Supplementary Information for **Future challenges of coastal landfills exacerbated by sea level rise**

Data sources consulted for the case study sites

Primary information sources consulted included: historical and contemporary Ordnance Survey maps from the 1870s to date (Digimap); Aerial photographs (various sources); Digital Elevation Mapping (DEM) sourced from the Environment Agency; and area (e.g. SSSI) and priority habitat (e.g. mudflats) designations, sourced from the Department of Food and Rural Affairs (Defra). Literature sources included published journal papers, site investigation, consultant and contaminated land assessment reports, land ownership records, planning permissions, borehole logs and geological/ hydrogeological maps and SMPs. Where relevant, site specific literature sources are referenced in the results section.

Detailed site maps

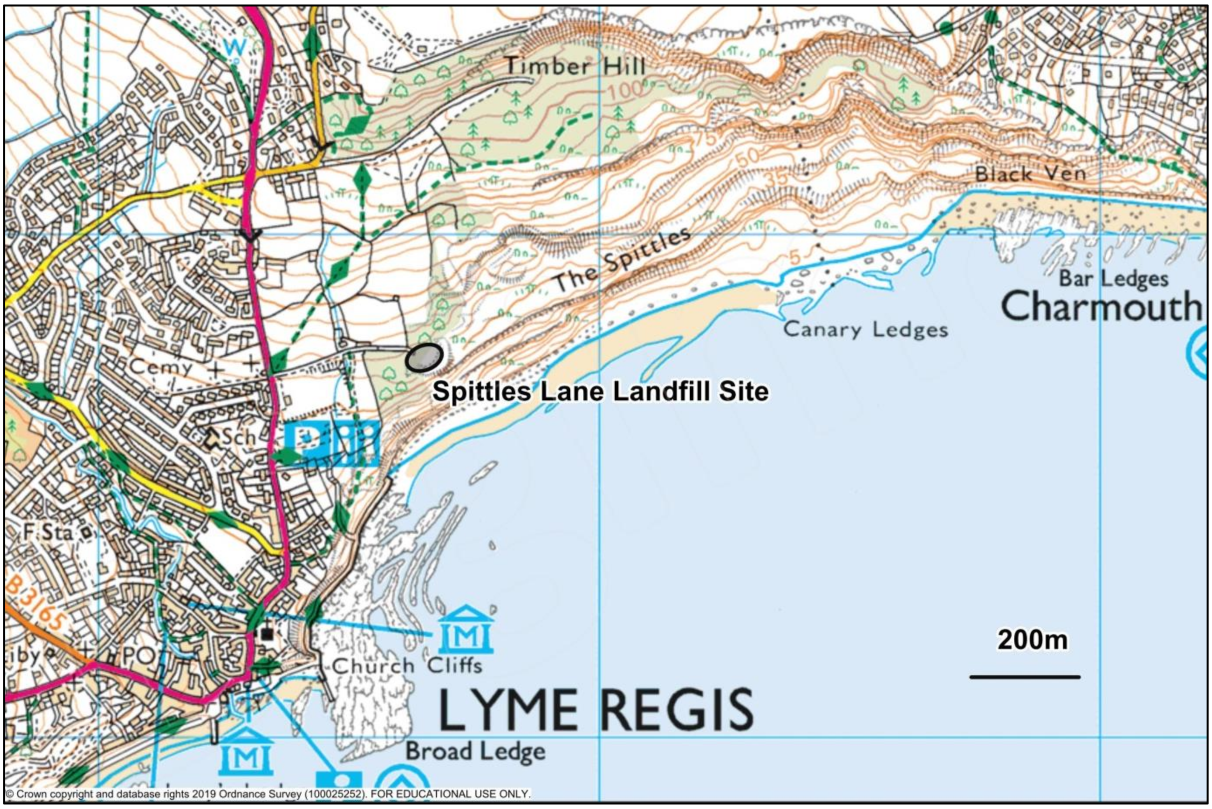

Figure S1: Location of Spittles Lane Landfill, near Lyme Regis

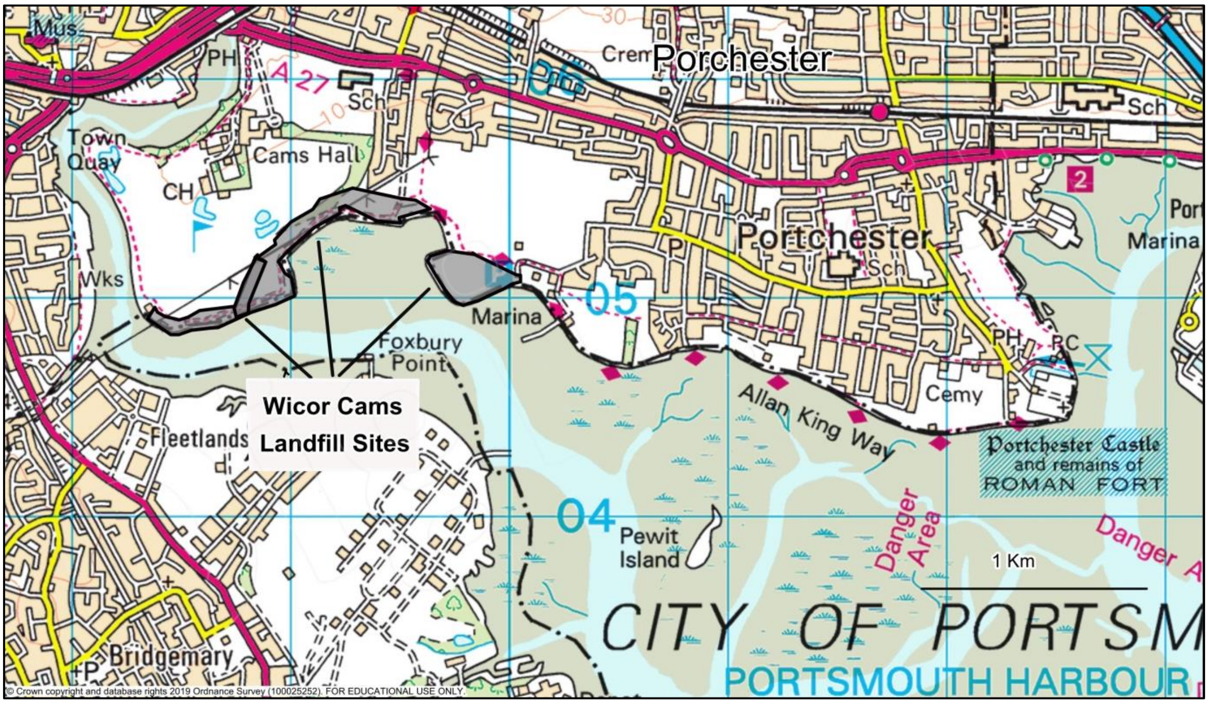

Figure S2. Location of Wicor Cams landfills, near Fareham

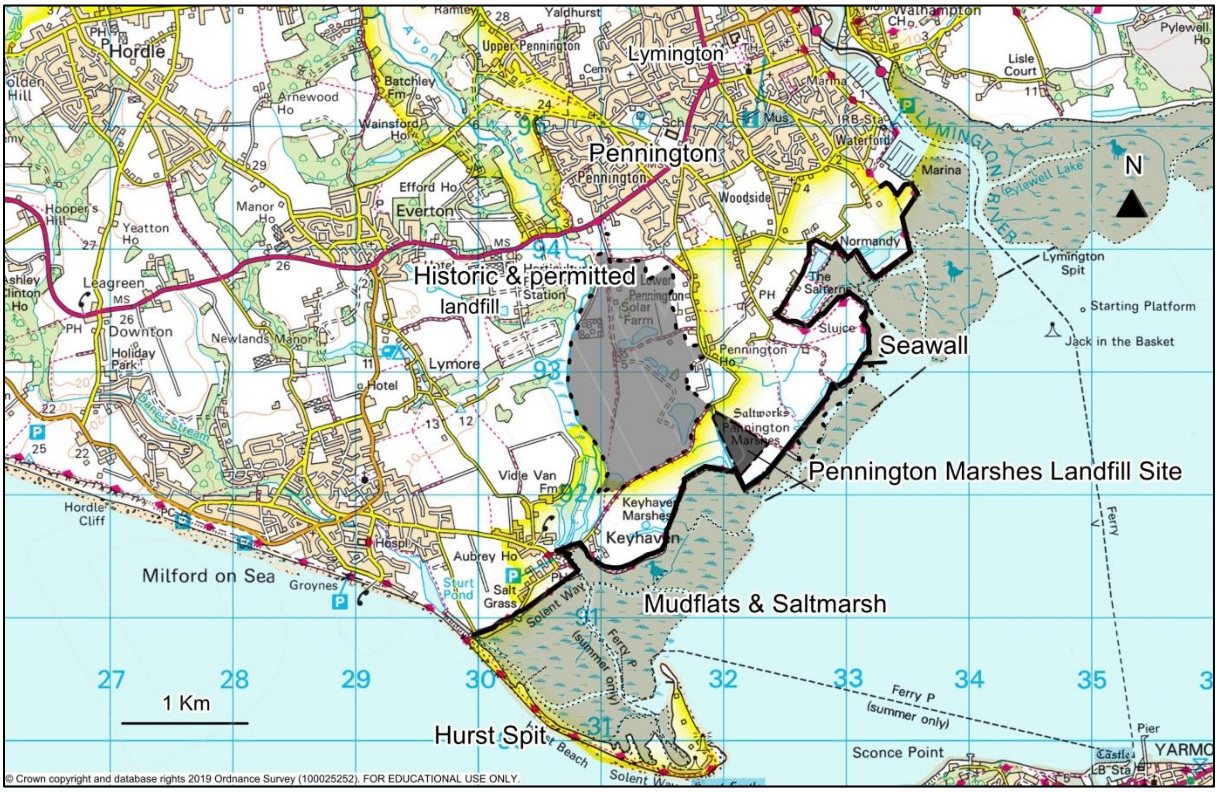

Figure S3. Location of Pennington Marshes landfill, near Lymington. Note the large historic and permitted landfills to the north of this site.

Climate change and sea-level rise scenarios

The UKCIP02 climate change scenarios (Hulme et al. 2002) give estimates of future potential change to mean precipitation and temperature for 50km x 50 km grid cells covering the UK. Winter precipitation is projected to increase across the UK, both in the short- and long-term, with the biggest relative changes in the south and east. By the 2080s, winter precipitation on the West Dorset coast is projected to increase by 10–15% under the Low Emissions scenario and 20–25% under the High Emissions scenario. Extreme winter precipitation will also become more frequent. For example, by the 2080s, winter daily precipitation intensities with a 2-year return period experienced on the West Dorset coast could become 10–15% heavier under the High Emissions scenario. The UKCP09 scenarios (Murphy et al., 2009) show similar trends. This will result in increased rainfall induced leachate production for all sites.

Sea levels have risen in the study area based on analysis of tide gauges at about 1.2 to 1.8 mm/yr over the last few decades (Haigh et al., 2009). Lowe et al (2009) provides low, medium and high sea-level rise projections around the UK coast to 2100, and a high H++ scenario which is plausible, but unlikely, and hence worth considering in this kind of analysis. These scenarios were adapted for the study area and are summarised in Table 3. By 2100, sea-level rise is estimated to rise between 0.2 and 0.75 metres compared to present water levels under the low to high scenarios. Under the H++ conditions, a 1.5 metres rise is considered as a plausible high-end scenario.

Coastal erosion (Pennington Marshes and Wicor Cams sites)

The analysis of potential coastal erosion used publicly available data as well as values and observations in published literature (see above). Erosion was assessed using the EA predictions for the short, medium and long term, and compared to evidence from Ordnance Survey mapping over the last 100 years together with topographic profiles of the landfill site and fronting shoreline. To assess the potential for the release of waste from the landfill site over time, lower and higher rates of erosion were calculated.

Cliff Erosion (Spittles Lane Landfill site)

One impact of SLR is an increase in sea cliff erosion rates, which is applicable to our case study site at Lyme Regis. A simple model of soft-cliff erosion is used to examine the impact of rising sea levels on the rate of erosion of the landfill site. Walkden and Dickson (2008) (equation 1) gives a relationship between historic and future rates of erosion (R1, R2), and historic and future rates of SLR (S1, S2). Historic rates of erosion are taken from the literature.

$$R_2 = \sqrt{R_1 \left(\frac{S_1}{S_2}\right)} \tag{1}$$

Brunsden (1996) quotes average erosion rates for the basal Lias of between 0.3 and 3.0 m per year. A report by HPR Ltd (2000) reported in Bennett (2007) quotes recession rates of 0.5, 0.8 and 1.3 m per year for areas of East Cliff prior to the construction of the defences.

There are, however, a number of limitations to the application of this equation. Firstly, the fronting beach to the cliffs must be assumed to be relatively narrow and volumetrically small. Secondly, the final 'future' rate of erosion predicted does not represent the actual (transient) rate that will occur, but rather the new equilibrium rate that the system is adapting towards. At the Spittles/Black Ven complex, erosion is episodic and long periods of relative stability may be punctuated by short periods of high instability resulting in landslides and cliff failure. This is expected to continue into the future.

Flood analysis (Pennington Marshes and Wicor Cams sites)

The exposure of the Pennington Marshes and Wicor Cams landfill sites to potential flooding under different still water level scenarios was assessed using a simple bath-tub flood analysis. In the bath-tub method, areas which lie below the current and projected still water levels will be flooded if they are hydraulically connected to the source of flooding. The topographic data (LiDAR DEM) was re-classified in ArcGIS to indicate the areas with an elevation below the still water levels predicted for each time-slice under low, medium, high and extreme high (H++) sea-level rise. These were then assessed for hydraulic connectivity and edited accordingly to remove any areas which were incorrectly classified.

Table S1. Organic and inorganic contaminants in waste/soil samples* from Spittles Lane Landfill, near Lyme Regis, Dorset

	As *mg/kg*	**Cd** *mg/kg*	**Cr** *mg/kg*	**Cu** *mg/kg*	**Ni** *mg/kg*	**Pb** *mg/kg*	**Zn** *mg/kg*	**PAH** *µg/kg*	**Benzo[a]pyrene** *µg/kg*
Average	14.8	3.4	42.0	213.1	104.5	613.7	509.3	26,400	1,500
STD	12.4	7.8	26.7	310.6	141.6	697.5	392.2	30,700	2,200
Max	62	40	129	1300	790	3351	1500	9,500	11,400
UK action level 2 [1]	100	5	400	400	200	500	800		
Canadian PEL guidelines[2]	41.6	4.2	160	108	42.8	112	271	10,000	763
NBC Principal [3]	32	1	n/a	62	42	180			500
NBC mineralised [3]	290	17	n/a	340	230	2400			n/a
NBC urban [3]	437	2.1	n/a	190		820			1800

* average values based on samples taken: March 2009; June 2009; Feb 2010; May 2012 and Sep 2013. (WPA Consultants Ltd, 2010 and 2013).

[1] MMO (2015)

[2]CCME, (2001)

[3] Normal background (soil) concentration. Johnson et al. (2012).

Table S2. Organic and inorganic contaminants in waste/soil samples from Wicor Cams landfill, Fareham

	As *mg/kg*	**Cd** *mg/kg*	**Cr** *mg/kg*	**Cu** *mg/kg*	**Ni** *mg/kg*	**Pb[1]** *mg/kg*	**Zn** *mg/kg*	**PAH** *µg/kg*	**Total petroleum hydrocarbons (TPH) [2]** *µg/kg*
Average	12.9	0.7	23.2	104.9	21.1	173.6	223.1	31,512	369,552
STD	7.3	1.2	8.8	209.8	10.4	171.7	282.1	62,608	454,791
Max	38.2	4.26	45	923	47.6	677	1020	255,000	1,480,000
UK action level 2[3]	100	5	400	400	200	500	800	n/a	n/a
Canadian PEL guidelines[4]	41.6	4.2	160	108	42.8	112	271	10,000	n/a
NBC Principal[5]	32	1	n/a	62	42	180	n/a	n/a	n/a
NBC mineralised[5]	290	17	n/a	340	230	2400	n/a	n/a	n/a
NBC urban[5]	437	2.1	n/a	190		820	n/a	n/a	n/a

[1] *Excluding one anomalous value of 24,300 mg/kg; n/a = not available*

[2] Total Aliphatics & Aromatic hydrocarbons:C5-35

[3] MMO (2015)

[4] CCME, 2001

[5] Normal background (soil) concentration. Johnson et al. (2012).

Removal of waste from Wicor Cams and Pennington Marshes landfills

The SMP policy for the areas including Wicor Cams and Pennington Marshes landfills is HTL for the next three epochs. Nevertheless, the costs to remove the site were estimated. Costs included excavation, transport and disposal to an alternative landfill, health and safety and environmental control measures and landfill tax. Costs for characterisation of the waste prior to excavation are included. There are many uncertainties with the cost analysis, not least because the values chosen against the various categories are mostly estimates and are not based on a detailed analysis of costs. However, the analysis does give an indication of the magnitude of potential costs. Planning permission would be required to remove waste from the landfill, and this would include a consideration of the impact of lorry and other environmental nuisances on the local community. The Environment Agency would also need to issue a permit to cover the operation.

Total removal of the Wicor Cams Tip landfill sites to an unspecified landfill, assumed to be within 80 km driving distance. The disposal of the waste to landfill is currently liable to landfill tax charges, and waste characterisation would need to be made to determine whether the waste is subject to the full tax charges (£91.35.40/tonne – rate applicable at time of costing (2019)) or at the lower rate for inactive waste (£2.90/tonne). This could cost in the region of £149M if all removed materials that were landfilled attracted the top rate of landfill tax (Table S3). In this scenario over two thirds of the costs (73%) are accounted for by landfill tax. If it is assumed that only 30% of the removed and re-landfilled material attracted the higher rate of landfill tax, the total remediation cost is halved to around £75M. Given the large cost of excavation and disposal, total removal of the landfills from Wicor Cams is not considered financially viable.

An estimate of the cost of removing the waste from Pennington Marshes landfill was made, again assuming that the waste will be transported to an unspecified landfill site 80 km away. The total cost for removal of the Pennington Marshes landfill would be approximately £23M if all removed materials attracted the top rate of landfill tax (Table S3). In this scenario, landfill tax would amount to 77% of the total costs. If it is assumed that only 30% of the removed and re-landfilled material attracted the higher rate of landfill tax, the total remediation cost is halved to around £11M.

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

Table S3. Potential costs to remove waste from Wicor Cams and Pennington landfills to an alternative landfill at 80 km driving distance.

Landfill	Wicor Cams		Pennington	
% attracting higher band of landfill tax	30	100	30	100
Estimated Volume of Waste (m^3)	1,000,000	1,000,000	160,000	160,000
Estimated mass of waste (Bulk density assumed 1.2t/m^3)	1,200,000	1,200,000	192,000	192,000
Excavation Costs (£2/tonne)	2,400,000	2,400,000	384,000	384,000
H&S environmental control measures (£5/tonne)	6,000,000	6,000,000	960,000	960,000
Transport Costs (£6/tonne)	7,274,000	7,274,000	1,164,000	1,164,000
Disposal Costs (£15/tonne)	24,000,000	24,000,000	2,880,000	2,880,000
Landfill Tax (£91.35/tonne)*	32,886,000	109,620,000	5,262,000	17,539,000
Landfill tax - lower rate (£2.90/tonne)*	2,436,000	0	390,000	0
Total costs (£)	74,996,000	149,294,000	11,040,000	22,927,000

* rate applicable at time of costing (2019)

An approach for calculating LS ratios of historic landfills

The liquid to solid ratio (LS) is a measure used in waste acceptance leaching tests that is the ratio of the amount of liquid (normally deionised water) that has been brought into contact with a dry mass of solid waste. LS values are normally reported as volume of water in litres divided by dry mass in kg. CEN/EN 14405 is the European standard for the leaching behaviour of inorganic and non-volatile organic substances in up-flow percolation tests through granular wastes. Waste in a column (typically ~0.3 m high and with a diameter of 0.05 to 0.1m) is pre-saturated with water before an up-flow leaching test is undertaken. Fractions of eluate are collected at various LS ratios between LS = 0.1 to 10 l/kg over a period of approximately 21 days. There are no imposed controls over the pH of the eluate. Concentrations of dissolved substances in the eluates are reported against LS.

In principle an average LS for a historic landfill can be calculated based on the total dry mass of waste in the landfill and the volume of leachate that has been produced over its whole history. A number of major assumptions and estimation of parameters is required to derive a landfill's LS, and there is no direct equivalence with a formal CEN leaching test. Nevertheless an approximate value of a landfill's LS is likely to provide a useful indication of how well a landfill has been flushed. Of critical importance are the average depth of the landfill (a shallow landfill will generate higher LS values in comparison to a deep landfill) and the average infiltration rate. Landfill depth will vary across the site, and so the LS will vary depending on location. Waste depth was assumed for each study site based on available data.

The dry mass of waste in a landfill can be estimated from the volume of landfilled waste and an average dry density. The average density of waste in a landfill will be dependent on many factors including waste composition, compaction and depth of burial (e.g. Beaven et al 2011). Landfill bulk densities have been reported to vary from between ~0.6 and 1.5 tonnes/m^3 for landfills containing municipal solid wastes and up to ~1.8 tonnes/m^3 for inert landfills. The equivalent dry density range is between 0.4 and 1.2 tonnes/m^3 for MSW containing landfills and 1.5 tonnes/m^3 for inert sites. Lack of compaction, shallow landfill depths, and the preponderance of low density waste components (e.g. plastics) favour low waste densities. Waste compaction, increased landfill depths (especially over 20 metres) and high proportions of soil-like materials lead to higher waste densities. Although all three of the case study sites were shallow (<5 metres on average) the evidence is that they all contained a reasonable proportion of soil-like materials and consequently average bulk and dry densities of 1.2 and 0.8 tonnes/m^3 are assumed for all sites.

There is no direct measurement of the volume of leachate that has been "leached" from each site, so an estimation is based on average regional effective rainfall in the location of the case study sites. Environment Agency (2008) contains maps of average summer and winter effective rainfall for England and Wales. All three case study sites are in areas that received between 201 and 300mm of winter effective rainfall and between 126 and 150 mm of summer effective rainfall. Assuming that regional effective rainfall is a reasonable proxy for infiltration at each of the case-study sites, then the volume of leachate production at each site can be based on between ~325 and 450 mm infiltration per year.

$$LS = \frac{Volume\ of\ leachate}{Dry\ mass\ of\ solid} = \frac{Annual\ Infiltration\ x\ Years\ x\ Area}{Average\ waste\ depth\ x\ Dry\ density\ x\ Area} = \frac{Annual\ Infiltration\ x\ Years}{Average\ waste\ depth\ x\ Dry\ density}$$

Table S3. LS ratios of case study sites (same as Table 4)

Site	Average waste depth	Dry density*	Average Infiltration**	Assumed average minimum duration of infiltration	LS ratio
	m	t/m^3	m/yr	years	
Spittles Lane	1-3	0.8	0.325-0.45	40	5 - 22
Wicor Cams	1.5-5	0.8	0.325-0.45	35	3 -13
Pennington Marshes	2	0.8	0.325-0.45	47	9 -13

* Assumed values

** Based on average effective rainfall for region (EA, 2008).

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