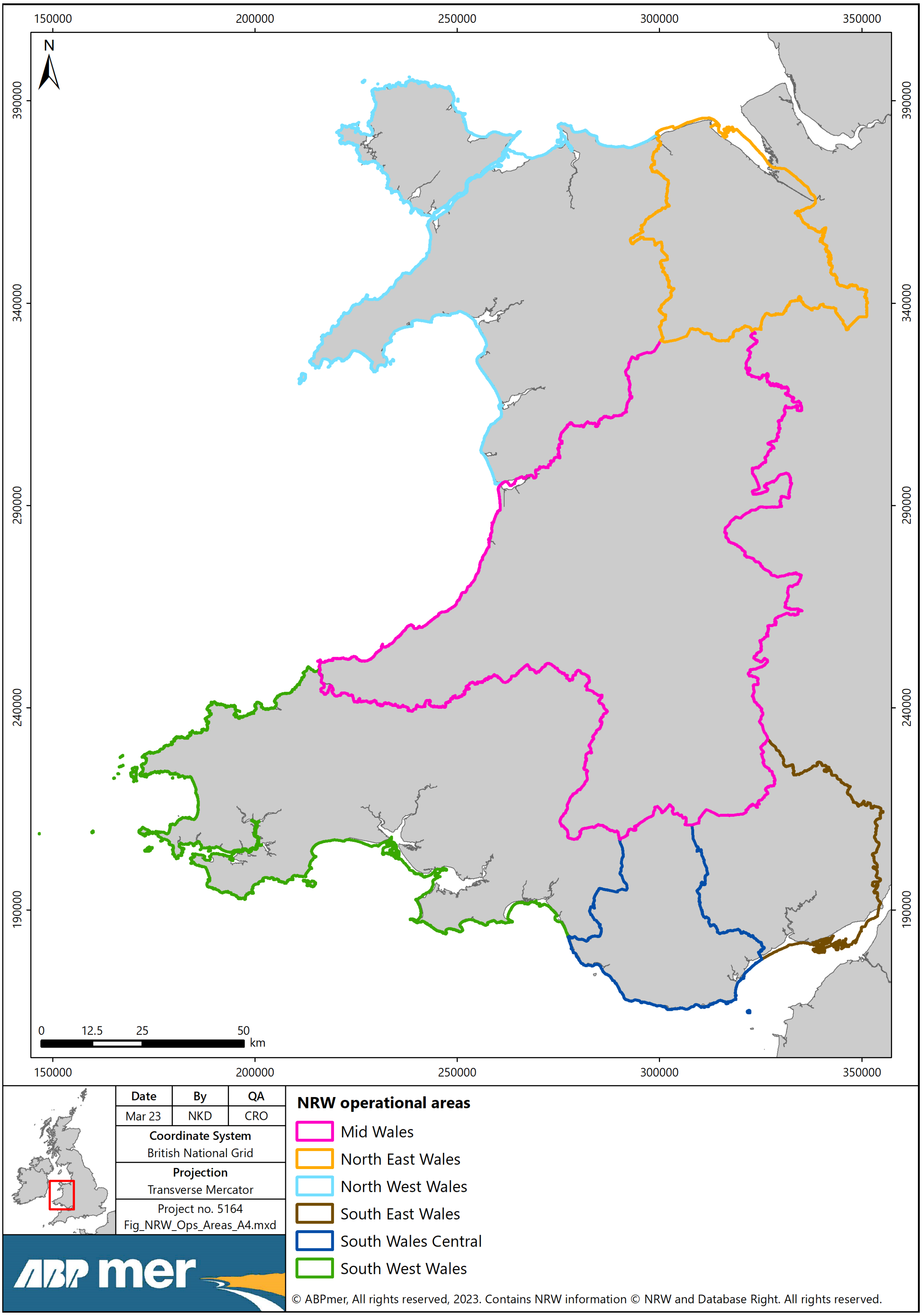


Figure 8. Welsh Operational Areas

Coastal landfill sites in the North West Wales Operational Area were assessed as having a high proportion of landfills with a high overall threat to MPA features in the medium and long-term epochs (Figure 9). However, these sites were relatively sparse with the highest concentration of landfill sites around Llandudno, Conwy and up the River Conwy where there are approximately six to nine landfill sites. The sites which presented a high overall threat to MPA features were scattered along the coastline with no clear concentrations highlighting particular hotspots. However, any coastal landfill sites which presented a high overall threat to MPA features should be investigated further.

In the North East Wales Operational area, the majority of landfill sites in this area were concentrated around the Dee Estuary (Figure 13). In addition, the majority of coastal landfill sites which presented a high overall threat to MPAs in this Operational Area were also along coast of the Dee Estuary. These landfill sites were generally undefended, or protected by high ground, and had a high susceptibility to erosion. Hence the landfill sites in this area could be the focus of further site-specific investigations.

Mid Wales Operation Area contained the fewest number of coastal landfill sites at risk of releasing waste to the marine environment (Figure 9), totalling between nine in the present day and 12 in the long-term epoch. Landfills in Mid Wales were relatively sparse with the highest concentration of coastal landfill sites in Mid Wales occurring in Aberystwyth where there are up to six coastal landfill sites at risk of releasing waste.

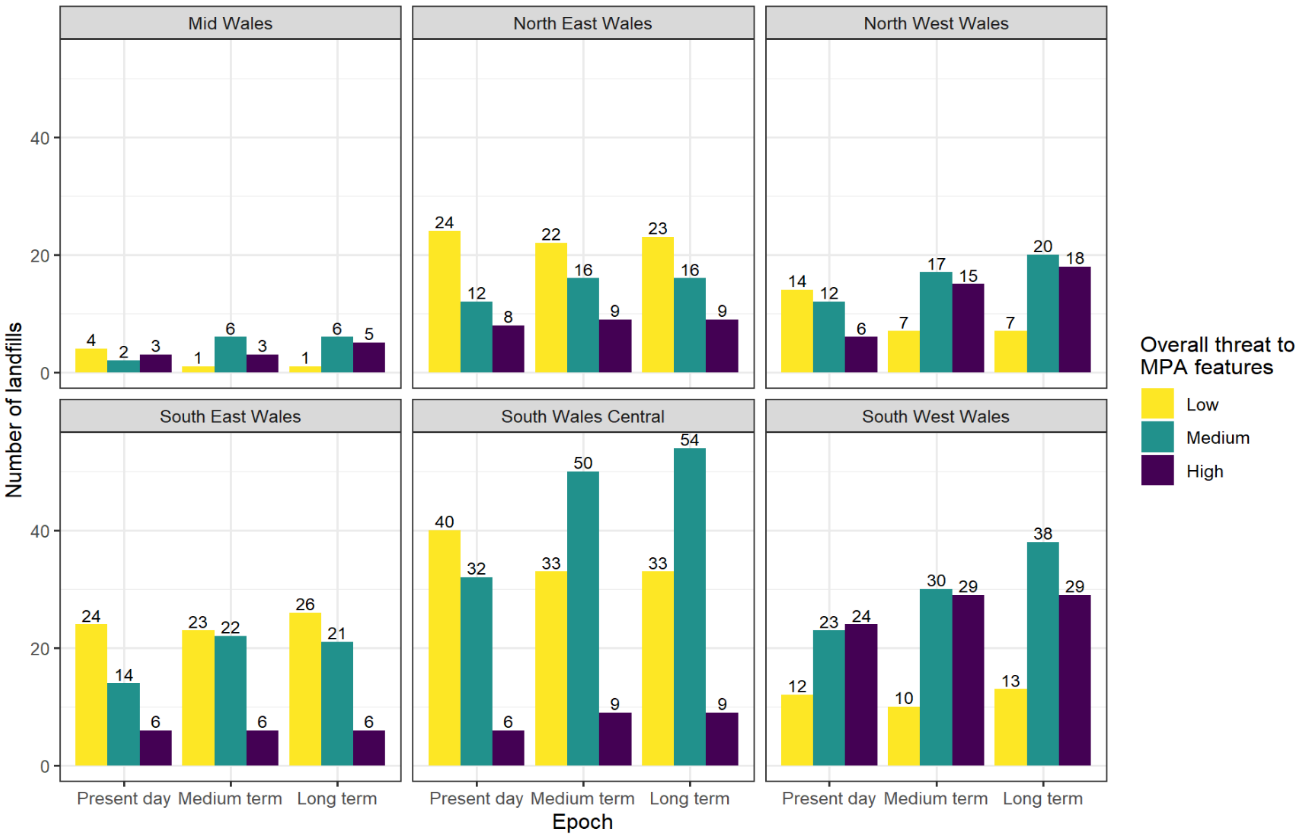


Figure 9. The overall threat of landfill sites to MPA habitat features in each Welsh Operational Area. The number of landfills in each Operational Area during each epoch and overall threat to MPA category is provided above each bar in the chart.

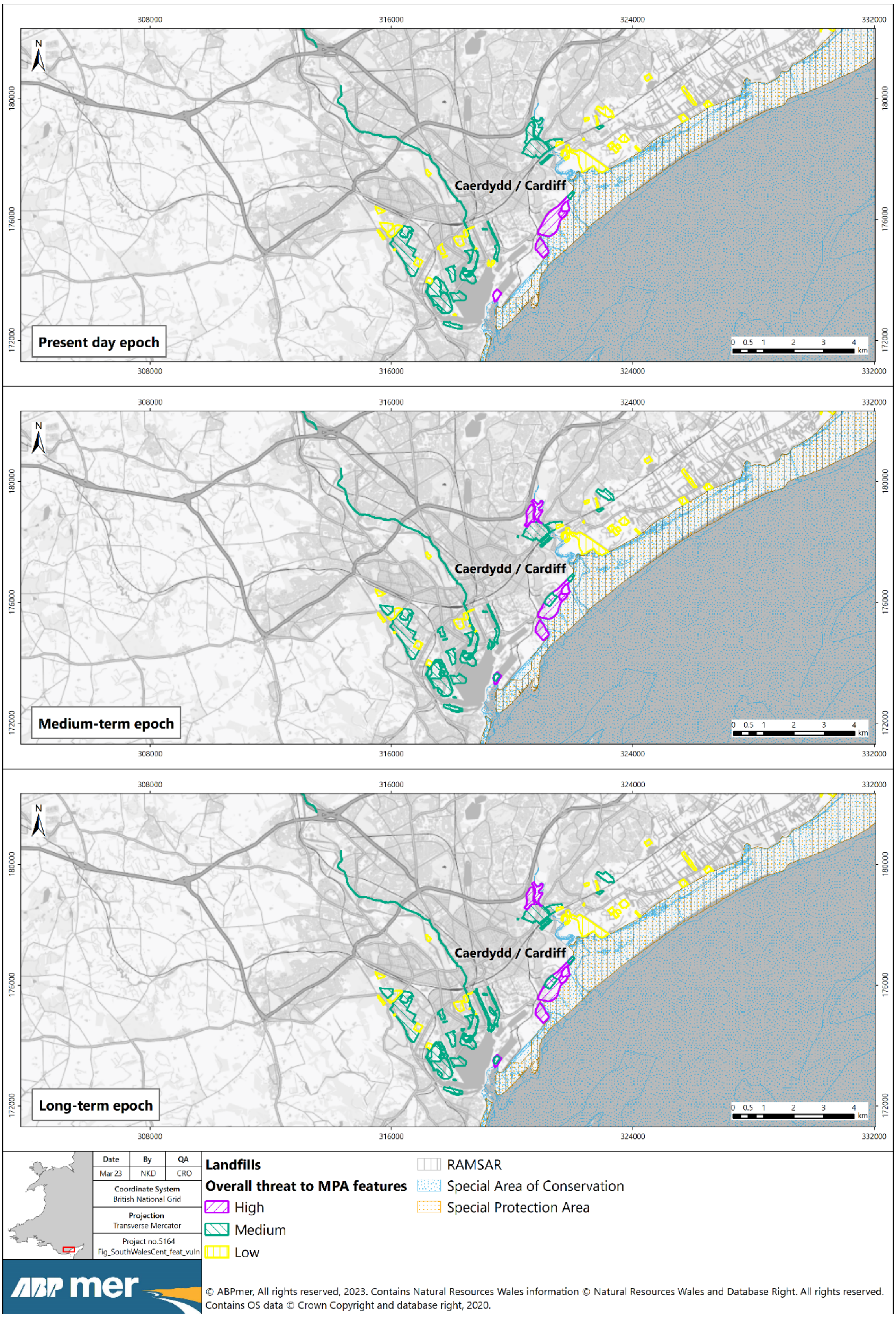


Figure 10. An example of the overall threat of landfill sites to MPA features in the South Wales Central Operation Area (showing concentrations of landfill sites around Cardiff and Rumney) in present-day, medium-term and long-term epochs.

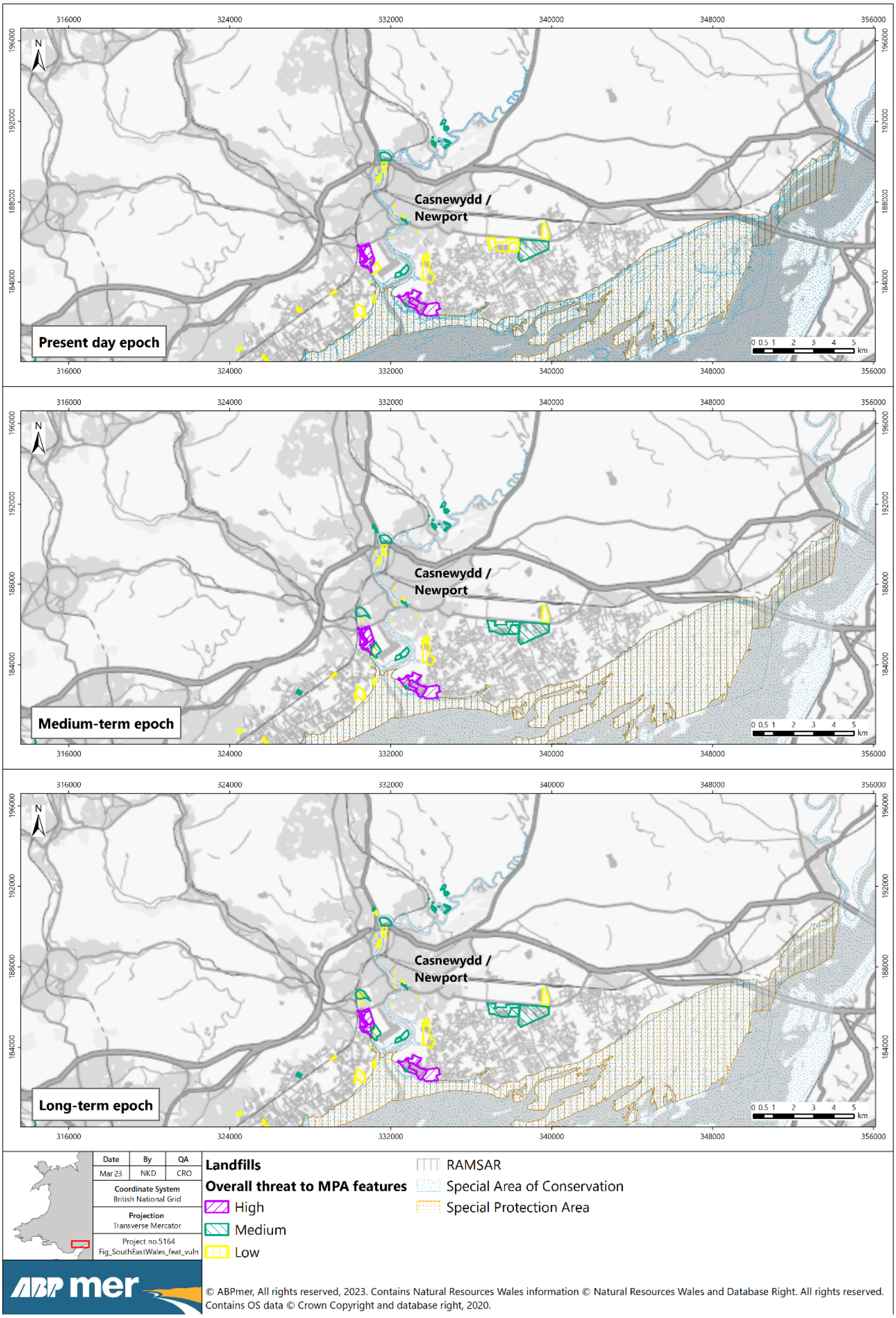


Figure 11. An example of the overall threat of landfill sites to MPA features in the South East Wales Operation Area (showing concentrations of landfill sites around Newport) in present-day, medium-term and long-term epochs.

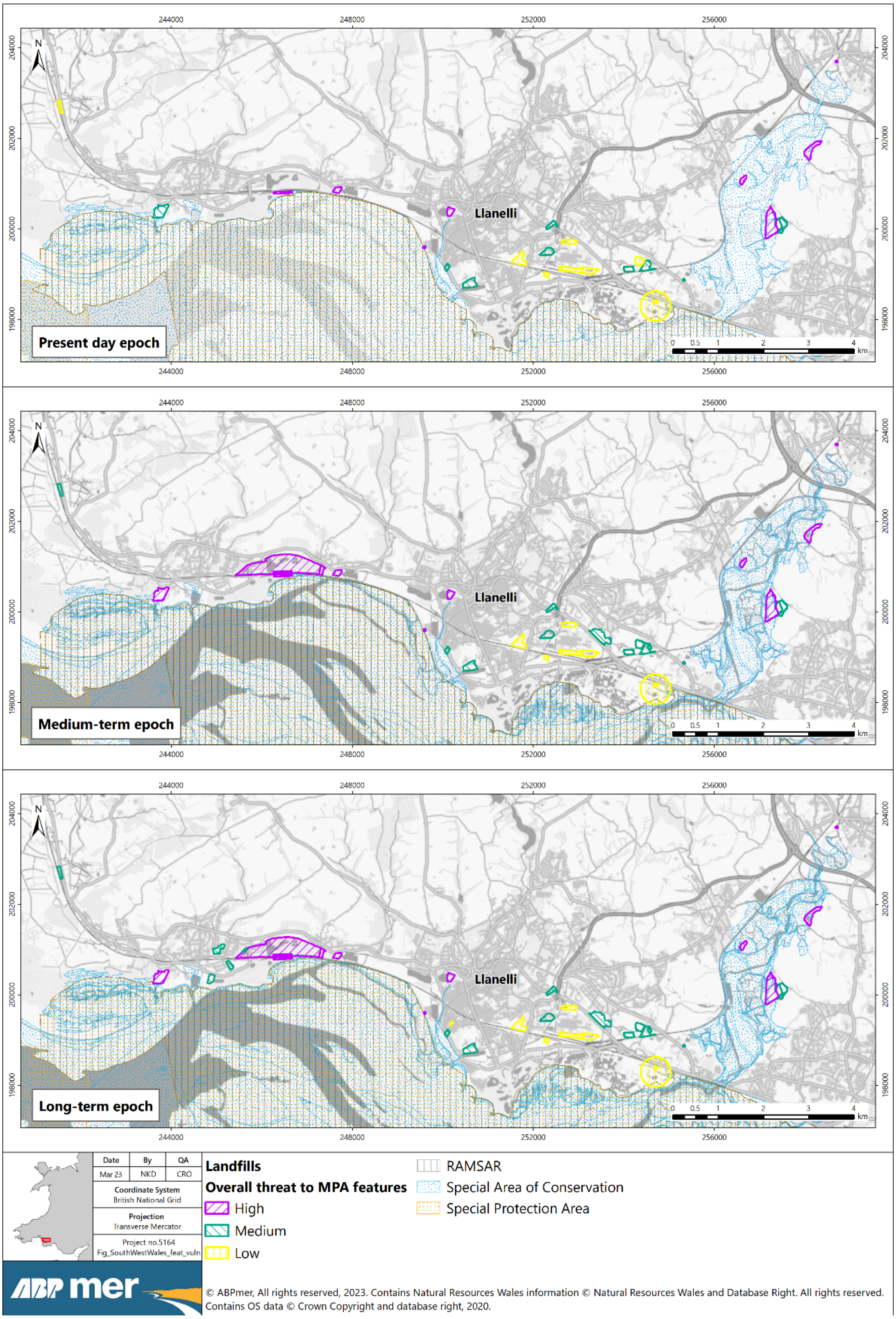


Figure 12. An example of the overall threat of landfill sites to MPA features in the South West Wales Operation Area (showing concentrations of landfill sites around Burry Inlet) in present-day, medium-term and long-term epochs.

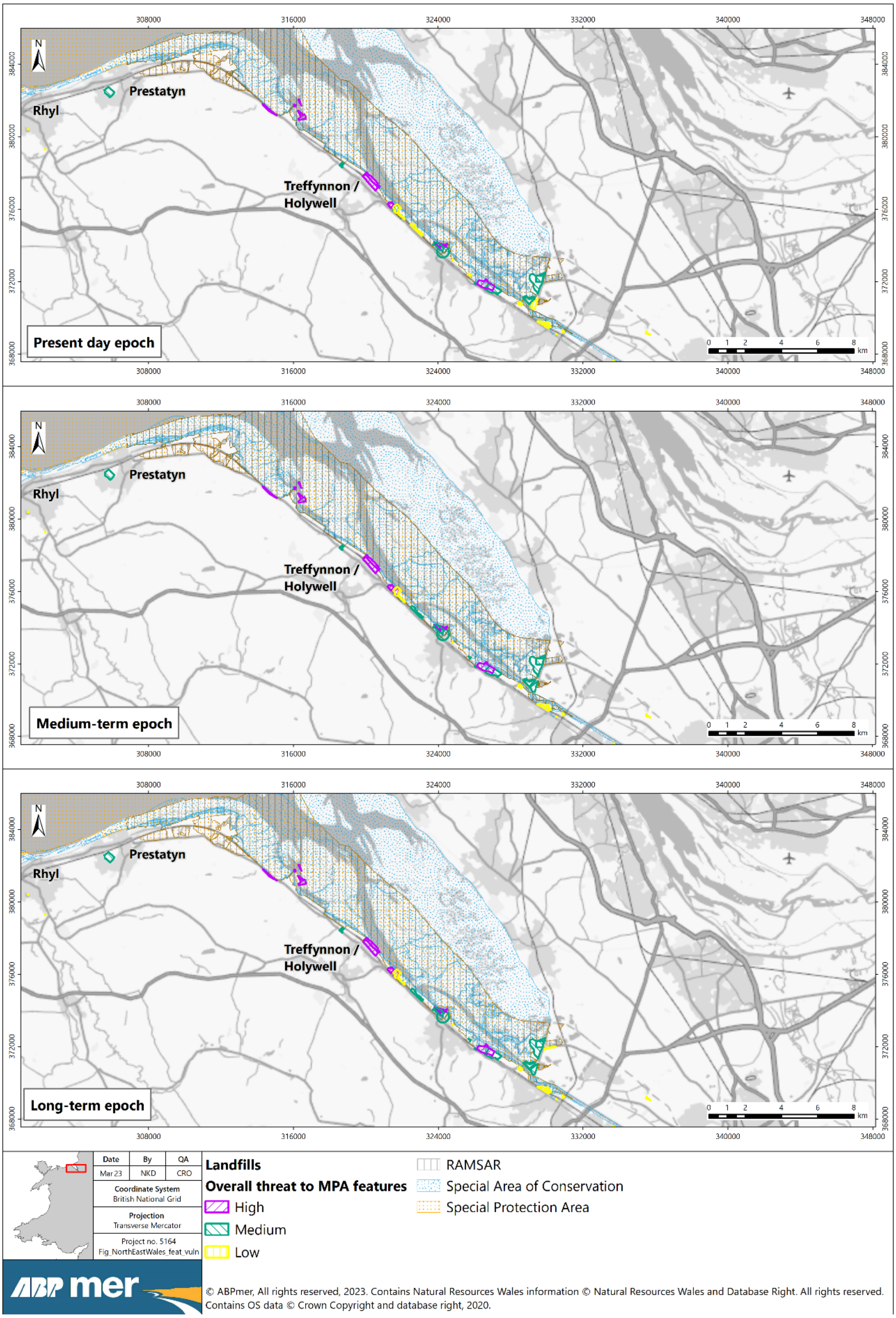


Figure 13. An example of the overall threat of landfill sites to MPAs in the North East Wales Operation Area (showing concentrations of landfill sites around the Dee Estuary) in present-day, medium-term and long-term epochs.

The MPA features deemed most at risk to the release of waste from coastal landfill sites were Estuaries and Reefs, with Sand Influenced Biogenic Reefs (SSSIs), Mudflats and Sandflats, and Atlantic Salt Meadows also being at high risk compared to the other MPA features assessed (i.e. intersected the highest number of zones of impacts). These features, particularly Mudflats and Sandflats, Sand Influenced Biogenic Reefs and Atlantic Salt Meadows are intertidal and hence were likely to be within the high intensity zones of impacts of coastal landfills.

It is likely that Estuaries and Reefs were assessed as most at risk due to the large spatial extent of these features compared to other features and hence intersected a large number of coastal landfill zones of impact. In addition, high concentrations of coastal landfill sites are situated on estuaries in Wales and hence may lead to these features being at a higher risk. Estuaries and Reefs were also considered to be highly sensitive to arrange of pressures which have the potential to arise from the release of landfill waste (Table 3).

Perennial Vegetation of Stony Banks, Annual Vegetation of Drift Lines, Chalk and Very Soft Rock (SSSI) were deemed the least at risk to the release of waste from coastal landfill sites. Perennial Vegetation of Stony Banks and Annual Vegetation of Drift Lines in Wales are mostly situated along the west Wales coastline where less than 10% of coastal landfills are situated. Chalk and Very Soft Rock is only designated at two SSSIs in Wales which are located away from the main coastal landfill hotspots, therefore, this feature may not have intersected many coastal landfill site zones of impact.

4 Assumptions and limitations

It is important to consider the results of this high-level assessment in the context of the large number of assumptions and limitations which were made during the analysis. These are summarised below:

- The approach to the assessment assumed that landfills with more than one type of waste present a higher risk than those with only one waste type.
- The specific information on exact waste type and quantity contained in each landfill site, as well as the levels of contamination (volume and concentration) are lacking for many sites. Such information would allow the assessment to be further tailored to regional or site level investigations, regarding the types of pressure arising from the waste or sensitivity of MPA features.
- Information on landfill engineering could not be included due to a lack of data. Engineered landfalls (such as those with capping or lining) have the potential to limit waste release. This should be included when undertaking site-specific investigations.
- There wasn’t scope in this project to include a detailed analysis on where the waste for each landfill site could end up (the Zone of Impact), hence the Zones of Impact used in the assessment are relatively crude. Site-specific investigations should examine local hydrodynamics and wind driven processes to further refine estimates of where waste could theoretically travel to and potential concentrations.
- Feature sensitivity was based on literature from MarESA which is not tailored towards landfill waste. In addition, sensitivity in this assessment was high-level/precautionary and some habitats within the features may not be as vulnerable as assumed. Expert

judgement was also applied, primarily because there was a lack of literature around the specific impacts of landfill waste on habitats and species.

- The assessment has not taken into account all interactions with climate change which may change the risk profile for waste release from landfill sites. Factors not considered include the additional risk from increased extreme weather/storm surges. Climate change may also affect the sensitivity of habitats and species to landfill waste.
- The assessment has not accounted for the interactions between different types of waste, particularly the interactions between different chemical contaminants, or the interaction between different / in combination pressures arising from the release of waste.
- The assessment has not taken into account the quantity or timescale for waste release. Waste could be released in a large amount over the short-term frame or in small amounts over the long-term. When large quantities of harmful substances are released into the marine environment, there could be an acute impact leading to large-scale mortality of organisms such as invertebrates and fish. However, lower quantities of release could also lead to long-term chronic effects due to the accumulation of pollutants within the organism.
- Landfill sites on the adjacent English coast, for example around the Severn Estuary, Bristol Channel and Dee Estuary were not considered in this assessment, however, they have the potential to negatively impact Welsh MPAs if waste were to be released.
- The impacts of coastal landfill sites on air quality were not included in this assessment. However, this should be considered in future assessments.
- The assessment has only looked at coastal landfill sites at risk of releasing waste directly into the marine environment from coastal flooding or erosion. It is important to consider that waste could be introduced from other landfill sites via rivers and transported by the wind. Hence there is likely a level of threat posed to MPA features from landfill sites not assessed in this study.
- Only known and previously licenced landfill sites were included in this assessment due to availability of data, however, it is important to acknowledge that other types of potentially contaminated land have the potential to present a threat to MPA features. More data are needed on the location of these areas and the threats they could pose to MPA features.

Although the assessment undertaken in this study was relatively high-level, it has identified areas and coastal landfill sites which present a potential threat to MPA features both now and in the future. The assessment has highlighted areas which could be the focus for further regional or site-specific investigation, for example around the Burry Inlet, Dee Estuary, and Cardiff and Newport in the Severn Estuary where the concentration of coastal landfill sites is high and where there is a higher proportion of landfill sites which pose a high overall threat to MPA habitat features. The coastal landfill sites in these areas may require management to reduce the risk of waste being released or reduce the impact of waste release on habitats and species. However, any coastal landfill sites which presented a high overall threat to MPA features should also be investigated on a site-by-site basis. As MPA species features were not considered in the prioritisation of coastal landfill sites, it is important to acknowledge that the overall threat of the landfill sites could change depending on protected species distributions, how they come into contact with landfill waste, and their level of sensitivity to landfill waste.

5 Potential management options

5.1 Review of management options

A range of management measures have been identified in the literature with the aim to mitigate against the potential impacts of landfill sites on the environment. These focus primarily on reducing the likelihood of waste being released in solid and leachate forms into the environment. These management options include:

- Removal of landfill waste;
- Coastal protection;
- Treating contamination;
- Novel approaches; and
- Inspection and surveillance.

Management of landfill sites is likely to be site specific, depending on factors such as current and future management already in place (e.g. respective SMP policies and implementation), the content and size of the landfill site and physical processes impacting the sites.

5.1.1 Removal of landfill waste

Removal of landfill waste

Removal of landfill sites by relocating the waste has the potential to directly remove the pressures on the marine environment associated with landfill. Relocating landfill waste to another landfill site would be subject to the landfill tax, with the standard landfill tax costing £98.60 per tonne in Wales for 2022 and 2023. A lower tax rate is applicable to landfills with waste that has the least potential for pollution (£3.15 per tonne), including qualifying materials under Schedule 1 of the Landfill Disposals Tax (Wales) Act 2017 (inc. non-hazardous material such as rock and soil, concrete or ceramic, processed minerals and low activity inorganic compounds). Beaven et al. (2020) described this option as economically unviable for large landfill sites due to the cost of the landfill tax in addition to the costs associated with the waste excavation, transportation and disposal of the waste. For example, Beaven et al. (2020) estimated that the relocation of all the waste from Wicor Cams landfill site in Portsmouth Harbour, which contains an estimated 1 million m^3 of waste, would cost in the region of £149 million in 2019 (£160 million when adjusted to 2022 tax rates) if all waste was taxed at the highest rate. In this scenario, landfill tax would account for 75% of the total costs. If only 30% of the waste attracted the highest rate of tax, it was estimated to cost around £75 million (£77 million when adjusted for 2022 tax rates).

Landfill waste removal has been undertaken in France at the Dollemard landfill, sited on top of an eroding cliff north of Le Harve (Nicholls et al., 2021). This landfill site, which contained inert waste along with plastics, rubber and metals, was estimated to be releasing 30 m^3 of plastic and metal onto the beach per year. Cleaning operations on the beach prior to landfill removal had cost the local authority approximately €22,000 per year since 2009. The cost of removal was estimated at €20 million (including landfill tax of €35 per tonne).

Removal of landfill waste could be considered for smaller landfills or landfills with material taxed at a lower rate, however, these types of landfills are likely to be of lower priority for management. The location of the landfill can limit the scope for total removal of landfills, for example, removal of waste from landfills located on unstable cliffs and near landslips would likely be considered impractical for safety reasons (Cooper et al., 2012).

Cooper et al. (2012) mentioned that removal of waste would require serious consideration in terms of the acceptability of excavating and transporting the waste to an alternative site and the associated environmental, health and safety issues. In addition, they mention that if material is excavated, the remaining void may leave the remainder of the site in an unstable condition or at increased likelihood of sea flooding, therefore, the impacts of excavation need to be thoroughly assessed. A survey of local authorities who own or are involved in managing coastal landfill sites in England showed that removal of landfill sites was considered to be the best long-term solution, however, it can take decades to achieve (Adams and Stratton, 2022).

In Wales, there is relatively limited data on what is contained in landfill sites, particularly in historic sites. However, prior to any removal of waste, it is important to understand the types of waste contained within the landfill site.

Regular waste collection

Where cliffs continue to naturally erode, in some cases the safest option is to remove the waste once it has been deposited on the beach. Beaven et al. (2018) stated that the current management plan by the local authority for the clifftop landfill site Spittles Lane is to remove any waste that reaches the beach due to coastal erosion. Removing waste that has eroded out of a landfill site can be a costly and ongoing process, for example costing €20,000 per year at Dollemard site in France. At Spittle Lane in Lyme Regis, around £60,000 has been spent since 2008 to remove waste and fund regular monitoring of the foreshore, however, no material had been removed since 2012 (Beaven et al., 2018). It is worth noting, however, that once waste arrives on the beach, it is within the marine environment and may impact MPA features. Removal on the beach may only reduce the amount of waste entering the sea. Removal of waste could be dangerous in situations where a cliff is unstable or during storm events or high tide when the highest amount of waste could be released. In addition, attending landfill sites affected by coastal erosion or flooding attending may not be a priority if erosion or flooding are a danger to, for example, human life.

In Wales, the release of waste into the marine environment from a landfill site would likely lead to an incident response from NRW. The Incident Management Enabling Plan 2015-2020 (NRW, 2015) states that incident plans aim to deliver an effective response to environmental incidents, including pollution events and floods. The response would depend on the scale, location, type of waste and quantity of the waste coming out of the landfill. However, the Incident Management Enabling Plan states that the primary objective is it prevent/reduce the likelihood or severity of an incident occurring, or improving preparedness if an incident does occur, which is likely cheaper than dealing with a major incident when it occurs. Hence it is useful to understand where serious incidents could occur. There is the potential that it is cheaper and easier to prevent incidents occurring.

Landfill mining

Landfill mining can be used to remove the most toxic material and potentially allow the more inert material to erode (Nicholls et al., 2021). In addition, mining could also be used to remove recyclable materials. This has the potential to limit the impact of the pressures which could arise if waste were released from a particular landfill site. However, the cost of removing material (including landfill tax for re-disposal) would likely make this management measure costly. Landfill mining has also been acknowledged as a potential source of obtaining valuable materials, such as metals, which are in limited supply for technology.

5.1.2 Coastal protection

In a recent survey of local authorities by the Local Government Association Coastal Special Interest Group (LGA Coastal SIG) and Coastal Group Network, it was found that new defence and protection measures were ranked as the best solution for managing coastal landfill sites, with the removal and remediation of sites ranked second and third, respectively (Adams and Stratton, 2022).

Coastal protection has the potential to directly reduce the risk of erosion or flooding of a landfill site. At Portchester Quay landfill site in Portsmouth Harbour, there is a plan to install sheet pile walls in front of the landfill site to reduce the risk of coastal flooding. However, success in securing flood and coastal risk management grant in aid funding Flood and Coastal Erosion Risk Management Grant in Aid (FCERM GiA) was influenced by the presence of development (400 residential properties and 100 commercial properties in the area), as opposed to the potential release of waste to the marine environment. Other contributions are expected from local levy and private contributions (Wadey et al., 2019).

Adams and Stratton (2022) stated that there are no specific funding mechanisms to deliver coastal protection with the aim of avoiding coastal pollution. In addition, funding for coastal protection, including the implementation of SMP policies tend to prioritise economic features and human life rather than landfill sites. However, landfill sites can be a taken into account in SMPs (for example the North West England and North Wales SMP2 (North West & North Wales Coastal Group, 2010)).

Coastal protection can be costly and requires regular maintenance. For example, at a historic landfill site at Broadmarsh in Havant the current coastal protection - in the form of a 2 km sloped concrete block revetment - has been slowly deteriorating in condition, costing £500,000 in refurbishment over the last 25 years (Wadey et al., 2019). Storms also led to emergency repairs being needed in 2015/2016 which was part funded by the FCERM GiA (£120,000) and Havant Borough Council (£50,000). However, the Environment Agency advised that further funding would not be available due to rules stating that Local Authorities were responsible for protecting areas contaminated by previous landfill. It has been recently proposed that a major seawall refurbishment be undertaken to protect the landfill from eroding onto the designated estuary, costing approximately £11 million. It should be noted, however, that in some circumstances coastal protection can lead to problems with coastal erosion on other parts of the coastline.

Coastal adaptation, including managed realignment or coastal habitat restoration and enhancement projects, which aim to restore and improve the condition of natural defences, such as saltmarsh, also have the potential to protect landfill sites from erosion whilst offering other benefits, such as providing a sink for pollutants, carbon sequestration and storage, and habitat. Saltmarsh restoration often requires regular maintenance in order to be effective, for example maintenance of polders to trap sediment, and hence can be a relatively costly management measure. It is worth nothing that future sea level rise has the potential to impact the extent of such natural defences, particularly where they are unable to migrate inland (coastal squeeze). Depending on the circumstances and the position of the landfill on the coast, managed realignment may not be appropriate as it could directly impact the landfill site and advance the impacts of coastal erosion or flooding (Wadey et al., 2019).

5.1.3Treating contamination

Leachate management

Modern environmental permits for landfill sites state the measures in place to manage the leachate produced by the non-hazardous and hazardous waste within the site. Historical landfills in the most part did not have systems in place to capture and treat leachate. These sites worked on a 'dilute and attenuate' model, where landfill leachate was allowed to discharge to groundwater and surface water.

Many different methods are used to treat landfill leachate, typically covering biological treatments and physical/chemical treatments (Cooper et al., 2012; Raghab et al., 2013). Such treatments include:

- Biological treatment – aerobically or anaerobically biodegrade organic components using micro-organisms;
- Soil vapour extraction – use of extraction wells to collect material such as hydrocarbons or metals for removal and treatment;
- Soil washing – process which separates and cleans soils with organic or inorganic contaminants;
- Stabilization and solidification – using reagents to stabilise hazardous components;
- Extraction of chemicals – use of acid or solvents to remove contaminants which is then neutralised using lime to raise the pH;
- Chemical reduction or oxidation – redox reactions used to convert contaminants to more stable or inert substances (used mostly on heavy metals or inorganic material); and
- Thermal desorption – heating contaminated material (up to 550 °C) to convert organic contaminants into gases which are removed and treated (not effective for heavy metal contamination).

Leachates can be transferred for treatment via sewers to sewage works for treatment, or via tankers to sewage works or treatment plants. One estimate of costs for disposal, energy and chemicals used in treatment is around £4 - £10 per m^3 (Pandhal et al., 2018).

Once the leachate is treated and the concentration of contaminants lowered, disposal of leachate can be undertaken which can involve discharging leachates to the sewerage network, by tanker to a wastewater treatment works or through discharge directly to the water environment using passive treatment like reed beds (authorised by the Environment Agency). It is worth noting, however, that such passive treatments require regular maintenance to be effective and therefore can be a costly measure to implement.

Leachate recirculation, which is described by the Environment Agency as ‘the practice of returning leachate to the landfill from which it has been extracted’ has been used widely since the 1970s to treat leachate (Environment Agency, 2009). Recirculation reintroduces the leachate to the surface of the landfill and encourages biodegradation of the waste by raising water content and transporting bacteria and nutrients to the landfill (White et al., 2011).

Treatments can be carried out either on-site or off-site, however, it is acknowledged by Cooper et al. (2012) that off-site treatment facilities can be advantageous. The advantages include not being constrained by space or not having to vary landfill environmental permits to accommodate treatment. However, material treated off-site that is then returned to the landfill site will be subject to a landfill tax.

5.1.4 Novel approaches

Revegetating landfill sites

Whilst landfill sites have been seen as having limited to no value, they can be reclaimed for a variety of ecological and social uses. Grasses are typically used to stabilise the surface of landfill sites and prevent run-off, however, trees and shrubs can be used where considerations are made to limit damage to the landfill surface/cap. Consideration is needed regarding the characteristics of the plant and area for revegetation, including but not limited to the soil and root depth, soil quality, topography, irrigation requirements and size of plant when fully grown.

Forest Research investigated the growth of trees on restored landfill sites and found that a minimum of 1.5 m of soil cover over a mineral cap will ensure trees can be established on landfills without posing a significant threat to cap integrity for at least 16 years (Forest Research, 2008). However, this could change as the trees become larger. Moffat et al. (2008) studied tree planting on UK contaminated landfill sites over a ten-year period. They found that tree survival was similar to that of trees on brownfield sites and growth of trees was similar to growth on greenfield sites.

In Wales, former capped landfill sites on Anglesey and Gwynedd are being restored into over 130 acres in total of varied meadows and woodland for plants and wildlife. This includes the planting of 40,000 trees and shrubs across the sites. A successful restoration has also taken place at the Penhesgyn landfill site on Anglesey (Cyngor Gwynedd, 2022).

A study by Tarrant et al, (2013) found that restoration of grass habitats at UK landfill sites can lead to similar species richness and abundance of plants and similar assemblages of pollinators, and hence they can act as a reserve for native plants and insects.

It is important to note, that it is unknown what potential influence revegetating coastal landfills sites would on the waste being released, where coastal erosion or flooding are the main drivers leading to waste release. More information/research would be required to determine if such approaches can reduce the amount of waste being released if a site is impacted by coastal erosion or flooding.

5.1.5Inspection and surveillance

If a risk assessment for a landfill site concludes that there is presently no or a low level of risk, then inspection and surveillance could be an appropriate management option (Cooper et al., 2012). This could include a plan detailing the frequency of inspection/surveillance to assess whether any maintenance is required to, for example sea walls, embankment or cliffs which protect a landfill site and if their condition changes over time.

Other inspection and surveillance options include regular monitoring of groundwater, leachate or surface water in the vicinity of the landfill site which could aid in assessing the particular pollutants at a site and define actions levels (thresholds that further action would be required).

6 Discussion of management options

The management options reviewed in Section 5 highlights that there are a range of techniques which can be used to mitigate the release of waste from landfill sites. However, the appropriateness of different management options for a particular site will depend on a variety of site-specific factors, such as:

- Waste types and quantities contained within the landfill site;
- Location of the landfill site and the localised site-specific physical processes which may lead to waste release;
- Current engineering at the site used for limiting waste release;
- Current land use at or on top of the landfill site (e.g. household, commercial or industrial use, recreational, open spaces, agriculture (Adams and Stratton, 2022));
- Who is responsible for the landfill site (e.g. local authorities, Government, Ministry of Defence, or privately owned (Adams and Stratton, 2022) and permits/regulations are required for different management activities; and
- Availability of funding.

It is therefore important to acknowledge the importance of site-specific discussions regarding what the most effective approach of management could be for a particular landfill site. It is likely that some landfills, particularly historic ones, will require detailed investigations to determine their contents, current release-rate of waste (such as monitoring leachate with borehole data), as well as the collection of local-scale coastal processes data to understand where waste released from the landfill sites may go. Selection of management options will also depend on the cost effectiveness of implementation at a particular site.

The majority of coastal landfill sites in the current assessment were located in densely population or industrialised areas. Careful consideration will therefore be needed on the appropriateness of certain management measures. For example, if the landfill site has been reclaimed (for example for housing or other developments such as the solar farm on the landfill at Lambey Way (Cardiff News Room, 2019)) it could make certain management options such as landfill removal or treatment of contamination more difficult to implement. In these cases, it might be more appropriate and cost effective to protect these sites from coastal flooding and erosion.

It was found in the survey of English local authorities by Adams and Stratton (2022) that there is often partial/limited or no records of the content of coastal landfill sites held by local authorities, however a similar survey has not yet been undertaken in Wales. In the present study, the specific waste included in the historic coastal landfill sites was generally unknown, therefore, the impacts the waste could have on MPA features was relatively high-level. Given the importance of understanding what waste is contained within a landfill site for determining its potential impact on the marine environment, and hence appropriate implementation of management measures, this should be a priority to investigate. This is particularly the case for landfill sites with HIC waste types or Special (hazardous) waste.

Funding will play a big part in managing these sites as managing landfills can be an expensive process. The availability of funding was identified as the biggest barrier for delivering solutions for coastal landfill sites by local authorities surveyed by Adam and Stratton (2022). Often clarity is needed to understand who is responsible for providing the funding or protection for these sites (Adams and Stratton, 2022), particularly for historic landfill sites where the original owners of the landfill sites may no longer exist (Wadey et al., 2019). In addition, this assessment focussed only on prioritising coastal landfill sites for potential management, however, it is important to consider that there are over 1,500 individual landfill sites across Wales. The large number of landfill sites across Wales has the potential to present further constraints on the availability of resources and funding for managing landfill sites.

The majority of coastal landfill sites in the present assessment were located in areas with a HTL SMP policy. However, the sites tended to be undefended. Whilst a HTL policy has the potential to protect landfill sites from flooding and erosion, it is important to note that funding for implementing these policies, or the upkeep of defences, is not guaranteed. Often funding will be focussed on other factors such as protection of populated areas (Wadey et al., 2019; Nicholls et al., 2021), as opposed to how release of waste from the landfill site will impact the marine environment. It is also important to note that implementation of management measures such as SMP policies (particularly No Active Intervention and Managed Realignment) where landfills pose a high threat to MPA features may not be appropriate.

7 Conclusion

This study provides a high-level assessment for determining which landfill sites at the coast in Wales have potential to pose the greatest threat to MPA features. It has highlighted that high concentrations of coastal landfill sites occur around the Dee Estuary, Burry Inlet and the Severn Estuary in Wales with the Dee Estuary and Burry Inlet in particular potentially having a high overall threat to MPA habitat features. In addition, coastal landfill sites which presented a high overall threat to MPA features are scattered across all Operational Areas in Wales and should be investigated in more detail on a site-by-site basis.

It is recommended that, given the high-level approach to this assessment, the results of the study are used to inform where more detailed investigations should be undertaken on specific landfills or regions of potential concern. Investigations should, for example, aim to ground-truth or gain a more detailed understanding of the different parameters used to characterise the coastal landfill sites, as well as understanding where waste could be transported when released. These further investigations can then be used to better inform the most appropriate management to implement.

Finally, it is important to consider that MPA species features were not scored in this assessment and therefore the threat that coastal landfill sites pose to these features is still relatively unknown. Further work should be undertaken to assess potential impacts of coastal landfill sites on these MPA species features.

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9 Abbreviations

ABPmer	ABP Marine Environmental Research Ltd
ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information System (Software)
BGS	British Geological Society
CIRIA	Construction Industry Research and Information Association
DDT	Dichlorodiphenyltrichloroethane
€	Euro
EA	Environment Agency
EC	European Commission
EcoQOs	Ecological Quality Objectives
EEC	European Economic Community
FCERM GiA	Flood and Coastal Risk Management Grant in Aid funding
FRAW	Flood Risk Assessment Wales
Futurecoast	Futurecoast Project (Defra)
GIS	Geographic Information System
HIC	Household, Industrial, Commercial waste
HTL	Hold the Line
IPCC	Intergovernmental Panel on Climate Change
LGA	Local Government Association
MarESA	Marine Evidence based Sensitivity Assessment
MarLIN	Marine Life Information Network

MCZ	Marine Conservation Zone
MHWS	Mean High Water Springs
MPA	Marine Protected Area
MR	Managed Realignment
NCERM	National Coastal Erosion Risk Mapping
NRW	Natural Resources Wales
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
PAH	Polyaromatic Hydrocarbons
PBBs	Polybrominated Biphenyls
PBDE	Polybrominated Diphenyl Ethers
PCB	Polychlorinated Biphenyls
PCDD	Polychlorinated Dibenzodioxins
PFAS	Per- and Polyfluorinated Alkyl Substances
POPs	Persistent Organic Pollutants
RCP	Representative Concentration Pathway
SAC	Special Area of Conservation
SCOPAC	Standing Conference on Problems Associated with the Coastline
SLR	Sea Level Rise
SMP	Shoreline Management Plan
SPA	Special Protection Area
SSSI	Site of Special Scientific Interest
TBT	Tributyltin
UK	United Kingdom
UKCP	United Kingdom Climate Projections
US	United States
WG	Working Group
ZOI	Zone of Impact

10 Appendices

10.1 Rationale for risk of waste release scoring parameters

Table 7. Rationale for selection of parameters informing the risk of waste release scoring (Adapted from Brand & Spencer, 2018)

Parameter	Justification
Tidal classification	Tidal range influences how vulnerable coastlines are to wave energy (McLaughlin and Cooper 2010) and flooding (Rosendahl Appelquist 2013): the greater the tidal range the lower the probability that high tide and high waves will coincide; hence the probability of wave-related erosion (McLaughlin and Cooper 2010) and the probability of flooding (Rosendahl Appelquist 2013) are reduced.
Flooding	Flooding increases the probability of landfills eroding both due to the movement of water over the site (Laner et al. 2008) and because infiltration of high volumes of water can adversely affect the structural integrity of the waste (Blight and Fourie 2005). The build-up of water pressure behind a flood defence can also cause it to fail, exposing waste (Cooper et al. 2013).
Landfill position	The closer the landfill is to mean high water, the greater the risk of it being eroded.
Exposed boundary	The length of the landfill boundary exposed to wave impact will also influence the probability of waste being eroded.
Geology	The geological composition of coast adjacent to the landfall will greatly influence response to coastal erosion. Erosion susceptibility has been informed using BGS GeoCoast open data which maps a number of geological engineering properties of cliff sections (and low-lying deposits) around the Great British coastline, assigning a susceptibility ranking at 50 m scale around the coast.
Defence condition	The likelihood of coastal landfills eroding and releasing waste is linked to whether there are effective flood defences present. It is important to note that some landfills act as flood defences.
Defence type	The likelihood of coastal landfills eroding and releasing waste is linked to whether there are effective flood defences present. It is important to note that some landfills act as flood defences.
Buffer zone	The presence of vegetated saltmarshes can significantly attenuate the impact of waves upon flood defences, dissipating up to half of the wave energy in the first 10–20 m of saltmarsh surface, reducing the risk of defences being overtopped or breached (Möller and Spencer 2002; Committee on Climate Change 2013).
Shoreline Management Plan	SMPs policies allow either natural processes to progress the erosion of the site, or prioritise protection of people and infrastructure. Where an SMP policy adjacent to a landfill site is ‘hold the line’ it can be assumed that efforts will be made to protect the landfill from erosion. On the contrary, where an SMP policy adjacent to a landfill site is ‘no active intervention’, it is assumed that there is an increased risk of landfills releasing waste due to unmanaged coastal erosion.

10.2Waste type, zone of impact and pressure interactions

Table 8. The characterisation of landfill waste type along with the nature of waste material and associated pressures

Inert landfill waste

Nature of waste material	Pressures with the potential to arise from each waste type and nature of waste material
Heavy solid waste	• Abrasion • Smothering and siltation rate changes (Light) • Smothering and siltation rate changes (Heavy)
Buoyant solid waste	• Abrasion
Suspended / particulate matter	• Changes in suspended solids (water clarity) • Deoxygenation • Smothering and siltation rate changes (Light) • Smothering and siltation rate changes (Heavy)

Household, Industrial, Commercial (HIC) landfill waste

Nature of waste material	Pressures with the potential to arise from each waste type and nature of waste material
Heavy solid waste	• Abrasion • Smothering and siltation rate changes (Light) • Smothering and siltation rate changes (Heavy) • Chemical contamination
Buoyant solid waste	• Abrasion • Chemical contamination

Suspended / particulate matter	• Changes in suspended solids (water clarity) • Deoxygenation • Nutrient enrichment • Organic enrichment • Smothering and siltation rate changes (Light) • Smothering and siltation rate changes (Heavy) • Chemical contamination
Leachate	• Changes in suspended solids (water clarity) • Deoxygenation • Nutrient enrichment • Organic enrichment • Chemical contamination

Special (hazardous) landfill waste

Nature of waste material	Pressures with the potential to arise from each waste type and nature of waste material
Heavy solid waste	• Abrasion • Deoxygenation • Chemical contamination
Buoyant solid waste	• Abrasion • Deoxygenation • Chemical contamination
Suspended / particulate matter	• Changes in suspended solids (water clarity) • Deoxygenation • Nutrient enrichment • Organic enrichment • Smothering and siltation rate changes (Light) • Smothering and siltation rate changes (Heavy) • Chemical contamination

Leachate	• Changes in suspended solids (water clarity) • Deoxygenation • Nutrient enrichment • Organic enrichment • Chemical contamination

Liquid sludge landfill waste

Nature of waste material	Pressures with the potential to arise from each waste type and nature of waste material
Suspended / particulate matter	• Changes in suspended solids (water clarity) • Deoxygenation • Nutrient enrichment • Organic enrichment • Smothering and siltation rate changes (Light) • Smothering and siltation rate changes (Heavy) • Chemical contamination
Leachate	• Changes in suspended solids (water clarity) • Deoxygenation • Nutrient enrichment • Organic enrichment

Table 9. The zones of impact for each nature of waste material. As discussed in Section 2.2.1.

Nature of waste material	Zone of impact
Heavy solid waste (e.g. rubble)	0 – 0.5 km 0.5 – 2 km 2 – 5 km
Buoyant solid waste (e.g. plastic)	0 – 5 km 5 – 20 km 20 + km
Suspended / particulate matter (e.g. sediment)	Spring tidal excursion distance
Leachate	Spring tidal excursion distance

10.3 Literature review: Protected species sensitivity to landfill waste

This high-level literature review was undertaken to assess the potential impacts of landfill waste on mobile species protected within the Welsh MPA network. There are 60 MPAs designated for species features in Wales, including SPAs, Ramsar, SSSI and SACs. These mobile features include birds (for example breeding and non-breeding waterfowl, wading birds, diving birds and surface feeding birds), fish (for example, River and Sea Lamprey, Atlantic Salmon, Allis and Twaite shad) and mammals (Bottlenose Dolphins, Harbour Porpoise, Grey Seals and Otters. The main impacts identified as having the potential to arise from the interaction of landfill waste and marine mobile species are:

- Physical impacts;
    - Entanglement;
    - Ingestion;
- Chemical impacts;
    - Contamination and bioaccumulation.

Overall, there are no known studies which examine the direct effects of landfill waste release on mobile species, which highlights this is an area that requires further research. In addition, there is limited information regarding the physical and chemical impacts listed above on species protected within the context of the Welsh MPA network. Therefore, studies which have investigated the impacts of different physical waste or contaminants (which are likely to arise from landfill sites) on marine mammals, birds or fish in general are summarised to provide an overview of the potential impacts on protected species.

It is expected that marine species which are coastal or feed into coastal locations have the potential to be exposed to higher concentrations of physical waste and chemical contaminants from landfills as it is assumed that concentrations of waste will decrease with increasing distance from the site. In addition, it is important to consider the potential long-term effects and potential build up over time of waste release on habitats and prey species upon which the mobile species will depend, leading to long-term indirect impacts on these mobile species.

10.3.1 Physical impacts

Solid waste from landfill sites has the potential to be released into the marine environment through flooding and erosion of landfill boundaries on the coast. The assessment of coastal landfill sites in this report found that all of the coastal landfill sites in Wales (with the potential to release waste to the marine environment) contained either Inert Waste, Household, Industrial and Commercial waste, and/or Special (hazardous) waste. Therefore, it was assumed all landfill sites had the potential to release solid waste. Solid waste from landfills, particularly plastic waste, does not always have the ability to biodegrade, hence it can persist in the water for decades or centuries and spread far from their points of introduction. Thus, such waste can present a constant threat to marine species once released to the marine environment, for example from landfill sites. Two of the main impacts likely to arise from solid waste release on mobile species are entanglement and ingestion. The potential impacts of these on marine mobile species are described below.

Entanglement

One of the main impacts likely to arise from the release of solid landfill waste on marine mammals, birds and fish is entanglement. Release of marine debris such as nets, monofilament line, rope, plastic rings and other litter from landfills has the potential to ensnare marine animals. This can lead to injury or fatality from reduced mobility, the infliction of cuts and wounds, or suffocation or drowning in marine mammals and seabirds (Sheavly et al., 2007).

Birds are likely to be one of the worst affected by entanglement, particularly diving or surface feeding seabirds, or seabirds which use plastic debris as nesting material (Bond et al., 2012). For example, northern gannets (*Morus bassanus*) often build nest using synthetic rope which has been shown to entangle and cause mortality to 65 birds per year on Grassholm, Wales, where there are approximately 40,000 pairs of gannets. However, it is not expected that this number of entanglements would have population-level impacts on this colony (Votier et al., 2011).

The majority of studies attribute entanglement to lost and abandoned fishing gear, which is recognised as the main source of large plastic pollution in the ocean. However, one of the main land-based sources of marine debris is recognised to be coastal landfills (Katsanevakis, 2008). It is unknown what level of pressure that waste released from landfill presents in terms of entanglement of marine species. However, there is the potential that waste release from landfill will come into contact with marine species.

Ingestion

Ingestion of solid wastes such as plastics has been recorded in marine mammals and birds which can lead to litter blocking the throat or digestive tract, internal injury, or starvation where litter which cannot be digested and remains in the stomach (Sheavy et al., 2007). Ingestion of plastic litter in seabirds can lead to the death of both adults and chicks, as adults feed their chicks through regurgitation. Surface plunging seabirds (such as great shearwaters and northern fulmars) have been shown to accumulate large amounts of plastic. A recent global literature review highlighted that shorebirds ingest plastic (particularly microplastics), with oystercatchers retaining high concentrations of plastic, followed by curlews, godwits and plovers (Flemming et al., 2022). Plastics in marine mammals can be ingested directly through feeding strategies such as filter-feeding in baleen whales, or indirectly through consumption of prey. A study by Nelms et al. (2019) found that plastics tend to be retained in the stomach of marine mammals, and mammals which have been found to have died of infectious diseases tended to have higher numbers of plastic particles in them, compared to those that died for other reasons.

There is also the potential that microplastics and fibres could adhere to the skin or gills (in fish) or translocate after being ingested to the liver and muscle tissues of marine species. However, there is currently limited information on this occurring.

Ingested plastic has also been found to carry and transfer hazardous chemicals into marine species. For example, contaminants, including but not limited to PCBs, PAH, polybrominated diphenyl ethers (PBDEs), polybrominated biphenyls (PBBs) and Bisphenol A are contained in plastic debris. Some of these compounds are added during manufacture whilst others can absorb compounds from the surrounding seawater (Teuten et al., 2009). A feeding experiment undertaken in Japan indicated that PCBs could transfer from contaminated plastics to seabird chicks (Teuten et al., 2009). In a study by Rochman et al. (2013), fish exposed to a mixture of plastics with and without chemical contaminants adsorbed from the marine environment, showed signs of stress in their livers (cell necrosis, glycogen depletion and evidence of tumour growth). More information on the impacts of chemical contaminants on marine species is included in Section 10.3.2.

10.3.2 Chemical impacts

Chemical contaminants have the potential to be released from landfill sites through flooding and erosion of landfill boundaries and leaching. Extensive research has shown that contaminants which can occur in landfill, such as heavy metals (e.g. mercury) and persistent organic pollutants (POPs) (e.g. PFAS, PCBs, pesticides such as Dichlorodiphenyltrichloroethane (DDT), and PAH), can have significant impacts on marine mobile species due to their toxicity, persistence and bioaccumulation potential (Law and Whinnett, 1992; Gómez-Lavín et al., 2011; Murphy et al., 2018; Kershaw and Hall, 2019). Contaminants released from a site can adsorb to particulate matter and accumulate in sediments. Whilst filter, suspension and deposit feeders are directly impacted by the increased contamination levels in the sediment and water column, predatory species including birds, mammals and fish are most likely to be affected indirectly. For example, predatory species could be impacted through the consumption of contaminated prey and bioaccumulation of chemicals (Nicolaus et al., 2015), Marine mammals and birds are at the top of the food web so can accumulate large concentrations of these chemicals within their tissues from consumption of contaminated prey. In addition, predatory species could be indirectly impacted due to a loss of prey availability. Contamination of habitats could lead to mortality of prey species on a large-scale which will affect the availability of food.

OSPAR recognises a wide range of chemical contaminants as pressures on marine environments and species. The pressures in OSPAR relating to chemical contamination include:

- Synthetic compound contamination (incl. pesticides, insecticides, herbicides, antifoulants, pharmaceuticals, PCBs);
- Transitional elements & organometal (e.g. arsenic, lead, mercury Copper, Tributyl tin (TBT)) contamination;
- Hydrocarbon & PAH contamination; and
- Radionuclides.

These pressures include priority substances listed in Annex II of Directive 2008/105/EC.

The assessment of coastal landfill sites in this report found that approximately 89% of the landfill sites in Wales contained either Household, Industrial and Commercial waste, and/or Special (hazardous) waste, and therefore were assumed to have the potential to release chemical waste. There are likely a large number of different chemical contaminants contained within landfills in Wales, therefore, this review is focussed on a handful of examples within each of the OSPAR pressures to demonstrate potential impacts of these on marine mammals, birds and fish. It is important to note, however, that impacts of landfill contaminants on marine mobile species are likely to be species specific and dependant on the exact chemicals and concentrations which may be released from the landfill.

Synthetic compounds

There are a large range of synthetic compounds which could be found in landfill sites. One of the key synthetic compounds which has been investigated in the literature are Polychlorinated biphenyls (PCBs) have been shown to bioaccumulate in living organisms. PCBs were banned in the UK in the 1980s, however, they are still present in sediments today and at concentrations exceeding environmental quality standards (Nicolaus et al., 2015). PCBs reside in historic landfill sites and have the potential to be released from these sites through leaching, into the atmosphere (Harrad et al., 1994) or directly as a result of erosion and flooding. A meta-analysis of stranded or biopsied cetaceans found that several European species, particularly bottlenose dolphin, striped dolphins and killer whales have elevated blubber PCB levels due to bioaccumulation through the food chain (Jepson et al., 2016). It was stated by Jepson et al. (2016) that PCB bioaccumulation could be a contributing factor to ongoing population declines with PCB considered to be toxic to all life stages of cetaceans (Williams et al., 2023). For example, PCB toxicity is recognised as a likely cause of reduced recruitment in cetaceans, as a result of reduced fertility, increased embryonic loss, increased calf mortality and increased susceptibility to disease (Williams et al., 2021; Schwacke et al., 2002). Despite regulations and mitigation measures to reduce PCB pollution, their biomagnification in marine food webs continues to cause severe impacts among top predators.

Henry (2015) reviewed the effects of PCBs on wild fish physiology across life stages by examining around 200 studies. They found that overall, there was little evidence that PCBs have had a widespread effect on fish health or survival. There is the potential that early life stages of fish are more sensitive to chemical contamination. For example, juvenile Atlantic salmon (*Salmo salar*) exposed to PCBs during smolting have been shown to negatively impact or inhibit predatory adaptations which could reduce marine survival as the fish move from freshwater environments (Lerner et al., 2007). A review of contaminants within sea lamprey (*Petromyzon marinus* showed that PCB and other contaminant concentrations are lower than those found in other top predators in the food web. This is primarily because blood (the food source of lamprey) is relatively low in certain contaminant concentrations compared to tissue. However, lamprey were found to be high in mercury concentrations (Madenjian et al., 2021). Dioxins (Polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs)) are also known to leach from landfills (OSPAR, 2007). Lamprey have been shown to accumulate relatively high levels of dioxins compared to other top predators, however, it has been suggested that they are capable of surviving such concentrations (Madenjian et al., 2021).

As well as accumulation through prey, the ingestion of plastic has been linked to the assimilation of PCBs and other POPs chemicals such as Polybrominated Diphenyl Ethers (PBDEs) and PCBs in seabirds (Ryan et al., 1988; Colabuono et al., 2010; Tanaka et al., 2013). Such chemicals have been shown to transfer from adult to eggs or chicks in seabirds (Hitchcock et al., 2019). For example, Guillemot eggs from Irish and Welsh (Skomer) colonies have been found to contain PCBs, PBDEs, other organochlorine compounds and metals (such as mercury). Skomer had the highest levels of contaminants in the study, and it was hypothesised that high levels were due to its proximity to historically industrial areas and pollutants in the Severn Estuary. Levels of contaminants have, however, been decreasing over time with decreased use of hazardous chemicals (Power et al, 2021a), however, these chemicals could still be present within landfill sites.

PFAS have been also found to accumulate in fish, seabirds, cetaceans, seals, and otters, typically accumulating in the liver (Lam et al., 2016; Robuck, 2020; Ali et al., 2021; Stockin et al., 2021; Androulakakis et al., 2022). A recent study by O'Rourke et al. (2022) found high levels of PFAS in otters from England and Wales, which was associated with the presence of wastewater treatment works, arable land (application of sewage sludge) and polytetrafluoroethylene manufacturing plants. Several studies suggest that accumulation of PFAS could affect liver and thyroid functioning and lead to increased susceptibility to disease. Suppression of the immune system and susceptibility to disease is one of the main recognised effects of chemical contaminants in marine mammals (Desforges et al., 2016).

Other materials contained in landfill sites include Pulverised Fuel Ash (flyash) which if released could accumulate in the tissues of marine species, particularly invertebrates (Jenner and Bowmer, 1990), which could affect prey populations of birds, fish and mammals. In addition, landfills are also recognised as a source of pharmaceuticals entering the marine environment through leachate (Gaw et al., 2014). There are reports of pharmaceuticals being found in dolphins and seabirds, however, the impact of pharmaceuticals on marine mammals, birds and fish is not well known and work is needed to assess potential accumulation in the food web (Gaw et al., 2014).

Transitional elements & organometal

Contamination of sediments can have direct effects on species which live on or predate on species within the sediment. For example, a study in the Netherlands measured heavy metal concentrations in soil, earthworms, and black-tailed godwit eggs and feathers at a polluted and a reference site. The results suggested that lead, mercury and cadmium were transferred from the soil to godwits even though they only spend a few months in the area during breeding (Roodbergen et al., 2008). The build-up of heavy metals within the bodies of black-tailed godwits was suggested to have an additive negative effect on the viability of local populations (Roodbergen et al 2008). Oystercatcher and tern eggs have also been found to contain mercury, PCB's and DDT's and in levels exceeding the Ecological Quality Objectives (EcoQOs) across sites in the North Sea (Dittmann et al., 2012). Greenshanks have also been found to contain mercury in their pectoral muscles in Iceland, possibly due to their piscivorous diet (Matz et al 2011).

Metals can also bioaccumulate in predators, and high levels of metals can lead to organ damage and failure in cetaceans. Heavy metal contamination in fish can have a range of impacts, including damage to immune and nervous systems, lesions and reduced functioning of organs, particularly the liver and gills (Zeitoun and Mehana et al., 2014; Javed et al, 2019). Heavy metals have the potential to lead to negative impacts on early developmental stages of fish, such as delayed or premature hatching, deformations and death (Jezierska et al., 2009).

Hydrocarbons and Polyaromatic Hydrocarbons (PAH)

With regards to PAH, there is the potential that top predators are able to metabolise and excrete PAH more efficiently than invertebrates, and hence concentrations of PAHs are not likely to be biomagnified in the food web like other chemicals (Lourenço et al., 2021; Power et al., 2021b). Whilst contamination may not bioaccumulate in the food web, a review by Gogard-Codding and Collier (2018) found that cetaceans are at high risk to adverse effects from direct exposure to crude oil (e.g. as a result of oil spills) which naturally contains PAH. For example, exposure of dolphins to crude oil, PAH and chemical dispersants has led to reduced immune responses to disease (De Guise et al., 2017; White et al., 2017). However, the release of PAH from landfill sites is unlikely to be on the same scale as large oil spills from ships, and hence the impact remains relatively unknown.

PAH have, however, been found in the eggs of seabirds, likely passed from the adult who has been exposed to PAH or fed on PAH contaminated prey. PAH are known to be toxic to chick embryos, however a study on seabird eggs in Ireland found that recent levels in guillemot, gannet, and tern eggs are low and likely an accumulation of background environmental levels which are unlikely to have embryotoxic effects (Power et al., 2021b). Power et al., (2021b) notes, however, that levels in eggs could significantly increase after pollution events.

Radionuclides

Radionuclides are also present in landfill sites and a review by Kolar and Gugleta (2019) showed that accumulation of radionuclides can lead to increased mortality, susceptibility to disease/parasites, changes in reproductive and developmental patterns and changes in the genetic make-up of marine and freshwater fish. They also found evidence that radionuclides can be passed across the trophic levels and in turn impact the entire food chain. A recent review by Kolar and Gugleta (2019), stated that large predatory fish species on the top of the food chain have been found to contain high concentrations of radioisotopes. Transfer through the food chain was also expected to the reason for absorbed radiation found in dolphins off the Portuguese coast, however, levels were below the levels which cause significant biological effects (Malta and Carvalho, 2011). It is unknown what the impact could be if radionuclides were released from landfill sites.

10.3.3 Conclusion

Overall, there are a large number of bird, fish and mammal species protected within the Welsh MPA network that have the potential to be impacted both directly and/or indirectly from waste released from coastal landfill sites. However, the mobile nature of these species presents a challenge when determining which landfill sites could impact upon them. Information on how protected species are distributed around Wales, including how they use the areas they inhabit (for example, roosting or haul out sites, feeding sites, or migratory routes), would allow an initial assessment of how different types of waste could come into contact with or affect these species.

With this in mind, it would be useful to understand the potential waste contained in the coastal landfill sites and the potential concentrations of waste that could be released. These factors could be used to help identify more accurate zones of impact relevant to mobile species.

In addition, investigations could be undertaken to increase current understanding of entanglement, ingestion of marine litter, or current contamination levels of Welsh mobile species and the impact of these on an individual or population level. It could then be investigated whether the waste and contaminants in coastal landfill sites have the potential to be a cause of these impacts or have the potential to exacerbate impacts if waste were released.

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10.4 Data Archive Appendix

Data outputs associated with this project are archived on server–based storage at Natural Resources Wales.

The data archive contains:

[A] The final report in Microsoft Word and Adobe PDF formats: NRW Evidence Report No. 673

[B] A series of GIS layers on which the maps in the report are based

[C] A series of Microsoft excel tables containing the overall scores on the threat of landfill sites to MPA habitat features over different epochs

[D] A Microsoft excel tables containing the MPA habitat features sensitivity to different pressures from landfills justification

Metadata for this project is publicly accessible through Natural Resources Wales' Library Catalogue https://libcat.naturalresources.wales (English Version) and https://catllyfr.cyfoethnaturiol.cymru (Welsh Version) by searching 'Dataset Titles'. The metadata is held as record no NRW_DS 125457

Further copies of this report are available from library@cyfoethnaturiolcymru.gov.uk