United Kingdom Nirex Limited

TECHNICAL NOTE

Summary Note for CoRWM on the Impact of Rising Sea Levels on Coastal Sites with Radioactive Waste Stores

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nirex

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CORPORATE COMMUNICATIONS ADMINISTRATOR

United Kingdom Nirex Limited
Curie Avenue
Harwell
Didcot
Oxfordshire
OX11 0RH
UK

Or by e-mail to: info@nirex.co.uk

ABSTRACT

The UK policy for the long-term management of radioactive wastes is currently undergoing review as part of the Government's Managing Radioactive Waste Safely (MRWS) Programme. The Committee on Radioactive Waste Management (CoRWM), was set up by Government in November 2003 to oversee a public consultation on such long-term management options. CoRWM's key task is to recommend to Government what should be done with wastes for which no long-term management strategy currently exists. CoRWM are due to make their recommendations to Government in July 2006.

Nirex is an independent body responsible for supporting Government policy to develop and advise on safe, environmentally sound and publicly acceptable options for the long-term management of radioactive materials in the UK.

This summary note has been prepared by Nirex in response to a request from CoRWM to summarise the current understanding concerning likely levels of sea level rise around the UK over the next 300 years and to comment on the potential impacts of changes in sea level or erosion for coastal sites where radioactive waste is currently stored. It is based on a compilation of information that Nirex has commissioned since the late 1980's, from additional work carried out by its contractors and from open literature.

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1 INTRODUCTION

The UK policy for the long-term management of radioactive wastes is currently undergoing review as part of the Government's[1] Managing Radioactive Waste Safely (MRWS) Programme [1]. The MRWS Programme sets out two key decisions to be made. Firstly, a decision to be reached on the option (or combination of options) to be selected for the long-term management of radioactive wastes in the UK. Secondly, a decision on the approach to implementation is required, which would include site selection strategy and criteria for the long-term management option(s) chosen.

An independent committee, the Committee on Radioactive Waste Management (CoRWM), was set up by Government in November 2003 to oversee a public consultation on long-term management options. CoRWM's key task is to recommend to Government what should be done with wastes for which no long-term management strategy currently exists – that is high-level waste (HLW), intermediate-level waste (ILW) and some low-level waste (LLW) unsuitable for disposal at Drigg[2]. CoRWM will also consider materials that may be declared as waste in the future, such as spent nuclear fuel and separated stocks of plutonium and uranium. The inventory of wastes and materials that is being considered by CoRWM are described in CoRWM Document [2]. CoRWM is due to make its recommendations to Government in July 2006. A Government decision on implementation is expected around 2007 [3].

CoRWM held a series of 7 Specialist Workshops in June/July 2005 to assist it in the assessment of how the various short-listed waste management options [4] perform against the assessment criteria CoRWM has developed. The aims of the workshops were to develop scoring schemes and identify what information is needed to enable scoring of the short-listed options. A record of the key aspects of the workshops can be found in CoRWM Document 1256.2 [5].

During these specialist workshops several questions or requests for information were raised by the specialist group members to help them understand or clarify issues related to the options. They particularly identified information that would allow them to assess options against key criteria or sub-criteria (as described in Reference [5]). These information needs are summarised in CoRWM Document 1254 [6].

Nirex is an independent body responsible for supporting Government policy to develop and advise on safe, environmentally sound and publicly acceptable options for the long-term management of radioactive materials in the UK. This includes setting specifications and standards based on a phased geological repository concept, and providing advice on how to treat and package radioactive waste through application of the Nirex Letter of Compliance process.

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[1] Department for Environment, Food and Rural Affairs and Devolved Administrations for Scotland, Wales and Northern Ireland.

[2] However, for some ILW and LLW, the Nirex Letter of Compliance system has provided a framework that enables helpful progress to be made on the conditioning and packaging.

In July 2003 the Secretary of State for the Environment, Margaret Beckett announced that: "*It is very important that Nirex stands ready, along with others, to help CoRWM reach its view and inform policy decisions. It is important also that the company can do this from a position where it is, and can be seen to be, independent of industry"* [7].

Nirex was asked by CoRWM to provide feedback on these information needs, in particular indicating where Nirex could provide information to support the scoring of options (this is described in Reference [8]). Some of the information requested by CoRWM was not available in an easily accessible or up to date format, therefore Nirex offered to provide this information in the form of summary notes.

This summary note has been prepared by Nirex in response to a request from CoRWM to summarise current understanding concerning the likely extent of any sea level rise around the UK over the next 300 years and to comment on the potential impacts of such changes in sea level and erosion rates for coastal sites where radioactive waste is currently stored. It is based on a compilation of information that Nirex has commissioned since the late 1980's, additional work carried out by its contractors and open source literature. Although the climate studies and associated research that Nirex has funded have been directed towards a better understanding of long-term climate and environmental change (millennial time scales and longer), climate change and associated environmental effects over the next several hundred years have also been investigated by Nirex, albeit to a lesser degree.

This Summary Note briefly considers projections of sea level change over the next 300 years and also presents a generalised view of the potential impacts of an increase in sea levels over this time frame. On the basis of extensive, but preliminary work carried out by a consultant to Nirex, on assessing the vulnerability of identified radioactive waste storage sites, a summary of the risk of inundation at those sites is presented together with an evaluation of the sites that may also be vulnerable to temporary flooding through storm surge effects or disruption due to coastal erosion.

2 IMPACTS OF SEA LEVEL RISE

Any increase in sea level might be anticipated to simply involve the gradual inundation of low-lying coastal locations around the UK. In practice, however, any evaluation of the consequences of an increase in sea level is more complex, both in terms of the regional extent of the areas likely to be affected and in terms of the processes involved. There are likely to be local variations in the most vulnerable areas to sea level rise as the land surface is itself dynamic, with some regions of the UK rising and others sinking, relative to mean sea level. These factors would locally exacerbate or ameliorate any overall rise in global sea level caused by a net increase in the volume of sea water. In terms of the processes associated with any increase in sea level, it should be noted that as a consequence of a global increase in temperatures through climate change, the intensity, frequency and area of occurrence of severe storms and tidal surges will vary as a direct result of the increased global energy budget. In the case of the UK this may mean an increase in storm and tidal surge intensity and the frequency of such events. Furthermore, the rates and extent of coastal erosion are often directly proportional to storm frequency and intensity and it is often the effects of coastal erosion that are more significant in terms of impact, as compared to gradually encroaching seas.

Some of the general potential impacts of the projected sea level and climate changes for the UK are considered below. Much research into the effects of various natural hazards has been carried out by the Benfield Hazard Research Centre (e.g. [9]) and some of the information below is based on work from that source. The specific risks associated with changing sea levels at some of the identified radioactive waste storage sites in the UK, are considered in more detail in the Appendix.

2.1 Inundation

In scenarios for a rise in sea levels over the next three hundred years, it can be presumed that as sea levels increase, the coastline (commonly represented by the limit of mean high tides) will in general gradually migrate landward, and this will eventually submerge areas currently above the tideline. The extent to which the coastline migrates landwards and the rates of such movement will vary in response to global sea level variations and due to local factors, such as the slope of the shore and the relative subsidence or uplift of the land. In shallow sloping areas, flooding will occur more frequently through the effects of higher tides and general encroachment. Consequently, over time sea water will be expected to inundate areas progressively further inland and any tidal wetlands and low-lying beaches will migrate with the tideline, also changing the environment of the area. Clearly, where radioactive waste stores are located in areas vulnerable to the effects of gradual sea encroachment, the facilities will need to be moved or protected from inundation in some manner.

2.2 Flooding due to storm surges

Storm surges result in a localised increase in sea level caused by low atmospheric pressure and strong winds. They can cause severe, but temporary, coastal flooding and accelerated coastal erosion. The height of a storm surge can be increased by funnelling of the sea, caused by the disposition of coastlines and as occurs on the east coast of the UK. The patterns and magnitude of storm surges in future climate scenarios are difficult to model at present, but it is predicted by the IPCC, UKCIP and others (e.g. [10]) that storm surges and consequent flooding and coastal erosion will increase in frequency and magnitude in the future, due to increases in sea levels and increased storminess due to a warmer climate.

Storm surges in the North Sea normally increase in intensity as they move south. This factor, combined with Scotland's generally erosion-resistant rocky coasts and isostatic uplift, suggests that north east Scotland would be likely to suffer less from storm surge flooding and damage compared to much of England and Wales.

Work reported by UKCIP [11] suggests that present-day 1 in 50 year storm events (i.e. a storm that has a 2% chance of occurring in any given year) may become more frequent in the future. For example, for the port of Immingham on the English east coast, a current 1 in 50 year event might occur as often as once every three years by the end of the 21st century. The UKCIP report also cites statistical distributions that have been fitted to model simulations of extreme storm surge heights. The models suggest that by 2080 the largest increases might occur off the southeast coast of England, where up to 1.4m increases in surge height are projected for the high emissions scenario (and taking into account vertical subsidence, change in storminess and global sea level rise). In Scotland a similar simulation also reported by UKCIP predicts that storm surges associated with a sea level rise will cause additional increases in water levels of 0.8m for a worst case climate scenario. This high emissions scenario is an extreme case and the uncertainties in the results are very large. Nevertheless, it can be appreciated that even with a more moderate increase in the frequency and intensity of storm surges, the effects of temporarily increasing sea levels through this mechanism, on top of any global rise in sea levels based on climate model projections, could have significant implications for the management of radioactive waste stores.

A conclusion of the UKCIP report is that some parts of the UK are consistently predicted to be badly affected by localised flooding as a result of storms, including the Lancashire/Humberside corridor, the south-east coast of England and major southern estuaries. The estimation of future flood risks is difficult due to uncertainties, but all scenarios predict a substantial increase in flooding.

2.3 Flooding due to tsunamis

Tsunami are low frequency sea waves that occur due to displacements affecting the sea and sea bed. They are extremely rare in UK waters, although they have occurred in the past (e.g. the Bristol Channel in 1607 [12] and the Shetland Islands and NE Scotland 7,900 years ago [13,14]). The Benfield Hazard Research Centre produced a risk analysis report in 2003 on earthquake triggered tsunamis in the Atlantic that might affect the UK [15]. Tsunamis are very unlikely to become more common in a 300 year future climate scenario, however, if a tsunami were to occur when sea levels were higher, the threat of inundation and destruction would be greater, and the zone at risk would reach further in land. Due to their low probability and highly variable potential impact, tsunamis are not considered in detail further in this note.

2.4 Erosion

Although coastal flooding is important and is also the most obvious result to be expected from a sea level rise, rapid coastal erosion leading to significant coastal retreat, is generally a far greater threat to current land use. The most dramatic erosion occurs during storms, because the highest energy waves are generated then. If storms become more frequent and more intense due to global warming, there will be greater erosion resulting from storm events. Stronger winds predicted in future climate scenarios, allied with higher sea levels will increase the strength and height of storm surges (see above), which will have high erosive power. In addition, mean coastal wave heights (which include those measured in normal weather conditions) are likely to increase in future climate scenarios as coastal wave height is controlled by local water depth (which will increase as sea levels rise) and the strength of offshore winds (which are predicted to increase). Therefore the increased energy in coastal waves will be transmitted to the shoreline, resulting in increased erosion [11].

The vulnerability of a coast to erosion is partly determined by the characteristics of that coast and will therefore be very variable depending on the region under consideration. Some of the most important characteristics that influence susceptibility include the lithology (the type of rock present), bedding plane geometry, and topography. These are discussed briefly below.

- Lithology: Different rock types vary in their susceptibility to erosion, with clay and mudrock dominated coastlines considered to be especially vulnerable. These soft rocks occur along much of the southern and eastern coast of the UK. Sedimentary rocks are typically layered, with alternating beds of rocks such as limestone and mudstone. If the bottom layer (which is subject to more erosion) is of weaker rock than the bed above, erosion of the base will cause the stronger rock on top to collapse. In this way even large sections of land can disappear quickly.

- Bedding plane geometry: Most sedimentary rocks were originally laid down in horizontal beds. Due to tectonic movements over millions of years, older beds have often been deformed by faulting, folding or tilting. Some bed geometries are more vulnerable to erosion than others, because the beds are arranged in such a way that a minor failure at an interface can cause slippage and the collapse of overlying beds.

- Topography: Undercutting of steep slopes could lead to periodic collapse and potentially large land slides of debris seaward

Other important factors requiring consideration are the orientation of the coast relative to the predominant wave direction and the availability of supplies of sediment. The latter may, in turn, be affected by any coastal protection measures that are put in place, i.e. protecting one area of a coastline can increase vulnerability elsewhere.

3 UK RADIOACTIVE WASTE STORE LOCATIONS

Many of the UK's nuclear power stations and storage facilities are located at or close to the coast (see Figure 1). Because of this Nirex recognises that an understanding of future sea level rise and coastal change processes is of great importance to the planning of site decommissioning and clean-up of nuclear liabilities, as well as for the operation of any coastal radioactive waste stores. This knowledge would also be required for assurance that stores would remain manageable and intact and that consequently there would not be any significant detriment that could affect safety, either of workers or of the public.

Figure 1 Radioactive waste producers' sites in Great Britain

Some current radioactive waste stores, such as at Harwell, Culham, Aldermaston, and Fort Halstead are located further than 10km from the present day UK shoreline and are not included for consideration in this Summary Note. Other sites that are not included in the review are located within 10km of the current coastline, but they are at elevations or within settings that would reduce their vulnerability to sea level rise and associated adverse processes (e.g. Trawsfynydd). The current radioactive waste storage sites considered in this Summary Note are listed in Table 1, with their elevation above sea level and their approximate distance from the coast.

Table 1 Postal addresses, elevations and distance from the coast for the radioactive waste storage sites considered in this Summary Note.

Site	Address	Elevation (m AOD)[3]	Distance from the coast (m)[4]
Berkeley	Berkeley Centre, Berkeley, Gloucestershire, GL13 9PB	0 to 2	125
Bradwell	Bradwell-on-Sea, Southminster, Essex, CM0 7HP	0 to 2	500
Dounreay	UKAEA Dounreay, Thurso, Caithness, KW14 7TZ	9 to 15	50
Drigg	Drigg, Holmrook, Cumbria, CA19 1XH	10 to 20	500
Dungeness	Dungeness A, Romney Marsh, Kent, TN29 9PP	2 to 5	160
Hinkley	Hinkley Point A, Nr Bridgewater, Somerset, TA5 1YA	10 to 14	75
Hunterston	Hunterston A, West Kilbride, Ayshire, KA23 9QF	8 to 21	270
Oldbury	Oldbury, Oldbury Naite, Thornbury, South Gloucestershire, BS35 1RQ	4 to 6	50
Sellafield	Sellafield, Seascale, Cumbria, CA20 1PG	6 to 32	50
Sizewell	Sizewell A, Near Leiston, Suffolk, IP16 4UE	3 to 5	50
Winfrith	UKAEA Winfrith, Dorchester, Dorset, DT2 8WG	25	10,000
Wylfa	Wylfa, Cemaes Bay, Anglesey, Gwynedd, LL67 0DH	9 to 13	100

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[3] AOD stands for Above Ordnance Datum, where AOD approximates to present-day mean sea level.

[4] The sites were located by their postcode, which will not be the exact location of the current radioactive waste stores. Distance from shore is therefore approximate. However, 1:50,000 OS maps have also been examined by a Nirex Contractor (Mike Thorne and Associates Ltd) to confirm that these distances and heights are appropriate.

4 PROJECTIONS FOR SEA LEVEL RISE

There is growing and widespread concern about likely increases in mean sea level that are projected to occur as a consequence of global warming, and the potential damage they may inflict on coastal areas. The evidence that climate change is now happening is compelling and an authoritative source of guidance in this area is provided by the Intergovernmental Panel on Climate Change (IPCC). In their latest published report, the IPPC [16] considered a range of scenarios, with consequent variations in climate patterns during the coming century and with implications for changes in global sea levels over similar time scales. The main scenarios derived during work reported by the IPCC are based on various estimates of anthropogenic greenhouse gas emissions and these were used in simulations of future climate change that were developed using calibrated models of coupled atmosphere-ocean climate interactions. The climate and sea level change results for the scenarios were:

- Mid-range scenario (IS92a). This resulted in an increase in global mean surface air temperature relative to 1990 of about 2˚C by 2100. The consequence of this warming would be an increase in global sea level of about 48 cm from the present to 2100, although the model results varied from 9 cm to 88 cm due to uncertainties in modelling [17].

- Low greenhouse gas emission and low climate and ice melt sensitivity scenario (IS92c). This would lead to a projected global sea level rise of about 15cm from the present to 2100.

- High emission and high climate and ice melt sensitivity scenario (IS92e). The simulations based on this scenario produce a projected global sea level rise of about 95 cm from the present to 2100.

Although the use of numerical models has increased confidence in projections of future climate and sea level change, important uncertainties remain. The major sources of uncertainty are future greenhouse gas emission rates (that contribute to global warming), the emissions of man-made and natural aerosols, e.g. sulphates and particulate carbon (that change radiative forcing and so lead to cooling), and various feedback effects – such as the time-dependant effects of deep ocean CO_2 turnover. However, these uncertainties have been taken into account in the published range of IPCC projections of global mean temperature and consequent global sea level change.

The results of the modelled scenarios consider global sea level change until 2100. Beyond this time predictions become less certain, however, in all cases, the IPCC scenarios result in sea levels that are projected to continue to rise in the immediate centuries beyond 2100, even if concentrations of greenhouse gases were to be stabilised by that time, and would continue to do so even beyond the time of stabilisation of global mean temperature. For the longer term, it is thought that future sea level variability is likely to depend greatly on future emissions and the stability of the Greenland ice cap and West Antarctic ice sheets in particular.

Specifically for the UK, the Climate Impacts Programme (UKCIP) [11] provides a framework for an integrated assessment of climate change and associated impacts. In 2002 the UKCIP developed a range of scenarios for climate change that closely reflects the range of emission scenarios published by the IPCC [9] and these were used to assess likely levels of future sea level variation around the UK (Table 2). It is important to note that unlike most of the IPCC projections that relate to global sea level change, the UKCIP estimates are for UK regional sea level variations as they take account of local land movements. This is significant because whereas much of northern Britain is undergoing uplift, in some places at rates in excess of 2mm per year, land in the south of Britain is currently gradually subsiding at a rate of up to approximately 2mm per year [11].

Table 2 Vertical land changes and sea level change around the UK (taken from UKCIP 2002 Scenarios report [11]).

Regional Isostatic Uplift (+ve) or Subsidence (-ve) (mm/year)		Projected Net Sea Level Change in 2080's (cm) Relative to 1961-90	
		Low Emissions Scenario	High Emissions Scenario
NE Scotland	+0.7	1	61
SE Scotland	+0.8	0	60
NE England	+0.3	6	66
Yorkshire	-0.5	15	75
East Midlands	-1.0	20	80
Eastern England	-1.2	22	82
London	-1.5	26	86
SE England	-0.9	19	79
SW England	-0.6	16	76
Wales	-0.2	11	71
Northern Ireland	n/a	~9	~69
NW England	+0.2	7	67
SW Scotland	+1.0	-2	58
NW Scotland	+0.9	-1	59
Orkney & Shetland	n/a	~9	~69
Global Average	n/a	9	69

Like the IPCC estimates, the UKCIP projections for sea level change are only for approximately the next 80-100 years. By simply extrapolating the projected rates of sea level change beyond 2100 for a further two hundred years, a reasonable estimate of three hundred years of sea level rise can be made. This is considered justified given the range of uncertainty involved in the projections. For the UK, this approach applied to IPCC and UKCIP projections suggest a minimum of 1.5 to 2m sea level rise around much of the coastline by 2300. This sea level rise is determined largely by the thermal expansion of sea water. However, significant melting of the Greenland and West Antarctic ice sheets could accelerate on this timescale and could somewhat add to the projected increases.

5 DISCUSSION

The work reported by the UKCIP and IPCC includes projections of rising sea levels until 2080 and 2100 respectively. From these dates until 2300, for the purposes of this Summary Note, the rates of change published by those organisations have been linearly extrapolated. However, beyond 2100 there is far more uncertainty concerning the factors that might contribute to climate change and hence to future sea level variations.

The Appendix to this Summary Note comprises a synthesis of information on the vulnerability of specific costal radioactive waste storage sites to sea level change. This information has been provided by a specialist consultant to Nirex (Dr Mike Thorne) who also undertakes biosphere-related work for other nuclear industry operators and organisations, such as the NDA and Nexia Solutions. The general susceptibility of the identified sites to coastal erosion and inundation is addressed in the Appendix. However, the analysis of the detailed impacts of sea level changes on the sites covered in this Summary Note is considered to still be relatively rudimentary and should not be used as a basis for any detailed plans.

Table 3 summarises Nirex's current view concerning the vulnerability of the coastal storage sites identified in the Appendix, based on extrapolation of the UKCIP projections for sea level rise until 2080, the IPCC projections for sea level rise until 2100, and site specific information provided by Mike Thorne. Clearly, the effects of sea level variations can be mitigated by the presence of coastal protection structures. However, it is generally accepted that these structures can only protect targeted sections of the coast in the short term, but may cause more erosion in the longer term.

The sites at Aldermaston, Fort Halstead, Culham, Harwell, Trawsfynydd, Capenhurst, Springfields and Chapelcross were not considered in depth in this Summary Note as they are all inland sites or at an elevation that is not likely to be directly affected by sea level rise or associated coastal processes over the 300 year time scale being considered.

Table 3 Summary of potential vulnerability of coastal radioactive waste stores sites to sea level rise.

Site	Details in Appendix	Presence of artificial protection	Inundation or flood risk	Storm surge risk	Risk of coastal erosion	Notes	Potential for site to be compromised within 300 yrs.
Bradwell	A1	Dyke, raised land.	Main risk and will be progressively more common over 100 years and more.	Risk will be progressively more common over 100 years and more.	Not established by Nirex	Future risk depends on continued management of dyke as sea level rises.	High potential. Main vulnerability: Inundation
Dounreay	A2	None.	Unlikely during next 300 years.	Unlikely	Cliff recession over 160-240 years expected to expose the Dounreay shaft.		Lower potential Main vulnerability: Erosion of shaft.
Drigg, Windscale, Sellafield	A3	Flood and erosion defences.	Flooding from River Calder. Tidal waters currently reach southern bounds of Drigg.	Possible impacts at site margins	Slow recession but fairly stable. Erosion may affect Drigg operations (but only likely beyond 300 years).	Vulnerable to change in wave regime.	High potential. Main vulnerability: Erosion
Dungeness	A4	Flood and shore defences. If management ceased, shingle beach likely to fail, causing inundation.	Highly vulnerable. Flooding currently from tides. Inundation will ensue if protection management ceases.	Likely risk	Vulnerable to rapid erosion and storms. In 1960s landward erosion rate 1.1 to 1.5m/yr.	Beyond 15 yrs protection measures not guaranteed. Considered most vulnerable NDA site.	Very high potential. Main vulnerability: Erosion
Hinkley	A5	Massive sea	Subject to tidal	Tidal range	Active erosion, and	Beyond 15 years	Higher potential (if sea

Site	Details in Appendix	Presence of artificial protection	Inundation or flood risk	Storm surge risk	Risk of coastal erosion	Notes	Potential for site to be compromised within 300 yrs.
Point		defences, rock cages. Some natural protection.	inundation in south. Increased risk if protection lost.	high, so adverse weather can cause water level to be 2m higher than predicted on basis of tides. Substantial storm surges and powerful waves possible.	rock cages being actively undermined.	protection measures not guaranteed. Over 100 years site likely to be isolated by high sea level and strong tides. Over 300 years is likely to be flooded and site surrounded by seawater on 3 sides.	defences not maintained). Main vulnerabilities are inundation and erosion
Hunterston	A6	Made ground constructed as protection.	Not established by Nirex	Not established by Nirex	Low vulnerability.	Protection should protect site for at least 15 years.	Low vulnerability - assessment based on information available to Nirex.
Oldbury, Berkeley	A7	Embankments, land reclamation, sea defences. More substantial at Oldbury. Berkeley has some natural protection.	Land subject to inundation. Occasional overtopping and flooding beyond 15 years expected.	Surges expected to inflict periodic damage.	Yes, from River Severn. Land around site is low and subject to coastal erosion.	Managed retreat over 100 years possibly inevitable.	High potential. Main vulnerability: Inundation
Sizewell	A8	Slightly raised ground, surrounded by	Nearby drained area subject to tidal inundation.	Storm surges likely to impact on vulnerable	Currently cliffs are retreating. Extensive retreat	Given vulnerability, local planning authority will not	Medium vulnerability beyond 100 years.

Site	Details in Appendix	Presence of artificial protection	Inundation or flood risk	Storm surge risk	Risk of coastal erosion	Notes	Potential for site to be compromised within 300 yrs.
		artificially drained land. Natural sandbanks, may increase as coast evolves.	These areas likely to flood in future.	areas.	possible on 100 year timescale. Nearby cliff retreat over 75 years by 150-190m, predicted. Rapid erosion in places, complicated evolution.	permit development of long design life structures.	Main vulnerability: Erosion
Winfrith	A9	River controlled by engineering works.	River Frome flooding or extreme events a possible risk.	Not established by Nirex	Not established by Nirex	Located 10km inland. Changes in river floodplain limited over 100 years.	Low vulnerability.
Wylfa	A10	Not established by Nirex	Not established by Nirex	Not established by Nirex	Currently subject to coastal erosion. Wave attack expected to increase in future, but geology highly resistant to erosion.	No significant changes in next 15 years, limited changes over 100 years.	Lower vulnerability. More information needed.

6 SUMMARY

Many of the UK’s nuclear power stations and storage facilities are located on sites at or close to the coast and are consequently potentially vulnerable to the direct and indirect effects of a rise in sea levels. Climate change has a major role to play in dictating the rates and amount of sea level change that might occur over the next 300 years, but local factors will also be important.

In Nirex’s view, certain sites, as identified in Table 3, are potentially susceptible to some of the risks considered in this Summary Note. However, in the absence of detailed risk assessments that take account of site specific information, and as a consequence of the uncertainty regarding sea level projections up to and beyond 2100, it is not possible to be definitive about potential impacts.

There is a finite probability of inundation at some of the sites, but as was mentioned earlier, for many radioactive waste storage sites inundation is less important than other consequences of sea level rise, particularly coastal erosion. Coastal erosion can be rapid and dramatic and may, for many if not most sites, provide a far greater worry than sea level rise alone. Intense extreme weather activity resulting in storms and increased localised flooding are further consequences of climate change that will need consideration if the vulnerability of coastal sites is to be more thoroughly assessed.

APPENDIX A

In this section, specific examples of potentially vulnerable coastal sites are considered in terms of their susceptibility to impacts from sea level change and associated coastal processes, especially erosion. Although a detailed review of all of the coastal sites for radioactive waste stores has not been possible, such assessments have and are being made by BNFL and the NDA at various levels of detail. The review of sites in this section is primarily based on work produced by Dr Mike Thorne, of Mike Thorne & Associates Ltd (personal communication to Nirex, 5/9/05). The review incorporates material provided to Mike Thorne & Associates Ltd by Dr Paul Kane of Kanvil Earth Sciences.

A1 - Bradwell

Current Context

Bradwell power station is located on the Blackwater river estuary in Essex, some 55 km south of Sizewell. The site is located in an agricultural area of low population density adjacent to a disused airfield. The nearest settlement of any size is Southminster, some 10 km away. The power station site lies at some 5 m AOD and has been raised above the surrounding land which, in the absence of the current or any future flood protection measures, would be subject to tidal inundation.

Projected Future Characteristics

The muddy Blackwater estuary was formed from a pre-existing valley that was flooded at the beginning of the Holocene. The estuary is constrained geologically at its mouth by outcrops of Terrace gravels at Bradwell and Mersea. These deposits were lain down by a proto-Thames river system.

At Bradwell, many years of human intervention have disrupted important links in the estuarine system, in particular the fine sediment ‘layer’ operating between the intertidal and saltmarsh environments, with the latter being essentially lost. The extensive reclamation of the intertidal areas that reached its peak in the 18th and 19th Centuries is estimated to account for 42% of the initial area [18]. The removal of such large areas has had a pronounced impact on the behaviour of the estuary system. For example, the decrease in estuary channel size has led to higher velocities and increased bed-scour and, as a result, the estuary is deeper than it otherwise would have been. The geological constraints at the estuary mouth have accentuated this tendency and increased the area of mudflat relative to that of salt marsh within the estuary as a whole.

The power station is protected from the estuary by a dyke (and associated drainage) that encloses reclaimed marshes formerly subject to inundation. The future risk to the station from landscape change driven by climate change is largely dependent on the management regime associated with maintenance of the dyke in the face of rising sea level. The geographic setting suggests that the main risk is from inundation rather than from erosion.

The 1:10,560 topographic map from 1881 shows the dyke in place and protecting farmland. Comparison with the modern 1:25,000 map shows that the station was built on ground artificially raised to about the level of the top of the dyke. This is also evident in the field, where the station site is seen to form an island within ‘fen’ lands.

Estuary translation or ‘rollover’ is the expected natural response of the Backwater estuary to sea level rise [19],[20]. This would, in effect, be a continuation of the Holocene transgression wherein it is suggested that the estuary will attempt to maintain its position relative to the tidal frame as sea level rises. Normally, this process would involve sediment inputs from marine sources that allow surface elevations to keep pace with sea level rise. At present, this process is thwarted at Bradwell by the extensive coastal protection measures. Thus, at present, there is no mechanism for low-lying areas to be inundated and for sedimentation to keep pace with sea level rise. As a result, the degree of disequilibrium between form and process within the estuary and its immediate hinterland will increase until in the longer term, possibly within a 300 year time frame, it becomes unsustainable.

On a 15 year timescale, there is no reason to suppose that the coastal defences will not be maintained to protect the station and the adjacent farmland. On a 100 year and greater timescale, it is likely that inundation will become progressively more common, especially resulting from storm surge.

A2 - Dounreay

Current Context

Dounreay is located in the far north of mainland Scotland on the north coast of Caithness, about 12 km west of Thurso. The site was built on a disused airfield on a low-lying and low-relief coastal plain within a shallow bay in the coastline. The buildings on the site extend to close to the coastline. The site was constructed on made ground and lies at 20 m AOD. The solid geology comprises sandstones and siltstone of Mid-Devonian age mapped as the Dounreay Siltstone Member and these strata form the rocky coastline. The rocks belong to the Upper Caithness Flagstone Subgroup, which is described as laminated carbonate-rich siltstones and shales with subordinate fine-grained, thinly bedded sandstones. A network of faults has been mapped within the site and over the general surrounding area. Over much of the site away from the coastline, the solid geology is overlain by Drift comprising diamicton, gravel, sand and silt.

Projected Future Characteristics

The site is located within an area of undissected coastal lowland known as the ‘Dounreay Ramp’ that measures some 6.5 km x 3.5 km and within which there is a remarkably even gradient towards the cliffs. At Dounreay, the rocky cliffs rise to between 10-15 m. They are exposed to strong marine attack. The cliff profiles are deeply indented due to the differential weathering and erosion of fine-grained, thinly bedded units relative to the coarser-grained, more massive and cemented ones. The toe of the cliff is not well defined, as it tends to merge with the rocks that form the upper shore platform.

The erosion of these cliffs has attracted attention because of the existence of a vertical Shaft located about 12 m landward of the cliff edge that was authorised in 1957 for the disposal of various types of radioactive wastes. The Shaft is some 65 m deep and 4.5 m in diameter. An account of erosion in the vicinity of the Shaft has been provided by Hutchinson, Millar and Trewin in [21]. These authors report that the erosion of the flagstones was found to proceed chiefly by the deepening of slots in the weaker, more fissile, bedded units that are present. The development of these slots subsequently facilitates the cantilevering of blocks and their removal through wave action. Estimates of the time required to expose the unprotected Shaft by cliff recession (about 12 m) range from 160 to 240 years [21]. The site is unlikely to be inundated over the next 300 years.

A3 - Drigg, Windscale, Calder Hall and Sellafield

Current Context

Drigg, Windscale, Calder Hall and Sellafield are all located on the West Cumbrian coastline. Windscale, Calder Hall and Sellafield are grouped together within the same nuclear industry complex, whereas Drigg is located some 5 km to the south. Drigg is a radioactive waste treatment and storage facility located within 1 km of the Irish Sea coast on the coastal plain that fringes the Cumbrian mountains. The site takes its name from Drigg village, but the nearest settlement of appreciable size is Seascale, a kilometre of so from the northern boundary. The site is roughly rectangular in shape and orientated parallel to the coastline. Its northeast boundary is formed by the Cumbrian coastal railway.

The solid geology is sandstones of Triassic age, but these are mantled by a thick cover of complex and glacitectonised Devensian sediments and by more recent sediments and peats. To the west, sand dunes cover the Devensian deposits. There is a cliff line developed in the Drift overlooking a wide intertidal zone that gentle shelves into the eastern Irish Sea. To the south lies the Ravenglass estuary into which flow the Rivers Irt, Esk and Mite. The course of the River Irt runs just south of the Drigg site and it has been diverted southwards by sediment movement along the coastline. The northern part of the site lies at about 20 m AOD, whereas the southern boundary is at about 10 m.

The Irt estuary is subject to tidal inundation and tidal waters may reach the southern boundary of the site. The Drigg stream flows through the site. The site is very exposed to the elements, and to blown sand and sea spray.

The Sellafield fuel reprocessing works, Windscale research centre and Calder Hall power station are all located on a ‘campus’ on the Irish Sea coast at Sellafield, West Cumbria. Like Drigg to the south, the Sellafield complex is situated on an open coastline orientated northwest-southeast between St Bees Head and the Ravenglass estuary. The solid and Drift geology are similar to those at Drigg, namely Triassic sandstones overlain by a variety of sediments mostly of Quaternary (Devensian) age. The predominant superficial lithology in the area is diamicton (Till), but the surface Drift cover within the ‘campus’ is mostly of sand and gravel. Thus, the Calder river, which runs through the site, is associated with a broad area of alluvium and river terrace deposits. The terrace deposits overly an extensive area of glaciofluvial deposits characterized by their content of sand, gravel and bounders. The climate and agriculture of the Sellafield area of the coastal plain are essentially the same as at Drigg.

The Sellafield complex extends for over 1 km inland from the coastline at Sellafield Banks where the buildings are at about 20 m AOD. The site slopes upwards inland and at the northwestern boundary the buildings are on ground up to 40 m AOD. The industrial complex comprises a large number of buildings with a generally rectalinear layout.

The River Calder, which rises in the Cumbrian mountains, passes through the site at a high angle to the coastline. The Calder Hall power station is to the south of the river with the Sellafield works to the north. The River Calder has been straightened and canalized, but still constitutes a flood risk. The River Ehen runs between the works and the coastline as does the coastal railway. The River Ehen has been diverted several kilometres south from its original point of discharge into the Irish Sea by the longshore drift of sediment from the north. Flood and erosion defences have been built to protect the site and the railway. The course of the River Ehen is associated with alluvium, with areas of dunes and blown sand, and with river terrace deposits.

Projected Future Characteristics

Drigg and the Sellafield Complex share a common climate, geographical setting and paraglacial inheritance. They are located in close proximity to each other and belong to the same set of contiguous coastal behavioural units. These considerations justify considering them together from the perspective of understanding the implications of climate and landscape change with respect to sea level rise.

The Cumbrian coastal plain on which Drigg and Sellafield are located is blanketed in Quaternary deposits derived primarily from the glaciation of Cumbrian and Scottish mountains during the last glacial phase, the Devensian. In the absence of the Quaternary deposits, the current shoreline would lie to the east of the sites and they would be ‘under water’. In this hypothetical picture, there would be no coastal plain and the shoreline would probably follow the outline of the Triassic/Lower Palaeozoic boundary. Thus, the paraglacial inheritance of Drigg and the Sellafield complex is a significant factor in any consideration of the future long-term evolution of the coastal landscape. However, it is not clear how much of the paraglacial inheritance of the coastline has still to be resolved within the current pattern of landscape change, and it is also not clear to what extent the Holocene rise and fluctuations in sea level have been accommodated in the existing form of the coastline and distribution of sediments. There is evidence, however, that the coastline has responded to past forcing by adjusting form and process to adsorb energy and minimise the rate of future change. This evidence comes from a detailed programme of work being undertaking by Halcrow Group Ltd into coastal change at Drigg and Sellafield for BNFL, undertaken in support of safety assessments. They have carried out field work, historical analysis, theoretical and modelling work and in particular have been developing a conceptual coastal change model [22] and coastal evolution scenarios [23].

The coastline from St Bees Head to Drigg comprises a multiple headland-bay system. The overall system for the West Cumbrian coastline includes some 18 coastal landforms, the characteristics of which are given, from north to south, in Table A1.

Table A1. Coastal Landform Units and their Description: St Bees Head to the Esk Estuary

Coastal landform unit	Description
St Bees Head	Sandstone cliffs with till cap and rocky shore
St Bees Promenade	Low till cliffs with protection measures
St Bees golf course	High till cliffs in push moraine
Pow Beck	River outlet and fan delta
North Coulderton	Relict landslides in till with toe protection measures
Coulderton	Barrier beach and till cliff headland
Nethertown Station	Rock platform and till cliffs with protection measures
Nethertown	Barrier beach and till cliff headland
Braystones	Barrier beach and till cliffs with protection measures
Ehen Valley	Barrier beach fronting low river valley
Sellafield (Ehen Spit)	Barrier beach fronting river valley and till cliffs
Ehen and Calder	River outlets with fan delta

Coastal landform unit	Description
Seascale	Barrier beach fronting low hinterland
Whitriggs Scar	Till cliff headland with protection measures
Carl Crag	Low till cliffs capped by blown sand
Barn Scar	Till cliff headland capped by blown sand
Drigg Dunes	Dunes overlying till and raised beach
Drigg Point	Dunes, estuary and delta deposits

The behaviour of each of the identified coastal landforms is linked to adjacent units both spatially and temporally to varying degrees. The shoreface influences wave climate at the shoreline, controlling transport and accumulation of beach material, while the shoreline and beach affords protection to the backshore or hinterland, and partly controls the extent of erosion or inundation that occurs. The hinterland may release sediments, e.g. from cliffs, or accumulate them, e.g. in estuaries, controlling sediment availability at the shoreline and shoreface. This in turn affects the morphology of these zones. A change in any element can potentially trigger readjustments in adjacent and other units to maintain the form and position of the whole system. Occasionally, a key threshold may be exceeded - triggering major readjustments of form and position of some elements, themselves initiating further changes. Each coastal landform, therefore, needs to be understood in terms of its along-shore connectivity with adjoining landforms.

At a regional scale, the west Cumbrian coastline appears to have achieved a high degree of alignment with significant coatal processes, with the implication that future rates of erosion may be low. According to this view, the sediment store remains *in situ* and is retained in the vicinity of the shoreline such that the overall landscape oscillates about a stable form in response to short-term fluctuations in forcing factors, such as a sea level rise. The geometry of the Irish Sea and the dominant south-westerly direction of prevailing winds and waves tends to keep sediment close up against the coastline, offering a measure of protection against erosion. This is quite different from the situation at Sizewell, for example, where sediment is continuously moving southwards, or at Dungeness, where there appears to be a zone of convergence of sediment flows from west and east. To give a complete account of sediment behaviour in support of coastal change prediction, it is necessary to account for the sources and sinks of each of the main textures of sediment (coarse, sand and mud) and relate these to the composition of eroding headlands and of offshore sediment stores.

At a smaller scale of observation, the analysis of individual headland-bay units suggests a less optimistic scenario with respect to erosion. In particular, the evolution of the headland-bay combination of Barn Scar and Carl Crag threatens the disruption of the Drigg site. The shape and development of individual headlands-bay units is explained by the way that the dominant waves approach the coast, refract around the headlands (or hard points) and move sediment within the bay, eventually forming a stable system controlled by the position of the headlands. Generally, as the headlands erode and regress, the bays respond to maintain the overall configuration. Increasing sea level and wave attack on the headlands increases erosion and results in general coastline recession. Loss of sediment from the system will increase the rate of recession.

The evidence for coastal change along the stretch of coast that includes the sites is of progressive, but slow recession taking place within a stable overall coastline configuration. In the longer term, probably greater than 300 years, it is clear that there is a real risk of disruption of the Drigg site by coastal erosion, but, as yet, the precise timescale for this is unclear. BNFL's Environmental Safety Case submitted in 2002 to the Environment Agency indicated that the Drigg facility is likely to be destroyed by coastal erosion in 500 to 5,000 years, which would result in radioactive waste reaching the beach, even if current sea level remains. The Environment Agency [24] agreed with this assessment but stated that even earlier destruction should be considered. However, if sea level rises, as it is likely to, destruction of Drigg would be even more likely. Estimates of sea level rise used for the Drigg assessment are based on IPCC figures and range from 1m to 10m. Uncertainties, and potential magnitude of change increase as longer timescales are considered.

Coastal processes also threaten to mobilise radionuclides from areas of contamination within the Sellafield complex. These risks can be addressed by development of a coastal-change model with the capability to simulate the evolution of the combined headland-bay-estuary system under conditions of changing climate and sea level.

A4 - Dungeness

Current Context

Dungeness is located on Dungeness Foreland on the southeast coast of Kent some 90 km south of Bradwell. There are two power stations on the site, namely 'A' and 'B' and they are situated side by side immediately inland from the beach. The stations face into the Strait of Dover on a cuspate foreland formed by the interaction of longshore drift from both east and west. The Foreland is made up of 500 or so beach ridges and is part of a large depositional complex, the origins of which have been investigated in studies funded by English Nature. The power stations occupy a very exposed location where the Foreland juts into the English Channel. This area is referred to as Denge Beach, behind which is Denge Marsh and the nearest significant settlement Lydd, some 5 km from the power stations. Inland from Lydd are two large areas of former marsh, namely Walland Marsh and Romney Marsh. These areas are now prime agricultural land and are classified as either Grade 1 or Grade 2. In contrast, Denge Beach is classed as non-agricultural and is a National Nature Reserve. The whole area is low lying and subject to tidal inundation.

The solid geology under the site comprises Lower Cretaceous Hastings Beds. The interface or unconformity between the solid geology and the overlying Drift is well below sea level. The erosion surface has a low-relief, faulted surface with palaeovalleys carved under reduced sea level conditions. During the Holocene rise in sea level (about 10 m over the last 7000 years at Dungeness), a sequence of shoreface and offshore sediments comprising gravels and sands has been deposited onto the bedrock. Shoreface formation at Denge Marsh started some 2000 years ago. Subsequently, gravel ridges and sand lenses developed during barrier and foreland formation. At the power station site (about 6 m AOD), the beach gravels are some 9 m thick and these overly some 5 m of sandy gravels that in turn overly the shoreface sands. The average maximum tidal height is 4m.

Projected Future Characteristics

The site on which Dungeness power station stands has only come into being since the 13th century and it is apparent from the chronology of events that this landscape owes its existence to the long-term effects of sea level change, storms, coastal erosion and sediment deposition. It is an active landscape that is subject to continued and rapid evolution and the site is liable to undergo major landscape change in the future. This marks out Dungeness as the most vulnerable of all the NDA sites to climate-driven landscape change, especially with respect to sea level rise.

There is likely to be a geomorphological response to climate and sea level changes, because these changes are likely to influence both the wave behaviour and patterns of sediment availability and transport. The landscape model that is most applicable to the evolution of the Dungeness foreland is that of the drift-aligned beach. However, the natural system has been subject to extensive human interference in various ways, including the development of Rye harbour, construction of shore defences and the recycling of shingle on the western shore. The Dungeness Foreland has built out across a sea bed that gently slopes to 18 m depth across a broad shelf up to 10 km wide, beyond which the water depths increase more rapidly. The eastward growth of the foreland has extended to the edge of the shelf and now appears to be limited by the deeper water. Relative sea level rise at Dungeness is rapid (2.2 mm y^{-1} 1961-1998), due to continued subsidence of southern Britain.

Evidence that the Dungeness area has a highly dynamic geomorphological history is uniquely preserved in its extensive set of shingle ridges. Eastward longshore drift transported shingle derived from glacial deposits on the seabed, supplemented with material derived from the erosion of flints from the chalk cliffs. This has fomed the shingle barrier-beaches that protect the now reclaimed, marshes of Pett, Walland and Romney. The shingle barrier developed between 6000-5000 yr BP (Before Present), driven primarily by storm activity. The gravel barrier was stable until 2000 yr BP when the orientation of the shingle ridges changed and a cuspate foreland (the “ness”) began to develop.

Stratigraphic evidence suggests that marine influence increased as the barrier proceeded to break down 3,000-2,000 yr BP. The breakdown of the shingle barrier and consequent increase in the marine influence to landward was possibly due to a reduction in sediment supply to the barrier, or possibly due to the growing size of the foreland. Evidence suggests that the area was inundated during storm surges in the 13th century. Today, the barrier in Rye Bay area is migrating inland, thus exposing previous back-barrier sediments to the foreshore.

The area in the vicinity of the cuspate foreland of Dungeness has accreted relatively recently, with the land on which Dungeness nuclear power station has been built being formed between 400 and 200 years BP. Estimates for sediment transport in the early part of the 20th century suggest that there was more erosion on the south coast compared to deposition on the east coast, perhaps due to the construction of coastal works, particularly the Rye harbour mouth development. Estimates of rates of erosion during the construction phase of the nuclear power station in the 1960’s indicated landward erosion of 1.1 to 1.5 m of shingle annually.

The recent geomorphology of Dungeness has been dominated by a number of human interventions that have altered and continue to alter the morphology of the coast. The main events responsible for these changes are:

- Construction of shore defences along the coast to the west of Dungeness; these, together with the depletion of seabed shingle deposits, have resulted in a reduction in sediment inputs to the area and caused a change from dominantly drift-aligned to a breakdown phase in which a swash-alignment is now developing;
- Gradual reclamation of the salt marshes of the Rother/Brede though the 19th and early 20th centuries, leading to reduction in tidal prism in the estuary of these rivers, and allowing shingle to block the harbour mouth and navigational access;
- Construction of the Rye Harbour terminal groyne and its predecessors, beginning in the 1920s, as a response to the blocking of the harbour mouth by shingle;
- Development of infrastructure, including the village of Winchelsea Beach, sections of Camber and the nuclear power station, in areas at risk from flooding or erosion by the sea; and
- Flood defence construction to protect built assets, including the recycling of shingle on the western shore and at the Ness and a number of secondary flood embankments landward of the shingle and sand dunes at Pett, Camber and Jury’s Gap.

It has been concluded, from the analysis undertaken by the author of this text that the retreat of the southern shore of Dungeness is a response to the reduction of sediment input due to the Rye Harbour terminal groyne and coastal defence works further to the west. The almost complete removal of such inputs has meant that the southern shore from Camber to the Ness is now in the breakdown phase of a change from a drift-aligned to a swash-aligned morphology. This process involves a re-orientation of the shore so as to reduce the wave approach angle, principally from southwest waves. The long term (approximately 1000 year) result of this re-orientation would be an asymmetric bay with its bay-head located along the line of the present Midrips and the western arm extending along the Rye town frontage. It is this ultimate geomorphological end point that must be considered in any assessment of the management options for the Dungeness system.

Current thinking is that, if all existing flood defence management practices were to stop, the shingle beach at the Power Station would be likely to fail. Inundation would therefore be very likely. However, it is assumed that the continuous cycle of beach nourishment that maintains the frontage at the site will be funded for at least the next 15 years. Beyond this time frame continued management or alternative mitigation measures would need to be put in place.

A5 - Hinkley Point

Current Context

The Hinkley Point stations are located on a rock platform at about 11m AOD overlooking the Bristol Channel and with an extensive rock outcrop in front within the inter-tidal zone. The land rises immediately beyond the site boundary to the west to 25-30 m – beyond lie the Quantock Hills. To the south the land falls to 5 m within the Wick Moor area and is subject to tidal inundation. It is protected by sea defences and has been drained for agricultural use.

Rainfall is highly variable across Somerset with a large contrast between Exmoor and the Somerset Levels. The average annual rainfall for the county is 1250 mm which is typical of its western location, but Hinkley has a favoured location (~750mm y^{-1} and high level of accumulated warmth during the growing season) which is reflected in the pattern of land use. The 1890 topographic map shows a mosaic of small fields and hedges, a number of which have subsequently been removed to facilitate mechanized farming.

The Severn Estuary is one of the largest estuaries in Britain and the Bristol Channel has one of the highest tidal ranges in the world. Locally, the tidal range varies considerably with the phases of the moon, weather and along the coast, generally increasing eastwards as far as Hinkley Point, where the highest recorded ranges have been up to 15 m. Adverse weather conditions can raise water levels by more than 2 m above predicted levels.

The solid geology of the area is Blue Lias and Charmouth mudstones of Jurassic (Rhaetian) age. The rocks are sub-horizontally bedded and outcrop in cliffs and over a wide expanse of the intertidal zone. The outcrops are observed to comprise alternate beds of mudstones and shales. A fault is mapped as passing through the site from north-east to south-west. The low lying Wick Moor area is mapped as alluvium. No superficial deposits are mapped over the mudstones and the resulting soils are mapped as lime-rich loamy and clayey soils with impeded drainage. The land corresponding to these soils is classified as Grade 3 for agriculture. The alluvial areas subject to flooding are variously loamy, sandy and peaty and are influenced by shallow groundwaters.

The power station is built on the point and is protected by massive sea defences. Comparison of the 1890 and modern maps shows that the point was reconfigured as part of the construction of the station. The rock outcrop in front of the station and along the coastline to the east and the width of the intertidal zone offers a measure of protection from erosion by tidal currents and storms. However, the shale beds within the mudstone formation offer little resistance to erosion and the cliff line and shoreline show evidence of active erosion. It is also observed that, where the sea defenses comprise rock cages, these have been locally undermined.

Projected Future Characteristics

The generic landscape behaviour model corresponding to the landscape and geomorphological situation at Hinkley Point is that of a Headland/Headland Bank. The headland at Hinkley Point is associated with the extensive mud and sand flats of Stert Flats within Bridgewater Bay to the east between the Point and Burham-on-Sea.

Hinkley Point is exposed to tidal and wave action within the Bristol Channel and is being actively eroded. The Bristol Channel is severely macrotidal and tidal currents exceed 1 m

s^{-1} over wide areas and for long periods. The shoreline is subject to strong winds, powerful waves and substantial storm surges. The general geomorphological context is one of on-going marine transgression with the inner Bristol Channel undergoing enlargement. The rate of marine transgression is very uncertain, however, but an advance (of the estuary) northeastwards along the Severn Vale of up to the order of 20 km over the last few millennia can by no means be excluded.

An extensive wave-cut platform and boulder bed has developed in the mudstones in front of the power station and this offers some measure of protection to the cliffs. The cliffs themselves are readily eroded because of the weak shale partings between the mudstone units. The main protection for the stations is provided by massive sea defences. Maintenance of these defences should ensure the integrity of the stations over the next 15 years. Over 100 years, expansion of the Channel and increased wave attack under the influence of rising sea level combined with strong tidal flows will tend to isolate the artificially protected headland. Over the next 300 years, if coastal processes operate as predicted, this area may well be flooded and the station site would be surrounded by sea water on three sides.

A6 - Hunterston

Current Characteristics

Hunterston ‘A’ power station is located on the coast 3 km northwest of West Kilbride and within the parish of the same name on the North Ayrshire coast facing the island of Little Cumbrae. The site about 5 km southwest of the village of Fairlie. Hunterston ‘A’ Power Station lies immediately to the south west of the Hunterston ‘B’ Power Station. The landscape around the site is rural.

A sloping platform cut into bedrock and generally backed by a steep relict cliff extends as an almost continuous feature along the coastline of the Inner Clyde. Typically the platform is narrow (up to 200 m across). Originally, this type of raised platform was considered to be a former abrasion platform cut by wave action at a time of higher relative sea level. However, it has been shown that, where ice seasonally develops, intense, freeze-thaw related, mechanical weathering can occur and produce rapid platform development. The platform has an elevation of 5 m AOD at the shoreline and the Spring tide[5] range is about 3 m. The station is located on the platform at 10 m with the land rising steeply to the south (Goldenberry Hill) and east (Campbelton Hill). The summits of both hills are within 1 km of the station and the steeper slopes are wooded.

The predominant solid geology of the area comprises non-marine Late Devonian sandstones belonging to the Kelly Burn Sandstone formation. These are described as mainly red, cross-bedded, pebbly sandstone with subordinate conglomerate beds. There are numerous small igneous intrusions of different ages mapped within the sandstone and an extensive sill (sub-horizontal sheet-like igneous intrusion) forms much of Goldenberry Hill south of the station. The rock platform on which the station stands is covered in raised marine deposits of Flandrian age comprising clays, silts, sand and gravel. The higher ground to the south is blanketed in glaciofluvial ice-contact deposits variously comprising gravel, sand and silt, but much of the Goldenberry sill is exposed. A number of generally N-S trending faults traverse the area, but do not appear to extend across the station site. There is an large area of reclaimed land and made ground immediately west of the site which extends the platform out to sea. This was presumably constructed as protection for the site from the sea.

The enclosed nature of the Firth of Clyde combined with the narrow fjords severely limits the wave field affecting the coastline of this area. As a result, the height and direction of waves reaching the coast is highly dependant on the dominant wind direction. For most areas, the fetch rarely exceeds 100 km and is often less than 10 km. As a result, the wave spectrum in the Firth of Clyde is primarily composed of waves generated within the confines of the estuary. For the outer estuary, wave heights exceed 2 m for 10% of the year and are less than 0.5 m for 75% of the year, although maximum wave heights of 3 m may occur. Wide sandy beaches are present immediately north of the station reflecting the degree of protection afforded by the shallow bay extending between Hunterston and Largs. The nearby islands of Great Cumbrae and Little Cumbrae may also reduce wave energy.

The most significant human impact on the outer coastline of the Inner Clyde occurs at Hunterston, where land reclamation, pier and jetty construction and major coastal

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[5] A spring tide is where the tidal range and the maximum high tide are higher than normal. This occurs twice a month.

defence works are associated with the power station, construction yard and ore terminal. It is likely that this activity has had an impact on local sediment budgets, in particular by blocking direct sediment movement between Hunterston and Southannan Sands.

Projected Future Characteristics

Comparison of the present day and historical maps shows that the coastline in front of the station has been considerably extended to provide additional protection against coastal erosion [25]. No information has been found during this study on current rates of erosion, but it is reasonable to assume that the coastal defences will protect the site for at least the next 15 years. In the longer term sea levels are expected to rise, although the current rate of isostatic uplift will continue to offset this partially. However, the offset is unlikely to keep rate with sea levels.

A7 - Oldbury and Berkeley

Current Context

The Oldbury Power Station and the Berkeley Centre sites both lie on the east bank of the Severn Estuary in low lying land within the Vale of Berkeley. Both stations are in Gloucestershire. Oldbury is some 35 km east and 45 km north of Hinkley. Berkeley is 7 km northeast of Oldbury and is situated just south of a minor estuary known as Berkeley Pill which is the estuary of the Little Avon River.

Embankments around the Pill protect the site from flooding. Annual rainfall at both sites is about 850 mm and the location is favoured relative to other higher and more inland areas within the county with regards to accumulated soil warmth during the growing season. At Berkeley, a substantial number of buildings have been constructed within an area immediately to the southwest of the station and alongside the estuary. These buildings comprise the Berkeley Technology Centre. The Oldbury site includes a jetty that marks a point of inflection in the shoreline.

The tidal range within the Severn Estuary is particularly large, primarily because of the funnel shape of the estuary and Bristol channel and their orientation with respect to the Atlantic ocean and the prevailing southwesterly winds. Mean High Water Spring Tides reach +7.5 m AOD at Sharpness just north of Berkeley. Both the power station sites are at about 10 m OAD and are protected by embankments. The whole of the area alongside the estuary between Oldbury and Berkeley is low lying at about 5-6 m AOD and is subject to tidal inundation; both sites are regarded as potential problem areas with regards to erosion. Regular inundation in historical times has resulted in a blanket cover of tidal flat deposits overlying the solid geology. Following the construction of sea defences in historical times, the land was drained and reclaimed for agriculture. As at Hinkley, the areas subject to inundation are characterized by loamy soils that are variously clay, silt or sand rich with a peaty surface and influenced by groundwaters at shallow depths. At both sites, the landscape within the coastal flats comprises a mosaic of fields, hedges, ditches, drainage channels and ponds.

The solid geology in the region of both sites comprises mudstones, siltstones and sandstones of the Mercia Mudstone Group of Triassic age (formerly known as Keuper Marl). These rocks are exposed within the estuary at low tide along with extensive areas of sand. At Oldbury, a tidal reservoir has been constructed alongside the station and, in part, over an area of exposed mudstone rocks (referred to locally as Count Rock and High Heron Rock). The tidal reservoir provides a secure source of cooling water within the tidal estuary. Lagoons have been constructed either side of the station along the side of the estuary and act as settling tanks for suspensions pumped from the reservoir. At Berkeley, Bull Rock and Black Rock form substantial masses of rock exposed within the estuary. Locally, Head deposits are mapped.

At both sites sea defences are present, but they are more substantial at Oldbury, which is further down the estuary. At Berkeley, the shoreline is protected by an armoured rock surface, but there is much evidence of erosion of the tidal flats. Erosion of the tidal flats is also evident at Oldbury.

Projected Future Characteristics

Both Oldbury and Berkeley lie on land subject to inundation and both stations are threatened by erosion from the tidal River Severn. The embankment at Berkeley is armoured, but is under attack, whilst at Oldbury the extensive intertidal mudflats merge with cliffs cutting back into marine alluvium.

As discussed in the context of Hinkley Point, the Severn Estuary is experiencing marine transgression and stratigraphic ‘roll-over’, an overall process that can only accelerate as sea level rises into the future, placing increased pressure on the existing embankments and other defences.

As at Bradwell, the land on which the power stations have been built alongside the Severn Estuary has been artificially excluded from the natural system that would regulate the distribution and accretion of fine sediment in areas subject to inundation.

Flood protection of valuable sites along the Severn Estuary over the next 15 years should not be unaffordable given the existing infrastrucutre, but storm surges may be expected to inflict periodic damage with occasional overtopping and flooding of low-lying areas. On a 100 year timescale, some degree of managed retreat may prove to be inevitable.

A8 - Sizewell

Current Context

Sizewell is located on the coast near Leiston in Suffolk. The location is almost the most eastern point in the UK.

Suffolk is one of the driest, warmest and sunniest counties in England, but the power station site climate is influenced by its immediate proximity to the North Sea and exposure to wind. The coastal zone where Sizewell is situated has an annual average rainfall of 630 mm y^{-1}. The site includes the two power stations Sizewell ‘A’ and Sizewell ‘B’, built side by side immediately inland from the beach. A topographic map dated 1905 shows the site to be a former warren located on slightly raised ground surrounded by artificially drained land. This land is subject to tidal inundation. The boundaries of the site, the field system and pattern of drainage and roads today is essentially unchanged from 1905.

At Sizewell and Leiston, Norwich Crag deposits of Pleistocene age and more recent deposits overly London Clay of Eocene age. The Norwich Crag varies considerably in lithic character and comprises beds of sand, laminated clays and pebbly gravels. The slightly elevated power station site (5-10 m above Ordnance Datum (AOD), where AOD approximates to mean sea level) is characterized by freely draining slightly acidic sand soils, which is natural heathland, with fen peats occupying the surrounding areas liable to inundation. The coastal flats that are subject to naturally high groundwater include areas of loamy and clayey soils. Along the coastline, the land is classified as either non-agricultural (dunes) or Grade 4 (heaths on sandy soils).

The Blyth area that includes Sizewell typifies much of rural Suffolk - small, scattered and, in some cases, quite remote settlements set in an undulating landscape. The river valleys, which give the inland part its character, are designated as Special Landscape Areas. The coastline is designated as part of the Suffolk Coast and Heaths Area of Outstanding Natural Beauty and a Heritage Coast.

The last event of geological significance in the area was submergence during Neolithic (Holocene) times following which subsequent coastal changes have been governed by the nature and availability of sediment. As most of the coastline is associated with soft or loosely-aggregated material, there has been an abundant supply of sediment available for movement by waves and currents. At Aldeburgh, to the south of Sizewell, longshore drift has created Orford Ness by depositing sediment across the estuary of the Alde and diverting its course southwards. The river outlet is now 12 miles from its original location.

According to Suffolk Coastal District Council [26]:

“The Shoreline Management Plan has concluded that average, long term, historical rates of erosion may be expected to accelerate in consequence of predicted sea level rise and lead to a further cliff retreat in the next 75 years of the order of 150 m at Dunwich Village (immediately north of Sizewell) to 190 m at the Greyfriars Wood. For the benefit of the built environment and certain conservation interests the shoreline management strategy will be to seek a means of controlling and slowing down the rate of cliff erosion.’…‘Until such means have been identified and a programme for their implementation has been drawn up, it must be assumed that uncontrolled erosion could occur as predicted and that, hence, for this length of the coast, a policy which generally prohibits development within the area indicated on the Proposals Map should be maintained.”

Projected Future Characteristics

Sizewell is a coastal site and the landscape has been created by coastal processes that have been continuously eroding, sorting and redistributing an abundance of available sediment over thousands of years. This sediment derives largely from the poorly-consolidated Quaternary deposits that outcrop along the coastline of Suffolk and Norfolk and that are available on the sea floor. The model of landscape change that is most applicable to the Sizewell site is that of a drift-aligned beach. There is a continuous cycle of change to the beach profile with storm draw-down being balanced by swash build-up. In addition, there is a long-term southerly drift-alignment caused by waves arriving at an oblique northerly angle to the coastline. A pool of offshore sediment is continuously being reworked by tides and wave energy and there is a 2-way exchange of sand between the beach and the backshore and dune sediment stores. The rapidly eroding soft cliffs at Dunwich to the north are judged to be one of the main sources of supply. This material is sorted and redistributed with a through-flow of coarse sediment at Sizewell and a net loss to the south.

According to Sutherland, Brew and Williams [27], ‘Longshore transport is southwards along most of this coastline. There is a supply of sediment of around 40,000 m^3/year from the eroding cliff at Dunwich [4-5 km north of Sizewell]. The percentage of shingle on the beach increases to virtually 100% at Orfordness. It is believed that sand leaves the coast at Orfordness.’

Various rates of longshore transport are quoted by Sutherland, Brew and Williams [27] for Sizewell and nearby locations. Rates vary greatly depending on year and on the model employed for calculation. Halcrow [28] gave a value for Sizewell of 3,450 $m^3\ y^{-1}$, which Sutherland, Brew and Williams [27] reflect on as being low. Vincent [29] gave a value for Sizewell of 85,000 $m^3\ y^{-1}$. Other values by Vincent and by Onyett and Simmonds [30] for the relevant coastline vary by a factor of 2 either side of 100,000 $m^3\ y^{-1}$.

The overall coastline is subject to rapid erosion, but this varies in time and space as local controls vary in influence. There are a number of ‘ness’ or uncliffed projections that appear to have an important bearing on sediment transport along the coast. The relevant nesses are Benacre Ness, Southwold, Thorpeness and Orford Ness [31]. The evolution of the nesses, which act as temporary sinks, and of offshore sandbanks seems likely to have a bearing on the stability of the coastline at Sizewell, which is located between the Southwold and Aldeburgh areas.

Rates of cliff erosion are very variable, ranging from nothing either at or close to the nesses, to high values elsewhere. At Covehithe, between 1882 and 1903, 5.2 m y^{-1} were lost, though the rate decreased to 2.7 m y^{-1} between 1925 and 1952. At Benacre between 1925 and 1958, 5.8 m y^{-1} were lost. Further to the south at Dunwich, rates of erosion are just as variable being between 0.06 m y^{-1} and 3.53 m y^{-1} between 1587 and 1975; an average of 1.15 m y^{-1}. At Easton Bavents, rates of approximately 2.80 m y^{-1} are the average since 1849 [32]. However, recently, due to the protection given by the enlarged Dunwich/ Sizewell sandbanks (see below), erosion has decreased immensely [31].

There are a number of sandbanks that are sinks for fine to medium sand, including Aldeburgh Ridge, Aldeburgh Napes, Sizewell and Dunwich Banks [31]. The Sizewell Bank, a banner bank from the Coralline Crag core at Thorpeness, and Dunwich Banks have amalgamated since 1824 when they were separate entities. They have expanded northwards at an average rate of 49 m y^{-1} up to 1965 [32]. At the same time, the banks have moved shoreward at a rate of up to 10.7 m y^{-1}. If this rate were to continue, these banks would amalgamate with the coastline by approximately 2150 AD. However, it is more likely that the combined bank will become a banner bank to the north of Thorpeness. This could mean, if the channel between the bank and the coast becomes increasingly flood dominant, that the sand volumes moving south will increase in the future along the coastline, with the Sizewell/Dunwich Bank, Aldeburgh Ridge and the Whiting Banks being among the principal recipients. A comparison of the losses of sediment from the nearby coastline and the gains on these two offshore banks, suggests that these are of the same magnitude [32]. However, sand could be moving in from the north or from offshore and thus complicate this simple relationship [31].

Comparison of the modern 1:25,000 map with an historic 1:10,560 topographic map dated 1905 suggests that drift-alignment has maintained a stable longshore coastline profile for the last 100 years. However, the coastline as a whole is undergoing shoreline retreat [26] and is vulnerable to accelerated retreat due to rising sea level and increased wave energy resulting from climate warming. For this reason, 'Pending the establishment of the means and programme for the implementation of the managed retreat of the shoreline, the local planning authority will not permit further new development within the area indicated on the Proposals Map unless it can be demonstrated that the design life of the development is commensurate with historically observed and predicted future rates of coastal erosion' [26].

The key to shoreline stability at Sizewell according to this model is the availability of sediment and, intuitively, the supply from erosion of the Norwich Crag would seem to be assured medium-term. The risk is that supply from the north decreases, resulting in a thinning of the beach and increased wave attack against the shoreline, leading to coastline retreat. Left without protection, the Sizewell site may then become an island with flooding of the areas currently recognised as being subject to inundation.

Intuitively, the steady-state drift-alignment of the coast at Sizewell is expected to be stable over the next 15 years, and, as mentioned above, the presence of Sizewell 'B' will ensure that a 'hold the line' policy of coastline management will be enforced. On a 100 year timescale, the coastline is considered to be vulnerable to change and extensive coastline retreat is a possibility. In order to improve estimates of change over this timescale, a regional sediment model is required, such that the drift-aligned model for Sizewell is given an appropriate spatial framework of sources and sinks both along the coastline and offshore.

There is an extensive literature on historical geomorphology and on modern process geomorphology and coastal oceanography relevant to the Suffolk coast [33]. This literature should be combined with future monitoring of coastal change and of sediment sources and sinks to support projections of coastal change over the next 100 years.

A9 - Winfrith

Current Context

The Winfrith site is in Dorset some 12 km east of Dorchester and Weymouth. The site is some 7 km inland from the well known English channel coastline features of Lulworth Cove and Durdle Door. The site is at an elevation of about 25 m AOD with land rising steeply to the south. Immediately to the north is the floodplain of the River Frome from which the site is separated by a railway and road. The floodplain lies at about 18 m AOD and the site does not lie within the area subject to flooding.

The solid geology of the site comprises Tertiary (Eocene) sands belonging to the Pool Formation. These sands are largely covered and obscured by alluvium within the river valley and by Head deposits, which are in turn overlain by river terrace sands and gravels, over the site. These lithologies have given rise to free-draining acidic sandy and loamy soils for which the natural vegetation of the area under the prevailing climate was heathland. In 1902, much of the area was still heathland. Some heathland remains and some areas have been wooded, but much has been reclaimed and improved and is given over to grazing.

Projected Future Characteristics

Winfrith occupies a lowland, valley bottom setting. The river is controlled by engineering works, but with a wide expanse of water meadows available for the storage of floodwater. The site lies beyond the immediate floodplain.

Comparison of the modern topographic maps with an historical map dated 1902 shows the floodplain largely unchanged over 100 years: some meanders are the same, whereas other channels have changed. Elsewhere, there has been a large loss of heathland and much industrialization, urbanisation and improvements of land for commercial farming.

Some caution is merited in relation to extreme hydrological events and their possible association with climate change, especially given the close proximity of the Winfrith site to the River Frome. However, direct and indirect effects due to sea level changes are unlikely and based on existing information, no change to the landscape with significance for the nuclear facilities at Winfrith is anticipated during the next 15 years from continuation of the current geomorphological regime. Any changes on a 100 year timescale are likely to be limited.

A10 - Wylfa

Current Context

Wylfa power station is located at Wylfa Head on the northernmost coast of the Isle of Anglesey in North Wales. It is a very remote and exposed location. The site faces out across the Irish Sea. The Isle of Man is some 70 km north. Wylfa Head is part of an indented rock coastline. The station is at 15 m AOD and is built on Pre-Cambrian metamorphic rocks of the New Harbour Group. These rocks comprise mica schists and psammites.

Most of the area other than Wylfa Head and the station site is blanketed in Devensian Till which is a diamicton. Much of the landscape of northwest Anglesey is characterized by the drumlin field formed by the mounding of diamicton by sub-glacial processes during the Devensian (the most recent glacial phase of the Quaternary).

Projected Future Characteristics

Wylfa has an exposed location on the rocky coastline of Anglesey and is subject to coastal erosion. Climate change and rising sea levels are expected to increase wave attack. The generic landscape behaviour model for a rocky shore is applicable to Wylfa. The power stations are founded on Pre-Cambrian metamorphic rocks that are highly resistant to erosion, but no specific information on modes of weathering or cliff recession at Wylfa came to light during this study. No significant landscape change is anticipated in the next 15 years and changes may also be limited over the next 100 years.

A11 - Summary

An assessment of the vulnerability of the case study sites to landscape change has been made. The focus is on the timescale for decommissioning and decontamination of the sites. This was typically 25 years to somewhat more than 100 years, except for Drigg. It is expected that for the 300 year timescale, the likelihood and significnace of any processes related to sea level rise will increase at vulnerable sites.

Table A2: Assessment of vulnerability of identified sites to landscape change (primarily sea level rise and associated coastal proceses).

NDA Sites	To 2020	To 2100
Sizewell	Possible	Vulnerable to erosion (1)
Bradwell	Unlikely	Vulnerable to inundation (2)
Dungeness	Possible	Very vulnerable to erosion (3)
Culham	Very unlikely	Unlikely (4)
Harwell	Very unlikely	Very unlikely (5)
Winfrith	Very unlikely	Unlikely (4)
Hinkley Point	Unlikely	Possible (6)
Oldbury & Berkeley	Unlikely	Vulnerable to inundation (7)
Trawsfynydd	Very unlikely	Very unlikely (5)
Wylfa	Unlikely	Unlikely (8)
Capenhurst, Springfields and Chapelcross	Very unlikely	Very unlikely (5)
Drigg and the Sellafield complex	Unlikely	Vulnerable to erosion (9)
Hunterston	Unlikely	Unlikely (8)
Dounreay	Unlikely	Unlikely (8), but possible for the shaft

Notes:

1. Vulnerable to loss of sediment availability from the north (drift-alignment).
2. Vulnerable to subsidence, rising sea level and rollover of the Blackwater estuary.
3. Very vulnerable to change in sediment availability, drift direction and human intervention.
4. Low risk of disruption by fluvial processes.
5. Inland site with very low rate of change (unverified).
6. Present massive sea defences provide protection.
7. Progressive marine transgression likely to claim the sites unless protected.
8. Hard rock coastal headland with low rate of erosion (unverified).
9. Currently considered to be protected by swash-alignment. Vulnerable to change in wave climate. Irt estuary likely to ‘flip’ with rising sea level.

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United Kingdom Nirex Limited
Curie Avenue
Harwell, Didcot
Oxfordshire
OX11 0RH

t +44 (0)1235 825500
f +44 (0)1235 831239
e info @ nirex.co.uk
w www.nirex.co.uk