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Coastal Landfills and Rising Sea Levels: A Challenge for the 21st Century

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Populated coastal areas worldwide have a legacy of numerous solid waste disposal sites. At the same time, mean sea level is rising and likely to accelerate, increasing flooding and/or erosion. There is therefore concern that landfill sites located at and near the coast pose a growing risk to the environment from the potential release of liquid and solid waste materials. This paper aims to assess our present understanding of this issue as well as research and practice needs by synthesizing the available evidence across a set of developed country cases, comprising England, France, Germany, the Netherlands, and the United States (Florida). Common insights gained here include: (1) a lack of data and limited appreciation of waste release from coastal landfill as a potential problem; (2) recognition of the scale and diversity of coastal landfill waste within a range of generic settings (or situations); and (3) a lack of robust protocols that allow the impact of different categories of waste release to the coast to be assessed in a consistent and evidence-based manner, most particularly for solid waste. Hence, a need for greater understanding of the following issues is identified: (1) the amount, character and impact of waste that could be released from landfill sites; (2) the acceptability and regulation of waste eroding from coastal landfills; (3) present and future erosion rates at landfill sites suggesting the need for more monitoring and relevant predictive tools; (4) the full range of possible management methods for dealing with waste release from landfills and the science to support them; and (5) relevant long-term funding mechanisms to address this issue. The main focus and experience of current management practice has been protection/retention, or removal of landfills, with limited consideration of other feasible solutions and how they might be facilitated. Approaches to assess and address solid waste release to the marine/coastal environment represent a particular gap. Lastly, as

solid waste will persist indefinitely and sea levels will rise for many centuries, the long timescale of this issue needs wider appreciation and should be included in coastal and waste policy.

Keywords: landfill, waste, erosion, flood, sea-level rise

INTRODUCTION

Our historic use of the coastal zone for the disposal of solid wastes has left a significant legacy, with a large (but unknown) number of landfills worldwide. In Europe alone, it is estimated that there are 350,000–500,000 landfills in total containing wide-ranging wastes – industrial, commercial, domestic, hazardous, and liquid sludge (Hogland et al., 2011). Around 90% of these pre-date modern European legislation pertaining to waste control and landfill (EURELCO, 2019) and significant numbers are located in coastal and alluvial areas prone to flooding and/or erosion (Wille, 2018). In 2019, the US Government Accountability Office reported that nationally at least 945 US "Superfund" waste sites, many of which are municipal solid waste landfills, face increasing risks from climate change effects including rising seas (Grandoni and Dennis, 2019). There is also increasing evidence that extreme flood and erosion events result in the release of large volumes of toxic material to adjacent waters. For example, 13 toxic waste sites in Texas were flooded by Hurricane Harvey in 2017 (USEPA, 2017), while storm-induced failure of the Fox River historic landfill in New Zealand polluted hundreds of kilometers of coastline (JonoB, 2019). In the developed world, improved regulations for landfills combined with waste minimization hopefully mean that new coastal landfill sites are limited or absent, but in the developing world it is almost certain that the volume and legacy of waste in vulnerable coastal areas continues to grow (e.g., Zalasiewicz et al., 2016).

At the same time, we are experiencing a significant global rise in mean sea levels due to human-induced climate change: stringent climate mitigation as proposed in the Paris Agreement will slow but not stop this rise which will continue for centuries (Oppenheimer et al., 2019). Sea-level rise (SLR) will cause a significant increase in a range of coastal hazards, including more flooding and erosion of landfills unless there is appropriate adaptation. There is therefore growing concern that such waste could be released at an increasing rate and pose a significant risk to the coastal and marine environment over the coming decades.

Importantly, while all potential consequences of the release of soluble and solid wastes to the marine environment are unknown, they are of significant concern (Chen et al., 2020). Where legacy or eroded wastes have been examined, organic and inorganic contaminants [e.g., lead, mercury and poly-aromatic hydrocarbons (PAHs)] are present at levels that could cause significant harm to the marine environment (e.g., Pope et al., 2011; Brand and Spencer, 2020), and whilst soluble contaminants released may be much lower (O'Shea et al., 2018; Brand and Spencer, 2020) elevated concentrations of emerging contaminants of concern have been identified in historical landfill leachate decades after disposal (Propp et al., 2021). In addition, a range of other solid waste materials could be released including asbestos, plastics and composite waste materials (e.g., batteries) that would cause physical damage to marine biota through ingestion, abrasion, and entanglement, as well as a reduction in amenity value for people using the coast for recreation. Even without considering SLR, Chen et al. (2020) have estimated that the cumulative plastic waste inputs to the ocean will continue growing due to mismanaged plastic waste (e.g., in open dumps and some landfills) in coastal areas.

Approaches to assessing and managing historical landfills have been considered in a number of countries but appear to vary widely. For example, in the United States, coastal landfills in some states have been ranked with respect to their vulnerability to climate change including SLR, tidal flooding, erosion and increased precipitation to assist the prioritization of remediation efforts (e.g., ADEC, 2015; Asher, 2019). Belgium is considering the possibility of eliminating landfills (through waste relocation and/or landfill mining) in areas prone to flooding (Wille, 2018). However, such national analyses are unusual. A series of recent papers have analyzed this issue for England (Brand et al., 2018; Wadey et al., 2019; Beaven et al., 2020; Nicholls et al., 2020). Given that coastal waste and landfill and the effects of SLR and climate change are a universal problem, and best management practices are lacking, more international exchange of these experiences could be beneficial.

Uncontrolled release of solid wastes to the coast by erosion would seem to be unacceptable, as evidenced by widespread scientific consensus that release of plastics into the marine environment is damaging to marine and human life (Eriksen et al., 2014; Bergmann et al., 2017). There is also widespread public/emotional concern over the issue (Dunn et al., 2020). In addition, waste has a long timescale – many solid wastes are persistent, potentially over geological timescales (Zalasiewicz et al., 2016). While solid wastes may be modified by leaching and degradation within a landfill, the risks associated with the release of solid waste are a long-term problem which will persist and become more widespread because of SLR.

Hence, coastal landfills and the threats of waste release will pose ongoing coastal management questions over the coming decades and longer. This raises fundamental questions such as should waste release be avoided at all costs, or is there an acceptable rate of release, depending on the nature of the waste material? If release is unacceptable how can this be prevented in terms of remediation and/or protection in perpetuity (e.g., Bardos et al., 2020) or relocation of the waste material outside areas subject to flooding and/or erosion? Funding for these issues will generally fall on public funds requiring a budget item that was not appreciated when the landfills were active and is still not fully appreciated today. While there is some guidance on coastal landfill management (Cooper et al., 2013;

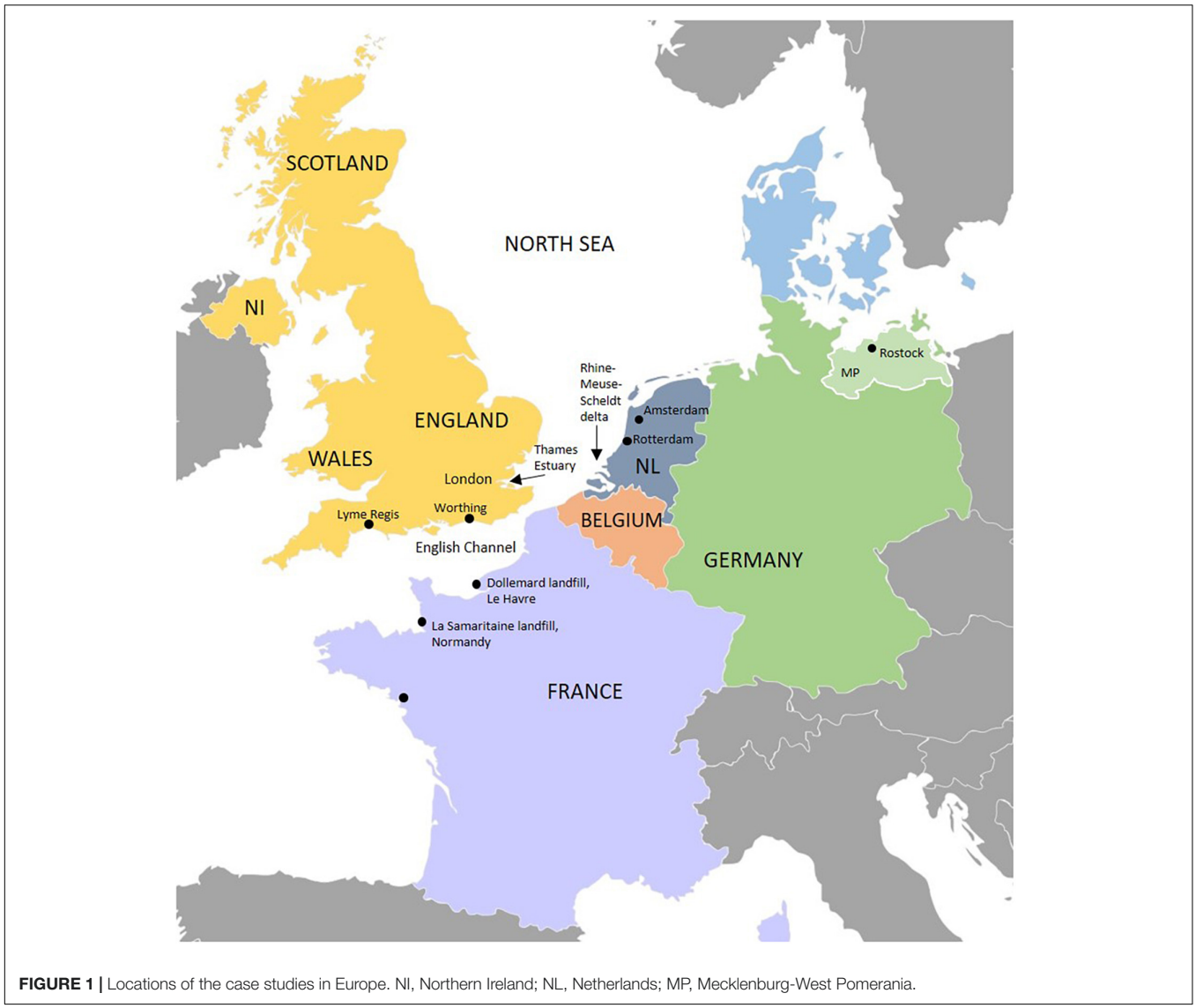

FIGURE 1 | Locations of the case studies in Europe. NI, Northern Ireland; NL, Netherlands; MP, Mecklenburg-West Pomerania.

Nicholls et al., 2018b), there is an absence of protocols that allow the impact of different categories of waste release to the sea to be assessed in a consistent and evidence-based manner, especially for solid wastes. This hinders strategic action and planning on this important issue.

The aim of this paper is to assess the implications of the release of waste materials from landfills into the marine environment, including erosion of solid waste and migration of leachates, and set our current understanding into a wider context, including research and development needs. We use the available evidence and experience in developed country settings, based on case studies in Europe (England, Germany, Netherlands, and France) (**Figure 1**) and the United States (Florida). First, it presents a generic typology of coastal landfills and waste release that is applicable across all the sites considered. It then reviews the evolution of landfills in the EU, setting the scene for the European case studies that follow. Then the status of landfills with respect to present and future flooding and erosion in each jurisdiction, including linking the analysis to the landfill and release typology. These case studies are heterogeneous by nature, reflecting different levels of awareness, analysis to date and policy responses in each country. This is followed by a cross-nation synthesis and an assessment of the status of coastal landfill management approaches for erosion and flooding. Finally the generic lessons are summarized, including research and development needs.

A GENERIC TYPOLOGY OF COASTAL LANDFILLS AND WASTE RELEASE

CIRIA guide C718 (Cooper et al., 2013) provides generic guidance on the identification and management of landfill sites and areas of land contamination located on eroding or low-lying coastlines drawing on United Kingdom experience.

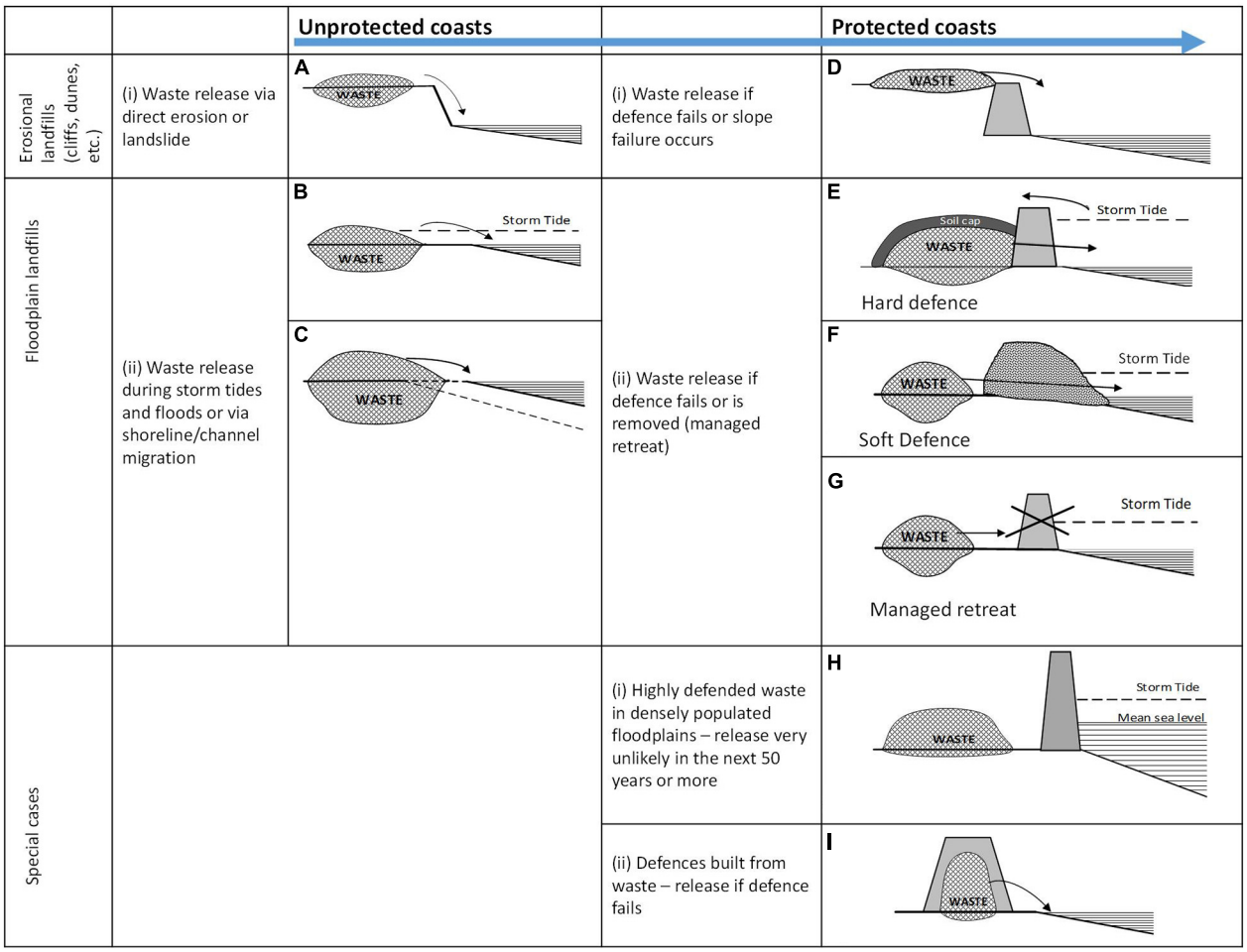

FIGURE 2 | The potential situations recognized in this paper where landfill materials can be released to the sea. The situations labelled **(A)** to **(I)** are described in the text.

The guide identified four main situations where wastes or materials could be released from a landfill by erosion or sea flooding (Beaven et al., 2020). Here we expand these to nine situations (A to I) that are broadly applicable across all the case studies considered in the paper. These include the geomorphological setting where the landfill is located and resulting hazards of concern – erosion and/or flooding – and also the presence or absence of coastal protection – undefended versus defended landfill sites (**Figure 2**). It also recognizes two special cases (H and I) that are relevant to the overall discussion of coastal landfills and waste release. The typology emphasizes the importance of coastal protection on future outcomes, whether the defense is built specifically to protect the waste or not.

Explaining **Figure 2** in detail, situations A and D occur on erosional coasts where flooding is not a consideration and landfills are situated, for example, on cliffs or in sand dunes. Here, waste can be released by episodic (e.g., individual storms) or chronic erosion. In general, SLR will exacerbate erosion although this is a complex process (e.g., for dunes, de Winter and Ruessink, 2017; for beaches Ranasinghe, 2016; Toimil et al., 2020; for cliffs, Walkden and Dickson, 2008). Landfill is also found widely in coastal floodplains. On undefended coasts (situation B and C), waste can be eroded during episodic events linked to extreme flood events and high tides. Waste release will be more of an issue under ongoing erosion as the shoreline and/or associated channels progressively migrate landward, a process which will be increased by SLR. On coasts with hard defenses, landfill releases depend on the nature and integrity of the defenses. Wastes defended by engineered structures (situation E) can be released by extreme events exceeding (or over-topping) the defenses, defense deterioration, or event-induced structure failure (ranging from minor exposure of waste to complete failure of large sea wall sections). Soft defenses, whether natural or artificial (e.g., beach nourishment), can stop or retard waste release (situation F) although they may still be subject to event-induced failure. The duration of release in these cases will depend on the management response. Deliberate defense abandonment (managed retreat) or removal of structures (situation G) is being actively debated and considered in many locations (Nicholls et al., 2013; CCC, 2018;

Siders et al., 2019), although the presence of waste sites often constrains decisions about how best to manage the coast given SLR and in some situations, new defenses are planned to defend waste at sites where otherwise retreat might be preferred (Wadey et al., 2019; Beaven et al., 2020). Two special cases are identified. Many coastal landfills around major urban areas (e.g., London, Netherlands, German North Sea Coast) are protected to such a high standard that landfill erosion is unlikely in the next few decades (situation H). The legacy of this waste will persist into the future as sea levels continue rising and, to avoid release, protection will be needed forever. There are also cases where coastal defenses themselves contain waste, so defense failure will release waste material (situation I) as is the case on the Thames estuary (Brand and Spencer, 2020).

This typology is used to compare the different sites across our case studies, including considering risks, long-term management options and their implications.

LANDFILLING WITHIN THE EUROPEAN UNION

Landfills in member states of the EU (which included England and the United Kingdom prior to January 2020) have been subject to the same European Directives that harmonize the regulation, financing, and certain design and operating requirements of landfill. Important Directives include the Waste Framework Directive, which originated in 1975 (EEC, 1975; latest amendment in 2006), and the Landfill Directive of 1999 [as amended in 2018 (EU, 2018)]. The Waste Framework Directive required the consistent regulation of waste disposal across member states, and the use of permits to ensure that waste disposal does not endanger health or harm the environment. Important provisions of the Landfill Directive control the type of wastes suitable for different classes of landfill, stipulate some minimum landfill engineering and technical requirements, and introduced the concept of landfill aftercare during which the operator of the landfill remains responsible for the contents of the site for however, long the site could pose a hazard. The reliance on landfill as a disposal route for wastes in Europe has decreased since the implementation of the Waste Framework Directive and, especially since the 1990s, a major emphasis on waste prevention, recycling, and processing of waste using alternative waste treatment technologies. Many countries have used landfill tax to reduce landfill use (e.g., Scharff, 2014). The landfill tax charge varies considerably across member states, but often now represents the largest component of cost for the disposal of waste in landfill. These policies, together with the change in the nature of wastes produced by society, mean that the composition of waste in landfills has changed over time.

European Directives are implemented through national legislation, which has obviously differed between member states. However, in broad terms landfills across Europe fall into two distinct categories:

(1) Landfills that closed prior to 1996, especially those prior to 1975, which will generally no longer have a permit and are usually referred to as legacy landfills. These are likely to make up the vast majority of the estimated 350,000+ landfills (Hogland et al., 2011). Most of these historical or legacy landfills have no leachate or gas management, or impermeable liners and there is evidence that during historical waste decomposition leachate has been released to the surrounding sub-surface environment where natural attenuation has resulted in localized 'hot spots' of sediment contamination (Njue et al., 2012; O'Shea et al., 2018).

(2) Post-Landfill Directive sites that have been constructed to high engineering standards, and will have permits to allow for ongoing long-term regulation. Landfill Directive sites are generally larger than legacy sites.

AN ENGLISH PERSPECTIVE ON COASTAL LANDFILLS

There are approximately 20,000 legacy or historical landfills in England. Around 1,200 historical landfills in England are located in coastal settings within the tidal flood zone (0.5% annual probability of coastal flooding) with many clustered around estuaries, large cities and industrial centers (Brand et al., 2018). They have a strong association with designated and environmentally sensitive areas because these areas were once considered low value land and hence suitable for waste disposal. Approximately 3,400 ha of landfill is at risk of flooding (0.1% probability or greater) (CCC, 2018). Many of these historical landfill sites are defended and in south east England there are a number of waste-filled coastal defenses such as along parts of the Thames estuary (Situation I, **Figure 2**).

Wadey et al. (2019) analyzed in detail the Central English Channel Coast (Lyme Regis to Worthing, **Figure 1**), a region where there is a concentration of coastal landfill sites which contain a mixture of waste types. By intersecting flood and erosion hazard data with historical landfill locations, they identified 144 historical coastal landfills covering 22 km^2 and occupying 86 km of shoreline length. About 89 sites are considered at risk of coastal erosion today (i.e., the landfill intersects with the present shoreline), while 136 landfills are in the coastal floodplain. As sea levels rise and the shoreline retreats, these sites are increasingly at risk of leakage, along with new sites further inland. Most landfills are in relatively low energy sites, mainly estuaries, with less than a quarter of landfills at sites exposed to larger waves. The predominant land use for these low energy sites is recreation and open space, with some commercial and/or industrial activity. However, about 6,500 residential properties are located on areas of historical landfill, with 4,400 of these in Portsmouth where substantial new defenses are being built over the next 10 years. The majority of the landfills are located on publicly owned land (local authority) and through Shoreline Management Plans (SMP) have a 'Hold the Line' (HTL) policy (Beaven et al., 2020). This is aspirational, however, as central government funding is not guaranteed unless there are additional benefits, particularly protection of other properties. As a regional illustration of the scale of potential costs involved, removal of all 144 threatened landfills to 'safe' locations is estimated to cost at least £4.3 billion (€4.9 billion; 2019 prices) based on landfill tax, with additional and substantial costs for

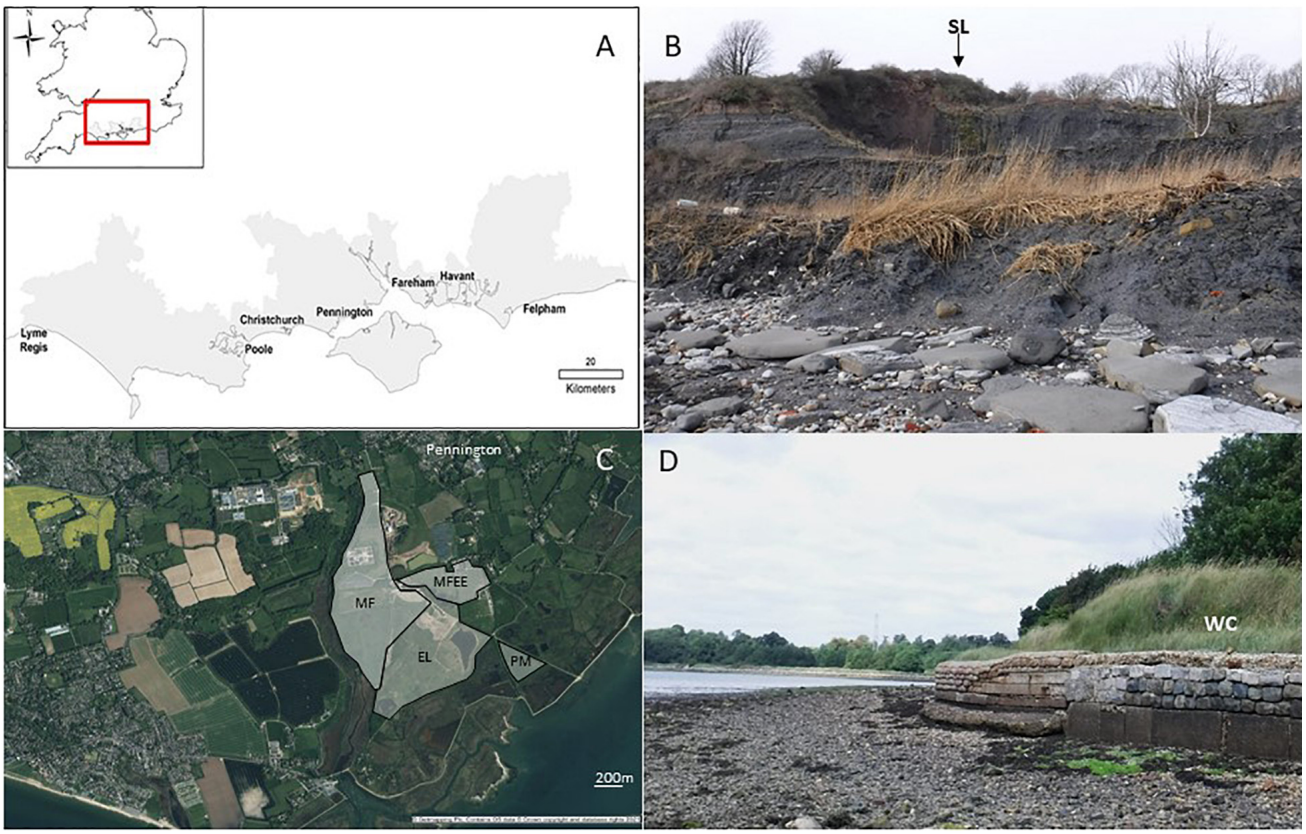

FIGURE 3 | (A) Location of study sites in England, highlighted is the region assessed by Wadey et al. (2019) and the locations of the case study areas referred to in Column 1 of **Table 1**. **(B)** View from the beach below Spittles Lane landfill site (SL), Lyme Regis. **(C)** Aerial photograph showing the location of Pennington Marshes landfill (PM), and the larger more landward landfill complex at Pennington comprising three landfills –EL, Efford Landfill; MF, Manor Farm Landfill; and MFEE, Manor Farm Eastern Extension. © Getmapping Plc. Contains OS data. © Crown copyright and database rights 2021. **(D)** View showing the informal coastal defenses of Wicor Cams landfill (WC) and foreshore, Fareham. Photographs B and D courtesy of Anne Stringfellow.

excavation and transport. Alternatively, to defend the 80 'higher priority' sites which are at risk of flood and coastal erosion over the next 100 years, would cost roughly £150 million (€170 million; 2019 prices), an order of magnitude less than the £1.3 billion (€1.5 billion; 2019 prices) estimate to remove this same waste.

Wadey et al. (2019) also assessed seven locations containing 13 distinct landfill areas in more detail (**Figure 3A** and **Table 1**). The survey underlined the complexity for future management with most landfills being situated behind natural and/or artificial defenses with a desire to continue to protect them, but no certainty of funding being available. Detailed analysis for three of these sites, also drawing on Beaven et al. (2020), illustrate the challenges (**Figure 3**).

The Spittles Lane landfill site at Lyme Regis (**Figure 3B**) is located on a 50 m high eroding cliff top where the cliff is prone to large-scale landslides, weathering, and surface and toe erosion (situation A, **Figure 2**). Average retreat rates are uncertain and in the range 0.3–3 m/year at present (Beaven et al., 2020). In 2008, a 400 m long stretch of cliff collapsed, releasing waste from the landfill to the cliff face and ultimately the beach below. The release of waste raised concerns of potential contamination and pollution. While an assessment found no significant contamination of controlled waters, lead and PAHs were found in the sediments together with fragments of asbestos or asbestos-containing materials which were attributed to the waste. Frequent beach inspections were established due to the risk assessment, and waste materials removed as necessary to prevent harm to beach users. No protection is planned at the site, so it is almost certain that the whole landfill (estimated to be 50,000 tonnes; Nicholls et al., 2018b) will erode into the sea over decades or longer (timescales are highly uncertain). Management options are limited due to the active erosion. Removal of the *in situ* waste and geotechnical stabilization of the site is one approach that could be considered, but these works could destabilize the cliff and increase the risk of further landslides limiting full consideration of the approach. Hence, monitoring and removal of these items at beach level appear to be the only practical steps available to limit harm to beach users. Given the long-term outlook of complete release of the landfill to the marine environment over many decades or longer, this approach will need to be sustained. The potential for adverse public reaction after a major waste release should also be considered.

There are four historical and authorized (permitted) landfills at Pennington to the southwest of Lymington, Hampshire

TABLE 1 | Selected case studies of coastal landfill sites on the central south coast of England [adapted from Wadey et al. (2019) with additional information for Spittles Lane, Pennington and Wicor Cams from Nicholls et al. (2018b) and Beaven et al. (2020)].

Case study area (see Figure 3)	Site name, location (and Situation defined in Figure 2)	Period active	Waste type	Size[1] (Ha)	Current land use	Shoreline length (km)	Coastal Type	Defended (Yes or No)	Current SMP Policy (over 100 years)	Releasing solid waste (Yes or No)
Lyme Regis	Refuse Tip East of Spittles Lane (A)	1910s–1978	Inert, Ind, Com, House	1.6*	Amenity	0.1	Open Coast; Cliff	N	NAI	Y
	Former Gas Holder Site (D)	1993–1994	Inert, Ind, Com, House	0.3	Residential	0.1		Y	HTL	N
Poole	Foreland Road, Turlin Moor, Eastern Lytchett Bay (C, E)	1984–1990	Inert, Ind	17.8	School, recreational	0.8	Sheltered Estuary; Floodplain	N	MR, then HTL	N
	Holes Bay North (E)	1977–1985	Inert, Com, House	45.4	Industrial/ Commercial, transport (road, cycleway)	2.1		Y	HTL	N
	Holes Bay South (E)	1982–1984	Inert							
	Whitecliff-Baiter (E)	1984–1990	Building rubble, House	24.3	Recreational, cycleway	1.8		Y/N	HTL	N
Christchurch	Stanpit Marsh (F)	1938–1981	Inert, Ind, Com, House	19.0	Amenity	1.4	Sheltered Estuary; Floodplain	N (protective marsh)	HTL, then MR, then HTL	N
Pennington	HCC Pennington Marshes Site A (E)	1962–1969	Inert, Ind, Com, House	7.5	Designated grazing marsh/habitat, adjacent to a regulated landfill	8.1	Exposed Estuary; Floodplain	Y	HTL (Currently under review)	N
	Efford (E)	1962–1969		147.2						
	Manor Farm (E)	1989-?								
	Manor Farm Eastern Extension (E)	–								
Fareham	Wicor-Cams I: Cams Bay Tip – Birdwood Grove (B, E)	1942–1993 -	Com, House	22	Recreation	2.5	Sheltered Estuary; Floodplain	Y/N (failing or absent)	HTL	Y (presently limited)
	Wicor-Cams II: Birdwood Grove Tip (B, E)		Inert, Ind							
	Wicor-Cams III: near Wicor Hard Cranleigh Road (B, E)		House							
	Portchester Quay, Land South of Hamilton Road (E)	–	Not known	11.7	Amenity, Industry		Sheltered Estuary; Floodplain	Y (Upgrade under consideration)	HTL	N

(Continued)

TABLE 1 | (Continued)

Case study area (see Figure 3)	Site name, location (and Situation defined in Figure 2)	Period active	Waste type	Size[1] (Ha)	Current land use	Shoreline length (km)	Coastal Type	Defended (Yes or No)	Current SMP Policy (over 100 years)	Releasing solid waste (Yes or No)
Havant	Harts Farm Way 'Broadmarsh'(E)	–	House	36.2	Amenity	1.1	Sheltered Estuary; Floodplain	Y	HTL	N
	Brockhampton (B, E)	–	House	12.2		0.7		N	HTL	? (waste visible)
Felpham	Longbrook (E, F)	1982–1983	Inert	2.5	Private Leisure	0.2	Open Coast; Floodplain	Y	HTL	N

*Ind, Waste Types – Industrial; Com, Commercial; House, Household and Domestic; SMP Policy, Current Shoreline Management Policy; HTL, Hold the Line; NAI, No Active Intervention; MR, Managed Realignment. *, at Spittles lane, 0.2 ha of landfill has been lost due to erosion. [1]A common feature of the analysis for all landfills was the difficulty in obtaining accurate waste depth and volume estimates from historical records.*

(situation E, **Figure 2**). These sites lie on low-lying land (collectively covering some 500 ha) adjacent to important designated habitat and landward of substantial coastal defenses exposed to high energy wave action. The most seaward historical landfill – Pennington Marshes landfill – occupies a triangle of land to the south-east of the main landfill complex (**Figure 3C**). SLR is reducing the level of protection offered by the seawall, while the protective saltmarsh fronting the seawall is also rapidly eroding and has completely disappeared on much of the frontage. The SMP policy is HTL for the next 100 years. To prevent flooding, the seawall will need to be raised and widened. Capital costs were estimated to range from £42 to £97.5 million (€48 to €111 million) under low to extreme high SLR scenarios (up to 1.5 m rise by 2100) (Nicholls et al., 2018b), with additional maintenance costs. Alternative management options include 'Managed Realignment' and the removal of the Pennington Marshes landfill. The former option would allow the sea to access the currently protected zone expanding the intertidal area, although habitat compensation would still be required showing the complexity within these choices. A new seawall could be relocated inland on higher ground, but the main, much larger Pennington landfill complex (**Figure 3C**) would still need to be defended to prevent erosion of waste. The capital cost of this option is reduced by 20–50%. If a 'No Active Intervention' policy was adopted the seawall would eventually breach. Pollution could be mitigated by removing the Pennington Marshes landfill, costing £10 to £21 million (€11 to €24 million), depending on the rate of landfill tax incurred (Nicholls et al., 2018b).

The Wicor Cams landfill complex, Fareham (situation E, **Figures 2**, **3D**) is situated on a low wave energy, estuarine environment adjacent to designated habitat. There are three landfills (**Table 1**); the last closed in 1993, and the site has been restored to recreational open space. The landfills are partly protected by informal coastal defense structures such as concrete sandbags or rock, while some landfill waste is unprotected and visible. The preferred SMP policy is HTL. With SLR, erosion is likely to release landfill without upgrading defenses. Defense costs were estimated to be up to £3 million (€3.4 million), although there are no clear funding avenues to implement the preferred SMP policy. An alternative approach would be to remove the landfill. Cost estimates range from £70 to £140 million (€80 to €160 million) depending on the rate of landfill tax paid, meaning that the removal of waste is not financially viable (Nicholls et al., 2018b).

These national, regional and local assessments of the historical coastal landfill in England indicate that it is, and will continue to be, a major issue which requires significant investment. Currently, there is insufficient funding to either manage these issues using conventional approaches or develop and test innovative management approaches.

A FRENCH PERSPECTIVE ON COASTAL LANDFILLS

About 1,000 French municipalities are located close to the coast, and each of them owns at least one landfill. A first inventory of

old landfills was financed by the French Environment Agency (ADEME) in the 2000s in order to assess the potential risks for ground and surface water, for the environment (e.g., impacts on landscape) and for human security (e.g., potential for landslides, etc.), as well as to assess the need for rehabilitation works. All these sites are in the BASIAS database (Basias-Georisques, 2021), the inventory of old industrial activities in France. Rehabilitation typically consists of preventing infiltration of rainwater by adding impermeable layers, conducting geotechnical works where needed, and landscaping. Hence, the wastes remain *in situ*. However, as in other countries, this national inventory remains incomplete. For example, the exact landfill location is often unknown, which prevents assessment of those located in erosion or flood prone areas. Furthermore, the surface area and/or volume of wastes, and their nature (household, inert, industrial, asbestos, etc.) are often poorly documented.

Coastal erosion and major storm surge events such as Xynthia (2010) (e.g., Lumbroso and Vinet, 2011) have exposed a few historical landfills on the French coast (Ouest France, 2014; La Presse de la Manche, 2020). These extreme events led public authorities to conduct emergency works such as reinforcement and waste containment, and then assess and ultimately rehabilitate the situation. Yet there is no specific consideration of the effects of SLR on coastal landfills over the 21st century and beyond. Adaptation in France is currently limited to informing coastal risk prevention plans with the impacts of a 60 cm SLR scenario by 2100 in order to prevent further urbanization of hazard-prone areas (Le Cozannet et al., 2017). A specific guide for coastal landfill is being prepared by BRGM and the Environment Ministry.

While coastal landfill erosion and flooding is expected to occur at multiple locations in the future, it is also already happening at a few sites. Two case examples are outlined here: (a) La Samaritaine landfill, Lingreville, and (b) Dollemard landfill, Le Havre, both in the Normandy region (**Figure 1**) and reflecting situation A (**Figure 2**). Waste release by chronic erosion, the willingness of the authorities to restore the coastal landscape, and societal pressure for restoration meant that removal of the landfill was the preferred solution in both cases.

La Samaritaine landfill (EPF Normandie, 2018) was located close to the shoreline in sand dunes (**Figure 4**) near the natural harbor of La Venlée in Lingreville municipality on the west coast of the Cherbourg Peninsula. It was a municipal landfill from the 1960s to the 1980s, then decommissioned and buried with sand in the 1990s. The landfill was then forgotten, not even recorded in the national database of landfills, until waste was uncovered due to chronic erosion of about 2 m/year of the sandy shoreline in the 2010s (**Figure 4A**). In November 2016, a storm accelerated the erosion of the waste and a temporary riprap and waste containment were installed in an attempt to prevent further release (**Figure 4B**) (La Presse de la Manche, 2020). To find a permanent solution, the owner of the site, the French Coastal Conservation agency, supervised the removal of 14,000 m^3 of waste mixed with sand from November 2017 to February 2018 (**Figure 4C**) (Ouest France, 2018). In this case, the ultimate aim was to restore the recreational and landscape value of the site, which is classified as Natura-2000. The main rehabilitation work involved sifting the sand for reuse *in situ* (4,000 tonnes; Les Champs Jouault, 2019), conducting a post-excavation diagnosis, sending the wastes to an inland landfill (12,652 tonnes; Les Champs Jouault, 2019) and restoring the site by filling with clean sand. The main difficulties encountered during the rehabilitation were adverse weather conditions, as a winter storm accelerated the erosion and rainfall slowed the sifting of the sand. Furthermore, asbestos was discovered in the waste requiring additional processing. The cost of this rehabilitation work was about €1.6 million, which was funded by public agencies and the administration (EPF Normandie, 2018). This includes the French landfill tax at €35/tonne in 2020.

The Dollemard landfill is part of a set of landfills which have been receiving construction and demolition waste since the 1960s. It is located north of Le Harve on top of 90 m high eroding cliffs composed of chalk and other materials (**Figure 5**). As at Spittles Lane (England), retreat of the cliff top allowed waste to be progressively released to an unstable vegetated slope at the toe of the cliff, which is difficult to access. This unstable slope is eroding at approximately 1–2 m/year, so the waste ultimately reaches the beach/sea. The total amount of waste is estimated to be 200,000 m^3 (SCE, 2012), predominantly comprising inert waste (concrete, stone, brick), mixed with other wastes such as metals (steel bars), plastic and rubber. The volume of plastic and metals migrating from the unstable slope to the beach is estimated at about 30 m^3/year, and this causes visual pollution on the coast, plastic pollution in the sea, as well as risks of injury for walkers (SCE, 2012). These issues were identified in the 1980s, but landfilling of waste continued until 2000 (SCE, 2012). Since 2009, the Le Havre municipality has funded an association to conduct cleaning operations at beach level (1–2 tons/year, €22,000/year). The scenarios available to manage this landfill in the long term include: (1) removal of the landfill, including excavation on the top of the cliff, transportation and treatment of all wastes (as at La Samaritaine), (2) confinement of the wastes with riprap or other coastal defenses, and (3) continue regular manual cleaning along the shoreline over the next 40 years. The costs of the removal action were estimated at €20 million (including landfill tax) over a 10–15 years work span, against €5 million for waste confinement, and €2 million for sustained cleaning. Despite its higher costs, the waste removal option has been chosen (Le Parisien, 2020) funded by the French Environment Agency ADEME (70% of the budget), City Council (20%) and the Water Agency (10%). A demonstration of the feasibility of waste removal and treatment was conducted in 2020 (**Figure 6**). Equipment and personnel reached the site by barge, wastes were removed from the cliff in big-bags by helicopter, transported by truck to a waste treatment center, separated into recyclable waste (mostly metals and inerts) and the residual waste landfilled. This demonstration also provided an improved assessment of waste characteristics.

In both these cases, the total amount and the nature of waste was not precisely known until the landfill began to rapidly erode (around 2 m/year). Funding of the remediation was difficult, especially at La Samaritaine, as no organization was willing to fund the entire costs. There, the 2016 storm and the potential for greater release of waste to the sea

FIGURE 4 | La Samaritaine landfill **(A)** prior to waste removal in 2016, **(B)** during waste excavation (November 2017) with erosion being stopped by riprap and a geotextile, **(C)** the restored site (May 2018). Photography **(A)** courtesy of Ouest-France archives, **(B,C)** courtesy of Geraldine Lebourgeois/La Presse de la Manche.

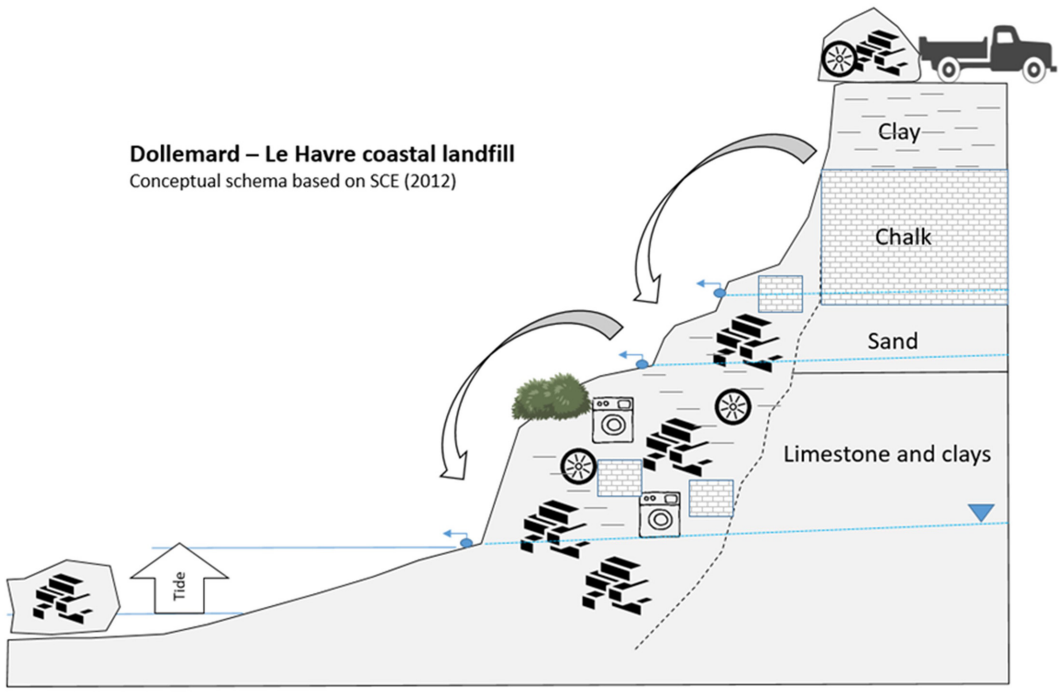

FIGURE 5 | Conceptual cross-section of the Dollemard landfill in Le Havre (France). Adapted from SCE (2012).

was key to stimulating a decision, and the operations were ultimately funded by a partnership of state agencies (Water Agency), the region, the department and the municipalities. Although removal was the selected option for both case studies, removal is not a national policy in France and other options were considered for the Dollemard case. These case studies highlight the need to anticipate better where and when other French coastal landfills might be flooded or eroded as sea level rises, so that more proactive management approaches can be followed.

FIGURE 6 | Trial waste removal at the Dollemard landfill (summer 2020). Photograph courtesy of Le Havre council.

A GERMAN PERSPECTIVE ON COASTAL LANDFILLS

Currently, 1,027 landfills are in active operation in Germany, of which 849 are landfills for excavated soil or inert waste and 213 sites receive hazardous wastes (DESTATIS, 2021). These numbers contrast with the vast legacy of nearly 67,000 inactive (i.e., former) waste disposal sites (LABO, 2018). Germany comprises a federal republic of 16 states, each being responsible for its own waste management. Five federal states (Hamburg, Bremen, Lower-Saxony, Schleswig-Holstein, Mecklenburg-West Pomerania) are potentially affected by coastal flooding, erosion and SLR. There is no systematic assessment on the number or size of active or inactive landfills directly on Germany's coastline and few active landfills are situated near the coast. Further, unlike in England and France, there are no reports of landfill waste being released to the marine environment. The extensive and continuous flood defense systems along the North Sea coast suggest that waste release is unlikely (Sterr, 2008), while on the Baltic coast there is more variability in terms of both geomorphology and presence of coastal defenses (van der Pol et al., 2021). For legacy sites, targeted information on the number close to the coast is also not available; although more information could be harvested from GIS data on location and local topography, which is available for some states. Readily available data, published on the websites of the respective five federal states, report the overall number of landfill sites as:

- Hamburg: No specific data on old waste deposits, but 1,099 confirmed contaminated sites (Hamburg, 2021)
- Bremen: 141 old waste deposits (Bauumwelt Bremen, 2021)
- Lower Saxony: 10,508 old waste deposits (LBEG Niedersachsen, 2021)
- Schleswig-Holstein: 3,023 old waste deposits (Schleswig-Holstein, 2021)
- Mecklenburg-West Pomerania: 2,400 old waste deposits (Regierung MV, 2021).

Note that in Germany the risk of flooding and the effects of erosion on landfills may also arise along rivers where climate change may increase peak flows. In Austria for example, Laner et al. (2009) showed that around 30% of the old waste deposits are located in areas prone to river flooding once every 200 years, indicating the potential scale of the problem.

As an exemplar, we consider the Hanseatic City of Rostock (**Figure 1**), which is one of 294 counties in Germany. With around 200,000 inhabitants and a land area of around 181 km^2, Rostock is the largest city in Mecklenburg-West Pomerania (MV) and is located where the Warnow (the largest river in MV) drains into the Baltic Sea. There are no active landfill sites. However, the inventory of potentially harmful soil changes, contaminated sites, and suspected contaminated sites for Rostock contains more than 3,550 historical sites, including 350 locations where waste and harmful substances have been deposited (e.g., landfills, including illegal sites). The majority of these sites have been assessed and 57 landfills are defined as contaminated, or sites that are still suspected of being contaminated.

We investigated the flood risk for these historical landfills. Landfills potentially flooded in a 200-year event (2.3 m water level; StALU MM, 2012) today are identified considering local topography assuming a simple first-order bathtub method and assuming that the existing coastal defenses are removed. As all the relevant landfills are inside the flood protected areas, they are all presently protected to design level or even higher with heights between 2.8 and 3.0 m. Mean SLR projections by 2100 associated with two Representative Concentration Pathways, RCP4.5 and RCP8.5 emission scenarios (Church et al., 2013), are added linearly to estimate the 200-year return levels by 2100 (2.78 and

3.07 m, respectively) and again potentially flooded landfills are identified using the same assumptions. Today, nine individual sites (16% of the contaminated locations) in Rostock are below the 200-year return water level. Under the RCP4.5 and RCP8.5 scenarios, current design levels are exceeded and the number of potentially affected landfills increases to 26 and 27 sites (64 and 47%), respectively. Assuming defenses continue to be upgraded for SLR, the risks to 2100 still appear low.

More generally, around 70% of the German Baltic Sea coast is affected by erosion, with recession rates of 34 m in 100 years, on average (Gurwell, 2008). All the landfills investigated here are situated at least 300 m inland of the open coast, so erosion is not expected to affect them appreciably over the coming decades. Nonetheless, given the long timescales of landfill waste degradation, more detailed assessments are worthwhile considering sites where release is most likely, as well as exploring the long-term implications for coastal management and defense.

A PERSPECTIVE ON COASTAL WASTE AND LANDFILLS FROM THE NETHERLANDS

The Netherlands is located in the low-lying delta of the Rhine, Meuse and Scheldt rivers which flow into the North Sea (**Figure 1**). The elevation of around half of the Netherlands' surface area does not exceed 1 m above mean sea level and around one third of the country lies below sea level. This region is also the most densely populated area in north-western Europe, home to the megalopolis formed by the county's main cities including Amsterdam and Rotterdam (Dutch: Randstad), and protected from flooding by a system of dike rings (Priemus, 2018). For centuries, land reclamation, continued pumping of water, and heightening of strategic areas have enabled human settlement and economic activities (Van Koningsveld et al., 2008; de Moel et al., 2011).

Next to the rise in mean sea level, threats of flooding induced by climate change include increased storm surges and increased river discharge (Katsman et al., 2011). Effects are aggravated by land subsidence rates of up to 5–8 mm/year (Hoogland et al., 2012). However, intrusion of saltwater, resulting from SLR in combination with lower river discharge during summer, is currently projected to threaten freshwater supplies from ground and surface waters more than direct flooding (Kwadijk et al., 2010). Coastal defenses in the Netherlands include the six key storm surge barriers such as the Eastern Scheldt and the Maeslant Barrier, dikes, flood protection walls, but also the coastal dune belt. Protection against coastal erosion is based on the principle of dynamic preservation of the sediment balance (Van Koningsveld and Mulder, 2004) by adding sand nourishment of the order of 12M m^3 annually. Options for adaptation to SLR in the Netherlands include additional/upgraded storm surge barriers, strengthening of dikes and dams, enhanced sand nourishment, increased pumping, construction of flood-proof buildings, land reclamation, and planned (or managed) retreat (Haasnoot et al., 2020).

A direct result of the dense settlement and the intensive economic activity in the Dutch delta is the multitude of former or legacy landfills, which are defined as landfills that ceased operation before September 1996. The base of most of these sites is located below current sea level and approximately 25% are in direct contact with the groundwater as backfills, for example, of sand or gravel pits. Post-medieval coastal defense structures in the Netherlands usually do not contain waste materials, although the filling of waste into concrete blocks for coastal defense structures has been considered in the recent past (Land+Water en Milieumarkt, 1994). The location of Dutch waste disposal sites therefore mostly corresponds to the situation depicted by **Figure 2**, situation H. A specific legal framework for legacy landfills is missing and competent authorities act on the basis of the Soil Protection Act and provincial environmental regulations. Information on type and volume of landfilled material is not available at a national level as records reside with the provincial or municipal authorities (Lieten, 2018) and, for around 10% of these legacy sites, information on their specific location is missing. In the 1990s, the Dutch government commissioned the NAVOS project (Dutch: Advies Nazorg Voormalige Stortplaatsen, "Advice on aftercare of former landfills"), which carried out a comprehensive inventory of the estimated 4,000–6,000 Dutch legacy sites (Tauw B V, 2016; Lieten, 2018). These sites, of which half are smaller than 0.6 ha, comprise an estimated surface area of 8,000 ha and possess neither bottom nor surface sealing systems. The absence of sealing components effectively means that the waste body has been leached for decades. The objective of the study was to assess the related environmental impacts, regulatory deficiencies and societal problems in order to estimate the scope, organization and financial implications of necessary aftercare or remediation measures. The assessment was based on historical data of waste composition, visual inspection of the cover soil, quality of the groundwater in the sites' vicinity and size of the affected plume based on a limited number of monitoring wells positioned on an assumed principal groundwater flow direction.

With respect to the condition of the landfill cover, it was found that in about 90% of cases the cover did not fulfill the regulatory thickness requirements of the Soil Protection Act. With respect to groundwater, the study concluded that for 75% of the sites the downstream groundwater quality was degraded, restricting its use, for example, for agricultural purposes. However, it was also seen that in some provinces, metal contamination in groundwater was more related to the elevated background geological conditions than to the landfill site. Furthermore, investigations into the natural attenuation potential concluded that in 70% of the cases the contamination was not spreading. Hence, it was judged that those landfills did not pose a significant environmental risk. In the remaining 30% of cases, further monitoring and possibly remediation measures were deemed necessary.

There are approximately 70 modern engineered landfills, with 19 of these sites still in operation (Lieten, 2018). All these landfills are constructed on elevated areas, meeting the distance between the bottom liner and the location-specific highest free groundwater table as required in the European Landfill Directive.

Not all, or not all individual landfill cells, however, are equipped with a combination base liner [high-density polyethylene (HDPE) membrane underlain by a mineral sealing layer].

The Dutch sustainable landfill project (iDS), enabled by a Green Deal between the Dutch competent authorities and Dutch landfill operators, comprises full-scale pilot stabilization projects by aeration and leachate recirculation at three closed landfills (Lammen et al., 2019; Dutch Foundation for Sustainable Landfilling, 2021). This project is at the forefront of international efforts to solve the long-term legacy issues relating to leachate and landfill gas emissions but does not consider the excavation and relocation of solid waste.

Experience with landfill mining in the Netherlands is limited. The projects carried out were motivated by property redevelopment, by gain in landfill capacity and by the need for remediation including installation of a bottom lining system, rather than risks posed by flooding or coastal erosion. However, the main hurdles to economically successful mining projects were found to be contamination with asbestos, availability of effective mining and separation techniques and the need to pay landfill tax for re-disposal of the excavated non-reusable or recyclable wastes (Lieten, 2018).

In view of the large uncertainties related to prediction of SLR, the Netherlands follow the adaptive Delta program 2021 (National Delta Programme, 2020), initiated in 2010 and updated annually, which strives to keep the Netherlands as the 'best protected river delta in the world'. Every 6 years, short- and long-term strategies for coastal and flood defense are reviewed and adapted based on predefined tipping points. The Delta program aims at: (1) protecting the country against flooding, now and in the future; (2) ensuring sufficient freshwater supplies; and (3) climate-proofing the country's spatial planning using the full range of adaptation options. Continued waste and landfill management in compliance with European, national and provincial regulations, are inevitably included in these aims and the corresponding actions, although not explicitly addressed in the Delta program. Therefore, it is not foreseen that SLR will motivate excavation, treatment or re-disposal of wastes in order to minimize environmental impact. This would only be needed if a planned retreat strategy is ultimately implemented triggered by large and rapid rises in sea level (cf. Olsthoorn et al., 2008; Haasnoot et al., 2020). To prepare for such an eventuality, the most obvious step would be to re-visit the assessment of the risk to the groundwater quality emanating from legacy landfills and from modern landfills lacking a bottom liner in light of increased saltwater intrusion. Possibly, the outcome might suggest future investment in surface sealing systems. The country's engineered landfills that are protected by dual-component bottom liners pose no concern in this respect. The clay component in the mineral layer may suffer from dispersion effects due to exchange of polyvalent cations with sodium; the functionality of the second component, the HDPE liner, should however, not be affected by increased groundwater salinity. In the unlikely event of a severe flooding disaster occurring because of failing flood defenses, the contribution of the former landfills in the region to environmental damages will be relatively small compared to those caused by all other anthropogenic contaminant sources.

A FLORIDA PERSPECTIVE ON COASTAL WASTE

Similar to the European examples discussed in the previous sections, thousands of active and inactive landfills are located in coastal counties around the United States, which is where nearly 40% of the population reside (NOAA, 2013). Amongst all 50 states, Florida is often considered most vulnerable to the effects of SLR with several population hotspots like Miami and Tampa/St. Petersburg listed globally in the top 10 among large coastal cities in terms of present and future flood risk (Hallegatte et al., 2013). Therefore, we focus here on Florida, but the general conclusions apply in similar ways to other U.S. coastal regions (as shown for Texas; Kiaghadi et al., 2020).

In addition to a high population density along its coastline, Florida's low-lying topography and geology, comprising porous limestone on top of bedrock, make the state susceptible to flood impacts. High-tide (or nuisance) flooding events already occur regularly in coastal cities like Miami and the number of events and places affected are projected to increase substantially even under moderate SLR scenarios (Sweet et al., 2018). Florida also lies in the paths of tropical cyclones, which can produce dangerous storm surges and waves and associated flooding and beach erosion, as experienced, for example, during Hurricanes Irma (in 2017) and Michael (in 2018).

Design and construction of municipal solid waste and hazardous waste landfills in the U.S. is regulated by Subtitle D and C, respectively, of the Resource Conservation and Recovery Act (RCRA) initially passed in 1989. Subtitle D requires composite liners with a minimum of 61 cm of 10^{-7} cm/s clay underlying a 1.5 mm HDPE membrane. The U.S. Environmental Protection Agency (USEPA) states that "landfills in 100-year floodplains must demonstrate that the unit will not restrict the flow of the 100-year flood, reduce the temporary water storage capacity of the floodplain, or result in washout of solid waste so as to pose a hazard to human health and the environment." However, prior to the RCRA, few if any regulations on landfill location existed. The legacy landfills in coastal areas are therefore of particular concern in terms of being affected by SLR, coastal flooding and erosion.

The Florida Department of Environmental Protection (FDEP) has been delegated by the USEPA to regulate landfills in the state following RCRA Subtitle D. Because of the geological conditions outlined above, the excavation depths for landfills are relatively shallow and they are elevated, instead of below ground. Hence, landfills in Florida are often landmarks and high points in the landscape. The FDEP Solid Waste Facility Locator shows over 10,000 sites in the state, including closed (the vast majority) and active municipal solid waste and construction and demolition debris landfills (95 at present), transfer stations, tire dumps, etc. This also includes disaster debris management sites used as intermediate staging areas in the wake of natural or man-made disasters. Hurricane Irma in 2017, for example, created up to 22M m^3 of debris across the state of Florida, as estimated by the U.S. Army Corps of Engineers (Florida Counties Foundation, 2021). Hurricane Maria in the same year produced 4.7M m^3 of debris (Kennedy and Migaki, 2017) overloading Puerto Rico's existing landfills, so that soccer fields and grounds of closed public schools

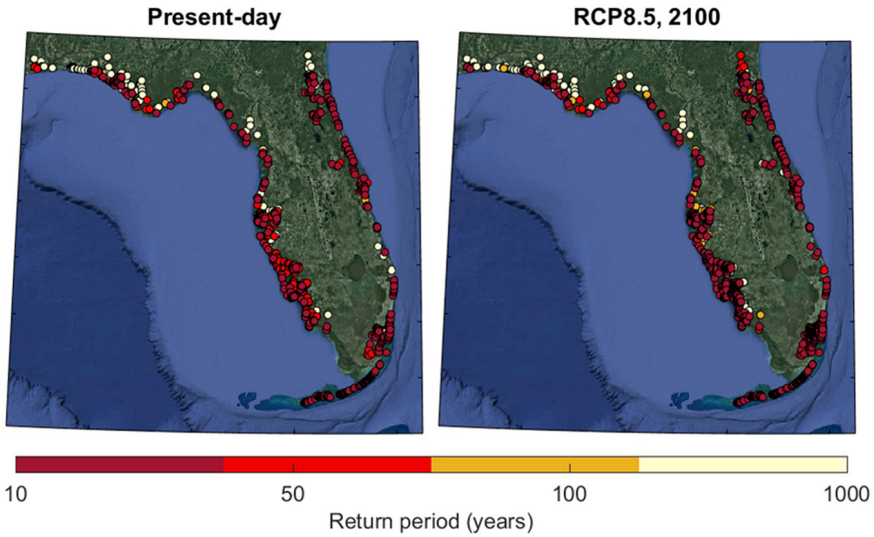

FIGURE 7 | Landfills across Florida located in the floodplain associated with different return periods (see color bar) under present sea level conditions (left) and with future SLR, considering the RCP8.5 scenario (right).

had to be used as interim storage sites; the heavy rain also left many landfills uncovered. These examples highlight that dealing with natural disaster debris is a recurring issue (as outlined in USEPA, 2019) that will escalate as the frequency and magnitude of these events is likely to increase due to SLR and global warming in the case of tropical storms.

In the FDEP database, we identified 8,082 individual locations in terms of latitude and longitude information (sometimes multiple facilities or components are at the same location). Of these, 3,026 are located within the Federal Emergency Management Agency's (FEMA) 100-year flood hazard zone, where the chance of experiencing flooding is at least 1% in any given year; 97 are in the V zone and 2,929 in the A zone. Sites located in the A zone may be affected by inland flooding or coastal flooding (or both), while the V zone is a particular case within the A zone, designating higher risk areas from storm surge flooding and wave impacts, potentially leading to erosion. Focusing only on the 473 sites categorized as Class I, II, or III municipal landfills [classified based on the amount of solid waste received daily, following Florida Administrative Code Rule 62-701.340(3)], 143 are within FEMA's 100-year flood hazard zone (3 in the V zone, 140 in the A zone).

While FEMA's flood zones are derived from extensive hydrodynamic numerical modeling and provide useful information on contemporary flood risk for given exceedance probabilities, the information is often insufficient to identify facilities threatened by flooding (Kiaghadi et al., 2020). Importantly, the effects of SLR are not included and it is also unclear which locations in the A zone are at risk from coastal versus inland flooding. Hence, we used a simple first-order bathtub approach with hydrologic connectivity to identify landfills that are at risk from coastal flooding resulting from extreme storm tides under present conditions and with different SLR scenarios. Note that this approach excludes velocity reduction due to bottom friction and therefore the flood extent could be overestimated. On the other hand, the extreme water level on the coast could be underestimated because wave action is not considered. A digital elevation model (NOAA, 2001) and extreme sea-level information derived with the latest version of the Global Tide and Surge Model (Muis et al., 2020) for the period 1979 to 2017 was used. The extreme sea-level data was bias corrected using tide gauge information and inverse distance weighting as described in Arns et al. (2015). Return periods (RPs) and associated water levels are derived with annual maxima and a Generalized Extreme Value distribution as well as peaks-over-threshold (using the 99th percentile) with a Generalized Pareto Distribution; the root mean squared error between empirical and theoretical distributions is used to select the best approach for a given grid point along the coast. For SLR scenarios, we consider a uniform rise of 0.5 m as a low-end scenario, 0.62 and 0.81 m as the average of the 50th percentile SLR by 2100, derived by Kopp et al. (2014) for the Florida coastline under RCP4.5 and RCP8.5 emissions respectively, and 1.5 m as a high-end scenario.

We estimate that 1,099 landfills are located within the present 100-year coastal flood zone (see **Figure 7**, left); this number increases to 1,642 by 2100 under the RCP8.5 scenario (see **Figure 7**, right) and reaches 2,454 when considering the 1,000 year return level and high-end SLR scenario. The results for a range of different return levels (10-, 50-, 100-, and 1000-years) and the four SLR scenarios are summarized in **Table 2**.

As an indicator for erosion potential, we use the coastal vulnerability index (CVI) (Thieler and Hammar-Klose, 2000). This is preferred over shoreline change rates derived from satellites and/or beach surveys (e.g., Kratzmann et al., 2017; Luijendijk et al., 2018) as it excludes the influence of the regular beach nourishment of Florida beaches (Elko et al., 2021); our goal is to combine information on flood potential with information on erosion potential and compare it with landfill locations. For

TABLE 2 | Number of landfills located in the coastal floodplain associated with different return periods and SLR projections.

SLR scenario (m)	Return period (years)			
	10	50	100	1000
0 (present)	616	1088	1099	1677
0.5 (low-end)	1051	1278	1357	1990
0.62 (RCP4.5)	1217	1440	1536	1997
0.81 (RCP8.5)	1404	1497	1642	2039
1.5 (high-end)	1611	1672	1869	2545

TABLE 3 | Number of landfills located near a coastline with low, moderate, or high coastal vulnerability index (CVI) under water levels associated with different return periods.

RP (years)	Coastal vulnerability index (CVI)		
	Low	Moderate	High
10	24	208	384
50	85	589	414
100	87	592	420
1000	188	875	614

example, of the 1,099 landfills located in the present 100-year coastal flood zone, 87 are located near a coastline with a low CVI, 592 with a moderate CVI, and 420 with a high CVI (**Figure 8**). Results for other return periods and under present-day sea level conditions are summarized in **Table 3**.

These results highlight that landfills along the entire Florida coast are exposed to SLR, especially on the east coast, from Cape Canaveral to the Keys, where a high CVI amplifies the threat of flooding and erosion. **Figures 9A,B** show two examples from South Florida, the South Dade landfill in Miami and Long Key landfill in Monroe County, both located at the water's edge. Another example is Virginia Key off the coast of Miami, where one of the city's biggest parks is being built on an old landfill (**Figure 9C**). The landfill opened in 1960, was closed in 1977 and capped in 1980. The cap has not been maintained and has been eroded by rainfall events to as little as several centimeters thick in places. Now, 60 cm of lime-rock fill, in combination with two pumps and a deep injection well to remove contaminated groundwater, will be installed (Viglucci, 2017). Being built up to 9 m high, the risk for overtopping is relatively low but being located on a barrier island the base of the site is highly exposed to future impacts from SLR, surges and wave impacts. In Key West, the Stock Island landfill (**Figure 9D**) collected waste from 1930 until its closure in 1990 (released from long-term care in 2016), growing to 27 m above sea level and occupying a 7.3 ha parcel (for comparison, the highest natural elevation across the entire Florida Keys is about 6 m). The landfill has passed testing for compliance with federal regulations, but does not have a liner, raising concerns about contamination of the surrounding soil. However, removing the landfill to road level and transporting the waste to other facilities has an estimated cost of $70 to $190 million (€60 to €160 million) and this has not been pursued (Blinckmann, 2018). All examples shown in **Figure 9** can be classified as situations B and C in **Figure 2**.

The results highlight the existing risk of flooding and erosion from storm surges and waves for coastal landfills across Florida, and by implication nationally. This risk will increase as sea level continues to rise and exacerbates beach erosion, which is constantly battled in Florida by recurring beach nourishment in support of the thriving tourism industry which is one of the largest contributors of the state's GDP (Elko et al., 2021). In the long-term, nourishment costs will increase as frequency is increased and sand availability is expected to decline. Ultimately, and without additional adaptation measures being implemented (e.g., building dunes, using sand fences or vegetation as sand traps, providing accommodation space for beach/dune

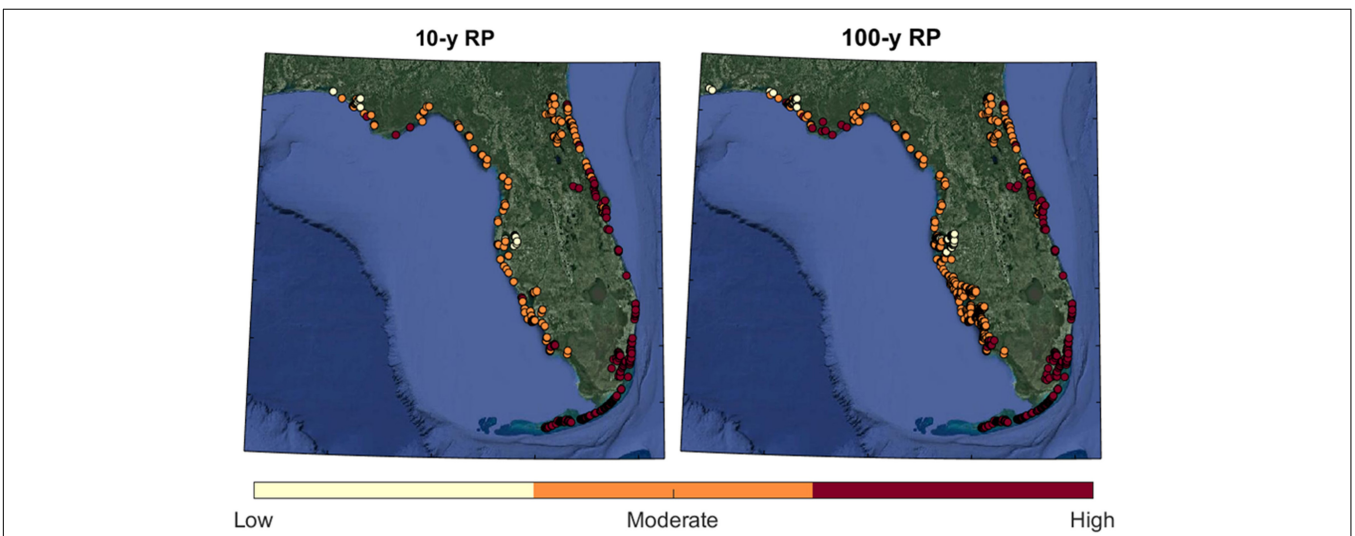

FIGURE 8 | Coastal vulnerability index (CVI) for coastline stretches with landfills located in the 10-year coastal flood plain (left) and 100-year coastal floodplain (right).

FIGURE 9 | Aerial photos of **(A)** the Long Key landfill in Monroe County, FL, next to the Gulf of Mexico, **(B)** the South Dade landfill in Miami, FL, next to Biscayne Bay, **(C)** the Virginia Key landfill in Miami Dade County, FL, between Biscayne Bay and the Atlantic Ocean, and **(D)** the Stock Island landfill in Key West, Monroe County, FL, next to the Gulf of Mexico (source: Google Earth).

migration), this may lead to shoreline retreat exposing some landfills to erosion. As experience of landfill reclamation grows globally (Jones et al., 2013), in the United States (USEPA, 1997) and in Florida (e.g., Jain et al., 2013), new options may arise (see section "Synthesis of the National Case Studies and Management Options for Historical Coastal Landfill"). Overall, the awareness of climate impacts on coastal landfills is increasing in the United States. Citizen concerns have been raised regarding the Key West landfill as discussed, but even in Alaska a report has identified solid waste management sites as vulnerable to flooding and proposed action plans for those of most concern (ADEC, 2015).

SYNTHESIS OF THE NATIONAL CASE STUDIES AND MANAGEMENT OPTIONS FOR HISTORICAL COASTAL LANDFILL

Table 4 summarizes the preceding case studies. This emphasizes the scale of the problem that exists today; there are thousands of coastal landfills that are of concern under present conditions and waste release events are already documented in England, France, and the United States. SLR (and maybe wider climate change) will increase this number, but are certainly not creating them alone. The wide range of situations where landfill releases can occur is apparent, and coastal adaptation choices are critical in future outcomes. For example, the expected abandonment of large lengths of defenses in England over the next century (CCC, 2018) has profound implications for landfill release beyond the magnitude of SLR. Without recognition of the problem, substantial release of waste into the sea would appear inevitable. The long timescale inherent in the management of landfill sites is also apparent, with potential consequences growing over time.

The management responses to these actual and potential landfill problems are wide-ranging and, in many instances untested. Building on earlier experience of Cooper et al. (2013); Nicholls et al. (2018b), Wadey et al. (2019); Beaven et al. (2020), and the results of this paper (see above sections), **Table 5** summarizes available options and current experience. These approaches draw on the source-pathway-receptor model used for controlling pollution risks (Watts, 1998). Beyond '*do nothing*' and simple '*inspection and surveillance,*' several distinct options can be selected over time to manage a coastal landfill, e.g., starting with '*reactively removing released waste*' after a storm, proactively '*remove the source*' of waste, '*break the pathway*' between the source and the receptor, and finally '*remove the receptor.*' While there is much experience of protection (break the pathway), and experience is growing for other options, such as waste relocation in France, or landfill mining in Belgium

TABLE 4 | Synthesis of the case study results.

Location	Number of landfills (to nearest 10^3)		Landfill Situations found (as defined in Figure 2)	Present and future coastal erosion and flood threats to coastal landfill (long-term > 50 years)
	At location	In coastal flood plain today		
England	20,000	1,200 occupying about 3,400 ha	All Situations found, except G, although expected to arise	Some active erosion and immediate threats, with many landfills threatened in the longer term – the long-term growth in these threats links as much to coastal management policy change as the magnitude of SLR – at least before 2100
Lyme Regis to Worthing (England)	Not known	144 threatened by flooding and/or erosion (covering 2,200 ha and 86 km of coast)	Situations A to F found, with Situation E being most common	
France	>14,000 nationally; 1,000 in coastal departments	Not known	Not known, but wide range of Situations possible	Some immediate threats, but poorly characterized nationally, longer term threats are uncertain
Germany (coastal states)	> 14,000 in all five coastal states	Not known	North Sea – mainly Situation H; Baltic – not known, but more variable	Long-term threat on North Sea, on the Baltic potentially more immediate in some areas, but no detailed assessment
Rostock (Germany)	57	9 rising to 27 with SLR of 0.8 m	Situation F and H	Long-term threat
Netherlands	4,000–6,000, occupying 8,000 ha (most are in flood plains)		Mainly Situation H	Long-term threat if current management policies change
Florida	<8,100	1,100 (rising to 1,900 with high end SLR of 1.5 m)	Mainly Situations B, C and F – landfills often form a high point in the landscape.	Some immediate threats, especially during hurricane landfall events, which will increase significantly and rapidly with SLR

TABLE 5 | Summary of potential historical coastal landfill management options from this analysis, using the source-pathway-receptor terminology for pollution risk (see also Cooper et al., 2013; Wadey et al., 2019).

Option	Description	Status	Implications	
Do nothing		Current situation for most historical landfills, mostly reflecting the default situation (rather than a deliberate policy decision) that exists through lack of funding and/or awareness of landfill erosion and flooding risks. Since many sites are situated on relatively stable (i.e., exposed to low energy wave conditions, estuaries, etc.), unmonitored shorelines, any erosion is unnoticed.	Emerging problems not appreciated. Change to another option triggered by unexpected waste release [e.g., Spittles Lane, England (Section "An English Perspective on Coastal Landfills") or La Samaritaine, France, Section "A French Perspective on Coastal Landfills"]. Hence, as a minimum a low level "Inspection and surveillance regime" is recommended – see below.	
Inspection and surveillance (monitoring)	Characterize risk/hazard by sampling and monitoring shoreline change	*Ad hoc* and unsystematic and a risk is that data is not being archived or shared – those responsible for these sites are often cautious about intrusive investigations due to potential legal implications and uncertainty over responsibility.	No standard method so significant uncertainty and inconsistency in how to use the monitoring data. Where waste release occurs in some cases there is an aspiration to follow the precautionary principle i.e., release should be stopped, but in other cases erosion is accepted with no mitigation.	
Reactively remove released waste from foreshore	Regular collection and disposal of waste materials identified as posing a risk	Has been practiced occasionally where eroding landfill is on a dynamic wave-exposed coast [e.g., Spittles Lane (section "An English Perspective on Coastal Landfills"), and as an emergency measure]. Liability issues and motivation often unclear (i.e., whether to avoid pollution to sea or risk to health).	Does not fully prevent waste posing a hazard especially on wave-exposed foreshores where fines and low-density wastes are rapidly dispersed. The landscape value is negatively affected (one of the reasons this option was rejected at Dollemard landfill, France, section "A French Perspective on Coastal Landfills"). Needs sustained funding. Absence of appropriate science hinders evidence-based analysis.	
Remove the source of the risk	Treat the waste	No experience in coastal landfills yet. The concept is to remove the more toxic waste components and leave a residual inert material which is acceptable to release to the environment.	Develops previous landfill mining and recovery experience for this application. A potential research and/demonstration activity to be explored; may be more viable/lower cost than total excavation (below).	
	Excavate/remove	A few examples: La Samaritaine and Dollemard landfills, France (section "A French Perspective on Coastal Landfills"), and Trow Quarry northeast England where partial removal occurred to regrade and stabilize the slope.	High costs due to landfill tax can be a major barrier to this option, especially where high tax rates are charged (e.g., United Kingdom), representing an unintended consequence of landfill tax policy. Finding disposal sites can be problematic, including transport of more hazardous substances increasing uncertainty about costs.	
Break the pathway between the source and the receptor	Erosion defenses (for cliffs, dunes, etc.)	The most commonly observed solution due to well-practiced coast protection methods; although, for example in England (and perhaps elsewhere), this is rarely implemented to protect landfill itself: funding depends on non-landfill benefits. It is unclear if the pathway is completely broken when defenses focus on non-landfill objectives (i.e., consider leachate gas, groundwater migration beneath the defenses, etc.).	Defend and prevent erosion – extensive and widespread experience, but can it be funded and for how long? Restricts sustainable shoreline evolution which may be preferable.	Waste remains *in situ* with uncertain long-term implications
	Flood defenses (for flood plains around estuaries or the open coast)		Defend and prevent flooding and erosion – extensive and widespread experience – only likely to be implemented in more developed areas. Can be expensive, especially when defenses are integrated with drainage solutions.	
	Beach nourishment (soft defenses)		Increasingly applied in all countries considered (e.g., Florida, the Netherlands). However, sediment supply is finite and SLR increases costs of this strategy.	
	Nature-based solutions	Natural defenses protect many landfills today but are widely declining. Artificial saltmarsh restoration via beneficial dredge re-use being investigated (e.g., in Poole Harbour, **Table 1**).	Limited experience and understanding of artificial enhancement – but rapidly developing area of research and practice.	
Remove the receptor to the risk	Move away from the landfill	It is usually not possible to move the coastal/marine environment (receptor) away from a landfill. In the other direction, people have been relocated from inland chemical dumps, but no experience/examples to date with coastal landfill.	With people as receptors this only occurs when health implications become obvious and critical.	

(Winterstetter et al., 2018), many gaps in knowledge are apparent which hinder the full range of these options being applied in an evidence-based manner. The large differences in cost between break the pathway (protect) and waste removal identified in the English case studies are noteworthy and suggest protection would be preferred. However, as the waste needs to be protected in perpetuity, the time dimension also needs to be considered and developing affordable, acceptable and more permanent solutions is essential. The lack of a method to assess the harm from waste release is a major limitation as it hinders the definition of (1) acceptable (if any) flux of release of different types of solid wastes into the marine environment, and (2) potential standards for landfill mining to remove the more hazardous materials. It is also noteworthy that landfill taxes can hinder relocation of waste, which was not part of its original intention: waiving or greatly reducing the tax could facilitate more use of this approach.

DISCUSSION

Based on the case studies discussed here, and the wider assessment of the status of coastal historical landfills, five main issues emerge which resonate with earlier assessments in England (Nicholls et al., 2018b; Wadey et al., 2019). First, the potential scale and implications of waste release to the coastal and marine environment is not sufficiently understood or appreciated. Hence, it remains important to develop a better understanding of the amount, character (biological, physical, and chemical) and potential impact on human health and the environment of waste release from coastal landfill sites for the countries considered and by implication, globally. While some national or regional situations have been assessed, as reviewed here, these are incomplete and have significant gaps. The case studies also highlight the large uncertainties at individual sites and that basic information such as the depth and volume of waste in historical landfills is often missing. A fundamental gap is the lack of methodology and suitable protocols to characterize waste in modern and historical landfills which captures waste heterogeneity and assesses the potential impact of solid wastes release into the marine environment. There is also a need to develop appropriate sampling protocols linked to the outcomes of any new waste characterization review. Landfills are currently being managed without this important information.

Second, there is a need to better address the regulation of solid wastes eroding from coastal landfills. To date, there has been only limited investigation of the hazards associated with the release of these waste materials to the marine environment. Current projections of waste release into the ocean are not compliant with the Sustainable Development Goals (Chen et al., 2020). This raises the following questions: are all such releases unacceptable, or is there an acceptable rate of discharge of certain solid wastes under specific circumstances? How can the limited funding available be used most effectively to manage/address the risk of waste release to the ocean from landfill erosion and flooding?

Third, while flooding and groundwater flushing of coastal landfills can generally be assessed to some degree, there are significant gaps in information and understanding on present and future release of waste due to erosion, including the impact of SLR. To understand this a wide range of factors beyond climate change need to be considered for each landfill site, including: (1) the dominant coastal hazard; (2) the coastal geomorphology/setting; (3) present and future coastal adaptation; (4) adjacent land use, including habitat designations; and (5) the waste and landfill properties (cf. Beaven et al., 2020). While systematic coastal monitoring data are becoming more widely available from national and regional monitoring activities like the Channel Coastal Observatory[1] and satellite-based observations in more data-sparse areas (e.g., Luijendijk et al., 2018), this problem requires more focus on local changes around coastal landfill sites. Small erosional changes can release significant amounts of waste materials as shown in the two French case studies. In addition, there is a need for more analysis of future geomorphic change in the diverse range of settings where coastal waste is found, especially estuarine settings where landfill sites are concentrated. It should be noted that changes in designated coastal habitats are often linked to, and significant for, coastal landfills. This suggests the need for an integrated climate service that takes information on SLR and climate change and other coastal data to translate these changes into threats to all human activities at the coast. In this regard coastal landfills could be seen as part of coastal infrastructure from this climate service perspective. Climate services have mainly focused on either the land, the sea, or climate change, without much focus at the coastal interface. A new core climate service for coastal adaptation to SLR is being developed as part of the European research project CoCliCo. There is a strong focus on flooding and erosion, but downstream services assessing cascading impacts of SLR, such as risks associated with landfills, could be developed as well.

Fourth, there is a need to develop more pragmatic and cost-effective remediation options that facilitate action rather than encouraging 'kicking the can down the road', which would seem to characterize many historical responses. In the case studies, identified problems are generally being ignored, but in the cases where it cannot be ignored, the main solution is to protect or relocate the landfills which are both expensive options. What other options are available (**Table 5**) such as landfill mining to remove the most toxic and unsightly materials and allow the residual more inert materials to erode? The role of landfill taxes in shaping these solutions should also be noted as the high costs attached to moving landfill are having effects that the original proposers did not have in mind. In general, the menu of proactive measures needs to be enhanced and developed.

Lastly, the widespread lack of funding hinders progress across these issues as these costs are not appreciated or considered in national budgets for coastal and environmental management. In highly developed flood-prone areas like the Netherlands, the German North Sea coast and the Thames Estuary in England, high and extensive defenses already protect most landfills so this is less of a consideration today. Elsewhere

[1] https://www.channelcoast.org/

funding is a real concern. In England, whilst HTL is the stated policy around most landfill sites, funding is limited and unless protection of other properties from flood and coastal erosion risk is also a benefit, the proposed policy often cannot be delivered (CCC, 2018; Wadey et al., 2019). This is increasingly recognized in policy circles (Stratton, 2019) and a national steering group has been established to champion these challenges to government in England. In France and the United States, funding is also raised as a challenge. Landfill mining experience in Belgium (Winterstetter et al., 2018) shows that the main benefit is the enhanced land value. However, mining has yet to be explored for coastal landfills (**Table 5**). To ensure long-term safety, dedicated funding is required to assess and proactively manage landfills rather than reacting to crises such as sudden waste release in a stormy year, as illustrated by La Samaritaine landfill, France. The appropriate scale of funding is open to debate.

This paper has focused on the current management challenges. The timescale of leachate release from modern landfills is already well-known as a concern that may last for centuries (Belevi and Baccini, 1989; Laner et al., 2012), and the concept of landfills acting as "final sinks" for wastes on a geological scale has also been recognized (e.g., Brunner, 2013). However, as far as we are aware, this paper is the first to acknowledge the geological scale of the problems that may arise from the release of solid waste to the environment through long-term erosion processes. As SLR will also continue for many centuries even if the Paris Agreement is fully implemented (Nicholls et al., 2018a; Oppenheimer et al., 2019), these problems will persist and worsen far into the future, reinforcing the need for research to improve scientific understanding and policy in this area.

The management measures for coastal landfills (**Table 5**) also need to be set in the wider context of coastal adaptation planning where a variety of strategies are available, including advance, protect, accommodate and planned retreat and growing interest in nature-based approaches (Oppenheimer et al., 2019; Hinkel and Nicholls, 2020). There are strong advocates for large-scale retreat (Siders et al., 2019) and the extent to which this occurs has significant implications for coastal landfill release and management (**Figure 2**). Using a benefit-cost analysis approach, Lincke and Hinkel (2018) conclude that 13% of the world's coast by length is worth protecting against SLR over the 21st century irrespective of the scenario and discount rate uncertainties, while 65% of the world's coast by length is never worth protecting and some form of retreat is likely. In terms of assets, the 13% of coast contains 96% of assets and any protection will therefore benefit many coastal landfill sites (situation H in **Figure 2**). If coastal defenses are deliberately abandoned or fail, large amounts of waste would be released, but as argued from the Netherlands perspective, in this situation other sources of anthropogenic material may dwarf the contribution of the historical landfill sources considered here. Nonetheless, further analysis of the implications of coastal landfill within strategic coastal adaptation planning would be prudent, especially when managed retreat is being considered.

CONCLUSION

Based on this analysis, the potential release of liquid and solid wastes from coastal landfill is an important threat which will worsen with SLR. Improved guidance is required to support risk assessment in relation to the long (geological) timescales of landfill sites, supported where necessary by new research and development activities to provide the required scientific understanding and evidence. This includes improved methods to characterize waste in landfills in terms of the potential impact of different categories of solid waste if released into the coastal and marine environment. The magnitude, transport, and impact of solid wastes need more consideration to develop appropriate assessment methods, including ranking sites for action. There is also a need to understand better the behavior of waste-associated contaminants in historical landfill materials and the likely response to leaching across the range of salinities from fresh to fully ocean conditions. Furthermore, there is a need to better identify both the site characteristics of coastal landfills and the potential costs (over different time frames) of the range of adaptation measures available to avoid adverse impacts.

Where protect (HTL) is the preferred adaptation policy for coastal landfills, the costs and benefits beyond avoided erosion and flood damage need to be considered. This is not arguing for universal defense, but rather asking what are the appropriate resources to plan and implement a response. Funding mechanisms need to be reviewed and coastal societies need to ask what level of current and future funding is appropriate for this issue. It should be noted that where landfill tax has been implemented, this may be a major cost impediment to removing historical landfill material to less vulnerable locations. This was not its original intention. A number of other remediation approaches are possible, but they are at various stages of development and providing a comprehensive menu requires science-based evidence that is not yet available. The cases considered in this paper are drawn from European and U.S. situations, but they are transferable more widely: while the context will vary, the fundamental issues appear generic. In conclusion, managing the legacy of coastal landfills over the next century (and beyond) poses a significant challenge to coastal societies, and our scientific tools to analyze these problems and the policies that are applied require significant enhancement.

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RN, RB, and AS conceived the manuscript, produced the overall manuscript framework, discussion and conclusions and together with KS. MW, and SC wrote the England section. DM and GL wrote the French section. TW, DR, VS, and AE wrote the Florida section. JG and TH wrote the Netherlands section. AA wrote the German section. All the authors completed and reviewed the final manuscript.

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